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Discharge diversion in the Patía River delta, the Colombian Pacific: Geomorphic and ecological consequences for mangrove ecosystems

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ABSTRACT

In the Patía River delta, the best-developed delta on the western margin of South America, a major water diversion started in 1972. The diversion of the Patía flow to the Sanquianga River, the latter a small stream draining internal lakes from the Pacific lowlands, shifted the active delta plain from the south to the north and changed the northern estuarine system into an active delta plain. The Sanquianga Mangrove National Park, a mangrove reserve measuring 800 km^2, lies in this former estuary, where major hydrologic and sedimentation changes are occurring. Overall, major environmental consequences of this discharge diversion in terms of geomorphic changes along distributary channels and ecological impacts on mangrove ecosystems are evidenced by: (1) distributary channel accretion by operating processes such as sedimentation, overbank flow, increasing width of levees, sedimentation in crevasses, interdistributary channel fill, and colonization of pioneer mangrove; (2) freshening conditions in the Sanquianga distributary channel, a hydrologic change that has shifted the upper estuarine region (salinity <1%) downstream; (3) downstream advance of freshwater vegetation, which is invading channel banks in the lower and mixing estuarine zones; (4) die-off of approximately 5200 ha of mangrove near the delta apex at Bocas de Satinga, where the highest sediment accumulation rates occur; and (5) recurrent periods of mangrove defoliation due to a worm plague. Further analyses indicate strong mangrove erosion along transgressive barrier islands on the former delta plain. Here tectonic-induced subsidence, relative sea-level rise, and sediment starving conditions due to the channel diversion, are the main causes of the observed retreating conditions of mangrove communities. Our data also indicate that the Patía River has the highest sediment load (27×10^6 t yr^{-1}) and basin-wide sediment yield (1500 t km^{-2} yr^{-1}) on the west coast of South America. Erosion rates from the Patía catchment have been more pronounced during the decades of 1970–1980 and 1990–2000, as a result of land degradation and deforestation. The high sediment and freshwater inputs into the mangrove ecosystem create additional stress (both at ongoing background levels and, occasionally, at dramatic levels), which may periodically push local environmental parameters beyond the thresholds for mangrove survival. The future environmental state of the Sanquianga Mangrove National Reserve deserves more scientific and governmental attention.

1. Introduction

Delta ecosystems are closely linked to their catchments. The rates and temporal variation of water discharge, sediment load, and delivery of nutrients from land surfaces to distributary channels strongly influence a range of ecosystem processes and the composition of biological communities. Regimes of fluvial discharges vary geographically with differences in natural climate, geology, vegetation cover, and human-induced factors, and, therefore, generate great spatial gradients in the structure of fluvial ecosystems (Resh et al., 1988; Poff et al., 2006).

The Patía River delta (Fig. 1), the largest and best-developed delta on the western margin of South America, is a littoral-barred delta influenced differentially by fluvial discharge, wave energy and tides at its several distributary mouths. Fig. 2 shows the morphologic classification of Colombian deltas, including the Patía, done by using the quantitative relationships between log mean tidal range/mean wave height versus log suspended sediment load (Hori and Saito, 2007; Restrepo and López, 2008). When comparing the Patía Delta with worldwide similar deltas, the Patía belongs to tide-influenced

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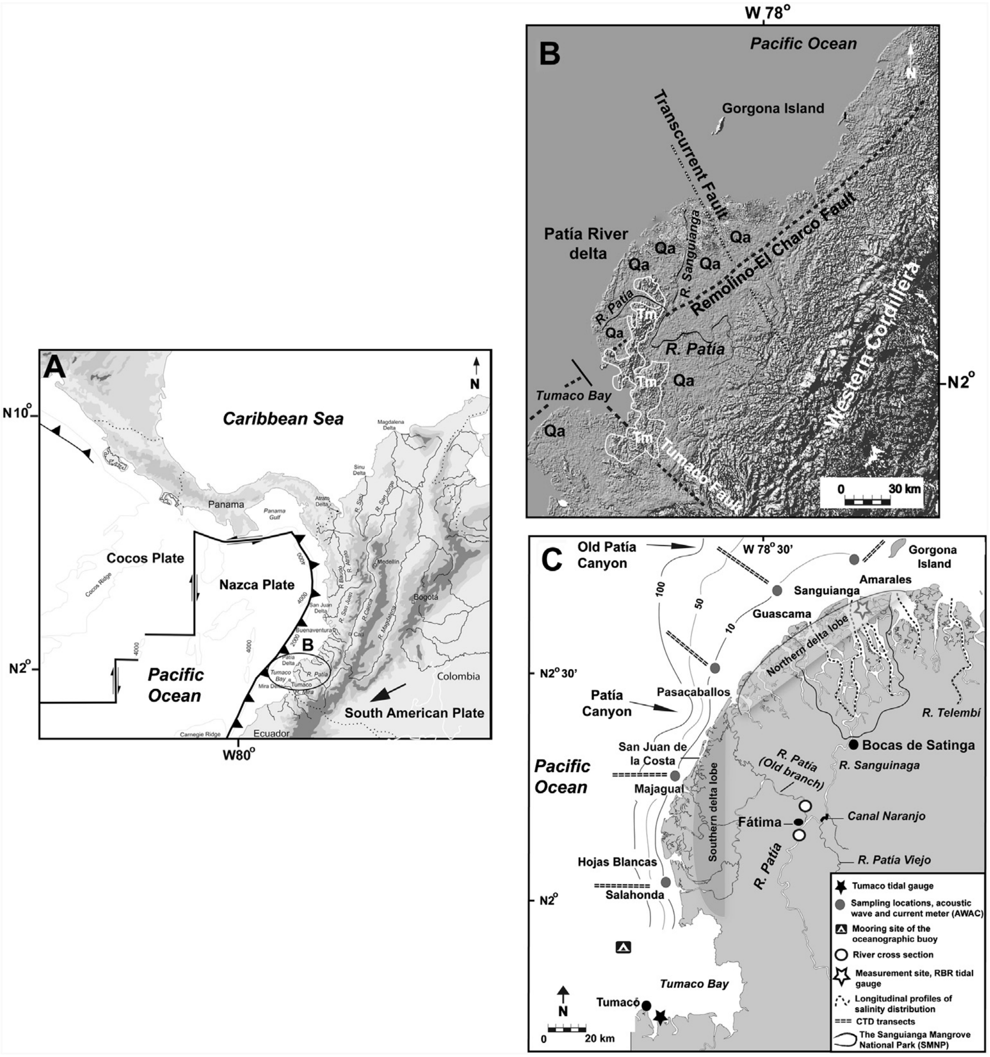

Fig. 1. (A) Map of the Pacific coast of Colombia, showing the tectonic setting of the Pacific margin. (B) Hillshade generated from DTEM data (SRTM, Shuttle Radar Topography Mission, 2002), showing the main tectonic features and geologic formations of the Patía River delta, including transverse paleofractures, recent alluvial deposits (Qa), and Tertiary formations of marine Miocene rocks (Tm). (C) Map of the Patía River delta, showing the locations of: (1) the channel diversion site at Fátima, (2) southern and northern delta lobes, and (3) sampling locations of oceanographic and hydrologic measurements.

delta type, similar to major deltas such as Fly, Mekong, Irrawaddy, Ganges-Brahmaputra, Changjiang, and Amazon. These tide-influenced deltas, which are common along mesotidal and macrotidal shoreline lines, exhibit funnel-shaped river mouth morphology. Although the Patía Delta has a significant river-produced bulge (Fig. 1), its shoreline has been smoothed into regular and rounded forms by wave activity. Continuous beach and beach ridge formations fringe the coastline of this delta. An interesting feature arising from this classification scheme is the contribution of wave energy to the morphology of the Patía Delta. Even though the Patía is not classified as mixed wave- and tide-influenced delta, its coast has been intensely eroded and reworked by wave action. As a result, marine energy conditions in the Patía are one of the highest of all Colombian deltas (marine power of 9.1), more comparable to the large deltas bordering the Atlantic ocean of South America such as the Orinoco and the Paraná deltas (Restrepo and López, 2008).

Natural and human-induced factors that control the evolution of delta environments vary in time and space (Galloway, 1975; Ashton et al., 2001; Penland and Kulp, 2005; Day and Giosan, 2008; Syvitski et al., 2009). For example, anthropogenic influences, including direct impacts affecting river discharge and sediment load such as water diversion, deforestation, hydroelectric dams and irrigation alter the structure and function of deltaic environments (IPCC, 2001; Hood, 2010). Deltas and their coastal ecosystems have been widely altered due to the reduction of active distributary channels to support navigation and elaborated irrigation systems. Major deltas such as the Magdalena, Nile, Vistula, Yellow and Indus have experienced a considerable decrease in their distributary channel numbers. Nowadays significant less fluvial water and sediment discharge reaches the delta plains through their distributary connections to the ocean (Syvitski et al., 2009).

In Colombia, one of the best examples of discharge diversion and its ecological implications occurred in the Magdalena River delta and its lagoon system, the Ciénaga Grande de Santa Marta (CGSM). The Colombian government constructed a coastal highway along the entire length of a barrier island system in the delta front during late 1950s, thereby eliminating several important outlets through the barrier islands and restricting water exchange with the Caribbean Sea. To drain wetlands and to prevent floodwaters from reaching agricultural lands, dikes were built along the eastern bank of the Magdalena River during the 1970s. As a result, the flow from several tributaries of the Magdalena River to the mangrove forests

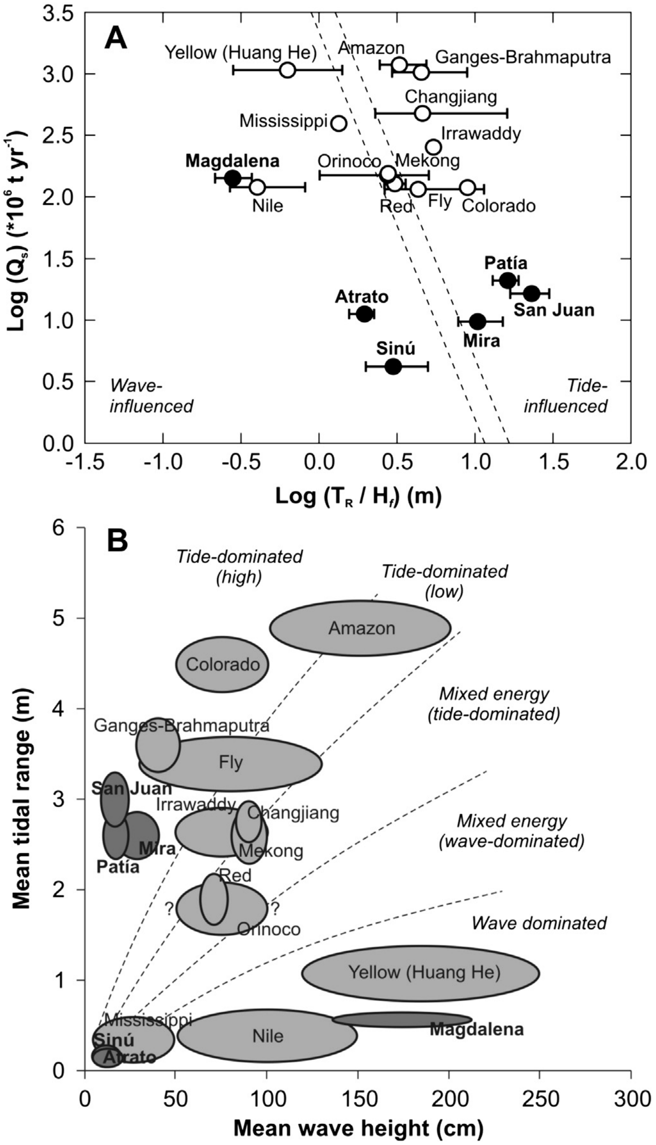

Fig. 2. (A) Classification diagram for major global deltas plotting mean tidal range/mean wave height versus log suspended sediment load. We also plot the classification of Colombian deltas, including the Patía River delta. The dashed lines divide the three types of deltas, including wave-influenced (left side), mixed tide and wave-influenced (center), and tide-influenced deltas (right side) (after Hori and Saito, 2007). (B) Mean wave height versus mean tidal range for major Colombian deltas. The regions are grouped into five morphological categories (after Hori et al., 2002; Restrepo and López, 2008).

was reduced or eliminated. Also, the diversion of water for agricultural irrigation has reduced freshwater runoff, while the erosion of deforested watersheds has led to ever-increasing sediment loads from the rivers (Polanía et al., 2000). The modification of hydrologic patterns and sedimentation processes in the CGSM has induced a gradual increase in salinity and total suspended solids and has altered the structure and abundance of mangrove ecosystems (Botero and Mancera, 1996). During the last 40 years, more than 70% of the original mangrove forest area has disappeared at an increasing rate of 1.5 ha yr^{-1} due to hyper-saline conditions. Nowadays most of the mangrove trees in western and northwestern areas of the CGSM are dead (Cardona and Botero, 1995).

In the Patía River delta (Fig. 1), a wood merchant constructed a 3 km-long channel (Canal Naranjo), which was dredged to connect the Patía Viejo tributary with the much smaller Sanquianga River to the north (Fig. 1C). This channel was built to transport wooden logs more easily from the Patía Viejo tributary to the Sanquianga River where most of the sawmills were located at this time, by means of a winch. Prior to the construction of the Canal Naranjo in 1972, the Patía Viejo distributary channel joined the Patía River at Fátima and the whole Patía River discharge flowed to Salahonda, the then active delta lobe in the southern part of the delta plain. After the diversion, the Sanquianga River, which was a small creek draining several internal lakes (Fig. 1C), started to increase its water discharge and became a river 700 m in width.

Located on the northern Patía River delta, the Sanquianga Mangrove National Park (SMNP), a highly productive ecosystem and the largest ecological reserve along the Pacific coast of South America is now part of the northern active delta plain. The mangrove complex, covering an approximate area of 800 km^2, comprises a large estuarine system from the current delta apex at Bocas de Satinga to the coast (Fig. 1C). The diversion of the Patía to the Sanquianga River through the Canal Naranjo has increased freshwater runoff and sediment load. The modification of hydrologic patterns and sedimentation processes in the SMNP has induced a gradual decrease in salinity and an increase in total suspended solids, altering the composition, distribution, zoning, and abundance of mangrove ecosystems.

In this paper, our goal is to provide an overview of the extent to which the discharge diversion of the Patía River has altered mangrove ecosystems across the delta. We also present major morphological variations along the delta front and active distributary channels due to this discharge diversion and changes in relative sea level. Finally, we discuss the role of land use and increasing trends in sediment load from the Patía drainage basin on the vulnerability of the Sanquianga Mangrove National Park.

Hydrologic variations alone can regulate certain ecological and evolutionary processes (e.g., Poff et al., 1997, 2006). However, a more complete view of the physical-biological linkage in rivers incorporates the interaction between hydrology and geomorphology. Geomorphic setting, including geology and topography, imposes boundary conditions that control shorter-term and local-scale hydrologic and geomorphic changes and processes such as erosion, transport and deposition. Together these create the physical structure and dynamics of fluvial ecosystems (Poff and Ward, 1990; Poff et al., 2006). The information presented here is a valuable tool to understand how natural and human-induced factors control the evolution of delta environments once hydrological thresholds push local environmental parameters beyond the thresholds for mangrove survival.

2. The Patía River delta

The morphology and recent evolution of the Colombian deltas (Fig. 1) are unique compared to other South American deltas because of their singular combination of extreme climatic, geological, and oceanographic conditions in which the deltas are built, including (1) high tectonic activity with the occurrence of shallow earthquakes and tsunamis (Kellogg and Mohriak, 2001); (2) narrow continental shelves with limited accommodation space (Correa, 1996) (Fig. 1A); (3) drainage basins that receive high rates of precipitation resulting in large quantities of water discharge and sediment load (Restrepo and Kjerfve, 2000); (4) the complexity of littoral dynamics resulting from micro and mesotidal ranges (Restrepo and Kjerfve, 2002; Restrepo et al., 2002), and the effect of significant swells and associated coastal currents (Restrepo et al., 2002); (5) strong oceanographic manifestations associated with the ENSO cycle, causing sea-level rises during El Niño years (Morton et al., 2000); and (6) increasing rates of relative sea level (Restrepo et al., 2002; Restrepo and López, 2008). It is worth noting that small rivers form extensive deltas along the Colombian Pacific coast, despite the occurrence of high energetic and destructive conditions.

The Patía (Fig. 1), with a sub-aerial area of ~1700 km^2, consists of distributary channels flanked by tropical humid forests, mangrove swamps, tidal flats, and barrier islands. The delta is characterized by high tectonic activity and progrades on a narrow shelf bordering a deep trench. Along the Colombian Pacific margin, the Nazca oceanic plate is converging with the South American continental plate at a rate of 54 mm yr^{-1} (Kellogg and Mohriak, 2001) (Fig. 1A). The convergence has produced an unstable coast characterized by the occurrence of large magnitude and shallow focus earthquakes. Severe earthquakes, accompanied by destructive tsunamis, impacted the Patía River delta in 1836, 1868, 1906 and 1979 (Pennington, 1981; Lockridge and Smith, 1984; Meyer et al., 1992; Kellogg and Vega, 1995; INGEOMINAS, 2007).

According to Restrepo and López (2008), the Patía delta is characterized by the interplay of (1) moderate wave conditions as a result of the effect of significant swells from the SW; (2) mesotidal ranges; (3) a steep subaqueous profile; and (4) a low attenuation index of deep-water waves. Overall, recent evolution of the Patía delta has been affected by a combination of factors: (1) high rates of rainfall (4700 mm yr^{-1}) which results in high fresh water discharge and sediment yield (1500 t km^{-2} yr^{-1}); (2) low discharge variability ($Q_{\max}/Q_{\min}$); (3) a relative sea-level rise of 5.1 mm yr^{-1} after the occurrence of the 1979 tsunami; (4) ongoing high tectonic activity in the receiving basin; (5) the occurrence of non-storm overwash on barrier islands associated with ENSO sea-level anomalies; and (6) the spatial switch of delta distributaries related to tectonic-induced subsidence and human impacts.

The Patía delta lies along the southern part of the Colombian Pacific coast, just north of Tumaco Bay (Fig. 1C). The Tumaco Bay–Patía delta area is located on the Tumaco segment (Orozco, 2004), which is the southernmost portion of the Atrato-Tumaco terrain (Etayo-Serna, 1983). The region is dominated by a Miocene sedimentary belt of marine successions of sandstones, siltstones and claystones of the Guapi and Naya formations (Correa and González, 1988). This sedimentary belt has a NNE regional trend and extends from Buenaventura Bay, where it is covered by recent alluvial sediments and tilted towards the west, to near Tumaco Bay, where it is more compressed and uplifted. From the delta plain to the basin's upper reaches, the area is characterized by Plio-Pleistocene fluvial-volcanic and massive Cretaceous volcanic-sedimentary sequences and andesitic lavas produced by the recent vulcanism of the western cordillera (Arango and Ponce, 1982).

Along the coastal zone, the sedimentary belt is expressed in a series of NNE-oriented structures that gradually decrease in relief north of Tumaco Bay. South of Buenaventura, the Cenozoic rocks lay sub-horizontally without any marked compressing effects that could produce a narrow folding (Gómez, 1986a). In contrast, the faulting and folding of the sedimentary sequence south of the Patía River delta have produced a series of hills with Tertiary rocks of the Guapi and Naya formations (Arango and Ponce, 1982; Gómez, 1986a) (Fig. 1B). In the area, transcurrent faults parallel to the coastline have been documented, including the Buenaventura and the Naya-Micay, both located to the north of the Mira delta, and the Remolino-El Charco fault within Tumaco Bay (Arango and Ponce, 1982; Gómez, 1986b; Cediel et al., 2003). This active transcurrent faulting has been associated with several transverse Cretaceous paleofracture zones (Case et al., 1971), including the Tumaco fault (Gómez, 1986a) and the paleofracture in the northern part of the Patía delta. The latter coincides with a submarine canyon at the Sanquianga mouth (Fig. 1B and C).

3. Data and analysis

Daily water discharge and suspended sediment load data (1969–2003) were obtained at 4 sites along the Patía River from the Hydrological Institute of Colombia, IDEAM (IDEAM, 2009) (Fig. 3). In addition, we took measurements of water discharge at two river cross-sections in the apex of the delta at Fátima during December 2009 (Fig. 1C). Water discharge measurements were obtained from velocity profiles measured with one Nortek acoustic wave and current meter AWAC. The measurements and cross-sectional integration were done following the USGS routine (Buchanan and Somers, 1969).

Morphometric variables (drainage basin area, relief and longitudinal profile) of the selected distributary catchments of the Patía basin were obtained from Shuttle Radar Topography Mission data (3′ horizontal and 1 meter vertical resolution), with an uncertainty ranging from ±1.1 to 2 m in the lowlands to ±6 m in the highland regions (Farr et al., 2007; Berry et al., 2007). River network patterns were explored to assess patterns of sediment retention throughout the river network. Basin-averaged temperature and precipitation

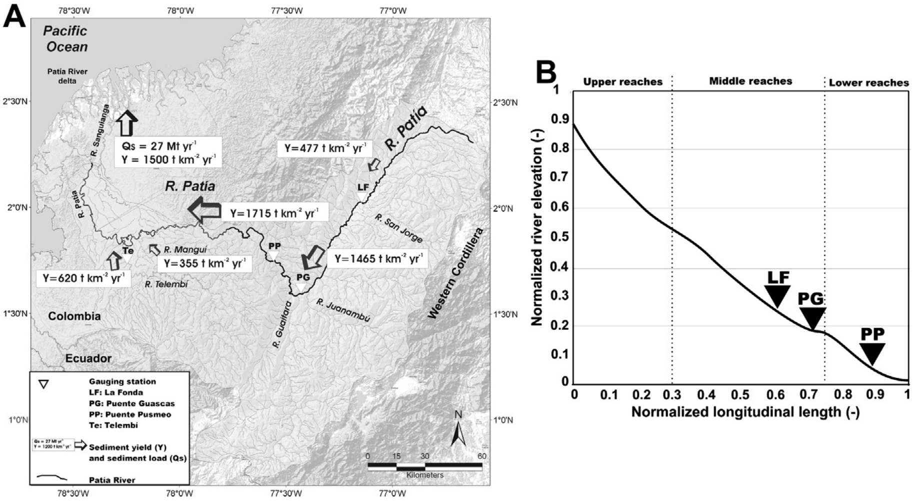

Fig. 3. (A) Map of the Patía River drainage basin, showing the principal tributaries, the four hydrological stations (triangles) where water discharge and sediment load were gathered, and the main sediment load values at the upper, middle and lower reaches of the Patía River (arrows). (B) Longitudinal profile of the Patía River, showing the location of main hydrological stations. It is worth noting the limited alluvial plain to trap sediments.

data were assessed using HidroSig Java (version 1.8) climate archives (HIDROSIG, 2006), which include all existing hydrological and meteorological databases of Colombia.

To assess morphological changes along the delta front and distributary channels and how delta environments have changed during the last four decades, after the channel diversion occurred in 1972, 30 m pixel resolution Landsat 7 satellite images from 1986, 1987, 1996 and 2001, obtained from the Global Land Cover Facility of the University of Maryland, were processed. The images were rectified to 1:25,000 topographical maps (Geographic Institute of Colombia, IGAC) after establishing ground control points. Detailed temporal analyses of distributary channel morphology at the diversion site and the SMNP were documented using aerial photographs from 1962 and 1986 at scale 1:40,000, topographic maps at scale 1:25,000, and interviews with inhabitants. In addition, we analyzed how delta morphology has changed during the past century by using a French Navy chart from 1875 and a local map from 1924.

To compare and contrast the physical changes occurring in the delta distributaries and associated environments, field observations were carried out along five main distributaries and their inlets, Sanquianga, Guascama, Pasacaballos, Majagual and Salahonda. Additional measurements at six stations along the delta front, south from the main current distributary channel, the Sanquianga River and its inlet, were obtained. The measurements consisted of (Fig. 1C): (1) time series observations of currents, wave parameters, and water level elevation at six stations in the Patía delta front using two Nortek acoustic wave and current meters AWAC (including pressure sensors with resolution of 0.25%); and (2) time series measurements of salinity, temperature and depth (CTD) along profiles up to 30 km seaward of the delta front mouth at a maximum depth of approximately 60 m, to investigate the stratification of water masses and plume front dynamics. Also, longitudinal measurements of vertical profiles of conductivity and temperature were taken along the Sanquianga, Guascama and Amarales distributaries from the entrance to the apex at Bocas de Satinga, to obtain a quasi-synoptic characterization of the longitudinal salinity distribution and the corresponding vegetation association (Fig. 1C).

In addition, hourly sea-level data were obtained from the tidal gauge at Tumaco (1953–2006) (IDEAM, 2007) (Fig. 1C). The sea-level data is approximately 94% complete and missing data are interpolated with harmonic analysis (Franco, 1988, 1992). The trend in relative sea level in the Patía delta is estimated by least-squares linear regression for the Tumaco time series.

4. Results and discussion

4.1. Water discharge and sediment load into the delta plain

The Patía River catchment with an area of 23,700 km^2 has the largest drainage basin of the Colombian rivers draining into the Pacific (Fig. 3A). Based on daily stage measurements from 1969 to 2003, the Patía River as gauged at Puente Pusmeo (Fig. 3) discharges on average 322 m^3 s^{-1}, with a seasonal root mean square (rms) of 80 m^3 s^{-1}. Peak flows exceeding 450 m^3 s^{-1} are observed during La Niña years 1973, 1984, and 2000, while low discharges below 300 m^3 s^{-1} are observed during El Niño years 1972 and 2001 (Fig. 4A). The mean river discharge into the delta plain is 1320 m^3 s^{-1} because of the large contribution of the Telembí River, the last tributary before the delta (Fig. 3A).

Based on daily sediment load data from 1972 to 2001 by IDEAM, sediment loads from the upper river measure 0.92, 16.2, and 13.9 × 10^6 t yr^{-1}, as gauged at La Fonda, Puente Guascas, and Puente

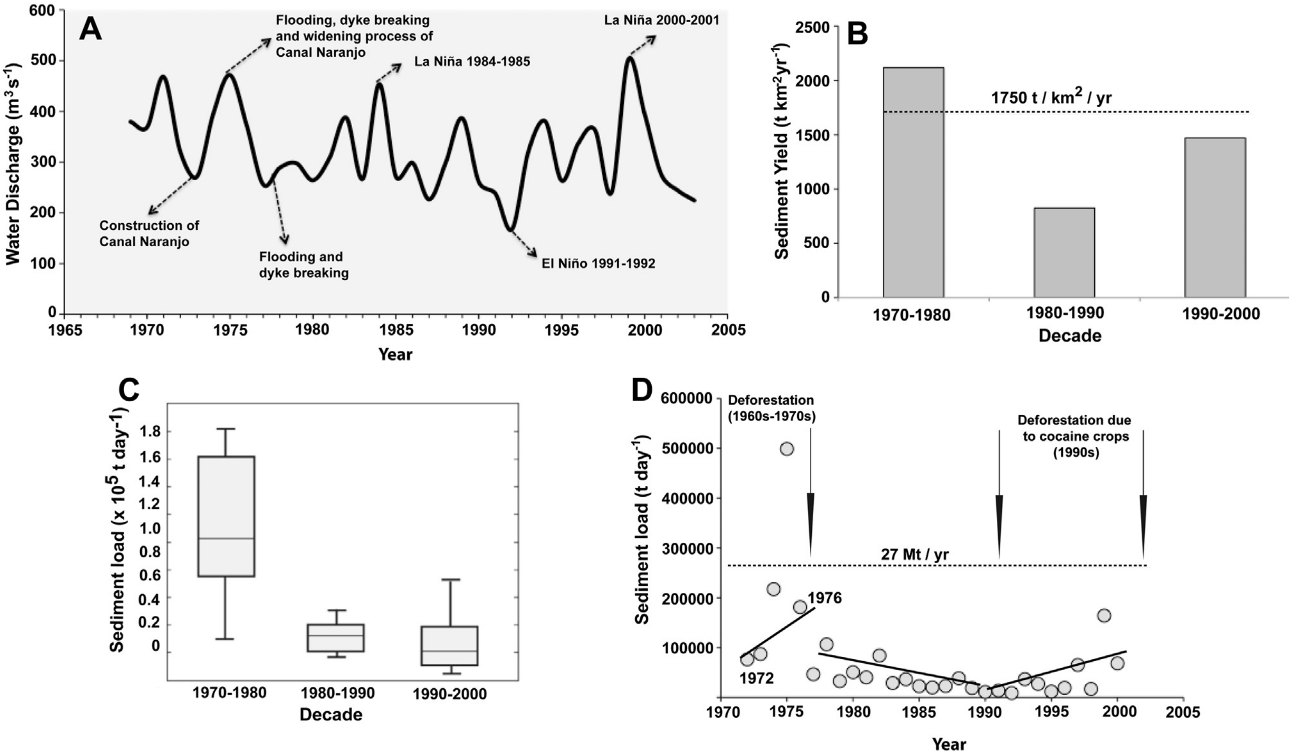

Fig. 4. Water discharge and sediment load variability for the Patía River at Puente Pusmeo. (A) River discharge data for the 1967–2002 yr-period. (B) Decadal variability of sediment yield. (C) Box-whisker plots annual sediment yield during the three analyzed decades in the lower reaches of the Patía River, showing the medians, 25th percentiles, 75th percentiles. (D) Scatter plot of annual sediment load at Puente Pusmeo for the 1972–2000 yr-period. The location of the hydrological station at Puente Pusmeo is shown in Fig. 3A.

Pusmeo, respectively (Fig. 3B). The corresponding sediment yield ranges from 477 t km^{-2}oyr^{-1} at La Fonda to 1715 t km^{-2} yr^{-1} at Puente Pusmeo for the most downstream portion of the river (Fig. 3A). The latter yield, which represents 60% of the whole catchment area, does not express the conditions of deposition and storage that occur in the entire basin. To remedy this, we further estimated sediment load for the non-gauged area of the Patía River from the regression of sediment yield on basin area from gauged stations. The mean sediment yield for the watersheds of Telembí and Magui rivers are 620 t km^{-2} yr^{-1} and 355 t km^{-2} yr^{-1}, respectively. Our best estimate of sediment load into the Pacific Ocean from both gauged and non-gauged Patía distributaries is 27 Mt yr^{-1}. This results in a sediment yield of 1500 t km^{-2} yr^{-1} (Fig. 3A).

Climate determines where tropical weathering occurs, while tectonics increases erosion rates and dictates the composition of erosion products (Stallard, 1988). Drainage basins with intense tectonic activity usually have high sediment yields (Meade, 1988; Milliman and Syvitski, 1992), as in the case of Colombian Pacific rivers (Restrepo and Kjerfve, 2000). Besides climate and weathering factors, other processes such as landslides lead to slumps that increase sediment loads. In humid uplands, landslides are the dominant mass wasting process (Hovius et al., 1997; Hovius, 1998). The Patía drainage basin is characterized by the presence of active fault systems, high precipitation rates, slopes frequently steeper than 25°, and dense tropical rain forests (West, 1957; Correa, 1996). According to Hovius et al. (1997), these conditions are favorable to the occurrence of rapid mass wasting caused mainly by hillslope erosion processes such as landslides, slumps and slides.

In addition to natural forces controlling sediment load from rivers, human activity can be an effective geologic agent in altering the landscape and affecting river erosion and delivery. Although the anthropogenic impact on global fluvial sediment fluxes cannot yet be calculated with any degree of accuracy, human activity may be directly or indirectly responsible for 80–90% of the fluvial delivery to the coastal ocean in regions unaffected by the trapping of sediment by reservoirs (Douglas, 1996; Farnsworth and Milliman, 2003). In contrast to the decreased erosion and sediment transport by rivers in much of the developed western world, erosion is increasing throughout many developing countries (Syvitski, 2003). Colombia is not an exception (Restrepo and Syvitski, 2006). For the Patía drainage basin, many human-induced drivers, including deforestation and land conversion due to agricultural and mining practices, may have accounted for the overall increasing trends in specific sediment yield.

The Patía River shows high decadal variability in sediment yield (Fig. 4B). Between 1972 and 1980, average sediment yield was 2200 t km^{-2} yr^{-1}. One of the human-induced drivers of this high sediment yield is deforestation. Since the 1960s, the Colombian government has given many licenses to big companies such as Cartón de Colombia and Maderas Pizano, among others, to cut off forests in the Patía drainage basin and its delta. According to the National Department of Statistics (Dane, 2003), 60% of the wood production in the country came from the Patía region. In contrast, the average sediment yield decreased to 825 t km^{-2} yr^{-1} during the 1980s. Since most of commercial forests in the catchment were cut off, many sawmills went out of business. In Bocas de Satinga, along the Sanquianga River (Fig. 1C), there were more than 40 sawmills during the seventies. Nowadays, only two sawmills remain. After using up most of the wood resources, an economic downturn was evident in the region. Since 1991, the average sediment yield has increased to 1470 t km^{-2} yr^{-1} (Fig. 4B). Expansion of the area of deforestation due to cocaine crops in the Patía catchment and its main downstream tributary, the Telembí River (United Nations Report, 2008), has apparently led to increased sediment yield (Fig. 4b). The statistical parameters of annual sediment yield during the three analyzed decades in the lower reaches of the Patía River are shown in a box-whisker plot (Fig. 4C). The medians, 25th percentiles, 75th percentiles, and maximum values indicate high decadal variability during the 1970–1980 and 1990–2000 yr- periods. The Patía River has witnessed increases in sediment load between 1972 and 1975. However, it shows a decrease in sediment flux between 1976 and 1990, with an average load of 11 MT yr^{-1} over the period. Since 1990, the average load has increased to 17 MT yr^{--1}. Expansion of the area of land conversion over the 1990–2000 yr-period has apparently led to increased sediment transport (Fig. 4D).

4.2. Discharge diversion in the Patía River

Prior to the construction of the Canal Naranjo in 1972, the Patía Viejo distributary channel joined the Patía River at Fátima and the whole Patía River discharge flowed to Salahonda (Fig. 1C). The Sanquianga River, which was a small creek draining several interior lakes (Fig. 5), started to increase its water discharge from approximately 50–1500 m s^{-1} (Bateman et al., 2009). A large flood triggered by a La Niña storm event in 1973 (Fig. 4A), caused a dike to collapse, such that the Canal Naranjo could start its widening process. The discharge diversion, which started at this flooding event, became even larger during an additional flood in 1977 (National Report of Defensoría del Pueblo). In addition, tectonic activity in the Patía River's drainage basin along an active fault increased the discharge diversion of the Patía River even more as a result of the 1979 earthquake. When the 1979 seismic event struck, the vertical elevations changed, and the Sanquianga River captured approximately 70% of the Patía River's discharge (Soeters and Gómez, 1985; Velásquez et al., 1994). After 1990, more than 80% of the Patía River discharge was redirected through the Canal Naranjo – Patía Viejo tributary – to the Sanquianga River system (Fig. 5). This discharge diversion left the southern delta plain under sediment starving conditions and reduced the fresh water flows. Currently, the Sanquianga River, discharging into Bocas de Satinga to the north (Fig. 1C), now carries more than 90% of the Patía River flux (Bateman et al., 2009).

Fig. 5 shows the morphological variations of the Patía and Sanquianga rivers at the diversion site. In 1962, there was no connection between the two rivers and the Patía Viejo was an active and meandering distributary channel. In 1978, after the Canal Naranjo was excavated, the Patía migrated towards the Sanquianga River. At this time, the Patía Viejo was an active branch with flow connection to the Sanquianga River. In 1986, the bifurcation continued active (see number 1, Fig. 5), but the channel morphology shows that discharge was approximately shared, half and half. In 1997, however, the Patía River showed less hydraulic capacity and sediment accumulation created elongated bars at the entrance to the Patía River. The new branch, now formed by the Patía and Sanquianga, named in the region Patianga, became a large river. Currently, the Patianga transports nearly all water discharge and its width is of the same magnitude as the former Patía River width.

Our measurements of water discharge at the Patía River cross-section during December 2009 (Fig. 1C) show that the average water discharge before the diversion site in Fátima is 1100 m^3 s^{-1}. Further measurements indicate that a small fraction of water discharge, only 84 m^3 s^{-1} flows to the old Patía branch. Thus, the Sanquianga River carries almost the whole Patía River flow. It is worth noting that measurements were taken at the beginning of rising levels in December, a period that coincides with the rainy season in the Patía River drainage basin.

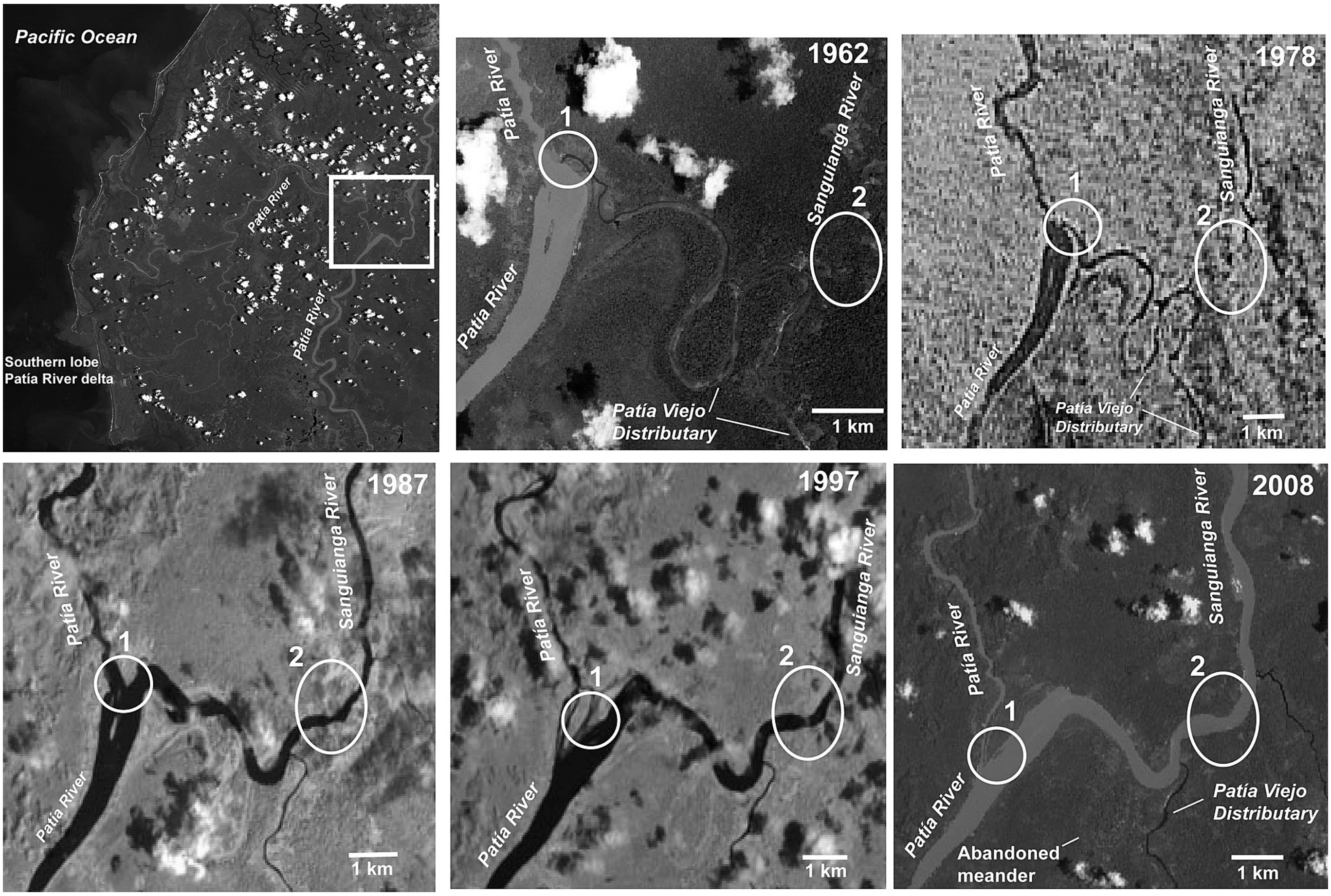

Fig. 5. Aerial photographs 1962–1978, Landsat satellite images 1987–1997, and Aster image from 2008, showing major morphological changes at the channel diversion site. Observe the widening process of the Sanquianga River and the confined flow of the Patía.

4.3. Morphological changes 1875–2001

During pre-Anthropocene times, river distributary channels often changed their location and pattern due to natural forces. In many deltas and throughout the recent Holocene, river distributary channels migrated across the delta plain, episodically switching their position and further aggradation delta lobes (Syvitski et al., 2009). Along the Pacific coast of Colombia (Fig. 1A), the overall southward displacement of the main delta tributary channels has been associated with the presence of active transcurrent faulting associated with several transverse paleofracture zones (Gómez, 1986a,b; Correa, 1996; González et al., 2002; Restrepo et al., 2002) (Fig. 1B). Evidence of paleochannels also suggests that delta distributaries have undergone rearrangements due to seismic movements (Gómez, 1986a). Tectonic activity in the Pacific deltas of Colombia has caused most of the active distributaries to switch their direction from northerly to southerly (Correa and Restrepo, 2002; Restrepo et al., 2002).

In the Patía delta (Fig. 6), geologic evidence indicates that the active delta lobe shifted to the south in the Quaternary, probably as a result of tectonic activity (Gómez, 1986a,b). Since then, the accreting delta front is located in the southern portion of the delta plain. The northern part became an estuarine system characterized by large extensions of mangrove ecosystems, little fresh water inflow and no significant fluvial sediment load from the western Andes.

Evidence of a paleo-canyon in the Patía delta suggests that the main channel of the Patía River was located at the northern delta lobe (Fig. 6C). Transcurrrent faulting associated with several transverse paleofracture zones, including the Tumaco fault and the Patía River alignment (Fig. 1B), may have influenced the discharge displacement from the northern tributary emptying into Bocas de Satinga to the Old Patía branch (Fig. 6D). Analysis of delta morphology between 1875 and 2001 indicates major morphological changes during this 126-year period (Fig. 6), including: (1) flow diversion from the Patía River to the Sanquianga River; (2) widening of the Sanquianga River; (3) narrowing of the Old Patía branch due to confined fluvial flows; (3) distributary channel abandonment at the former delta apex; (4) narrowing of inlets at the southern delta lobe, formation of ebb tidal deltas, and overall retreat conditions in the delta front; (5) coastline erosion at the former northern tributary, the Pasacaballos inlet; (6) active sedimentation at the new delta apex, Bocas de Satinga; and (7–8) migration of active fluvial discharge points from the southern delta lobe to the new active delta lobe. The barrier islands present in 1875 at Sanquianga and Amarales were accreted to the main delta lobe. Also, there is an evident widening of active distributary channels and overall frontal accretion of the Sanquianga River mouth (Fig. 6B and D).

4.4. Delta geomorphology, channel diversion and vegetation change

The overall vegetation distribution in the delta corresponds to specific geomorphic settings. Similar to other deltas along the Pacific coast of Colombia (see West, 1957; Restrepo et al., 2002), the communities are distributed landward in five main morphological

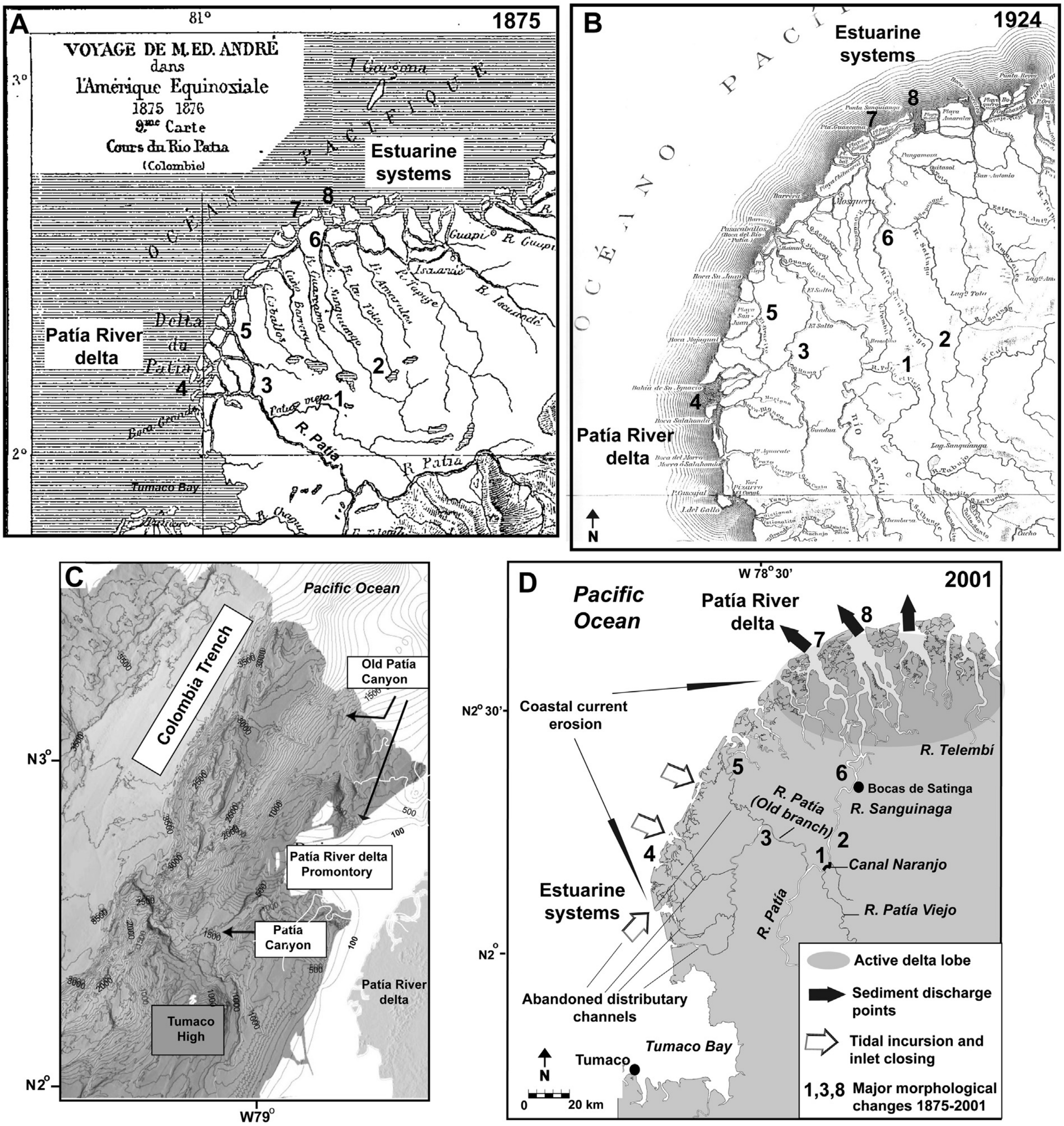

Fig. 6. Analysis of major morphological changes in the Patía delta from 1875 to 2001 based on a French Navy chart (1875) (A), a local map from 1924 (B) and a Landsat image from 2001 (D). (C) We also show major bathymetric features in front of the Patía delta promontory, including the old canyon in the northern delta lobe and the current canyon in the southern delta front (Modified from Collot et al., 2005).

units, including backshore, beach ridge system, and tidal flats with mangrove, transitional swamps, and freshwater swamps in the distributary channels. The representative vegetation species, comprising each morphological unit, are shown in Table 1.

Frequency inundation and longitudinal salinity distribution have major effects on mangrove distribution. Salinity intrusion varies primarily with freshwater discharge, which controls inundation, substrate composition, and distribution of fringing vegetation within the distributary channel network in tropical deltas (Vann, 1959a,b; Thom, 1967; Restrepo and Kjerfve, 2002). Along the former active distributary channels on the southern delta lobe, maximum mangrove intrusion is ∼6 km upstream (Fig. 7), and vegetation succession from freshwater to brackish conditions is characterized by: (1) association of freshwater forests; (2) a brackish zone where salinity varies between 4 and 8‰, the mangrove *Mora oleifera* is associated with palms and trees typical of freshwater swamps; and (3) near the mouths, red mangrove communities of *Rhizophora* occupying channel banks and black mangrove *Avicennia* present in higher and drier habitats.

In the northern delta lobe, the Sanquianga area, an estuarine zone characterized by the presence of well-developed belts of *Rhizophora* and *Avicennia* along the edge of the estuarine lagoons and tidal channels, became an active distributary system after the channel diversion of the Patía River. Longitudinal measurements of vertical profiles of salinity (psu) along the main axis of distributary channels, including Sanquianga, Guascama and Amarales (Fig. 1C), show clear dependence on the discharge pattern of the deltaic plain. Prior to the channel diversion, the 1 salinity interface at the

Table 1
Main vegetation associations present in each morphologic unit in the Patía River delta.

Morphologic unit	Environment interpretation	Vegetation species/associations
Backshore (Bck)	Along berm crests on prograding beaches. Occupied by halophyte species that tolerate adverse environmental conditions, including salt spray and wave splash, and limited supply of nutrients.	*Canavalia maritima* *Ipomoea pes-caprae* *Ipomoea stolonifera* *Pectis arenaria* *Cenchrus pauciflorus* *Gynerum sagittatum*
Beach ridge system (Br)	Along sandy barrier islands and broad, low, shore-parallel, and heavily vegetated beach ridges. Floristic groups, which are distributed in swales (troughs) and ridges form this unit.	*Symphonia globulifera* *Mora megitosperma* *Euterpe cuatrecasana* *Campnosperma panamensis* *Dyalyanthera* spp. *Virola* spp. *Cecropia* spp. *Apeiba aspera* *Ficus* spp.
Tidal flat with mangroves (Ms)	Lower part of the estuarine mixing zone, including delta front, estuarine lagoons, and tidal and tributary channels.	*Rhizophora harrisonii* *Avicennia germinans* *Laguncularia racemosa* *Pelliciera rhizophorae* *Mora oleifera*
Transitional swamp (Ts)	Behind beach ridges and intertidal mangrove swamps and tidal channels; only flooded by spring tides every month.	*M. oleifera* *Rhizophora mangle* *A. germinans* *Mora oleifera* *P. rhizophorae* *Symphonia globulifera* *Pachira aquatica* *Pterocarpus officinalis* *Euterpe cuatrecasana* *Socratea exorrhiza* *Manicaria saccifera* *Mauritia pacifica* *S. globulifera* *C. panamensis* *Dyalanthera* spp.
Fresh water swamps (Fws)	Along tributary channels without salinity. It is an indicator of the end of the mixing estuarine zone where mangrove species are not present.	All species of *beach ridge system* and *transitional swamp* units.

bottom intruded 27 km further upstream up to Bocas de Satinga, the current delta apex. Nowadays the 0 salinity interface near the bottom was found 18, 15 and 14 km upstream on the Sanquianga, Guascama, and Amarales distributaries, respectively. The longitudinal salinity distribution qualitatively reflects the amount of freshwater discharged by the Sanguinga River. Also, the effect of increased freshwater after the channel diversion is to flush out the wedges of saline waters from the main distributary channels. In contrast, abandoned distributaries of the former Patía delta, which currently lack fluvial flows for at least 8 months each year, posses more saline waters and exhibit salinity distributions further upstream (Fig. 7A).

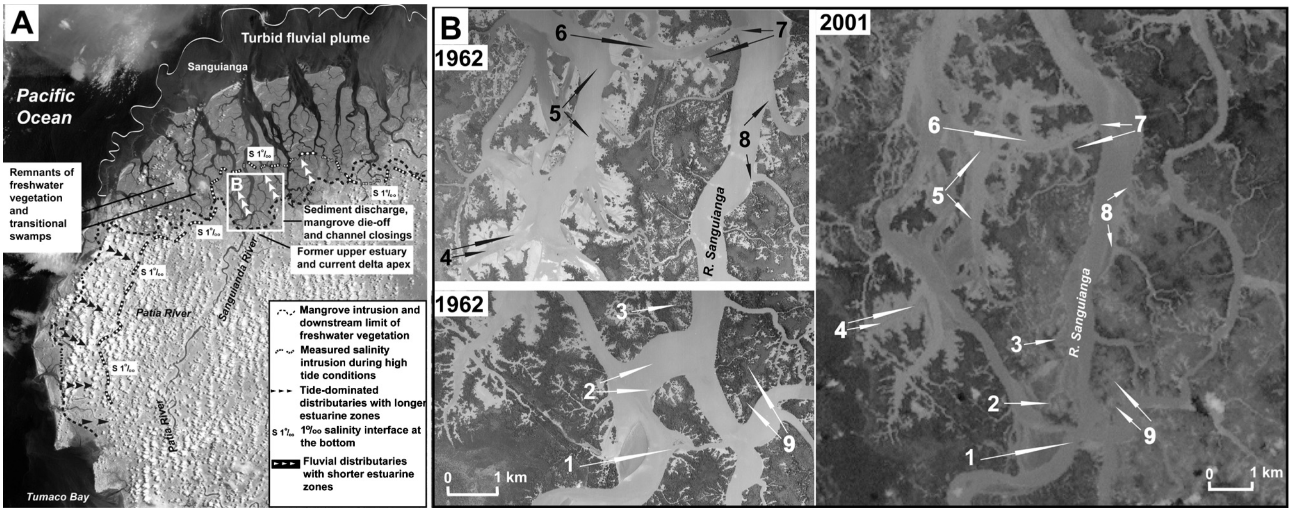

Fig. 7. (A) Aster image from 2008, showing major longitudinal limits of salinity intrusion and downstream limits of freshwater vegetation. (B) Temporal analysis of morphological changes at the current delta apex, Bocas de Satinga, based on aerial photographs from 1962 and a Landsat image from 2001. Numbers indicate major areas of sedimentation and channel fills in the Sanquianga distributary channel and associated tidal creeks. Areas of dead mangrove are also shown (number 9).

Habitats for plant growth in deltas are constantly changing as a result of the interaction of physical forces, which cause the formation or decay of topographic forms. Changes in the areas of sedimentation and freshwater discharge, subsidence, compaction, and sea-level rise are some of the most important controls affecting vegetation distribution in any delta plain. Given the tendency for mangrove species to prefer a given habitat, it is to be expected that with changes in the physical environment there will be corresponding changes in the pattern of mangrove distribution (Thom, 1967).

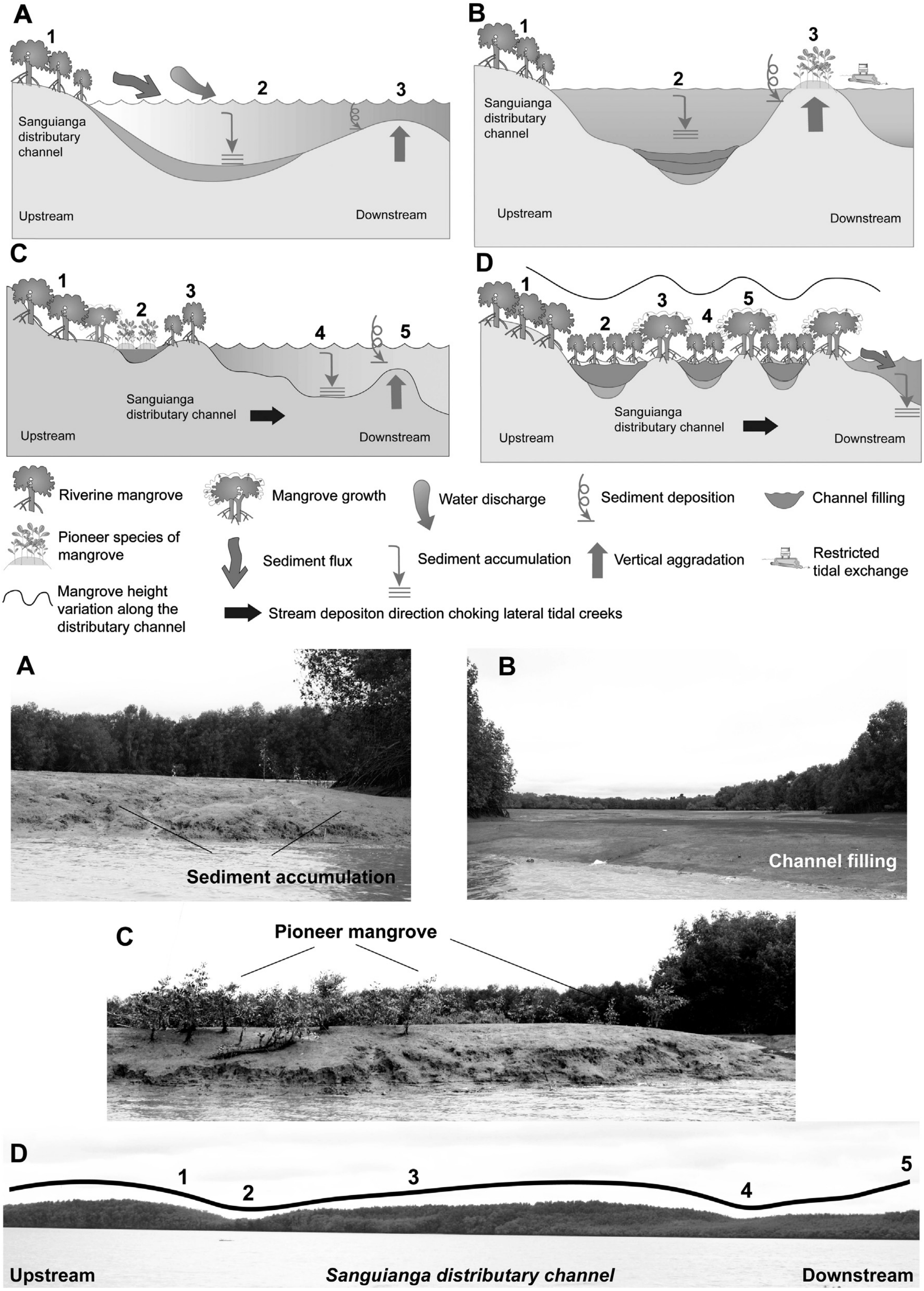

Fig. 8. (A–D) Stages of channel lengthening and corresponding sequences of mangrove colonization along the Sanquianga distributary channel.

One of the main factors controlling the dynamic ecology of mangroves in deltas is the shifting process of areas of active sedimentation and freshwater discharge. The favored channel at any time, receiving increased upstream flow, gradually widens and becomes the main hydraulic outlet of the deltaic plain. Further channel lengthening involves the occupation of numerous distributaries and consequent migration of points of active sedimentation. This process has been widely documented in the Mississippi delta (Fisk, 1952; Morgan et al., 1953), the Tabasco delta in Mexico (Thom, 1967) and along the Guyana coast of South America (Vann, 1959b).

Fig. 7B shows major morphological changes that occurred in the current delta apex at Bocas de Satinga between 1962 and 2001. As a result of the channel diversion, the Sanquianga River is receiving most of the Patía sediment load. The migration of the active distributary channel from the southern lobe to the northern delta plain has led to active sedimentation, overbank flow, increasing width of levees, sedimentation in crevasses, interdistributary channel fill, and further lengthening of the Sanquianga River, the current main distributary channel.

We have inferred from the present mangrove distribution in the Sanquianga River several stages in the process of channel lengthening and the corresponding sequence of vegetation change (Fig. 8): (A) during the seaward advance of the Sanquianga distributary channel, submerged levees gradually emerge above sea level due to active sedimentation of fine sediment deposited by overbank flow; (B) pioneer mangroves start to colonize the fine sediments of levees and mudflats, particularly those areas which are exposed during low tide conditions. Once the levee height above low water level reaches its maximum, the process of channel fill in the interdistributary channel begins; (C) once the interdistributary channel fill is completed, pioneer mangroves colonize the

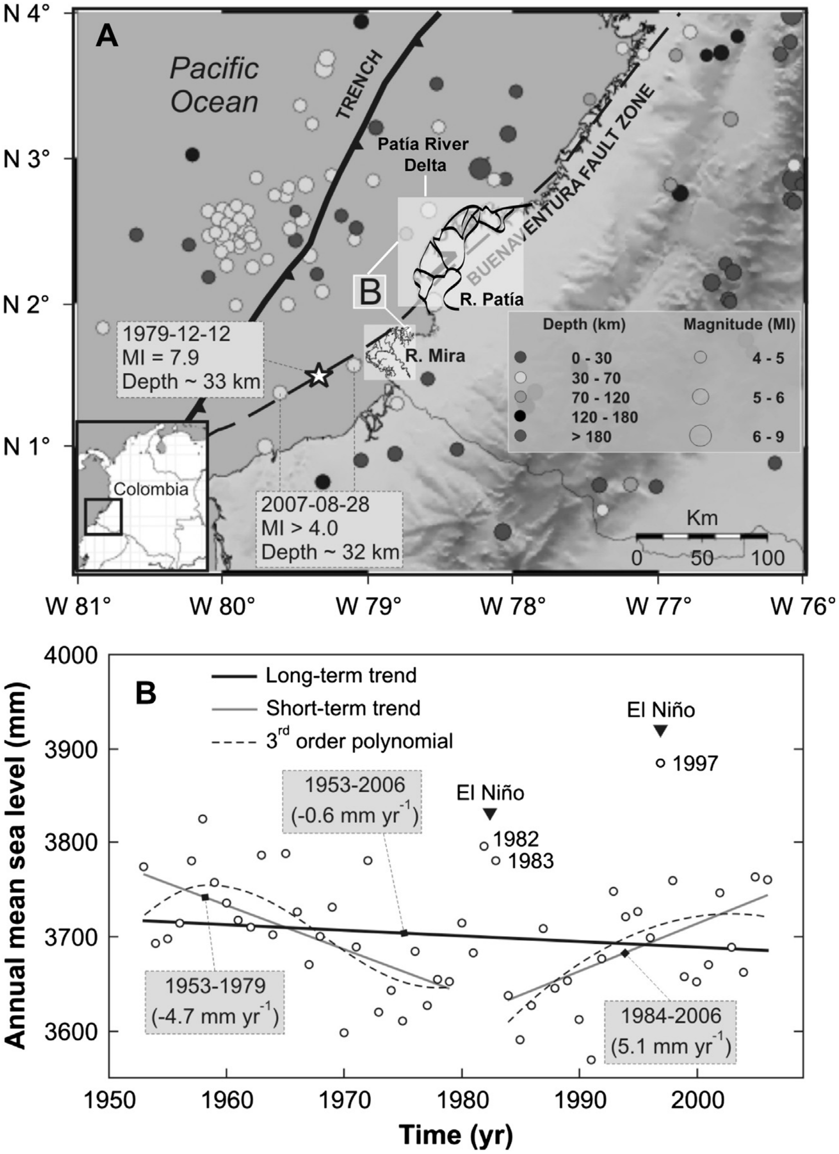

Fig. 9. (A) Location and magnitude of earthquakes that occurred in the southern Colombian Pacific between 1993 and 2007. More than 120 seismic events with magnitudes (Ml) greater than 4, were recorded by the Geological Survey of Colombia between 1993 and 2007 (INGEOMINAS, 2007). We also show the locations of two recent seismic events (August 2007) and the tsunami (December 1979) (white star) that impacted the Patía delta coast. (B) Mean relative sea level (mm) from Tumaco, Pacific coast of Colombia (IDEAM, 2007), showing the trend for the 1953–2006 period with slope = $-0.6\ \mathrm{mm\,yr^{-1}}$ (bold line) and the short-term trends (grey line) for the 1953–1979 period (slope = $-4.7\ \mathrm{mm\,yr^{-1}}$) and 1984–2006 period (slope = $5.1\ \mathrm{mm\,yr^{-1}}$). Solid triangles indicate the occurrence of two major El Niño sea-level anomalies in 1982–1983 and 1997, which were removed from the analysis.

lateral channel; (D) the stages A, B, and C continue progressively downstream and the banks of the Sanquianga River show the sequence of longitudinal advance as seen by the periodic lows and highs of mangrove heights along the channel (Fig. 8D).

We assume that this process of distributary channel advance was actively initiated after the diversion event started 37 years ago. According to local inhabitants, the colonization and further growth of these mangrove communities took place in approximately 30 years and sedimentation from the delta apex at Bocas de Satinga to the Sanquianga River became more pronounced since the 1990s (Fig. 5). Although the conditions of channel diversion shifted the sedimentation from the Patía River to the Sanquianga, giving the constructive conditions for mangrove colonization, the increased water discharge has freshened the former estuarine system and created different hydrologic conditions with further ecological implications. This latter situation will be discussed later.

The processes of mangrove colonization on active and accreting distributary channels have been well described in the Tabasco delta in Mexico (Thom, 1967). In general, long-term changes are dictated by physiographic processes in the delta plain, which influence the degree of water saturation of the soil, salinity distribution, soil type, and drainage patterns of landforms. These long-term changes may be interpreted as cyclic fluctuations with freshwater communities of flora giving way to mangrove communities, when the area of active sedimentation shifts elsewhere. Under continuous subsidence and compaction, mangrove areas become wetter, peats develop, more water-tolerant plants spread laterally, and lagoons and tidal creeks enlarge where the rate of organic accretion cannot keep up with subsidence. In this way, a gradient will be created and the focus of sedimentation and freshwater discharge may shift, inducing changes in the vegetation distribution. Another cycle will then be initiated.

4.5. Mangrove erosion due to tectonic-induced subsidence and channel diversion

Along the Patía delta front, more than 20 earthquakes with magnitude 4–6 occurred within 200 km of the shoreline from 1993 to 2007 (INGEOMINAS, 2007) (Fig. 9A). In addition, the most intense earthquakes during the 20th century occurred in 1906 and 1979, and caused both regional and local subsidence. During the tsunami in 1979, coastal areas of the Patía delta, including San Juan de la Costa and the northern distributaries at Sanquianga (Fig. 1C), subsided as much as 1.6 m, causing an apparent sea-level rise along at least a 200 km stretch of the Colombian coast north of the Ecuadorian border (Herd et al., 1992; Correa and González, 2000).

It is well documented that when relative sea level increases, deltaic lowlands become more vulnerable to inundation, flood events and erosion (e.g. Day et al., 1995; Ericson et al., 2006). In the Pacific deltas of Colombia there are no quantitative measurements of recent coastal subsidence to verify tectonic subsidence. However, few qualitative evidences in the Pacific deltas suggest that subsidence is occurring on this part of the coast (Restrepo et al., 2002), including (1) the correspondence of increasing trend in relative sea level with tectonic setting (Fig. 9B), (2) the increased occurrence of non-storm washover events and earthquake activity, and (3) transgressive barrier islands with exposed peat soils on the beach front (Figs. 10 and 11).

The trend in relative sea level was estimated by least-squares linear regression for the Tumaco 1953–2006 time series (Figs. 1C and 9B). In Tumaco the relative sea-level rise measured $-0.6\ \mathrm{mm\ yr^{-1}}$ in the 1953–2006 period, indicating a decreased trend in sea level for the 53 yr-period. However, an increasing trend in relative sea level of $5.1\ \mathrm{mm\ yr^{-1}}$ is observed for the 1984–2006 period, after the occurrence of the 1979 tsunami (Fig. 9B).

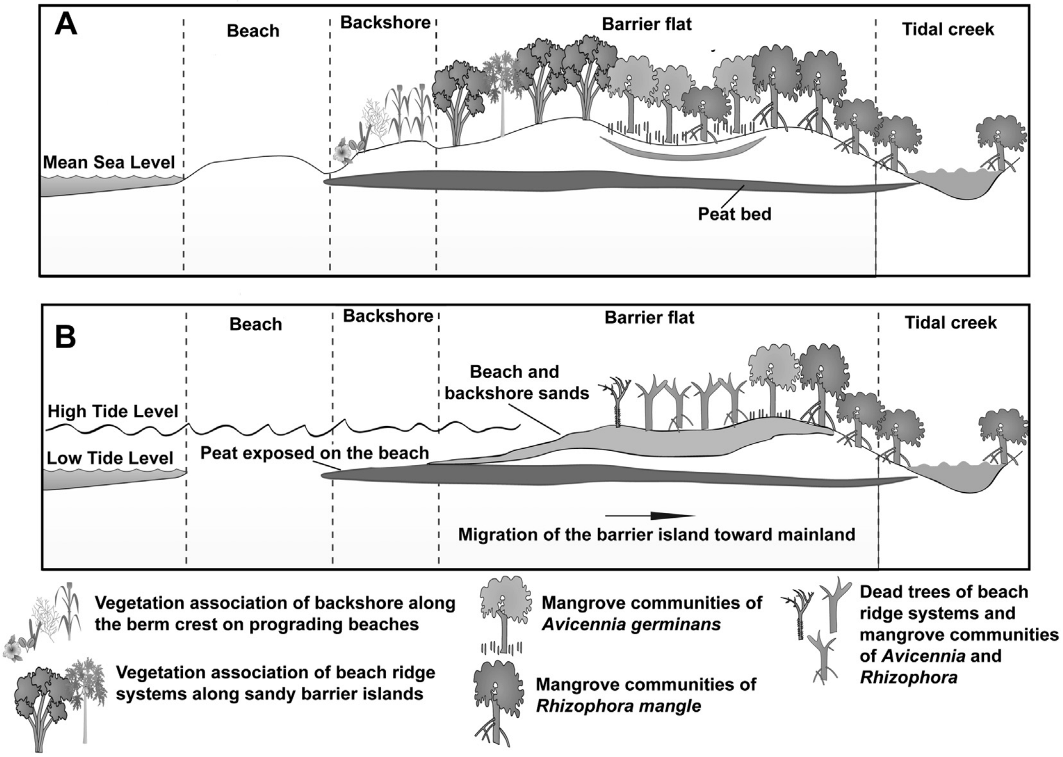

Fig. 10. (A) Scheme of a transgressive barrier island along the southern lobe of the Patía delta. (B) Due to tectonic-induced subsidence and sediment starving conditions after the channel diversion in 1972, transgressive barrier islands migrate landward and peat soils become exposed on the oceanfront.

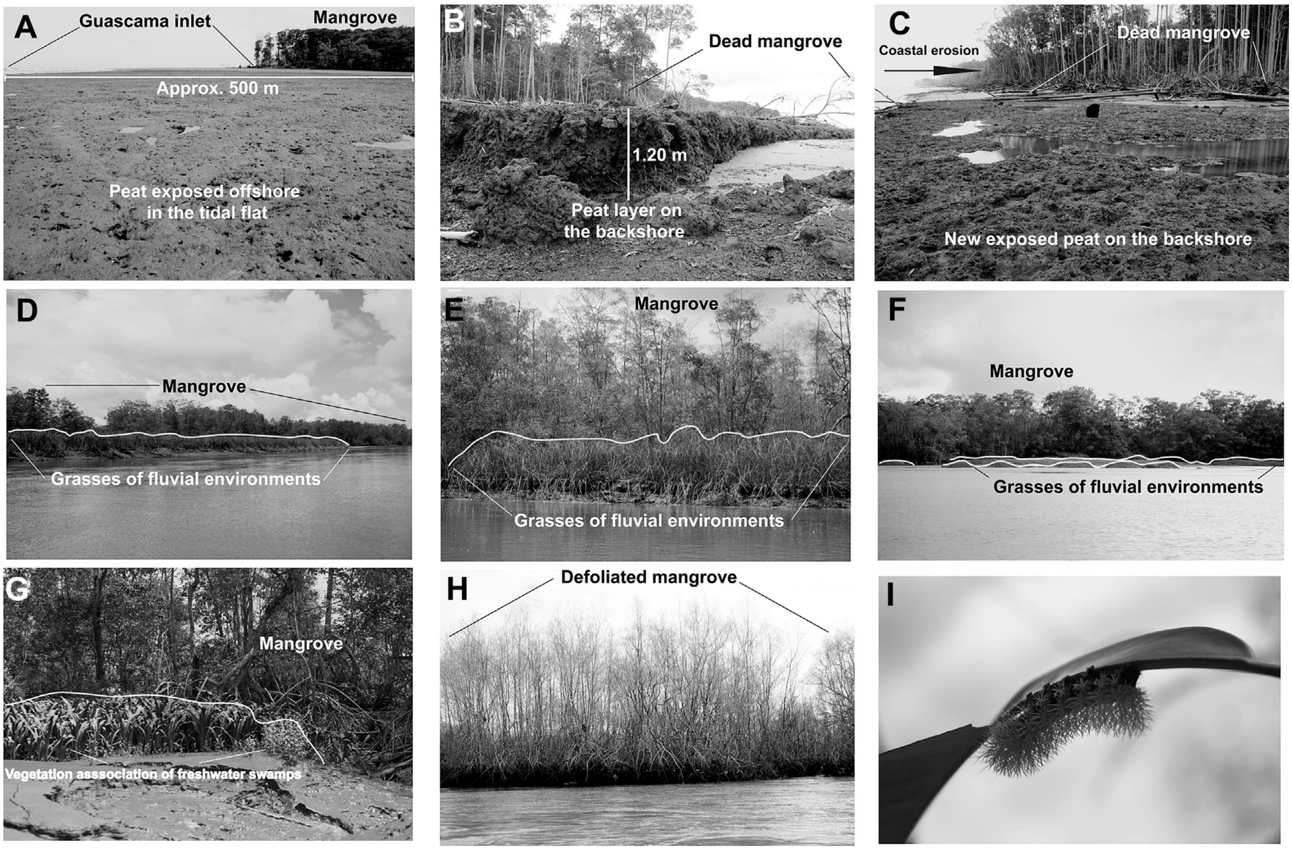

Fig. 11. (A–C) Exposed peat soils on the tidal flat and beach along the Guascama inlet (Fig. 1C). Note strong conditions of mangrove erosion on the inlet margin (A). Due to increased rates of water discharge and relative sea level, the inlet has witnessed a widening process of approximately 500 m on the northern side. (D–G) Vegetation of fluvial environments such as grasses (*Panicum* and *Paspalum*) and scrubs, are invading channel banks in the upper estuarine zone, a region characterized by the presence of dense mangrove forests of *Rhizophora*. (H) Defoliated mangrove communities of *Rhizophora* and *Avicennia.* Under environmental stressors (e.g., changing conditions of salinity and sediment deposition), mangrove forests become more vulnerable to worm plagues like the one observed in Sanguanga (Saturnidae family) (I).

The Pacific deltas of Colombia do not experience subsidence due to compaction of underlying sediments, because these deltas are sand-rich systems that lack organic and thick pro-delta mud deposits. In addition, there are no human-induced activities such as water abstraction or gas mining. Thus, subsidence is tectonically driven and one of the principal evidences that could indicate relative sea-level rise is the increased frequency of non-storm overwash on barrier islands (e.g. Morton et al., 2000; Restrepo et al., 2002). According to interviews with the local inhabitants in Mulatos, a village located in the Sanquianga inlet, the occurrence of non-storm washover of barrier islands was not linked with raised sea levels due to ENSO events prior to the tsunami in 1979. However, the El Niño events in 1982–1983 and 1997 created non-storm overwash on the barrier island at Pasacaballos and eroding conditions started to prevail 25 years ago, just after the El Niño 1982–1983 event. The agreement of relative sea-level changes for the 1984–2006 year period with tectonic settings (Figs. 1 and 9), the occurrence of non-storm washover events and earthquake activity, and the frontal erosion of barrier islands along the southern and northern delta lobes (Figs. 10 and 11), may suggest that subsidence is continuing in the Patía delta.

As a result of relative sea-level rise (Fig. 9B), transgressive barrier islands are present along the Patía delta front (Figs. 10 and 11). These islands appear to migrate because the front side of the island is constantly eroded by wave action. These islands lack healthy dune systems and backshore vegetation that act as sand anchors on the beach. This deficiency makes the islands susceptible to erosion, allowing wind-generated waves to carry sediment from the beaches to the backside of the island. Due to the flooding of storm waves over the island, dead mangroves of *Rhizophora* and *Avicennia* as well as peat soils of former backside mangrove swamps are exposed on the shoreline (Figs. 10 and 11).

Erosion of mangroves is a common geomorphic feature in the Patía southern delta lobe. This former delta plain, exposed to predominant wind waves from the southwest, lacks sufficient sediment for the offshore zone to build shoals, which could mitigate the effects of wave action and sea-level rise. Some barrier islands, including those at Pasacaballos and San Juan de la Costa (Fig. 1C), have retreated as much as 500 m after the occurrence of both events, the 1979 tsunami and the more pronounced flow diversion during the 1980s (Fig. 5).

4.6. *Further ecological implications on mangrove communities*

Freshening conditions in the Sanquianga distributary channel have shifted the upper estuarine region downstream (salinity <1) (Fig. 7A). According to nature experts in the area, the effect of increased freshwater discharge on plant ecology has become more marked during the last decade. Near the current delta apex at Bocas de Satinga, characteristic grasses of fluvial environments such as *Panicum* and *Paspalum,* are colonizing point bars and mud flats in front of channel banks with *Rhizophora*. In addition, vegetation associations of freshwater swamps are invading channel banks in the lower and mixing estuarine zone (Fig. 11D–G). Further environmental consequences include the die-off of approximately 5200 ha of mangrove near Bocas de Satinga, where the highest sediment accumulation rates occur (Fig. 7b). These zones have been colonized by the opportunistic fern *Acrostrichium aureum* and other shrubs characteristic of freshwater environments.

The mentioned changes observed in the mangroves of the SMNP are primarily the response to an ever-changing series of habitats, the result of geomorphic changes associated with the development of an active delta plain. Similar processes of have been observed in other deltas, including Tabasco, Mexico (Thom, 1967), Mira and San Juan, on the Pacific coast (West, 1957; Restrepo et al., 2002), Atrato, on the Caribbean coast of Colombia (Vann, 1959a), and are similar to the Purari, Papua New Guinea (Conn, 1983).

It is worth mentioning that the current active distributary channel, the Sanquianga, was an estuarine system with very low inputs of water discharge and sediment load. These hydrologic conditions, together with the mesotidal range, characteristic on this part of the coast, favored the formation of extensive mangrove swamps. According to Thom (1967), mangroves are not present unless the stream is in deteriorating phase, otherwise, freshwater plants would occupy this habitat. Also, mangroves on natural levees simply indicate channel deterioration and hence the presence of saline water at any given time. Thus the observed ecological changes in the northern lobe of the Patía delta are the first environmental signs of shifting conditions from an estuary to a delta system. In fact, these processes act on long-term time scales.

Another environmental issue observed in the Sanquianga Mangrove National Park (SMNP) has been the recurrent periods of mangrove defoliation (Fig. 11H), which, prior to the channel diversion, were not seen in the area. Under environmental stressors, mangrove communities become more vulnerable to plagues like the one present in the SMNP, a worm of the *Saturnidae* family (Fig. 11I).

5. Conclusions

The results shown in this paper indicate that a former estuarine system, with the largest mangrove reserve in Colombia, and on the west coast of South America, is becoming an active delta system. Overall, major environmental consequences of the Patía River discharge diversion, in terms of ecological impacts on mangrove ecosystems, are evidenced by: (1) distributary channel accretion by operating processes such as interdistributary channel fill and colonization of pioneer mangrove; (2) freshening conditions in the Sanquianga distributary channel, a hydrologic change that has allowed the downstream advance of freshwater vegetation, which is invading channel banks in the lower and mixing estuarine zones; (3) die-off of approximately 5200 ha of mangrove near the delta apex at Bocas de Satinga, where the highest sediment accumulation rates occur; and (4) recurrent periods of mangrove defoliation due to a worm plague.

The Patía River appears to have the highest sediment yield of the medium-large rivers along the Atlantic and Pacific coasts of South America. Its yield, 1500 t km^{-2} yr^{-1}, is higher than the previous top one value reported for the San Juan River on the Colombian Pacific shore, 1150 t km^{-2} yr^{-1} (Restrepo and Kjerfve, 2000), almost four times greater than the yield of the Amazon, 167 t km^{-2} yr^{-1}, Orinoco, 158 t km^{-2} yr^{-1} (Latrubesse et al., 2005), or Negro (Argentina), 140 t km^{-2} yr^{-1} (Milliman and Syvitski, 1992), and much greater than the yield of the Paraná, 43 t km^{-2} yr^{-1}, Uruguay, 16,4 t km^{-2} yr^{-1} (Latrubesse et al., 2005), and São Francisco, 10 t km^{-2} yr^{-1} (Milliman and Syvitski, 1992). Our conclusion is that many natural and human-induced controls, including (1) high runoff conditions, (2) steep relief within catchment, (3) low discharge variability, (4) episodic sediment delivery due to either geologic events or climatic anomalies, and (5) ongoing land degradation due to deforestation, may account for this high sediment yield.

Under these physical conditions, we expect that the geomorphic and ecological changes in the mangrove communities of the SMNP will be enhanced as a result of ongoing trends of deforestation, soil erosion, and increasing sediment load. Further research in the mangroves of the SMNP should focus on the interaction between deltaic sedimentation and associated changes in vegetation patterns.

Recently, the Colombian government constructed a channel near the delta apex at Bocas de Satinga, to deviate some of the Sanquianga flow and thus control flood events in the village. Although this is a partial hydraulic solution, the problem of increased sedimentation has not received any attention. There are no restoration programs or mitigation strategies assessing this channel diversion and its impact on mangroves. As mentioned before, the high sediment and freshwater inputs into the mangrove ecosystem create additional stress (both at ongoing background levels and, occasionally, at dramatic levels), which may periodically push local environmental parameters beyond the thresholds for mangrove survival. The future state of health for the Sanquianga Mangrove National Reserve deserves more scientific and governmental attention.

Acknowledgments

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