Online ISSN 2215-9045

CIOH Scientific Bulletin

Cartagena de Indias, D.T. y C., Colombia

Ministerio de Defensa Nacional-Dirección General Marítima
Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe-CIOH
Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico-CCCP
Vol. 42 Num. 1. Pages 3 to 59. June 2023

Ministerio de Defensa Nacional
Dirección General Marítima
Autoridad Marítima Colombiana

Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe

Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico

CIOH Scientific Bulletin

No. 41 Núm. 2
June 2023

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CIOH Scientific Bulletin
Dirección General Marítima (Dimar)

Centro de Investigaciones Oceanográficas
e Hidrográficas del Caribe (CIOH)

Centro de Investigaciones Oceanográficas
e Hidrográficas del Pacífico (CCCP)

No. 42 (1), pages 3-59, june 2023

Cover
Actividades de levantamientos en litorales.

Editorial Dimar

Design and Assembly
Fenix Media Group S.A.S.

The CIOH Scientific Bulletin is a serial scientific journal, specialized in the different research areas of marine sciences (oceanography, hydrography, integrated management of coastal zones, protection of the marine environment, etc.), aimed at the scientific community and academia on a global level. It publishes unedited and refereed scientific articles every six months, the product of research projects carried out by the research centers from the General Maritime Directorate and other institutes, and researchers who make original contributions to the development of new knowledge. It is published in digital format under the online ISSN 2215-9045, in Spanish and English. Its distribution is done from the platform Open Journal System (OJS) (http://ojs.dimar.mil.co) and the Colombian Center for Oceanographic Data (Cecoldo) (https://cecoldo.dimar.mil.co/web/). This intellectual product has an open access policy (OA) for consultation, its conditions of use and distribution are defined through Creative Commons licensing.

Editorial

Science and Sovereignty: Scientific contributions from the CIOH Scientific Bulletin to the defense of Colombia before the International Court of Justice in The Hague

Ciencia y soberanía: contribuciones científicas desde el Boletín Científico del CIOH a la defensa de Colombia ante la Corte Internacional de Justicia de La Haya

DOI: https://doi.org/10.26640/22159045.2023.622

José Andrés Díaz Ruiz[1]

Citation:

Díaz Ruiz, J. A. (2023). Science and Sovereignty: Scientific contributions from the CIOH Scientific Bulletin to the defense of Colombia before the International Court of Justice in The Hague. *CIOH Sci. Bull.;* 42(2), 3-6. Online ISSN 2215-9045. DOI: https://doi.org/10.26640/22159045.2023.622.

On Thursday 13 July 2023, the International Court of Justice (ICJ) in The Hague issued its judgment, rejecting Nicaragua's claims for the recognition of its right to an extended continental shelf rights beyond 200 nautical miles from its coast, all of which fell within the exclusive economic zone (EEZ) and the continental shelf generated by the archipelago of San Andrés and the mainland coast of Colombia.

The entire nation, from the government, its institutions, and the general public, has acknowledged the enormous importance of the contribution made by the oceanographers and hydrographers of the Colombian National Navy (ARC) in preparing and creating scientific and technical documents, official nautical charts, high-resolution underwater maps, and so on, which were used in Colombia's defense against Nicaragua's claims and demands.

In the words of the Chinese judge at the ICJ in a section of her judgment:

> "[...] 54. Refuting Nicaragua's claim, Colombia's expert reports present the analysis of scientific evidence gathered from public sources and the **Colombian Navy** regarding the natural extension of the land and seabed from Nicaragua's mainland territory into the Caribbean Sea. **The key conclusion of the reports relevant to this case is that the edge of Nicaragua's natural extension of mainland territory into the Caribbean Sea is not the Hess Escarpment (the southern limit of the Nicaraguan Rise), as asserted by the Applicant (Nicaragua), but rather the Pedro Bank-Providencia Depression escarpment line**, which separates the southern edge of the Nicaraguan Rise proper from the Lower Nicaraguan Rise. According to Colombia's experts, the extent of Nicaragua's continental margin is much smaller than what Nicaragua's experts suggest, **and consequently, Nicaragua's landmass does not extend within the 200 nautical miles from the mainland coast of Colombia.**"

This statement is the result of the excellent work carried out by the scientists and researchers of the Colombian Navy's. The judge refers to them as "Colombia's experts," and they have conducted these researches from the Center for Oceanographic and Hydrographic Research (CIOH) and some of these, has been published in this Scientific Bulletin over recent decades.

True to the scope of this journal, the CIOH Scientific Bulletin, through open access to its bilingual content, has enabled greater visibility

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of the work conducted by CIOH researchers, academia, and other institutions on topics related to **physical oceanography** (Dagua, Torres, & Monroy, 2018; Monroy & Zambrano, 2017; Rangel *et al*. 2015; Andrade & Barton, 2013; Torres & Lonin, 2007; Molares *et al*. 2004; Molares, 2004; Andrade, Giraldo, & Lonin, 1996; Garay *et al*. 1988; González, 1987); **chemical oceanography and pollution** (Garay & Castro, 1993; Garay & Gutiérrez, 1984); **hydrography and geomorphology** (Andrade, 2005; Tabares, Soltau, & Díaz, 1996; Soltau, Díaz, & Molina, 1993; Elhuyar, 1988); **coastal hazards** (Andrade, 2022; Rey *et al*. 2019; Echeverry & Marriaga, 2013; Andrade & Pinzón, 2011; Díaz & Andrade, 2011; Plazas, Ortiz, & Lizcano, 2011; Collazos, Ospina, & Muñoz, 2007); **marine biology** (De La Hoz and Betancur, 2019; Lonin, Prada, & Castro, 2010; Prada *et al*. 2009; Taylor *et al*. 2007; Téllez, Márquez, & Castillo, 1988); **spatial planning** (Rueda, 2017; Molina *et al*. 2003), **coastal dynamics** (Lonin *et al*. 2022; Fajardo & Lonin, 2021; Zambrano & Andrade, 2011); **renewable energy from thermal gradients** (Torres & Andrade, 2006), and recently, **submerged cultural heritage** (Moreno & Báez, 2021). Articles published in this producer of new knowledge contributed to the foundation on which Colombia's position was built and defended. It's a humble but valuable contribution made by our Scientific Bulletin to the great satisfaction that fills the entire country today.

As the Director of the CIOH, I publicly recognize and congratulate the scientific staff of the Center for Oceanographic and Hydrographic Research and all their collaborators who, in one way or another, contributed through the CIOH Scientific Bulletin with their articles that added to and formed the basis on which the Colombian Navy, using their knowledge, successfully defended the maritime territory of Colombia from external threats.

The raison d'être of a navy is to win the war at sea! Today, it can be stated that the Colombian Navy, in its bicentenary, won a war in the Caribbean using its weapons of science, technical rigor, and the CIOH Scientific Bulletin as part of this.

Captain José Andrés Diaz Ruiz
Director of the Center for Oceanographic and Hydrographic Research of the Caribbean

Bibliography

Andrade, C. A. (2005). Surveying a natural deep sediment trap in the south-western Caribbean. CIOH Sci. Bull., 23: 129-133. https://doi.org/10.26640/22159045.143

Andrade, C. A. (2022). Colombian Caribbean warming and the intensity of hurricanes between June and December 2020. CIOH Sci. Bull., 41(2): 55-65. https://doi.org/10.26640/22159045.2022.602

Andrade, C. A., Giraldo, L. Lonin, S. (1996). Nota sobre la circulación de las aguas en el bajo Alicia y el sector de San Andrés Islas. CIOH Sci. Bull., 17: 27-36. https://doi.org/10.26640/22159045.82

Andrade, C. A.; Pinzon, V. (2011). Efectos de la sobreelevación del nivel del mar por el cambio climático en las playas de los cayos del archipiélago de San Andrés, mar Caribe Colombia. CIOH Sci. Bull., 29: 60-72. https://doi.org/10.26640/22159045.229

Andrade, C. A.; Barton, E. D. (2013). Sobre la existencia de una celda de circulación atmosférica sobre el Caribe y su efecto en las corrientes de Ekman en el mar Caribe suroccidental. CIOH Sci. Bull., 31: 73-94. https://doi.org/10.26640/22159045.252

Collazos, G.: Ospina, H.; Muñoz, A. (2007). Estudio descriptivo de la influencia del huracán Beta en las islas de Providencia y Santa Catalina. CIOH Sci. Bull., 25: 61-70. https://doi.org/10.26640/22159045.163

Dagua, C.; Torres, R.; Monroy, J. (2018). Condiciones oceanográficas de la reserva de biosfera Seaflower 2014–2016. CIOH Sci. Bull., 37: 53-74. https://doi.org/10.26640/22159045.2018.449

De La Hoz, L.; Betancur, S. (2019). Nuevo registro de la especie Cladopyxis hemibrachiata del grupo dinoflagelado para la reserva de la biósfera Seaflower, Caribe colombiano. CIOH Sci. Bull., 38(1): 41-43. https://doi.org/10.26640/22159045.2019.466

Díaz, J. A.; Andrade, C. A. (2011). Variaciones de la línea de costa en cayo Serrana y estrategias para su conservación ante las amenazas de origen natural. CIOH Sci. Bull., 29: 72-86. https://doi.org/10.26640/22159045.230

Echeverry, J. P.; Marriaga, L. (2013). Descripción fisiográfica de la isla de San Andrés: aproximación inicial al entendimiento integral de la problemática erosiva. CIOH Sci. Bull., 31: 49-72. https://doi.org/10.26640/22159045.251

Elhuyar, M. (1988). Estudio geomorfológico y sedimentológico del complejo carbonatado de las islas Providencia y Santa Catalina. CIOH Sci. Bull., 8: 35-70. https://doi.org/10.26640/22159045.28

Fajardo, O.; Lonin, S. (2021). Dinámica costera en la barrera arrecifal localizada en el sector nororiental de la isla de San Andrés, Caribe colombiano. CIOH Sci. Bull., 40(2): 13-33. https://doi.org/10.26640/22159045.2021.525

Garay, J.; Castillo, F.; Andrade, C.; Aguilera, J.; Niño, L.; De La Pava, M.; López, W. Márquez, G. (1988). Estudio oceanográfico del Caribe colombiano en el área del archipiélago de San Andrés y Providencia y cayos adyacentes. CIOH Sci. Bull., 9: 3-73. https://doi.org/10.26640/22159045.33

Garay, J.; Gutiérrez, H. (1984). Contribución al estudio oceanográfico químico del archipiélago de San Andrés y Providencia. CIOH Sci. Bull., 5: 25-59. https://doi.org/10.26640/22159045.16

Garay, J.; Castro, A. (1993). Niveles de hidrocarburos del petróleo en la isla de San Andrés, Caribe colombiano. CIOH Sci. Bull., 13: 85-101. https://doi.org/10.26640/22159045.57

González, E. (1987). Oceanografía física descriptiva del archipiélago de San Andrés y Providencia, con base en el análisis de los cruceros Océano IV a IX. CIOH Sci. Bull., 7: 40-55. https://doi.org/10.26640/22159045.24

Lonin, S.; Prada, M.; Castro, E. (2010). Simulación de dispersión de las larvas de caracol pala Strombus gigas en la reserva de biósfera Seaflower, Caribe occidental colombiano. CIOH Sci. Bull., 28: 8-24. https://doi.org/10.26640/22159045.212

Lonin, S.; Adames, R.; Payares, J., Marriaga, L. (2022). Patrones de oleaje a partir de un modelo óptico en la isla Cayos de Serranilla, Caribe colombiano. CIOH Sci. Bull., 41(1): 63-72. https://doi.org/10.26640/22159045.2022.603

Molares, R. (2004). Clasificación e identificación de las componentes de marea del Caribe colombiano. CIOH Sci. Bull., 22: 105-114. https://doi.org/10.26640/22159045.132

Molares, R.; Vanegas, T.; Bustamante, J.; Andrade, C. (2004). Aspectos oceanográficos de las aguas sobre la depresión Providencia en mayo de 2004. CIOH Sci. Bull., 22: 11-25. https://doi.org/10.26640/22159045.124

Molina, A.; Niño, L.; Sierra, L.; García, C.; Velasco, S. (2003). La caracterización como base para el manejo integrado de las islas. CIOH Sci. Bull., 21: 114-133. https://doi.org/10.26640/22159045.120

Monroy, J.; Zambrano, A. (2017). Aspectos físicos del agua de mar entre las islas de Providencia y cayo Bajo Nuevo durante la época de lluvias de 2016. CIOH Sci. Bull., 35: 3-12. https://doi.org/10.26640/22159045.428

Moreno, M; Báez, L. (2021). Expedición Seaflower: el paisaje cultural marítimo de Providencia y Santa Catalina. Resultados preliminares. CIOH Sci. Bull., 40(1): 83-90. https://doi.org/10.26640/22159045.2021.566

Plazas, J. M.; Ortiz, J. C., Lizcano, O. (2011). Evaluación de la actividad ciclónica y el impacto del oleaje en la isla de San Andrés desde 1851 hasta 2010. CIOH Sci. Bull., 29: 8-26. https://doi.org/10.26640/22159045.226

Prada, M.; Castro, E.; Pomare, C.; Bent, K.; Pomare, M. (2009). Identificando patrones espaciales y temporales de la abundancia de langosta en el archipiélago de San Andrés: una experiencia de comanejo. CIOH Sci. Bull., 27: 156-166. https://doi.org/10.26640/22159045.208

Rangel, O. E.; Herrera, E.; Palomino, A.; Herrera, G.; Andrade, C. A. (2015). Análisis de rasgos del clima hidrodinámicos encontrados en el

Atlas de los datos oceanográficos de Colombia 1922-2013. CIOH Sci. Bull., 33: 3-17. https://doi.org/10.26640/22159045.275

Rey, W.; Monroy, J.; Quintero-Ibáñez, J.; Escobar, G.; Salles, P.; Ruiz-Salcines, P.; Appendini, C. (2019). Evaluación de áreas susceptibles a la inundación por marea de tormenta generada por huracanes en el archipiélago de San Andrés, Providencia y Santa Catalina, Colombia. CIOH Sci. Bull., 38(2): 57-68. https://doi.org/10.26640/22159045.2019.465

Rueda, S. (2017). Medidas regionales de planeamiento espacial marino para mejorar la sostenibilidad del área marina protegida de Seaflower en el mar Caribe colombiano. CIOH Sci. Bull., 35: 41-62. https://doi.org/10.26640/22159045.431

Soltau J.; Díaz, J.; Molina, C. (1993). Descripción del proyecto carta batimétrica de las aguas económicas exclusivas de Colombia en la zona de San Andrés, Providencia y los cayos. CIOH Sci. Bull., 14: 157-169. https://doi.org/10.26640/22159045.68

Tabares, N.; Soltau, J.; Díaz, J. (1996). Caracterización geomorfológica del sector suroccidental del mar Caribe. CIOH Sci. Bull., 17: 3-16. https://doi.org/10.26640/22159045.80

Taylor, E.; Hernández, D.; Howard, F.; Peñaloza, G.; Posada, S.; Howard, N.; Robinson, R.; Prada, M. (2007). Impactos en los arrecifes de coral ocasionados por el huracán Beta en la plataforma insular de Old Providence y Santa Catalina. CIOH Sci. Bull., 25: 71-77. https://doi.org/10.26640/22159045.164

Téllez, C.; Márquez, G.; Castillo, F. (1988). Fitoplancton y ecología en el archipiélago de San Andrés y Providencia: Crucero Océano VI en el Caribe colombiano. CIOH Sci. Bull., 8: 3-26. https://doi.org/10.26640/22159045.26

Torres, R. R.; Andrade, C. A. (2006). Potencial en Colombia para el aprovechamiento de la energía no convencional de los océanos. CIOH Sci. Bull., 24: 11-25. https://doi.org/10.26640/22159045.145

Torres, R. R.; Lonin, S. (2007). Estudio del espectro de oleaje en el Caribe observado con boyas y su representación en el espectro JONSWAP. CIOH Sci. Bull., 25: 8-18. https://doi.org/10.26640/22159045.158

Zambrano, J. A.; Andrade, C. A. (2011). Cambios en la línea de costa del cayo Serranilla entre 1944 y 2009, archipiélago de San Andrés, Colombia. CIOH Sci. Bull., 29: 87-103. https://doi.org/10.26640/01200542.29.87_103

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

DOI: https://doi.org/10.26640/22159045.2023.611 **Date received:** 2023-02-01 / Date accepted: 2023-06-16

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Citation:

Cantero, Y. C.; Astaiza, C. A.; Mesías A. M.; Quintero, P. A. (2023). Study of the sedimentation and erosion rates of the La Barra sector of the San Andrés de Tumaco navigable channel, Nariño. *CIOH Sci. Bull.;* 42(1): 7-25. Online ISSN 2215-9045. DOI: https://doi.org/10.26640/22159045.2023.611

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).

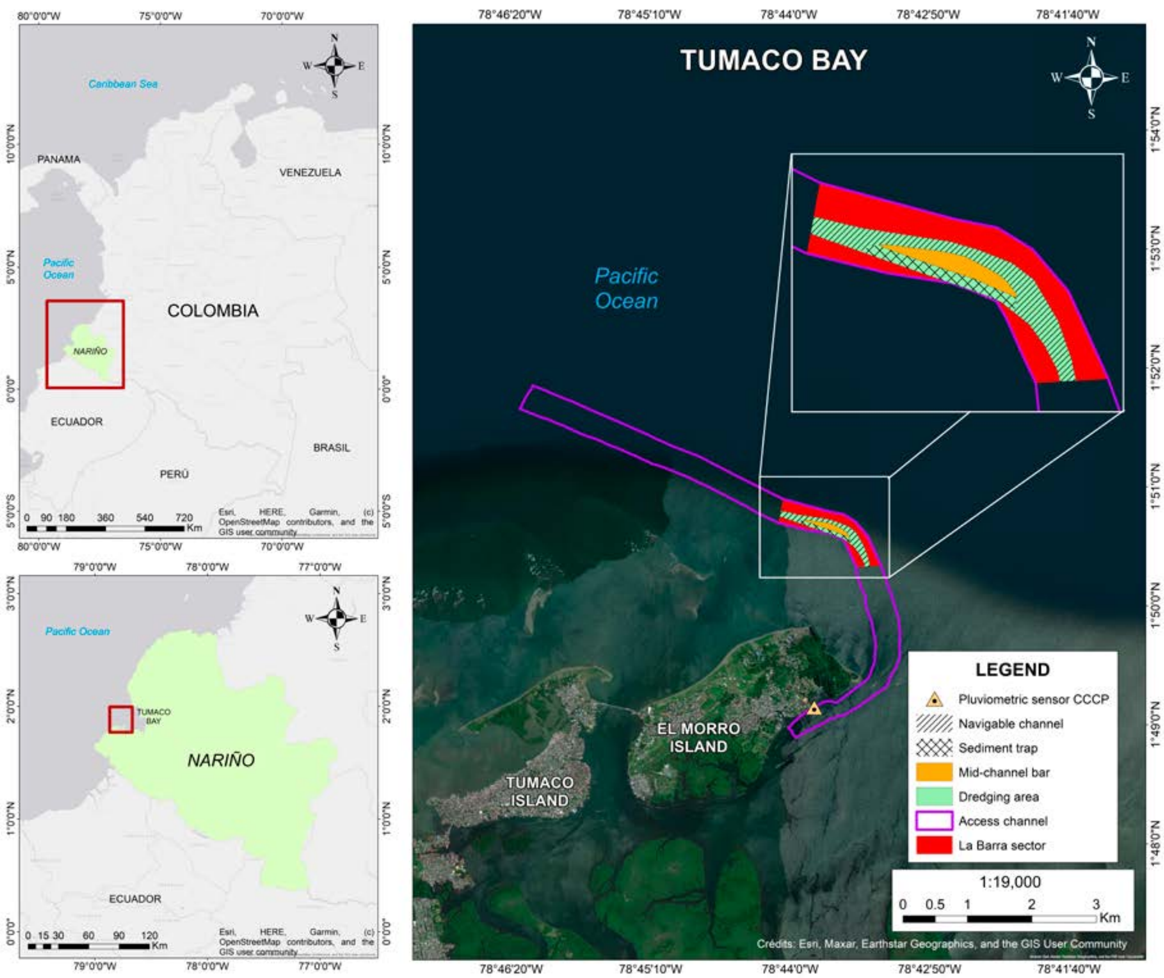


Figure 1. Geographic location of the study area

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

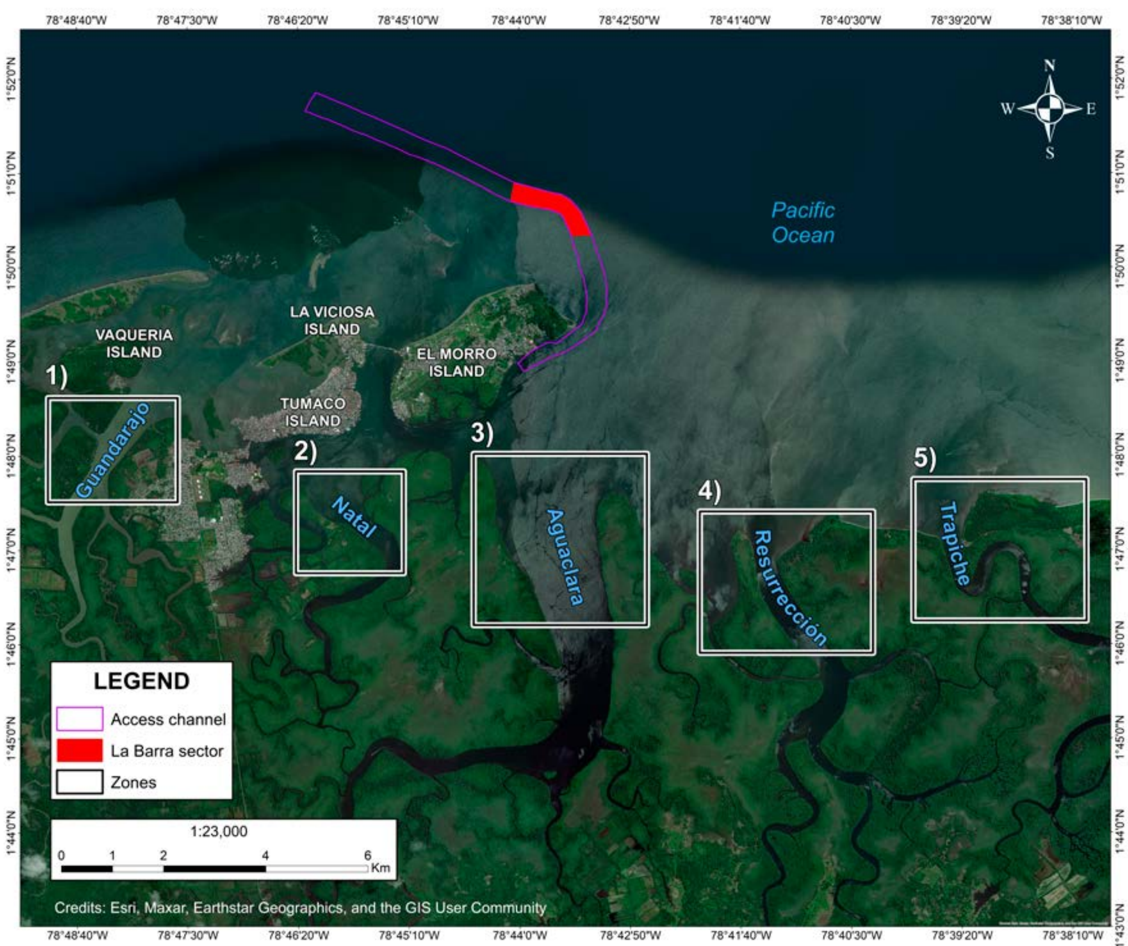


Figure 2. Geographic location of the study area and areas for coastline dynamics analysis in the estuaries of the Mira River estuary system

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.

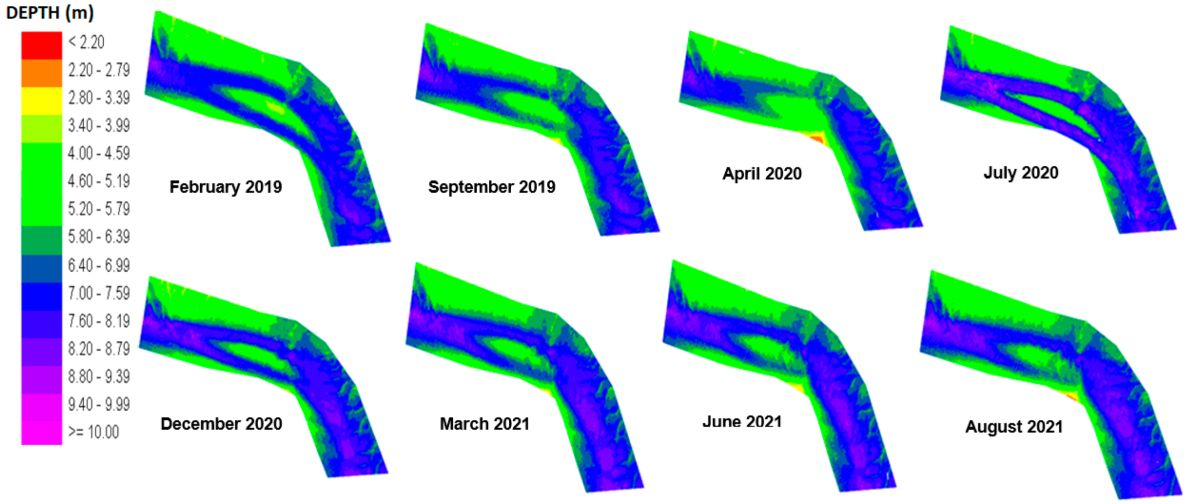


Figure 3. Bathymetry from 2019 to 2021

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).

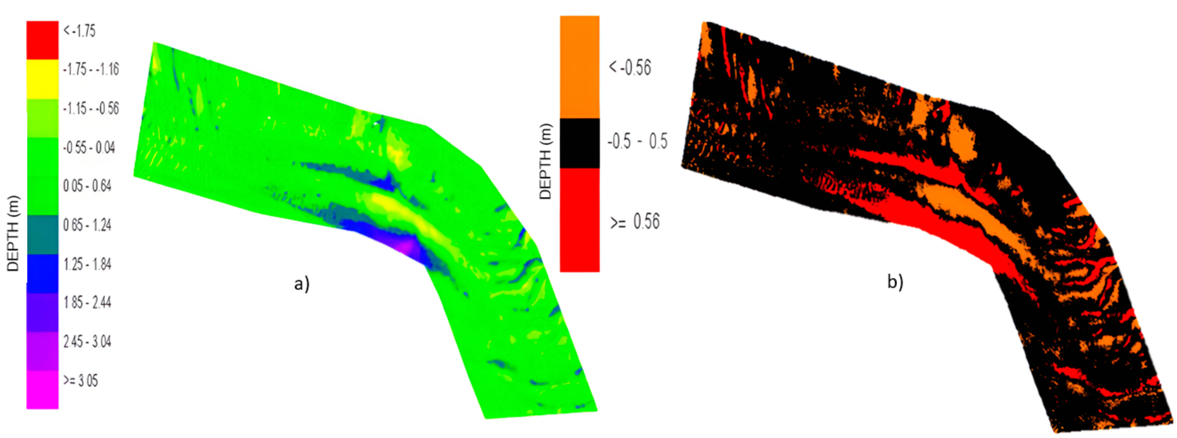


Figure 4. TIN to TIN Difference February 2019 - September 2019, La Barra sector

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).

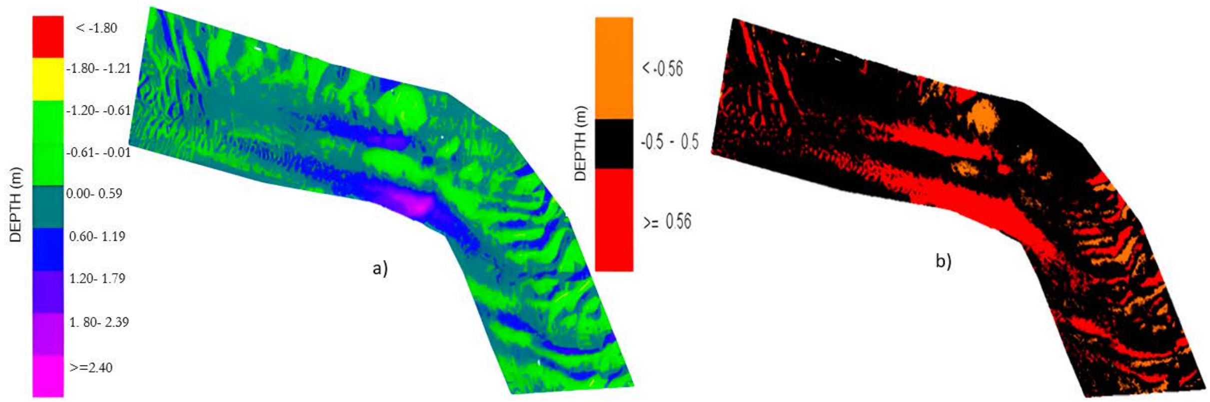


Figure 5. TIN to TIN Difference September 2019 - April 2020, La Barra sector

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).

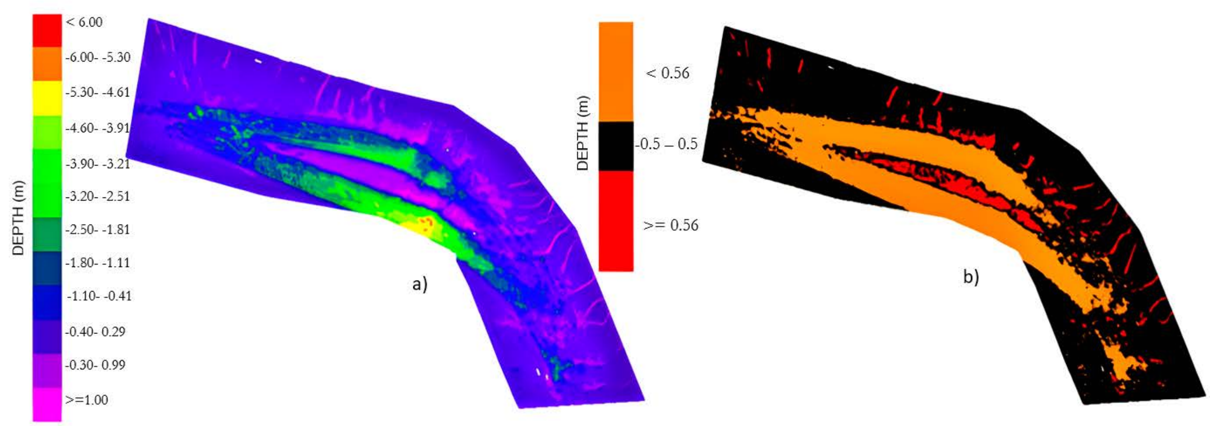


Figure 6. TIN to TIN Difference July 2020 - April 2020, La Barra sector

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.

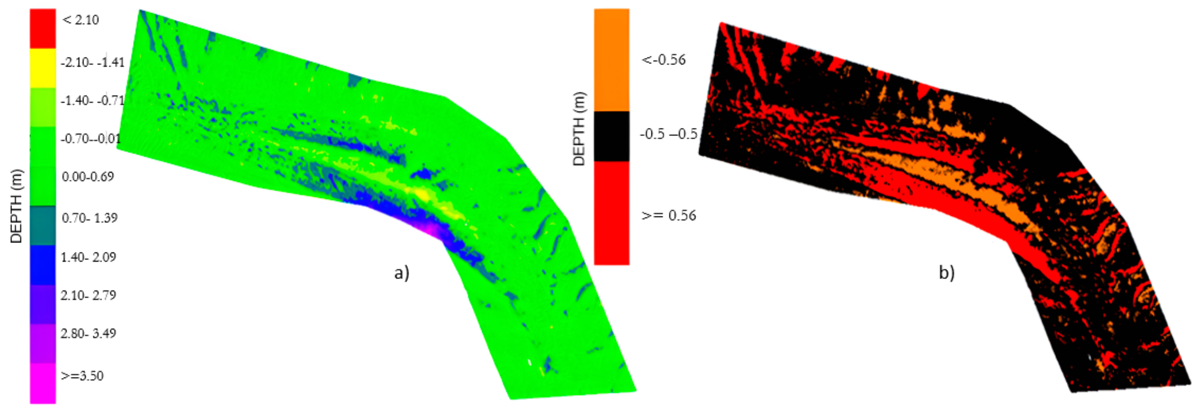


Figure 7. TIN to TIN Difference July 2020 - December 2020, La Barra sector

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.

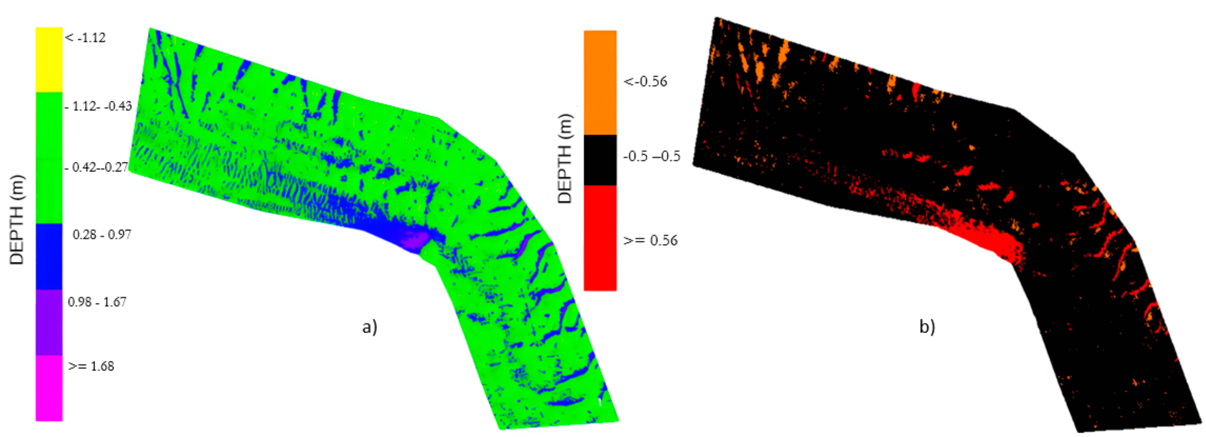


Figure 8. TIN to TIN Difference December 2020 - March 2021, La Barra sector

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.

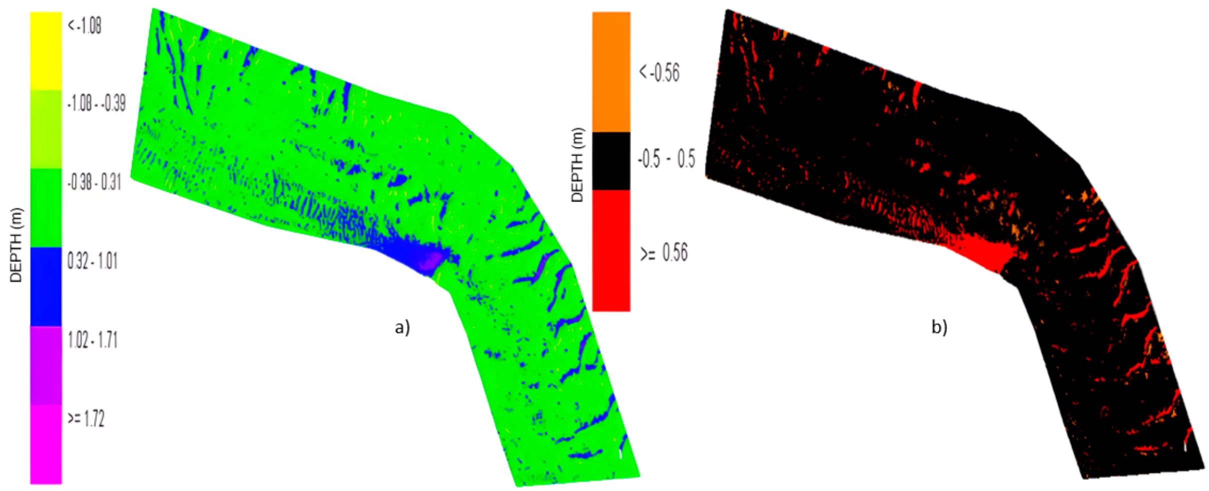


Figure 9. TIN to TIN Difference March - June 2021, La Barra sector

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.

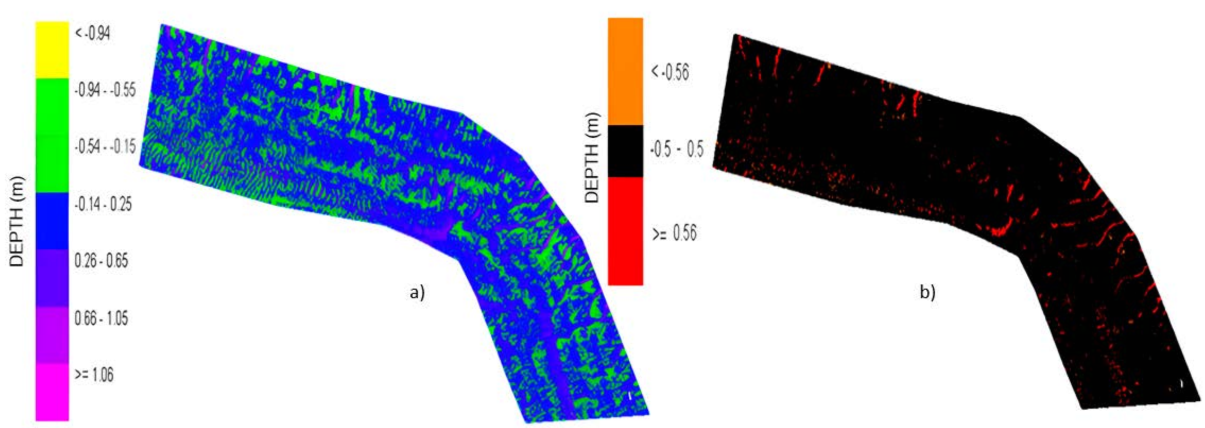


Figure 10. TIN to TIN Difference June - August 2021, La Barra sector

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.

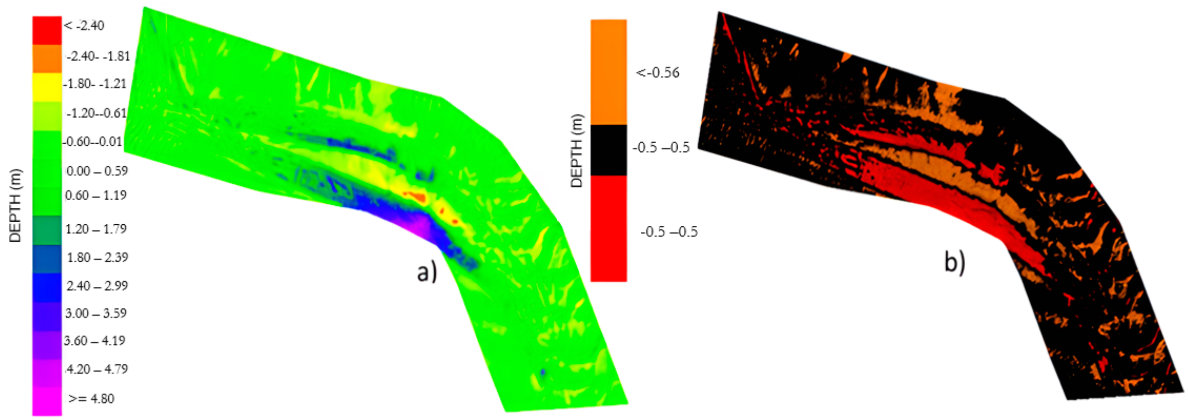
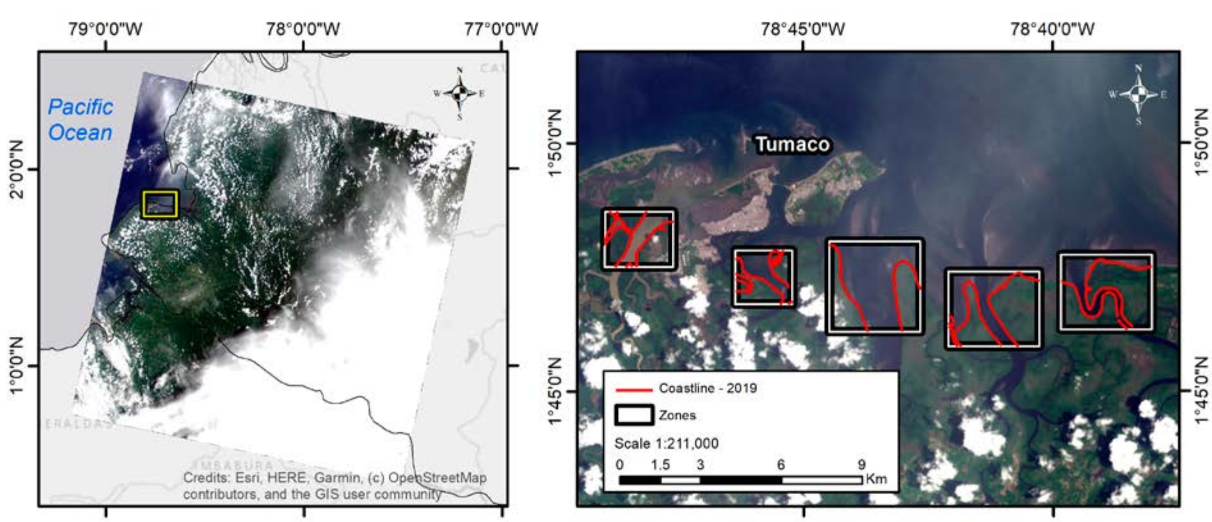


Figure 11. TIN to TIN Difference July 2020 - August 2021, La Barra sector

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.



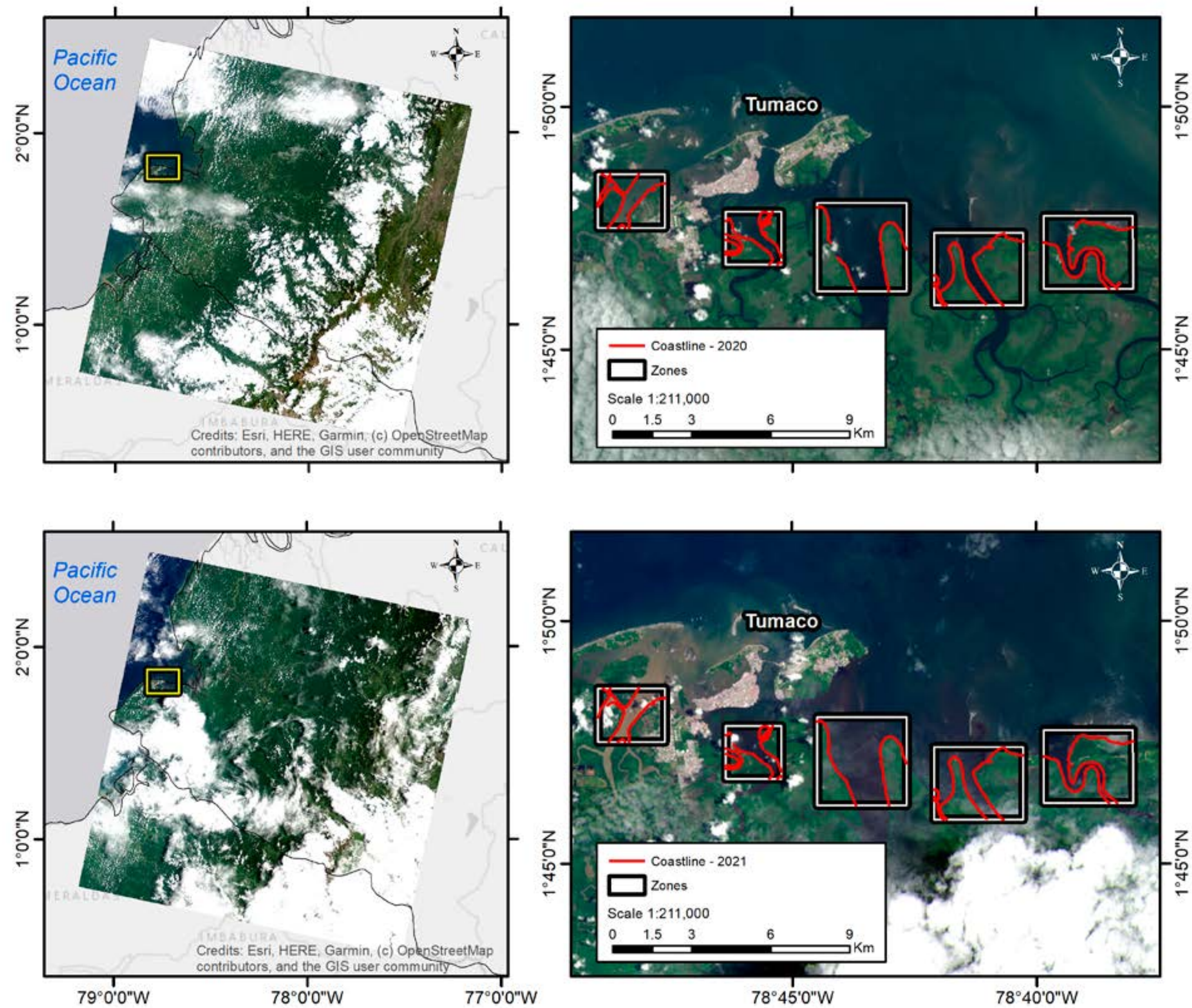


Figure 12. (Left) Visualization of the satellite images used. (Right) Coastline tracing for each satellite image

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.

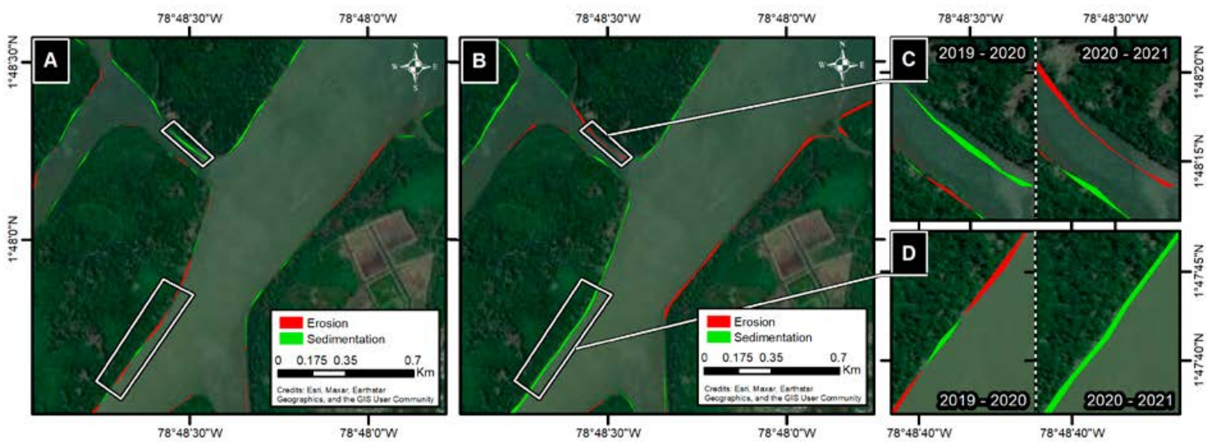


Figure 13. Areas of erosion and sedimentation in Zone 1. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

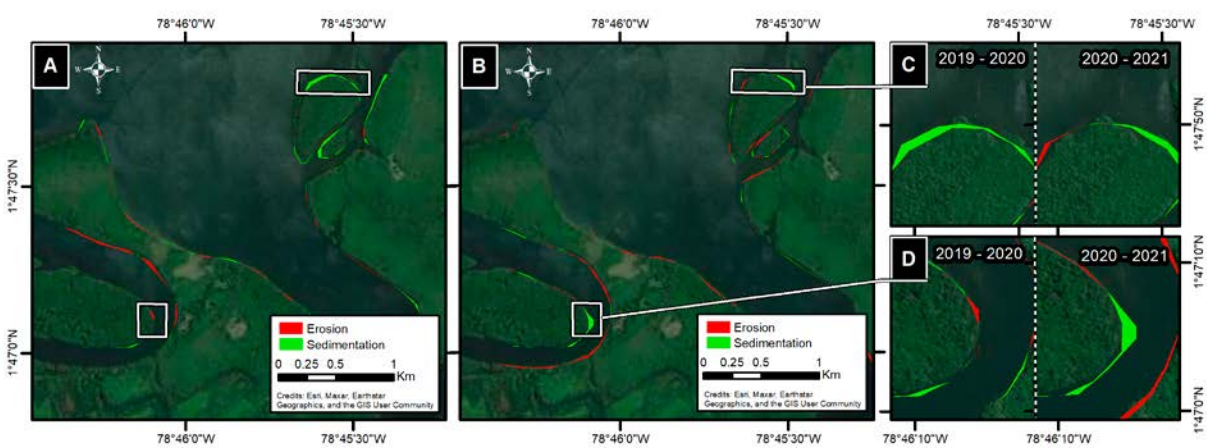


Figure 14. Erosion and sedimentation areas in Zone 2. **A)** 2019 - 2020. **B)** 2020 - 2021. **C)** and **D)** Enlargement of specific areas for better visualization

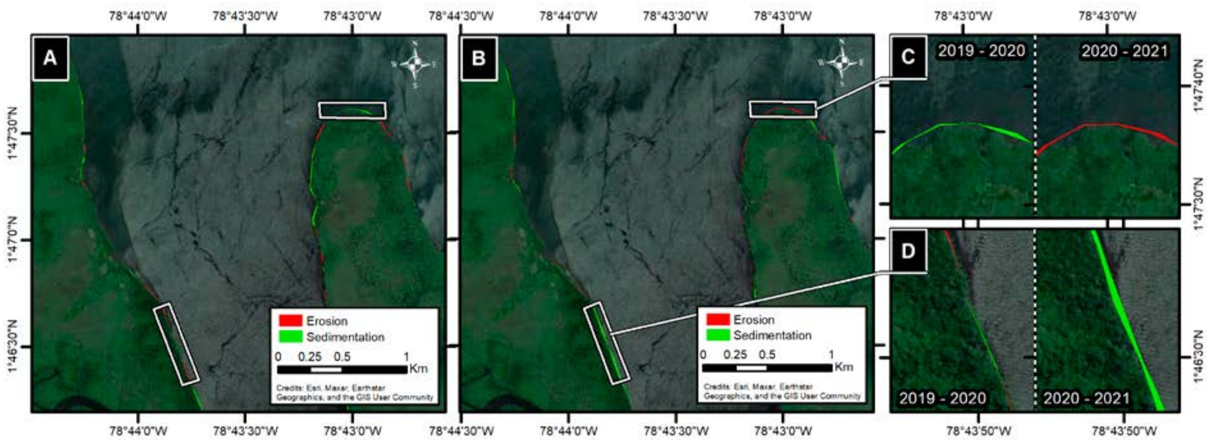


Figure 15. Areas of erosion and sedimentation in Zone 3. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

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 m^2 of retreat and 10 880 m^2 of accretion, while during the 2020-2021 period, sedimentation increased and erosion decreased, with 35 440 m^2 of accretion and 23 572 m^2 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.

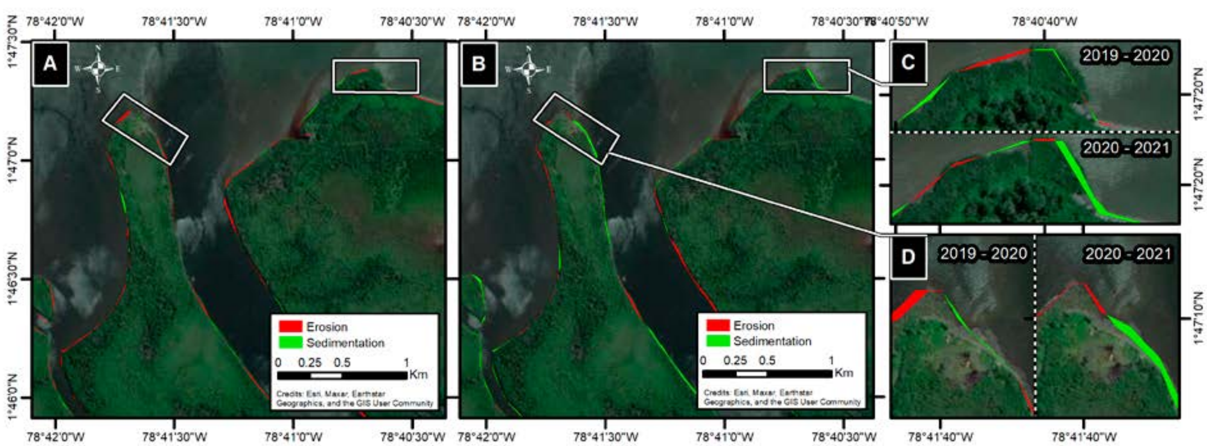


Figure 16. Areas of erosion and sedimentation in Zone 4. **A)** 2019-2020. **B)** 2020-2021. **C)** and **D)** Enlargement of specific areas for better visualization

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.

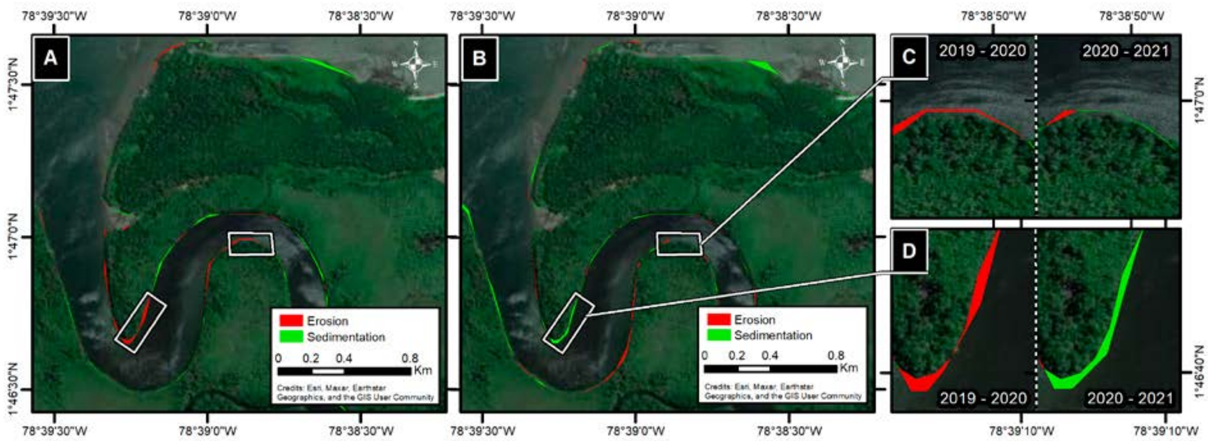


Figure 17. Areas of erosion and sedimentation in Zone 5. **A)** 2019-2020. **B)** 2020-2021. C and **D)** Enlargement of specific areas for better visualization

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.

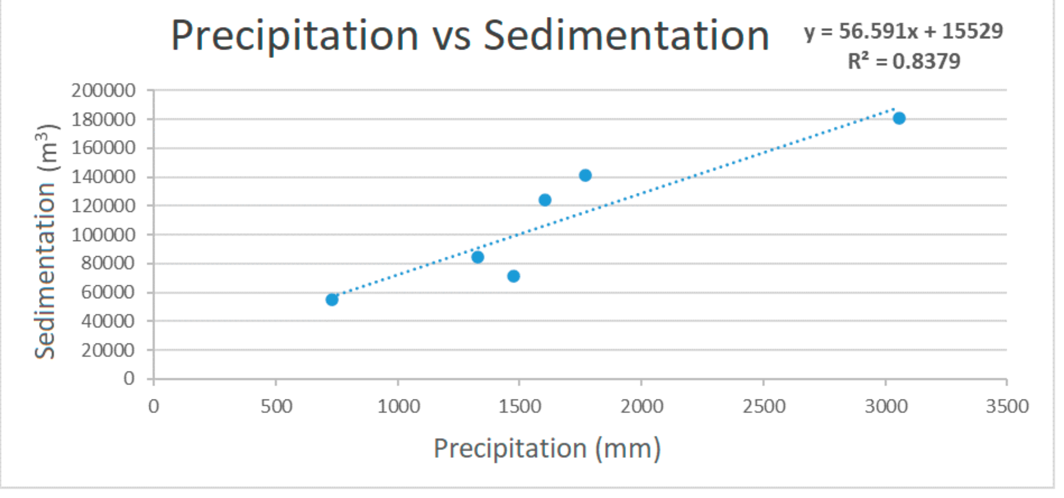


Figure 18. Accumulated precipitation (mm) vs. accumulated sedimentation (m^3)

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.

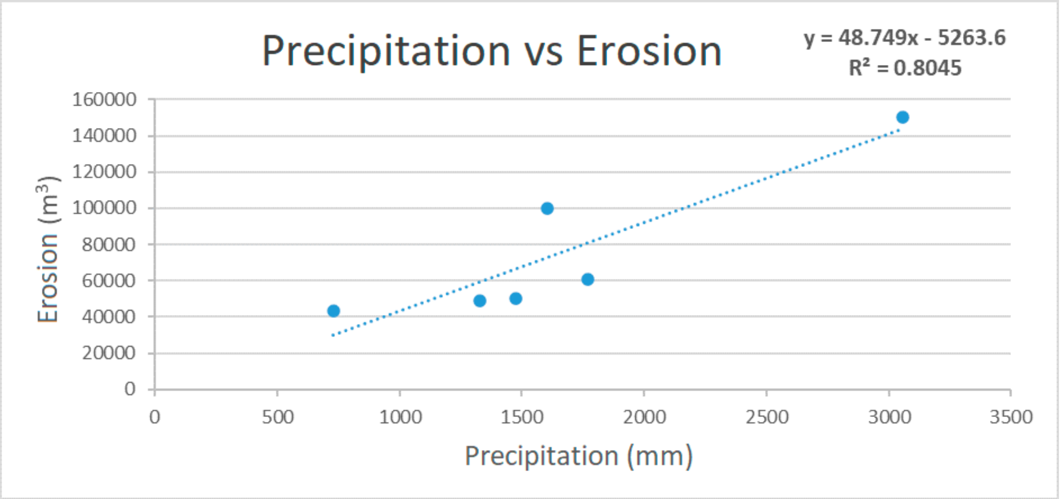


Figure 19. Accumulated precipitation (mm) vs. erosion (m³)

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 m³ 50 368 m³, 55 187 m³ – 43 172 m³, 84 136 m³ – 48 796 m³, 146 038 m³ – 88 973 m³, 123 894 m³ – 100 172 m³, 141 336 m³ – 61 008 m³, and 180 881 m³ – 150 245 m³.

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 m³/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.

Acknowledgments

The authors would like to express their gratitude to the members of the Integrated Coastal Zone Management Area – Bathymetric Surveys Section of the CCCP, especially to Carlos Ruz, Laureano Sarmiento, Juan Sanabria, José Munir de la Rosa, and the crew of ARC Cascajal for their support and assistance during the field data acquisition phase. They would also like to thank David Padilla for his support during the processing phase.

Funding Source

This work was carried out with financial support from the Center for Oceanographic and Hydrographic Research of the Pacific (CCCP) of the General Maritime Directorate (Dimar).

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Bibliography

Álvarez, M.; Pulido, D.; Solano, L.; Oviedo, F. (2018). Construcción de la superficie hidrográfica de referencia vertical para las bahías de Buenaventura y Málaga, Pacífico colombiano. *CIOH Sci. Bull.,* 36: 53-69. https://doi.org/10.26640/22159045.438

BAGGERWERKEN DECLOEDT & ZN|Colombia. (2020). *Dagrado de mantenimiento del Canal de Acceso al Puerto de Tumaco, en el departamento de Nariño.* Zoon N.V Sucursal Colombia: DEME, Creating land for the future.

Barajas, S.; García, M. (2014). *Variación decadal de batimetrías dentro del canal de tránsito marítimo de Tumaco y su relación con parámetros ocenaográficos.* Cartagena de Indias: Escuela Naval de Cadetes "Almirante Padilla".

Bermúdez, C.; Álvarez, M.; Niño, D. (2014). Caracterización de la geomorfología costera y sus coberturas vegetales asociadas, a través de sensores remotos, en la costa de Tumaco, Nariño. *CIOH Sci. Bull.,* 32: 27-46. https://doi.org/10.26640/22159045.262

Castañeda, D. J. (2017). Análisis de la línea de costa en el municipio de Buenaventura (Valle del Cauca, Colombia). Bogotá: Universidad Distrital Francisco José de Caldas.

Ceballos, J. D. (2011). Modelación hidráulica y morfodinámica de cauces sinuosos aplicación a la quebrada La Marinilla (ANT). *Boletín de Ciencias de la Tierra,* 30: 107-118.

Cifuentes, J. L.; Torres, M. P.; Frías, M. (1997). E*l océano y sus recursos II. Las ciencias del mar: ocenografía geológica y oceanografía química. 2ª. Edición.* México, D. F.: Fondo de cultura económica.

Cifuentes, C.; Mejía, G. (2015). Sedimentación en la bahía de Cartagena un impacto socioeconómico. *Dictamen Libre, Barranquilla*

Colombia. https://doi.org/10.18041/2619-4244/dl.16.3065

Collot, J.; Sallares, V.; Pazmiño, N. (2009). Geología y geofísica marina y terrestre del Ecuador desde la Consta Continental hasta las Isalas Galápagos. París: IRD – Institut de Recherche pour le Développement /INOCAR – Instituto Oceanográfico y Antártico de la Armada del Ecuador.

Corporación Autónoma Regional de Nariño. (2007). Zonificación y codificación de cuencas hidrográficas en el departamento de Nariño. Corponariño.

Correa, I.; González, J. (1989). Geomorfología general y sedimentología de la bahía de Tumaco. Instituto Nacional de Investigaciones Geología y Minería. Convenio Ingeominas-CCCP-Progog.

Dirección General Marítima. (2011). Resolución No 157 de 2011 de Dimar. Por la cual se fijan las especificaciones técnicas para la realización de levantamientos hidrográficos y generación de información batimétrica en los espacios marítimos y fluviales colombianos bajo la jurisdicción de Dimar. https://www.dimar.mil.co/sites/default/files/res_1572011.pdf

Dirección General Marítima. (2021). Resolución No 0693-2021 MD-Dimar-Subdemar-Ginsem-Arinv 3 de agosto de 2021. (pág. 2). Bogotá.

ESRI. (2016). ¿Qué es una superficie TIN?. ArcGIS Desktop. Obtenido de https://desktop.arcgis.com/es/arcmap/latest/manage-data/tin/fundamentals-of-tin-surfaces.htm

Gómez, J.; Peñaranda, J. (2012). Descripción del comportamiento de variables atmosféricas y oleaje en el Puerto de Tumaco a partir de observación de datos. *CIOH Sci. Bull.,* 30: 75-92. https://doi.org/10.26640/22159045.244

Guido, P.; Ramírez, A.; Godínez-Orta, L.; Cruz-León, S.; Juárez-León, A. (2009). Estudio de la erosión costera en Cancún y la Riviera Maya, México. Avances en recursos hidráulicos, 20: 41-55.

Niño, D.; Oviedo, F. (2018). Determinación de la variación morfológica costera de la Bahía de Tumaco, a partir de análisis multitemporal de sensores remotos. *CIOH Sci. Bull.,* 36:71-86. https://doi.org/10.26640/22159045.439

Nivia, A.; Pérez, C.; Sepúlveda, J. (2003). Geomorfología y geología de la Plancha 383 Tumaco. Cali: Ingeominas.

Pulido, D.; De Lisa, A.; David; D.; Guzmán, R. (2013). Determinación de los datums de referencia vertical con fines hidrográficos para la Bahía de Cartagena. *CIOH Sci. Bull.,* 31: 175-190. https://doi.org/10.26640/22159045.258

Restrepo, J. D. (2005). *Los sedimentos del río Magdalena: reflejo de la crisis ambiental.* Medellín, Colombia: Fondo Editorial Universidad EAFIT.

Restrepo, J. C.; Otero, L.; López, S. (2009). Clima de oleaje en el Pacífico Sur de Colombia, delta del río Mira: Comparaciones estadísticas y aplicaciones a procesos costeros. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales,* 33: 339-357.

Rojas, D.; Rodríguez, H.; Uribe, S.; Osorio, L.; Iregui, P.; Pérez, N.; Pedroza, W.; Vega-Barbosa, G.; León, H.; Monroy, J.; Grisales, C.; Delgado, N.; Medina, O.; Rivera-Páez, S. (2018). *Intereses de Colombia en el mar: reflexiones y propuestas para la construcción de un país marítimo.* Bogotá: Escuela Superior de Guerra: Samuel Rivera Páez.

Survey, U. S. (2021). Earth Explorer. Obtenido de https://earthexplorer.usgs.gov/

Tejada, C. (2003). *Clima marítimo y dinámica litoral de la bahía de Tumaco, datos básicos para la evaluación de riesgos ambientales marinos. Bol. Cient. CCCP,* 10: 67–76. https://doi.org/10.26640/01213423.10.67_76

Tejada, C.; Otero, L.; Castro, L.; Afanador, F.; Devis, A.; Solano, J.; Fonseca, A. (2003). *Aportes al entendimiento de la bahía de Tumaco.* Entorno oceanográfico, Costero y de Riesgos. Colombia: Dimar.

Scientific and technological research article

Oceanographic cruises within a spatial data infrastructure. Colombia case study

Cruceros oceanográficos sobre una infraestructura de datos espaciales. Caso de estudio Colombia

DOI: https://doi.org/10.26640/22159045.2023.615 **Date received:** 2023-05-18 / Date accepted: 2023-07-18

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Citation:

Ortiz-Martínez, R.; Castañeda, D. P.; Santizo, M. A. (2023). Oceanographic cruises within a spatial data infrastructure. a Colombian case study. *CIOH Sci. Bull.;* 42(1): 27-37. Online ISSN 2215-9045. DOI: https://doi.org/10.26640/22159045.2023.615

Abstract

Oceanographic cruises, and scientific expeditions at sea in general, constitute an important contribution to the historical memory of the beginnings and evolution of marine scientific research and, within the framework of the Decade of Ocean Science, access to the data collected for decades support sustainable ocean development. For this reason, the Colombian Center for Oceanographic Data carried out a process of archaeology and recovery of data and information from oceanographic cruises carried out in the Colombian Pacific and Caribbean from 1969 to 2020. Subsequently, the information was structured in a geographic database known as the national Maritime, Fluvial and Coastal Spatial Data Infrastructure. In addition, metadata was documented under a profile of the ISO 19115 standard, implementing good international practices, and a software application was developed to facilitate the search for geographic information and open access to measurements made on site. As a result, information from 130 oceanographic cruises (1969-2020) was made available, 96 technical cruise reports were recovered, 87 track charts were reconstructed, and 130 metadata were published, with the possibility of continuing to feed the system with new cruises and scientific expeditions.

Keywords: Research vessel, expedition reports, oceanographic data, Geographic information systems.

Resumen

Los cruceros oceanográficos y, en general, las expediciones científicas en el mar, constituyen un importante aporte a la memoria histórica de los inicios y evolución de la investigación científica marina; y en el marco del Decenio de las Ciencias Oceánicas, el acceso a los datos recopilados durante décadas apoya el desarrollo sostenible del océano. Por esta razón, desde el Centro Colombiano de Datos Oceanográficos se llevó a cabo un proceso de arqueología y recuperación de datos e información de los cruceros oceanográficos realizados en el Pacífico y Caribe colombianos desde 1969 hasta el 2020. Posteriormente, se estructuró la información en la base de datos geográfica denominada Infraestructura de Datos Espaciales Marítima, Fluvial y Costera de Colombia. Además, se documentaron metadatos bajo un perfil del estándar ISO 19115 implementando buenas prácticas internacionales, y se desarrolló una aplicación software para facilitar la búsqueda de información geográfica y acceso abierto a las mediciones realizadas en sitio. Como resultado se dispuso la información de 130 cruceros oceanográficos

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(1969-2020), se recuperaron 96 informes técnicos de cruceros, se reconstruyeron 87 rutas de buques de investigación y se publicaron 130 metadatos, con la posibilidad de seguir alimentando el sistema con nuevos cruceros y expediciones científicas.

Palabras claves: *buque de investigación, reportes de expedición, datos oceanográficos, sistemas de información geográfica.*

Introduction

Between 1969 and 1970, the first oceanographic cruises in the Colombian Caribbean and Pacific were carried out aboard the vessel ARC San Andrés. This initiative arose from the need to conduct oceanographic research within the framework of the then Colombian Oceanography Commission. It aimed to address the scientific and economic significance of the country's coastlines and establish a basic infrastructure to contribute to the knowledge and sustainable technical exploitation of ocean resources. The effort involved close coordination between national institutions and international organizations (ARC, 1970, 1971). Other countries in the region also launched significant oceanographic operations around the same time. For example, Chile began in 1960 using the former Chilean Navy corvette Chipana (Sievers, 2017), and Peru initiated an intensive monitoring program of marine conditions up to 150 miles off the coast aboard the BAP Bondy between 1958 and 1963 (Zuta & Flores, 1980).

These activities took place in a global context under the coordination of the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). The International Oceanographic Data and Information Exchange (IODE) of the IOC implemented a system of national oceanographic programs and the Reports of Observations/Samples Collected by Oceanographic Programs (ROSCOP) in the late 1960s to facilitate information sharing about planned and conducted research cruises (Rickards, 2007).

ROSCOP initially served as a primary inventory for tracking measurements and samples collected at sea aboard research vessels, covering various data disciplines, including physical, chemical, and biological oceanography, marine geology and geophysics, fisheries, marine pollution and marine meteorology. In the late 1980s, the International Council for the Exploration of the Sea (ICES) led the digitization of cruise reports initially available in paper format. ICES pioneered the development of a database to manage this information (Rickards, 2007).

Following a significant revision, in 1990 the Cruise Summary Report (CSR) succeeded the ROSCOP form and, though it was developed for ICES member countries, it was extended to others interested in providing their information (Rickards, 2007). This activity received a boost in Europe during the development of the SeaDataNet infrastructure between 2006 and 2011. The French Institute for Research and Exploitation of the Sea (IFREMER), under the framework of SeaDataNet, took over this task. The CSR database, combined with ICES and SeaDataNet, contains information from oceanographic research cruises primarily conducted in Europe and other regions worldwide (POGO, 2023). In the same vein, the Partnership for Observation of the Global Ocean established a database covering open ocean research vessels operated by institutes worldwide (Rickards, 2007).

It is worth noting that CSR is part of the data management strategy throughout its life cycle. Its contributions range from data management plans to the point where the collected data is accessible, not only through metadata but also for data discovery, extraction, and analysis from various sources. This justifies the high cost of the expedition (Che-Bohnenstengel & Nast, 2013). Therefore, there has been significant interest in Latin American and Caribbean countries in recent years in creating databases related to ships and scientific expeditions.

In Colombia, several needs have arisen regarding the management of oceanographic cruises. In this regard, the Pan-European Infrastructure for Ocean and Marine Data Management (SeaDataNet) provides tools based on international standards and best practices related to its CSR management experience. It utilizes a geospatial data model designed specifically for the marine geographical information system (GIS) community, developed by researchers from Oregon State University, Duke University, the National Oceanic and Atmospheric Administration (NOAA), the Danish Hydrological Institute, and the Environmental Systems Research Institute (ESRI), called "Arc Marine" (Serpa & Wright, 2005). This model is implemented using Colombia's maritime, riverine, and coastal Spatial Data Infrastructure (SDI) as a computer system containing a set of resources (catalogs, servers, programs, applications, etc.) that allow access to and management of the datasets and geographic services available on the network. It also complies with a series of standards, regulations, and specifications that regulate and ensure the interoperability of geographical information (Iniesto & Núñez, 2020) for the administration of open data from the Colombian Oceanographic Data Center (Cecoldo). Together, these components provide a solution to meet the needs for managing this type of information in the country.

Study Area

Figure 1 shows the study area covered by Colombia's oceanographic cruises and scientific expeditions at sea, coordinated or involving the General Maritime Directorate (Dimar). In the Caribbean, it encompasses the Colombian maritime territory between 11°00′00″ N and 16°00′00″ N and 71°00′00″ W and 82°00′00″ W, where oceanographic cruises have been conducted as part of initiatives such as 'Océano,' the programs of the Cooperative Investigation of the Caribbean and Adjacent Regions, 'Caribe,' 'Golfo de Urabá,' 'Guajira,' 'Islas del Rosario,' 'San Andrés Islas', the oceanographic and atmospheric forecasting system (SPOA, for its Spanish acronym), fishing research, and the most recent 'Expedición Científica Seaflower' (Scientific expeditions of the Seaflower biosphere reserve). On the other

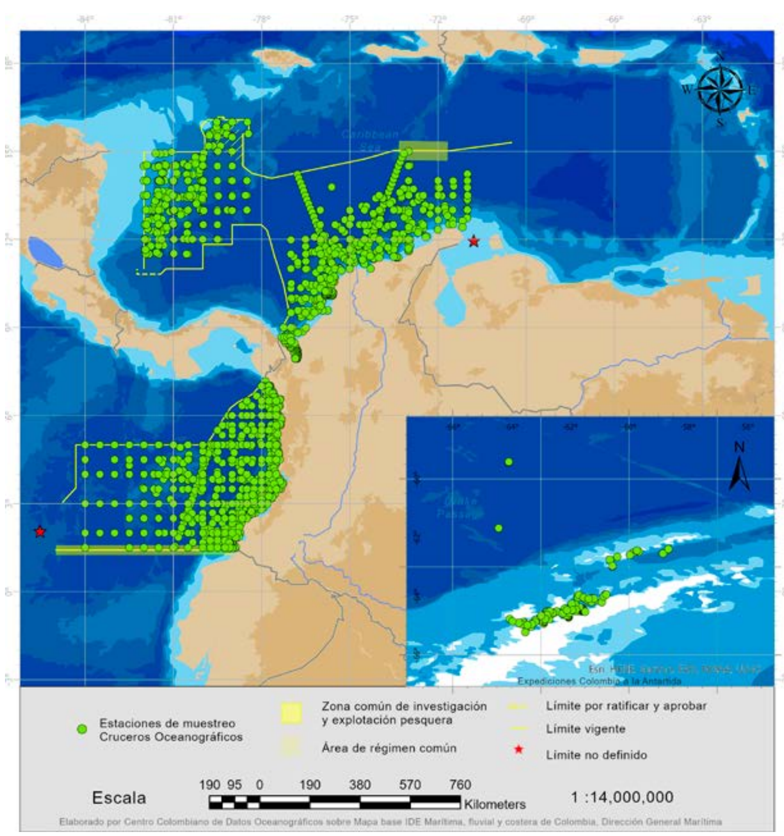

Figure 1. Location of sampling stations for oceanographic cruises (1970-2020) available from Cecoldo

hand, in the Colombian Pacific, oceanographic cruises cover the area between 01°20’00’’ N and 07°10’00’’ N and 77°00’00’’ W and 84°00’00’’ W, from 1970 until today, as part of initiatives such as the Regional Study of the El Niño Phenomenon (ERFEN, for in Spanish acronym), SPOA, fishing research, and the ‘Expedición Científica Pacífico’ (Scientific expedition of the Pacific).

In the context of the Colombian Antarctic Program, since the austral summer of 2014-2015, Colombia has also participated in expeditions to Antarctica through various research projects in the region. Specifically, in the Gerlache Strait, located between 63° 56 ‘43’’ S to 64° 59’ 29’’ S and 61° 24 ‘33’’ W to 63° 57’ 09’’ W.

Methodology

The methodology that was applied integrated international standards and best practices from various disciplines and was developed in three phases (Fig. 2). For the archaeology and retrieval of information regarding oceanographic cruises, the methodology proposed by Hernández, Ortiz, and Suárez (2007) was used. This methodology is based on the conceptual foundation of the Global Oceanographic Data Archaeology and Rescue (GODAR) project, aimed at increasing historical oceanographic digital archives for inclusion in databases accessible to the global community (IOC, 1993).

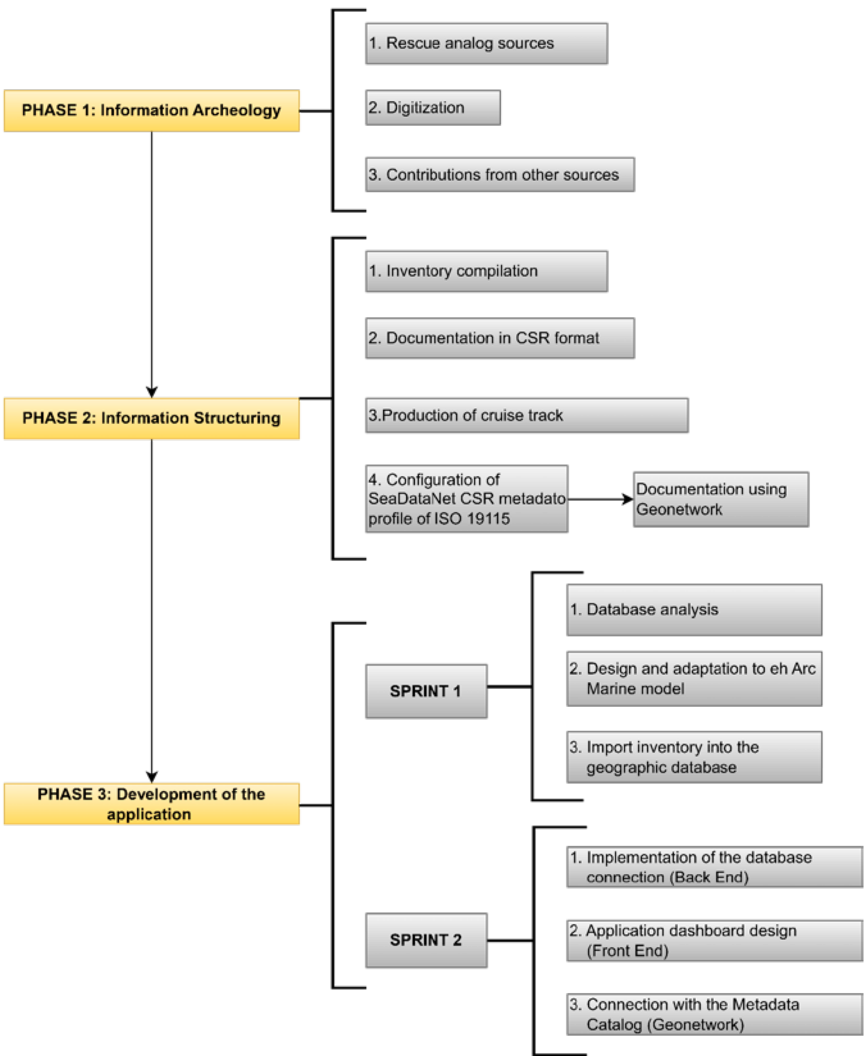

Figure 2. Summary of the methodology applied in the case study

Once the digital files were obtained, the CSR form was used to gather the required information, and each cruise track chart (derrota[4]) was prepared using a standardized template of the Colombian Maritime Authority (Dimar). This used information from the maps available in the technical reports of oceanographic cruises, and this information was correlated with the geographical and temporal data available in the collected data files.

In cases where it was not possible to retrieve the track chart because it was not included in the technical report of the oceanographic cruise, the ship's route was reconstructed based on the records of date, time, and geographical coordinates of the data collected on-site. This process began in spreadsheets, including the classification of information as public (unclassified or classified) in accordance with Colombian Law 1712 of 2014: "By which the Law for Transparency and the Right of Access to National Public Information are created, and other provisions are enacted." This information was imported into ArcGIS Pro to georeference the sampling stations. Subsequently, the ship's route was traced using the Points to Line tool, and the information was finally stored in a GeoDatabase (GDB).

For metadata capture, the ISO 19115 standard SeaDataNet CSR profile was configured in the Geonetwork Open Source catalog tool, as recommended in Volume 5 of the "Ocean Data Standards" (IOC, 2021). To implement the geospatial application, the Agile Scrum software development methodology was used, with a total of two sprints or work processes that included both the database and software components. The first sprint resulted in the GDB being implemented based on the ESRI Arc Marine model on the Maritime, Riverine, and Coastal SDI of Colombia. In the second sprint, the geospatial viewer was designed using the ArcGIS Online dashboard tool to configure geographical and thematic search filters, content visualization, and connection to the Geonetwork metadata catalog.

Results

Phase I. Information Archaeology

Data and information archaeology were conducted based on the results of the 'Strategic Positioning of the Colombian Oceanographic Data Center' project (2015-2017), funded by Dimar. Once the information sources were identified, on-site paper document management was carried out, following the recommendations of the National General Archive (AGN). The digitization efforts focused on recovering: (i) oceanographic cruise reports; (ii) forms with oceanographic and marine meteorological data; (iii) scientific articles, special publications, and related gray literature.

Additionally, a search for information in electronic media such as servers, computers, external hard drives, floppy disks, or any storage media was conducted to complement the digitized information. This effort resulted in the recovery of 96 technical report files (final or preliminary) from 130 oceanographic cruises and scientific expeditions conducted between 1969 and 2020 by the Colombian Navy (ARC) and Dimar, 35 track charts, eight CSRs, and the majority of data reported in the technical reports, except for data collected by institutions invited to the cruises.

Phase II. Information Structuring

Based on the content of the technical reports, and after validation with the geographical and temporal data collected in the field, 122 CSR forms were filled out and registered in Cecoldo's Single Format for Inventory of Oceanographic Cruises and Scientific Expeditions.

Since 67% of the technical cruise reports did not include a track chart, it was necessary to reconstruct the route of each of these cruises based on oceanographic and meteorological measurements. Key data for reconstructing the routes were the date, time, and geographical coordinates of the sampling stations, especially those recorded together with temperature and salinity measurements of the water column obtained with a conductivity, temperature and depth profiler (CTD), which is typically deployed at all stations, or with data from the onboard automatic weather station on the ship.

The key data were organized in a spreadsheet and imported into ArcGIS Pro, where the sampling stations were georeferenced, and the ship's route was traced. Upon completing

[4] The Colombian Maritime Authority defines "derrota" as the representation of the navigation that must be carried out, and indeed is carried out, to go from one point to another, while having to follow one or more courses. The "carta de derrota", or cruise track chart, precisely represents the trajectory followed by a vessel.

this geoprocessing, a set of polylines called tracks was obtained, and their attributes were subsequently adjusted to the Arc Marine model. As a result, 6 536 sampling stations were georeferenced, covering approximately 160 599 nautical miles traveled in 130 oceanographic cruises and/or scientific expeditions at sea, and 116 cruise tracks were drawn for 87 track charts, considering that an oceanographic cruise can have more than one study area and therefore more than one track.

As an example, Figure 3 shows the track chart originally found in the technical report of the Pacific XXVIII / ERFEN XXVI Cruise of 1997 and the track chart reconstructed in this research. It is worth noting that it was not possible to reconstruct the track chart of 12 oceanographic cruises due to a lack of sufficient information related to the date, time, and geographical

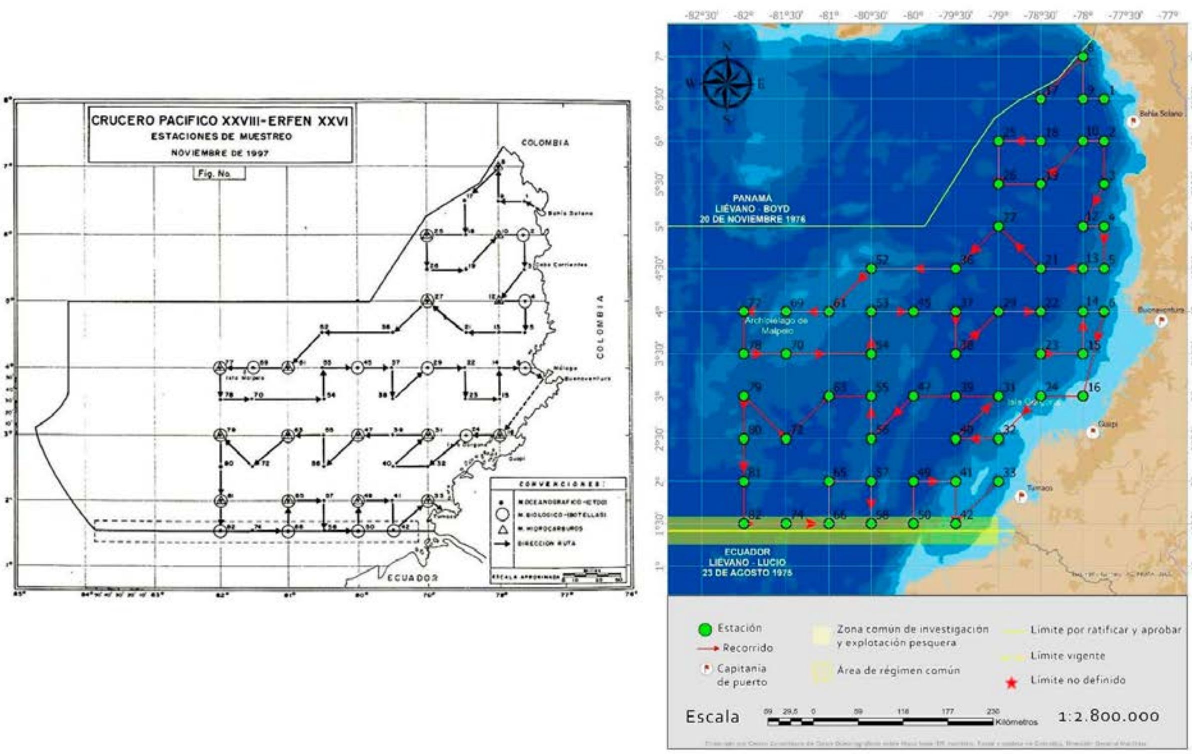

Figure 3. Original (**A**) and reconstructed (**B**) track chart of the Pacific XXVIII / ERFEN XXVI Cruise from 1997

coordinates of the sampling stations, which prevented the tracing of the ship's route.

Finally, the profile of the ISO 19115 standard SeaDataNet CSR and the encoding in the Extensible Markup Language (XML) version 5.2.0 available in SeaDataNet (2020) were configured in the Geonetwork Open Source catalog tool adapted by Cecoldo. Subsequently, 130 metadata records were captured based on the information documented in the CSR form and 118 graphic samples of track charts. For the tracks that could not be reconstructed, a graphic presentation with sampling stations was loaded.

Phase 3: Development of the application

This phase began with the design of the database based on the ESRI Arc Marine model implemented in the Maritime, Riverine, and Coastal SDI of Colombia. It was considered that this is a generic model that can be used as a central building block for the development of applications in coastal and marine environments (Wright *et al*., 2007). For this case study, the classes associated with oceanographic cruise inventory information, ship tracks, and sampling stations were adapted.

The resulting Geodatabase (GDB) consists of four alphanumeric tables (green) from the original Arc Marine schema that store basic information related to each oceanographic cruise (departure date, arrival date, ship name, track chart, etc.) and two auxiliary tables (red) to address specific CSR requirements, such as ship description and the Unique Metadata Identifier (UUID) assigned by GeoNetwork for each documented metadata. Additionally, two geographical layers were implemented to store the geometry of the tracks (line type) and sampling stations (point type). The specifications of each type of attribute and other features were documented in the data dictionary of the geographical application. To conclude, the inventory information was imported into the Cruise table, and the established relationships in the Entity-Relationship (ER) model were validated (Fig. 4).

This phase concluded with the development of the geographical application that allowed the consolidation of the content of the CSRs, i.e., the information stored in the Arc Marine model, along with geographical and alphanumeric information, and the connection with the Geonetwork metadata catalog. With the support of the Maritime, Riverine, and Coastal Spatial Data Infrastructure

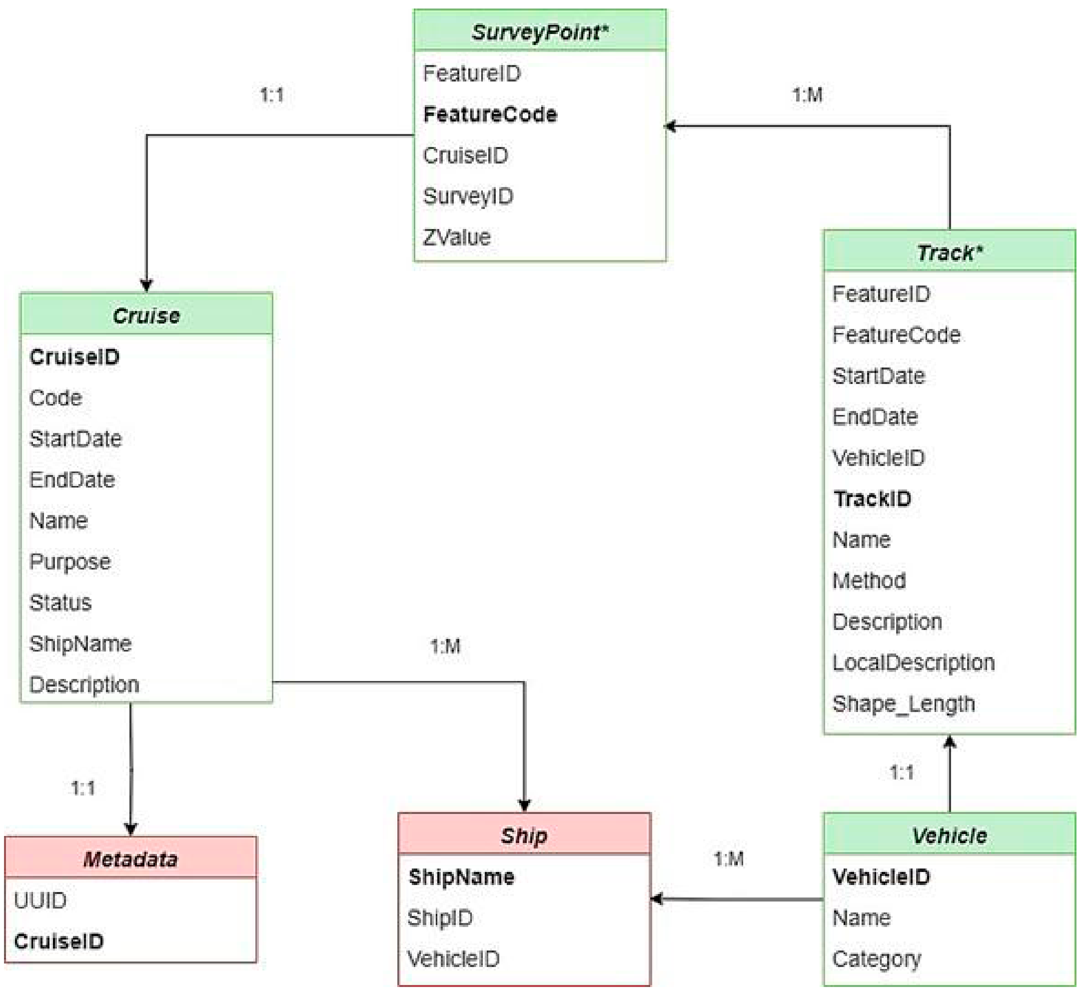

Figure 4. Adapted Arc Marine Entity-Relationship (ER) Model for the Geodatabase (GD**B)**

of Colombia, the process began by loading the GDB to their platform and establishing connection parameters for the publication of information.

Next, using an ArcGIS Online dashboard, the user interface (Front End) of the geographic application was configured, including the display of the data table (Data Frame) on the institutional base map of Dimar with the cruise tracks (Fig. 5). Additionally, a view with the data from the GDB of the CSR from Cecoldo was configured, which includes the UUID attribute for each piece of metadata, so that the user can access detailed information about the oceanographic cruise (metadata) and download the related open data from the Geonetwork catalog.

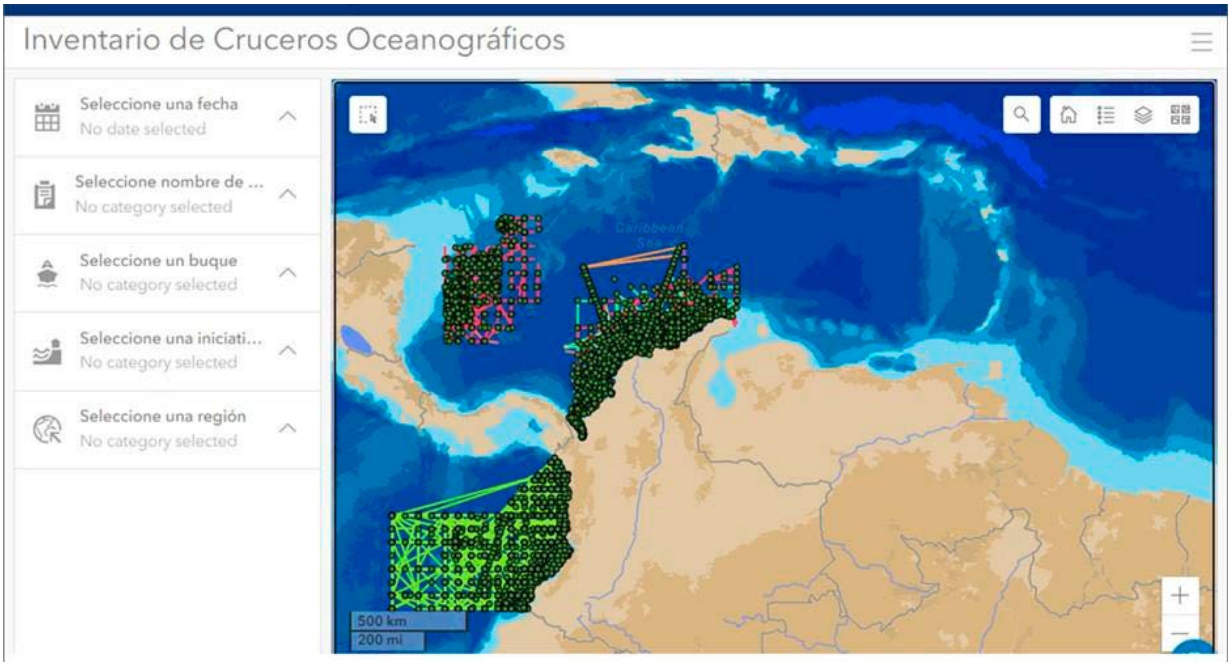

Figure 5. User interface appearance for CSR search

Discussion

The process of data archaeology and information recovery of Colombian oceanographic cruises allowed for the gathering and structuring of relevant content for the CSR. However, it also revealed historical information gaps regarding the cruises, which might be associated with the abandonment of the ROSCOP best practice of documenting, as evidenced in the technical reports of cruises conducted in the Colombian Pacific by the Center for Oceanographic and Hydrographic Research of the former General Maritime and Port Directorate in the 1990s (CIOH, 1993). Around the late 1990s, there was a correlation of this best practice with the Southeast Pacific initiatives, which were supported by the Tropical Ocean Global Atmosphere (TOGA) program that contributed to the objectives of the Regional Study of the El Niño Phenomenon (ERFEN), within the framework of joint regional cruises of the Permanent Commission for the South Pacific (CPPS) (CPPS, 2000).

Therefore, the information recovery phase allowed the identification of the deficiency in the necessary records to report all the elements that make up the global inventory of cruises and expeditions at sea. Consequently, it is currently imperative to reintroduce this international best practice to contribute, not only by using online catalogs but also by incorporating the original CSR form into official technical cruise reports. The latter represents a significant contribution to the historical memory of oceanographic cruises and other activities, as are the devices that were installed, launched, and/or recovered during these initiatives.

For its part, the IOC (2019a) recommends using controlled vocabularies from the NERC Vocabulary Server to describe marine and oceanographic data sets, in order to integrate permanent identifiers, concise text strings, and complete term descriptions in different applications. However, in the implementation of the XML encoding recommended by IOC (2021) for SeaDataNet CSR metadata, controlled vocabularies for 'projects,' 'vessels,' and 'organizations' could not be adapted, and they do not include initiatives from the Latin American community.

Two of these vocabularies correspond to the themes being addressed in the architecture of the Ocean Data and Information System within the framework of the "United Nations Decade of Ocean Science for Sustainable Development," especially the Ocean Infohub (OIH) - Latin America and the Caribbean (LAC) mechanism of the pilot project "Clearing-House Mechanism LAC," implemented from Recommendation SC-IOCARIBE-XV.1 – IOC New Capacity Development Strategy: Implementation Plan (IOC, 2019b). OIH LAC allows for a hybrid model to provide access to information on resources identified in the region, including the themes of 'vessels' and 'projects.' This demonstrates the need to visualize global cruise initiatives in catalogs and, for the case study, the potential interoperability of the Maritime, River, and Coastal SDI of Colombia with the national cruise inventory developed.

Furthermore, while Arc Marine served as a base data model, meeting the primary needs of structuring and storing geographic data related to CSR and allowing for a logical representation of these data, it did not cover all the identified requirements. Therefore, it was necessary to add alphanumeric tables to the model, which turned out to be adaptive, as stated by Andrews and Ackerman (2008). They coincided in that "the Arc Marine data model provides both the basic elements to represent or model common marine data types and the tools to extend these basic representations to more complex marine objects through particular relationships and needs."

After a series of adaptations made to the Arc Marine model, Lord-Castillo *et al*. (2009) pointed out a key concept that can help guide future developments, consistent with the results of this study. It's the idea that "the model's foreseen multidimensionality can be effectively expanded with additional dimensions (such as time)." This way, the multidimensionality of the model was verified, successfully integrating the reconstructed ship route tracks for the 87 cruises by linking the *Survey Point* and *Cruise* tables.

Lastly, it is worth mentioning that Isenor and Spears (2013) emphasized the practicality of the Arc Marine model for incorporating aspects of the ISO 19115 standard for geographic metadata. This conclusion was confirmed in the present study, as the Metadata attribute was added, integrating the SeaDataNet CSR metadata model adopted by Cecoldo.

Conclusions

The Inventory of Colombian Oceanographic Cruises is the product of integrating records from various sources and formats, resulting from a process of data archaeology and information recovery, applying international best practices and information technologies. It is essential to recognize that the contribution of this process goes beyond the recovery of cruise information, delving into the beginnings of marine scientific research in the country and the evolution of oceanographic platforms and instrumentation used. It supports Colombia's work as an oceanic power for decades and highlights efforts to understand and explore Colombian maritime territory.

The objective of the inventory of oceanographic cruises should be seen as more than just implementing a database or providing access to collected data. It should be a tool for discovery to aid in the planning of cruises and expeditions, the efficient use of research vessels, and inter-institutional participation. In this sense, the initiative developed by Cecoldo on the Maritime, River, and Coastal SDI of Colombia represents an important starting point for improving the exchange of historical and current information about oceanographic cruises conducted in the country and in Antarctica, with growth potential to contribute to decision-making at different levels of management.

The ESRI Arc Marine model provided a scalable framework for the Maritime, River, and Coastal SDI of Colombia, easy to adapt to encompass broader concepts in line with the current needs of marine geographic information management, especially related to CSR and its spatial representation. It can be combined with tools for configuring and developing geographic applications in a hybrid environment (cloud-based and on-site).

Adapting the SeaDataNet CSR metadata profile to the Geonetwork metadata catalog opens up possibilities for interoperability because the use of the XML schema enables communication and exchange with other data centers and platforms, using a common language and contributing to the FAIR principles (Findability, Accessibility, Interoperability, and Reuse). An important step toward a comprehensive and long-term archive of national oceanographic cruise information is to include metadata in the global SeaDataNet CSR database managed by IFREMER. This management can be performed through programs or projects associated with cruises via the Maritime, River, and Coastal SDI of Colombia and Cecoldo.

Finally, it is essential to continue making improvements to the CSR workflow to make it more efficient, timely (providing information as quickly as possible after a cruise ends) and decentralized (allowing input from different data providers and producers), and promoting interoperability with other processes related to the data lifecycle. This will help to avoid the need for future historical information recovery.

Acknowledgments

To the crew members of the centers for oceanographic and hydrographic research of the Pacific and the Caribbean, under the General Maritime Directorate. To the personnel of the Maritime, River, and Coastal Spatial Data Infrastructure of Colombia. To the 'State Youth' program of the Ministry of Labor of Colombia, which facilitated the participation of university students as interns at the Colombian Oceanographic Data Center (Cecoldo) between 2021 and 2022.

Funding Source

General Maritime Directorate through the Colombian Oceanographic Data Center (Cecoldo) under its jurisdiction.

Authors' contributions

Conceptualization: R. O.; Methodology: R. O., D. C.; Analysis: D. C., R. O.; Software: M. S., D. C., R. O.; Writing - Original Draft Preparation: R.O., D. C., M. S.; Proofreading and Editing: R. O.; Visualization: D. C. All authors have read and approved the final published version of the manuscript.

Bibliography

Andrews, B.; Ackerman, S. (2008). Federal/State mapping program supports ocean management and research. *Federal GIS Connection.* Woods Hole Coastal and Marine Science Center. https://pubs.er.usgs.gov/publication/70197185

Armada República de Colombia. (1970). *Crucero oceanográfico en el Caribe colombiano. Océano I - 1969.* Resultados preliminares. Ministerio de Defensa – ARC.

Armada República de Colombia. (1971). *Crucero oceanográfico en el Pacífico colombiano. Pacífico I - 1970.* Resultados preliminares. Ministerio de Defensa - ARC.

Che-Bohnenstengel, A.; Nast, F. (2013). *Modernised Cruise Summary Reports Management, in particular with a Link to Data. International Conference on Marine Data and Information Systems.* Lucca, Italy, 23-25 September 2013. https://www.vliz.be/imisdocs/publications/ocrd/251124.pdf

Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe. (1993). *Informe técnico Crucero Oceanográfico Erfen XX.* CIOH. Cartagena de Indias, Colombia.

Comisión Permanente del Pacífico Sur . (2000). *II Crucero Regional de Investigación Oceanográfica del Pacífico Sudeste realizado en mayo de 1999.* CPPS. Quito, Ecuador. http://cpps.dyndns.info/cpps-docs-web/dircient/erfen/crucero/ii_crucero/informe_ii_crucero_1999.pdf

Hernández Jaimes, J. L.; Ortiz Martínez, R. V.; Suárez Pinzón, I. (2007). Metodología archivística para la recuperación de información oceanográfica del Pacífico colombiano. *Bol. Cient. CCCP,* 14: 123-150. https://doi.org/10.26640/01213423.14.123_150

Iniesto, M.; Núñez, A. (2020). *Infraestructuras de datos espaciales,* 21. http://www.ign.es/web/biblioteca_cartoteca/abnetcl.cgi?TITN=49999

Comisión Oceanográfica Intergubernamental. (1993). IOC-CEC-ICSU-ICES *Regional Workshop for Member States of Eastern and Northern Europe (Global Oceanographic Data Archeology and Rescue [GODAR] Project).* World Data Centre B, Oceanography Obninsk, Russian Federation 17-20 May 1993. IOC of UNESCO. https://aquadocs.org/handle/1834/5577

Comisión Oceanográfica Intergubernamental. (2019a). *Ocean Data Standards, Vol.4: Technology for SeaDataNet Controlled Vocabularies for describing Marine and Oceanographic Datasets - A joint Proposal by SeaDataNet and ODIP projects.* Oostend, Belgium, IODE of UNESCO. (IOC/2019/MG/54 Vol.4). DOI: http://dx.doi.org/10.25607/OBP-566

Comisión Oceanográfica Intergubernamental. (2019b). *Fifteenth Session of the IOC Sub-Commission for the Caribbean and Adjacent Regions* (IOCARIBE-XV), Oranjestad, Aruba, 6-10 May 2019. IOC of UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000370299

Comisión Oceanográfica Intergubernamental. (2021). *Ocean Data Standards, Vol.5: SeaDataNet Cruise Summary Report (CSR) metadata model for Cruise Reporting – XML encoding (including SeaDataNet CSR metadata profile of ISO 19115-2 – XML encoding, V5.2.0).* Oostend, Belgium, IODE of UNESCO. http://dx.doi.org/10.25607/OBP-1644

Isenor, A.; Spears, T. (2013). Combining the Arc Marine Framework with Geographic Metadata to Support Ocean Acoustic Modeling. *Transactions in GIS,* 18(2): 183-200. https://doi.org/10.1111/tgis.12029

Lord-Castillo, B.; Mate, B.; Wright, D.; Follett, T. (2009). A Customization of the Arc Marine Data Model to Support Whale Tracking via Satellite Telemetry. *Transactions in GIS*, 13: 63-83. https://doi.org/10.1111/j.1467-9671.2009.01159.x

Serpa, P.; Wright, D. (2005). *Using Arc Marine in ArcGIS 9.x Tutorial for Beginners.* https://dusk.geo.orst.edu/djl/arcgis/ArcMarine_Tutorial/index_v9.html

POGO. (2023). *Cruise Summary Reports. Partnership for Observation of the Global Oceans (POGO).* https://www.pogo-oceancruises.org/cruise-summary-reports

Rickards, L. (2007). *IODE data flow (National Oceanographic Programmes (NOPs) and Cruise Summary Reports (CSRs).* https://aquadocs.org/handle/1834/2779

SeaDataNet. (2020). *SeaDataNet CSR Profile of ISO 19139 Metadata - Inspire Compliant.* https://www.seadatanet.org/Standards/Metadata-formats/CSR

Sievers, H. (2017). A 50 años del primer proyecto de construcción de un buque oceanográfico para Chile. *Revista de Marina* (Vol. 134, pp.62). Chile: Armada de Chile https://revistamarina.cl/es/articulo/a-50-anos-del-primer-proyecto-de-construccion-de-un-buque-oceanografico-para-chile

Wright, D.; Blongewicz, M.; Halpin, P.; Breman, J. (2007). *Arc Marine GIS for a Blue Planet.* ESRI. http://dusk.geo.orst.edu/djl/arcgis/book.html

Zuta, S.; Flores, L. (1980). Oceanography Development in Peru. En Third International Congress on the History of Oceanography (Eds.), *Oceanography: The Past* (pp. 642–655). https://link.springer.com/chapter/10.1007/978-1-4613-8090-0_59

Short article

Mapping the seabed of the Colombian Caribbean: Proposal for a cartographic scheme of the underwater geomorphology of Colombia (South and Central Section of the continental margin)

Mapeando el fondo marino del Caribe colombiano: propuesta de un esquema cartográfico de la geomorfología submarina de Colombia (sección sur y central del margen continental)

DOI: https://doi.org/10.26640/22159045.2023.605 **Date received:** 2022-09-23 / Date accepted: 2023-05-03

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Citation:

Santos-Barrera, Y.; Calderón Grande, M. F.; Gutiérrez Rincón, E. L.; Sánchez Reyes, D. M.; Álvarez Orduz, O. S.; David Viteri, D; Uribe Rivera, J. J. G. (2023). Mapping the seabed of the Colombian Caribbean: Proposal for a cartographic grid for the underwater geomorphology of Colombia (southern and central sections of the continental margin). *CIOH Sci. Bull.*, 42(1): 39-50. Online ISSN 2215-9045. DOI: https://doi.org/10.26640/22159045.2023.605

Abstract

This paper shows the progress made in relation to the project to carry out submarine geomorphological and structural mapping of Colombian maritime territory, which started with the design of a cartographic grid divided into 22 charts at a scale of 1:250 000. This paper presents the first two charts developed between the years 2020-2021. These charts were prepared with the use of bathymetric information, 2D seismic data, magnetic and gravimetric anomalies, and satellite data, all integrated in Geographic Information Systems (GIS). As a result, the geomorphological units that characterize the southern and central part of the continental margin of the Colombian Caribbean were published in two thematic charts numbered 1408 and 1409, as established in the cartographic grid designed for this purpose.

Keywords: Submarine geomorphology, Caribbean, continental margin, Sinú, Magdalena Fan, bathymetry

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Resumen

Esta publicación muestra los avances obtenidos en el proyecto de mapeado geomorfológico y estructural submarino del territorio marítimo colombiano, el cual parte desde el diseño de un esquema cartográfico para el Caribe que se dividió en 22 cartas a escala 1:250 000. En este trabajo se avanza con la presentación de dos primeras cartas desarrolladas entre los años 2020 y 2021. La elaboración de estas cartas se realizó con el uso de información batimétrica, sísmica 2D, anomalías magnéticas y gravimétricas, y datos satelitales, todo integrado bajo herramientas de sistemas de información geográficas (SIG). Como resultado se obtuvieron las unidades geomorfológicas que caracterizan la parte sur-central del margen continental del Caribe colombiano en dos cartas temáticas enumeradas 1408 y 1409, acorde a lo establecido en el esquema cartográfico diseñado para tal propósito.

Palabras claves: *geomorfología submarina, Caribe, margen continental, Sinú, abanico del Magdalena, batimetría.*

Introduction

Solid understanding of the geomorphological environment of the seabed is key for maritime spatial planning, the designation of marine protected areas, the construction and operation of offshore infrastructure and the implementation of environmental monitoring programs (Micallef, Krastel & Savini, 2017). Collecting remotely sensed data to map the seabed is difficult due to its high cost; however, in the last decade, the General Maritime Directorate (Dimar), through the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH) and the National Hydrographic Service (SHN), has made efforts to strengthen its technological research capacities by acquiring sonar equipment, data from which helps to generate new knowledge about the deep seabed of the Colombian Caribbean and Pacific.

Dimar is responsible for producing the nation’s nautical charts, in accordance with item 4 of Article 5° of Decree-law N°. 2324 of 1984, and items 2 and 6 of Article 2 of Decree N°. 5057 of 2009, whilst also complying with Chapter V “Safety in Navigation” (Dimar, 2021). Consequently, the CIOH has proposed the development of a grid of thematic charts of the geomorphology and structure of the country’s maritime territory, consisting of 22 charts at a scale of 1:250 000. They are to be numbered under the 1400 series for the Caribbean, and will delineate and describe the geomorphological units of the seabed of the Colombian Caribbean.

This article presents the first fruits of the labor of developing the cartographic grid for the Colombian Caribbean Sea, according to color-coded geomorphological charts, which delineate the geomorphological units and trace fault lines in two sectors located between the departments of Córdoba and Atlántico. These maps provides bathymetric information with a 250 m resolution (single beam) on the continental shelf, and 10 m to 50 m resolution (multi-beam) for the continental slope and abyssal plain of the Colombian Caribbean; as well as the interpretation of 2D seismic lines acquired and processed in the framework of exploration projects of the National Hydrocarbons Agency (ANH), stored in its Exploration and Production Information Service (EPIS) database; satellite gravimetry and magnetometry information obtained from the SEEQUEN database, corresponding to regional models from Sandwell *et al*. (2014) and EMAG2 (v3); and the use of GIS for processing and managing geo-referenced information.

Study area

Thematic Charts 1408 and 1409 cover the maritime territory of five departments of the Colombian Caribbean (Fig. 1), with a total coverage area of approximately 33 027 km². The coastline shown in Submarine Geomorphology Chart 1408 extends from the coast of the department of Córdoba, near Bahía Rada, to the coastal area near Galerazamba, in the department of Bolívar; its maritime zone or submerged area extends out to a depth of 3 300 m, according to the bathymetry acquired and processed by the CIOH. For its part, Chart 1409 covers from the coast of Galerazamba, in the department of Bolívar, where it borders Chart 1408, to the vicinity of Tasajera, Magdalena; the marine territory shown in it reaches a maximum depth of 3 700 m.

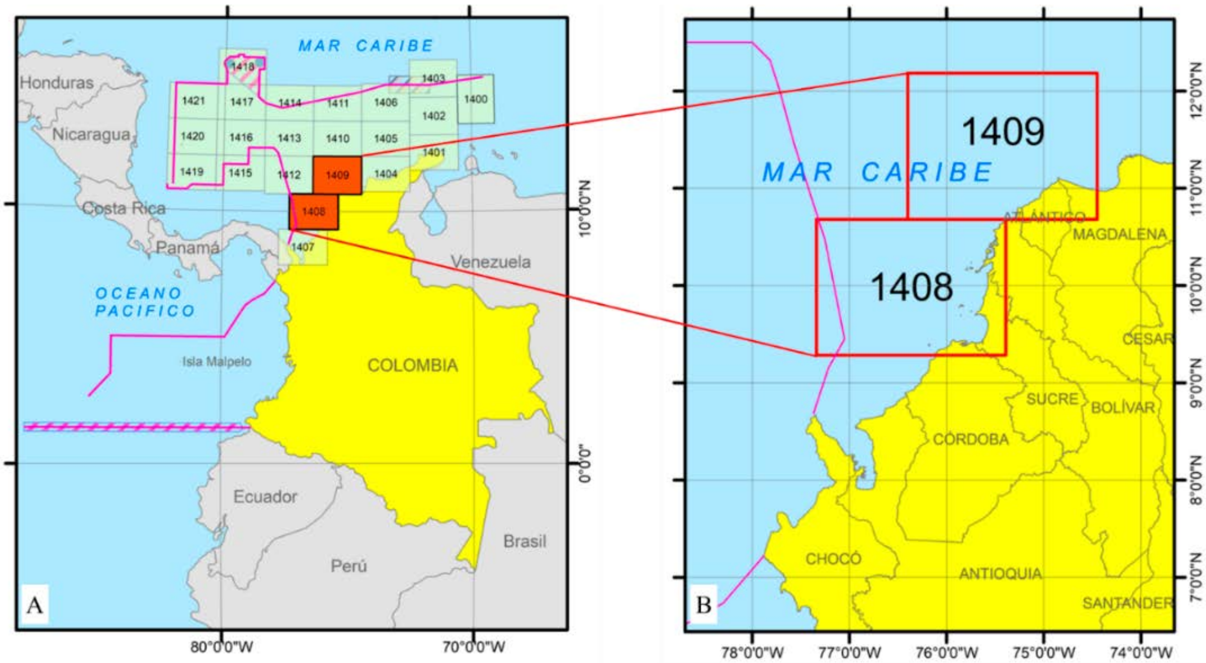

Figure 1. (**A**). Distribution of the cartographic grid for the submarine geomorphology of the Colombian Caribbean: 22 charts at a scale of 1: 250,000. (**B)** Geomorphological Charts 1408 and 1409.

General geological aspects of the mapped area

In terms of its geological context, the mapped area is located in the zone of influence of the South Caribbean Deformed Belt, which, in its southern section, is forming the Sinú accretionary prism on the seabed, as a result of the compressional interaction between the Caribbean plate and the South American plate (Veloza *et al*., 2012). To the north we can find the River Magdalena fan structure, and then reach the Sierra Nevada de Santa Marta mountain range, where the Santa Marta, Bucaramanga and Oca faults have an influence (Cediel, Shaw & Cáceres, 2003). On the mainland, the predominant structural provinces are: the Sinú and San Jacinto fold belts, the Plato Geofracture, and the Sierra Nevada de Santa Marta (Carvajal, 2012). The width of the continental margin, marked at the 200 m isobath, varies, being approximately 79.70 km in a straight line from Coveñas, but thinning towards the northern section. It is also possible to observe different processes associated with dykes, channels with important mass transport phenomena (Rangel-Buitrago & Idárraga-García, 2010), as well as areas of predominantly steep slopes, mainly forming canyon walls and important discrepancies in the relief (Vinnels *et al*., 2010).

The Magdalena Fan, most of which can be found in Chart 1409, extends off the coast of the department of Atlántico with a radius of 181.22 km. This area is not precise, since this data is obtained from the change in bathymetry observed in the analyzed data, but it is included in what is mapped and partially presented in this geomorphological chart. However, based on the geophysical data, the total section of the Magdalena fan has been divided into the upper, middle and lower fan. This suggests that it extends out to depths of approximately 4 500 m in its lower section, a zone in which changes in relief are scarce in comparison with the continental slope (Idárraga-García *et al*., 2019).

Methodology

In order to present the characteristics of the submarine relief, geomorphological mapping was carried out in the area of coverage beginning in 2020, applying the workflow designed by the authors for developing thematic charts (Fig. 2).

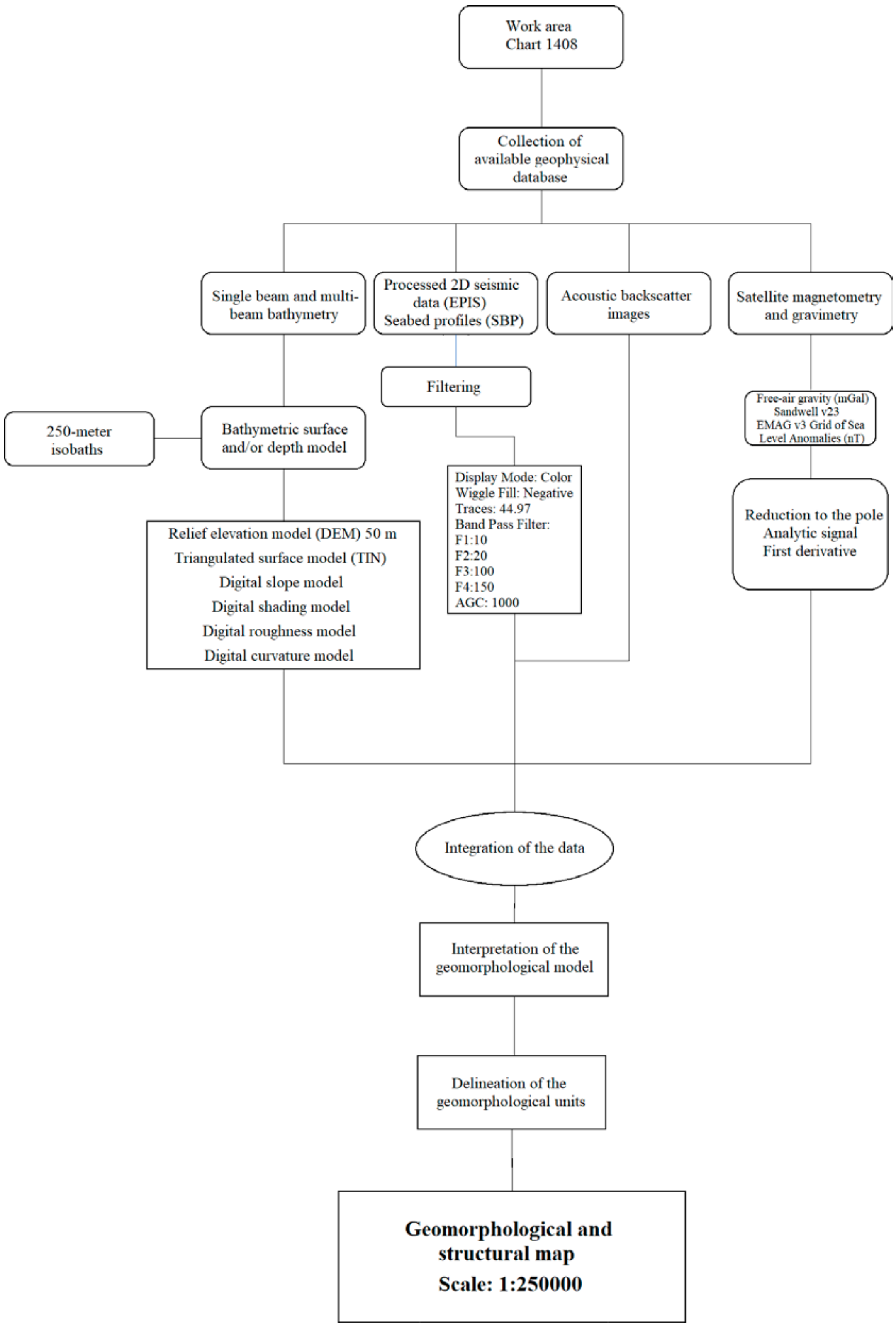

Figure 2. Methodological flowchart used for the elaboration of submarine geomorphology charts of the Colombian Caribbean Sea.

The methodology used was based on the criteria proposed by Micallef *et al*. (2017), which establish techniques and methods to identify and map underwater geoforms with the use of sonar. The main input for this work was the bathymetry provided by the CIOH, which was used to generate the digital depth models, giving a real 3D view of the seafloor. In addition to this information, seismic data was used to determine the deformation processes that gave rise to the configuration of the relief, such as uplifts, depressions, diapirs, landslides, lineaments and fault jumps, among others.

The gravimetry and magnetometry data correspond to a satellite data grid from the Sandwell *et al*. (2014) and EMAG2 (v3) models, respectively, in a section of the Caribbean that included the continental margin, with which regional structural lineaments and faults were identified. The seismic data was processed and, therefore, filters were applied to the images to aid their interpretation (Fig. 2). The interpretation was based on the free-air gravity (mGal) model. This model, based on satellite data, has a spatial resolution of ½ wavelength of 7 km (Sandwell *et al*., 2014); the magnetometry (EMAG2 v3) has a resolution of 2 arc-minutes and an altitude of 4 km above the geoid (Meyer, Saltus & Chulliat, 2017).

Raster images were generated from the depth model based on the surface, with a spatial resolution of 100 m in those areas with depths greater than 200 m. This 3D surface enables the identification of geoforms and underwater terrain features, with which each polygon was delineated. The digitized vector information was incorporated into a geodatabase, with a storage structure known as a feature dataset, which allowed the information to be standardized and the structures ordered according to the *esquema de jerarquización geomorfológica* (geomorphological hierarchy scheme) proposed by Carvajal (2012). In this way, the basic thematic information was obtained to enable the elaboration of the geomorphological map of the area.

The depth models made it possible to obtain digital representations of the underwater relief, from which variables such as slope, roughness, shading and transverse profiles, among others, were obtained. The data were integrated based on the lower resolution bathymetry in the continental shelf, but making maximum use of the possibility to identify structures in the zones of higher resolution in the slope and abyssal plain; therefore, based on the resolution of the data, it was considered prudent to perform the mapping at a scale of 1:250 000,

GIS Modeling

The first model obtained corresponds to the Digital Elevation Model (DEM), which, according to Olaya (2020), is the key piece of the geomorphometric analysis and is the digital equivalent of classic elevation mapping, represented by contour lines ranging from 10 m to 200 m depth on the continental shelf and from 200 m to 3 700 m from the slope to the abyssal plain. For this case, the DEM, the main input used in the other digital models, was obtained using the isolines or isobaths, and the resolution or cell size of the image depended on the distance between them.

The digital models generated included: a slope model, which identifies the gradient or maximum range of change in the Z-axis for each cell; a shading model, in which a shaded relief is created, considering the angle of incidence of the light source; a curvature model, which provides information on the concavity or convexity of the surface; an aspect model, which provides the direction of the slope; and a roughness model, which denotes the irregularity or unevenness of the terrain.

By integrating the interpretations of the geophysical data (bathymetry, 2D seismic, acoustic backscatter, 2D SBP, and GIS tools) it was possible to produce a geomorphological map in two sections, at a scale of 1:250,000, corresponding to Thematic Charts 1408 and 1409. The nomenclature used to characterize the geomorphological structures was based on the geomorphological hierarchy proposed by Carvajal (2012). That work proposes the classification of zones or terrains according to the size and area they occupy, and the level of study, or scale, with which one wishes to work. Therefore, it proposes that each category constitutes a system, and the lower systems are contained within the upper ones.

For the case of this study, carried out at a scale of 1:250 000, the areas were classified into units. The unit is the individual geoform, homogeneous in their origin, generated by a geomorphological process of accumulation or erosion. To name each unit in the thematic table, the nomenclature containing the main formation process or environment (called 'region' in the hierarchy) was used, plus the initials of the name of the geoform. Thus, geomorphological units characterized as denudational, such as debris flow complexes (cfd), turbidity flow complexes (cft), slope deposits (dt), dykes (d) and landslides (dz), are prefixed with a capital D; geomorphological units characterized as morpho-structural, e.g., escarpments (e), depressions (dp), homoclinal ridges (sh), terraces (t) and mud volcanoes (vl) are prefixed with the capital letters MS.

Thus, it is important to mention the processes observed in this submarine geomorphological classification: Denudational (D), Marine (M), Coastal Marine (CM), Marine Denudational (DM), Marine Morpho-structural (MMS), Morpho-structural (MS); and we also mention the observed geoforms: Coral Area (ac), Channel (ca), Canyon (cñ), Debris Flow Complex (cfd), Turbidity Flow Complex (cft), Holocene Deposit (dh), Slope Deposits (dt), Landslide (dz), Dyke (di), Escarpment (e), Abyssal Plain (lla), Continental Shelf (pc), Homoclinal ridges (sh), Valley (v), Mud Volcano (vl).

Results and discussion

The thematic charts obtained are the result of the interpretation of geophysical variables (bathymetry, 2D seismic data, magnetometry, and satellite gravimetry) and their integration in GIS tools. The bathymetric information has a spatial resolution ranging from 15 m to 250 m, the latter in the shallowest areas such as the continental shelf. From this, relief elevation models (DEM), 3D visualizations, transverse profiles and GeoTIFF images were generated, and these were analyzed with GIS tools. These gave profiles with depth data, so isobaths for every 50 m and 250 m depth could be generated and added to the model.

Interpretation of satellite magnetometry and gravimetry

This data showed significant anomalous fields in the submerged accretionary prism and the Magdalena Fan. The most important gravimetric anomalies have values between 13.0 mGal and 80.4 mGal, and geomagnetic behavior between 21.9 nT and 94.09 nT; with elevated values closer to the fan structure, and with negative or low anomalies towards the abyssal plain of the Caribbean basin (Fig. 3).

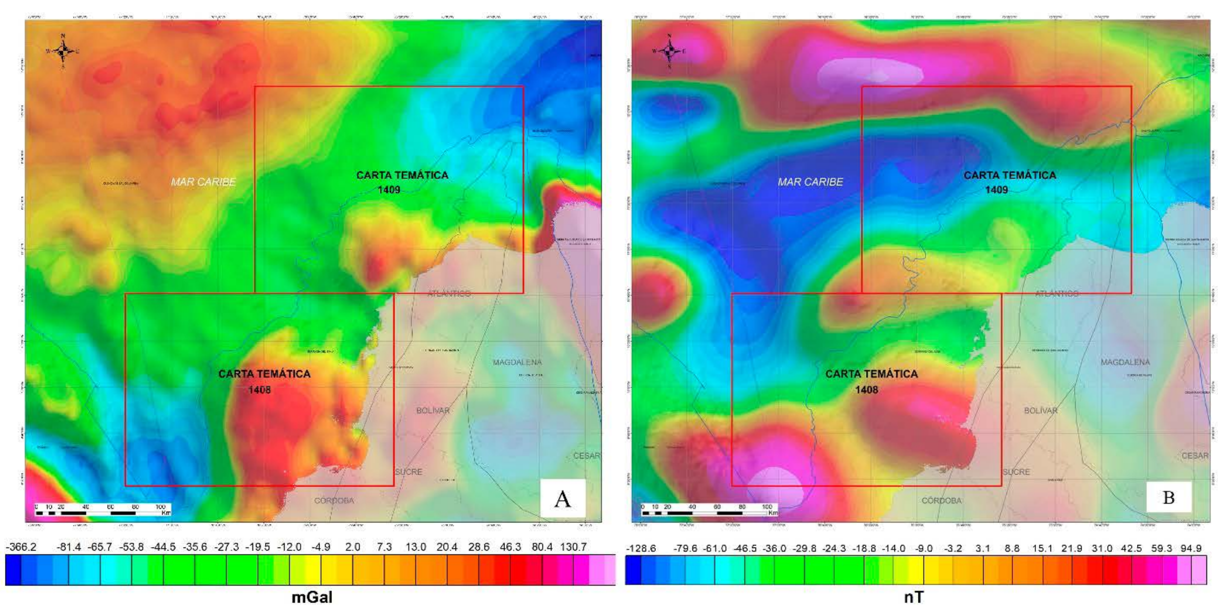

Figure 3. (**A**) Free-air gravity anomalies, Sandwell model; (**B**) EMAG v3 sea level magnetic anomaly. Grid taken from the SEEQUENT database. https://public.dap.seequent.com/

The gravimetric and geomagnetic interpretation, determined by the textural changes of the images, allowed the identification of three basins clearly differentiated by the behavior and distribution of the anomalies. Figure 3A, corresponding to free air gravimetry, shows high anomalies in the continental margin, at the previously mentioned points, and low anomalies towards the deep zone of the abyssal plain, from where the figures increase towards the NW, in the direction of the Cayos Basin. A similar trend is observed in the magnetometry (Fig. 3B); however, the highest anomalies identified are located in the southern part of the continental margin, while the low magnetic anomalies are found towards the Caribbean Basin. An important feature is the coincidence of the high gravimetric and magnetic anomalies in the area of the Sinú Deformed Belt, in the southern part of the mapped area, which takes up a large proportion of the map.

2D seismic interpretation

In the mapped zones there are two important structures: the Magdalena Fan in the north, and in the south the accretionary prism that forms part of the Sinú Deformed Belt. The continental platform narrows to the north of the chart, with evidence of coral units visible in the bathymetry. Structurally, there are important uplifts and depressions in the seabed, as well as processes related to the sedimentary activity of the Magdalena Fan (Fig. 4).

The superposition of the sub-bottom information, obtained with seismic and bathymetric data, enabled the identification of channels generated by sediment flow (Fig. 4), mainly on the continental slope; as well as the presence of large-scale cross-stratification in the slope cross-section (Fig. 5). These seismic lines belong to the section of chart 1409 corresponding to the Magdalena Fan.

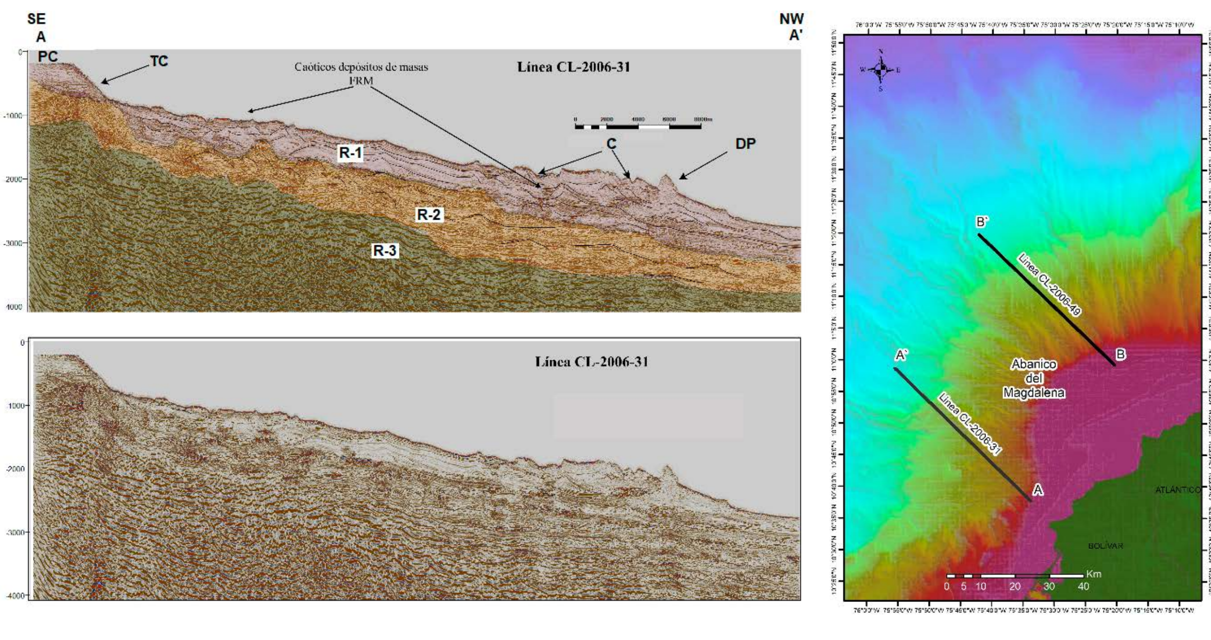

Figure 4. The A-A' cross-section shows the sedimentary deposits of the Magdalena Fan, represented by seismic reflectors that show signs of chaotic deposition in R-1 and R-2, which are associated with mass movement phenomena (FRM) and marked diapiric activity. Reflector R-3 corresponds to the basement rock in the zone. PC: continental platform, TC: section of the continental slope, C: channel, DL: Mud Diapir.

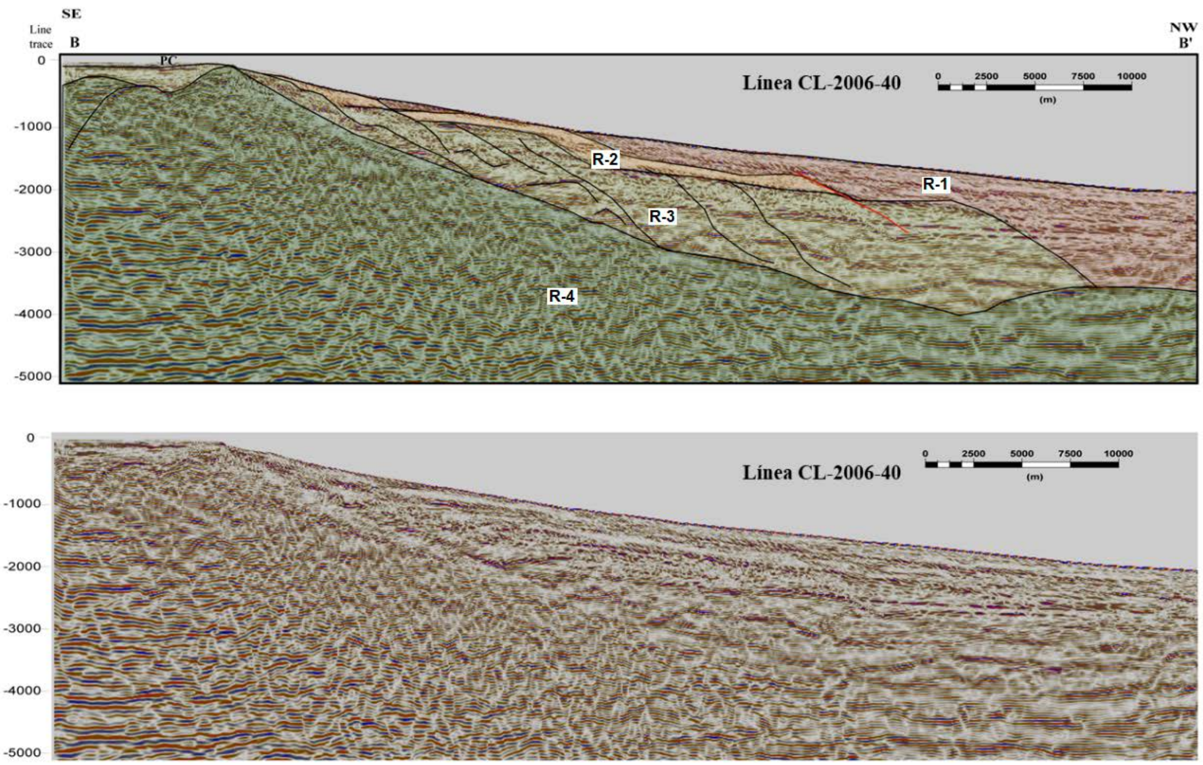

Figure 5. Seismic reflectors R-1, R-2 and R-3 show regional scale depositional processes, with discontinuous reflectors, suggesting faulting and displacement of layers. The last reflector, R-4, is associated with the basement rock in the area.

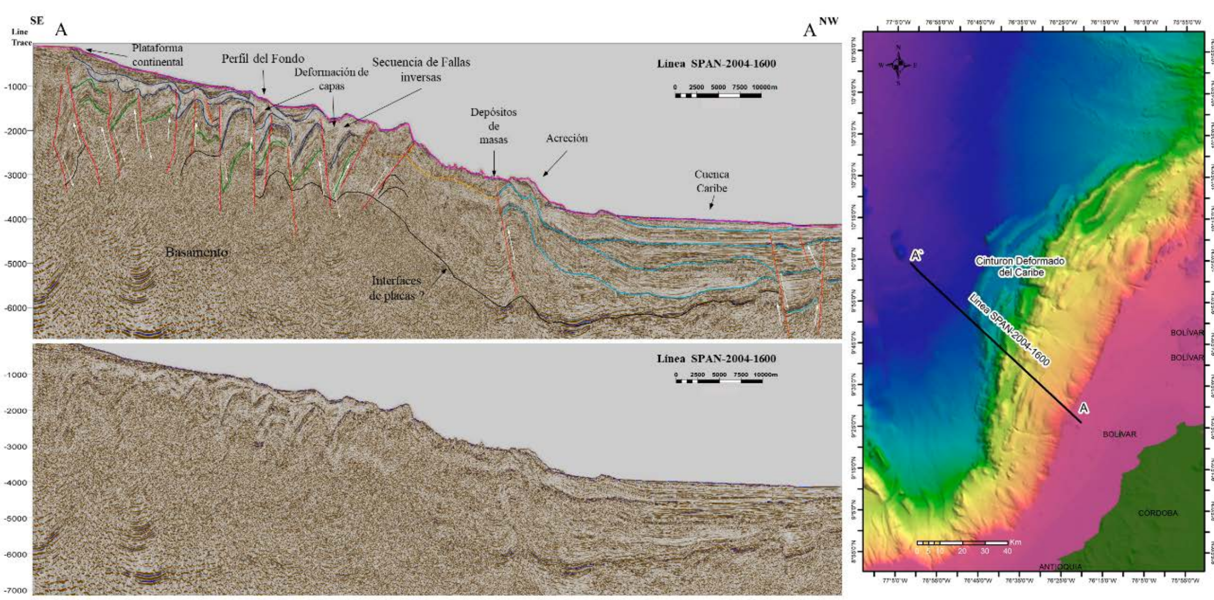

Figure 6. The seismic reflectors are discontinuous thrusts and deformed towards the slope, showing a sequence of reverse and normal faults and mass deposits, along with accretion of the oceanic plate in the Caribbean basin. The A-A' line corresponds to the southern section of Chart 1608.

The southern section of the mapped zone consists of successive continuous uplifts and valleys oriented in a NE-SW direction, dissected by channels associated with a system of reverse or thrust faults. This folding is evident towards the most distal part of the coastline, where it meets the abyssal zone, where the continuity of the deformation front is inferred, while some covered normal faults can be identified towards the platform and in the middle of the deposit. The latter extends to the abyssal zone within the Colombia Basin (Fig. 4).

This zone is affected by normal faults towards the coastline and reverse or thrust faults towards the boundary between the platform and the continental slope; on the latter, the important folding of the southern Sinú Deformed Belt can be identified (Fig. 6).

Continuing to the NE, the Sinú Deformed Belt reappears. This folding, a product of the deformation processes in the area, was defined as a homoclinal ridge, due to the configuration of the layers, which in turn are separated by valleys and dissected by channels corresponding to the fallen blocks of the sector (Fig. 6). In this area, diapiric activity is more evident, as there are protuberances associated with mud volcanoes. This area is also affected by the Bucaramanga-Santa Marta sinistral fault system, which extends from the continent (Cediel *et al*., 2003) to the submarine part of this area. This system generates satellite normal faults that affect the area where the continental shelf narrows.

Finally, the thematic charts (Fig. 7) show the geomorphological units using a color code, which is given in detail in Table 1 and Annex 1.

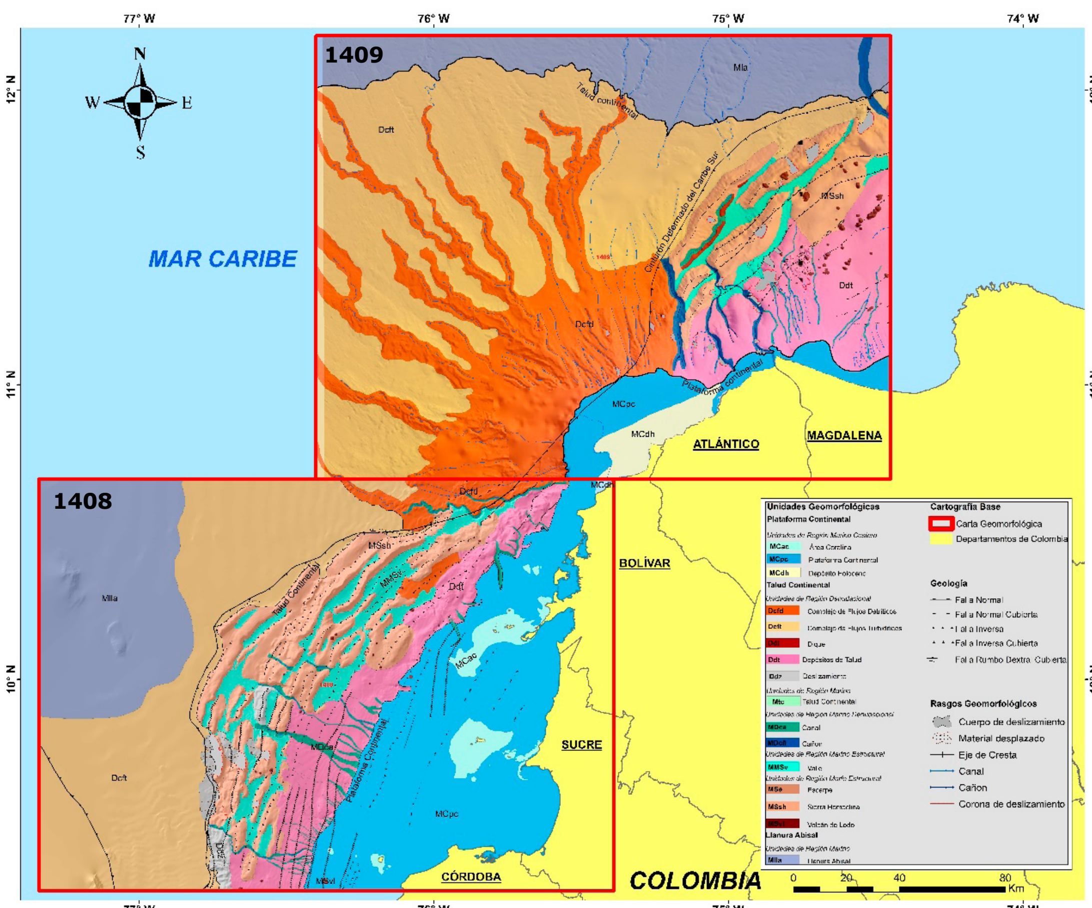

Figure 7. Charts nos. 1408 and 1409, showing the geomorphological units of the Colombian Caribbean on a scale of 1:250 000.

Table 1. Proposed nomenclature for the 229 geomorphological units delineated in the two geomorphological charts

	REGIÓN / PROCESO	UNIDAD GEOMORFOLOGICA	NOMENCLATURA DE UNIDAD	NÚMERO DE UNIDADES
CARTA TEMÁTICA 1408 Cinturón deformado del Sinú	MARINO COSTERO	Área Coralina	MCac	18
	MARINO DENUDACIONAL	Canal	MDca	40
	DENUDACIONAL	Complejo de flujos de detritos	Dcfd	2
	DENUDACIONAL	Complejo de flujos turbidíticos	Dcft	2
	MARINO COSTERO	Depósito Holoceno	MCdh	1
	DENUDACIONAL	Depósitos de Talud	Ddt	22
	DENUDACIONAL	Deslizamiento	Ddz	8
	MARINO	Llanura Abisal	Mlla	1
	MORFO ESTRUCTURAL	Sierra Homoclinal	MSsh	21
	MARINO MORFO ESTRUCTURAL	Valle	MMSv	13
	MARINO MORFO ESTRUCTURAL	Volcán de Lodo	MSvl	31
				Total de Unidades: 159

	REGIÓN / PROCESO	UNIDAD GEOMORFOLOGICA	NOMENCLATURA DE UNIDAD	NÚMERO DE UNIDADES
CARTA TEMÁTICA 1409 Abanico Río Magdalena	MARINO DENUDACIONAL	Canal	MDca	8
	MARINO DENUDACIONAL	Cañon	MDcñ	4
	DENUDACIONAL	Complejo de flujos de detritos	Dcfd	1
	DENUDACIONAL	Complejo de flujos turbidíticos	Dcft	1
	MARINO COSTERO	Depósito Holoceno	MCdh	1
	DENUDACIONAL	Depósitos de Talud	Ddt	2
	DENUDACIONAL	Dique	Ddi	1
	MORFO ESTRUCTURAL	Escarpe	MSe	1
	MARINO	Llanura Abisal	Mlla	1
	MARINO COSTERO	Plataforma Continental	MCpc	3
	MORFO ESTRUCTURAL	Sierra Homoclinal	MSsh	6
	MARINO MORFO ESTRUCTURAL	Valle	MMSv	5
	MARINO MORFO ESTRUCTURAL	Volcán de Lodo	MSvl	36
				Total de unidades: 70

Conclusions

We identified 229 geomorphological units in charts 1408 and 1409, which correspond to structural and denudational processes associated with the environments of the platform and slope of the continental margin; these include homoclinal ridges, slope deposits, mud volcanoes, etc., as well as linear geomorphological features, such as channels and canyons.

We also identified mass movements and plotted the tectonic features observed in the 2D seismic data associated with normal, reverse and strike-slip fault lineaments.

Acknowledgments

The authors wish to thank the geologist Henrry Carvajal Perico for his collaboration and guidance as a result of his experience and knowledge of interpreting and mapping geomorphological units; and the Exploration and Production Information Service for supplying the seismic images to develop the structural interpretation.

Funding source

This project was funded with operating and marketing resources assigned to Center for Oceanographic and Hydrographic Research of the Caribbean – National Hydrographic Service of the General Maritime Directorate.

Author contributions

Conceptualization: Y.S.; methodology: Y.S.; software: Y.S., M.C., E.G.; visualization: M.C.; analysis: Y.S.; data curation: D.S., O.A., D.D., J.U.; writing and preparing the original draft: Y.S., M.C., E.G.; writing, checking and editing: Y.S. All the authors have read and accepted the published version of the manuscript.

Bibliography

Carvajal, J. H. (Ed.). (2012). *Propuesta de estandarización de la cartografía geomorfológica en Colombia.* Servicio Geológico Colombiano. Bogotá. 83 pp. https://doi.org/10.32685/9789589952825

Cediel, F.; Shaw, R.; Cáceres, C. (2003). Tectonic assembly of the northern Andean Block. 2003. En: Bartolini C., R. Buffler y J. Blickwede (Eds.). *The Circum-Gulf of Mexico and Caribbean: Hydrocarbon habitats, basin formation and plate tectonics, AAPG Memoir 79: 815-848*. https://doi.org/10.1306/M79877C37

Dirección General Marítima. (2021). *Esquema de Cartografía Náutica Nacional.* Cuarta actualización. Dimar. 89 pp. Bogotá.

Idárraga-García, J.; Masson, D.; García, J.; León, H.; Vargas, C. (2019). Architecture and development of the Magdalena Submarine Fan (southwestern Caribbean). *Marine Geology,* 414: 18-33. https://doi.org/10.1016/j.margeo.2019.05.005

Meyer, B.; Saltus, R.; Chulliat, A. (2017). *EMAG2v3: Earth Magnetic Anomaly Grid (2-arc-minute resolution).* Version 3. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5H70CVX

Micallef, A.; Krastel, S.; Savini, A. (Eds.). (2017). Submarine geomorphology. Springer. 556 pp. https://doi.org/10.1007/978-3-319-57852-1

Olaya, V. (2020). Sistemas de información geográfica. *Un libro libre de Víctor Olaya.* volaya.github.io/libro-sig/index.html

Rangel-Buitrago, N.; Idárraga-García, J. (2010). Geología general, morfología submarina y facies sedimentarias en el margen continental y los fondos oceánicos del mar Caribe colombiano. En: INVEMAR (Eds.). *Biodiversidad del margen continental del Caribe colombiano,* 29-51.

Sandwell, D.; Müller, R.; Smith, W.; García, E.; Francis, R. (2014). New global marine gravity model from Cryo-Sat-2 and Jason-1 reveals buried tectonic structure. *Science,* 346: 65-67 https://doi.org/10.1126/science.1258213. PMid:25278606

Veloza, G.; Styron, R.; Taylor, M.; Mora, A. (2012). Open-source archive of active faults for northwest South America. *GSA Today,* 22(10): 4-10. https://doi.org/10.1130/GSAT-G156A.1

Vinnels, J.; Butler, R.; McCaffrey, W.; Paton, D. (2010). Depositional processes across the Sinú accretionary prism, offshore Colombia. *Marine and Petroleum Geology,* 27(4): 794-809. https://doi.org/10.1016/j.marpetgeo.2009.12.008

Annex 1 - Details of the geomorphological units and base cartography of Charts 1408 and 1409 showing the geomorphological units of the Colombian Caribbean Sea at a scale of 1:250 000.

Short article

About the need for an assessment on the risk of pollution from the fuel on board the shipwreck of the former USS Peacock in the Bay of Cartagena de Indias

Sobre la necesidad de una evaluación del riesgo de contaminación por el combustible a bordo del naufragio del USS "Peacock" en la bahía de Cartagena de Indias

DOI: https://doi.org/10.26640/22159045.2023.614 **Date received:** 2023-04-27 / Date accepted: 2023-07-28

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Citation:

Andrade Amaya, C. A. (2023). About the need for an assessment on the risk of pollution from the fuel on board the shipwreck of the former USS Peacock in the Bay of Cartagena de Indias. *CIOH Sci. Bull.*, 41(2), 51-59. Online ISSN 2215-9045. DOI: https://doi.org/10.26640/22159045.2023.614.

Abstract

The tugboat USS Peacock was sunk near the tip of the Castillogrande peninsula in the Bay of Cartagena when it accidentally collided with the Norwegian-flagged merchant ship MS Hindanger on 23 August 1940. Almost split in two, it quickly sank, killing three crew members while 23 were rescued. Since it started to be monitored in 1992, it has been noted that fuel drops sporadically come out of the shipwreck and its position coincides with the measurements of the highest concentration of hydrocarbons in the bay. The Diving and Salvage Department of the Colombian Navy has been monitoring this situation that is still ongoing. Therefore, this article suggests a research project to evaluate of the amount of fuel that the shipwreck may have on board and to study the alternatives to remove it in order to allay the environmental risk.

Keywords: Bay of Cartagena, shipwrecks, USS Peacock, fuel pollution.

Resumen

El remolcador USS "Peacock" se encuentra hundido cerca de la punta de Castillogrande, en la bahía de Cartagena, producto de un accidente cuando fue abordado por el buque mercante de bandera noruega MS "Hindanger", el 23 de agosto de 1940. Casi partido en dos se hundió rápidamente, muriendo tres tripulantes y 23 fueron rescatados. Desde su reubicación, en 1992, se ha observado que esporádicamente salen gotas de combustible del naufragio. Su posición coincide con mediciones de alta concentración de hidrocarburos en la bahía. El Departamento de Buceo y Salvamento de la Armada de Colombia ha estado monitoreando esta situación que aún continúa. Por ello, se recomienda un proyecto de investigación para la evaluación de la cantidad de combustible que pueda tener a bordo el naufragio, y que se estudien las alternativas para retirarlo, con el fin de despejar el riesgo ambiental.

Palabras clave: *bahía de Cartagena, naufragios, USS Peacock, contaminación por combustible.*

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Introduction

As a result of World War II (1939-1945), more than 6 300 ships lie submerged in the world's oceans, with an estimated 2.5 to 20.5 million tons of fuel remaining in their tanks. This represents a potential contamination equivalent to 700 times the Exxon Valdez oil tanker accident in Alaska (Deutsche Welle, 2020). Currently, several shipwrecks have started to show signs of significant fuel leakage due to the gradual corrosion-induced deterioration of the metal walls of their tanks. Some countries, such as Norway, have taken on the task of extracting fuel from shipwrecks in their waters, understanding that if fuel still remains in the shipwrecks' tanks, it is a ticking time bomb (Schmidt-Ekin, 2011).

The maritime tugboat USS Peacock is one of the shipwrecks that fit into this narrative of World War II. Although it appears to be an accident, when it encountered a Norwegian-flagged merchant vessel, the MS Hindanger, at a critical point in the navigation channel of the Bay of Cartagena de Indias, it was violently struck on the starboard side near the engine room and sank rapidly. The wreck has been marked on navigation charts since the time of its sinking (Fig. 1) and has been previously characterized (Santos & Rojas, 2015; Andrade, 2021) concerning its position, layout, and stability. In this context, this article addresses the concern that it may still contain significant quantities of fuel and its proximity to the coastline within the inner bay.

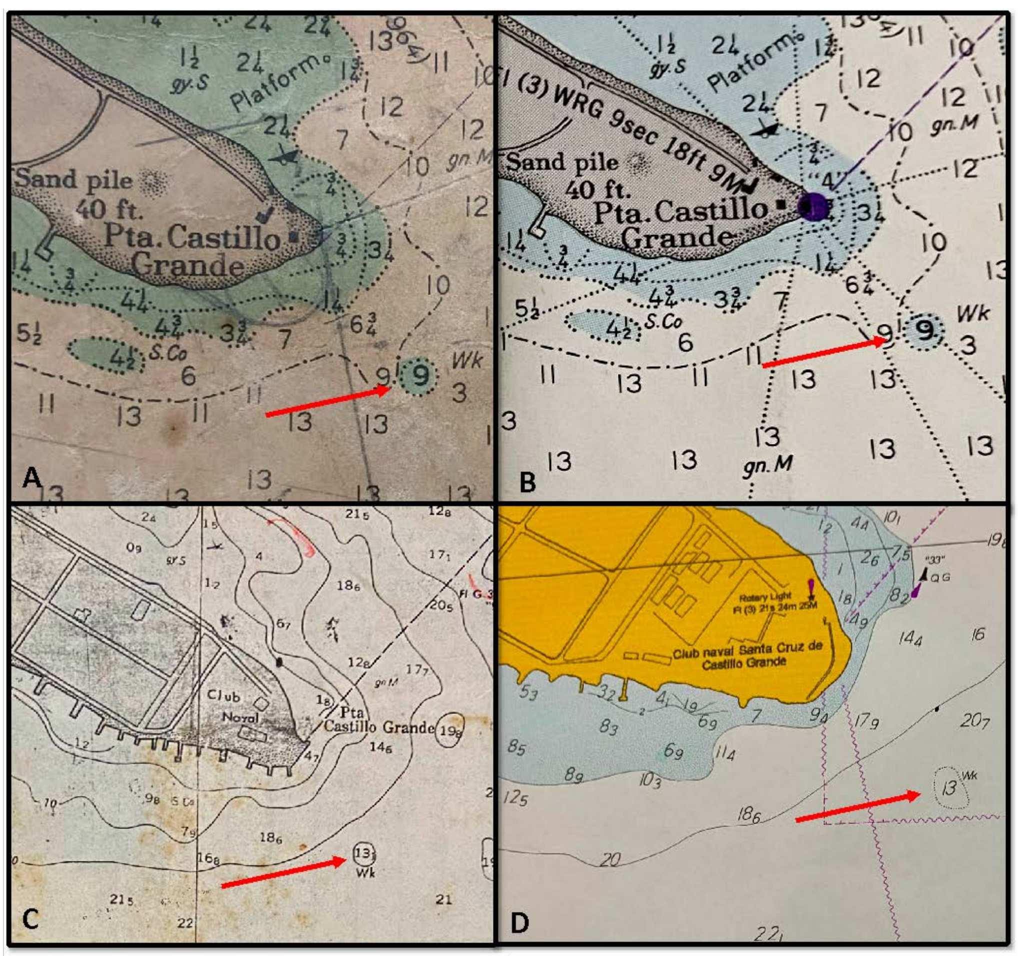

Figure 1. The wreck's position on navigation charts: (**A**) On chart US 24505, Rev. 1966. (**B**) On the same chart updated in 1976. (**C**) On chart COL 262 from 1982. (**D**) On chart COL 840 from 2000 (indicated as Wk)

Study Area

In a strict sense, the study area corresponds to the area of the shipwreck in the navigation channel, near the tip of the Castillogrande peninsula, in Bay of Cartagena (Fig. 2). However, in a broader sense, if the possibility of an oil spill were to be part of the hypothesis, it includes the entire bay.

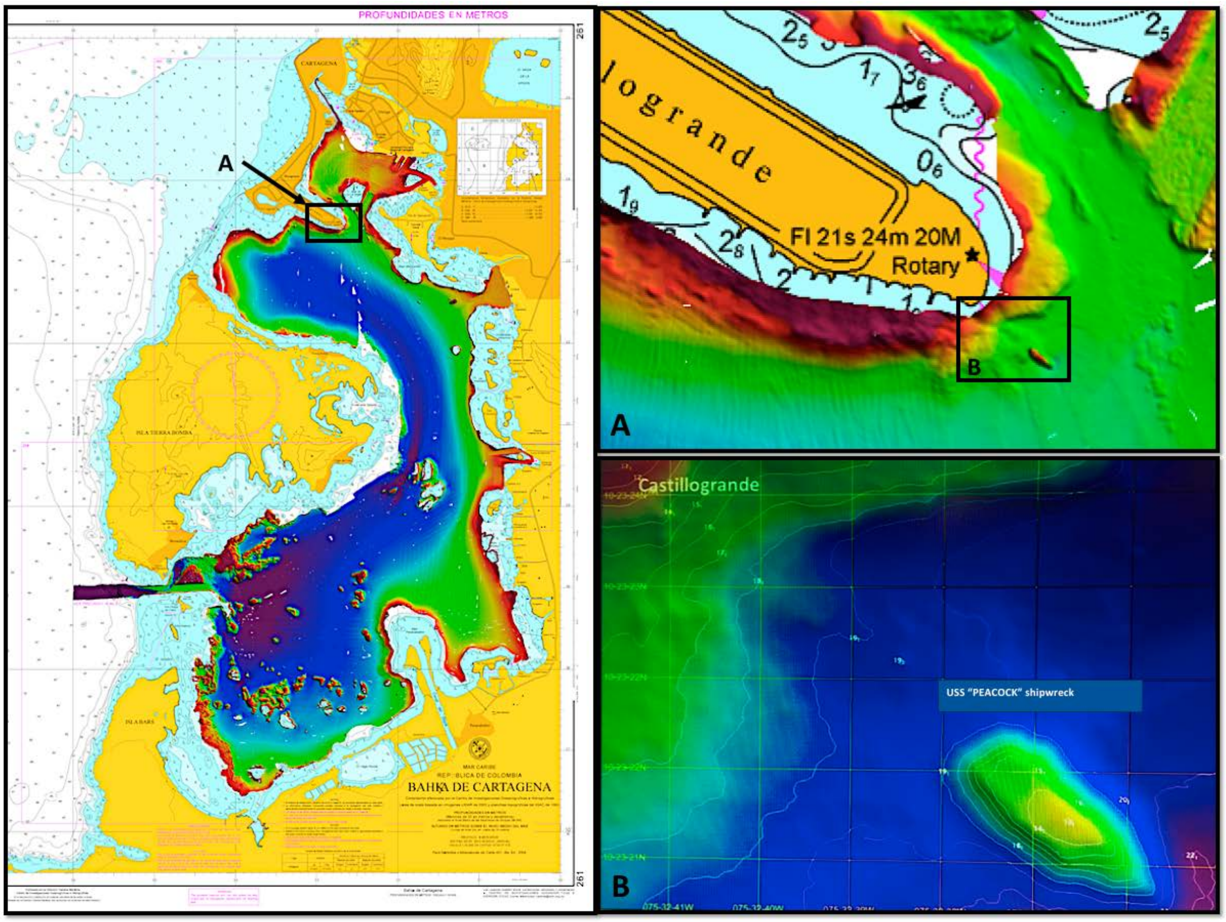

Figure 2. Bathymetric surface, created using a multibeam sonar, overlaid on nautical chart COL 261 on order to identify features in Cartagena Bay (Mora et al., 2018). In the Cuatro Calles area (**A)**, the anomaly representing location of the wreck (**B)** can be observed in the navigation channel in front of the Castillogrande peninsula.

The area in which the wreck is located is commonly known as Cuatro Calles. It is the deepest point in the channel, where hydrodynamic forces from the Bocagrande Channel converge, and where ocean currents, driven by the tide within the outer bay, pass by the wreck as they enter and exit the inner bay, carrying sediments from the Canal del Dique to the area (Andrade, Arias, & Thomas, 1988).

As a result, the sediments in the area are very fine within the channel and the inner bay (Thomas *et al*., 2005; Andrade *et al*., 2004). The bottom currents are relatively higher along the navigation channel (Lonin & Giraldo, 1996), creating a layer of high turbidity near the bottom. Consequently, visibility is low (around 1 m) in the deep area. This characteristic improves in the intermediate zone below the surface layer, where clear waters are often found, allowing for professional diving operations, with all the mentioned limitations.

Methodology

A description of the vessels involved in the accident and what was known about the circumstances surrounding the collision and subsequent sinking of the tugboat was made based on a review of historical documents. The bathymetric surface used for this description was the result of processing conducted to identify geomorphological features in the Bay of Cartagena, which were found and analyzed during the first-order bathymetric survey carried out using a Reson 7125 multibeam echosounder at 200 and 400 kHz with 512 beams. This equipment was accompanied by a Trimble differential global positioning system and Octans motion sensors, all used during investigations conducted by the Center for Oceanographic and Hydrographic Research of the Caribbean (CIOH) in the Bay of Cartagena between 2015 and March 2016, as documented in Mora *et al*. (2018).

To describe the current situation of the wreck, we used images from an Edgetech 4100FS side-scan sonar provided by the company Exocol, captured along profiles controlled with high-resolution positioning (DGPS). The very low visibility on the seabed in that area has prevented the presentation and better description through underwater photography. Finally, the present wreck is placed in the context of the growing attention to the need to take action and evaluate the condition of the wreck of the USS Peacock and similar sunken ships from World War II to prevent potential consequences within the bay.

Results and Discussion

The tugboat USS Peacock

The USS Peacock was the former minesweeper with the hull number AM 46. It had a displacement of 840 tons, a length of 187.1 feet, a beam of 35.5 feet, a depth of 8.10 feet, and a design draft of 14 feet (Fig. 3). Its keel was laid on 31 August 1918 at the Staten Island Shipbuilding Company. It was launched on 08 April 1919, with Miss A.M. Danner as its sponsor, and commissioned on 27 December 1919. Lieutenant John Danner served as the commanding officer.

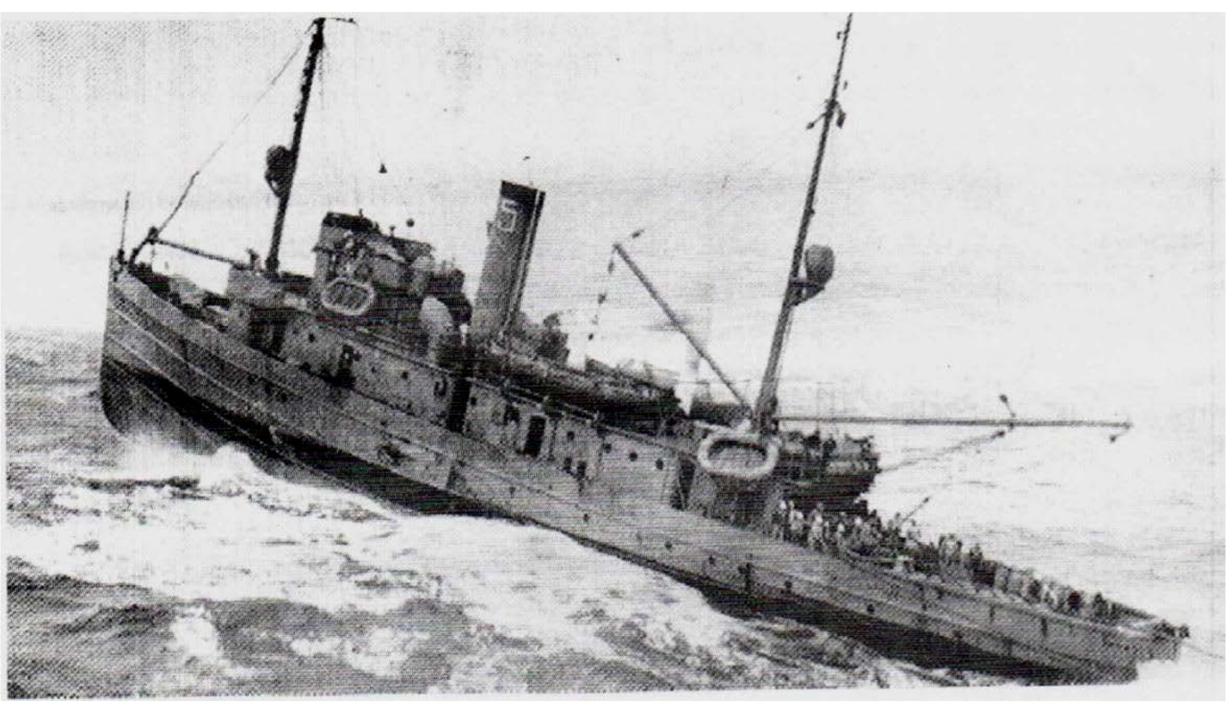

Figure 3. Image of the USS Lapwing, the sister ship of the USS Peacock, which sank in Cartagena Bay (images at en.wikipedia.org/wiki/Lapwing-class minesweeper)

After provisioning, the USS Peacock remained at the Navy pier in New York until it was officially decommissioned on 14 February 1920. On the same day, it was handed over for charter to the Office of Shipping. Converted into a salvage tug, the USS Peacock served under contract in various commercial activities until 24 August 1940, when it collided with the Norwegian merchant vessel MS Hindanger near the tip of the Castillogrande peninsula and sank. It was struck from the United States Navy's ship registry on 22 April 1941 (Naval History and Heritage Command, 2022).

The MS Hindanger

The MS Hindanger was a Norwegian-flagged merchant vessel (Fig. 4), with a tonnage of 4 885 gross tons and 8 200 tons deadweight (TDWT), a length of 395 feet, a beam of 54.6 feet, and a draft of 28.9 feet. It was powered by two 6-cylinder 4-stroke 4 200 hp engines, which gave it a top speed of 12.5 knots. Its call sign was LDKC. It was delivered in October 1929 by Sir W. G. Armstrong, Whitworth & Co. Ltd., Newcastle upon Tyne.

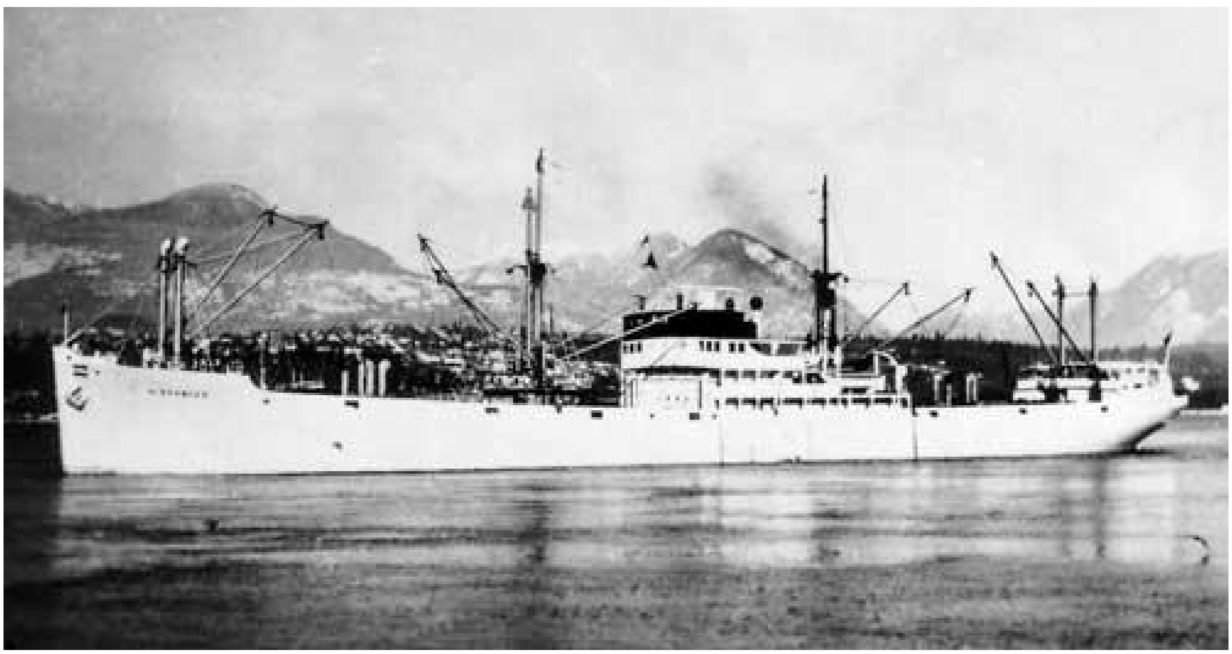

Figure 4. Image of the MS Hindanger (Photo received from Aage A. Wilhelmsen, Norway - owned by Kaspar Skjerve at the Westfal-Larsen & Co. A/S agency in Bergen)

It was leaving the inner bay when it encountered the USS Peacock right at the tip of the Castillogrande peninsula, where the channel is narrow for maneuvering, and ended up colliding head-on with the beam of the tugboat. Following the collision in the Bay of Cartagena (Fig. 4), the SM Hindanger became a victim of the war. It had arrived in Liverpool on 21 August 1942, and later joined the North Atlantic convoy ON 127, heading west, departing from Liverpool on 04 September. It was enroute to New York but never reached its destination. On 11 September 1942, it was torpedoed by U-584 (Kapitänleutnant Joachim Deecke) at position 49° 39'N – 32° 24'W (Warsailors, 2011).

News of the accident and sinking of the USS Peacock

In the words of a newspaper of the time:

> *"The USS Peacock was unable to perform the evasive maneuver and this caused the bow of the Norwegian steamer to split it in two. José Rodríguez, a Portuguese citizen, jumped into the water and was saved. He was doing laundry in the kitchen when the collision occurred. The casualties were: Chief Engineer Mr. Robert A. Casid, Radio Operator John Harston, and Sailor Louis Nelson; initially, the wreckage of the tugboat was not located, which led to a subsequent search. Of*

the crew, 23 were saved: Captain A. Hansen, M. Rivewrs, W. Rosso, T. Ziegles, K. Krogidad, L.H. Sorensen, George Culberston, Jacob Jacobsen, Henrick Palker, M. Sculman, McCarty, Doug Lopez, John Saloon, John Bauer, L. Stoab, Patzy H. Soilor, Martin Rehien, Stanley Pumpenger, J. Croops, and A. Norad. The news clarified that the tugboat belonged to the USN and not to the Tropical Fruit Company, being leased to Merritt Chapman and Scott Corp, and the agency in Cartagena and Panama was Tropical Oil." (El Fígaro, Monday 26 August 1940).

Subsequently, a note was written about the efforts to locate the site of the wreck to assess potential navigational hazards:

"The technical personnel from the Naval Base managed to locate the site where the remains of the American tugboat were found the following day, and the Norwegian steamer resumed its journey a few days later. By conducting surveys, it was determined that it had sunk in the deepest part of the channel, presenting itself as 'a blessing for our port,' as a large vessel had sunk and had not affected navigation." (El Fígaro, Tuesday 27 August 1940).

Current status of the wreck

The wreck of the Peacock has been marked in Notices to Mariners and incorporated into nautical charts since the time of its sinking, as shown in Figure 1. More recently, the wreck has been visually visited and inspected through diving operations since July 1992 by the Marine Infantry Special Forces and the Diving and Salvage Department of the Colombian National Navy. Since then, the wreck has been continuously visited and has become a mandatory location for diver training in low-visibility inspections. From the earliest dives, it became evident to the divers that the ship's internal structure retains a large quantity of "black droplets" that rise to the surface (fuel oil drops) and mark the wreck's location, which has always raised interest and concern due to its proximity to the city.

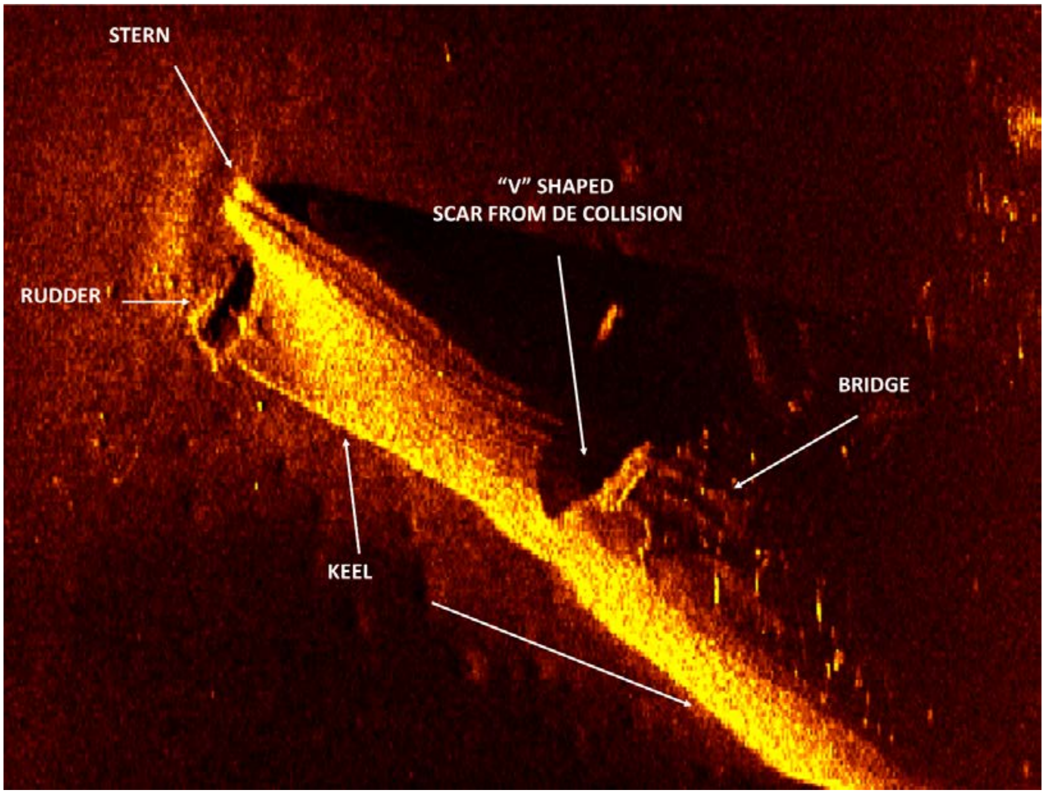

Figure 5. Side-scan sonar image (600 kHz) of the wreck of the tugboat USS Peacock in the Bay of Cartagena. Note the V-shaped scar on the hull resulting from the collision.

The side-scan sonar image (Fig. 5) shows that the ship rests on its port side in one piece, with a deep V-shaped scar near the engine room, a result of the collision with the MS Hindanger

Images from sonar surveys indicate that the ship's structure is still well-preserved. However, dive inspections report that the structure is completely encrusted, especially in the shallower part, up to about 17 m in depth, which is the lower limit of the oceanic water that is more transparent to sunlight. A significant amount of fine silt has accumulated on top of these encrustations. Additionally, reports indicate that metal deterioration is evident in many places on the starboard side. Further aspects of the wreck can be found in Santos and Rojas (2015) and Andrade (2021).

Apart from the continuous release of fuel oil drops that rise to the surface, no specific studies or analyses related to environmental contamination at this site have been conducted. Only on an ad hoc basis, in 1985, were concentrations of dissolved and dispersed hydrocarbons detected at the Caripol program station (Caribbean Pollution - an Iocaribe Program), located closest to the wreck in Bay of Cartagena, with a value of 17.9 µg/L. At that time, these residues were mostly attributed to maritime transport, docking and landing activities, and industrial uses (Garay, 1987).

Recent studies in the Bay of Cartagena have examined polycyclic aromatic hydrocarbons (PAHs) in sediments and dissolved and dispersed hydrocarbons in water. For the sediments, the results of Tous *et al*. (2015) and Mejía (2015) agree that the bay's sediments are contaminated with PAHs, inferring that some of these compounds arise from port activity in this bay. Regarding the water matrix, Sánchez *et al*. (2020) conducted a physicochemical characterization of a loading port in the Bay of Cartagena and detected the presence of dissolved and dispersed hydrocarbons at the surface water sampling points near the port's loading and unloading area. However, there are no specific studies on dissolved or dispersed hydrocarbons in water at the tip of the Castillogrande Peninsula, the location of the wreck.

On the brink of an ecological disaster

Likewise, at the bottom of the sea, a large number of ships that were sunk by the forces of the world wars lie dormant. It is estimated that there are at least 6 338 ships sunk worldwide solely as a result of the Second World War, many of which have characteristics similar to the USS Peacock.

It is estimated that wrecks contain between 2.5 and 20.5 million tons of fuel oil in their tanks, which could rupture and cause the same type of damage as an oil spill today. This could mean that there is much more oil contained in tanks sunk in the sea than previously estimated.. In response to this situation, in 2010, officials from the National Oceanic and Atmospheric Administration (NOAA) aboard the USS Baseline Explorer made an inventory and database, applying 21 criteria, and resulting in the risk classification of the sunken ships in US waters (McCay *et al*., 2014).

Being inside the Bay of Cartagena, the USS Peacock poses a real risk. A potential leak would reach the shore in a short time. This is a situation similar to the one that identified in Puck Bay, Gdynia, Poland by the oceanographic vessel Imor from the Gdansk Maritime Institute. Inspections of the wreck of the German hospital ship Stuttgart, which sank on 09 October 1943, 2 km from Gdansk Bay and at a depth of 20 m, revealed significant amounts of emulsified fuel in the sediment (Rogowska, Wolska, & Namiesnik, 2010).

It is known that steel plates lose between 1.5 mm and 2 mm of thickness per decade, which may seem insignificant, but over the decades following 1940, they have become unstable and can rupture under minimal pressure. This presents the greatest challenge for controlled oil recovery, as it is difficult with ships that are over 50 years old due to the progressive corrosion they have suffered. For these reasons, it is important to assess the possibility of doing it now because in 10 or 20 years, an oil recovery operation may be impossible. The long-term cost may be much worse, and waiting is not a solution. Norway has already taken action by removing fuel from wrecks in their waters (DW-Deutsche Welle, 2020).

Several issues require immediate attention and answers. For example, it is necessary to understand whether or not the fuel on board the USS Peacock would be emulsified to the same extent as the German ship. The ship had just completed a voyage; how much fuel did it have on board? How can valves be installed without breaking the tank walls? Since it was a former minesweeper converted into a USN tugboat, can measures be taken without the permission of the US government?

Conclusion and Recommendation

As mentioned earlier, this manuscript does not intend to present conclusions regarding the USS Peacock's situation. Instead, it aims to inform in the context of the environmental situation about what is happening and how similar situations are being addressed worldwide.

The author's opinion is that this is a chronic problem that must be confronted. It is urgent to invest in ensuring the environmental health of the Bay of Cartagena, especially along the coast of Castillogrande. In this regard, it is essential to conduct a detailed inspection of this situation. If there is a significant amount of fuel on board the USS Peacock, solutions must be found to extract it from the ship because a leak from a fuel oil tank within the bay could be disastrous. If there is fuel on board, the question is not whether a leak will occur, but when it will happen.

Acknowledgments

The author expresses gratitude to Major of the Marine Infantry (RA) Miguel Enrique Rozo, my diving partner when we "rediscovered" the wreck site. Thanks to the divers of the Diving and Salvage Department of the Naval Base in 1992 for their collaboration and assistance in the interior characterization of the wreck's stability. Thanks also to the oceanographers and hydrographers of the CIOH for their support over the years. Many of them took part in and helped with the numerous diving and echo sounding sessions during all these years, getting to know the wreck. And finally, thanks to the proofreaders from this journal for their anonymous help and contributions

Funding Source

This manuscript was produced with funds from the company Exploraciones Oceánicas de Colombia (Exocol S.A.S.).

Bibliography

Andrade, C. A. (2021). Interpretación de imágenes de sonar de barrido lateral y de sonda multihaz sobre anomalías culturales en la bahía de Cartagena. *CIOH Sci. Bull.,* 40(1): 19-24. https://doi.org/10.26640/22159045.2021.559

Andrade, C. A.; Thomas, Y.; Lonin, S.; Parra, C.; Menanteau, L.; Cesaraccio, M.; Kunesch, S.; Andriau, A.; Piñeres, C.; Velasco, S. (2004). Aspectos morfodinámicos de la bahía de Cartagena de Indias. *CIOH Sci. Bull.,* 22: 90-104. https://doi.org/10.26640/22159045.131

Andrade, C. A.; Arias, F.; Thomas, Y. (1988). Nota sobre la turbidez, circulación y erosión en la región de Cartagena. *CIOH Sci. Bull.,* 8: 71-82. https://doi.org/10.26640/22159045.29

DW-Deutsche Welle. (2020). The Black Tears of the Sea: The Lethal Legacy of Wrecks. TV documentary produced by Längengrad Filmproduktion for the WDR in cooperation with Arte. Written and directed by Christian Heynen; camera by Michael Kern; underwater cameras by Konrad Dubiel, Matthias Granberg, Jörn Kumpart, Allison Low and Chris Selman; edited by Jan Wilm Schmülling; music by Thomas Wolter. English version released in July 2020 by Deutsche Welle. Running time: 42 minutes.

Garay, J. A. (1987). Vigilancia de la contaminación por petróleo en el Caribe Colombiano (Punta Canoas hasta Barbacoas, Cartagena, Colombia). *CIOH Sci. Bull.,* 7: 101-118. https://doi.org/10.26640/22159045.25

Lonin, S.; Giraldo, L. (1996). Influencia de los efectos térmicos en la circulación de la Bahía Interna de Cartagena. *CIOH Sci. Bull.,* 17: 47-56. https://doi.org/10.26640/22159045.84

McCay, D. F.; Reich, D.; Michel, J.; Etkin, D.; Symons, L.; Helton, D.; Wagner, J. (2014). For Response Planning: Predicted Environmental

Contamination Resulting from Oil Leakage from Sunken Vessels. In: *International Oil Spill Conference Proceedings.* p. 300108. https://doi.org/10.7901/2169-3358-2014-1-300108.1

Mejía, G. E. (2015). *Hidrocarburos aromáticos policíclicos en la Costa Caribe colombiana y posibles fuentes de contaminación*. Tesis de maestría. Universidad de Cartagena. Cartagena, 109 pp.

Mora, H.; Carvajal, J. H.; Ferrero, A.; Leon, H.; Andrade, C.A. (2018). Sobre emanaciones de gas natural y subsidencia en la bahía de Cartagena de Indias. *CIOH Sci. Bull.,* 37: 35-51. https://doi.org/10.26640/22159045.2018.448

Naval History and Heritage Command. (2022). *Peacock III (AM-46).* https://www.history.navy.mil/research/histories/ship-histories/danfs/p/peacock-ii.html

Rogowska, J.; Wolska, L.; Namiesnik, J. (2010). Impacts of pollution derived from ship wrecks on the marine environment on the basis of s/s "Stuttgart" (Polish coast, Europe). *Science of the Total Environment,* 408: 5775–5783. https://doi.org/10.1016/j.scitotenv.2010.07.031. PMid:20863551.

Sánchez, F.; Mayo, G.; Rivero, J.; Mercado, J.; Johnson, B. (2020). Caracterización fisicoquímica de aguas y sedimentos en puerto de carga de la bahía de Cartagena, Colombia. *CIOH Sci. Bull.,* 39(2): 41-50. https://doi.org/10.26640/22159045.2020.505

Santos, Y.; Rojas, H. (2015). Aplicación de la hidrografía en la prospección, exploración y conservación del patrimonio cultural sumergido de la nación. *CIOH Sci. Bull.,* 33: 221-230. https://doi.org/10.26640/22159045.288

Schimdt-Etkin D. (2011). Spill occurrences: A world overview. In: *Oil Spill Science and Technology, December.* https://doi.org/10.1016/B978-1-85617-943-0.10002-4

Thomas, Y. F.; Cesaraccio, M.; Kunesch, S. ; Andrieu, A. ; Menanteau, L.; Andrade, C. ; Lonin, S.; Parra, C.; Piñeres, C.; Velasco, S. (2005). *Étude morpho dynamique de la baie de Carthagène des Indes (Colombia), Milieux littoraux: Nouvelles perspectives d'étude.* 171-191. Editorial L'Harmattan.

Tous, G.; Mayo, G.; Rivero, J.; Llamas, H. (2015). Evaluación temporal de los niveles de los hidrocarburos aromáticos policíclicos en los sedimentos de la bahía de Cartagena. *Revista Derrotero,* 9(1): 7-12.

Warsailors. (2011). https://www.warsailors.com/singleships/hindanger.html

CIOH Scientific Bulletin

Cartagena de Indias, D.T. y C., Colombia
Vol. 42. Num. 1. Pages 3 to 59. June 2023

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