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Siltation on a highly regulated estuarine system: The Magdalena River mouth case (Northwestern South America)

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ABSTRACTS

Comparison of geo-referred bathymetric datasets from 2000 to 2017, at different timescales, allowed to analyze changes in the sedimentary balance and to determine patterns of morphological adjustment in the Magdalena River (South America). The Magdalena River has one of the highest sediment yields among the major rivers of the world. In addition, it is a laterally constrained river mouth due to a series of man-made structures inhibiting its morphological response. Thus, it provides an illustrative example to study siltation processes in a river mouth system where a low capacity of morphological response interacts with a high-magnitude sediment transport regime. The river mouth exhibited an overall slow-pace deepening trend between 2000 and 2017. However, it experienced cyclic shifts between erosive and siltation states, both at interannual and intra-annual scales. The rates of erosion were 310 mm yr^{-1} on average during the erosional stages. Whereas sedimentation rates were 293 mm yr^{-1} on average during the sedimentation stages. Maximum rates of erosion and sedimentation were 1450 mm yr^{-1} and 2625 mm yr^{-1}, respectively. However, intra-annual rates of sedimentation/erosion were of the same magnitude or larger compared with the interannual rates. Such high rates and the rapid changes in the sedimentary balance is the result of the cumulative effect of its limited morphological response capacity and its large suspended sediment load. These rapid processes generate constraints and threats to navigation. Particularly, at intra-annual scales. Consequently, innovative intervention proposals, recognizing the rapid transitions and geomorphological adaptations, are required for managing this type of river mouths.

1. Introduction

Galloway (1975) classic scheme states that tides, waves and fluvial inputs are primary controls over the morphology and structure of river mouths. Typical geomorphological and sedimentological configurations are generated according to the preponderance of these morphodynamic agents and their interaction with secondary factors, such as sediment properties, accommodation space in the delta front, and the drainage basin setting (e.g. Orton and Reading, 1993; Li et al., 1998; Burpee et al., 2015). Consequently, changes in the preponderance and the characteristics of these factors lead to variations in the morphology and structure of deltas and estuaries. Under such conditions, these systems undergo a state of dynamic equilibrium (Wright and Coleman, 1973; Ta et al., 2002; Correggiari et al., 2005). However, these conceptual models of evolution and morphological and sedimentary response do not take into consideration the effects of the anthropic intervention and recent environmental changes (Syvitski and Saito, 2007; Prandle and Lane, 2015). New models of morphological evolution should consider the conjugated effect of natural and anthropic drivers, since a growing number of engineering structures, such as groynes, breakwaters, training wall, sluices, and dikes, among others, have been constructed or are planned for the near future in river mouths worldwide, with the aim of regulating navigation and protecting strategic infrastructure (e.g. Perillo et al., 2005; Pye and Blott, 2014; Luan et al., 2018; Zarzuelo et al., 2018). These man-made structures limit the natural evolution of morphological processes such as lateral erosion, avulsion, formation/abandonment of distributaries (levee breakthroughs or infilling), crevasse splays formation and lateral shifting of the active channels in estuaries and deltas (Van Niekerk et al., 2019). This minimizes the capacity of morphological response of estuaries and deltas in the face of the changes in the

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morphodynamic agents and sediments properties (Pye and Blott, 2014; Restrepo et al., 2016). Human interventions lead to the formation of laterally constrained river mouth systems, in which most of the morphological and architecture changes occur in the subaqueous domain. Such adjustments mainly lead to changes in the bedforms and the riverbed structure along the river mouths (e.g. Dai et al., 2013; Restrepo et al., 2016; Luan et al., 2018). Recognizing the feedback between hydro-sedimentary and anthropogenic factors lead to a better understanding of the dynamic evolution of these systems. A crucial step to improve their measures of management and/or preservation (e.g. Cuadrado and Perillo, 1997; Jiang et al., 2012; Wang et al., 2013; Brunier et al., 2014).

Several studies have documented transitions from pristine to regulated states in various river mouths, highlighting their changes and the progressive deviation from natural patterns (Syvitski and Saito, 2007; Restrepo and López, 2008; Pye and Blott, 2014). Parametric predictive relationships have described changes in key morphodynamic features of river mouths in response to potential anthropogenic impacts, reflecting the growing control of human engineering over the evolution of river mouths (Syvitski and Saito, 2007; Yang et al., 2015; Zhu et al., 2017; Zarzuelo et al., 2018). Nevertheless, a comprehensive understanding of the morphological evolution of river mouths requires a more detailed *in-situ* information and analysis of its morphodynamic patterns/cycles and sediment transport regime (e.g. Brunier et al., 2014; Weber and Pasternack, 2017). This is particularly important in deltas and estuaries in which the hardening and stabilization of distributary channels have led to laterally constrained river mouth systems. A common feature of these systems is the periodic or permanent need to develop additional human interventions, including the maintenance of structures, supplementary construction projects, and periodic dredging (e.g. Dai et al., 2013; Luan et al., 2018). Thus, central questions are whether despite these major interventions, human-dominated river mouths would exhibit cyclic changes in their riverbed morphology in response to variations in controlling factors, reaching a state of dynamic equilibrium, and how natural and anthropic factors interact to reinforce or minimize sedimentary processes. These subjects become particularly

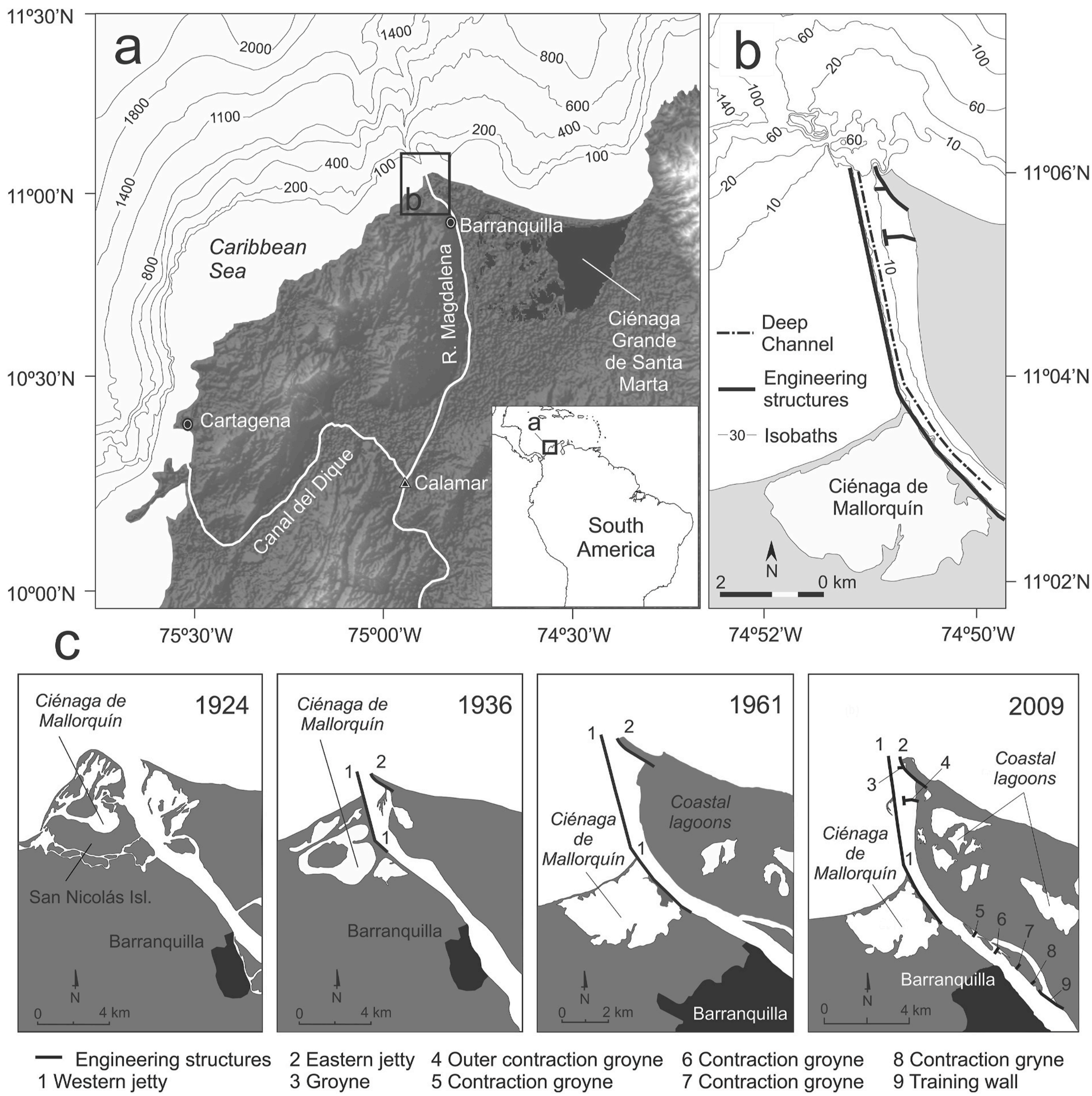

Fig. 1. Magdalena River mouth: (a, b) location and (c) schematic representation of its evolution between 1924 and 2009 – highlighting the deep channel and the main engineering structures (1–9) (Modified and adapted from Borda et al., 1973).

complex when considering the relationships among hydrodynamics, sediment transport, and morphology in estuaries (e.g. Restrepo et al., 2018; Luan et al., 2018).

The Magdalena River (Northwestern South America) (Fig. 1) has one of the highest sediment yields among the major rivers of the world and provides nearly 38% of the total amount of suspended sediment discharged into the Caribbean Sea (Restrepo et al., 2017). The main distributary was intervened in 1936 after the construction of two extensive groynes (Heezen, 1956). Since then, several additional engineering structures have been built along the river mouth (Fig. 1). A series of maintaining activities, such as dredging, have been also carried out on a periodic basis (Alvarado, 2008). According to Restrepo et al. (2016), these man-made structures inhibit the planform morphological response of the river mouth to the changes in the sediment transport regime, leading to severe changes in the patterns and rates of sedimentation and in coastal morphodynamics. Thus, the Magdalena River mouth provides an illustrative example to study siltation processes in a river mouth system where a low capacity of morphological response to environmental changes interacts with a high-magnitude sediment transport regime. Such insights would improve the understanding of morphological evolution in laterally constrained river mouth systems.

This study aims to compare recent georeferenced bathymetries, on different time scales, with emphasis on the deep channel (thalweg), identifying patterns in the sedimentary balance (cycles of sedimentation and erosion) and recent rates of change. We discuss also the process of morphological response and adjustment that the river mouth undergoes, considering potential conditions of dynamic equilibrium. The study is not aimed to discriminate quantitatively the specific influence of natural and anthropic factors, but to analyze the net morphological evolution of the river mouth under their conjugated influence. Such influence is called mixed condition hereafter.

2. Magdalena River mouth

The mouth of the Magdalena River is located in the northwest of South America (Fig. 1). It could be classified as a wave-dominated delta before its intervention in 1936. This system was characterized by the presence of extensive beach ridges, several river-mouths and barrier islands, swamps, and an extensive network of interconnected coastal lagoons and frontal bars in the distributaries (Restrepo and López, 2008). The lower course of the Magdalena River (~90 km) is a north-oriented single channel system with a meandric course. It has many fluvial islands, submerged bars, and a series of minor connections with a large coastal lagoon in the east margin (i.e. Ciénaga Grande de Santa Marta). Maximum depths rarely exceed 15 m in this fluvial section (Alvarado, 2008). The construction of man-made structures in the river mouth, that seek to remove the frontal bars and thus promote navigation, led to a significant deterioration of the coastline and the progressive loss of the barrier and river-mouth islands; particularly, a large coastline retreat in the westward and the progressive formation of a subaqueous delta in the eastward of the river mouth. It also limited the connection with coastal lagoons, especially toward the west end. However, the formation of frontal bars in the mouth is still taking place (Alvarado, 2008; Restrepo and López, 2008; Restrepo et al., 2016). Currently, a west jetty (7.4 km), an east jetty (1.4 km), six contraction groynes, ranging from 85 m to 607 m, and a training wall of 1.1 km control the river mouth (Fig. 1). These manmade structures have constrained the planform morphological responses to changes in the sediment transport regime, promoting changes in the position and size of frontal bars, channel gradient, and/or average channel depth (Restrepo et al., 2016). The width along the final strecht of the river mouth (0–15 km), where these structures are located, ranges between 454 m and 1297 m. The minimum depth along the deep channel usually reaches 9.15 m. The volume of dredged material over this area amounted to 9.05×10^6 m^3 during the last 15 years (Cormagdalena, 2018).

The Magdalena river mouth is a micro-tidal system with a maximum tidal range of 0.6 m during spring-tide. Tidal wave usually propagates through the last ~12 km of the river mouth (Ospino et al., 2018). Under extreme low streamflow conditions (<2000 m^3 s^{-1}) its influence might reach up to ~38 km upstream of the river mouth (Alvarado, 2008). It is also currently a fluvio/wave-dominated and turbid system. Stratified conditions have been reported along the lower course of the river mouth. Such conditions are more developed under low streamflow conditions (<4500 m^3 s^{-1}), leading to the formation of a salt-wedge estuary up to 10 km upstream from the river mouth. During high streamflow conditions stratification restricts to the river mouth (<2 km) (Ospino et al., 2018; Restrepo et al., 2018). Other physical parameters also exhibit large seasonal differences. During the low streamflow season (January to April) the river averages 4360 m^3 s^{-1} of freshwater and 218×10^3 t d^{-1} of suspended sediment load (SSL) (Higgins et al., 2016). The maximum reported suspended sediment concentration (SSC) reaches 11450 mg l^{-1} in the river mouth (Restrepo et al., 2018). During this season, the river mouth also experiences high-energy wave conditions ($H_s > 2.5$ m), caused by strong north-eastern trade winds and cold fronts (Ortiz et al., 2013). During the high streamflow season (September to December) the average amount of freshwater and SSL increases to 8063 m^3 s^{-1} and 531×10^3 t d^{-1}, respectively. The maximum reported SSC in the river mouth experiences a large decrease to 5031 mg l^{-1} (Higgins et al., 2016; Restrepo et al., 2018). During this season the delta experiences low/moderate energy wave conditions ($H_s < 1.5$ m), with swells coming predominantly from the west and northwest (Ortiz et al., 2013). During the transition period (May to August) the river exhibits a minor peak of streamflow and SSL in May and intermedium values of the main physical parameters. No extreme wave events, such as storm surges, has been recorded in this river mouth (Otero et al., 2016). The properties of the suspended sediment also change seasonally. The dominant particle sizes in the water column are coarse silts during the high streamflow season and medium silts during the low streamflow season. There is also a large increase in the clay fraction during the low streamflow season (Restrepo et al., 2016). The riverbed sediments range from medium silts to silty medium sands, mainly composed of plagioclase and quartz (Kolla and Buffler, 1985; Alvarado, 2008). Most of the sediments comes from upstream watersheds, despite the accelerated processes of erosion experienced in the lower course of the river (Alvarado, 2008; Higgins et al., 2016; Restrepo et al., 2016). Sediment inputs from littoral drift are negligible (Torregroza et al., 2020). Average sedimentation rates of 152 mm yr^{-1} have been measured at the river mouth (Restrepo et al., 2016).

3. Data and methods

3.1. Bathymetric data

Channel bed comparisons were based on digitized and geo-referred bathymetric datasets, comprising the years 2000, 2004–2006, 2011 and 2016–2017 (Table 1). Dataset was provided by the National Hydrographic Service (*Servicio Hidrografico Nacional – Centro de Investigaciones Oceanograficas e Hidrograficas*). Such bathymetries were performed following the standard procedures proposed by the International Hydrographic Organization (IHO) for shallow waters (See Supplementary Material). Spatial coverage of the dataset includes the lower course of the river mouth (from 0 to 7.5 km upstream of the river mouth) along the navigation channel. The cloud of points over this area ranged between 464 and 1′019 686. For a density of ≥458 points per km^2 (Table 1), a much larger value compared to similar studies (i.e. Maillet et al., 2006; Brunier et al., 2014; Jiang et al., 2012; Wang et al., 2013). The National Hydrographic Service also applied hydrographic corrections (i.e. tide level, sound velocity and dynamics corrections) to the raw data.

The dataset was geo-referred using the Universal Transverse Mercator (UTM) WGS 84. Elevation values (m) are relative to the Colombian lowest-low tide level and converted to relative mean sea level (MSL) based at the Colombian datum located in Cartagena (Fig. 1). Data

Table 1
Specific information on bathymetry datasets.

Bathymetric Dataset	Survey Duration (Days)	Cloud of Points (COP)	Density (COP km^{-2})
Interannual Comparisons			
2000	1	622	614.0
2004	1	1638	1616.9
2011	1	464	458.0
2017	2	339 538	335 180.6
Intra-annual Comparisons			
Jan. 2016	1	295 441	205 595.4
Feb. 2016	1	268 859	187 097.4
Mar. 2016	1	258 001	179 541.4
Apr. 2016	1	260 394	181 206.6
May. 2016	2	1′019 686	709 593.6
Jun. 2016	2	266 985	185 793.3
Jul. 2016	1	292 721	203 702.8
Aug. 2016	2	268 815	187 066.8
Sep. 2016	2	315 775	219 745.9
Oct. 2016	2	307 595	214 053.6
Nov. 2016	2	332 285	231 235.2
Dec. 2016	2	336 815	234 387.6
Thalweg Profiles Comparisons			
Oct. 2004	1	837	582.5
Sep. 2005	1	963	670.1
Nov. 2005	1	747	519.8
Feb. 2006	1	1123	781.4
Apr. 2006	1	937	652.0
May. 2006	1	1056	734.8
Sep. 2006	1	895	622.8
Oct. 2006	1	765	532.3
Nov. 2006	1	915	636.7
Dec. 2006	1	842	585.9
[a]Feb. 2016	1	268 859	187 097.4
[a]May. 2016	2	1′019 686	709 593.6
[a]Nov. 2016	2	332 285	231 235.2
Jan. 2017	2	335 513	331 207.3
[a]Feb. 2017	2	339 538	335 180.6
Mar 2017	3	222 847	219 987.1

Note.
[a] Datasets used also in the interannual or intra-annual comparisons.

accuracy amounts to 0.1 m in the vertical and 1.0 m in the horizontal plane. The standard error of bathymetric data with 0.1 m accuracy in surveys from 1 to 16 years apart range between 100.00 mm yr^{-1} to 6.25 mm yr^{-1}. These values of accuracy and standard error were considered as parameters to define the significant changes in the accretion/erosion rates, as well as to establish rates useful for obtaining volumetric estimates. Accordingly, this study considers that changes in the accretion/erosion rates in the interval between −0.5 m and 0.5 m are no significant.

During the surveyed timeframe there were 67 dredging campaigns with total annual volumes ranging from 0.40 to 1.38 × 10^6 m^3, covering the last 22 km of the river mouth along the navigation channel (Table 2). However, such campaigns were performed at least three months (180 days) before the bathymetric surveys listed in Table 1. Particularly, during 2016 (i.e. intra-annual comparisons) there were not dredging campaigns (Table 2). Therefore, it is considered that these bathymetric datasets do not reflect directly or largely the effect of such dredging campaigns. They reflect mainly (completely for 2016) the influence of mixed conditions on morphology (i.e. Maillet et al., 2006; Jiang et al., 2012; Wang et al., 2013).

3.2. Processing and analysis of data

The areas of net erosion/accretion in the river mouth, as well as the corresponding volumetric gains/losses, were determined by overlapping successive soundings of comparable hydrological seasons. Interannual comparisons were carried out for the years 2000–2004, 2004–2011, and 2011–2017. Intra-annual comparisons were carried out for the year 2016 (Table 1). It is assumed that such comparisons reflect the net

Table 2
Dredgings performed in the lower sector of the Magdalena River mouth (km 0 to km 22) - Official reports from Cormagdalena (2018).

Year	Dredging		
	Total Volume (x10^6 m^3)	Campaigns (Number)	Average Volume per campaign (x10^6 m^3)
2000	–	–	–
2004	–	–	–
2005	1.381	10	0.138
2006	1.139	8	0.141
2007	0.984	5	0.196
2008	1.011	6	0.168
2009	0.518	9	0.056
2010	0.407	7	0.057
2011	0.490	7	0.070
2012	0.404	1	0.400
2013	–	–	–
2014	0.887	5	0.176
2015	–	–	–
2016	–	–	–
2017	0.869	3	0.286
2018	0.953	6	0.158
Average	**0.817**	**6.3**	**0.167**

Note. - There were no dredging campaigns according to the official report.

morphological evolution under mixed conditions (i.e. Maillet et al., 2006; Jiang et al., 2012; Wang et al., 2013). The bathymetric surface comparisons require the development of tridimensional models estimated from rectangular grids (i.e. kriging) or triangular irregular networks (TIN) (Maher and Lawrencetown, 1987). The rectangular models are good interpolators for sparse data, whereas the TIN model allows high precision with respect to the density of the source data (Maillet et al., 2006; Jiang et al., 2012). Consequently, for these comparisons the Digital Elevation Models (DEMs) were configured by means of Triangular Irregular Network (TIN) interpolation, using ArcGIS V. 10.1®. DEMs were constructed with cell sizes of <5 m, providing more detailed comparisons than similar studies (i.e. Van der Wal et al., 2002; Blott et al., 2006; Jiang et al., 2012; Wang et al., 2013; Restrepo et al., 2016; Luan et al., 2018). In this scheme, volumetric differences are based on a geometric comparison between two equally sized surface triangles, one acting as a reference and other as a baseline (ESRI, 2020) (see Supplementary Material). As a complement to the TIN modelling, the program Auto Cad Civil 3D 2018 was used to define the break-lines, which supplied greater detail to the tridimensional model and reduced the error sources. ArcGIS V. 10.1® was also used for the configuration of the graphic outcomes, into which the TIN models and the satellite photography obtained from the Autodesk BIM database were loaded. The volumetric values were converted into gravimetric sediment masses by estimating the bulk properties of the sediment. Sediments at the Magdalena river mouth are predominantly coarse and medium silts, mainly composed of plagioclase and quartz (Kolla and Buffler, 1985). Considering that the density of unconsolidated sediments with these minerals ranges from 2.63 g cm^{-3} to 2.76 g cm^{-3}, we used a dry bulk density of 2.65 g cm^{-3}. Sediment porosities up to 73% have been reported for *in-situ* silt-sand aggregates deposited in bays and estuaries (Leeder, 2011). We decided to use a mean porosity of 80% to be conservative in the estimation of gravimetric sediment masses. This approach was successfully employed in various estuarine systems, including the use of similar values for bulk properties (Van der Wal et al., 2002; Lane, 2004; Maillet et al., 2006).

A comparison of the thalweg line was also carried out with the aim of obtaining a general description of the morphology and evolution of the channel bed, as well as an estimation of its accretion and erosion rates. The methodology of Brunier et al. (2014) was followed for the determination of the thalweg line, establishing two-point vector files with an elevation Z in ArcGIS V. 10.1® and identifying the lowest point in each depth profile from the raw data. To ensure coherence between these identified point-lines and the general channel bottom morphology, the capture of the lowest points was carried out from the respective images depicting mapped depths. This procedure allows aligning these points on an axis representing the thalweg throughout the channel (e.g. Brunier et al., 2014). Comparison of thalweg profiles requires the same spatial interval and the same origin. Therefore, the initial profiles were re-projected with Cartesian coordinates of distance and depth, enabling a linear depiction of the initial profile. A polyline was generated using ArcGIS V. 10.1® from profile points, and new points were obtained from this line every 1 m, with X (distance to the mouth) and Y (depth) coordinates, from 0 to 7.5 km upstream of the river mouth. These generated profiles are thus comparable. Depth changes are depicted in a cartographic format representing mean variations every 1 m. Interannual comparisons were carried out between the years 2005–2016, 2006–2016, and 2006–2017, taking as a reference the high, transition, and low streamflow seasons, respectively. A comparison at the beginning and at the end of the hydrological annual cycle was also carried out for 2006 and 2016. In addition, the cumulative (positive and negative) and maximum instantaneous (positive) depth changes were also estimated from daily sounding data of 2016 (depicted every 100 m). Finally, the long-term average depth, its standard deviation, and its maximum variability range along the thalweg (every 100 m) were estimated using bathymetric surveys performed between 2004 and 2017 (n = 28). Considering the timeframe difference which separates dredging campaigns and bathymetries (i.e. three months), it is also considered that thalweg comparisons depict the net morphological evolution under mixed conditions.

4. Results

4.1. River mouth changes

4.1.1. Interannual changes

Processes of sedimentation predominated in the period 2000–2004. Processes of erosion prevailed in the period 2004–2011. While between 2011 and 2017 there was a mixed domain, with a preponderance of the erosive processes (Fig. 2 and Table 3). The ratio between the areas exhibiting processes of sedimentation and erosion was ~9:1 between 2000 and 2004, while the ratio between the volume of sediment deposited and the volume of sediment removed was ~14:1 (Table 3). During this period there was a net accumulation of 1.23 × 10^6 m^3 of sediment and the average rates of deposition and removal of sediments were 293 mm yr^{-1} and 183 mm yr^{-1}, respectively. The largest rates of sedimentation (1500 mm yr^{-1}) were recorded around km 1.8 (Fig. 2A). The rates and patterns changed between 2004 and 2011. The ratio between the areas exhibiting processes of sedimentation and erosion was ~1:21 and the ratio between the volume of sediment deposited and the volume of sediment removed was ~1:63 (Table 3). There was a net removal of 2.36 × 10^6 m^3 of sediment and the average rates of

Table 3
Inter-Annual comparison of areas and volumes of accretion and erosion in the Magdalena river mouth. Numbers in parentheses represent the percentage (%) of coverage respect to the surveyed area.

Period of comparison	Area (km^2)		Volume (x10^6 m^3)	
	Accretion	Erosion	Accretion	Erosion
2004–2000	0.906 (89.6)	0.105 (10.4)	1.329	0.096
2011–2004	0.046 (4.5)	0.965 (95.5)	0.038	2.398
2017–2011	0.363 (35.9)	0.648 (64.1)	0.611	0.751

deposition and removal of sediments were 103 mm yr^{-1} and 310 mm yr^{-1}, respectively. The largest rates of erosion (1450 mm yr^{-1}) were recorded near the contraction dyke (km ~1.8) (Fig. 2B). The ratio between the areas exhibiting processes of sedimentation and erosion was ~1:2 and the ratio between the volume of sediment deposited and the volume of sediment removed was ~1:1.2 between 2011 and 2017 (Table 3). There was a net removal of 0.14 × 10^6 m^3 of sediment during this period. Although the processes of sedimentation were lower in terms of area and volume, sedimentation rates were larger. The average and maximum rates of deposition of sediments were 230 mm yr^{-1} and 2625 mm yr^{-1}, respectively. Such values were at least 45% larger than the average and maximum average of removal of sediments, which amounted to 165 mm yr^{-1} and 968 mm yr^{-1}, respectively. There was also a clear differentiation in the spatial distribution of sedimentary processes during this period (Fig. 2C). The northern sector of the river mouth, downstream from km ~3.5, particularly near the western bank, underwent processes of sedimentation. The largest rates of sedimentation were recorded near the contraction dyke (km ~1.8). Whereas the southern sector of the river mouth, upstream from km ~3.5, underwent processes of erosion. In this case, the largest rates of erosion were recorded near km ~4.5, where the alignment of the river mouth changes (Fig. 2C).

4.1.2. Intra-annual changes

Monthly comparisons showed that the processes of scouring were dominant during five periods (Feb.–Jan, Sep.–Aug, Oct.–Sep, Nov.–Oct, Dec.–Nov.) and the processes of sedimentation predominated for two periods (Mar.–Feb, Aug.–Jul.). In the remaining four periods there was a mixed domain, with spatial differences in the distribution of the sedimentary processes (Fig. 3 and Table 4). In the periods with a predominance of the processes of scouring, the ratio between the areas exhibiting processes of sedimentation and erosion varied between ~1:2.3 and ~1:26. The ratio between the volume of sediment deposited and the volume of sediment removed oscillated between ~1:2.6 and ~1:48 (Table 4). The net volume of sediments removed fluctuated between 0.12 × 10^6 m^3 and 0.91 × 10^6 m^3 during these periods. The average rate of removal of sediments varied between 194 mm m^{-1} (Oct.–Sep.) and

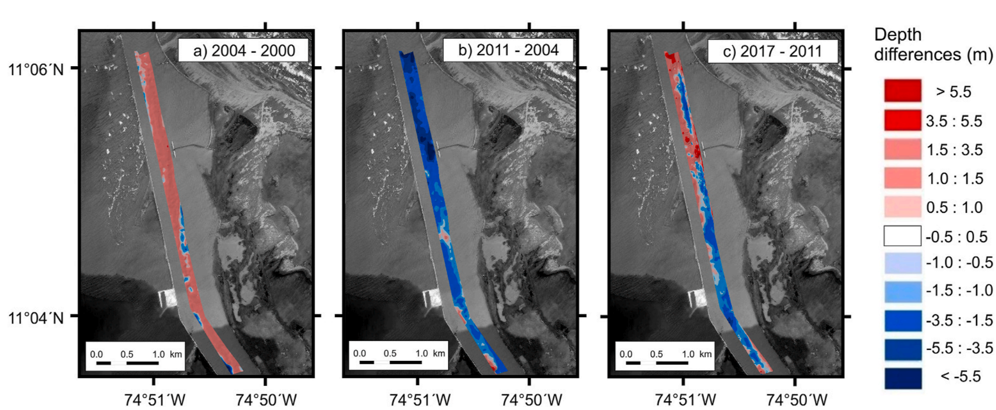

Fig. 2. Interannual comparison of the accretion (positive values in red) and erosion (negative values in blue) volumes in the Magdalena River mouth: (a) 2004–2000, (b) 2011–2004, y (c) 2017–2011. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

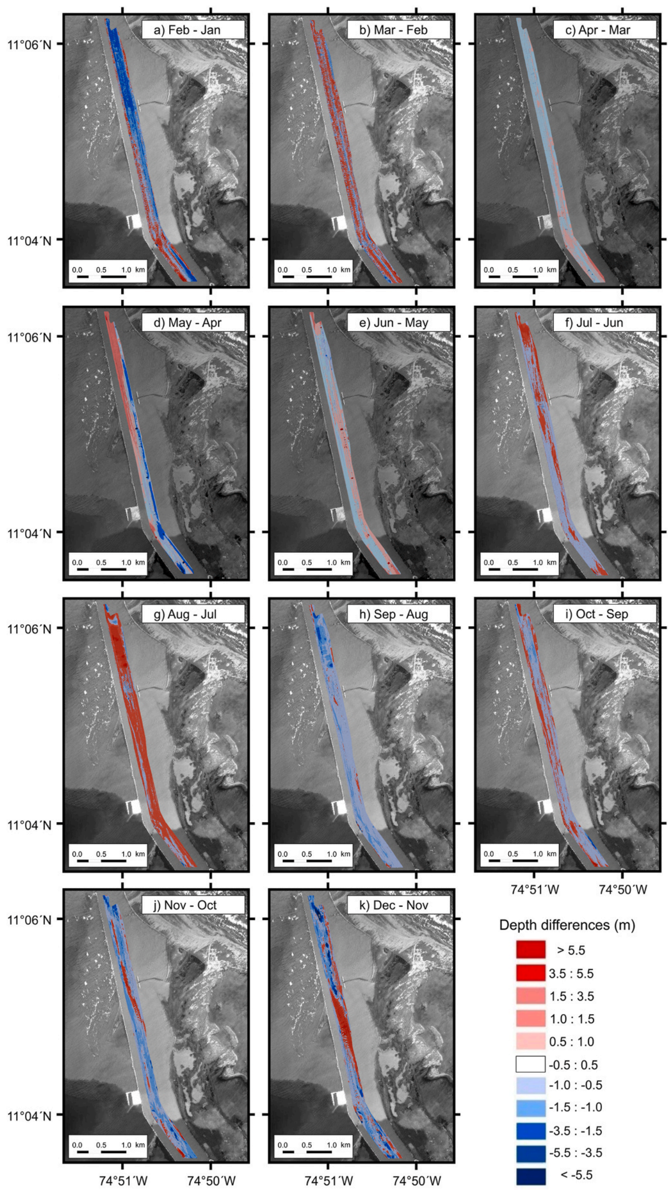

Fig. 3. Intra-annual comparison of the accretion (positive values in red) and erosion (negative values in blue) volumes in the Magdalena River mouth during 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Monthly comparison of areas and volumes of accretion and erosion in the Magdalena river mouth; data from 2016. Numbers in parentheses represent the percentage (%) of coverage respect to the surveyed area.

Period of comparison	Area (km^2)		Volume ($x10^6$ m^3)	
	Accretion	Erosion	Accretion	Erosion
February–January	0.350 (24.3)	1.087 (75.7)	0.124	1.036
March–February	0.893 (62.1)	0.544 (37.9)	0.789	0.432
April–March	0.469 (32.6)	0.968 (67.4)	0.077	0.109
May–April	0.606 (42.1)	0.831 (57.9)	0.505	0.694
June–May	0.577 (40.1)	0.860 (59.9)	0.161	0.213
July–June	0.458 (31.8)	0.979 (68.2)	0.112	0.139
August–July	1.077 (74.9)	0.360 (25.1)	0.292	0.078
September–August	0.053 (3.7)	1.384 (96.3)	0.012	0.575
October–September	0.438 (30.5)	0.999 (69.5)	0.074	0.194
November–October	0.183 (12.8)	1.254 (87.2)	0.079	0.666
December–November	0.391 (27.2)	1.046 (72.8)	0.198	0.770

952 mm m^{-1} (Feb.–Jan.), with maximum values of 13222 mm m^{-1} during the period December–November, near km 4.5 (one of the zones of greatest depth) (Figure 3a and 3h-k).

During the periods with a predominance of sedimentation processes the ratio between the areas exhibiting processes of sedimentation and erosion varied between ~1.6:1 and ~2.9:1. The ratio between the volume of sediment deposited and the volume of sediment removed oscillated between ~1.8:1 and ~3.7:1 (Table 4). The net volume of sediments deposited fluctuated between 0.21 × 10^6 m^3 and 0.36 × 10^6 m^3. The average rate of sedimentation varied between 271 mm m^{-1} (Aug.–Jul.) and 883 mm m^{-1} (Mar.–Feb.), with maximum values of 8628 mm m^{-1} near km 4.5 (one of the zones of greatest depth) in August–July (Fig. 3b and g).

Although the ratio and the magnitude of the processes of erosion and sedimentation were similar in the periods of the mixed domain, there was a slight predominance of the erosive processes. The rates of erosion and sedimentation exhibited ranges of average value of 112–835 mm m^{-1} and 165–833 mm m^{-1}, respectively. Nevertheless, the ratio between the areas exhibiting processes of sedimentation and erosion varied between ~1:1.3 and ~1:2.1, and the ratio between the volume of sediment deposited and the volume of sediment removed oscillated between ~1:1.2 and ~1:1.4 (Table 4). In these periods the net volume of sediments removed fluctuated between 0.02 × 10^6 m^3 and 0.18 × 10^6 m^3. There was also a marked differentiation in the spatial distribution of the processes of sedimentation and erosion, in which the processes with the greatest intensity of sedimentation were located where the alignment of the channel changes (Apr.–Mar.), in the final stretch of the river mouth (km 0–3) (May–Apr: western sector - Jul.–Jun: eastern sector), and in the river mouth (Jun.–May) (Fig. 3c–f).

The periods of erosive, sedimentary and mixed domain can be clustered into two temporal seasons (Fig. 3 and Table 4). The season of erosive domain comprises the periods from Sep.–Aug. to Feb.–Jan. The heterogeneous season begins and ends with the periods of sedimentary domain (Mar.–Feb. and Aug.–Jul.), with the periods of mixed domain between them (Fig. 3 and Table 4). Overall, during the season of erosive domain the volume of sediment deposited and removed was 0.49 × 10^6 m^3 and 3.24 × 10^6 m^3, respectively. Thus, there was a net removal of 2.75 × 10^6 m^3 of sediments during this season. The processes of largest magnitude occurred during the period Feb.–Jan. (Fig. 3 and Table 3). During the heterogeneous season the volume of sediment deposited and removed was 1.93 × 10^6 m^3 and 1.66 × 10^6 m^3, respectively. Consequently, there was a net deposition of 0.27 × 10^6 m^3 of sediments during this season. The processes of largest magnitude in this season occurred during the period Mar.–Feb. (Fig. 3 and Table 4).

4.2. Thalweg (deep channel) changes

4.2.1. Interannual changes

The thalweg deepened between February-2006 and February-2017 (February - low streamflow season) (Fig. 4a). Erosion were greater than 2 m upstream from km 4, with values up to 6 m and 8 m in the deepest zones. Magnitudes of erosion were usually less than 1 m downstream from km 4. Except close to the river mouth, where values increased up to 2 m (Fig. 4a). A comparison of the profiles of May-2006 and May-2016 (May - transition streamflow season) showed differences between the upper and lower stretches of the thalweg (Fig. 4b). Erosive processes dominated upstream from km 4, with values of erosion close to 2 m. Maximum values of erosion of 4.4 m and 8.4 m were measured at km 4.7 and km 5.6, respectively. Processes of sedimentation prevailed downstream from km 4. This stretch characterized by the growing accumulation of deposits toward downstream, reaching values of sedimentation larger than 2 m near the river mouth (Fig. 4b). The deepening of the thalweg was recorded between November-2005 and November-2016 (November - strongest high streamflow season) (Fig. 4c). This deepening was relatively homogenous, with values of erosion greater than 1 m along all the thalweg. The greatest value of erosion (5.2 m) was

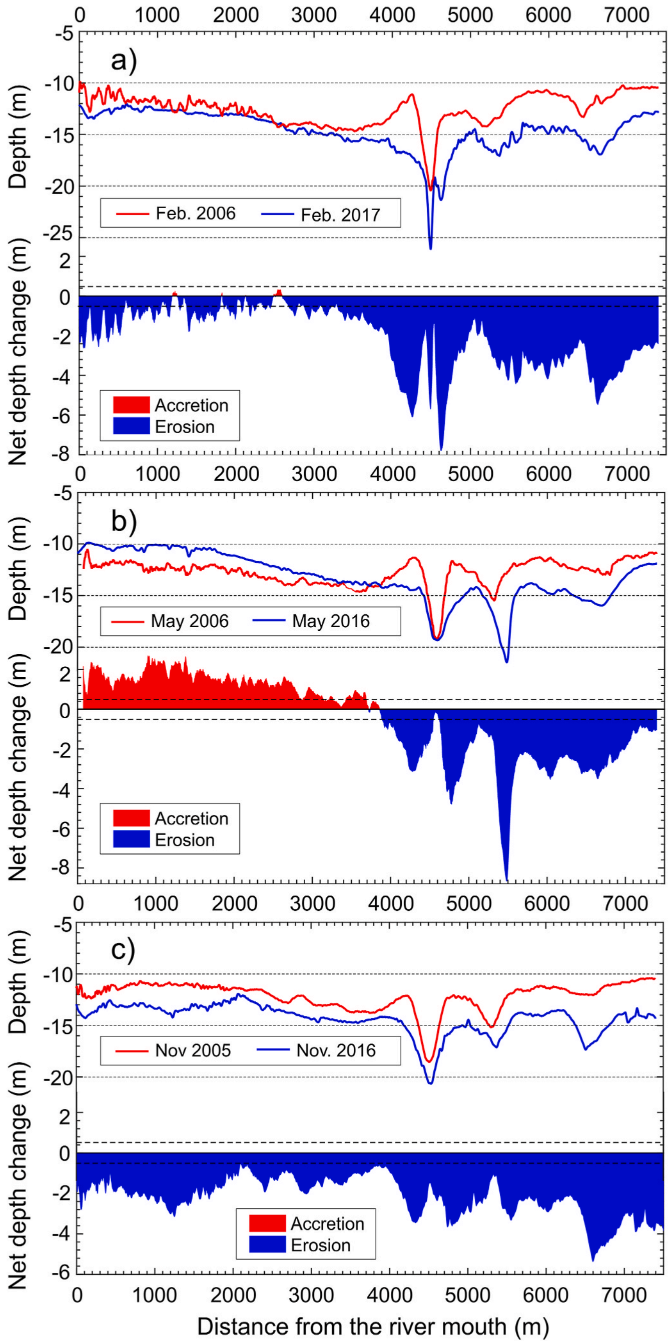

Fig. 4. Long-term changes in the depth along the thalweg considering different streamflow conditions: (a) February 2006–February 2017 (low streamflow), (b) May 2006–May 2016 (Transition) and (c) November 2005–November 2016 (High streamflow). The long-dotted line represents the threshold for significant data.

measured at km 6.6 (Fig. 4c).

Except for the sedimentation recorded downstream from km 4 during the transition season (May), there was a general deepening (erosion) of the thalweg on a long-term basis. The changes of the greatest magnitude (>2 m) occurred upstream from km 4 in all the scenarios (Fig. 4). The shape and the major features of the thalweg remained relatively steady despite these changes. It exhibits a series of large subaqueous dunes, with minor irregular superimposed dunes. These dunes are dissected by relatively narrow and deep pools. The largest depth changes in the longitudinal profiles occurred in or nearby these pools (Fig. 4).

4.2.2. *Intra-annual changes*

The erosive processes were predominant along the thalweg between February-2006 and November-2006 (Fig. 5a). Erosion exhibited a progressive increase downstream from km 3.6, reaching values of ~2 m near the river mouth. There was a transition between erosion and sedimentation zones upstream from km 3.6. The deepest pools of the thalweg exhibited sedimentation, with values less than 1.2 m on average. Except in the km 4.5, which experienced a rate of sedimentation of ~4 m (Fig. 5a). The predominance of the processes of erosion was more noticeable and stable between February-2016 and November-2016 (Fig. 5b). Values of erosion were higher than 0.5 m during this period, with values up to 2.4 m. Sedimentation only occurred in the zone of the greatest depth of the thalweg (km 4.5), with values of sedimentation around 0.8 m (Fig. 5b). Despite the differences in the magnitude, the intra-annual patterns (February–November) observed in these years (2006 and 2016) were similar, especially the preponderance of the erosive processes. Furthermore, the shape and the features of the major river bedforms (subaqueous dunes with irregular superimposed dunes and pools) remained relatively stable. Only the basic dimensions (height and length) and position of these bedforms experienced minor changes (Fig. 5).

The patterns of the accumulated change in depth in 2016 (January to December) are similar to those observed in the interannual comparison performed between May-2006 and May-2016 (Figs. 4 and 6). There is a clear spatial differentiation between the zones of erosion and sedimentation (Fig. 6). Processes of accretion occurred in the areas nearest to the river mouth, between km 0.5 and km 2.2, with values usually less than 1

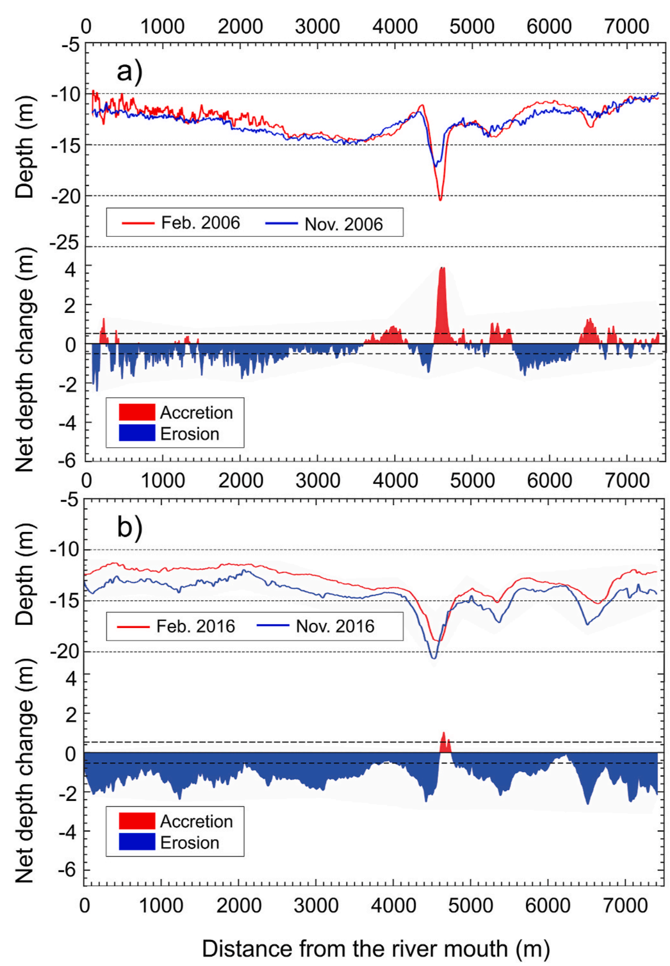

Fig. 5. Annual changes in the depth along the *thalweg* for: (a) February 2006–November 2006 and (b) February 2016–November 2016. The long-dotted line represents the threshold for significant data.

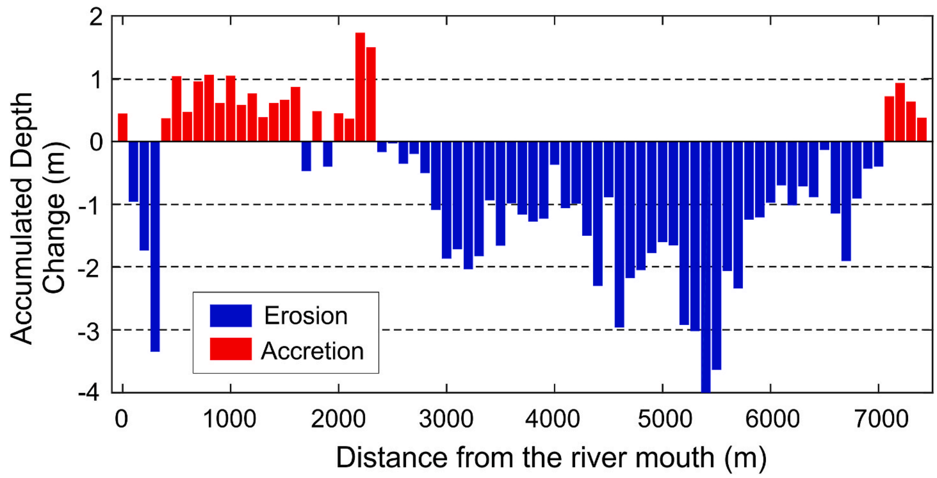

Fig. 6. Accumulated depth change along the *thalweg* during 2016. Positive values (red bars) represent accretion whereas negative values (blue bars) indicate erosion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

m. The processes of erosion exhibited a greater magnitude compared with those of accretion. Such processes were mainly located upstream from km 2.2. From this point up to km 5, the values of erosion increased from values $<$ 0.5 m–3.0 m. The largest values of erosion ($>$3 m) occurred at km 5.5. On the contrary, there were processes of accretion with values $<$ 1 m upstream from km 7 (Fig. 6).

5. Discussion

5.1. Results interpretation and historical comparison

The cyclic alternation between the erosive and sedimentary processes at different time scales in the Magdalena River mouth (Figs. 2 and 3) stands out, despite the existence of a slight general tendency (i.e. seasonal and long-term scale) toward its deepening, particularly in the thalweg (Figs. 4–6). This slow-pace deepening reflects an overall negative sediment budget pattern over seasonal and long-term periods (Figs. 3 and 7). Despite this general deepening pattern, the rapid transitions from erosive to accretional states, and of the relatively high rates of removal and deposition of sediments, the shape and features of the major geomorphological features remain relatively stable, in time and space (Figs. 2–5).

Results also highlight that the monthly and/or intra-annual rates of sedimentation/erosion (Figs. 3 and 5) are of the same magnitude, or even larger, when compared with the respective interannual rates (Figs. 2 and 4). As a whole, the rates of sedimentation and erosion obtained in the Magdalena River mouth can be considered to be relatively high compared with the values obtained in other human-intervened river mouths and/or with large fluvial sediment inputs (e.g. Van der Wal et al., 2002; Yang et al., 2003; Maillet et al., 2006; Brunier et al., 2014). Therefore, the magnitude of the processes observed in the Magdalena River mouth suggests that the channel bed evolution over the time intervals of comparison has not been driven merely by natural agents. It is largely influenced for the built man-made structures.

Several studies have shown that for timescales shorter than a few decades (i.e. <20 years), marked changes in channel bed and thalweg morphology may be triggered by the ongoing human interventions, which modify or exacerbate the geomorphological and hydrodynamical processes (e.g. Cuadrado and Perillo, 1997; Perillo et al., 2005; Dai et al., 2013; Brunier et al., 2014; Pye and Blott, 2014; Luan et al., 2018; Zarzuelo et al., 2018). Consequently, our results and the surveyed time-frame (2000–2017) might indicate that the high rates and rapid changes in the patterns of sedimentation/erosion (Figs. 2–6) observed in the Magdalena River mouth are the result of the cumulative effect of its limited morphological response/adjustment capacity (planform) and its large suspended sediment load (142.6 $\pm$ 48 $\times$ 10^6 t yr^{-1}) (Restrepo et al., 2017). In this context, the laterally constrained character of the Magdalena river mouth might be a key element within such erosion/deposition cycles and the deepening overall trend, since it largely modulates the effects posed by hydrodynamic and geomorphological processes. Morphodynamic evolution is closely related to the hydrodynamic processes, since to maintain values of river flow velocity within an equilibrium range (i.e. Densimetric Froude), estuaries must find a balance between channel depth and breadth (Prandle and Lane, 2015; Zhu et al., 2017). In laterally constrained river mouths, such as the Magdalena River, channel widening does not occur. Therefore, deep-level oscillations, due to changes in streamflow and tide range, lead to rapid adjustments in the flow conditions and the sediment transport regime, which in turn lead to a reinforcement of the vertical changes in the subaqueous morphology. Such reinforcing effects have been observed in other highly human-intervened river mouths (e.g. Hu and Ding, 2009; Jiang et al., 2012; Brunier et al., 2014; Zarzuelo et al., 2018). It is to be presumed that this effect will be much larger in the Magdalena River mouth considering the ratio between the width of the channel and the streamflow (streamflow per width) and the suspended sediment load (suspended sediment load per width). These ratios are larger by at least an order of magnitude compared to other large rivers ratios (Table 5). Thus, considering unit stream power (Ω) and boundary shear stress (τ°), a steady channel width implies that changes in streamflow must be balanced by changes in bed slope and/or average depth. Consequently, Magdalena River ratios suggest that small changes in the sediment transport regime would lead to major changes in the sub-aqueous morphology, due to the large variations in the unit stream power (Ω) and/or boundary shear stress (τ°) (e.g. Jiang et al., 2012; Brunier et al., 2014).

Despite the general deepening tendency of the channel and the high rates of removal/deposition of sediments, the transitions between sedimentation and erosion stages and the relative stability of the structure and the configuration of the major bedforms of the thalweg suggests that the river mouth undergoes a state of dynamic quasi-equilibrium (Figs. 2–5). A statistical synthesis of all the data presented in this study reveals that depths of the thalweg are relatively quasi-stable and their variability is relatively low at long-term (Fig. 8), which would support the forgoing hypothesis. For example, in the thalweg, the long-term average depth ranged between 12.0 and 18.8 m. The ~30% of the thalweg exhibited long-term average depths lower than 13 m, while only 7% exhibited long-term average depths greater than 15 m. The upper band limit of the standard deviation zone (i.e. shallower depths) varied between 11.1 and 16.8 m. Nevertheless, most of this upper band (76%) had depths of less than 14 m. The lower band limit of the standard

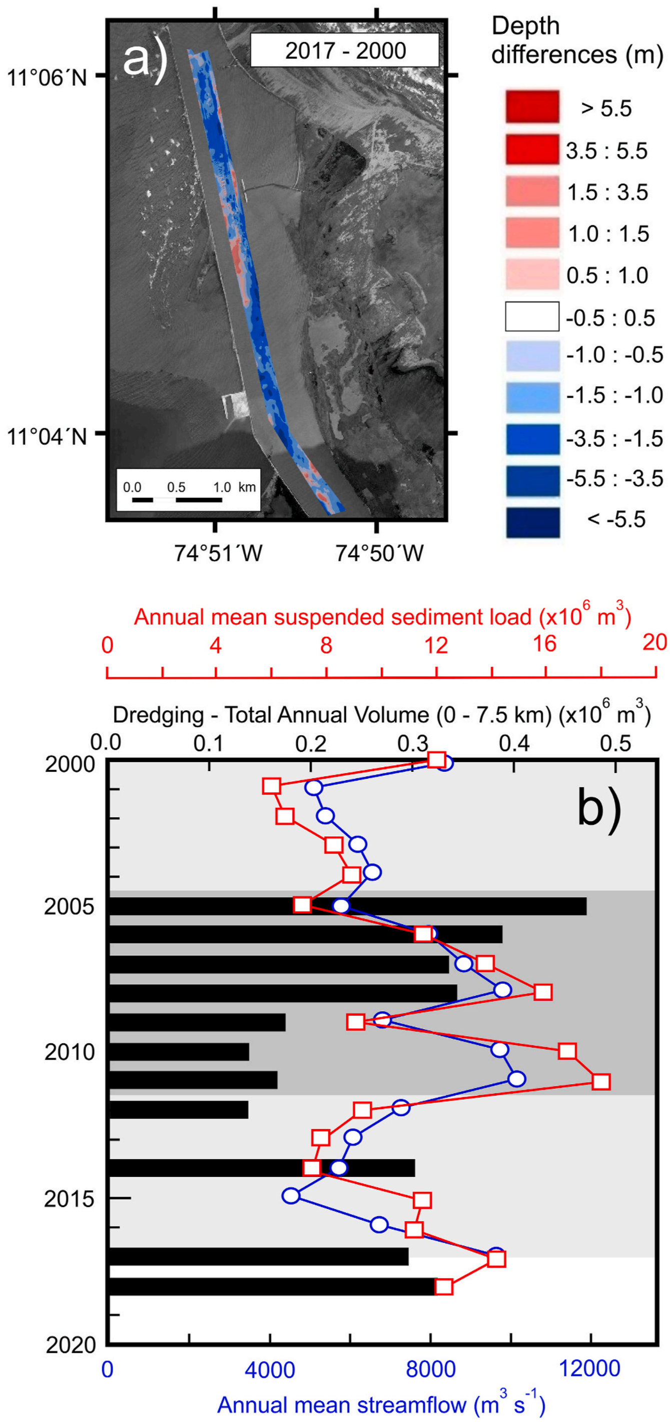

Fig. 7. (a) Net interannual comparison of the accretion (positive values in red) and erosion (negative values in blue) volumes in the Magdalena River mouth: (2017–2000) and (b) total annual volume of dredging in the surveyed area (0–7.5 km) and annual mean streamflow and suspended sediment load (2000–2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

deviation zone (i.e. greater depths) oscillated between 13.2 and 20.8 m, but only 25% of this lower band had depths greater than 15 m. Furthermore, at a given point, the range of variation of the standard deviation zone was mainly found to be below 2.5 m, with a maximum value of 4.5 m. Finally, the minimum historical depth (2000–2017) varied between 8.8 and 13.4 m, while the maximum historical depth (2000–2017) varied between 14.0 and 26.5 m. At a given point the range of maximum and minimum values of depth was between 2.8 and 17.9 m (Fig. 8).

O'brien (Dyer, 1998) formulated a widely accepted relations for describing a state of morphological equilibrium in an estuary,

$$A = cP^n \qquad \text{(Eq. 1)}$$

where A is the cross section (m^2), P is the tidal prism (m^3), c and p are constants of adjustment. Since the Magdalena River mouth has fixed side boundaries (i.e. laterally constrained river mouth) (Fig. 1) that completely inhibit the horizontal changes in the section of flow and the existence of an intertidal flat, it is to be expected that changes in Eq. (1) occur in the vertical components of A and P. These changes in turn generate adjustments in the sediment transport regime, which finally affects the rates of removal and deposition of sediments (e.g. Dyer, 1998; Hu and Ding, 2009; Jiang et al., 2012). Furthermore, in natural or semi-natural conditions, the water depth along a river channel determines how much surface area is available for sediment to settle or erode (e.g. Zhu et al., 2017). However, in laterally constrained river mouths, the area available for sediment to settle or erode depends on the channel width, regardless of the depth. And the channel width is steady over time. Thus, the narrower the channel, the larger the accumulation or removal of sediments is expected per unit area, depending on the flow regime condition. Therefore, the large changes of depth recorded in this study do not seem unrealistic, considering the large changes that are undergone in the flow conditions of the Magdalena River mouth, its large fluvial sediment input and small channel width (<1.3 km) (Restrepo et al., 2016, 2018).

The existence of a dynamic equilibrium state requires diverse mechanisms to take an estuary from flood condition to ebb condition and vice-versa. Flood-dominated estuaries are generally shallow, whereas ebb-dominated estuaries are relatively deep and tend to become deeper (Dyer, 1998). The Magdalena River mouth is an ebb-dominated estuary (Restrepo et al., 2016, 2018). Consequently, those processes linked to the strengthening of the flood flows and/or to the weakening of the ebb flows, such as salt wedge penetration and frictional losses due to channel alignment changes and riverbanks revetment, favor a transition toward conditions of dynamic quasi-equilibrium by promoting siltation. Of course, this process is reversible, since the progressive sedimentary infilling increases the currents in the estuary until they are strong enough to prevent further sedimentation and promote sediment scouring (e.g. Hu and Ding, 2009; Jiang et al., 2012; Zarzuelo et al., 2018). This process would explain the reason why the zones where occur significant changes in the alignment and the amplitude of the channel, experience the largest rates of erosion and sedimentation (Figs. 2 and 3). It would also explain why the final stretch of the river mouth (km 0–4) experienced stable processes of sedimentation (Figs. 2–4 and 6), since this stretch experience an increase in the frictional effects as a result of the engineering structures and the contraction of the channel (Fig. 1), and a sustained penetration of the salt wedge is undergone in conditions of low streamflows (e.g. Ospino et al., 2018; Restrepo et al., 2018). Furthermore, the cyclic nature of the sedimentary processes reflects the changes of the fluvial inputs. Between 2000 and 2004, when the fluvial inputs of sediment and freshwater averaged 108.4×10^6 t yr^{-1} and 6389.4 m^3 s^{-1}, the siltation processes prevailed with a net deposition of 1.23×10^6 m^3 of sediments. Between 2004 and 2011, when the fluvial inputs of sediment increased by 55% (168.9×10^6 t yr^{-1}) and freshwater by 29% (8278.5 m^3 s^{-1}), there was a change toward the predominance of the processes of erosion. With a net removal of 2.36×10^6 m^3 of sediments (Table 3 and Fig. 2). Finally, between 2011 and 2017, when there was an intermediate rate of fluvial inputs of sediment (132.3×10^6 t yr^{-1}) and freshwater (7236.5 m^3 s^{-1}), the river mouth underwent a mixed domain, with a slight predominance of the processes of erosion. Thus, the net volume of removal of sediments was 0.14×10^6 m^3 (Table 3, Figs. 2 and 9). The intra-annual scale also reflects a relationship with the changes in the fluvial inputs. For

Table 5
Comparison of rivers with large drainage areas and suspended sediment load with an emphasis on the ratio of streamflow and suspended sediment load to total channel width (measured at the river mouth).

River mouth	Drainage Area (x10^6 km^2)[a]	Total channel width (B) (km)	Streamflow (Q) (x10^3 m^3 s^{-1})[b,c]	Suspended Sediment Load (S_L) (x10^6 t yr^{-1})[a,b,c]	Q/B (m^3 s^{-1} m^{-1})	S_L/B (x10^6 t yr^{-1} m^{-1})
Amazon R.	4.64	101.87 (6)	185.18	900.0	1.81	0.0088
Congo R.	3.80	9.89 (1)	41.00	43.0	4.14	0.0043
Paraná R.	1.95	261.81 (1)	14.05	79.0	0.05	0.0003
Yangtze R.	1.80	38.65 (3)	30.17	150.0	0.78	0.0038
Orinoco R.	1.00	89.36 (8)	33.05	150.0	0.36	0.0016
Huanghe R.	0.77	3.75 (3)	2.57	150.0	0.68	0.0400
Brahmaputra R.	0.61	57.82 (9)	19.30	540.0	0.33	0.0093
Pearl R.	0.44	36.37 (5)	10.60	69.0	0.29	0.0018
Magdalena R.	**0.25**	**0.57 (1)**	**6.49**	**142.6**	**11.39**	**0.2491**

Note. Values in parentheses in the total channel width column represent the number of main distributary channels of each river mouth.
Source.
[a] Milliman and Syvitski (1992).
[b] Best (2019).
[c] Restrepo et al. (2017).

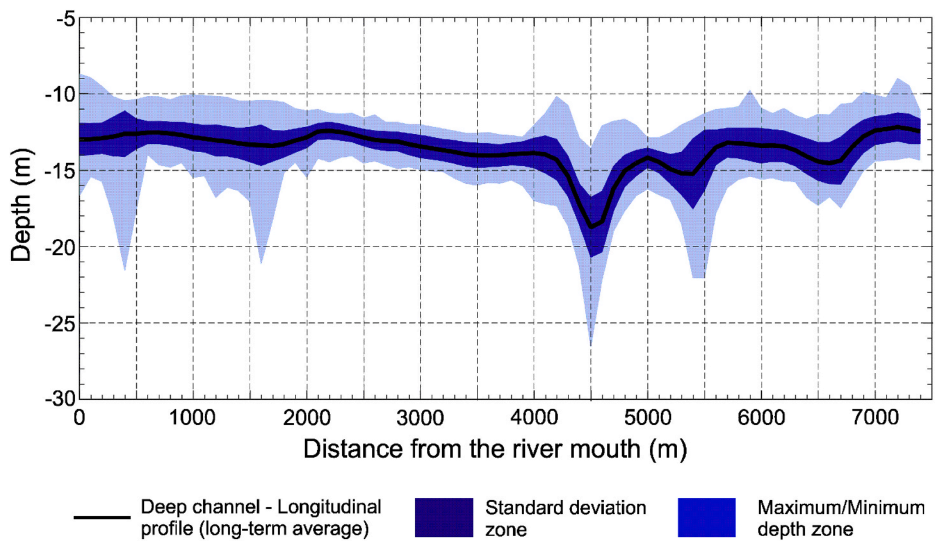

Fig. 8. *Thalweg* – longitudinal profile: long-term average, standard deviation zone and maximum/minimum depth zone based on historic information from 2000 to 2017.

example, the period of erosive domain identified in 2016, which experienced a net removal of 2.75 × 10^6 m^3 of sediments (Fig. 3 and Table 4), coincided with the major high streamflow season, including its early rising and falling stages. On the contrary, the heterogeneous period identified in 2016, which had a net deposition of 0.27 × 10^6 m^3 of sediments (Fig. 3 and Table 4), coincided with the transition, low, and minor high streamflow seasons. The periods exhibiting a predominance of the sedimentary processes (Mar.–Feb. and Aug.–Jul, Fig. 2) correspond to the low streamflow seasons, in which the largest sediment concentrations in the river mouth have been measured (e.g. Restrepo et al., 2018). Consequently, the Magdalena River mouth would experience a state of dynamic quasi-equilibrium characterized by a seasonal balance, superimposed on a general long-term tendency, instead of a balance based on a tidal scale (i.e. semi-diurnal/diurnal, spring/neap tide) (Wright and Coleman, 1973; Dyer, 1998). For the case of the observed period, the long-term tendency corresponds to a slight deepening, which coincides with an ebb-dominated estuary.

5.2. Considerations for the river mouth management

Navigation is one of the prominent uses of the Magdalena River. Despite multiple efforts, mainly referred to the engineering structures built since 1936 (Fig. 1), navigation face severe problems due to siltation episodes, especially at the river mouth (Alvarado, 2008). Our results showed successive shifts from erosional to accretional states at the Magdalena River mouth, at different time scales, depending on hydrodynamical and sedimentological conditions. Depth changes linked to such morphological shifts are of high magnitude (Figs. 2–6) mainly due to the large fluvial sediment input and the laterally constrained condition of the river mouth. Furthermore, erosion/sedimentation rates were much larger at intra-annual scales than at interannual scales (Figs. 2–6, Tables 1 and 2). In such a scenario, constraints and threats to navigation are more likely linked to intra-annual than interannual changes. For example, the ratio of the accumulated rate of sedimentation in 2016 (i.e. annual scale) to the long-term average depth of the thalweg was extremely low. Most of these ratios were 0.0, some lied below 0.1 and none exceed 0.2 (Fig. 9a). Conversely, the ratio of the maximum rate of sedimentation measured in 2016 (i.e. monthly scale) to the long-term average depth of the thalweg was significantly larger. All these ratios lied above 0.1, with the larger values (>0.20) close to the river mouth (km 0–2) and upstream from km 5. Some of these ratios even represent the equivalent to a quarter or half of the long-term average depth of the thalweg (0.25–0.50) (Fig. 9b). These latter ratios pose serious threats to navigation.

To maintain operational depths for navigation in the river mouth is a permanent challenge. Currently, efforts focus mainly on performing

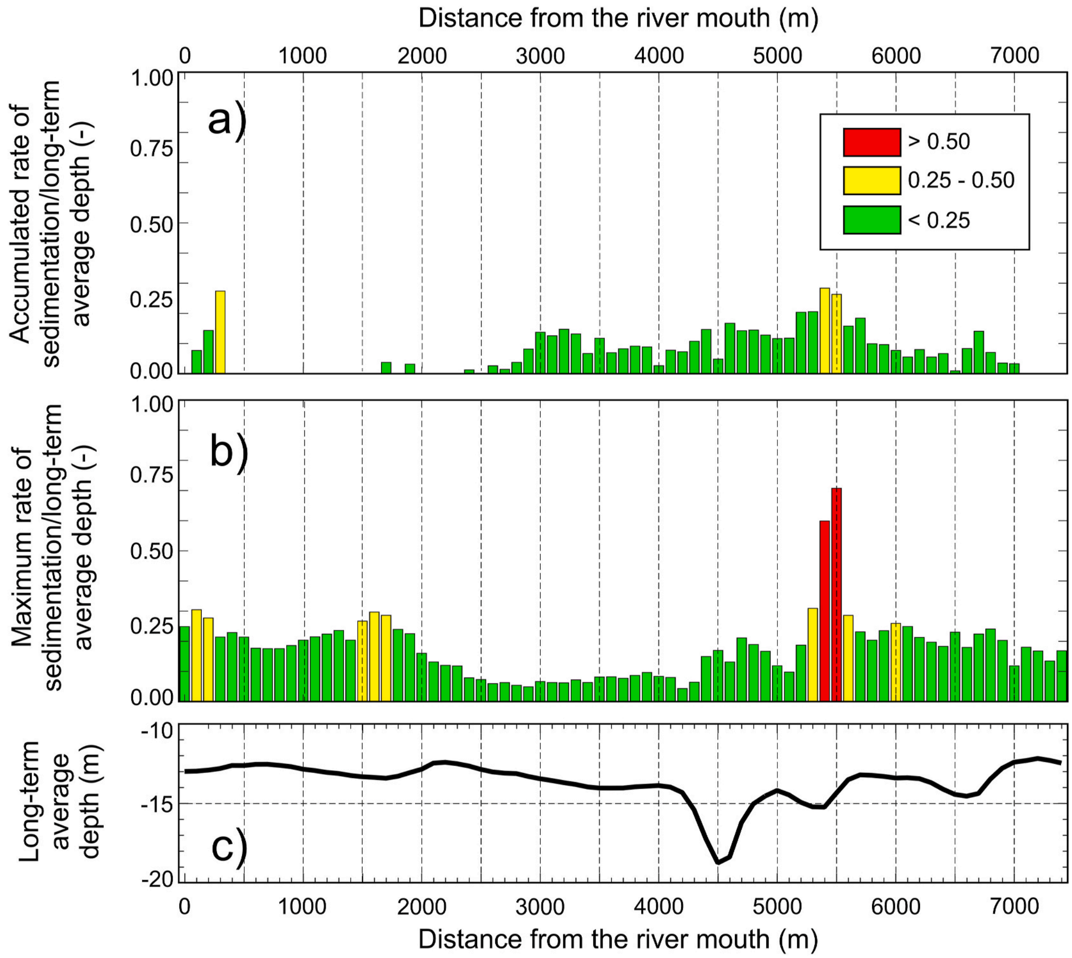

Fig. 9. Ratio between (a) the accumulated and (b) the maximum rate of sedimentation and the long-term average depth; (c) long-term average depth of the Magdalena river mouth used for reference.

periodic maintenance dredging (Table 2) (Cormagdalena, 2018). From 2005 to 2018 the total volume of dredged sediment in the lower course of the Magdalena river, from km 0 to km 22, was 9.04×10^6 m^3, with an average of $0.82 \pm 0.3 \times 10^6$ m^3 and $0.16 \pm 0.1 \times 10^6$ m^3 of sediments annually and per campaign, respectively (Table 2). Extrapolating steadily for the last 7.5 km of the river mouth, values would amount to 0.27×10^6 m^3 and 0.05×10^6 m^3, respectively. Meanwhile, the sediment accumulation in the river mouth (km 0 to km 7.5) at interannual scale (2000–2017) varied between 0.005×10^6 and 0.330×10^6 m^3 yr^{-1} (Table 3), whereas at intra-annual scale (2016) ranged from 0.01×10^6 to 0.79×10^6 m^3 m^{-1} (Table 4). Thus, the annual average volume of dredged sediment between 2005 and 2018 (0.27×10^6 m^3) was of the same order of magnitude than the annual volumes of sediment deposited in the river mouth. Interannual volumes of removed sediments (0.02–0.34×10^6 m^3 – Table 3) were also of the same order of magnitude than average annual dredged volumes. However, the average volume of dredged sediment per campaign (0.05×10^6 m^3) was much lower than the intra-annual volumes of sediment deposited in the river mouth during such a period. Intra-annual ($\geq 0.07 \times 10^6$ m^3 – Table 4) volumes of removed sediments were also larger than dredged volumes per campaign. Moreover, the average of dredged sediment per campaign over the entire area (0.16×10^6 m^3) was substantially much lower than the monthly average volume of sediment transported by the Magdalena River ($\sim 0.99 \times 10^6$ m^3) in such a timeframe (2000–2018). The annual average of dredged sediment over the entire area (0.82×10^6 m^3) was also significantly lower compared to the annual average volume of sediment transported by the Magdalena River at the same time period ($\sim 11.8 \times 10^6$ m^3) (Fig. 7b). Such previous comparisons would imply that the Magdalena River mouth poses a large capacity for replenishing the sediments removed by dredging; particularly because dredge promotes changes in the hydrodynamics conditions and tends to reduce the gradient of the riverbed profile by changing the relative depth. Under these conditions of fluctuating flows, coupled to the laterally constrained character of the river mouth, the excavations would be gradually infilled and the slope profile would go back to its equilibrium value (i.e. Brunier et al., 2014; Jiang et al., 2012; Zarzuelo et al., 2018). One of the most dramatic cases of this sediment-replenishment process occurred in June of 2017 when the river mouth exhibited critical depths (<10 m), just one month after dredging 0.34×10^6 m^3 of sediments between 27th-April and 10th-May to reach depths of 11.4 and 12.2 m in the navigation channel. As we assumed, the results suggest that observed and analyzed changes reflect the net morphological evolution under mixed conditions. Such evolution is largely controlled by changes in the sediment transport regime and the laterally constrained character of the river mouth. Dredging poses a minimum effect on the assessed cases. Some results stand by as support for this statement: (*i*) the overall stability of the major bedforms, structure, and shape of the thalweg observed at different timescale (Figs. 4, 5 and 7), reflecting cycles and successional stages, instead of localized or punctual events; (*ii*) hyper-concentrated or erratic spatial patterns of morphological changes were not recognized in the surveyed area, such patterns have been observed in areas where anthropic removal of sediment (i.e. dredging, sand mining) is significant (e.g. Bravard et al., 2013; Brunier et al., 2014); (*iii*) the correspondence between the morphological changes (patterns and magnitudes) and the influence of the sediment transport regime shifts and the laterally constrained character of the river mouth;

(*iv*) the morphological change patterns and riverbed major structure when comparing a year experiencing dredging (2006) with another not experiencing dredging (2016) are very similar (Fig. 5), highlighting the large preponderance of the sediment transport regime and the effects of its laterally constrained character over dredging; and (*v*) the relatively low proportion of dredging volumes compared to accretion/erosion volumes, particularly at intra-annual scales, and also to the fluvial sediment inputs (Fig. 7), which highlight the sediment replenishing and self-regulation capacities of the river mouth.

Engineering works have contributed to improving navigation at river mouths at long-term. Nevertheless, frequently, they have generated unexpected impacts on their hydrodynamical and/or geomorphological processes (e.g. Hu and Ding, 2009; Jiang et al., 2012; Brunier et al., 2014). Estuarine responses after navigational improvements include changes in the exchange of water and sediments, accretion in the groynes areas due to the geometrically-controlled eddies produced by the frictional effects of the groins on the flow, changes in the amplitude and propagation of the tidal wave along the estuary, shifting from ebb dominance to flood dominance and vice versa, estuarine eutrophication, coastline erosion, ecosystems degradation, among others (e.g. Cuadrado and Perillo, 1997; Hu and Ding, 2009; Jiang et al., 2012). Particularly, deepening through dredging, may either foster the side-slope instability of the deep channel, or enhance saltwater intrusion during low streamflows, allowing the lateral flow of sediments and promoting the sediment trapping in the deep channel, respectively (e.g. Zhang et al., 2010; Brunier et al., 2014; Yang et al., 2015). All such processes generate further threats and constraints for navigation. Dredging activities are not in equilibrium with the dynamic of the river mouth. It might lead to local and short-term adverse effects, including accelerated siltation, since promotes an enhanced saltwater intrusion and rapid bed slope adjustments (e.g. Cuadrado and Perillo, 1997; Hu and Ding, 2009; Jiang et al., 2012). In the specific case of the Magdalena River mouth, despite the continuous efforts for deepening the channel, there are still periodic restrictions to navigation and the depth conditions required for the transit of larger vessels (i.e. Post Panamax) seem not possible (Figs. 7 and 8). Our results showed no large departures of the long-term average depths at the thalweg respect to measured depths in the river mouth during the pre-intervention stage (c.a. 1936) and the existence of a dynamic quasi-equilibrium state, with large depth variations linked to the sediment transport regime changes and its laterally constrained character. However, this quasi-equilibrium state may respond to additional drivers than the sediment transport regime. The existence of geological controls, lithological or structural (i.e. crystalline underlying rocks, faulting systems, alignments) should be analyzed thoroughly. The potential effect of ship-induced waves and tidal wave influences at specific periods and scales should be also addressed by future research. It is essential to investigate the mechanism driving the morphological evolution of laterally constrained river mouths for effectively managing and reducing the potential environmental hazards associated with these systems (e.g. Zhu et al., 2017; Zarzuelo et al., 2018). Consequently, more dynamic, nature-based, and innovative intervention proposals are required for managing this type of river mouths. Such proposals should recognize the rapid responses/transitions and the geomorphological adaptations of these river mouths. They should also incorporate the effects of the hydrodynamic/morphodynamic high-resolution processes occurring at different conditions (i.e. turbulence, particle settling velocity, bars and riverbed dune patterns). It is also important to identify the limits of the natural systems for human uses and adapt the human development to those limits, instead of forcing natural systems to experience in out-of-equilibrium and unsustainable conditions. Otherwise, the need for additional anthropic interventions will be incessant and increasing as it has been up to now.

6. Conclusions

The Magdalena River mouth experience a state of dynamic quasi-equilibrium characterized by rapid seasonal/interannual transitions, superimposed on a general long-term tendency. For the case of the observed period, this long-term tendency corresponds to a slow-pace deepening, reflecting the ebb-dominance. Interannual comparisons revealed transitions from a sedimentation stage (2000–2004) to an erosion stage (2004–2011). And finally, to a mixed stage wherein the prevalence of erosional processes (2011–2017). Intra-annual comparisons also revealed shifts from an erosional season (Sep–Aug to Feb–Jan) toward to a heterogeneous season, which comprises the periods of sedimentation and mixed domain (Mar–Feb to Aug–Jul). The thalweg also exhibited differences in its interannual patterns of erosion/sedimentation when different hydrological periods were analyzed. However, deepening also prevailed along this specific area. Despite this overall deepening pattern and the rapid transitions from erosive to accretional states, the shape and features of the riverbed remained relatively stable, in time and space.

The magnitude of the processes observed in the Magdalena River mouth suggests that the channel bed evolution over the time intervals of comparison has not been driven merely by natural agents. At the interannual scale, the rates of erosion were 310 mm yr^{-1} on average during the erosional stages. Whereas sedimentation rates were 293 mm yr^{-1} on average during the sedimentation stages. Maximum rates of erosion and sedimentation were 1450 mm yr^{-1} and 2625 mm yr^{-1}, respectively. However, erosion/sedimentation rates were much larger at the intra-annual scale. Erosion rates ranged between 194 mm m^{-1} and 952 mm m^{-1} on average, with a maximum value of 13222 mm m^{-1}. Wherein sedimentation rates oscillated from 271 mm m^{-1} to 833 mm m^{-1} on average, up to a maximum value of 8628 mm m^{-1}. Furthermore, the ratio of the maximum rate of sedimentation (2016 - monthly scale) to the long-term average depth of the thalweg was significantly larger than the equivalent ratio for the accumulated rate of sedimentation (2016 - annual scale). Consequently, constraints and threats to navigation are more likely linked to intra-annual than interannual changes.

Our results showed successive shifts from erosional to accretional states at different time scales, depending on hydrodynamical and sedimentological conditions. The high rates and rapid changes in the patterns of sedimentation/erosion of the Magdalena River mouth are the results of the cumulative effect of its limited morphological response/adjustment capacity and its large suspended sediment load. As a result, despite the continuous efforts for deepening the navigation channel, there are still periodic restrictions to navigation. Therefore, future proposals of managing should identify the limits of this natural system for human uses, recognize its rapid responses/transitions, its geomorphological adaptations and incorporate also the effects of the hydrodynamic/morphodynamic high-resolution occurring at different conditions.

CRediT authorship contribution statement

Juan C. Restrepo: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Andrés Orejarena-Rondón:** Methodology, Formal analysis, Writing - original draft. **Carolina Consuegra:** Methodology, Formal analysis, Writing - original draft. **Javier Pérez:** Methodology, Formal analysis, Writing - original draft. **Humberto Llinas:** Methodology, Formal analysis, Writing - original draft. **Luis Otero:** Conceptualization, Writing - review & editing. **Oscar Álvarez:** Conceptualization, Writing - review & editing.

Declaration of competing interest

On behalf of all authors, I may declare that there is no conflict of interest at all in the development of this study.

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This study constitutes a contribution from the research project

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Appendix A. Supplementary data

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