Ocean Science Journal (2022) 57:556–575
https://doi.org/10.1007/s12601-022-00093-9

Online ISSN 2005-7172
Print ISSN 1738-5261

REVIEW

# Gulf of Urabá (Caribbean Colombia), a Tropical Estuary: A Review with Some General Lessons About How it Works

**Sebastián Contreras-Fernández**[1,2] · **Lennin Florez-Leiva**[1] · **María Camila Bernal-Sánchez**[1,3] · **Wilberto Pacheco-Paternina**[1,3] · **Shalenys Bedoya-Valestt**[1,4] · **Lorenzo Portillo-Cogollo**[1,3,5]

Received: 20 October 2021 / Revised: 21 August 2022 / Accepted: 13 September 2022 / Published online: 2 December 2022

**Abstract**

Estuaries are highly diverse ecosystems that occur at the interface between land and sea and thus possess a high degree of environmental variation over short spatial and temporal scales. The Gulf of Urabá (1800 km 2; mean depth ~ 40 m) is a semi-closed estuarine area located in the southwestern part of the Caribbean Sea (South America). This large coastal–estuarine ecosystem operates as a biogeochemical reactor due to it featuring examples of high nutrient concentrations on the surface (NO 3- = 1619 µM; NO 2- = 0.505 µM; NH 4+ = 2.938 µM; PO 4 3- = 7.603 µM), high Chl α (max = 30.17; min = 0.02; mean = 9 mg m$^{-3}$), as well as blooms of toxic algae, mostly *Pseudo-nitzschia pseudodelicatissima*. An outbreak of *Tripos fusus* causes bioluminescence and about 20 events of hypoxia (< 2–4 mg O 2 L$^{-1}$) within a time series of 10 years. Despite this, information regarding the biological and biogeochemical oceanography (chlorophyll α, biomass, planktonic composition, nutrient cycling, mass balance of elements, and interannual variability) remains non-existent. Therefore, elucidating an ecosystem's thresholds for various features is necessary for managing marine ecosystems, and especially for climate change projections. We here present a review of the functioning of this estuary, evaluating and reviewing each aspect of oceanographic variability.

**Keywords** Phytoplankton · Nutrients · Tropical estuary · Gulf of Urabá · Colombia

## 1 Investigation History Gulf of Urabá

The first approaches to the marine environment of the gulf studies began with exploration and visits to areas close to Panamá. The first studies of the hydrography of the region near the Gulf of Urabá (Caribbean Colombia) were made between 1675 and 1679 by William Dampier, considered one of the greatest naturalists in the Caribbean. Nearly 200 years passed before some global expeditions were carried out, particularly in the Caribbean Sea (Table 1). However, the Challenger Expedition (1873–1876) considered the most complete oceanographic expedition in the 1870s, which influenced many countries and their maritime territories in the understanding of oceanography and later helped to improve techniques, equipment development and to form an official field that understood the functioning of the oceans (Brunton 1994), inspiring later studies in the Caribbean and near the gulf (Johns et al. 2002; Centurioni and Niiler 2003).

For the Gulf of Urabá, oceanographic expeditions began in the 1870s after that (Selfridge 1874; Zeigler and Athearn

✉ Sebastián Contreras-Fernández
sebasconfer@gmail.com

[1] Ocean, Climate and Environment Research Group, Environmental Academic Corporation, University of Antioquia, Turbo 052038, Colombia

[2] Marine Environmental Quality Program, Institute of Marine and Coastal Research "José Benito Vives de Andréis" Invemar, Santa Marta 47008, Colombia

[3] Marine and Coastal Geosciences Program, Institute of Marine and Coastal Research–INVEMAR, Santa Marta 47008, Colombia

[4] Centro de Investigaciones Sobre Desertificación, Consejo Superior de Investigaciones Científicas (CIDE-CSIC), Moncada 46113, Spain

[5] Biotechnology Group, Exact Sciences Faculty, University of Antioquia, Turbo 052038, Colombia

**Table 1** Brief historical summary of some studies evaluating the Gulf of Urabá in Colombia

| Cruises/investigations | Importance/observations | Years | Authors |
|---|---|---|---|
| William Dampier | During his travels in the Caribbean Sea, which included the former<br>Darien region (i.e. the present-day territory between Panama and Colombia), he collected plants and animals, describing many of their characteristics with absolute accuracy. His greatest legacy, however, was the way he described some of the characteristics of the hydrography, climate and indigenous culture of this part of the Colombia and Panamanian Caribbean | 1675 and 1679 | Williams (2015) |
| Expeditions of the USS Blake and USS albatross under John Elliott Pillsbury and Alexander Agassiz | For the Caribbean Sea, the first approximations were based on basin-scale mean circulation maps | 1885 | Wüst (1964) |
| | This study provides the first description of the Atlantic inflow passages to the Caribbean Sea. New observed data are revealed to numerically model the total inflow, circulation patterns and water transport through the Caribbean basin, including the main passage and inflow(28 Sv) in Yucatan channel<br>Spin-up and spin-down of the cyclonic gyre (Panamá-Colombia) was also analyzed | Unknown | Johns et al. (2002) |
| | Reconstructed maps of the surface circulation of the Caribbean Sea from 5 years of surface current observations. These measurements show a cyclonic gyre with strong currents in the southern basin of Colombia, whose average magnitude exceeds 0.7 m $s^{-1}$ | 1996–2001 | Centurioni and Niiler (2003) |
| Darien expedition | In the early 1870s, Thomas Selfriedge traced the route of what would become the Panamá Canal and provided the first plans for the Gulf of Urabá during the so-called Darien expedition | 1870 | Selfridge (1874) |
| | It was not until 1965 that some records on the hydrography and sedimentology of the Gulf of Darien (i.e., Gulf of Urabá) appeared | 1965 | Zeigler and Athearn (1965) |
| | This expedition allowed, through the information gathered during his two visits, detailing potential fishing areas, but in oceanographic terms, little information was documented | 1966? | Robins (1971) |
| Expeditions and studies in the Gulf of Urabá | Makes a compilation of the southwestern sea of the Colombian basin, including several works on currents, flow structures, cruises and images Landsat | 1967, 1986, 1986, 1988 and 1997 | Andrade (2015) |

**Table 1** (continued)

| Cruises/investigations | Importance/observations | Years | Authors |
|---|---|---|---|
| Expeditions ANH I and and ANH II | Recent expeditions in the Colombian continental shelf were carried out by ANH I (Oct-December 2008) and ANH II (Oct-December 2009) to explore the oceanography of the region. These expeditions described the current system that affects the entire Caribbean basin and spatially characterized the marine plankton communities | 2009 | Lozano-Duque et al. (2010) |
| | First Colombian oceanographic atlas for both the Atlantic and Pacific basins. This study summarized the existing information from climatological data (temperature, salinity, and density of seawater), and included values for an approximation of the geostrophic current speed of both sea basins, and thus represents a contribution to the oceanographic conceptualization in Colombia | 1922–2015 | Andrade et al. (2015) |
| | First compilation of coastal ecosystems from Antioquia and Chocó, including details and aspects of the oceanographic characteristics | Twentieth century | García-Valencia (2007) |
| Estuarine expedition, Gulf of Urabá | Contribution to the basic sciences of zoology, botany, ecology, geology and coastal oceanography | 2007–2013 | Blanco (2013) |
| South Caribbean expedition: Coastal Antioquia and Chocó | A database of geomorphological, oceanographic, forest and faunal characteristics of mangroves along the 609 km of the coastal contour in Urabá | 2013 | Blanco-Libreros and Londoño-Mesa (2016) |
| Models and observations data | Hydrodynamics through a numerical simulation, including tidal forcing, waves, stratification, wind effects and river action in the estuary | | Escobar (2011, 2015); Toro et al. (2019) |
| | Dynamics of sediment export using monthly amounts of precipitation (mm), flow ($m^3\ s^{-1}$), and export of sediments (Kton $day^{-1}$) on the eastern slope of the Gulf of Urabá | 1961–2007 | Arroyave-Rincón et al. (2012) |
| | Studies of hydrology and hydrodynamics (precipitation, evaporation, surface circulation and flows) have constituted the basic knowledge of the estuary | | Molina et al. (1992); Chevillot et al. (1993); Escobar (2015); Toro et al. (2019) |
| REDCAM time series | One of the most complete marine datasets of the support networks in the Colombian territory, including the Gulf of Urabá | 2001–present | siam.invemar.org.co/redcam |
| TARENA expedition | TARENA Expedition carried out with fixed stations along 80 km (north–south of the estuary) in order to better understand the functioning of the Gulf of Urabá | 2018–present | Ocean, Climate and Environment Group (OCE) and in association with other research groups from the University of Antioquia (GIGA and Biotechnology groups). Toro et al. (2019); Córdoba-Mena et al. (2020) |

1965; Robins 1971; Table 1). However, many of these campaigns described the region only briefly, with some insight into the coastal dynamics. One cruise ship that visited the Gulf of Darien region was named R/V Jhon Elliott Pillsbury (Robins 1971). Other similar cruises (e.g., R/V James M Gill through the University of Miami, the R/V Thomas G Thompson 001 cruises from the University of Washington, and R/V Discoverer NOAA-CARIB) visited the northern part of Colombia intending to study the upwelling zone of La Guajira. The exact records of these visits are not well documented, but could date back to 1977. However, a contribution to the knowledge of local oceanography came from Andrade (2015); Andrade et al. (2015) (see details in Table 1). The landmark of marine science, especially in studies within the gulf, appeared in the 2000s when several expeditions began and the establishment of programs related to marine sciences led by the University of Antioquia, Colombia (Blanco et al. 2013; Blanco-Libreros and Londoño 2016). Recently, through the leading research group (i.e., Oceans, Climate and Environment Group, OCE) and in association with other research groups from the University of Antioquia, Colombia (GIGA and Biotechnology groups), the TARENA expedition (2018–2019) was carried out to understand how the Gulf of Urabá works, with fixed stations along 80 north–south km of the estuary and the work was published recently (Toro et al. 2019; Córdoba-Mena et al. 2020). Other studies have been conducted on the basis of REDCAM database (siam.invemar.org.co/redcam) implemented by the INVEMAR (Instituto de Investigaciones Marinas y Costeras) and CORPOURABÁ Corporation.

Finally, to date, cruises with oceanographic purposes have not been undertaken in an integrated manner. We assume it is relevant to integrate the studies so that the estuary can be understood globally and function holistically, to take management and conservation measures and value.

## 2 A Coastal System

Caribbean Colombia has two large coastal–estuarine ecosystems. One of these ecosystems is the Ciénaga Grande de Santa Marta (CGSM), located in northern Colombia, with a daily production of 16 g C $m^{-2}$ $d^{-1}$ (Hernández and Gocke 1990), which is considered one of the most productive estuaries in the world (Cloern et al. 2014). The second one is the Gulf of Urabá (7° 55′–8° 40′ N and 76° 53′–77° 23′ W), located in the southwestern part of the Caribbean Colombia, which is larger than the first and extends 80 km from north to south, with an approximate width of 49 km from Cabo Tiburón to Punta Caribaná (Fig. 1). These estuaries have

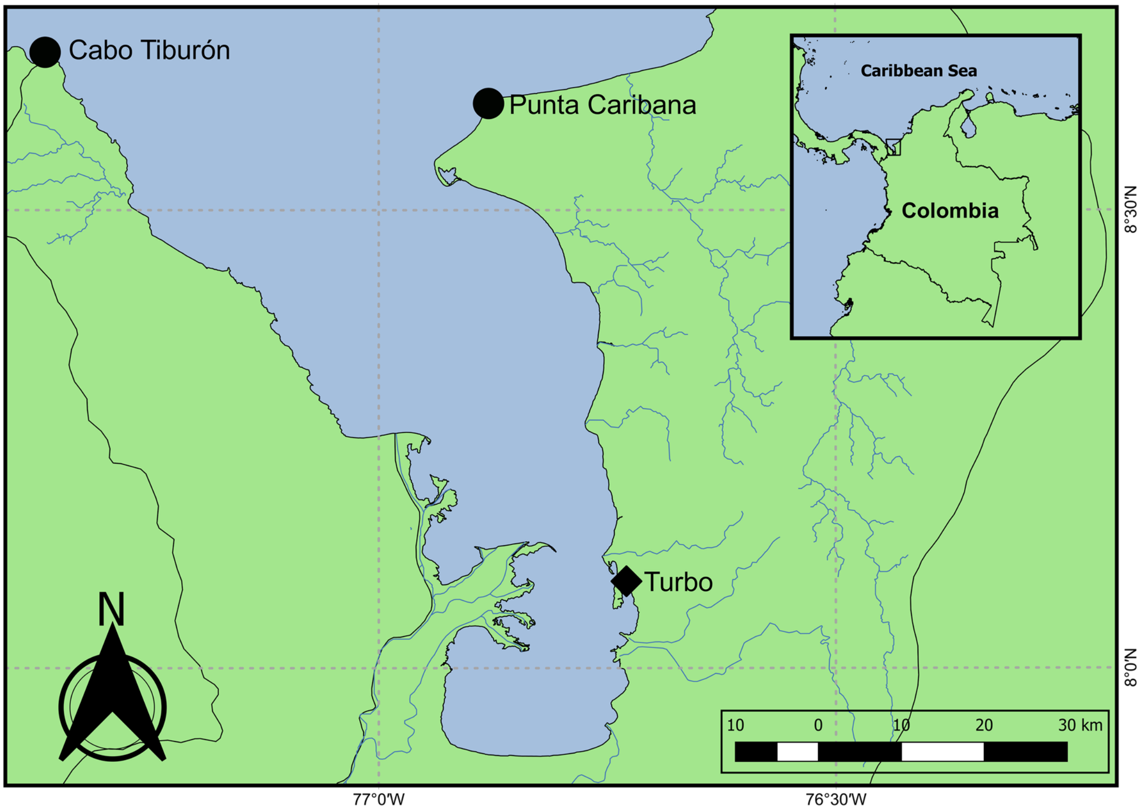

**Fig. 1** Study area: Gulf of Urabá, Caribbean Colombia

**Fig. 2** Conceptual diagram of communities present along a salinity gradient in the delta region of Atrato River

a high diversity of ecosystems such as mangroves (Blanco et al. 2013; Sandoval et al. 2020), coral reefs (López-Jiménez et al. 2020, 2021), seagrass, floodplains, rocky shore, and soft bottoms (Quiceno et al. 2015) that keep these adjacent ecosystems interconnected (Fig. 2), even across the continent by the most important river in the area (i.e., Atrato River), and interaction between the ocean and atmosphere plays a crucial role in the dynamics of the estuaries (Fig. 3).

The bathymetry of the Gulf indicates it is concave with depths increasing from 5 to 20 m in the vicinity of the deltaic front and more than 70 m in the oceanic sector, near the estuarine mouth. Great rivers such as the Atrato and León discharge into the estuary, as well as many other secondary streams that also flow into the gulf (Francois et al. 2007). The Atrato River freshwater input $> 200 \times 10^6$ $m^{-3}$ $d^{-1}$ is the highest in the region and modulates the dynamics of the estuary. Further, it is considered to be a source of inorganic nutrients (i.e., DIN and DIP) and contributes to other tributaries by about 70% (Table 2).

Considering the strategic position of the Gulf of Urabá region, it has been the focus of numerous ecological studies due to the multiple marine ecosystems and the high biological diversity (Quiceno et al. 2015). Likewise, the study by García-Valencia (2007), one of the studies that evaluated the region from a geographical, historical, and cartographic perspective, constitutes one of the most complete documents concerning the region because it generated information regarding biophysical, climatological, socioeconomic, and oceanographic characteristics of the Gulf of Urabá, as well as reviews the geohistory of the area. In addition, physical–chemical variables such as salinity, temperature, turbidity, nutrients, and dissolved oxygen, in some cases between the yearly seasons, have been considered (Francois et al. 2007; Bonilla 2020). Ecologically, this gulf has an estuarine pattern due to its mixture of freshwater from the rivers and saline water from the Caribbean Sea (Córdoba-Mena et al. 2020). The estuary is an ocean–coastal ecosystem, which represents a biogeochemical “hot spot”, because these environmental systems receive large amounts of nutrients and organic carbon from the continent and the ocean and thus

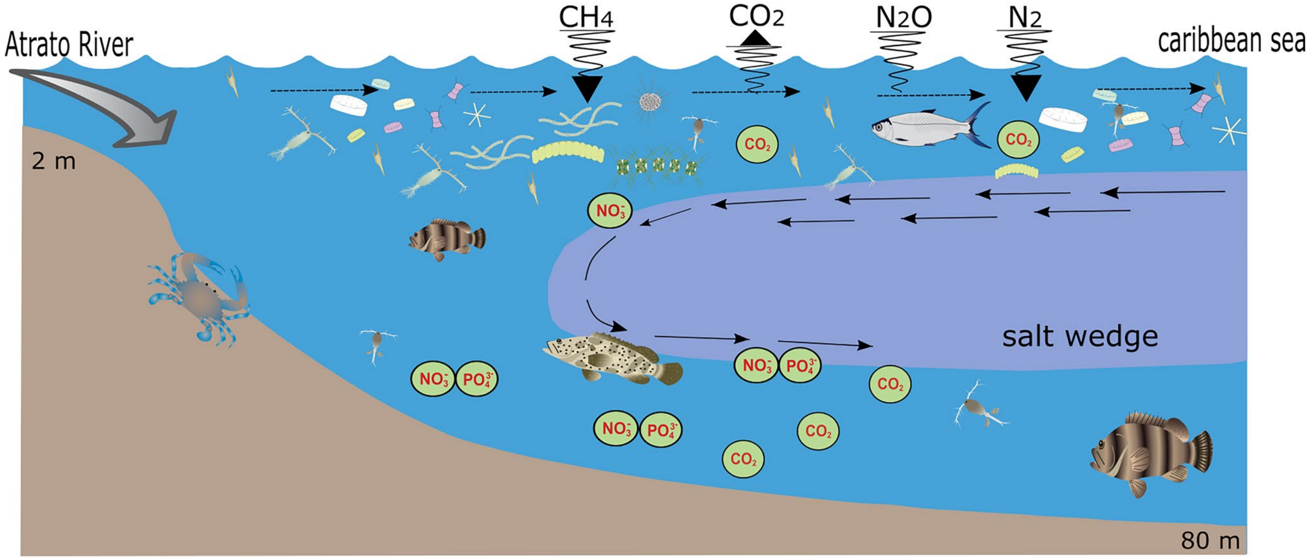

**Fig. 3** Cross section of the Gulf of Urabá. Note the arrows that indicate the direction of the flow of the Atrato River toward the Caribbean Sea and in the shaded part the entrance of the body mass of the Caribbean and its extension into the interior estuary. In addition, biological communities and the water–atmosphere interaction with gas exchange are shown

support high metabolic rates and primary production (Li et al. 2020). As a result, the estuary operates as a biogeochemical reactor (Cloern et al. 2014) serving as a source of gases (e.g., $CO_2$) to the atmosphere with high emission rates and in part to a large amount of organic matter and high nutrient load that are drained into them from the land (Borges 2005).

## 3 Chemical and Physical Considerations

Chemical oceanography in Caribbean Colombia has been little addressed in research. Some studies using the methodologies of this discipline have been extended to open-ocean studies. However, Caribbean Colombia and the Gulf of Urabá require a better understanding of oceanography in its entire context. Many of these methodologies have been evaluated and obtained from the Joint Global Ocean Flux Study (JGOFS). The JGOFS is a strategy used by the intergovernmental commission on oceanography that seeks to generate a standard protocol for measurements of chemical oceanography in multiple oceanographic campaigns.

The coastal and oceanic dynamics near the Gulf of Urabá are modulated by the discharges of the main rivers, among them perhaps the most important being the Atrato River, with a sedimentation rate of 11 tons year$^{-1}$ of sediments and discharge of 4900 m$^3$ s$^{-1}$ (Montoya 2010), lower rate values than those reported in other Colombian rives. For example, Magdalena River contributes the largest sediment amount with $142.6 \times 10^6$ tons year$^{-1}$ (de Lacerda 2004; Restrepo et al. 2018).

Also, there are other influential tributaries in the same estuary with a high nutrient load and influence on the chemical dynamics (Table 2), as well as high rates of evaporation and rainfall (Fig. 4). In another study, Ayala and Marquez (2017) carried out five in situ samplings of the physicochemical parameters of temperature, total dissolved solids, conductivity, salinity, pH, and dissolved oxygen. These authors describe some sampled sites, where they conclude that the values of some parameters (i.e., salinity and temperature) are from typical estuaries conditions. Although much knowledge was gained through expedition and previous studies, it is evident that scientific information has to be integrated. For example, our data analysis of precipitation and evaporation demonstrates the importance of these for the dynamics of the estuary (Fig. 4; Table 2). Predominantly the region where the Atrato River originates is the rainiest area in the world according to the models of the heavy precipitation associated with tropical cyclones is projected in a global warming scenario (Hoegh-Guldberg 2018), even for areas with high rainfall will be rainier. In chemical terms, salinity measurements above the halocline increased with proximity to the Caribbean Sea, creating stratification along the estuary, showing a layer of fresh water of up to 5 m (Córdoba-Mena et al. 2020). Simultaneously, the northeast (NE) trade winds and the oscillation of the Intertropical Convergence Zone (ITCZ) define regional changes in precipitation (Nystuen and Andrade 1993), which follows two contrasting patterns: rainy (April–November) and dry seasons (January–March). During the last decade, monthly rainfall has

**Table 2** Average water flow ($Q$), nutrient concentrations ($C_Q$), loads, and nutrient flux from tributaries into the Gulf of Urabá through its fluvial, estuarine, and oceanic zones in both dry and rainy seasons between 2001 and 2011

| Zone | River | Season | $Q$ ($\times 10^6$ m$^3$ d$^{-1}$) | $C_Q$ (μM) | | Load ($\times 10^9$ mol d$^{-1}$) | | Flux ($\times 10^6$ mol m$^{-2}$ d$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | DIP | DIN | DIP | DIN | DIP | DIN |
| Fluvial | Currulao | Dry | 0.10[c] | 0.75 | 12.1 | 0.07 | 1.25 | 0.00029 | 0.00521 |
| | Currulao | Rainy | 0.85[c] | 0.87 | 8.33 | 0.74 | 7.07 | 0.00308 | 0.02946 |
| | León | Dry | 2.23[c] | 1.12 | **81.71** | 2.49 | 182.49 | 0.01038 | 0.76038 |
| | León | Rainy | 7.46[c] | 0.97 | 45.04 | 7.25 | 335.99 | 0.03021 | 1.39996 |
| *Estuarine* | Atrato | Dry | **208**[a] | 0.61 | 20.79 | **127** | **4328** | 0.10496 | 3.57686 |
| | Atrato | Rainy | **242**[a] | 1.95 | 4.41 | **471** | **1067** | 0.38926 | 0.88182 |
| | Turbo | Dry | 0.30[d]* | 1.09 | 19.78 | 0.33 | 5.93 | 0.00027 | 0.00490 |
| | Turbo | Rainy | 0.30[d]* | 1.45 | 8.42 | 0.44 | 2.52 | 0.00036 | 0.00208 |
| | Bobal | Dry | 0.20[e]* | ND | ND | ND | ND | ND | ND |
| | Bobal | Rainy | 0.20[e]* | **2.74** | 15.79 | 0.55 | 3.18 | 0.00045 | 0.00263 |
| | C. Nuevo | Dry | 0.30[e]* | 0.75 | 4.26 | 0.22 | 1.26 | 0.00018 | 0.00104 |
| | C. Nuevo | Rainy | 0.30[e]* | 1.35 | 6.8 | 0.4 | 2.01 | 0.00033 | 0.00166 |
| | Necoclí | Dry | 0.03[e]* | 0.55 | **65.02** | 0.02 | 2.02 | 0.00002 | 0.00167 |
| | Necoclí | Rainy | 0.03[e]* | 0.46 | 31.54 | 0.01 | 0.98 | 0.0000083 | 0.00081 |
| | Guadualito | Dry | 0.23[c] | 1.49 | 4.6 | 0.34 | 1.05 | 0.00028 | 0.00087 |
| | Guadualito | Rainy | 0.45[c] | 1.49 | 12.86 | 0.54 | 5.78 | 0.00045 | 0.00478 |
| *Oceanic* | Mulatos | Dry | 0.65[b]* | 0.002 | 20.65 | 0.001 | 13.33 | *ND* | 0.00587 |
| | Mulatos | Rainy | 0.65[b]* | 1.14 | **95.43** | 0.74 | 61.59 | 0.00033 | 0.02713 |
| | Acandí | Dry | 0.75[e]* | ND | ND | ND | ND | ND | ND |
| | Acandí | Rainy | 0.75[e]* | 0.62 | 19.89 | 0.46 | 14.94 | 0.00020 | 0.00658 |

Numbers marked in bold indicate numbers with relatively high values

*ND* no data

*$Q$ with no season distinction

[a] IDEAM

[b] Restrepo and Kjerfve (2004)

[c] Roldán (2008)

[d] Montoya (2010)

[e] Velásquez (2013)

amounted to around 80 mm in the dry season and around 862 mm in the rainy season (Restrepo et al. 2009).

To corroborate this, we argue that 17 years of REDCAM time series showed high variability in essential parameters in the estuary, such as temperature, salinity, and pH (Fig. 5). Our data analysis reinforces the concept of a salinity gradient from south to north, generating typical conditions of an estuary, with high rainfall that modulates this parameter and its influence on interannual variability. In addition, the variation of the values of both temperature and typical pH found in tropical estuaries is noted. Similarly, Ricaurte-Villota and Bastidas-Salamanca (2017) studied the Sinú-Urabá region, one of the southernmost areas of the Caribbean Colombian. In their study, they highlight the importance of the Gulf of Urabá in the contribution of continental water to marine systems, depending on the climatic seasons and evaluate its climatology and oceanographic conditions.

Several relevant results can be concluded from their work: (1) in terms of salinity, the Atrato River modulates the water column, generating a flow toward the Caribbean and creating a film of water in the less dense surface layer of water, and (2) the sediment signal is located in the coastal zone and the interior of the gulf. Similar results have been previously evaluated, which demonstrated the density gradient of the surface (Bernal et al. 2005; Montoya 2010; Córdoba-Mena et al. 2020).

Recently, the chemical characteristics of two of the main rivers that drain water into the gulf, León ($Q < 200$ m$^3$ s$^{-1}$) and Atrato ($Q > 2000$ m$^3$ s$^{-1}$), were evaluated, where a saline intrusion in the dry season was evidenced in both rivers (Jiménez and Campillo 2020). Also, these authors found a body of warm water trapped between two bodies of water with a lower temperature and stratification in the wet season. These results are relevant, considering the hydrology of the two rivers and their influence on the dry and rainy seasons

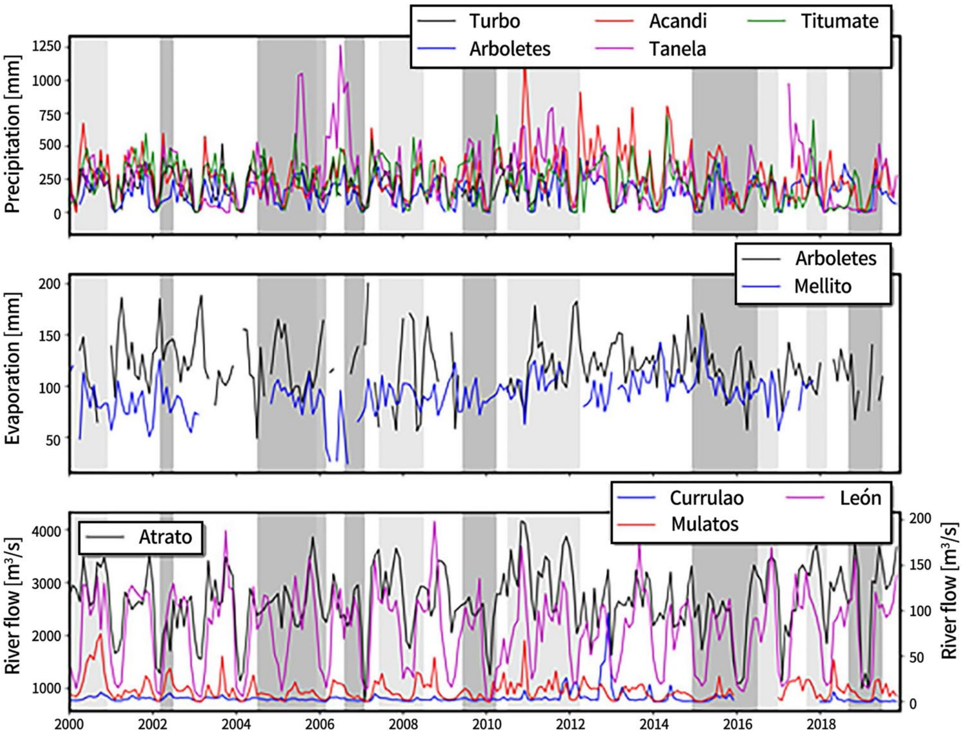

**Fig. 4** Time series of precipitation, evaporation, and flow of the rivers of Urabá, from 2000 to 2018 (Source: IDEAM data). Areas shaded in light and dark gray correspond to negative and positive ENSO, respectively

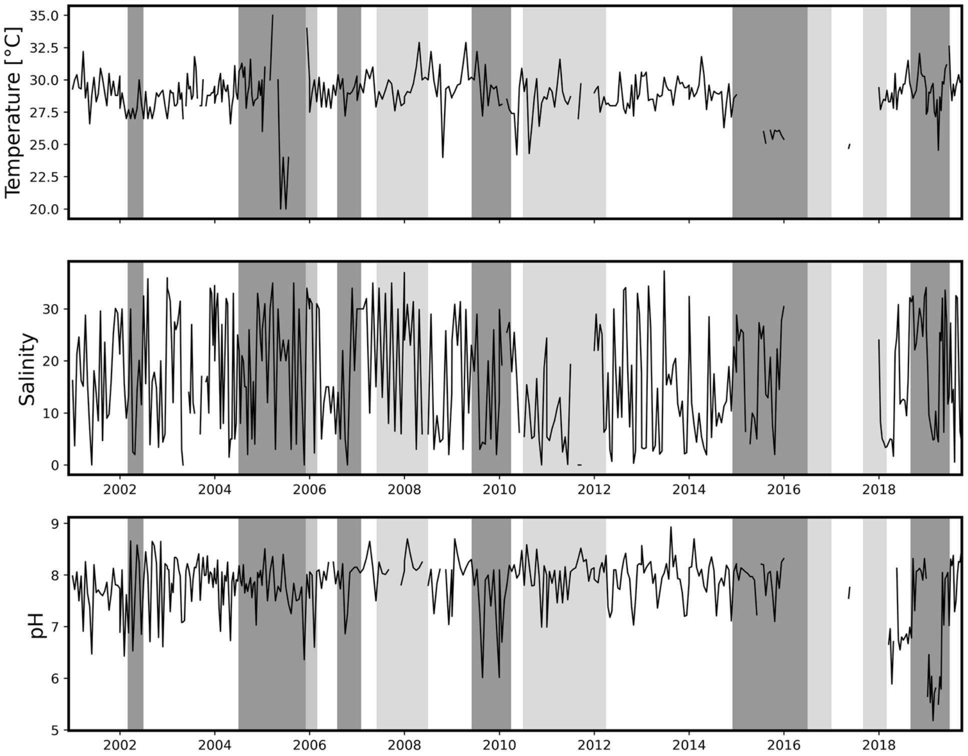

**Fig. 5** Physical–chemical parameters time series. Salinity, temperature, and pH in the estuary from 2000 to 2018. Areas shaded in light and dark gray correspond to negative and positive ENSO, respectively

in the Gulf of Urabá. In the same way, our analyses of nearly 17 years confirm (1) the importance of these two rivers and (2) the gradients of the analyzed physical–chemical variables in this estuary being studied (Figs. 4, 5; Table 2). The magnitude of the discharges of the Atrato River is also seen compared with other tributaries, which makes it an important tributary in the estuary (Fig. 4).

Calderón (2019) corroborated the results found by Jiménez and Campillo (2020) in terms of stratification. However, his chemical considerations went a little further and showed that in addition to stratification in the estuary system, the energy potential was evaluated at contrasting times. The center of the gulf exhibits high variations in the saline gradient, with values of 1.3 MJ $m^{-3}$ in the rainy season and 0.6 MJ $m^{-3}$ in the dry season. Additionally, the study makes a theoretical calculation that shows that it is possible to generate energy of about 12,096 kWh $m^{-1}$ and supply some nearby and coastal populations of the gulf.

In addition, based on the results of the REDCAM database for 17 years, the characteristics of many coastal areas of the Gulf of Urabá can be summarized in several aspects: (1) high content of nutrients (e.g., nitrites 3–640 µg $L^{-1}$, ammonia 70–2000 µg $L^{-1}$, nitrates 100–11,900 µg $L^{-1}$, orthophosphates µg $L^{-1}$); (2) high concentration of suspended solids (9–4600 mg $L^{-1}$) and (3) pH values within the normal range for areas with freshwater influence ($<8$) and marine water (8.1). However, we analyze the REDCAM database to show that the quality of water in the coastal areas of the eastern edge of the Gulf of Urabá (considered between the categorization of bad to good water conditions) is the product of inadequate treatment of wastewater and the excess of nutrients that reach the ecosystem (modified from REDCAM database; Fig. 6). In addition, most of the riverside inhabitants reside on the side adjacent to the mouth of the Atrato River. This requires special attention for environmental organizations to define public policies that may affect the treatment of water that reaches the estuary.

Our analyses also revealed recurrent hypoxia with values below 2 mg $L^{-1}$ DO and ranging from 0.2 to 8.7 mg $L^{-1}$ DO. These hypoxic events were observed throughout the estuary for 10 years and we found a deficit of oxygen (REDCAM expedition, Fig. 7). In the same idea, an analysis carried out for other Colombia eutrophic estuaries showed changes in dissolved oxygen (DO) after two decades of monitoring, where they found fish kills were related to variations of this parameter due to an increase in phytoplankton densities (Espinosa-Díaz et al. 2021). This same phenomenon could occur in the Gulf of Urabá; in other words, this deficit of oxygen can generate mass mortality in local fisheries since our analysis confirms DO low concentrations, and it should be a topic for the next generations of environmental decision-makers in the region. However, the causes have not been documented and require more studies.

Finally, in physical terms, we found that the maximum values of surface currents were found in the external part of the estuary near the Caribbean Sea, with values above 0.3 m $s^{-1}$, while the lowest values were located in the central–southern region (Fig. 8). The magnitude of the wind follows the annual trend of the Colombia areas, exhibiting a maximum when the trade winds intensify in the dry months, but the lowest values during the rest of the year do not exceed 3 m $s^{-1}$ and are in the center–south part of the estuary (Fig. 9). Recently, similarly, Toro et al. (2019) found

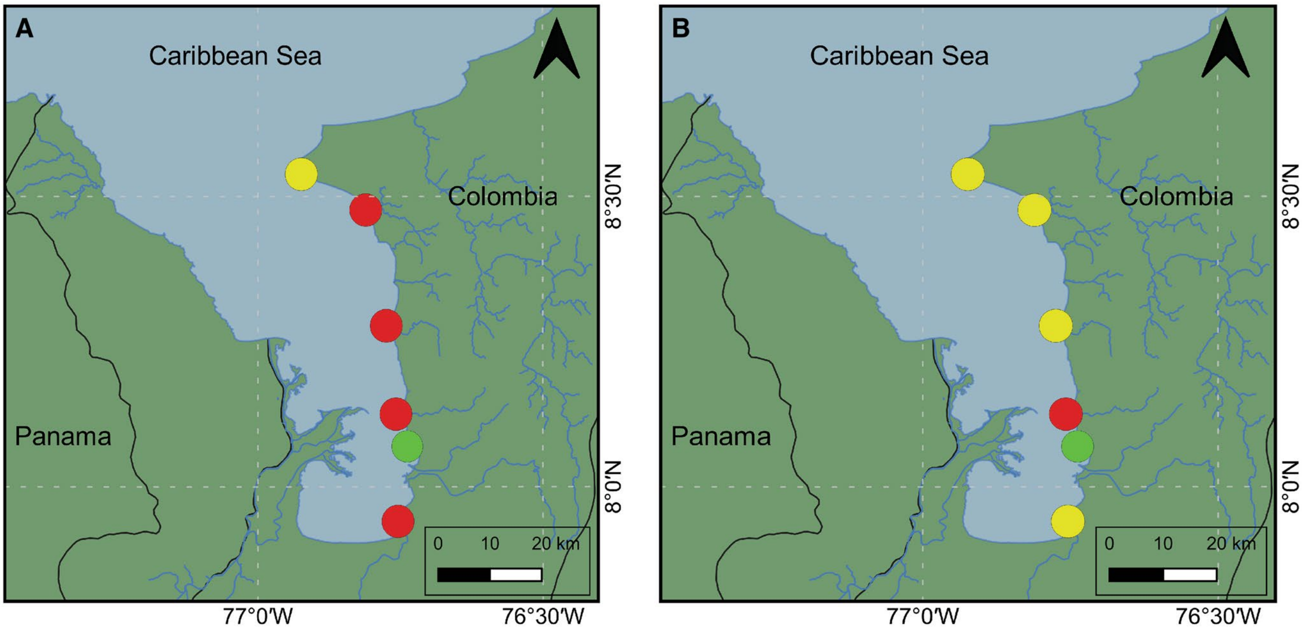

**Fig. 6** Quality of coastal marine waters of the Gulf of Urabá valued under the index (ICAMPFF) for two contrasting periods in 2015 (modified from Redcam database). Note that the green color = water with good conditions; yellow = water that maintains good conditions and few restrictions on use; red = waters with many restrictions that do not allow proper use. Stations 1 = Ríonegro; 2 = Necoclí River mouth; 3 = New Cayman River mouth; 4 = Turbo River mouth; 5: Dock of the Navy; 6 = León River mouth

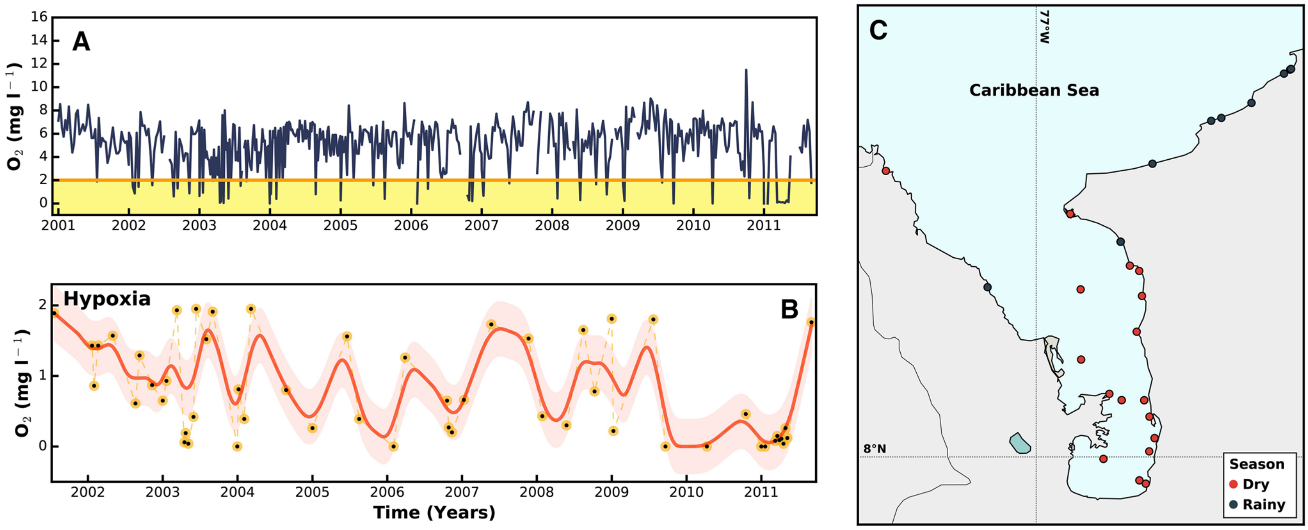

**Fig. 7** The oxygen concentration and outbreaks of hypoxia in the estuary. Note that panel **a** limit, **b** refers to the dissolved $O_2$ concentration with values considered for hypoxic events ($<2$ mg L$^{-1}$), and **c** refers to stations with hypoxic events in dry (red) and rainy (blue) seasons. Source: REDCAM database

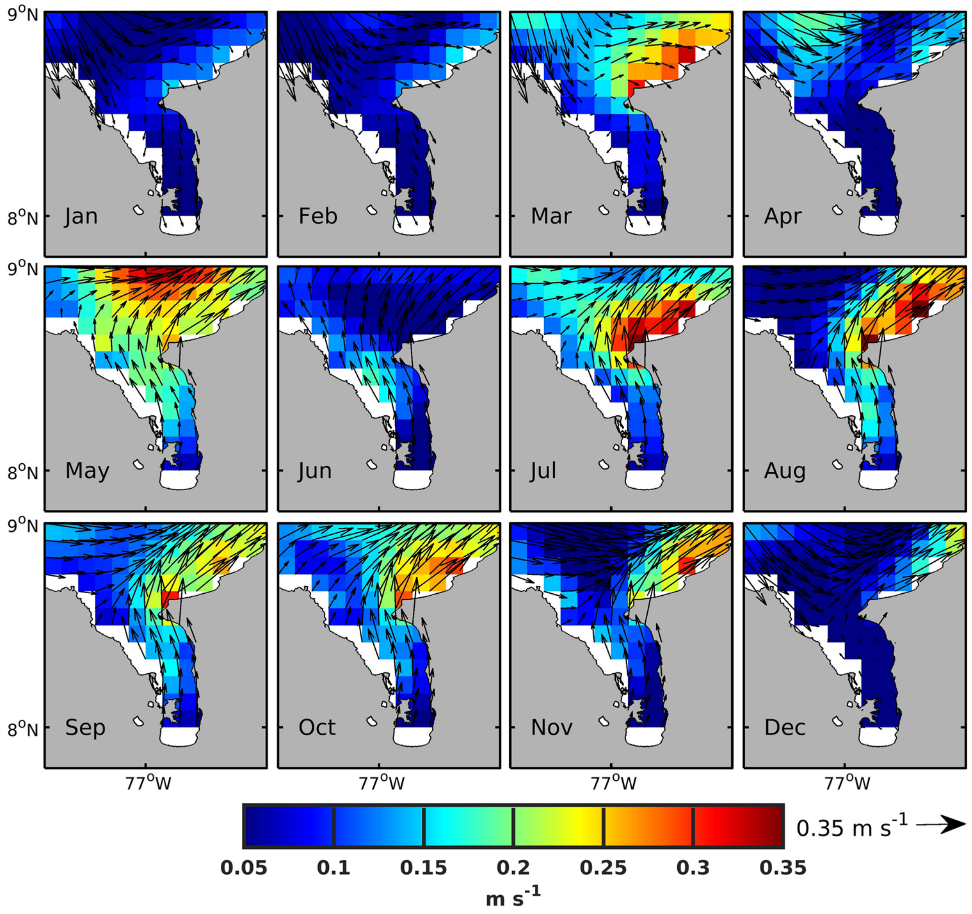

**Fig. 8** Marine current climatology for the period from 2007 to 2017 with a ~ 8 km spatial resolution in the study area

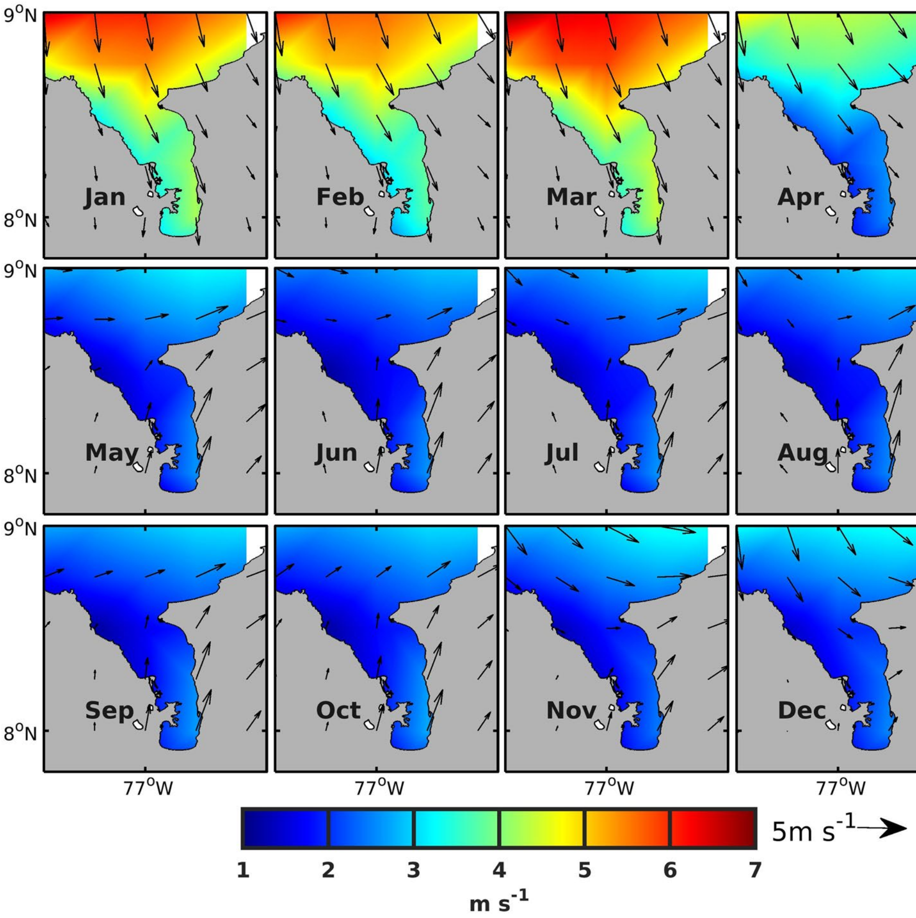

**Fig. 9** Seasonal average wind speed and direction for year 2020 and 12 km spatial resolutions in the study area (data from ERA-5 reanalysis). From January to April, the wind direction comes from the northwest, with speeds from 2 to 7 m s$^{-1}$ and from May to December from the southwest with speeds from 2 to 3 m s.$^{-1}$

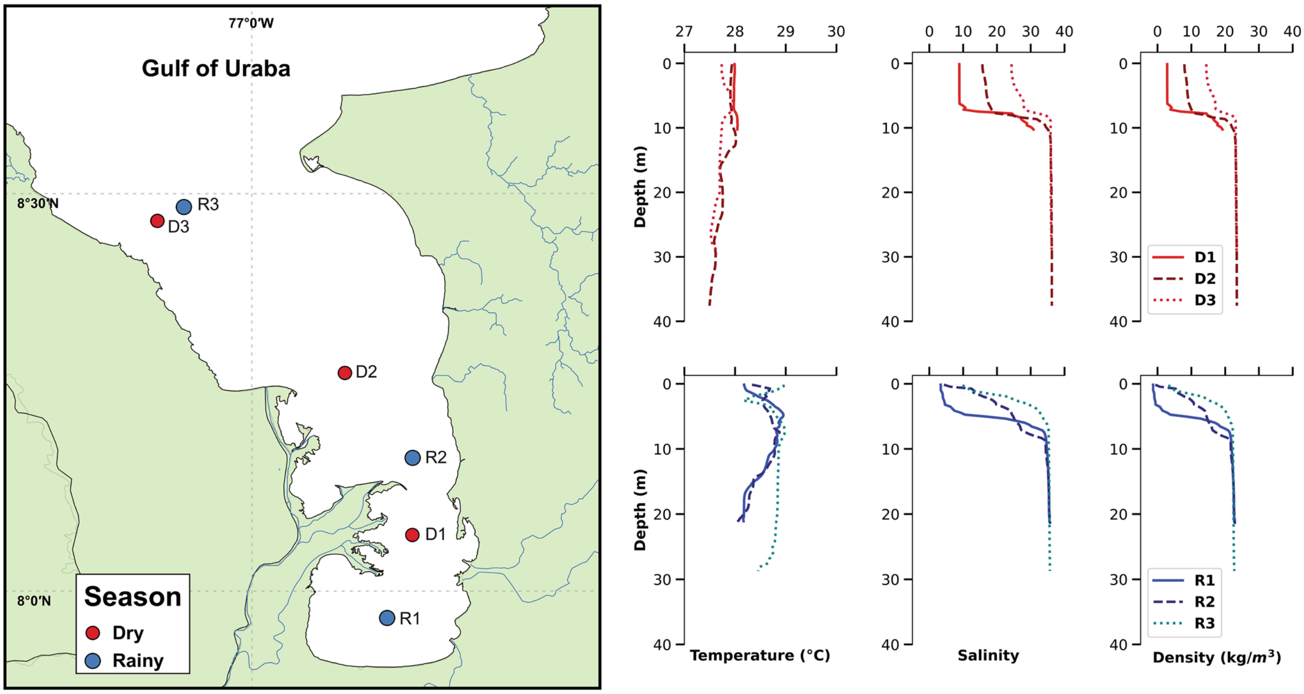

**Fig. 10** Temperature, salinity, and density profiles at six different stations along the estuary. Dry (red) and rainy (blue) seasons

that processes such as wind fields, density differences, and fluvial discharges inside the Gulf of Urabá and using the regional oceanic circulation numerical model during the 2010–2015 period could modulate estuarine physics. These results are important considering their importance in the water column and zonation along the estuary, as we have verified with some vertical profiles of the water column (Fig. 10). This can be seen in how the influence of the rivers and the saltwater intrusions of the Caribbean Sea below the sediment plume in the gulf can change the depths of the thermocline, halocline, and pycnocline in the dry and rainy seasons through a longitudinal transect**.**

## 4 Biological Considerations

The plankton communities in Caribbean Colombia have been studied at the coastal level and in terms of composition (Gocke et al. 2003; Vidal 2010; Córdoba-Mena et al. 2020). However, oceanic phytoplankton studies by Lozano-Duque et al. (2010) that found the dominance of the central diatoms group was the most abundant, followed by pennal diatoms, dinoflagellates, cyanobacteria, chlorophytes and silicoflagellates.

Moreover, Medellín-Mora and Martínez-Ramírez (2010), in a study of zooplankton communities in Caribbean Colombia, showed that copepods were numerically dominant with almost 75%, followed by appendicularians 9%, fish eggs, and chaetognaths and mollusks at 3% and 2%, respectively. Furthermore, spatial distribution showed that the surface layers of the southern, central, and northern zones exhibit the highest abundances of zooplankton organisms with $< 900$, $< 800$, and $< 3000$ Ind $m^{-3}$, respectively, while the areas' deep layers did not exceed 500 Ind $m^{-3}$. This study is important because it shows that the influence of rivers can define the composition of these groups and divide them in such a way that the representatives are benthic in the case of the southern zone and more pelagic in the northern zone. In the case of zooplankton, the highest abundance and biomass values were found in the north and south, also confirming that the holoplankton groups were dominant and represented about 90% of the abundance compared with meroplankton.

Meanwhile, in the Gulf of Urabá, there has been few studies of planktonic communities (Echeverry 2012; Cuesta-Córdoba 2017; Bonilla 2020; Córdoba-Mena et al. 2020). Echeverry (2012) evaluated the diatom communities associated with surface sediments in the Gulf of Urabá. The results showed that pennate diatoms were the most abundant, represented by the species *Diploneis*, *Amphora*, *Nitzschia*, *Navicula*, and *Tryblionella*. This phytoplanktonic abundance of benthos may explain why diatom communities are an important food for many commercially valuable fish species.

Recently, Córdoba-Mena et al. (2020) described the phytoplankton communities in this estuary (i.e., Gulf of Urabá) and their response to environmental changes, with an emphasis on potential toxin producers. The results showed that the abundance of diatoms was 11,166 cells $L^{-1}$ in the river zone, while dinoflagellates had a maximum of 4250 cells $L^{-1}$ in the same area during the dry season. Some algae biotoxin producers were found, e.g., *Dolichospermum*, *Prorocentrum*, *Dinophysis*, and *Pseudo-nitzschia*, the latter represented 44% of the total diatoms in the rainy season with detectable domoic acid production in the range between 25.54 and 1580.7 pg $L^{-1}$. One of the important conclusions of these authors is that the abundance of these groups can be defined by the high load of nutrients that increase growth and therefore their abundance, because the gulf is surrounded by areas of plantain and banana crops that use fertilizers and these, due to runoff, reach the estuary. Similarly, these authors consider that the high abundance of toxic algae may reflect the variability of the climatic seasons. However, this needs to be evaluated in more detail.

From the perspective of phytoplankton biodiversity, the Biotechnology and Oceans, Climate and Environment Group OCE research groups of the University of Antioquia, Colombia, identified around 160 species of phytoplankton, distributed as follows: 15 species of cyanobacteria, 21 green algae, 92 diatoms, 30 dinoflagellates, and 2 euglenoids (Figs. 11, 12, 13, 14, 15), higher than that previously reported for the same estuary (Bonilla 2020).

In this same investigation, a strain of *Leptolyngya sp* cyanobacteria, isolated under different lighting and temperature conditions, showed a variation in the biomass and protein yield as well as in the spectrometric behavior of the phycobiliproteins as a response to obtaining advances in biotechnological terms (Obando-Montoya et al. 2022). These results are important, since they opened up an unknown field and led us to develop a bioprospecting line in the estuary and its role as a producer of protein compounds. All this research will generate a detailed record of the biological diversity baseline in the interior of the estuary and contribute to complementing this line in Colombia.

In terms of chlorophyll-*a* (Chl-*a*) and primary productivity, several studies carried out by the University of Antioquia, Colombia, have shown the variability of these indicators (Ayala and Marquez 2017; Jurado 2019). For example, Ayala and Marquez (2017) sampled 13 stations within the estuary within the area of influence of the Atrato

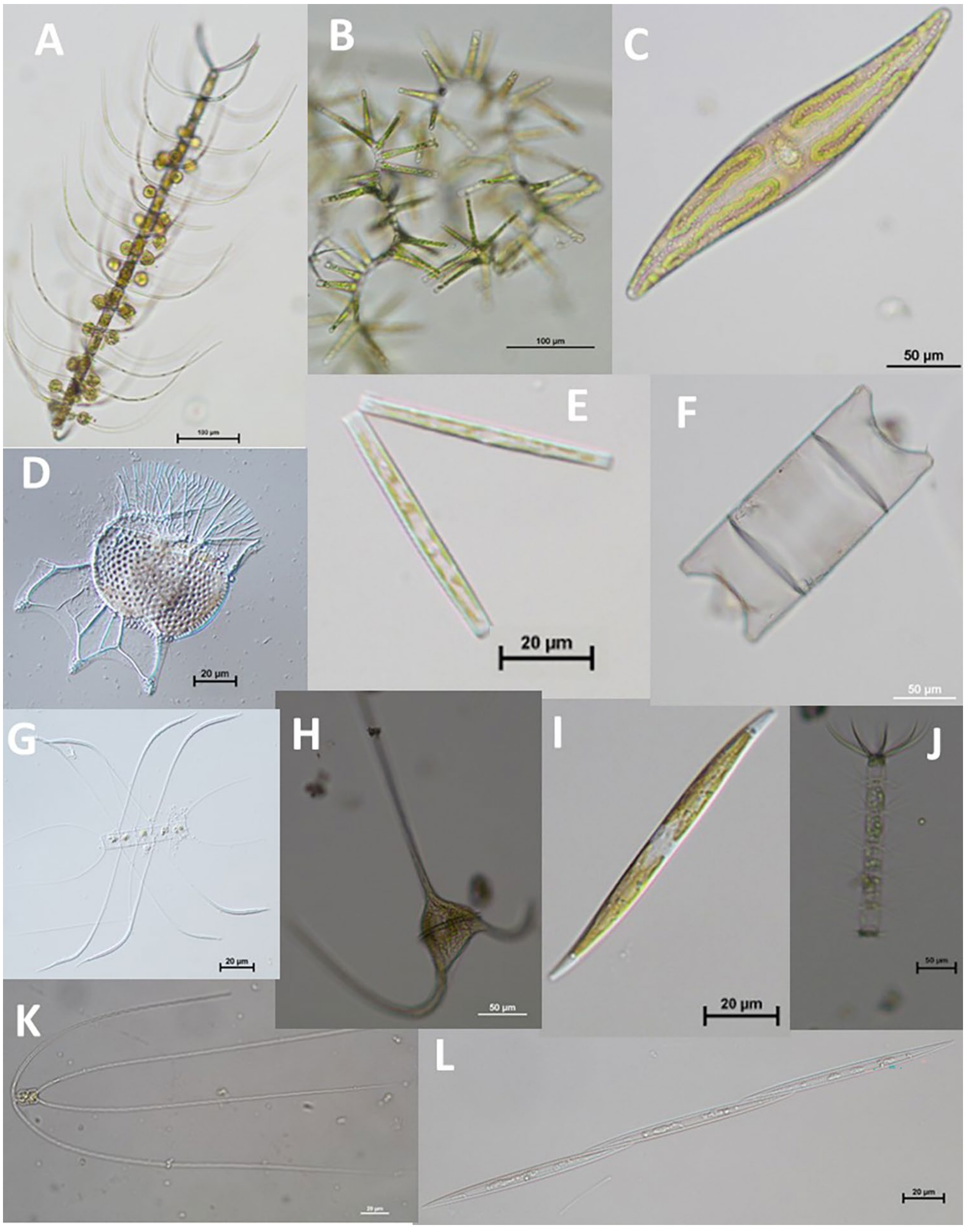

**Fig. 11** Phytoplankton images in the estuary Gulf of Urabá, Caribbean Colombia. **A** *Chaetoceros coarctatus*, **B** *Bleakeleya notata*, **C** *Pleurosigma normanii*, **D** *Ornithocercus magnificus*, **E** *Thalassionema* sp. , **F** *Lampriscus shadboltianum*, **G** *Chaetoceros diversus*, **H** *Tripos massiliensis*, **I** *Nitzschia cf. lorenziana*, **J** *Bacteriastrum comosum*, **K** *Chaetoceros peruvianus*, **L** *Pseudonitzschia* sp.

River plume using the trophic status index, or TSI, and showed that the estuary exhibits a mesotrophic status and chlorophyll values for the rainy season between 0.97 and 23.4 mg m$^{-3}$ and 0.382–15.643 mg m$^{-3}$ in the dry season. Likewise, another study evaluating four contrasting ecosystems at the mouth of the Atrato River found values between 14.8 and 70 mg m$^{-3}$ (Jurado 2019), with concentration ranges and trophic states similar to those obtained by Ayala and Marquez (2017). Moreover, Córdoba-Mena et al. (2020) evaluated the Gulf of Urabá in a transect of 80 km in a north–south direction. Approximatelym 15 stations were evaluated in terms of chlorophyll-a, sectoring the estuary into three large zones, fluvial, estuarine, and oceanic at two contrasting times. The results showed higher chlorophyll-a concentrations in the fluvial zone, with differences between the concentrations of 1.27 mg m$^{-3}$ and 2.86 mg m$^{-3}$ during the rainy season, and 0.22 mg m$^{-3}$ and 0.20 mg m$^{-3}$ in the rainy season for the estuarine and oceanic zones, respectively. Similarly, during a bloom episode in the river zone, there was an increase in the chlorophyll-*a* of close to 4.1 ug L$^{-1}$. Our analyses in this review revealed interannual Chl-*a* variability of the Gulf of Urabá, showing high values of concentration (10 mg m$^{-3}$) throughout the year, but with slight increases in the dry season (Fig. 16). This is significant since it allows knowing and understanding the most productive sites in the area under study, detecting hypoxic areas, fishing

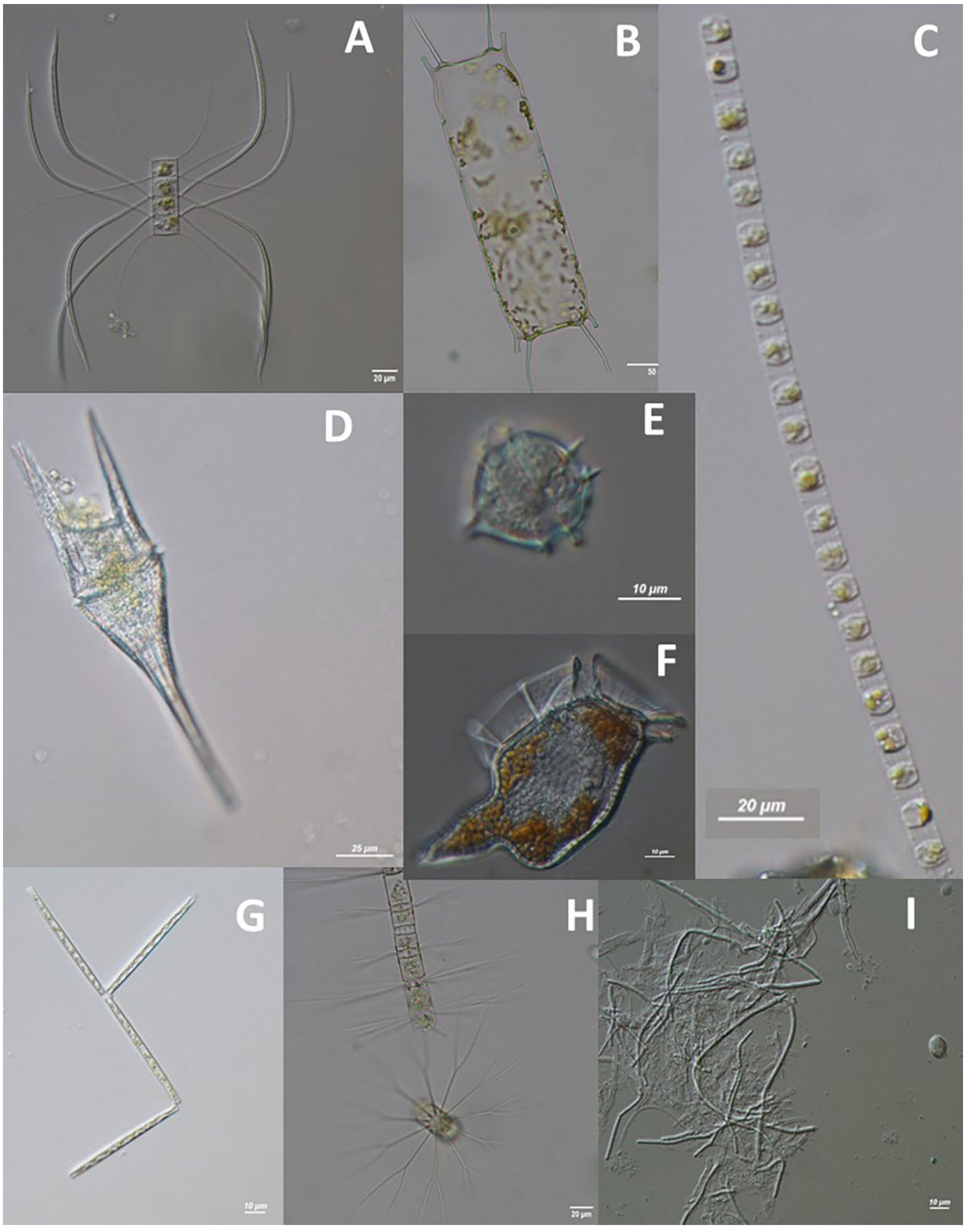

**Fig. 12** Phytoplankton images in the estuary Gulf of Urabá, Caribbean Colombia. **A** *Chaetoceros diversus*, **B** *Odontella sinensis*, **C** *Skeletonema tropicum*, **D** *Tripos furca*, **E** *Protoperidinium* sp. , **F** *Dinophysis caudata*,**G** *Thalassionema nitzschioides*, **H** *Bacteriastrum delicatulum*, **I** *Leptolyngbya* sp.

grounds and defining management guidelines in the estuary. Having information like the one made in this analysis will serve local decision-makers. At this time, knowledge of productivity, chl-*a*, and biodiversity is still scarce, as literature is poorly known and, in some cases, not published.

Zooplankton communities are another little-studied biological component. However, Cuesta-Códoba (2017) studied the zooplankton communities in an estuary regime in the delta of the Atrato River, showing that salinity is the main factor that regulates the distribution of zooplankton, with the highest abundances at ~ 4500 ind $m^{-3}$ (Fig. 17). Additionally, it was found that zooplankton occur in different stages of their life cycle and that the Calanoida group was the most dominant throughout the area. Recently, Córdoba et al. (2020) evaluated the structure of the community of mesozooplankton in two climatic seasons in the Gulf of Urabá. Preliminary results have shown that the copepods are groups numerically dominant in the estuary, and in general, the highest abundances of mezooplankton are located near river stations.

Some studies have shown the indirect interaction of the physical and chemical properties with the biological factors such as the abundance and functions of plankton (Coronado-Franco et al. 2018; Bonilla 2020; Zambrano 2021). However, it remains unknown how these communities respond to these environmental stressors in the Gulf of Urabá. Coronado-Franco et al. (2018) based on the fluorescence line height (FLH) data showed that the Gulf of Urabá could be

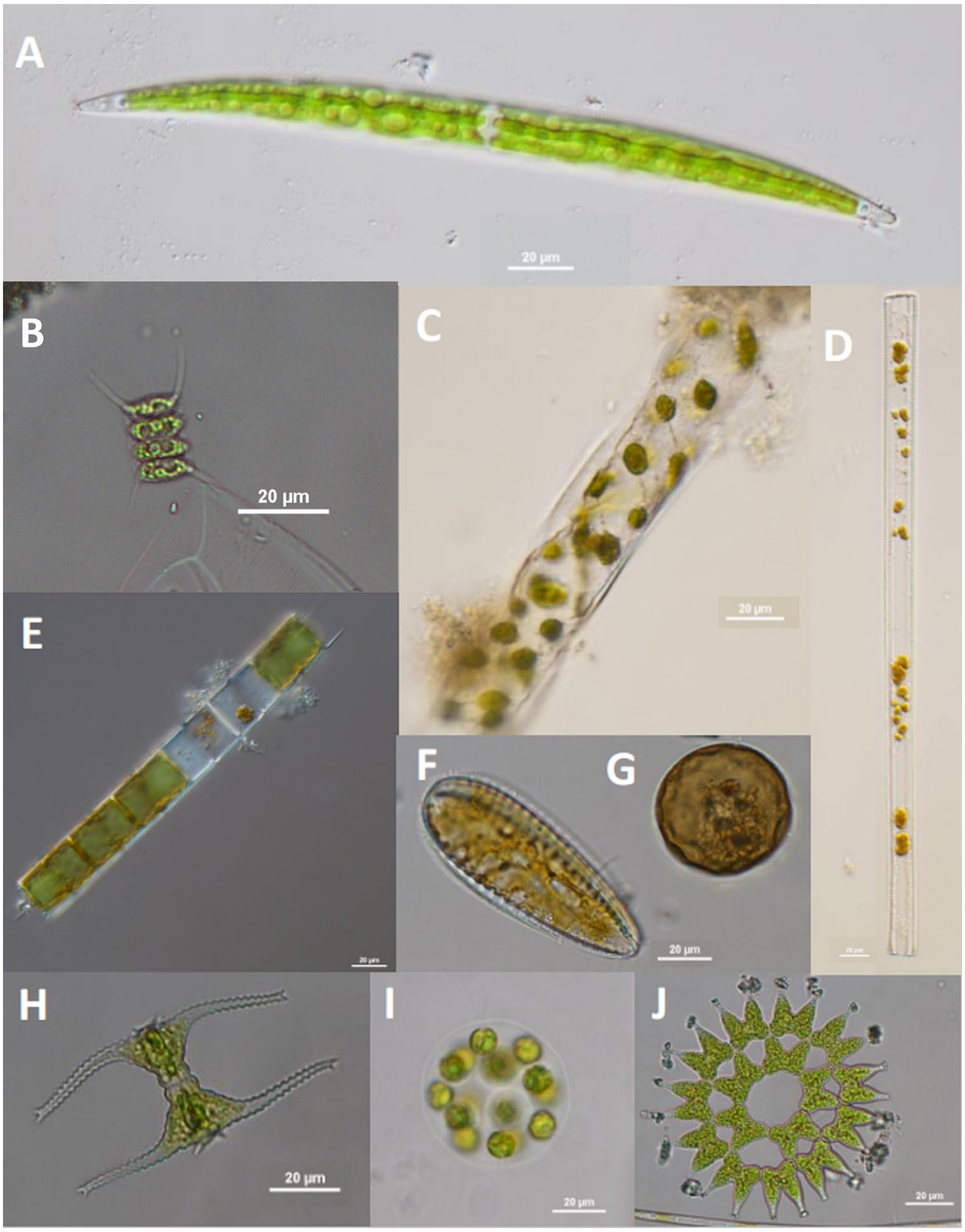

**Fig. 13** Phytoplankton images in the estuary Gulf of Urabá, Caribbean Colombia. **A** *Closterium* sp., **B** *Desmodesmus* sp., **C** *Spirogyra* sp., **D** *Synedra* sp., **E** *Aulacoseira* sp., **F** *Surirella* sp.,. **G** *Arcella* sp., **H** *Staurastrum* sp., **I** *Eudorina* sp., **J** *Pediastrum duplex*

considered an area with high persistence of harmful algal blooms, mainly due to the excess of nutrients, mostly in the rainy season in the region and even Niña events. This is important since the estuary is surrounded by one of the most agricultural areas of the country, with banana plantations and other tropical fruits that use high loads of nutrients that are then washed by the rain and transported via rivers to the estuary (Blanco-Libreros 2009). Besides, some data have also been also documented in the estuary where physicochemical and microbiological quality found high concentrations of values related to coastal contamination (Murillo et al. 2017). Recently, Zambrano (2021) evaluated the environmental component of the erosive process in the eastern sector of the Gulf of Urabá, particularly the coast, and found that the high richness of phytoplankton species was related to the season of high winds, in addition to the high values of chlorophyll-*a* (17 mg $L^{-1}$) relationship with bloom of algae that were observed during this study. However, the effects of other environmental variables on the zooplankton, nekton, and benthic groups were highly variable.

## 5 Conclusions

This study provides a comprehensive analysis of the estuarine dynamics in an oceanographic context and provides integrated base information to manage and project the Gulf of Urabá from the interactions between physical, chemical,

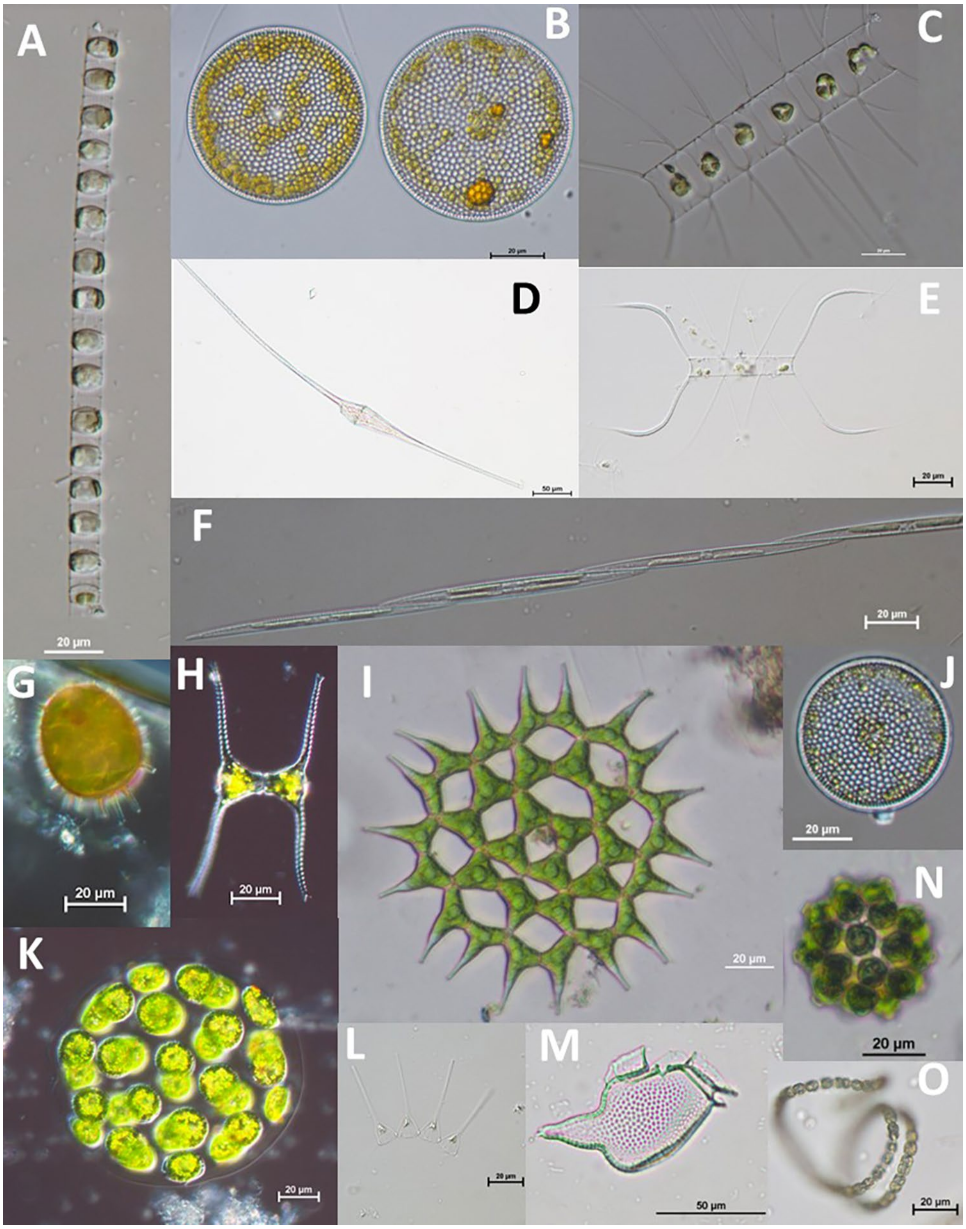

**Fig. 14** Phytoplankton images in the estuary Gulf of Urabá, Caribbean Colombia. **A** *Skeletonema tropicum*, **B** *Coscinodiscus* sp. , **C** *Chaetoceros lorenzianus*, **D** *Tripos fusus*, **E** *Chaetoceros affinis*, **F** *Pseudonitzschia* sp., **G** *Trachelomona armata*, **H** *Staurastrum* sp,. **I** *Pediastrum simplex*, **J** *Coscinodiscus* sp. , **K** *Eudorina* sp., **L** *Asterionellopsis glacialis*, **M** *Dinophysis caudata*, **N** *Coelastrum* sp. , **O** *Anabaena* sp.

and biological factors. The study highlights of the variables analyzed are modulated mainly by the seasonal interaction between the Atrato River and the Caribbean Sea. Information on biological, chemical, and physical processes in the Gulf of Urabá remains poorly because of the lack of oceanographic data. The analysis suggests that the estuary presents a high abundance and planktonic diversity and highlights the importance of knowing the dynamics of river discharge to determine the distribution and composition of planktonic organisms. The enriched trophic state and the physicochemical characteristics of the estuaries depend in large part on the dynamics and sediment discharges of the Atrato River, and we underline the presence of hypoxic zones throughout the gulf. The seasonal changes in the vertical gradients of salinity, temperature, and density reflect that the interactions of the Caribbean Sea under the plume of the Atrato River are conditioned by the dynamics of winds and surface currents. Moreover, this work constitutes an added value, since it makes for the first time a review of its history in the field of coastal oceanography,

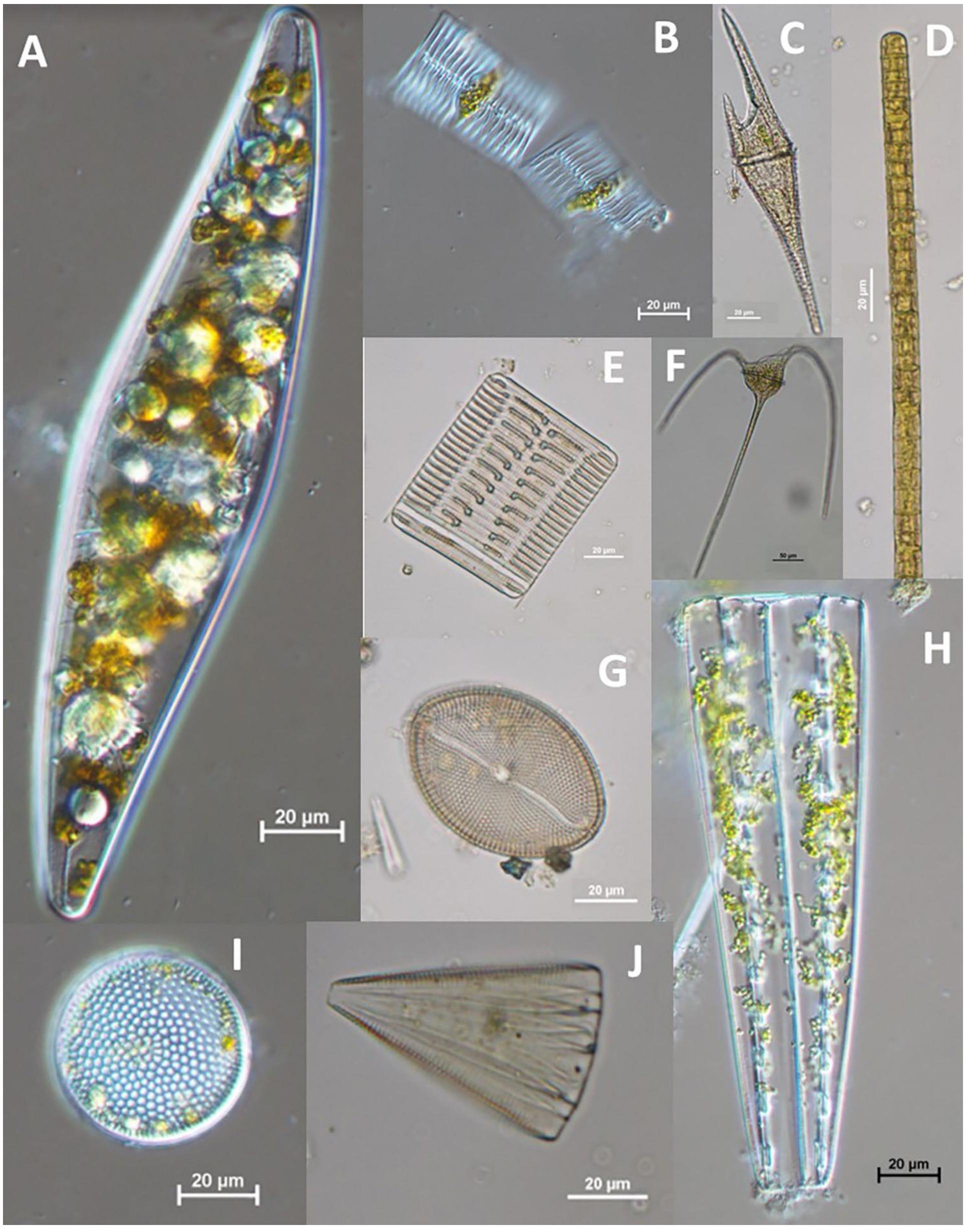

**Fig. 15** Phytoplankton images in the estuary Gulf of Urabá, Caribbean Colombia. **A** *Pleurosigma nicobaricum*, **B** *Tabellaria flocculosa*, **C** *Tripos furca*, **D** *Tychonema* sp. , **E** *Rhabdonema adriaticum*, **F** *Tripos massiliensis*, **G** *Mastogloia punctatisima*, **H** *Climacosphenia moniligera*, **I** *Coscinodiscus* sp. , **J** *Licmophora* sp.

its analysis, and discussions of some literature findings, to generate the knowledge base of an unexplored area of the country. Finally, the Gulf of Urabá can be considered a biotechnological laboratory in the development and a potential source of energy about which future research should deepen in knowledge, as well as work in understanding some physical and biochemical components (potential toxin producers, hypoxia events, biogeochemical nutrient cycles, and budgets, among others) to comprehend the estuary in the oceanographic context.

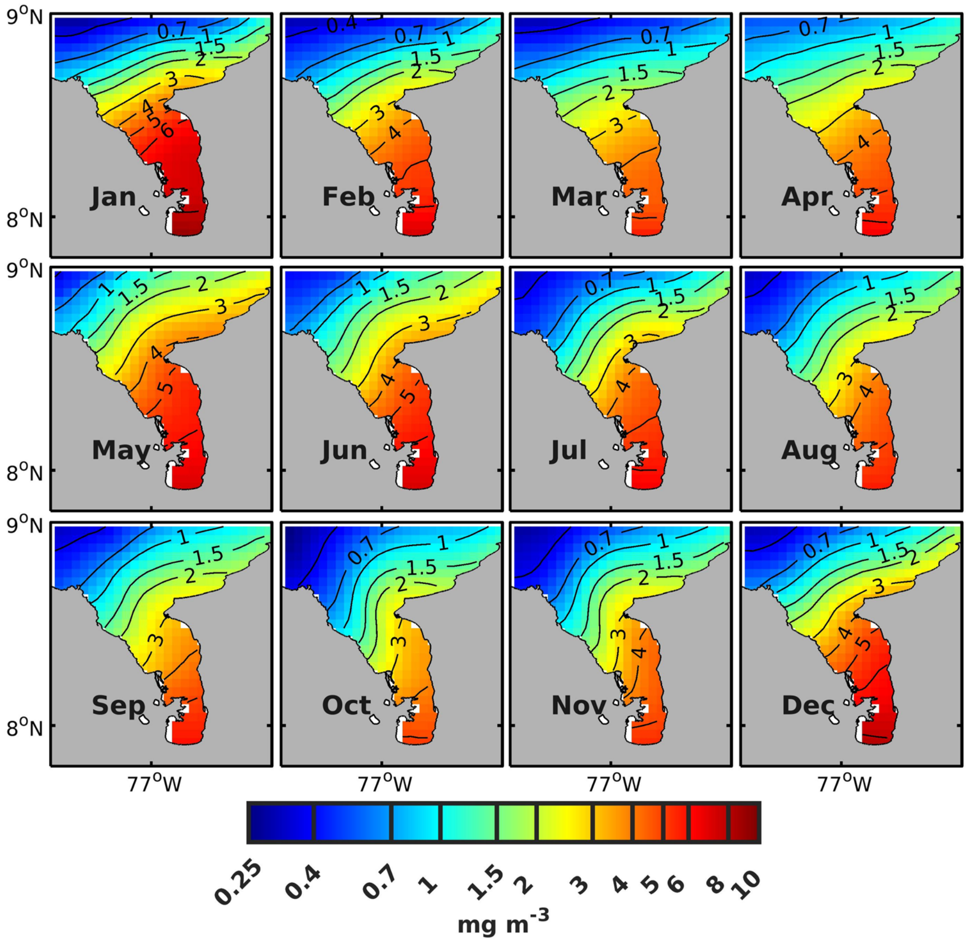

**Fig. 16** Annual cycle of Chl-*a* for the period from 1997 to 2017 and ~ 4 km spatial resolution in the study area

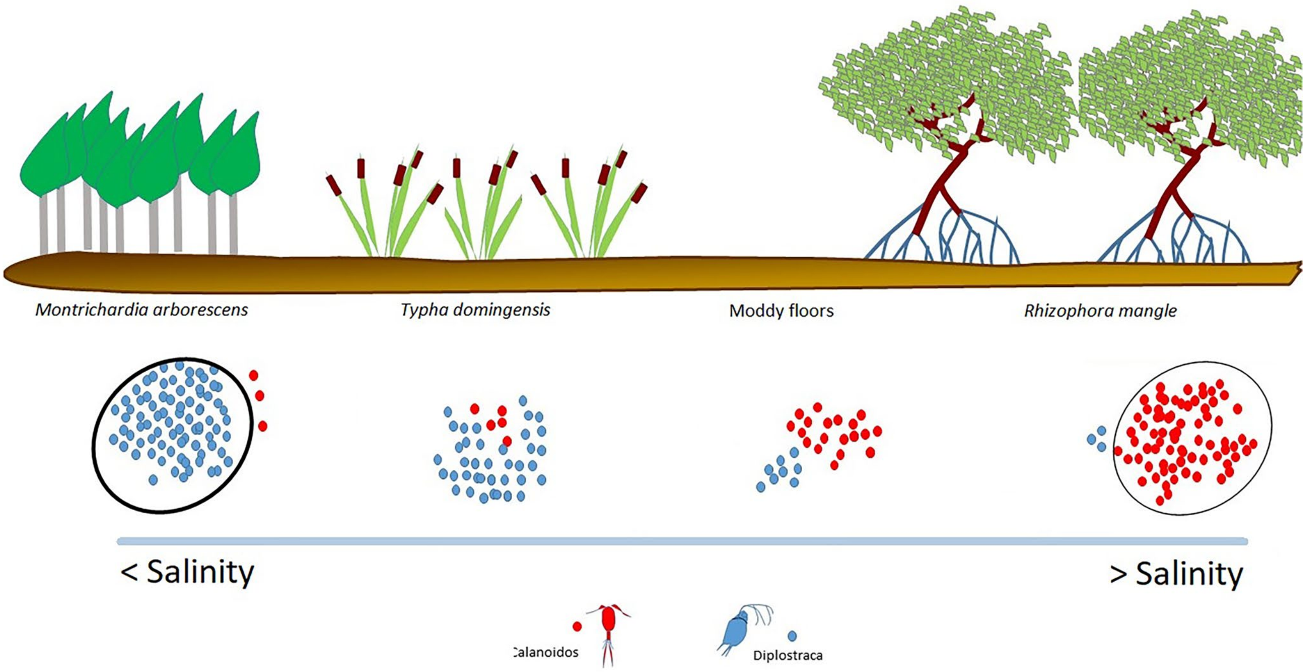

**Fig. 17** Distribution of *Calanoid* and *Diplostraca* (zooplankton) through the salinity gradient in the delta of the Atrato River to the Gulf of Urabá, Caribbean Colombia

**Acknowledgements** The authors wish to thank the research group OCE (Oceans, climate, and Environment) of Universidad de Antioquia (Colombia) for the supply of instruments and technicians during the study. Also, we are thankful to IDEAM for their database and to the Marine and Coastal Research Institute—INVEMAR and CORPOURABÁ for providing the REDCAM database. The authors thank the Copernicus Marine Environment Monitoring Service for providing current data (CMEMS), available online at https://marine.copernicus.eu/, and express thanks to the European Centre for Medium-Range Weather (ECMWF) for providing the ERA-5 wind reanalysis, available at https://climate.copernicus.eu/climate-reanalysis, and the European Space Agency (ESA) for the production and distribution of the Ocean Colour Climate Change Initiative dataset, Version 3.1, available online at http://www.oceancolour.org/ (Pawlowicz 2020).We would also like to acknowledge the anonymous reviewers for their valuable comments and suggestions about the original manuscript.

**Data availability** Data are available in/from:

REDCAM – For temperature, salinity, oxygen and pH data.
IDEAM – For river flow, precipitation and evaporation data.
CMEMS – For Chlorophyll and marine currents data.
ERA 5 – For wind speed data.
OCA – For temperature, salinity and density data (profiles).

Phytoplankton data are not openly available because they are being used for an identification catalog under construction.

## References

Andrade C (2015) Oceanografía dinámica de la cuenca de Colombia. Escuela Naval de Cadetes “Almirante Padilla”, Cartagena de Indias, p 201

Andrade CA, Rangel OE, Herrera E, Palomino A, Herrera (2015) Atlas de los datos Oceanográficos de Colombia 1922–2013. Dirección General Marítima, Cartagena de Indias, p 116. https://doi.org/10.26640/22159045.275

Arroyave-Rincón A, Blanco JF, Taborda A (2012) Sediment exports from the eastern basin in the Gulf of Urabá: climatic and anthropogenic influences. Rev Ing Univ Medellín 11:13–30

Ayala-Serrano T, Márquez-Palencia V (2017) Clorofila-a como indicador de calidad de agua en el área de influencia de rio Atrato entre octubre 2015 y agosto 2016, Golfo de Urabá—Caribe colombiano. University of Antioquia

Bernal G, Montoya L, Garizábal C, Toro M (2005) La complejidad de la dimensión física en la problemática costera del golfo de Urabá, Colombia. Gest Ambient 8:123–135

Blanco JF, Londoño MH, Correa ID, Osorio AF, Bernal GR, Polanía JH, Urrego LE (2013) Exploración del Golfo de Urabá 2007–2013. University of Antioquia, p 59

Blanco-Libreros JF (2009) Banana crop expansion and increased river-borne sediment exports to the gulf of Urabá, Caribbean coast of Colombia. Ambio 38:181–183. https://doi.org/10.1579/0044-7447-38.3.181

Blanco-Libreros JF, Londoño-Mesa MH (2016) Expedición Caribe sur: antioquia y Chocó costeros. Comisión Colombiana del Océano, p 323

Bonilla NS (2020) Comunidad fitoplanctónica presente en el Golfo de Urabá 2018. v.1.0 Instituto de Investigaciones Ambientales del Pacifico John Von Neumann (IIAP). Dataset/occurrence. https://doi.org/10.15472/r1ln4m

Borges AV (2005) Do we have enough pieces of the jigsaw to integrate $CO_2$ fluxes in the coastal ocean? Estuaries 28:3–27. https://doi.org/10.1007/BF02732750

Brunton E (1994) The challenger expedition, 1872–1876: a visual index. Natural History Museum, London, p 289. https://doi.org/10.5962/bhl.title.87402

Calderón Y (2019) Variabilidad espacio-temporal del potencial energético salino por medio de mediciones in situ en el golfo de Urabá, mar Caribe colombiano. University of Antioquia

Centurioni L, Niiler P (2003) On the surface currents of the Caribbean Sea. Geophys Res Lett 30:1279. https://doi.org/10.1029/2002GL016231

Chevillot P, Molina A, Giraldo L, Molina C (1993) Estudio geológico e hidrológico del Golfo de Urabá. Bol Cient CIOH 14:79–90. https://doi.org/10.26640/22159045.62

Cloern JE, Foster SQ, Kleckner AE (2014) Phytoplankton primary production in the world’s estuarine-coastal ecosystems. Biogeosciences 11:2477–2501. https://doi.org/10.5194/bg-11-2477-2014

Córdoba-Mena N, Florez-Leiva L, Atehortúa L, Obando E (2020) Changes in phytoplankton communities in a tropical estuary in the Colombian Caribbean Sea. Estuar Coast 43:2106–2127. https://doi.org/10.1007/s12237-020-00750-z

Coronado-Franco KV, Selvaraj JJ, Mancera Pineda JE (2018) Algal blooms detection in Colombian Caribbean Sea using MODIS imagery. Mar Pollut Bull 133:791–798. https://doi.org/10.1016/j.marpolbul.2018.06.021

Cuesta-Córdoba CC (2017) Distribución espacial y temporal del zooplancton según el gradiente de salinidad en el brazo Leoncito y la bahía Marirrío (delta del río Atrato). University of Antioquia

de Lacerda LD, Santelli RE, Abrao JJ, Duursma EK (2004) Environmental geochemistry in tropical and subtropical environments. In: Restrepo JD, Kjerfve B (eds) The Pacific and Caribbean rivers of Colombia: water discharge, sediment transport and dissolved loads. Springer, Berlin, Heidelberg, pp 169–187

Echeverry A (2012) Diatomeas en sedimentos superficiales del golfo de Urabá, Caribe colombiano. University of Antioquia

Escobar CA (2011) Relevancia de procesos costeros en la hidrodinámica del Golfo de Urabá (Caribe Colombiano). Bol Invest Mar Cost 40:327–346

Escobar CA, Velásquez L, Posada F (2015) Marine currents in the Gulf of Urabá, Colombian Caribbean Sea. J Coastal Res 31:1363–1374. https://doi.org/10.2112/JCOASTRES-D-14-00186.1

Espinosa-Díaz LF, Zapata-Rey YT, Ibarra-Gutierrez K, Bernal CA (2021) Spatial and temporal changes of dissolved oxygen in waters of the Pajarales complex, Ciénaga Grande de Santa Marta: two decades of monitoring. Sci Total Environ 785:147203. https://doi.org/10.1016/j.scitotenv.2021.147203

Francois Y, García C, Cesaraccio M, Rojas X (2007) Atlas del golfo de Urabá: una mirada al Caribe de Antioquía y Chocó. In: García-Valencia C (ed) El paisaje en el golfo. INVEMAR, Santa Marta, pp 75–128

García-Valencia C (2007) Atlas del golfo de Urabá: una mirada al Caribe de Antioquia y Chocó. Publicaciones Especiales de Invemar No. 12, Santa Marta, p 180

Gocke K, Meyerhöfer M, Mancera-Pineda JE, Vidal LA (2003) Phytoplankton composition in coastal lagoons of different trophic status in northern Colombia determined by microscope and HPLC-pigment analysis. Bol Invest Mar Cost 32:263–278. https://doi.org/10.25268/bimc.invemar.2003.32.0.270

Hernández CA, Gocke K (1990) Productividad primaria en la Ciénaga Grande de Santa Marta, Colombia. Bol Invest Mar Cost 19–20:101–119. https://doi.org/10.25268/bimc.invemar.1990.19.0.430

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F, Guiot J, Hijioka Y, Mehrotra S, Payne A, Seneviratne SI, Thomas A, Warren R, Zhou G (2018) Impacts of 1.5 ºC Global Warming on Natural and Human Systems. In: Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC

Jiménez GA, Campillo LL (2020) Caracterización termohalina de las masas de agua del golfo de Urabá. Caso específico desembocadura del río León y el río Atrato. University of Antioquia

Johns WE, Townsend TL, Fratantoni SM, Wilson WD (2002) On the Atlantic inflow to the Caribbean Sea. Deep-Sea Res Pt I 49:211–243. https://doi.org/10.1016/S0967-0637(01)00041-3

Jurado A (2019) Análisis de la variabilidad estacional en la productividad primaria a partir de la determinación de la clorofila-a en aguas superficiales del sector sur del golfo de Urabá. University of Antioquia

Li M, Li R, Cai WJ, Testa JM, Shen C (2020) Effects of wind-driven lateral upwelling on estuarine carbonate chemistry. Front Mar Sci 7:588465. https://doi.org/10.3389/fmars.2020.588465

López-Jiménez IT, Flórez-Leiva L, Quan-Young LI (2020) Influence of herbivory on coral-algal interaction in a coral reef, Capurganá Bay, Colombian Caribbean. Rev Biol Trop 68:729–742. https://doi.org/10.15517/rbt.v68i3.38760

López-Jiménez IT, Florez-Leiva L, Quan-Young L (2021) Effect of terrigenous sediments on macroalgae functional-form groups of coral reefs in Capurganá, Colombian Caribbean. Sci Mar 85:125–135. https://doi.org/10.3989/scimar.05146.013

Lozano-Duque Y, Vidal LA, Navas GR (2010) Check-list of diatoms (*bacillariophyta*) reported from the colombian Caribbean Sea. Bol Investig Mar Costeras INVEMAR 39:83–116

Medellín-Mora J, Martínez-Ramírez O (2010) Distribución del mesozooplancton en aguas oceánicas del mar Caribe colombiano durante mayo y junio de 2008. In: INVEMAR (ed) Biodiversidad del Margen Continental del Caribe colombiano. Ser Publicaciones Especiales. INVEMAR, Santa Marta, pp 119–148

Molina A, Molina C, Chevillot P (1992) La percepción remota aplicada para determinar la circulación de las aguas superficiales del Golfo de Urabá y las variaciones de su línea de costa. Bol Cient CIOH 43–58. https://doi.org/10.26640/22159045.45

Montoya LJ (2010) Dinámica oceanográfica del golfo de Urabá y su relación con los patrones de dispersión de contaminantes y sedimentos. Ph.D. Thesis, The National University of Colombia

Murillo Y, Quesada Z, Vargas L (2017) Evaluación de la calidad fisicoquímica del agua de la bahía de Turbo teniendo en cuenta dos temporalidades. Bioetnia 14:65–79. https://doi.org/10.51641/bioetnia.v14i1.180

Nystuen JA, Andrade CA (1993) Tracking mesoscale ocean features in the Caribbean Sea using Geosat altimetry. J Geophys Res 98:8389–8394. https://doi.org/10.1029/93JC00125

Obando-Montoya EJ, Zapata-Ocampo PA, Cuesta-Astroz Y, Atehortua L (2022) Impact of light wavelength on the transcriptome of Porphyridium cruentum and culture yield. Algal Res 67:102856. https://doi.org/10.1016/j.algal.2022.102856

Pawlowicz R (2020) M_Map: a mapping package for MATLAB, version 1.4m. [Computer software]. https://www.eoas.ubc.ca/~rich/map.html

Quiceno PA, Zapata JL, Sánchez A (2015) Estado del arte de la investigación en ecología de zonas costeras en la región de Urabá: herramienta para la participación y apropiación del conocimiento por parte de la comunidad. Eitorial L Vieco SAS, p 195

Restrepo JD, López SD, Restrepo JC (2009) The effects of geomorphic controls on sediment yield in the Andean rivers of Colombia. Lat Am J Sedimentol Basin Anal 16:79–92

Restrepo J, Schrottke K, Bartholomä A, Ospino S, Ortíz J, Otero L, Rondón A (2018) Estuarine and sediment dynamics in a microtidal tropical estuary of high fluvial discharge: Magdalena River (Colombia, South America). Mar Geol 398:86–98. https://doi.org/10.1016/j.margeo.2017.12.008

Ricaurte-Villota C, Bastidas-Salamanca ML (2017) Regionalización oceanográfica: una visión dinámica del Caribe. In: Ordoñez-Zuñiga SA, Peña CE, Bastidas ML, Ricaute C (eds) Región 8: Sinú-Urabá. Serie publicaciones especiales del INVEMAR, pp 138–155

Robins CR (1971) Distribution patterns of fishes from coastal and shelf waters of the tropical western Atlantic. In: Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions, Papers on Fisheries Resources, FAO, Rome, pp 249–255

Roldán P (2008) Modelamiento del patrón de circulación de la bahía Colombia, golfo de Urabá. Implicaciones para el transporte de sedimentos. The National University of Colombia

Sandoval LL, Leal-Florez J, Blanco-Libreros JF (2020) Linking mangroves and fish catch: a correlational study in the southern Caribbean Sea (Colombia). B Mar Sci 96:415–430. https://doi.org/10.5343/bms.2019.0022

Selfridge TO (1874) Reports of explorations and surveys to ascertain the practicability of a ship-canal between the Atlantic and Pacific Oceans by the way of the Isthmus of Darien. US Government Printing Office, Washington DC, p 263

Toro VG, Mosquera WA, Barrientos NS, Bedoya YA (2019) Circulación oceánica del golfo de Urabá usando campos de viento de alta resolución temporal. Bol Cient CIOH 38:26–35. https://doi.org/10.26640/22159045.2019.516

Velásquez L (2013) Modelación del transporte de sedimentos en el golfo de Uraba, Colombia. Ph.D. Thesis, EAFIT University

Vidal LA (2010) Manual del fitoplancton hallado en la ciénaga grande de santa marta y cuerpos de agua aledaños en Colombia. University of Bogota Jorge Tadeo Lozano, Bogotá, p 384

Williams G (2015) The historical context and influence of William Dampier's hydrographic science. Great Circle 37:53–81

Wüst G (1964) The major deep-sea expeditions and research vessels 1873–1960: a contribution to the history of oceanography. Prog Oceanogr 2:1–52. https://doi.org/10.1016/0079-6611(64)90002-3

Zambrano (2021) Capítulo 6: componente ambiental. In: Gobernación de Antioquia, Universidad de Antioquia, Universidad Nacional y Universidad del Norte (eds) Erosión Costera en el Litoral Antioqueño, Medellín, pp 105–116

Zeigler JM, Athearn WD (1965) The hydrography and sediments of the gulf of Darien. In: Caribbean Geological Conference, 4th Port-of-Spain, Trinidad and Tobago, Defense Technical Information Center, pp 335–341