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The Orinoco megadelta as a conservation target in the face of the ongoing and future sea level rise

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HIGHLIGHTS

- Underpopulated deltas are ignored as conservation targets against sea level rise.
- We explore potential effects of sea level rise on the Orinoco river megadelta.
- Models predict drowning of wetlands and biodiversity and cultural losses.
- Natural compensating factor may allow coastal wetlands to adapt in the short term.

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ABSTRACT

Currently, risk assessments related to rising sea levels and the adoption of defensive or adaptive measures to counter these sea level increases are underway for densely populated deltas where economic losses might be important, especially in the developed world. However, many underpopulated deltas harbouring high biological and cultural diversity are also at risk but will most likely continue to be ignored as conservation targets. In this study, we explore the potential effects of erosion, inundation and salinisation on one of the world's comparatively underpopulated megadeltas, the Orinoco Delta. With a 1 m sea level rise expected to occur by 2100, several models predict a moderate erosion of the delta's shorelines, migration or loss of mangroves, general inundation of the delta with an accompanying submersion of wetlands, and an increase in the distance to which sea water intrudes into streams, resulting in harm to the freshwater biota and resources. The Warao people are the indigenous inhabitants of the Orinoco Delta and currently are subject to various socioeconomic stressors. Changes due to sea level rise will occur extremely rapidly and cause abrupt shifts in the Warao's traditional environments and resources, resulting in migrations and abandonment of their ancestral territories. However, evidence indicates that deltaic aggradation/accretion processes at the Orinoco delta due to allochthonous sediment input and vegetation growth could be elevating the surface of the land, keeping pace with the local sea level rise. Other underpopulated and large deltas of the world also may risk immeasurable biodiversity and cultural losses and should not be forgotten as important conservation targets.

1. Introduction

Coastal regions and tidal zones are among the most vulnerable areas to current climate change. It is probable that these areas will be affected by rising sea levels because of submergence, coastal flooding, shoreline erosion and saline intrusion (IPCC, 2013). Individually or in combination, these processes are expected to have strong effects on coastal ecosystems and human populations. During the 20th century, global mean sea level (GMSL) increased by 0.19 m at an average rate of 1.7 (1.5-1.9) mm/year and will continue to rise at higher rates. Updated projections of the GMSL increase over the 21th century range from 0.26 m to 0.98 m (IPCC, 2013). Additionally, there is strong evidence that other ocean characteristics related to climate have changed over the past 40 years, including temperature, salinity, carbon, pH and oxygen, and will most likely continue to change (IPCC, 2013). It has also been suggested that the Earth might be facing a sixth mass extinction within a few generations if the pressures that are pushing today's species towards extinction are not released promptly (Barnosky et al., 2011). In this context, the current sea level rise (SLR) might be seen as a significant extinction force. A review of global mass extinction episodes during

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the Earth's history indicates that sea level rise is related to large eustatic inflexions (see Hallam and Wignall, 1997; Hallam and Wignal, 1999 and literature therein).

Approximate estimates of the amount and rate of sea level rise during these events are generally lacking. One exception to this lack of information is an attempt made for the Pliensbachian–lower Toarcian biostratigraphic section (Yorkshire, England), one of the most complete and best studied sections in the world (Hallam and Wignall, 1997). Extrapolating from the best available estimates for the Early Jurassic (period between 183 and 175.6 MA), the lowest and highest millennial-scale rates of the past SLR of 1 cm in 1.2 ka (~0.08 mm/year) and 1 cm in 0.4 ka (~0.25 mm/year) have been inferred, respectively. These rates might have been higher if the estimates could have been based on centennial-scale data. An extremely high percentage of benthic and nektobenthic species disappeared, and this extinction event coincided with the spread of anoxic bottom waters (Hallam and Wignall, 1997). In fact, the majority of extinctions appear to have occurred during transgressive pulses when anoxic bottom water expanded into epicontinental seas (Hallam and Wignall, 1997; Hallam and Wignal, 1999; Pearce et al., 2008; Barnosky et al., 2011). Based on a rough comparison, these estimated SLR rates are lower than those given for the 20th century (IPCC, 2013; Cronin, 2012).

The IPCC projections (IPCC, 2013) show that sea level change will most likely have a strong regional pattern, especially towards the end of the 21st century, and this factor is important in defining biodiversity conservation and societal issues, raising concerns regarding coastal zones. On approximately 70% of the coastlines worldwide, SLR is expected to increase as much as 20% above the GMSL, but the increase could be greater, as global factors such as changes in ocean mass or volume and regional factors such as ocean circulation, regional subsidence, isostatic adjustments or sediment transport may specifically contribute to current sea level change along any particular coast. Of the different types of coastal formations, deltas are low-lying plains and show a high sensitivity to changes in sea level, to climate and also to impacts from rivers upstream, e.g., changes in freshwater inputs and quality. Most deltas have experienced intense transformations due to a vast array of human activities and in many cases, deltas harbour large and rapidly growing populations (Seto, 2011; Giosan et al., 2014). Taken together, these factors make deltas even more vulnerable to SLR (IPCC, 2007, 2014 and literature therein). Many important deltas (e.g., Mekong, Yangtze and Rhone) are even sinking due to human activities (Syvitski et al., 2009). The risk due to the current sea level rise is exacerbated because approximately one-half billion people live on or near deltas with valuable assets and infrastructures (Syvitski and Saito, 2007; Jongman et al., 2012). It is to be expected that risk assessments and the adoption of defensive or adaptive measures will focus on such densely populated deltas, where economic losses might be important, particularly in the developed world. While this approach is certainly unquestionable, it is worrisome that many deltas exist that neither are densely populated nor have valuable assets and infrastructures but harbour high levels of diversity, which also makes them vulnerable to SLR and at risk of immeasurable losses. A question that arises is whether the mere existence of important intangible and unmarketable values, e.g., biodiverse ecosystems or ethnic richness, will spur sufficient concern to improve the protection of sparsely populated deltas.

Research on the relative risks and impacts of SLR on specific localities is still in an early stage.

In this paper, we analyse the vulnerability of wetland ecosystems located in the giant Orinoco Delta (Venezuela, Northern South America) in terms of the current SLR and with available datasets and models. Our aim is to place the Orinoco delta and its potential future state in a worldwide context thus enabling comparisons with other similar megadeltas. Unlike other deltas of large tropical rivers showing high population densities and connected to urbanisation, such as the Ganges–Brahmaputra (Bangladesh), Mekong (Vietnam), the Nile (Egypt) or the Magdalena (Colombia), the sparsely populated Orinoco River Delta is among the few large deltas that have changed relatively little due to human activities during the 20th century (Syvitski et al., 2009). Indeed, a large proportion of the Orinoco Delta is almost pristine. Additionally, it is noteworthy that the Orinoco Delta forms part of one of the most biodiverse areas on earth, i.e., Latin America and the Caribbean (ICSU-LAC, 2010), but has not yet been studied in terms of climate change impacts. Our study area is located in the lower Orinoco Delta, the most vulnerable portion of the delta to SLR. In this study, we explore and critically discuss the derived scenarios of ecological and social impacts using commonly applied methodologies (Klein and Nicholls, 1999 and literature therein) and available forecasting models and datasets. In particular, we explore the potential effects of erosion, inundation and salinisation on wetland ecosystems and on indigenous populations living in this region. We compare our results with past SLR situations to encourage long-term thinking about threatened coastal zones, and we consider alternatives involving resilient or adaptive approaches based only on natural processes.

2. Study area

Our study area at Punta Pescador is located (Fig. 1) in the lower Orinoco Delta close to the "Delta del Orinoco Biosphere Reserve" (UNESCO, 2011). Topographically, it ranges in elevation from 1 m above to 1 m below mean sea level and is almost perennially flooded. The study area extends over a large wetland area that houses a mosaic of diverse freshwater swamps and marshes distributed among an extensive network of distributary and tidal channels (caños), which are controlled primarily by semi-diurnal tides of 2.5 m average range and secondarily by river floods and local precipitation. The vegetation consists of swamp forests (36.8%), meadows (32.8%), mangroves (22.1%), palm forests composed primarily of *Mauritia flexuosa* L.f. (8.41%), and shrublands (3.27%) (Vegas-Vilarrúbia and López, 2008). The study area is representative of the ecosystem structure and composition of the central and northwest portion of the lower Orinoco Delta. The southeastern portion is a river- and tide-dominated ecosystem complex, whereas the north-western part is a tide- and precipitation-influenced ecosystem complex. The observed geomorphic features and processes of the near-shore marine and coastal plain systems of French Guiana, Suriname, and Guyana (Guiana) are similar to those of the Orinoco coast (Warne et al., 2002).

The Orinoco Delta has been the home of the nomadic South American Warao Indians since at least early Indo-Hispanic times. The Waraos speak a language of the Macro-Chibchan group and also inhabit areas eastwards to the Pomeroon River of Guyana. Additionally, some Waraos live in Suriname (Britannica, 1994). Their population reached a total of 36,028 individuals in Venezuela by 2001, of which 83% lived in the delta, and 85% in traditional communities (INE, 2002, see Section 4.2). Our study area includes three settlements located at the mouth of the caños Mariusa, Macareo and Cocuina (Fig. 2), with a population that reached 488 inhabitants by 1992 and 433 by 2001 (Gruson, 2008).

3. Methods

3.1. Baseline studies

This research is based in part on an earlier Environmental Base Line Study of the study area, the Punta Pescador Block, conducted by multiple scientific institutions and sponsored by the oil company Amoco de Venezuela between 1997 and 1998. This earlier study is the source of the hydrochemical, vegetation and soil data used in this paper (Geohidra Consultores, 1998; Vegas-Vilarrúbia et al., 2007; Vegas-Vilarrúbia and López, 2008; Vegas-Vilarrúbia et al., 2008, 2010). Due to its remoteness, the study area has remained virtually unchanged until now and represents an excellent environmental reference against which to compare the probable current and coming transformations. In this paper, we selected hydrochemical variables that are relevant to assess future changes in the composition of riverine and marine water and to assess the expected effects of such changes on wetland

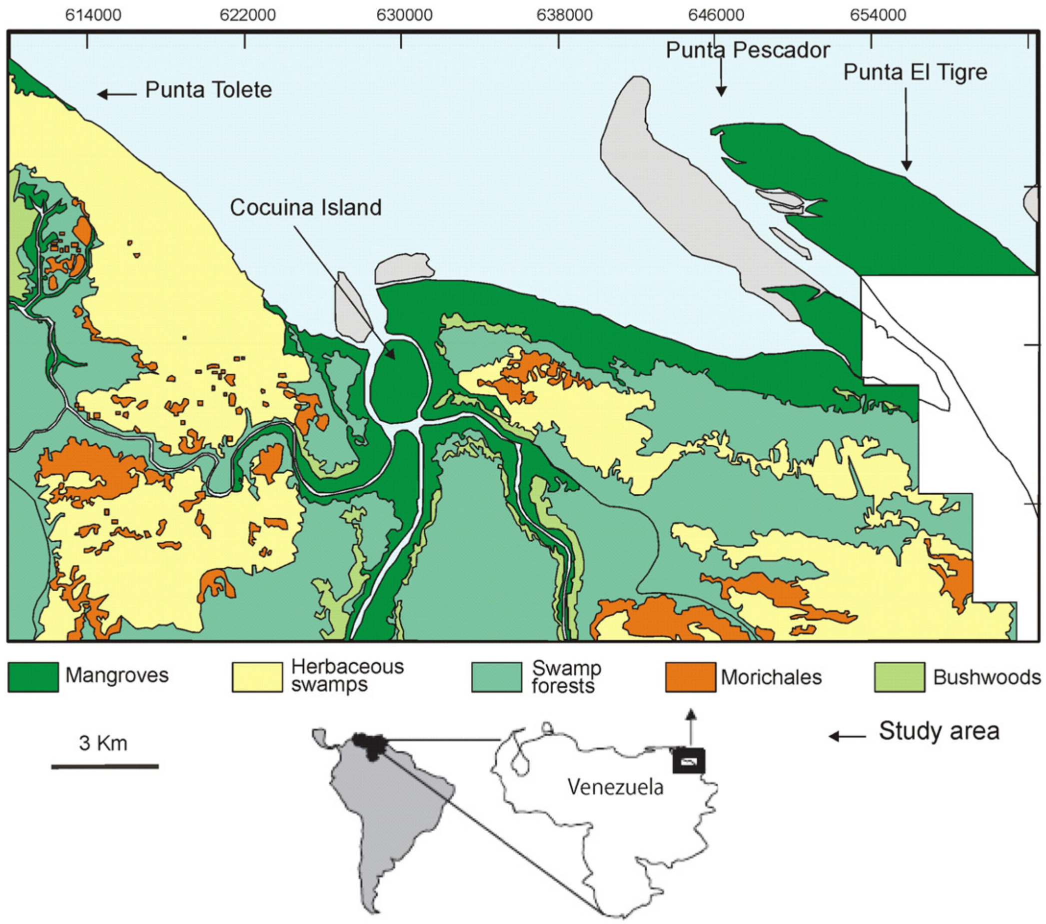

Fig. 1. Location of the study area and wetland vegetation types.
Modified from Vegas-Vilarrúbia et al. (2007).

ecosystems that are vulnerable to SLR. Surface data on water temperature (T), salinity (Sal), pH, dissolved oxygen (O_2), alkalinity ($CaCO_3$), solids (ST, SST) dissolved organic carbon (DOC), oxidised nitrogen ($NO_3^- + NO_2^-$), ammonium (NH_4^+) and phosphate (P-PO_4^{3-}) from 44 sampling points distributed among marine, coastal and fluvial environments (Fig. 2) were analysed for the dry (April) and the wet (June) seasons. Sampling was conducted during the peak of both the rainy and the dry seasons. In situ measurements, chemical analyses and quality control and assessment (QA/QC) procedures were performed following standard methods for water and wastewater analyses (Greenberg et al., 1992) (Supplementary material Appendix 2). We performed statistical analyses – linear regression and Principal Components Analysis (PCA) – using PAST (Paleontological Statistics) software, version 3.0 (Hammer et al., 2001). The data were log-transformed, and the PCA was calculated from a correlation matrix.

As basic information, we used three baseline reports on the living conditions of the Warao in the entire Orinoco Delta. These reports were published in 2008 and 2009 by the Centre for Social Research (Gruson, 2008; CISOR, 2009).

3.2. Sea level rise forecasts

Regional changes in sea level are expected to reach values between 10% and 20% above the global mean value in equatorial regions (IPCC, 2013). In the absence of relevant information about local SLR for the study area, the projections to 2100 considered in this study include the best estimates issued by the IPCC (2013). We also work with more extreme estimates provided by independent studies (Horton et al., 2008; Vermeer and Rahmstorf, 2009; Grinsted et al., 2009; Jevrejeva et al., 2008). These estimates are being used to forecast SLR in the Caribbean region (Simpson et al., 2010). These authors suggest that the actual SLR could surpass the IPCC's forecasted values by a factor of three. We also incorporate the rate of land subsidence, which varies between 2.8 and >6.0 mm/year with a mean value of 4.4 mm/year near Punta Pescador (Warne et al., 2002; Mikhailova, 2010). According to these authors, subsidence in the Orinoco delta is due to the continuing tectonic processes in the Eastern Venezuela Basin, as well as to the slow compaction of the bed of Holocene deltaic sediments in the middle and the lower delta plain. Both processes are very slow and allow provisional extrapolation of these rates linearly out to 2100, as no significant geological changes are expected during this time frame. Additionally, estimates of the relative contribution of either tectonics or sediment compaction to subsidence rates are unavailable for the Orinoco's delta. In any case, subsidence estimates should be updated as soon as new data are available.

SLR produced by occasional storm surges is neglected because they currently do not affect the Orinoco Delta (Syvitski et al., 2009). The hurricanes that migrate from the central Atlantic into the Caribbean region follow a pathway that lies just to the north of the delta (Warne et al., 2002).

3.3. Erosion and inundation assessments

To assess the impact of erosion and floods, we decided to apply widely used and widespread models. Bruun's rule is a simple, two-dimensional model used to predict the horizontal migration of the shoreline associated with a given rise in sea level (Bruun, 1988). We utilised Bruun's rule for landward erosion because the coastline at the

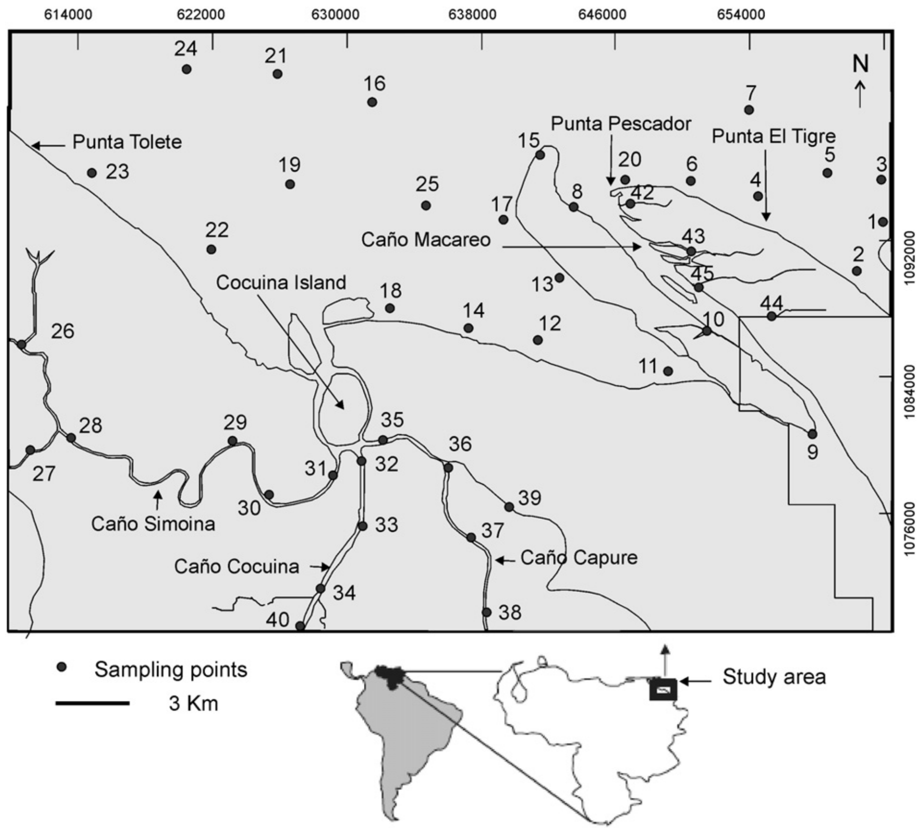

Fig. 2. Sampling points distributed among coastal/marine and fluvial environments.

study area shows unconsolidated beach materials (>60% silt) and an absence of coastal protection structures. This method is a simple, two-dimensional model used to predict the horizontal translation of the shoreline associated with a given rise in sea level. Due to a scarcity of data, the horizontal coastline retreat (R) is calculated using an alternative equation to the original one (Davidson-Arnott, 2005) (Supplementary material Appendix 2, Eqs. A2.1, A2.2).

From the few online available models with web map visualisation tools to tentatively forecast potential effects of SLR, we choose the ClimateGEM software of the University of Arizona ClimateGEM programme (2012), a general screening-level tool for investigating low-lying coastal areas prone to be affected by inundation (ClimateGEM, 2012; Weiss et al., 2011). ClimateGEM is based on the analysis of the GTOPO30 world digital elevation model, which is suitable for many regional and continental applications, such as climate modelling (see Supplementary material, Appendix 2, for details and limitations). As it is a screening model, ClimateGEM data and maps illustrate the scale of potential flooding, not the exact location, and does not include subsidence, tidal height, hydrological connectivity and those features recognisable at the spatial scale of the model that may either facilitate or impede advancing seawater at a given location (Weiss et al., 2011).

3.4. Change in the magnitude of seawater intrusion

Seawater intrusion into river mouths occurs where freshwater and salt or brackish water interact. This phenomenon is expected to increase with rising sea level and to cause damage to ecosystems, the environment, human populations and the economy. Thus, risk evaluation and the prevention of adverse effects emerge as a central issue. Unfortunately, however, this phenomenon is poorly studied to date (Mikhailova, 2013). To obtain a preliminary evaluation of the trend of present day seawater intrusion into the caños of the study area during low river discharge (dry season, see above) and to explore several possible risk scenarios, we adopted an empirical approach based on available field data (Geohidra Consultores, 1998). We first determined the type of vertical mixing at the mouth of caño Capure as representative of caños Cocuina, Guairina and Caijirina, using the stratification parameter n based upon salinity (*Sal*) measurements. According to the obtained n value, we roughly estimated the present-day seawater intrusion into the river mouth, Ls, during high tide. Finally, we predicted the increase in the distance of saltwater intrusion into the caños as a result of sea level rise and subsidence at Punta Pescador (2.8 and 6.0 mm/year) using the same equations (Supplementary material Appendix 2, Eqs. A2.3, A2.4, A2.5 and A2.6).

3.5. Expected population dynamics of the Warao Indians to 2100

To describe the current population dynamic of the Warao, we used the demographic growth rate r based on the geometric population growth model. This model of constant population growth is proportional to the varying population size and ignores migration movements (Krebs, 2001), which in the case of the Warao people are basically local within the state of Delta Amacuro (i.e., the Orinoco Delta) (Supplementary material Appendix 2, Eqs. A2.7, A2.8, A2.9).

3.6. Vulnerability assessment

The vulnerability to SLR of the study area was assessed broadly following the IPCC's Common Methodology, which has been widely applied and subjected to extensive evaluation (Klein and Nicholls, 1999 and literature therein). This method involves seven steps and is useful as an initial baseline analysis for country-level studies where little knowledge about coastal vulnerability is available (IPCC, 1990). The steps are as follows: (1) delineate the case study area, (2) inventory the ecological and socioeconomic characteristics of the study area, (3) identify the relevant socioeconomic development factors,

Table 1
Summary SLR predictions taken from different sources. IPCC (2013) predictions are averages of the lowest and highest values obtained by 4 different scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5).

Used models	By 2100 (SLR in m) Lowest range	By 2100 (SLR in m) Mean	By 2100 (SLR in m) Highest range
IPCC (2014a)	0.34	–	0.66
Rahmstorf (2007)	0.5	0.9	1.4
Horton et al. (2008)	–	1	–
Vermeer and Rahmstorf (2009)	0.75	1.24	1.8
Grinsted et al. (2009)	0.40	1.25	2.15
Jevrejeva et al. (2008)	0.60	1.2	1.75

(4) assess physical changes and the socio-natural environment, (5) formulate response strategies, (6) assess the vulnerability profile, and (7) identify future needs. In this paper, these steps developed in the standard sections of this paper: steps 1–4, involving aspects related to changes in physico-chemical characteristics and relevant socioeconomic factors, are developed in the "Study area" and "Results" sections, whereas steps 5–7 are included in the "Discussion" section.

4. Results

4.1. Hydrochemical characterisation of fluvial and marine environments

All hydrochemical variables measured during the wet and dry seasons displayed a variation coefficient ranging from 2 to <100% (Table 2). Coastal/marine waters showed higher SST and O_2 concentrations than fluvial waters and, if compared with current sea water salinity values (~35‰), appear rather diluted. In contrast, fluvial waters were enriched with marine salts, showed double the DOC concentrations of coastal/marine waters and showed significant oxygen depletion (<40% saturation). Both in fluvial and coastal/marine waters, DOC and nitrogen concentrations were higher during the rainy season, whereas pH, alkalinity and salinity values were lower.

PCA helped reduce the number of explanatory variables. For fluvial environments, the first three principal components (PCs) explained 75.5% of the total variance (Table 3). On the biplot for the dry season (April, Fig. 3a), PC1 appears to be significantly correlated with DOC (−0.858), pH (+0.789) and O_2 (+0.723). We infer that acidity and oxygen depletion are strongly related to a higher content of decomposing organic matter at the sampling points located at the left side of PC1 (26, 27, 28, 29) and to more buffered and open waters on its right side (32, 33 and 45). PC2 was correlated with $NO_3^- + NO_2^-$ (+0.792) and with salinity (−0.777), most likely reflecting the high rate of nitrification in less saline water and also the degree of tidal influence on the caños. During the rainy season (June, Fig. 3b), the main tendencies remained similar, but the influence of pH and DOC decreased, and TSS gained importance due to the input of solutes from upstream and surface runoff of the surrounding wetlands. In fact, PC1 showed significant correlations with O_2 (+0.891), TSS (+0.723) and DOC (−0.785) and PC2 with salinity (+0.884) and oxidised forms of nitrogen (+0.774). The sampling points located on the right side of the biplot are relatively close to the sea and therefore more exposed to tidal influence, whereas the few points located on the right side (26, 27, 36, 40) receive higher amounts of DOC from the neighbouring peats and experience dilution due to precipitation and higher fluvial discharge. Points 39, 42, 43, 44 and 45, located in the lower part of the biplot, differ from the remaining points by their relatively low concentrations of $NO_3^- + NO_2^-$; additionally, point 39 also differs from the remaining points by its relatively higher concentration of DOC.

Table 3
Summary of results of the PCA for fluvial stations (Joliliffe cut-off 0.7).

PC	April		June	
	Eigenvalue	Variance (%)	Eigenvalue	Variance (%)
1	2.73	27.4	3.22	32.3
2	1.86	18.6	2.88	28.3
3	1.74	17.4	1.49	14.9
Accumulated variance		63.4		75.5

For marine and coastal environments, the first three PCs explained 65.3% of the total variance (Table 4). During the dry season (April, Fig. 4a) PC1 was significantly correlated with salinity (+0.871) and $CaCO_3$ (+0.830) and negatively with temperature (−0.863). PC2 showed positive correlations with DOC (+0.757) and SST (+0.710). The sampling points are scattered along PC1, showing heterogeneity regarding salinity and temperature, most likely related to the distance from the coast. During the rainy season (June, Fig. 4b) PC1 showed correlations with $CaCO_3$ (+0.870) and salinity (+0.838), and pH was more important (+0.724). PC2 was correlated with SST and negatively correlated with $NO_3^- + NO_2^-$ concentrations. Three conspicuous groups are shown on the biplot. At the upper right side of the biplot is one group formed by sampling points located to the east of Punta el Tigre and outside the fluvial influence of caño Macareo, whose water flows to the west due to the littoral current (Warne et al., 2002). The second group is at the upper left side and shows those points located along

Table 2
Averages and standard deviations (σ) of hydrochemical variables of fluvial (n = 19) and coastal/marine (n = 25) water samples during the wet and the dry seasons.

	SST	DOC	NH_4^+	$NO_3^- + NO_2^-$	PT	$CaCO_3$	pH	T	O_2	Sal
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		°C	mg/L	‰
Fluvial April										
Mean	30	3.5	1.24	0.12	0.041	57	7.19	29.6	3.08	13.8
σ	17	2.3	0.28	0.08	0.044	15	0.44	0.6	1.60	4.9
Coef. var (%)	56.7	65.7	22.6	66.7	107	26.3	6.11	2.03	51.9	35.5
Fluvial June										
Mean	33	12.8	3.67	0.34	0.055	33	6.51	28.5	3.00	6.0
σ	38	9.2	1.24	0.19	0.031	19	0.27	0.9	1.49	3.8
Coef. var	115	71.9	33.8	55.9	56.4	57.6	4.14	3.16	49.7	63.3
Marine April										
Mean	72	1.5	1.34	0.08	0.081	70	8.01	29.2	6.26	21.6
σ	46	0.7	0.40	0.04	0.056	20	0.17	0.9	0.96	8.2
Coef. var	63.9	46.6	29.9	50.0	69.100	28.6	2.12	3.08	15.3	38.0
Marine June										
Mean	150	7.2	3.38	0.13	0.075	42	7.27	28.4	5.51	9.2
σ	118	8.0	0.79	0.11	0.06	29	0.54	0.5	1.23	8.8
Coef. var	78.7	111	23.4	84.6	80.0	69.0	7.42	1.76	22.3	95.6

the coast and under the fluvial influence of caño Macareo. The third group lies at the lower left side of the biplot and includes sampling points showing a high $NO_3^- + NO_2^-$ concentration three times greater than the mean and TSS relatively below its mean value, most likely owing to the freshwater plume generated by the caños that join at Cocuina Island and discharge $NO_3^- + NO_2$ from the floodplains into the marine environment.

4.2. Relevant socioeconomic development factors

Traditionally, the Warao people, known as "canoe people", are gatherers who live by fishing, hunting, collecting fruits, larvae, and crustaceans and exploiting the *M. flexuosa* palm. More recently, they have also started to perform shifting horticulture and occasional salaried logging of the palm *Euterpe precatoria*. The Waraos are sedentary during the rainy season and nomadic during the dry season. They live in scattered villages located along the caños and composed of extended families. Families are large, polygynous and matrilocal, forming large clan-families. A village may consist of only three dwellings for 20 people but can reach a considerable size. Dwellings are made of stems and leaves of the palms *M. flexuosa*, *Manicaria saccifera* Gaertn. and *Euterpe* sp. The Waraos are custodians of traditional ethnobotanical information on plant species growing in the delta. The uses of these plants include health care, food, building construction, weapons, canoe construction and handicrafts (Vegas-Vilarrúbia et al., 2007; Gruson, 2008).

This traditional mode of subsistence is currently maintained in combination with more recent economic activities. Throughout the past half century, collective subsistence activities were replaced by individual wage labour. The advent and consolidation of such socioeconomic changes was triggered by unfortunate programmes of credit management for rice cultivation offered through agricultural credit institutions. This type of financing brought insolvency and indebtedness to everyone belonging to the Warao cultivation groups. As a result, these individuals were forced to accept any means of

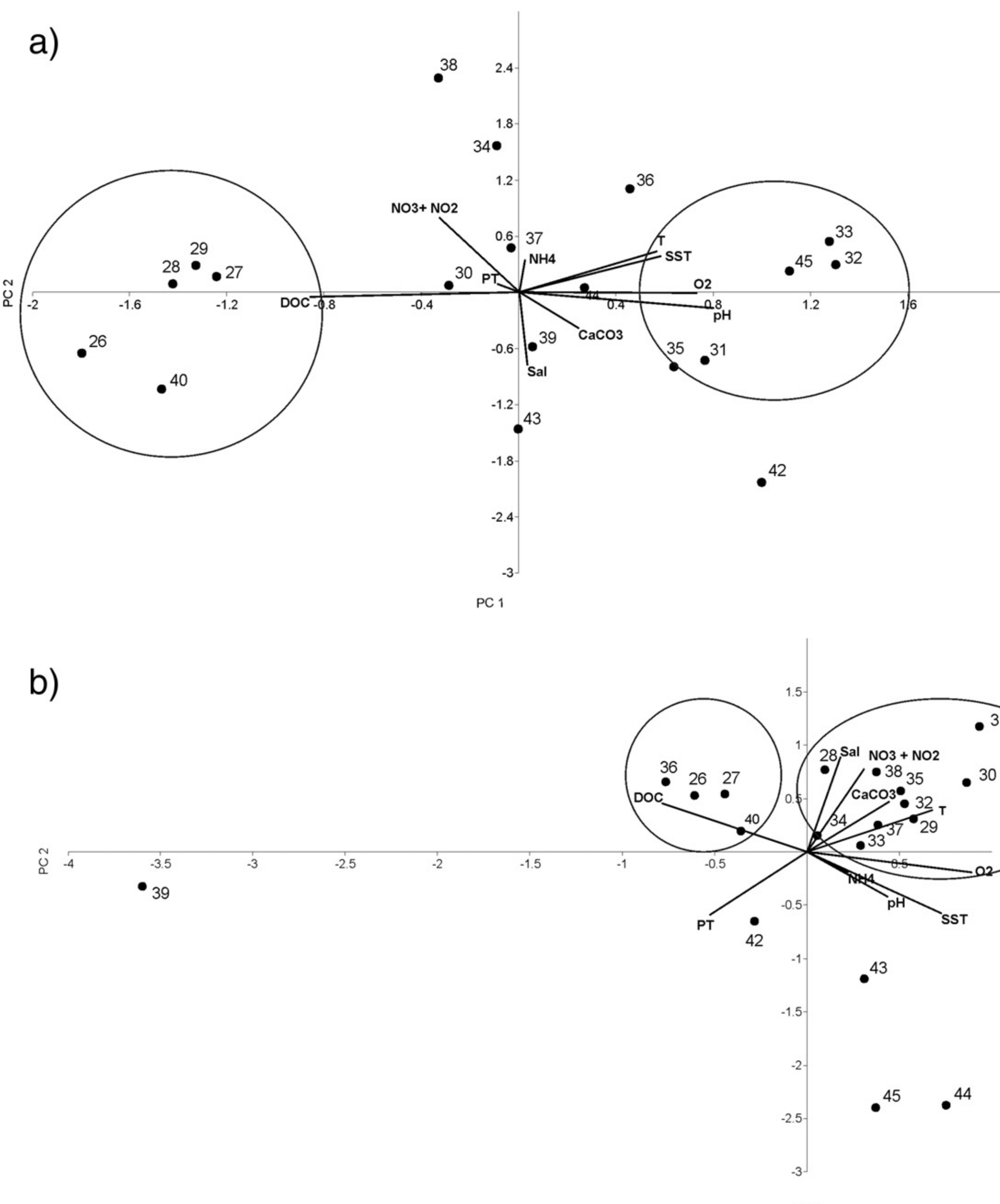

Fig. 3. PCA biplots for the fluvial environment. a) Dry season in April; b) wet season in June.

Table 4
Summary of results of the PCA for marine stations (Joliliffe cut-off 0.7).

	April		June	
PC	Eigenvalue	Variance (%)	Eigenvalue	Variance (%)
1	2.76	27.6	3.24	32.4
2	2.16	21.6	2.12	21.2
3	1.31	13.1	1.17	11.7
Accumulated variance		62.3		65.3

obtaining an individual livelihood, including daily wage labour. Currently, many of the indigenous settlements of the Orinoco Delta combine traditional socioeconomic activities with monetised business and public employment (e.g., education, health care). However, many young Warao have migrated and are employed as civil servants, whereas the less fortunate live by begging in the major cities of the country. Currently, all these forms of subsistence coexist in varying degrees, producing a variety of socio-economic circumstances in Warao settlements (Fig. 5). Due to this great variety, it is impossible to make generalisations. In concrete terms, the settlements of Punta Pescador combine traditional activities with fishing for the market and Warao microenterprises. Cultivation is difficult due to the poor quality of the soils (Vegas-Vilarrúbia et al., 2008, 2010). A variable that should be included in this study as an indicator of the socioeconomic development of the Warao is their contribution to the gross domestic product (GDP) of the country (Venezuela). Unfortunately, this information is

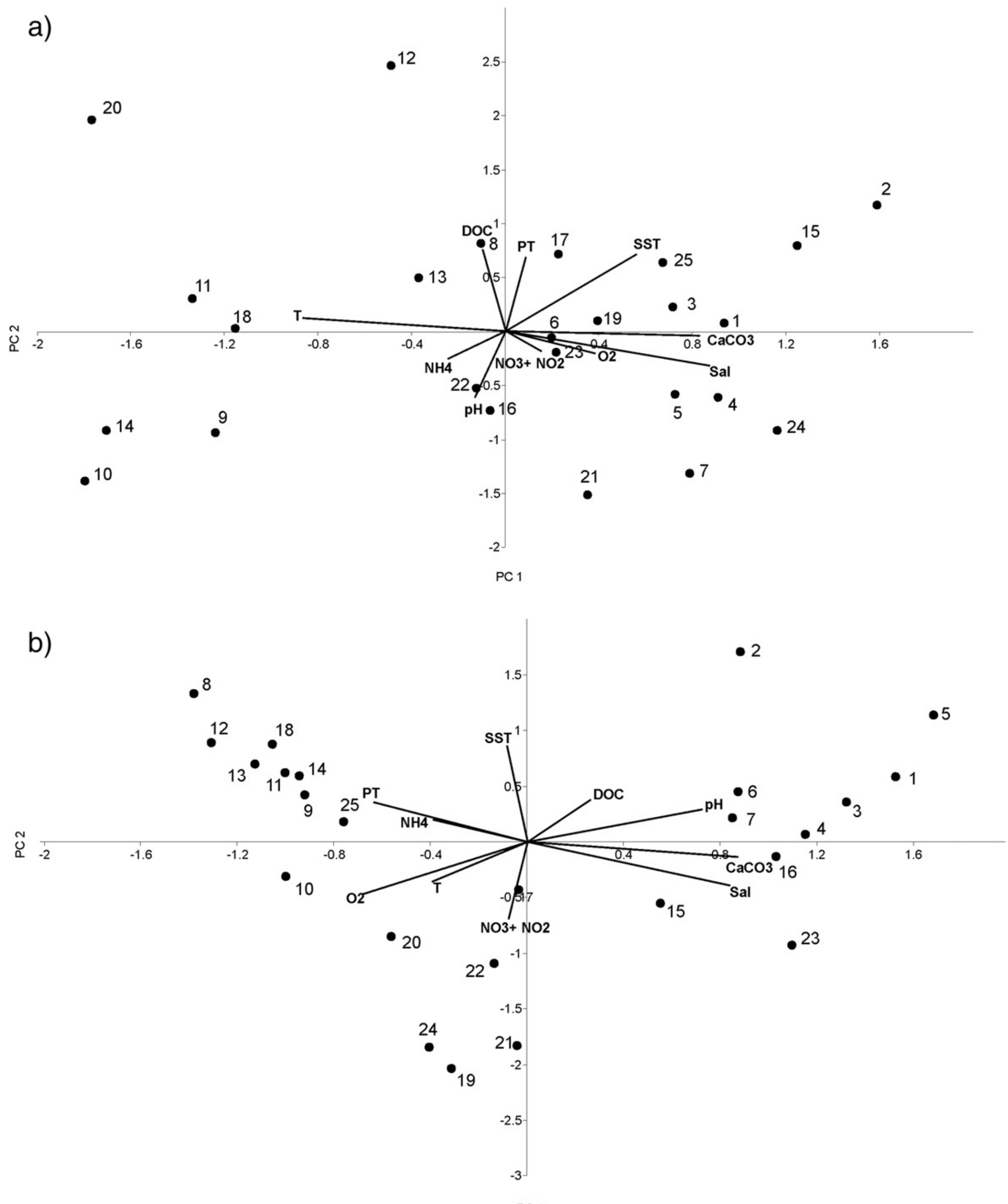

Fig. 4. PCA biplots for the coastal/marine environment: a) dry season in April, b) wet season in June.

currently not available. The Warao economy is primarily a component of the informal economy of the country, based on individuals working for absolute subsistence and representing a precarious situation relative to other economic sectors of the country. Informal economy is neither formally organised, nor does wear any kind of accounting or expansion plans to generate dividends and, most substantial, is not registered in any of the forms expressing the current legal system (Díaz and Corredor, 2008).

In terms of literacy, almost all major settlements have a public school with food service that accommodates students from nearby villages. The schools in the study area (Macareo, Mariusa and Punta Pescador) have fewer than 100 students each. Presently, the organisation of school programmes (e.g., time, calendar, curriculum) does not allow Warao children to learn and be trained in the traditional activities that would help them survive in the Orinoco Delta. After they finish their studies, as they lack such traditional knowledge and skills, they must often move to the cities. The spread of public education and the growth of purchasing power resulting from wages and handouts provided by the government favour the spread of Creole cultural patterns and primarily signify the occupation of the Warao space by the State, which represents employer and benefactor.

In addition to the development of the Warao economy, the Orinoco Delta has been the site of substantial oil production since the beginning of the past century. The oil industry continues to bring industrial activity to the area. In fact, an oil refinery is located at Pedernales. Presently, this activity is an enclave and does not directly affect the local people, although they benefit from programmes of corporate social responsibility conducted by multinational companies and from the environmental protection programmes of the Venezuelan state. In terms of the current uses of the soil, the study area remains almost unexploited with the exception of sparse subsistence agriculture in the form of shifting cultivation. For this reason, the capital value of the soil, defined by the IPCC (1992) as the total value of the soil plus infrastructure, is virtually impossible to measure with the exception of the standing dwellings of the Warao.

4.3. Estimated changes in the physical environment and population growth

4.3.1. Estimates of coastline retreat and land loss

To estimate coastal retreat and land loss, we used the 1 m SLR forecast of Horton and added the average subsidence rate at Punta Pescador until 2100. This analysis produced an estimated value of 1.44 m, which approaches the highest estimate obtained by Rahmstorf (see Table 1). We then assumed a beach slope value of 0.02% and assumed a homogeneous displacement landwards. In this scenario, the application of Bruun's rule (Supplementary material Appendix 2, Eq. A2.2) yielded a mean value of coastline retreat of 72 m at a rate of 0.7 m/year along ~80 km for the study area; this retreat is approximately 30% greater than it would be with 1 m SLR computed without considering the subsidence effect. The lowest and highest estimated SLR values (Table 1) reflect the uncertainty of the predictions. Although their occurrence is, therefore, less probable, the precautionary principle states that the most extreme possibilities must be considered in the absence of scientific certainty. Thus, a rough prediction of the potential erodible area at the study site due to coastal shoreline retreats of 72 m, 39 m and 130 m (Table 5) along 80 km of coast until 2100 would yield losses of land of ~5.76 km^2 (0.06%), 3.12 km^2 (0.33%) and 10.3 km^2, respectively (1.1%). These areas currently support mangroves and meadows (Fig. 1).

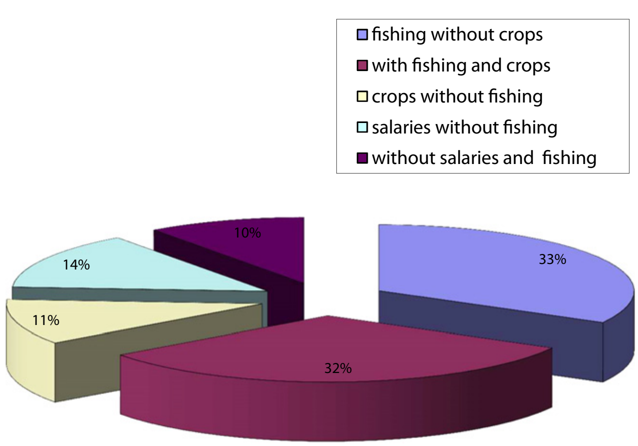

Fig. 5. Main forms of subsistence in the Warao communities of the Orinoco. Modified from Cisor (2009).

4.3.2. Inundation extent and land and habitat loss

We obtained Fig. 6 with the ClimateGEM software. This figure shows topographic elevations at or below 1 to 2 m in the study area, illustrating the scale of potential flooding. These elevation values are equal to the predicted amounts of SLR that we consider valid for this century and beyond (Table 1). According to this model and without considering any factor that would palliate inundation (e.g. vegetation, microtopography), not only the study area but also the entire Orinoco Delta, with all its unique and diverse plant and animal communities, could be potentially impacted by a SLR of only approximately 1 m.

4.3.3. Seawater intrusion

Seawater intrusion into the numerous tidal channels and river branches of the delta determines the extent to which estuarine conditions prevail and also the upstream extent of riverine mangroves, which grow on the river banks. The conditions under which seawater enters river mouths depend significantly on the vertical mixing and stratification of the water. We classified water mixing at the mouth of caño Capure according to the applicable n value as Type I ($n = 0$–0.1), denoting complete mixing and weak stratification. We used an approximate value of 17.1 km as the present distance of seawater intrusion into caño Capure. Beyond this boundary, freshwater habitats are expected to prevail within the channels. Applying the same model and assuming no changes in environmental conditions (i.e., discharge, river morphology, salinity), we obtained estimates for seawater penetration, Ls, under a 1 m SLR and subsidence scenarios of 2.8 mm/year and 6 mm/year. Under these scenarios, the distance of seawater intrusion reached 19.8 and 20.4 km, respectively. This result suggests that salt/brackish water environments may replace current freshwater habitats for a distance of 2–3 km upstream from the present boundary by 2100.

4.3.4. Expected population growth of the Warao to 2100

The population dynamics of the Warao Indians of Punta Pescador may become a sensitive topic in the context of 21st century SLR. Therefore, we tried to estimate the population growth rate r according to the geometric model, in order to estimate the potential population growth by 2100. In the absence of more precise information, we calculated r using census data for this ethnic group available from the Venezuelan

Table 5
Retreat of the coastline in metres at the study area value by 2100 under different SLR forecast (Table 1) scenarios: with and without (brackets) considering mean subsidence (4.4 mm/year) at Punta Pescador. In bold central, maximum and minimum estimates (see text).

Models used	Lowest estimates	Central estimates	Highest estimates
IPCC (2007)	**39** (17)	–	55 (33)
Rahmstorf (2007)	47 (25)	67 (45)	92 (70)
Horton et al. (2008)	–	**72 (50)**	–
Vermeer and Rahmstorf (2009)	59.5 (37.5)	84 (62)	112 (90)
Grinsted et al. (2009)	42 (20)	84.5 (62.5)	**130 (108)**
Jevrejeva et al. (2008)	52 (30)	82 (60)	110 (87.5)

National Institute of Statistics (INE) for the entire delta, with 2001 as the reference year (P_0) and 2011 as representative of the 2011 population (P_f). The obtained value of *r* was 0.0379–4%. This value is consistent with the geometric growth rate of the indigenous populations from other Venezuelan states (Olivo, 1997).

However, the fact that population size was of 488 individuals by 1992 and of 433 by 2001 (Gruson, 2008) indicates that population seems to be decreasing at the study site. On the other hand, forecasting the Warao population size for the year 2100 with simple models (geometric or exponential) without considering local demographic determinants of population change through time (e.g. socioeconomic, health and migration indicators) would yield unrealistic figures. In fact, the minimum required information recommended by the he United States Census Bureau to forecast human population dynamics is a base population sorted by age and sex with mortality information, a fertility pattern considering mother ages and, if applicable, a migration pattern also sorted by age and sex. To our knowledge such data are not available for the Warao population. On the other hand, Warao migration from rural to urban areas is occurring at present (see qualitative information in Section 4.2, this article) and an exacerbation of current migration rates is expected to take place in response to increasing SLR.

5. Discussion

5.1. Hydrochemistry

The variation in the measured hydrochemical variables is high (variation coefficients 2 to <100%) and suggests that fluvial and nearshore water masses are substantially affected by climatic seasonality and by their spatial position relative to stream outlets. This shifting pattern may influence the availability of aquatic niches and the seasonal behaviour of aquatic species. This variability also affects the distribution of plant species on the interdistributary plains because tides and river discharge promote periodic overflows of river banks and, hence, the inundation of neighbouring wetland environments. Our results show that coloured, humic freshwaters are a distinctive sign of the discharge of the Orinoco River and contribute to the river plume, which flows into the Caribbean Sea and converges with the Amazon River plume (Warne et al., 2002). The Orinoco discharge contributes a river plume with seasonally varying amounts of nutrients, dissolved and solid materials. Huh et al. (2004) found extremely dark-coloured, low-salinity water masses in the North Atlantic Ocean and the Caribbean Sea thousands of kilometres away from the river mouths and related these water masses to the Orinoco and Amazon mouths and plumes. The dark colour is a sign of a high content of dissolved organic matter, which changes the optical properties and colour of these water masses. The analysis of these water masses serves to link the river mouths with patterns far offshore that are stable over time and seasonally recurrent. It is still not clear how SLR will change all these seasonal and spatial patterns. The present patterns of supply and distribution of freshwater, salt, materials and nutrients derived from the continental margin to the open sea are crucial for primary productivity, biogeochemical cycling and oceanic circulation. Any impact of SLR on these patterns will most likely produce important regional changes with unknown consequences.

5.2. Coastal retreat and associated land loss

Based on the application of Bruun's rule, our estimated amount of coastal retreat and associated land loss until 2100 is relatively small but could be even smaller if we could consider and quantify all processes controlling sediment movement in the nearshore area. In particular, shoreline accretion and erosion are relatively complex along the coast of the Orinoco Delta and are influenced by the Amazon River, which is a major contributor of sediment to the Orinoco Delta (Warne et al., 2002). Approximately 1×10^8 tons of Amazon sediments are transported yearly along the South America coast by the Guayana littoral current over a distance of 1600 km to the Orinoco Delta coast, and approximately one-half of this sediment load is deposited along the coast and shelf of the delta (Eisma et al., 1978; Warne et al., 2002). Additionally, approximately 50% of the yearly discharge of 1.5×10^8 tons of Orinoco River sediment is deposited on the delta plain (Meade, 1994). The supply of such large volumes of suspended sediment from both rivers promotes the development of mudflats and mudcapes such as Punta Pescador and Punta Mariusa (Fig. 1), demonstrating the predominance of deltaic vertical accretion processes (Warne et al., 2002). Additionally, the aggradation rate of the Orinoco Delta is approximately 1.3 mm/year and has been constant throughout the 20th century, remaining in balance or even exceeding subsidence and relative SLR (Syvitski et al., 2009). Nevertheless, aggradation/accretion and erosion rates could change during the 21st century. First, to maintain the current balance, the Amazon and Orinoco Rivers should continue to supply large amounts of suspended sediments while sea level rises during this century. However, it is still not clear how climate change will affect the runoff and sediment transportation processes of these rivers (see Section 5.2). In contrast, the construction of modern dams, floodplain engineering practices and similar interventions that decrease sediment delivery to the delta will most likely occur, as is normal in developing countries pursuing economic growth and global progress. In fact, one of the main branches of the Orinoco Delta, the caño Mánamo, was closed by the Volcán Dam in 1965. This engineering project decreased water and sediment runoff and distribution in this branch, and damming generated many negative impacts, e.g., the transformation of freshwater bodies into tidal channels, the loss of arable soils by salinisation and acidification, the creation of backwaters serving as foci of infection, the disappearance of fisheries and the decoupling of several Warao settlements from their traditional socioeconomic patterns (García-Castro and Heinen, 1999; Echezuría et al., 2002; Mikhailova, 2010).

5.3. Inundation and saltwater intrusion

Globally, sea–land interfaces are important sites of biogeochemical processing and the exchange of nutrients, sediments and organisms between marine and freshwater environments (Kristensen et al., 2008). These interactions are also important in determining the composition of the water that produces inundations, on which many ecological and biogeochemical features of the wetland depend. To date, no clear consensus exists on whether or how river discharge, precipitation and water quality have changed during the past decade or if they will be modified by climate change between the present and 2100. Multimodel ensemble projections extending 50–100 years indicate that in much of the Orinoco and Amazon catchments, the mean annual runoff will change less than in other wet tropical regions (10%–40% increase expected) (Milly et al., 2007; IPCC, 2013). Such a conservative scenario suggests that the current balance between fluvial inputs and marine influence may be altered with SLR, leading to the salinisation of nearshore waters by attenuating the dilution effect of river discharge to the ocean. Increases in the distance of seawater intrusion into the caños of the study area may be less than expected. Enhanced water salinity can directly harm aquatic biota and cause the upstream expansion of many euryhaline and halophytic species, whereas stenohaline and non-halophytic species can suffer local extinction. Indirect changes can also occur if taxa that provide refuges and food and/or determine predation pressure are eliminated or added, thereby modifying community function and structure (Nielsen et al., 2003 and literature therein).

The results of the ClimateGEM model suggest that the Orinoco Delta may be submerged by 2100. The inundation scenario depicted by the ClimateGEM model is consistent with many models of this type that forecast that 20–60% of the world's coastal wetlands will be submerged by 2100 (Kirwan et al., 2010), based solely on coastal topography and no other factors which could possible change water levels and inundation


Débé
Siparia
Basse Terre
Moruga
Guayaguayare
Fullarton
Bonasse
San Francique
Guanoco
Pedernales
Caño Colorado
San Jose de Buja
El Respiro
La Horqueta
Los Guires
Corozal
La Culata
San Diego
Mata Palo
Boca de Uracoa
Tabasca
Puerto Amador
Tucupita
Temblador
Mata Venada
Camorra
Uracoa
Coporito
El Pelón
Piedritas
Pena Negra
Morenero
Uverito
Guarucara
Cojoida
Curiapo
Piacoa
Los Pozos
Manoa
Los Barrancos
CIUDAD GUAYANA
19
Caruachi
El Arrozal
El Pao
Upata

extent. A limitation of these global models is the lack of enough resolution for local and regional studies. The trend towards increasing geographical and topographical resolution by decreasing the modelling grid size is a common practice in modern climate change studies and should be attempted in the case of the Orinoco delta. However, studies like the present one have an obvious advantage that is to place the Orinoco delta and its potential future state in a worldwide context thus enabling comparisons with other similar megadeltas and coastal wetlands. We consider our study a first step in the way towards more detailed analyses at local scale without ignoring the global context, possibly by a combination of local, regional and global modelling tools. In particular, our study may serve as a warning on the potential consequences of near-future SLR on the Orinoco delta, enough to justify more detailed studies, but the results are still too preliminary as to serve for conservation planning, adoption/mitigation strategies or legal purposes.

Nonetheless, in spite of the limitation of the ClimateGEM and similar SLR forecast models, sea level will very likely continue to rise beyond 2100 (IPCC, 2013) and sooner or later, the inundation forecast depicted by ClimateGEM, i.e. drowning of the entire delta, will be fulfilled. It is therefore meaningful to discuss the main expected variations in sediment trapping, sediment deposition, biological processes and their likely effect on the deltaic ecosystems along the following paragraphs. At present, wetland zonation in the study area depends not as much on topographic elevation as on the proximity of waterbodies, as the estimated limit of tidal influence is approximately 5–6 km inland. Mangroves and other halophytic vegetation thrive well within this fringe if the mesotopography is suitable (mangroves need flat substrates with a constant sediment supply; they do not grow in environments dominated by coastal erosion). In contrast, communities strictly limited to freshwater and depending solely on precipitation grow towards the centre of the interdistributary plains (Vegas-Vilarrúbia et al., 2010). This pattern is consistent throughout the Orinoco Delta (Warne et al., 2002). The sea-level transgression predicted by the ClimateGEM model would enable saltwater to penetrate far beyond tidal boundaries, gradually drowning freshwater wetlands and causing their collapse. It is well known that salty environments prevent the vegetative and reproductive growth of woody non-halophytes, even at low salt concentrations, by inducing severe physiological dysfunctions and by direct or indirect toxic effects (see Kozlowski, 1997 and literature therein). In the tropics, sedimentary records of past sea level rise events furnish evidence for die-offs of mangroves, replacement of mangroves by open water during periods of rising sea levels, and replacement of mangroves by freshwater forest with sedimentary infill or, sometimes, landwards retreats of mangrove zones (Ellison, 2008 and literature therein). Pollen studies from the nearby Cariaco Basin (northeast Venezuela) indicate that rapid expansions of salt marsh vegetation occurred in the past as responses to rapid SLR associated with northern Atlantic Heinrich events stadials (González and Dupont, 2010). On the northeastern Caribbean coast, a SLR approximately 6000–7000 years before the present enabled the establishment of coastal mangroves (Rull et al., 1999; Urrego et al., 2013). Evidence of such dynamics also exists for the eustatic SLR occurring over the past 150 years (Cohen et al., 2005; Urrego et al., 2013; Gilman et al., 2007). Recently, the salinisation of ground and soil associated with the current SLR has been recognised as a major factor in the reduction of freshwater wetlands and the proliferation of halophytic vegetation (Ross et al., 1994).

Large-scale vegetation shifts such as that predicted in this study are expected to produce enhanced amounts of organic detritus and thus worsen the current depletion of dissolved oxygen in coastal and fluvial waters, with negative consequences for aquatic life. Anoxia, as a consequence of excessive nutrient loading and organic matter decomposition, is an important driver of extinction owing to direct toxicity and large-scale marine and coastal habitat loss, as has been shown for historical and modern periods (Harnik et al., 2012). Unfortunately, increased anoxia and waterlogging also contribute to greenhouse emissions to the atmosphere, especially methane (Kayranli et al., 2010), enhancing the positive feedback loop of global warming (Chapman and Thurlow, 1996).

The past and present studies suggest that wetland vegetation (marsh, mangrove) is able to maintain the surface elevation relative to a rapidly rising sea level via plant growth and the accretion of sediment and organic matter (Morris et al., 2002; Ellison, 2008). Simulations from numerical models quantify the dynamic feedbacks between these compensating factors and SLR-driven inundation and the conditions under which such feedbacks would allow coastal wetlands to adapt to predicted SLR. Combining different models (see Kirwan et al., 2010 and literature therein), it is suggested that the survival and threshold rates above which marshes would be replaced by subtidal environments would depend strongly on sediment availability and tidal range, with high tidal ranges (>4 m) and high suspended sediment concentrations (>20 mg/L) leading to resilience to SLR and conversely. In our case, where the lowest mean sediment load is high (30 mg/L) and the tidal range is considered moderate (mesotidal), we obtain a lowest predicted threshold rate of SLR of approximately 20 mm/year (200 cm/100 year), which is higher than the expected sea level rise by 2100 provided that a collapse of the Antarctic ice sheet will not occur during this period (IPCC, 2013). This rate also appears to be fairly high in comparison with other regional values. Using Holocene analogues, Ellison and Stoddart (1991) and Rull et al. (1999) show that past Caribbean mangroves did not resist SLR rates of 9–12 cm/100 year in the absence of allochthonous sediment input and under the microtidal range of the Caribbean Sea (Kjerve, 1981). Recently, empirical research has focused on better understanding the links between biotic processes and the rates of vertical accretion and surface elevation rates (e.g., McKee 2011).

5.4. Warao populations

With a 1 m sea level rise during this century, our models predict moderate erosion of the deltaic shoreline with subsequent mangrove loss or probable migration landwards, the partial or total inundation of the Orinoco Delta with corresponding losses of freshwater wetlands, and a moderately increased distance of sea–water intrusion into streams, with the loss or displacement of many freshwater taxa. Changes are expected to occur extremely rapidly due to the dynamic nature of deltaic landscapes and the relatively rapid SLR rate, producing more or less abrupt shifts in the Warao's traditional environments and resources. The expected year-round scarcity of freshwater and the loss of important sources of livelihood, e.g., the *Mauritia* palm forest upon which the Warao culture is based, will affect Warao populations strongly and force them to gradually abandon their current settlements and migrate upstream in search of freshwater. *Mauritia* does not tolerate brackish water; in fact, the average salinity of the swamp water associated with *Mauritia* palm forests in the study area is $0.91 \pm 0.74‰$ (Vegas-Vilarrúbia et al., 2010). Depending upon the true extent of marine transgression until 2100 and beyond, migration movements of the Warao may be more or less localised and adaptive or may produce a devastating impact on the already otherwise-vulnerable populations of the Orinoco Delta, threatening their own persistence as a culture and implying the impossibility of continued existence as a distinctive ethnic group. The accumulated traditional knowledge of the Warao establishes them as privileged observers of environmental changes and related impacts. In principle, therefore, they should be able to formulate strategies to maintain their ways of life. However, the combination of

Fig. 6. Modified output maps from the ClimateGEM model application. Above: Orinoco delta. Below: The dark layer represents the area of the delta lying ≤1 m elevation and therefore susceptible of inundation and erosion by 1 m SLR. The blue rectangle represents the study area. Scale 1:10,000,000.

negative effects of SLR with other stressors, e.g., negative acculturation, could trigger non-linear behavioural responses. For example, awareness of impeding changes due to small SLR increases could accelerate their already unstoppable exodus to urban areas, where their survival as a differentiated culture is not feasible. The antiquity of the Warao as residents of the Orinoco Delta is not known because reliable dating does not exist. Likewise, it is not known whether they have previously faced a sea level rise, as sea level reached its current stage 6000–3000 year before the present (Warne et al., 2002). For the Warao people, SLR may be the "coup de grace" and precipitate the disintegration of their culture. Studies of the past suggest that abrupt climate changes similar to that currently underway have had profound impacts on ecosystems and civilisations. Such rapid changes remain in the collective memory of people for a few generations, and this awareness has enabled adaptation or mitigation in response to new conditions, i.e., resilience to change (Hassan, 2009). However, it has also been suggested that climate stress might have precipitated the collapse of declining or vulnerable societies, e.g., the Classic Maya Collapse (deMenocal, 2001; Hassan, 2009).

Note that several important projects have already invested in the Orinoco Delta. These projects are devoted to the conservation of biological and cultural diversity. In 2008, the International Fund for Agricultural Development (IFAD, 2014) launched a support programme (2010–2017) for the Orinoco Delta Warao to establish "a process of territorial development that reinforces cultural identity while protecting and expanding the rights of indigenous peoples and their capabilities for self-governance". The Global Environment Facility (GEF, 2014), a partnership for international cooperation, has allocated funds for the project entitled "Conservation of the Biological Diversity of the Orinoco Delta Biosphere Reserve and Lower Orinoco River Basin" (Novoa, 2014). Climate change appears not to be included in these projects in any way. However, we argue that it should be included if the projects address agriculture and territorial development. The phenomenon of SLR and the global risk that it represents to coastal systems have been known since at least the 20th century (IPCC, 1990). Additionally, early warnings related to the Venezuelan coast have appeared since the last decade of the past century (Volonté and Arismendi, 1995; Olivo, 1997). The chief concern is that large deltas where national and international programmes converge will be profoundly changed or even vanish from the present until 2100, resulting in losses in investments.

6. Conclusions

Unlike other megadeltas, the Orinoco Delta has not received a massive influx of capital to generate economic growth and social development. For this reason, it is not the site of large urban areas or valuable assets and infrastructure that must be protected from SLR. Therefore, it is unlikely that measures or structures and engineering projects designed to stop the flooding of the Orinoco Delta caused by SLR will be implemented, although the risk to important non-material values (biological, cultural and spiritual diversity) is clear. Worldwide, this will be the fate of many important tropical river deltas with similar characteristics, e.g., the Fly, Jaba, Purari, Niger, Rufiji and Zambezi Rivers (Table 6). Biodiversity is an asset on its own and is an important element for many businesses. However, the financial sector is not entirely convinced of its material significance because effective measures to link biodiversity performance to financial performance are still lacking (European Biodiversity Summit, 2012). Note that most tropical deltas are relevant Freshwater Ecoregions of the world, harbouring high

Table 6
Major tropical river deltas of the world. Rivers selected from Huh et al. (2004). "No" means that infrastructures and/or urbanisation are not important (Google Earth). Freshwater ecoregions taken from Abell et al. (2008).

Nr.	River delta	Country	Climate	ID, world freshwater ecoregion	Towns, cities, infrastructure
America					
1	Grijalva	Mexico	Subtropical (BShs)	173, Grijalva–Usumacinta	Yes
2	Magdalena	Colombia	Savanna (Aw)	302, Magdalena–Sinu	Yes
3	Orinoco	Venezuela	Rain forest (Af)	309, Orinoco Delta & Coastal Drainages	No
4	Paraiba Do Sul	Brazil	Savanna (Af)	329, Paraiba do Sul	Yes
5	Sao Francisco	Brazil	Savanna (Aw)	327, S. Francisco	Yes
Asia					
6	Baram	Malaysia	Rain forest (Af)	742, Northwestern Borneo	Yes
7	Chao Phraya	Thailand	Savanna (Aw)	732, Chao Phraya	Yes
8	Fly	Papua, Guinea	Savanna (Aw)	815, Southwest New Guinea–Trans-Fly Lowland	No
9	Ganges–Brahmaputra	India	Rain forest (Am)	709, Ganges Delta & Plain	Yes
10	Irrawaddy	Myanmar	Rain forest (Am)	720, Sitang–Irrawaddy	Yes
11	Jaba	Papua, Guinea	Rain forest (Af)	818, Solomon Islands	No
12	Kelang	Malaysia	Rain forest (Af)	735, Northern Central Sumatra–Western Malaysia	Yes
13	Krishna	India	Humid subtropical (Caf)	714, Southern Deccan Plateau	Yes
14	Mahanadi	India	Savanna (Aw)	713, Northern Deccan Plateau	Yes
15	Purari	Papua, Guinea	Rain forest (Af)	815, Southwest New Guinea–Trans-Fly Lowland	No
16	Red River	Vietnam	Rain forest (Af)	761, Song Hong	Yes
17	Sungai Mahakam	Indonesia	Rain forest (Af)	745, Eastern Borneo	Yes
Africa					
18	Betsiboka	Madagascar	Savanna (Aw)	580, Northwestern Madagascar	Yes
19	Niger	Nigeria	Rain forest (Am)	506, Niger Delta	No
20	Pungwe	Mozambique	Savanna (Aw)	576, Zambezian Lowveld	Yes
21	Rufiji	Tanzania	Savanna (Aw)	564, Coastal East Africa	No
22	Senegal	Senegal	Steppe (BShw)	509, Senegal–Gambia	Yes
23	Tana	Kenya	Savanna (Aw)	567, Tana, Athi & Coastal Drainages	Yes
24	Zaire	Congo	Savanna (Aw)	550, Lower Congo	Yes
25	Zambezi	Mozambique	Savanna (Aw)	561, Lower Zambezi	No
Australia					
26	Burdekin	Queensland	Savanna (Aw)	807, Eastern Coastal Australia	Yes
27	Ord		Savanna (Aw)	805, Arafura–Carpentaria	No

biodiversity as well as important freshwater resources and regulating water flows (Table 6); this panorama will also change with SLR. Therefore, biological and cultural diversity per se are as important as defending valuable assets and infrastructures against SLR and should not be forgotten. From a scientific point of view, the pristine condition of the lower Orinoco Delta makes it a privileged place which to study the effects of an extraordinary Holocene sea level rise. It is a unique opportunity to acquire empirical, first-hand scientific information from many ongoing phenomena that we only know from the past. The study of the effects of SLR on ecological sustainability is highly complex and dependent on geographical location. Thus, a strategic array of physical, biogeochemical and biological monitoring/experimental stations would represent suitable initiatives to fill critical knowledge gaps. This approach would result in general improvements in SLR forecasting models and the depicting of more realistic scenarios for planning or legal purposes, not only for tropical deltas but also worldwide.

To adequately address the fate of the Warao people of the Orinoco Delta, a detailed analysis and assessment of the risks to their culture caused by SLR should be urgently incorporated in programmes aimed at improving their quality of life and retaining their distinctive traits despite the expected loss of their ancestral territory. The Warao people should seek the most appropriate solutions for their adaptation to SLR though sustainability strategies. Their voices should be heard and their concerns considered. If this is not possible, the world will have to mourn the extinction of one of its most original ancestral cultures, with all that this implies in terms of loss of cultural diversity and resources for the future and of traditional knowledge useful for confronting climate change (Couzin, 2007).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.01.056.

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