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BEACH PROCESSES AND SHORE PROTECTION ALONG THE NORTHERN COLOMBIA COAST

PROCESSOS LITORÂNEOS E PROTEÇÃO COSTEIRA AO LONGO DA COSTA NORTE DA COLÔMBIA

PROCESSUS LITTORAUX ET PROTECTION DU RIVAGE LE LONG DE LA CÔTE NORD DE LA COLOMBIE

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ABSTRACT

The shoreline of northern Colombia is located in the tropical zone along the south coast of Caribbean Sea. Its coastal processes are strongly influenced by the northeast trade wind, which results in the dominating northeasterly approaching wave occurring over 95% of the time. This drives a persistent southwestward longshore sand transport. The state of the beach along the generally northeast-southwest trending northern Colombia coast is strongly influenced by this constant unidirectional longshore sediment transport. At locations where this westward longshore sand transport is interrupted, naturally or anthropogenically, beach accretion occurs along the updrift shoreline coupled with erosion at the downdrift side. Natural interruption of longshore transport can be caused by tidal inlets, protruding headland, shoreline orientation change, and nearshore bathymetry variations. Anthropogenic interruption of the longshore transport along the northern Colombia coast is mainly caused by the construction of groins, as well as harbors at some locations. Numerous groins were constructed due to their local success in creating beach accretion at the drift side. However, severe beach erosion occurs along the downdrift shoreline. Shoreline protection along the northern Colombia coast, and coasts in the tropical area in general, should carefully consider the persistent unidirectional longshore sand transport and should not be misguided by the local updrift accumulation as being a successful project.
Key words: Beach erosion. Shore projection. Tropical coast. Longshore sediment transport. Caribbean Sea.

RESUMO

O litoral do norte da Colômbia está localizado na zona tropical ao longo da costa sul do Mar do Caribe. Seus processos costeiros são fortemente influenciados pelos ventos alísios do nordeste, o que resulta na onda dominante de aproximação do nordeste ocorrendo em 95% do tempo. Isso leva a um transporte persistente de areia ao longo da costa sudoeste. O estado da praia ao longo da linha de costa geralmente nordeste-sudoeste da costa norte da Colômbia é fortemente influenciado por este transporte de sedimentos costeiros unidirecionais constantes. Em locais onde esse transporte de areia ao longo da costa oeste é interrompido, natural ou antropogenicamente, o acúmulo de praia ocorre ao longo da linha da costa ascendente, juntamente com a erosão a sotamar. A interrupção natural do transporte litorâneo pode ser causada por entradas de marés, promontórios salientes, mudança de orientação da linha costeira e variações da batimetria próxima à costa. A interrupção antropogênica do transporte de longo curso ao longo da costa norte da Colômbia é causada principalmente pela construção de molhes costeiros, bem como de portos em alguns locais. Inúmeros molhes costeiros foram construídas devido ao seu sucesso local na criação de acreção de praia no lado da deriva. No entanto, ocorre severa erosão da praia ao longo da costa a jusante. A proteção da linha costeira ao longo da costa norte da Colômbia, e costas na área tropical em geral, deve considerar cuidadosamente o transporte persistente de areia costeira unidirecional e não deve ser mal orientada pelo acúmulo local de corrente ascendente como um projeto de sucesso.
Palavras-chave: Erosão de praia. Projeção de costa. Costa tropical. Transporte de sedimentos litorâneos. Mar do Caribe.

RÉSUMÉ

Le littoral du nord de la Colombie est situé dans la zone tropicale le long de la côte sud de la mer des Caraïbes. Ses processus côtiers sont fortement influencés par l'alizé du nord-est, qui se traduit par la vague dominante d'approche du nord-est se produisant plus de 95% du temps. Cela entraîne un transport de sable long-littoral persistant vers le sud-ouest. L'état de la plage le long de la côte nord-est-sud-ouest de la Colombie, généralement orientée nord-est/sud-ouest, est fortement influencé par ce transport constant unidirectionnel de sédiments côtiers. Aux endroits où ce transport de sable vers l'ouest est interrompu, naturellement ou anthropiquement, l'accrétion des plages se produit le long du rivage ascendant, associée à une érosion

du côté descendant. L'interruption naturelle du transport hauturier peut être causée par des estuaires, des promontoire saillant, par un changement d'orientation du littoral et des variations bathymétriques près du littoral. L'interruption anthropique du transport côtier le long de la côte nord de la Colombie est principalement causée par la construction de jetées, ainsi que de ports à certains endroits. De nombreuses jetées ont été construites en raison de leur succès local dans la créati d'accrétions de plage du côté de la dérive. Cependant, une grave érosion des plages se produit le long du rivage descendant. La protection du littoral le long de la côte nord de la Colombie, et des côtes de la zone tropicale en général, devrait soigneusement considérer le transport de sable long-littoral unidirectionnel persistant et ne devrait pas être trompée par l'accumulation locale ascendante comme un projet réussi.
Mots clés: Érosion des plages. Projection du rivage. Côte tropicale. Transport de sédiments côtiers. Mer des Caraïbes.

INTRODUCTION

Coasts along tropical oceans, especially the sandy beaches, are arguably one of the most beautiful earth environments with crystal warm water and colorful diverse marine life. Being popular tourist destinations as well as desirable living areas, tropical coasts can be very valuable economically. Along the Caribbean Sea and tropical Atlantic Ocean, tourism along the coast, particularly at sandy beaches, constitutes the major economical income for many countries and communities. Tropical coasts are very vulnerable to numerous natural and anthropogenic stressors. Managing this delicate environment is a challenging task.

Areas in tropical zone, both land and ocean, are dominated by the trade winds, aka, the easterlies. The trade winds blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. In the coastal areas, the trade winds generate waves approaching from the easterly directions constantly. If the coastline extends in a generally east-west direction as in the case of northern Colombia, the easterly waves would approach the shoreline at a highly oblique angle. These persistent highly oblique approaching waves from the east would drive constant westward longshore sediment transport. The coastal conditions, i.e. being accretionary or erosive, are significantly controlled by the continuity of the westward longshore sediment transport. When interrupted, sediment accumulation would occur on the updrift (east) side and persistent erosion along the downdrift (west) side.

In addition to the dominant westward unidirectional forcing as driven by the trade winds, the tropical coasts of the Caribbean Sea and Atlantic Ocean are characteristic of very limited terrestrial sediment input. The warm clear ocean water and the lack of terrestrial sediments-nutrients input constitute the main reasons for the widespread development of coral reefs. The sandy beaches often occur landward of, and therefore be protected by, the barrier reefs and their associated sensitive habitats such as seagrass beds and mangrove mangals. Often, the sandy beaches are just narrow and thin strips of sand deposited over limestone, with the sand being produced within the carbonate environment or eroded from the barrier reefs by energetic waves associated with storms.

When this narrow strip of sand, i.e., the beach, is eroded by tropical storms, which occur frequently in the Caribbean and tropical Atlantic Ocean, restoring the eroded beach can be very challenging. The extremely delicate coral reefs and their associated sensitive environments prevent large-scale beach fill through dredging sand from offshore. Furthermore, it is often difficult to find beach compatible sand resources even if environmental impacts are ignored. The complicated beach morphology, e.g., pocket beaches associated with limestone outcrops, often makes large-scale beach fill not practical even if large amounts of sand exist offshore. These environmental restrictions combined with morphological characteristics have led to applications of structures, particularly groin fields, as main measures of shore protection.

In this paper, I discuss the dominant processes that drive the beach morphodynamics along tropical oceans, using northern Colombia coast as a case study. Coastal management and shore protection considerations incorporating adequate considerations of temporal and spatial scales, e.g., not inducing extensive and persistent downdrift erosion, are discussed based on several case studies.

STUDY AREA

The northern Colombia coast is located along the south side of the Caribbean Sea in the tropical zone. Roughly 600 km stretch of northern Colombia coast, from Barranquilla eastward to Cabo De La Vela, is studied here. The latitude and longitude of the west and east boundaries of the study area are 11.1° north 74.9° west and 12.2° north 72.0° west, respectively (Figure 1). The general meteorological and oceanographic conditions are dominated by the northeast trade winds (THOMAS; NICOLAE-LERMA; POSADA, 2012). This is clearly illustrated in the regional wave climate as discussed in the following section. Northeasterly approaching waves occur by far the most frequently, driving a persistent westward longshore sediment transport.

The general shoreline orientation in the study area (Figure 1) is roughly 60 degrees, or striking WSW-ENE. The relatively straight shoreline is interrupted by two protruding headlands, Santa Marta and Cabo De La Vela. A broad shoreline orientation change occurs near Riohacha. To the west, the shoreline orientation is roughly 68 degrees, while to the east, the orientation is roughly 52 degrees, or a change of 16 degrees around the broad Riohacha headland. As discussed in the following, these shoreline orientation changes play a significant role in beach processes. The general conditions of this coast are discussed in Posada e Henao (2008).

Figure 1 - The northern Colombia coast is located on the south side of the Caribbean Sea. Two short-term wave measurement projects were conducted. The locations of both the actual and WAVEWATCHIII (WWIII) numerical wave stations are shown.

Source: Google Earth.

Rocky coast dominates at both the Cabo De La Vela and Santa Marta headlands, with pocket sandy beaches distributing in the numerous embayment areas (Figure 2). Sandy beaches distribute along most of the coastline except at the headlands. Numerous rivers discharge into the Caribbean Sea along this section of the coast, with several relatively large ones shown in Figure 1. The turbidity associated with the river discharge is likely the reason that this stretch of the tropical coast is not dominated by coral reefs and reef type shoreline, except along part of the Santa Marta headland. Most of the sandy beaches distribute directly along the mainland (Figure 3). The westward longshore sand transport is apparently illustrated in this example from Riohacha by the sand impoundment along the east updrift side of the long groin (Figure 3).

Figure 2 - Example of rocky coast at Santa Marta headland. Photo by Ping Wang

Source: The author

Figure 3 - Example of sandy beach at Riohachia. Source: Photo by Ping Wang. The aeril photo inset i from Google Earth.

Source: The author

Several spit type barrier islands extend along this stretch of coastline. The longest barrier island extends from the just west of the Santa Marta headland to just east of Barranquilla. Based on aerial photos, all the barrier islands appear to be originated from westward spit growth and are of the wave-dominated type (DAVIS; HAYES, 1984). All the tidal inlets are quite narrow with small flood and ebb deltas. This is controlled by the fact that the tidal range is mostly less than 0.3 m even during spring tides, while wave forcing (discussed in detail in the following) is relatively strong. Therefore, beach-inlet interaction only has localized influences on beach erosion and accretion, and is secondary to the dominant westward longshore sediment transport.

Wave plays a dominant role in shaping the coastline, particularly for the studied coast since it is the dominating forcing, causing beach erosion or accretion. Therefore, characterizing the wave conditions is crucial to the understanding of coastal processes. No long-term wave measurements were conducted along this stretch of the coast. However, short- term wave measurements (less than 2 months) were conducted at two locations (Figure 1) and were available on the US NOAA NDBC (National Oceanographic and Atmospheric Administration National Data Buoy Center) website. Longer-term computed wave data can be obtained from NOAA's hindcast numerical model WAVEWATCHIII (WWIII) (https://polar.ncep.noaa.gov/waves/). WWIII is a community wave modeling framework that includes the latest scientific advancements in the field of wind-wave modeling and dynamics (WAMDIG, 1988; KOMEN *et al*., 1994; TOLMAN, 1992; BOOIJ; HOLTHUIJSEN, 1987; TOLMAN, 2002a; TOLMAN 2002b).

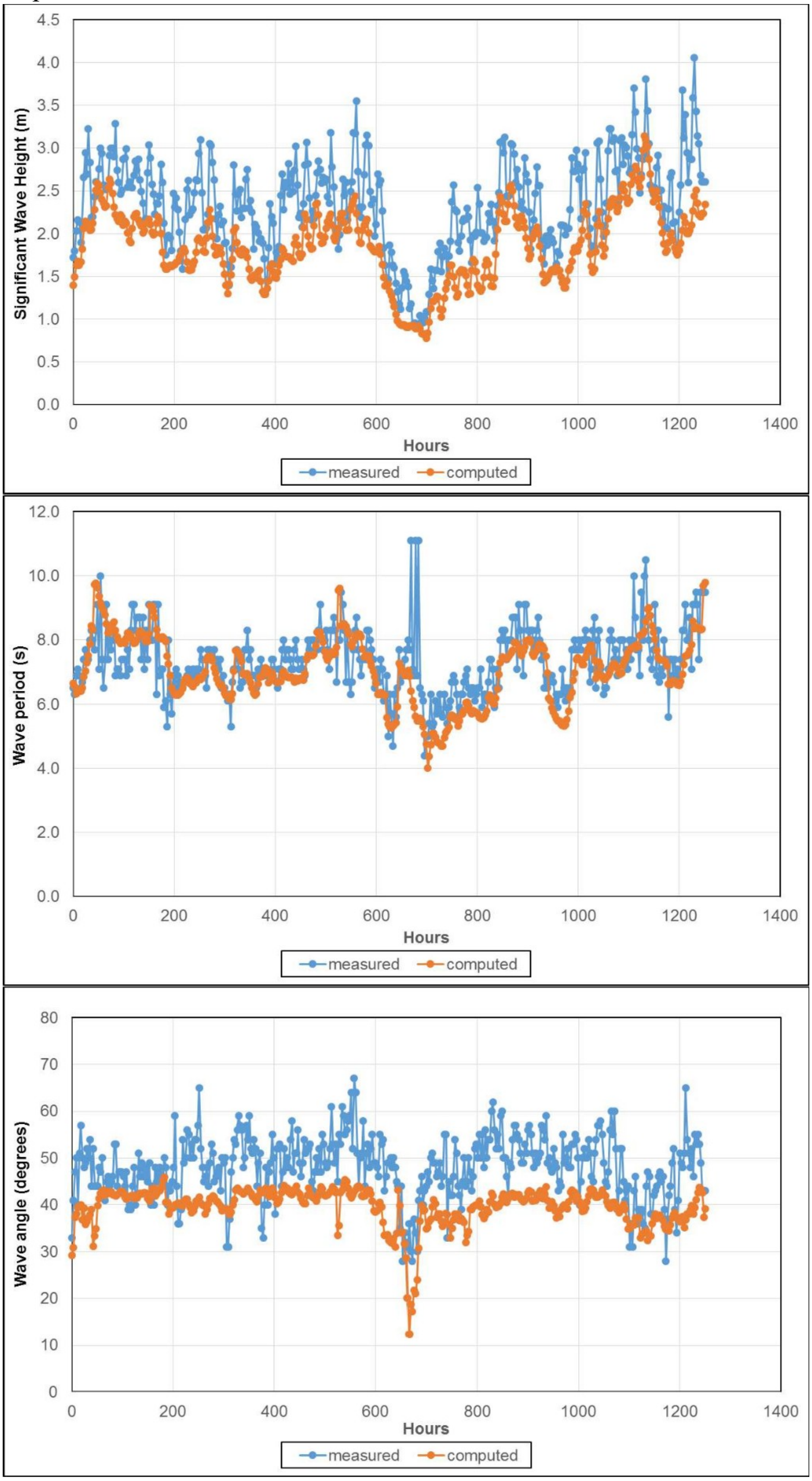
The computed wave conditions are available from February 2005 to present. In this study, computed wave conditions during a 9-year period from the beginning of 2006 to the end of 2014 were analyzed to characterize the wave conditions along the northern Colombia coast. The locations of the WWIII numerical wave station used in this study to quantify the wave climate are also shown in Figure 1. The computed significant wave height, peak wave period and principal wave direction are compared with the measured wave conditions at the same locations, as discuss in the following section, to ensure the accuracy of the WWIII model for the study area.

METHODOLOGY

Nearshore wave conditions are strongly influenced by the nearshore bathymetry. Therefore, accurate nearshore bathymetry data are crucial to accurately modeling the nearshore wave field and the understanding of the nearshore processes. A beach profile and bathymetry survey along the entire study area (Figure 1) were conducted by this study. The beach profile survey was conducted following the traditional level-and-transit procedure. The bathymetry survey that extends the beach profiles seaward to approximately 10 m water depth was conducted using a precision echo sounder and a GPS (Global Positioning System) mounted on a vessel. One profile was surveyed approximately every 1 km along the entire 600 km study area. In areas of special interest, e.g., at erosional hotspots, much denser survey coverage was executed. A total of 270 sediment samples were also collected on the beach along the entire studied coast. The up-to-date nearshore bathymetry data are used in the modeling of nearshore wave field.

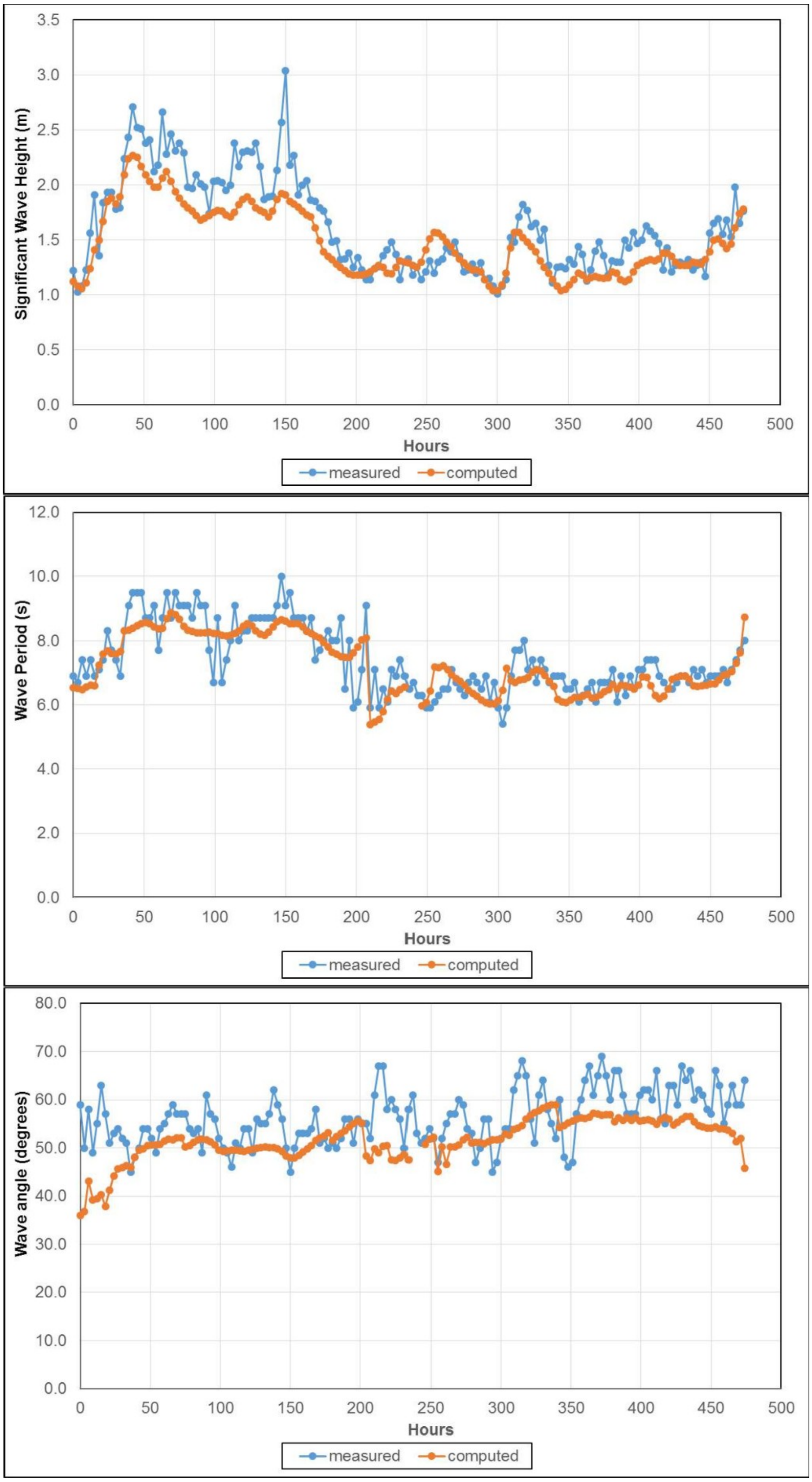
The wave propagation patterns along the northern Colombian coast were investigated using the CMS-Wave model (http://cirp.usace.army.mil/wiki/CMS-Wave) (LIN; DEMIRBILEK; MASE, 2011; WANG; BECK; ROBERTS, 2011). For this study, offshore wave data obtained from the WWIII model, as discussed in the following, were used as input to the CMS-Wave. JONSWAP type wave spectra were generated based on wave height and period.

Figure 4 - Comparison of measured and calculated significant wave height at station 41194 near Barranquilla.



Source: The author

Figure 5 – Compariso'n of measured and calculated significant wave height at station 41193 near Puerto Bolivar.



Source: The author

The wave climate was analyzed based on a 9-year dataset of computed wave conditions by the WWIII model. In order to examine the accuracy of the computed wave conditions, the modeled and measured wave conditions were compared. The short-term measured wave conditions by DIMAR, which are available at the NOAA NDBC website (Figure 1), were obtained and compared with the computed wave by WWIII. Figures 4 and 5 illustrate the comparison between the measured and computed wave height, wave period, and wave direction at the two locations, one offshore Barranquilla (station 41194) near the western boundary of the study area and one offshore Puerto Bolivar (Station 41193) near the eastern boundary.

Overall, the computed wave conditions match the measured wave conditions reasonably well at both locations (Figures 4 and 5). The computed wave heights are generally lower than the measured wave height with less temporal variation. At the offshore Barranquilla site, the average computed wave height during the period of verification, from 12/23/2008 to 02/13/2009, is 1.86 m. This is nearly 20.7% lower than the measured significant wave height of 2.34 m. Computed and measured wave period matched well, on average 7.08 s computed versus 7.36 s measured. The computed wave period is about 3.7% less than the measured period. The incident wave angle also matched well, on average 40 degrees computed versus 48 degrees measured. The standard deviation of the incident wave angle is 6.6 degrees for the measured waves and 4.1 degrees for the computed waves, suggesting the waves are approaching from a rather constant angle, as expected due to the dominance of the trade winds.

At the offshore Puerto Bolivar site, the average computed wave height during the period of verification, from 12/23/2008 to 01/11/2009, is 1.47 m. This is about 9.5% lower than the measured significant wave height of 1.63 m. It is worth noting that the average wave height along the Barranquilla coast is 43.6 % higher than that along the Puerto Bolivar coast to the west, 1.63 m versus 2.34 m. Computed and measured wave period matched well, on average 7.23 s computed versus 7.41 s measured. The computed wave period is about 2.4% less than the measured period. The incident wave angle also matched well, on average 52 degrees computed versus 56 degrees measured, with small standard deviation suggesting a constant incident wave angle. Based on the above comparison of measured and computed wave conditions, the WWIII model produced accurate wave data for the northern coast of Colombia. It is therefore, acceptable to use the computed wave data for the analyses of coastal processes.

Time-series aerial photos available from Google Earth are analyzed to depict beach/dune changes at various locations. Since no time-series beach surveys are available in the study area, Google Earth aerial photos provide a valuable and the only tool to depict historical shoreline and duneline changes. Aerial photos from 2005 to 2016 are available on Google Earth for the study area. Limited information on storm impact along the studied coast is available in the literature. In this study, historical hurricane tracks from the US NOAA National Hurricane Center are analyzed to assess potential impacts of tropical storms to the northern Colombian coast.

RESULTS

The coastal processes along the northern Colombia coast are analyzed based on statistical wave climate as summarized from the 9-year WWIII data. Storm impacts are estimated based on the proximal passages of tropical storms during the past 150 years as obtained by the US National Hurricane Center database. Nearshore wave fields are simulated using the CMS-Wave model. The wave field provides insights on sediment transport patterns and gradients and therefore trends of beach erosion and accretion, which are essential in developing shore-protection methods.

Characteristic of Regional Wave Climate

Nine-year wave data from six numerical WAVEWATCHIII (WWIII) wave stations along the northern Colombia coast were analyzed to characterize the regional wave climate. Two of the stations, WWIII44 and WWIII55 (Figure 1), roughly in the middle of the study area are discussed here. Station 44 is located approximately 10 km offshore the Santa Marta headland. Station 55 is located about 30 km offshore Riohacha where a broad shoreline orientation change occurs. The angle of incident waves plays an essential role in driving longshore sediment transport (WANG; KRAUS; DAVIS JR., 1998; WANG, 1998; WANG; KRAUS, 1999; SMITH *et al*., 2009) and subsequently beach morphology change. The incident wave angles were grouped into 16 brackets of 22.5 degree each (Table 1). The frequency of occurrence for waves in each bracket was analyzed. The average wave height and dominant period, the top 2% wave height and dominant period, and top 1% wave height and dominant wave period in each wave-angle bracket were calculated.

Offshore Santa Marta headland the waves approach the coast from the NE angle (i.e., from 33.75 to 56.249 degrees) at about 92.2% of the time (Table 1). The second most frequent incident wave angle is from ENE (i.e., from 56.25 to 78.749 degrees) at 3.2%. The third most frequent incident wave angle is from NNE (i.e., from 11.25 to 33.749 degrees) at 1.5%. Overall, the waves approaching from N-E quadrant at nearly 97% of the time, apparently dominated by the trade winds. The NW incident waves occur about 1% of the time. The rest of the 12 incident wave directions are all less than 1% of the time each, and totaling 2.1% of the time over the 9-year period from 2006 to 2014. Furthermore, the average wave heights from the 12 less frequent incident wave angles are considerably lower than the dominant NE incident waves. The NE incident wave propagates roughly parallel to the shoreline, driving a persistent westward longshore sediment transport nearly all the time.

The highest wave as computed by the WWIII model during the 9-year period from 2006 to 2014 was 3.4 m, which is much lower than typical high waves generated by strong tropical storms. This is consistent with the fact that the northern coast of Colombia has not been hit directly or closely by tropical storms over the past 30 years, as discussed in more detail in the following. On average, the NE approaching waves are 1.6 m high with an average dominant wave period of 7.0 seconds (Table 1) offshore Santa Marta headland. This rather energetic average wave condition is related to the strong and persistent northeast trade winds. As a matter of fact, the northeast incident waves are the highest on average as compared to the waves from all other directions (Table 1). The average of the top 2% highest waves from the NE direction is 2.87 m with an average dominant wave period of 8.19 s. The top 1% of the highest waves have an average wave height of 2.99 m with a period of 8.32 s. The rather similar top 1% and 2% highest wave conditions is consistent with the fact that the study area is not significantly influenced by extreme storms and therefore extremely high storm waves, which should have significantly influenced the top 1% highest wave conditions.

Numerical wave Station WWIII55 is located offshore Riohacha and to the east of the Santa Marta station as discussed above. As shown in Table 2, similar to the case at Santa Marta headland, the waves at Riohacha area also approach the coast most frequently from the NE angle (i.e., from 33.75 to 56.249 degrees) at about 92.2% of the time. The second most frequent incident wave angle is from ENE (i.e., from 56.25 to 78.749 degrees) at 3.0%. The third most frequent incident wave angle is from NNE (i.e., from 11.25 to 33.749 degrees) at 1.7%. Overall, the waves approaching from N-E quadrant at nearly 98% of the time, apparently dominated by the trade wind, as expected. The W and NW incident waves occur at about 1% of the time, respectively. The rest of the 11 incident wave directions are all far less than 1% of the time each, and totaling 1.2% of the time over the 9-year period from 2006 to 2014. Furthermore, the average wave heights from the 11 less frequent incident wave angles are considerably lower than the dominant NE incident waves. The highest wave as computed by the WWIII model during the 9-year period was 3.1 m.

Table 1 - Statistical wave conditions at Station WWIII44 about 10 km offshore Santa Marta headland. The highlighted rows indicate onshore directed waves

		% occurrence	average sig H	average wave period	top 2% sig H	top 2% wave period	top 1% sig H	top 1% wave period
Direction	Direction range Degrees		m	S	m	s		
N	348.75-11.249	0.32	0.81	6.64	2.55	8.30	2.61	8.23
NNE	11.25-33.749	1.54	1.39	7.31	2.70	8.88	2.75	8.81
NE	33.75-56.249	92.20	1.61	7.00	2.87	8.19	2.99	8.32
ENE	56.25-78.749	3.15	0.64	7.51	1.40	9.02	1.60	10.63
E	78.75-101.249	0.01	0.00	0.00	0.00	0.00	0.00	0.00
ESE	101.25-123.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SE	123.75-146.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SSE	146.25-168.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	168.75-191.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SSW	191.25-213.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SW	213.75-236.249	0.09	0.85	3.86	1.09	3.98	1.09	3.98
WSW	236.25-258.749	0.24	0.65	4.07	1.09	4.54	1.09	4.54
W	258.75-281.249	0.71	0.78	5.70	1.80	7.81	1.85	7.58
WNW	281.25-303.749	0.37	0.70	6.26	2.11	8.71	2.14	8.67
NW	303.75-326.249	1.03	1.03	7.61	2.15	8.93	2.18	8.81
NNW	326.25-348.749	0.36	0.84	6.70	2.36	7.80	2.40	7.90

Source: The author

On average, the NE approaching waves are 1.3 m high with an average dominant wave period of 7.0 seconds (Table 2). This rather energetic average wave condition is generated by the strong trade winds. As a matter of fact, the NE and NNE incident waves are the highest on average as compared to the waves from other directions (Table 2). The average of the top 2% highest waves from the NE and NNE directions are 2.34 m and 2.61 m, respectively, with an average dominant wave period of 8.09 s and 8.54 s, respectively. The top 1% of the highest waves from NE and NNE have an average wave height of 2.44 m and 2.73 m, respectively with a period of 8.27 s and 8.61 s, respectively (Table 2). The rather similar top 1% and 2% highest wave conditions is consistent with the fact that the study area is not significantly influenced by extreme storms, which should have influenced the top 1% highest wave conditions. Compared to Station WWIII44 to the west at Santa Marta headland, waves computed at Station WWIII55 are lower. The average wave height over the 9-year period at Station WWIII55 is 1.31 m, which is 15.5% less than the average wave height of 1.55 m at Station 44. Wave shadowing by the protruding headland to the east of the study area (Figure 1) may be attributed to the increasing wave height to the west.

Table 2 - Statistical wave conditions at Station 55 about 30 km offshore Riohacha areas. The onshore directed waves are highlighted

		% occur-rence	average sig H	average wave period	top 2% sig H	top 2% wave period	top 1% sig H	top 1% wave period
direction	direction		m	s	m	S		
N	348.75-11.249	0.28	0.91	7.53	2.06	8.43	2.66	8.26
NNE	11.25-33.749	3.00	1.37	7.28	2.61	8.54	2.73	8.61
NE	33.75-56.249	92.21	1.34	7.03	2.34	8.09	2.44	8.27
ENE	56.25-78.749	1.66	0.58	7.45	1.17	8.69	1.27	10.24
E	78.75-101.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ESE	101.25-123.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SE	123.75-146.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SSE	146.25-168.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	168.75-191.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SSW	191.25-213.749	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SW	213.75-236.249	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WSW	236.25-258.749	0.02	0.35	5.47	0.65	6.72	0.65	6.72
W	258.75-281.249	0.93	0.77	5.59	1.76	7.16	1.81	6.99
WNW	281.25-303.749	0.56	0.80	6.23	2.19	8.78	2.21	8.81
NW	303.75-326.249	0.96	0.95	7.75	1.98	8.80	2.03	8.82
NNW	326.25-348.749	0.38	0.75	6.84	2.06	7.81	2.21	7.76

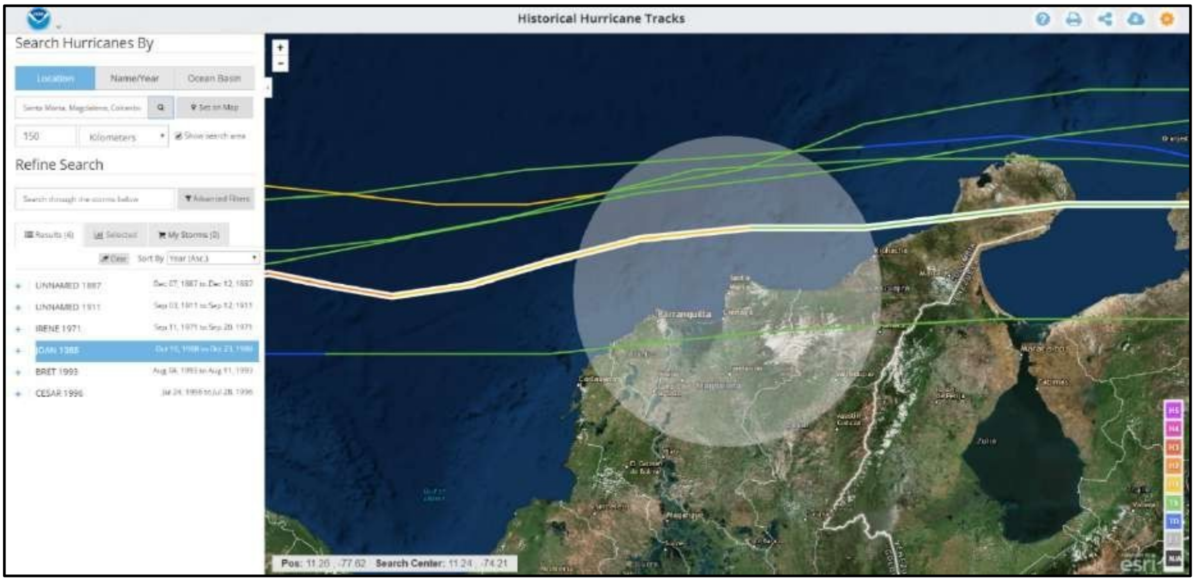
Source: The author

Impacts of Tropical Storms

Extreme energetic conditions associated with direct hit or nearby passage of tropical storms can have significant and long-lasting impacts on coastal morphology. Figure 6 illustrates the historical tropical storms and hurricanes that have passed within 150 km of Santa Marta since 1850 based on the database of the US National Hurricane Center. This covers the western half of the study area. Only six storms passed within 150 km of Santa Marta since 1850. Four of the six passed pretty far from the coastline and were of Tropical Storm strength. No substantial impact to the coast is expected. The most significant storm is Hurricane Joan in 1988 as highlighted in Figure 6, which was a category 2 hurricane when it passed within 70 km from the study area. No wave data are available during the passage of this hurricane. It is not clear if there is systematic documentation of the storm impact along the coastline. Regardless, this storm passed the study area nearly 30 years ago, its effect to present beach morphology should not be significant.

Figure 7 illustrates the historical tropical storms and hurricanes that have passed within 150 km of Manaura, about 55 km east of Riohachia, since 1850. This covers the eastern portion of the study area. A total of ten tropical storms passed through this area. The most nearby tropical storm passage was still Hurricane Joan in 1988. However, Joan was a strengthening Tropical Storm when it passed this section of the coast. Another significant hurricane passage was an unnamed category 3 hurricane in 1892. No wave data are available during the passage of this hurricane. It is not clear if there is systematic documentation of the storm impact along the coastline.

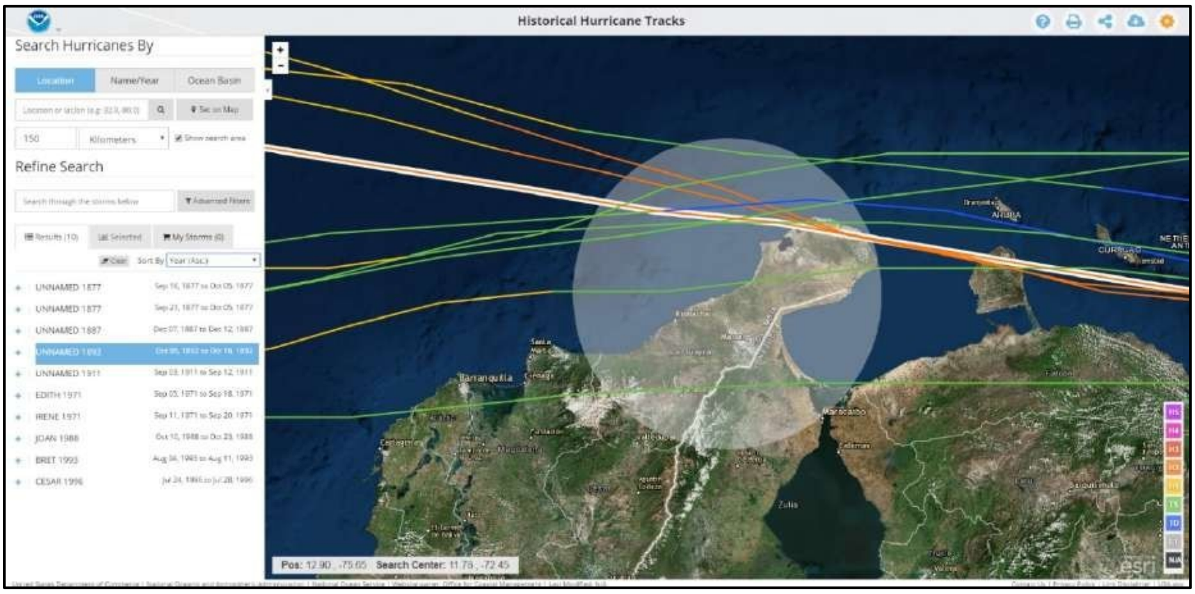
Figure 6 - Historical hurricanes that passed nearby Santa Marta since 1850. The highlighted track is that of Hurricane Joan in 1988



Source: Historical hurricane tracks from NOAA: https://coast.noaa.gov/hurricanes/#map=4/32/-80

Overall, the northern coast of Colombia has not been significantly impacted by strong tropical storms over the past 30 years. This is also reflected in the relatively low extreme wave height in the wave climate between 2006 and 2014 as discussed above. Therefore, the coastal processes are dominated by the persistent westward longshore sediment transport driven by the northeasterly trade winds and subsequent easterly approaching waves as discussed above.

Figure 7 - Historical hurricanes that passed nearby Manaure since 1850. The highlighted track is that of an Unnamed storm in 1892.



Source: Historical hurricane tracks fromNOAA: https://coast.noaa.gov/hurricanes/#map=4/32/-80

Nearshore Wave Conditions Based on Numerical Wave Modeling

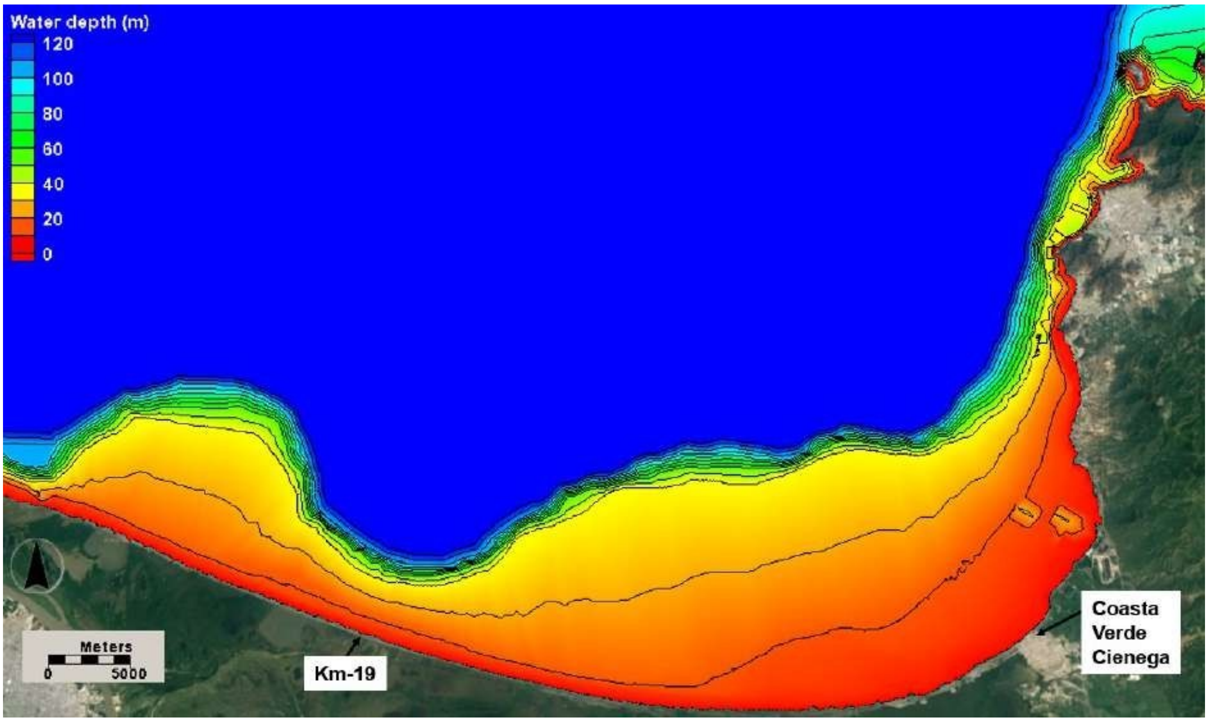
Wave propagation patterns in two characteristic areas were modeled using the CMS-Wave. The goal of the wave modeling here is to investigate the influence of protruding headlands and shoreline orientation changes on regional scale (~50 km) beach processes. Specifically, beach erosion or accretion is caused by a gradient in sediment transport rate, dominantly westward longshore transport rate in this case. When more sand is moving into a particular stretch of beach than moving out, i.e., with a positive transport gradient, beach accretion at that site occurs. In contrary, when more sand is moving out of a particular beach than moving into it, i.e., with a negative transport gradient, beach erosion at that site occurs. Regional scale wave modeling provides valuable information for the analysis of potential sediment transport gradients. In the following, the influences of Santa Marta Headland and shoreline orientation change at Riohacha on nearshore wave field are examined. Statistical wave conditions as summarized in Tables 1 and 2 are used as input wave conditions for the modeling.

Santa Marta – Barranquilla Area: Influence of Headland

The wave modeling domain and bathymetry for the Santa Marta – Barranquilla area are shown in Figure 8. Two sections of severely eroding beach, the km-19 coast and Coasta Verde Cienega as indicated in Figure 8, are included in this modeling domain. Beach morphology changes at these two locations are discussed in the following sections as case studies. The nearshore bathymetry to roughly 10 m water depth and the beach profiles were surveyed by this study. The bathymetry beyond 10 m water depth was digitized from south Caribbean navigation charts. Figure 8 illustrates the bathymetry of continental shelf till the water depth of 120 m. The area with water depth of greater than 120 m is illustrated with one color in order to more clearly illustrate the bathymetric characteristics of the continental shelf. Since the dominant wave periods are less than 10 s, patterns of wave propagation should not be significantly influenced by water deeper than 120 m. Several distinctive bathymetric characteristics can be identified from Figure 8. The continental shelf is very narrow around the Santa Marta headland, as typical of rocky headlands. The continental shelf is the widest around the bent, or offshore Coasta Verde Cienega study site. The shelf becomes quite narrow, roughly 5 km wide, offshore the km-19 stretch. Although all eight onshore directed wave cases were modeled, the wave field associated with the dominant NE approaching wave, which occurs over 92% of time with the most energetic waves (Table 1), is illustrated and discussed in detail in the following.

The protruding Santa Marta headland has significant influence on the wave field, particularly to the west of the headland due to the easterly approaching wave. A wave shadow zone occurs to the west of the headland, as expected. For the dominant NE incident wave, the edge of the shadow zone of Santa Marta headland is in the vicinity of the km-19 site (Figure 9). Substantial westward wave-height increase occurs at the km-19 site. This combines with wave focusing associated with the narrow continental shelf (Figure 8) leads to a significantly higher wave at the km-19 site than the wave to the west (Figure 9). This westward wave- height increase leads to a negative longshore sand transport gradient, i.e., more sand is being transported to the west from the km-19 site than sand being transported into the site. This negative transport gradient is responsible for the aggressive beach erosion at the km-19 site, as discussed in the following section. It is worth emphasizing that the NE incident wave occurs over 92% of the time and has the greatest wave height as compared to waves from other directions except the slightly higher wave from NNE (Table 1). This negative transport gradient persists over 92% of the time. The situation is much intense during energetic conditions, e.g., for the top 2% and 1% wave heights, because the influence of the narrow continental shelf is more significant for the longer period higher waves.

Figure 8 - Regional wave modeling grid from Santa Marta headland to Barranquilla.

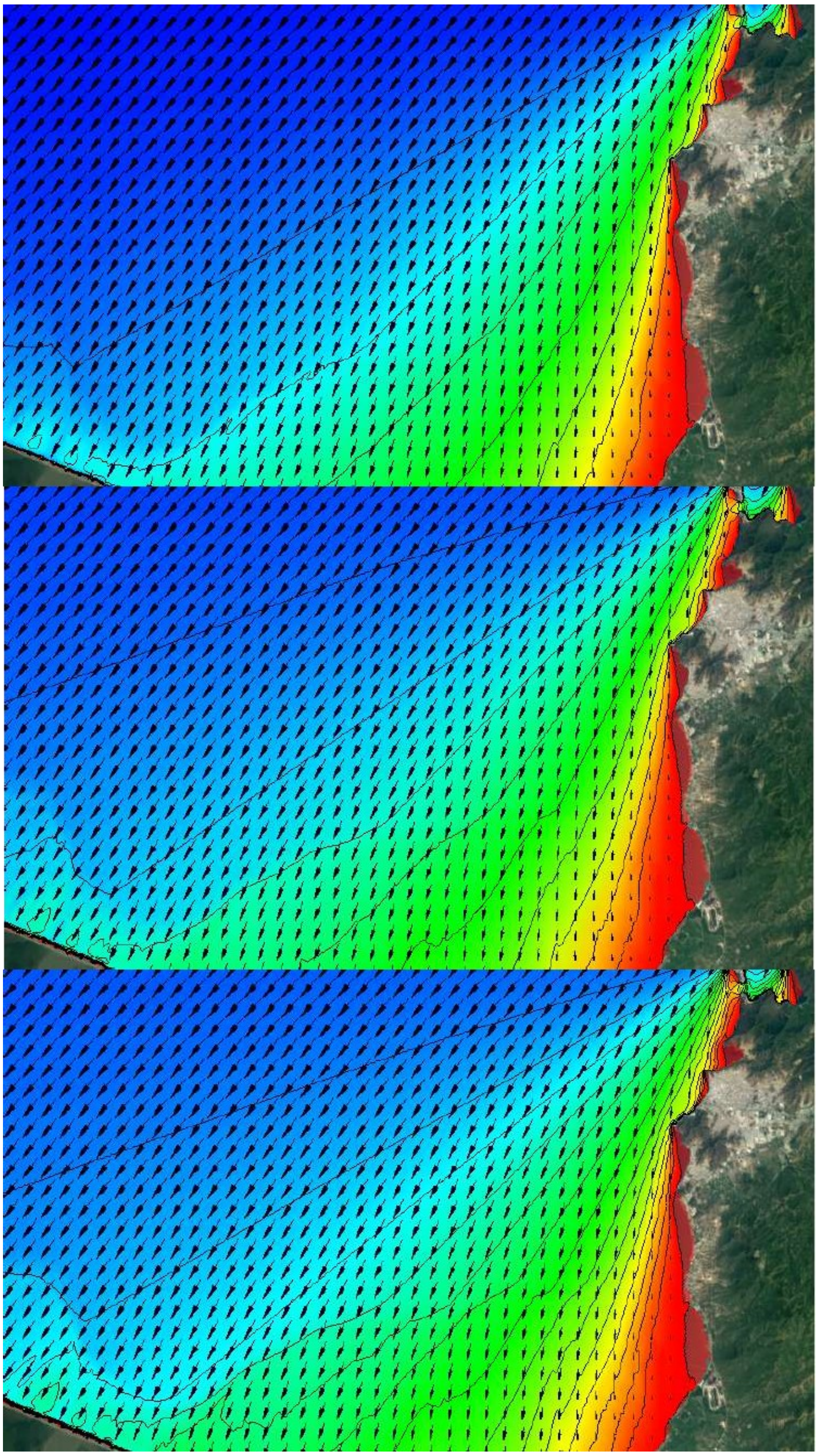


Source: The author.

The west flank of the Santa Marta headland protrudes to the west (Figure 8). This particular morphology creates a secondary wave shadow zone near the headland (Figure 9). The edge of this secondary shadow zone is located in the vicinity of Coasta Verde Cienega, which is another erosional hot spot along this stretch of the coast. Although the wave height along the Coasta Verde Cienega stretch is much lower than that along the km-19 stretch due to the shadowing of the Santa Marta headland, the wave-height gradient created by the secondary shadowing still resulted in aggressive beach erosion. The beach morphology changes there is discussed in the following section.

The wave shadowing by the headland also occurs for the rest of the seven onshore directed wave conditions as summarized in Table 1. Due to the different incident angles, the shapes of the shadow zone are different. In general, the shadow zone is wider for more easterly approaching waves and narrower for the rare westerly approaching waves. The secondary shadow zone is not as significantly influenced by the incident wave angle since it is partly caused by the over-hanging west flank of the headland (Figure 8). The NNE incident wave has similar shadow zone as compared to the NE wave. Since NE and NNE waves occur over 95% of the time and have the highest wave by a large margin, they largely dominate the beach processes. In addition, the substantial variation of the continental shelf width also has a considerable influence on the nearshore wave conditions.

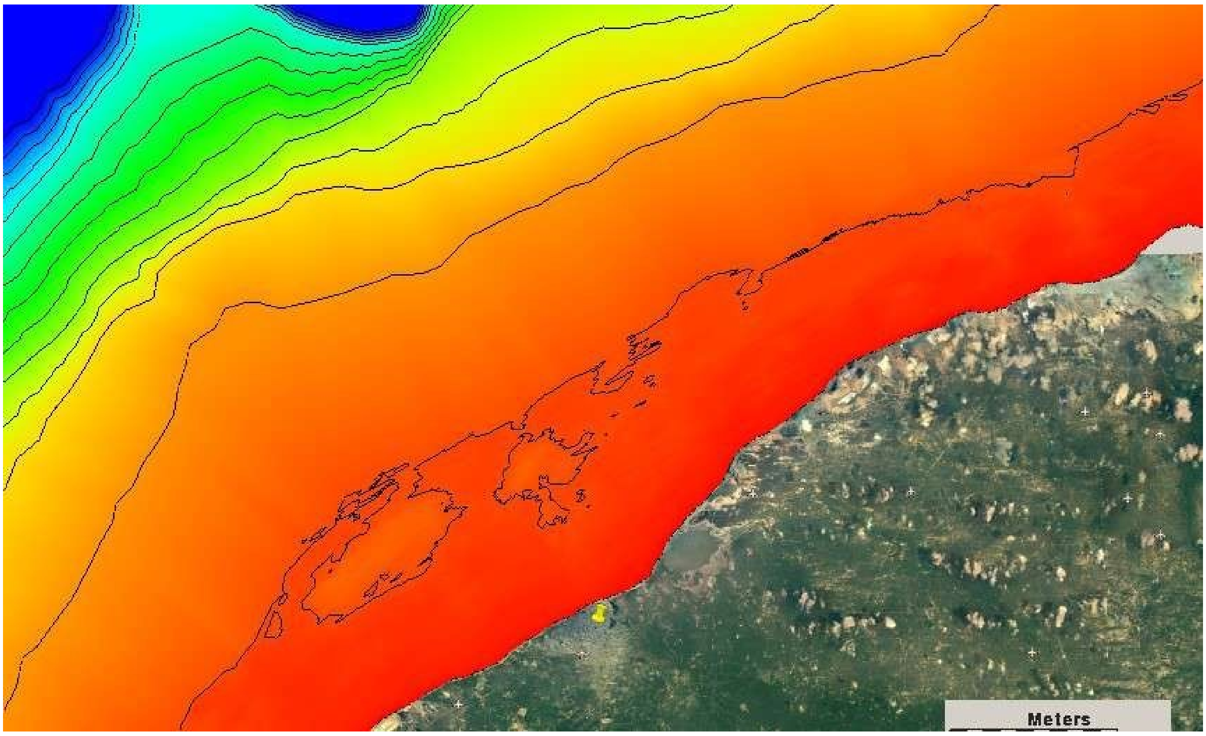
Figure 9 - Regional wave modeling results for NE (45 deg) approaching wave: upper panel: average wave condition; middle panel: top 2% wave condition; lower panel: top 1% waveRiohacha Area: Influence of Shoreline Orientation Change



Source: The author

The Riohacha area is characteristic of a gentle shoreline change. The shoreline orientation is roughly 68 degrees along the eastern portion and changes to about 52 degrees along the western portion. Overall, the shoreline orientation is about 60 degree, which is roughly parallel to the dominant NE incident wave. The bathymetry of the over 20-km wide continental shelf is relatively uniform alongshore with roughly shore parallel contours (Figure 10). A submarine canyon exists offshore the study area. However, the canyon is quite from the shoreline and in deep water (>100 m) and therefore has minimal influence on the bathymetric characteristics of the continental shelf and the nearshore wave field.

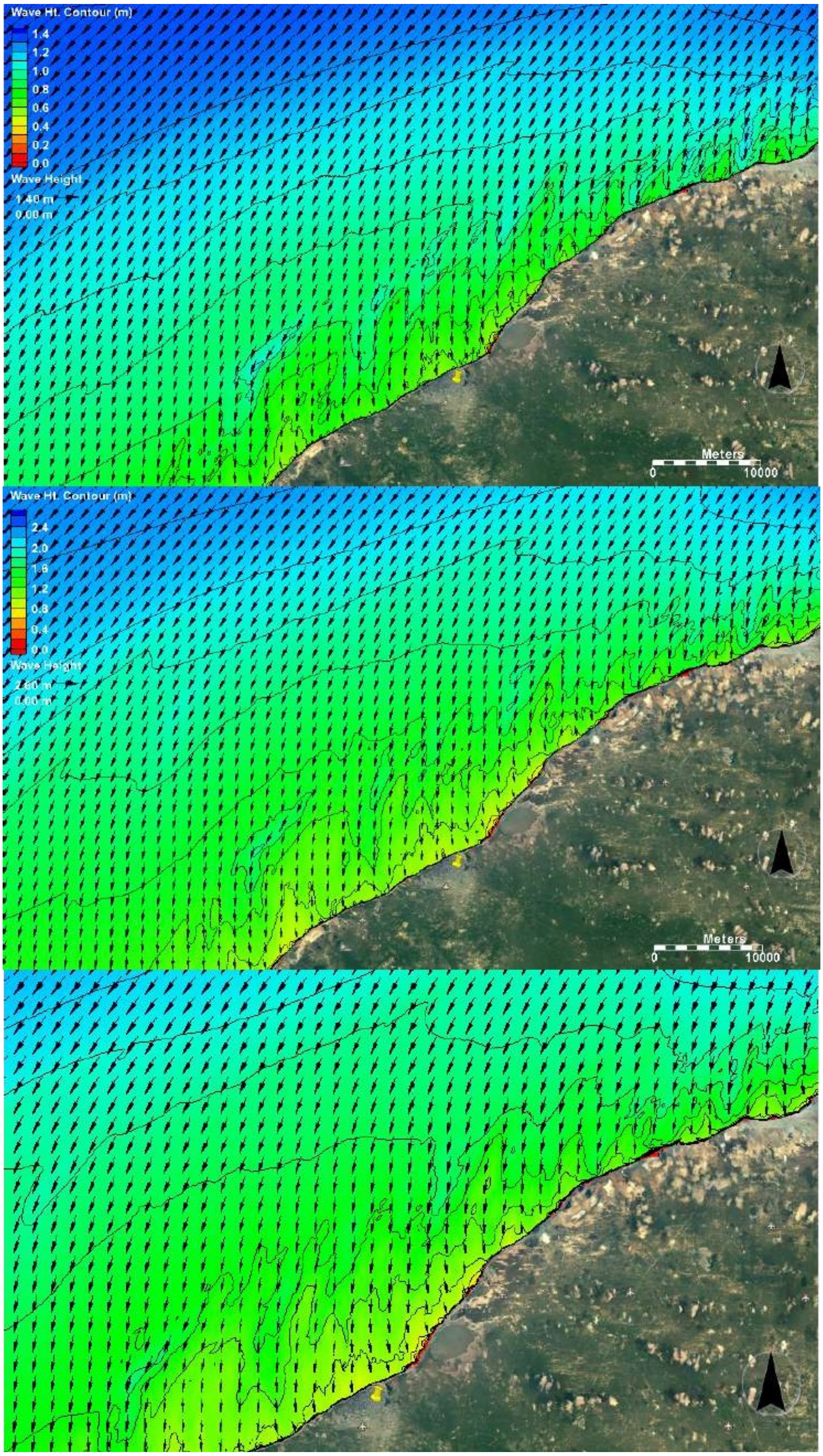
Figure 10 - Regional wave modeling grid for Riohacha area



Source: The author

Substantial refraction occurs as the nearly shore-parallel NE incident wave propagates onshore (Figure 11). Waves offshore the eastern flank of the broad headland is slightly higher than those offshore the western flank. However, the wave heights in the nearshore areas are rather similar, with no apparent wave-height gradient along shore. Despite the significant refraction, the wave arrives in the nearshore area at a large oblique angle, which drives a westward longshore sediment transport. Since the easterly approaching wave occurs over 97% of the time and includes the most energetic conditions, the westward longshore transport occurs almost all the time and is by far the dominant process. Due to the relative straight shoreline despite the gentle hump and parallel bathymetry, no apparent wave-height gradient occur along this stretch of the shoreline occur naturally. In addition, there are no large river mouths or tidal inlets that impose significant interruptions to the westward longshore sand transport. As discussed in the following section, beach erosion and accretion along this stretch of the shoreline are mostly related to the interruption of the westward longshore sand transport by anthropogenic activities.

Figure 11 - Regional wave modeling results for NE (45 deg) approaching wave: upper panel: average wave condition; middle panel: top 2% wave condition; lower panel: top 1% wave



Source: The author

DISCUSSION

The beach processes along the studied northern Colombia coast are relatively simple, driven predominantly by westward longshore sand transport as discussed above. The coast has not been directly hit by any extreme storms over the past 30 years (Figures 6 and 7). As a matter of fact, no more than 10 tropical storms passed within a 150-km radius of the studied 600 km coast. No storm made landfall over the past 150 years at this coast. In addition, coral reefs, which is typical of Caribbean coast, are not well developed along this stretch of coast. This is likely influenced by the terrestrial sediment input into the sea. Some coral reefs can be found locally along the Santa Marta headland. Modifications to nearshore wave field by coral reefs are not a major factor along the studied tropical coast.

The trend of beach erosion or accretion and the state of the beach are largely controlled by the gradients of longshore sand transport. Therefore, understanding the cause of sediment transport gradient is essential to the quantification of beach erosion or accretion, which in turn is crucial to the development of effective shore-protection methods. The longshore sand transport gradient can be caused by both natural and artificial factors. In the following, two of the main factors that are responsible for the majority beach erosion problems along the studied coast are discussed.

Longshore Sediment Transport Gradient Induced by Natural Morphological Conditions

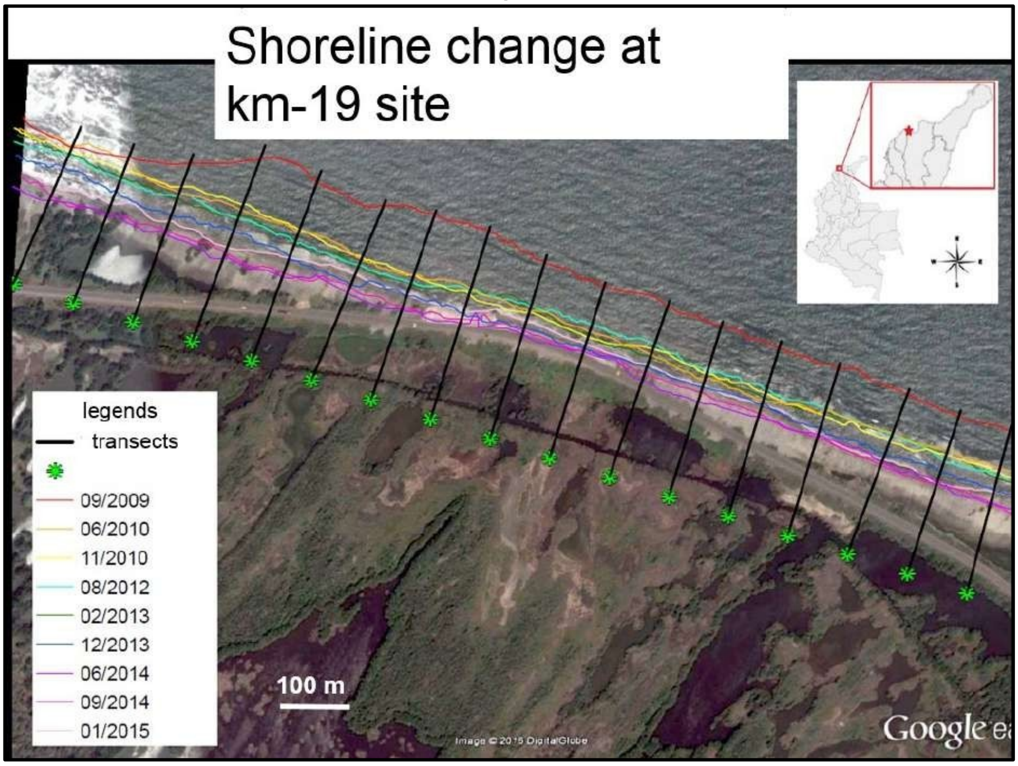
The km-19 site is a highly publicized erosional hot spot located about 19 km west of Barranquilla. Severe beach erosion has threatened a section of a major coastal highway (Figure 12). Presently, the highway is protected by recently installed and expanded rip-rap revetment. However, continued beach erosion is undermining the foundation of the rip-rap and likely the road in the near future. Furthermore, the area experiencing aggressive erosion may continue to expand westward and propagate the problem over a larger area. At the time of this study, the riprap revetment is being extended to the west to keep up with the expanding beach erosion.

Figure 12 - Severe beach erosion at km-19 site threatening a major highway. The recently installed riprap is experiencing toe scour due to continued erosion

Source: Photo by Ping Wang

Analysis of time series aerial photos from Google Earth has shown that the beach along the km-19 coast is experiencing persistent rapid erosion in recent years from 2009 to 2015, at over 15 m per year (Figure 13). The sediment transport gradient along this stretch of coastline is caused by the shadowing effect of the Santa Marta headland, as discussed above (Figure 9). The Santa Marta headland shadow zone of the by far most frequent NE incident wave creates a westward increasing wave height along the km-19 site. This results in more sediment being transported westward from the km-19 site than being transported into the site. This transport gradient is the cause of the rapid erosion along the km-19 coast. A major coastal road to the city of Barranquilla is now practically at the shoreline. Originally, the road is several hundred meters landward of the shoreline. As recent as 2009, or 7 years before the present study, the road was 115 m from the shoreline. It is therefore crucial that the aggressive beach erosion by this persistent longshore transport gradient be accurately quantified to ensure that adequate buffer zone is allowed between key infrastructure, a major highway in this case, and the shoreline. In this case, several hundred meters is apparently not enough. As apparent in Figure 12, the waves along this section of the coast is quite energetic nearly all year round.

Figure 13 - Historical shoreline changes at KM19 site depicted from time-series aerial photos from Google Earth



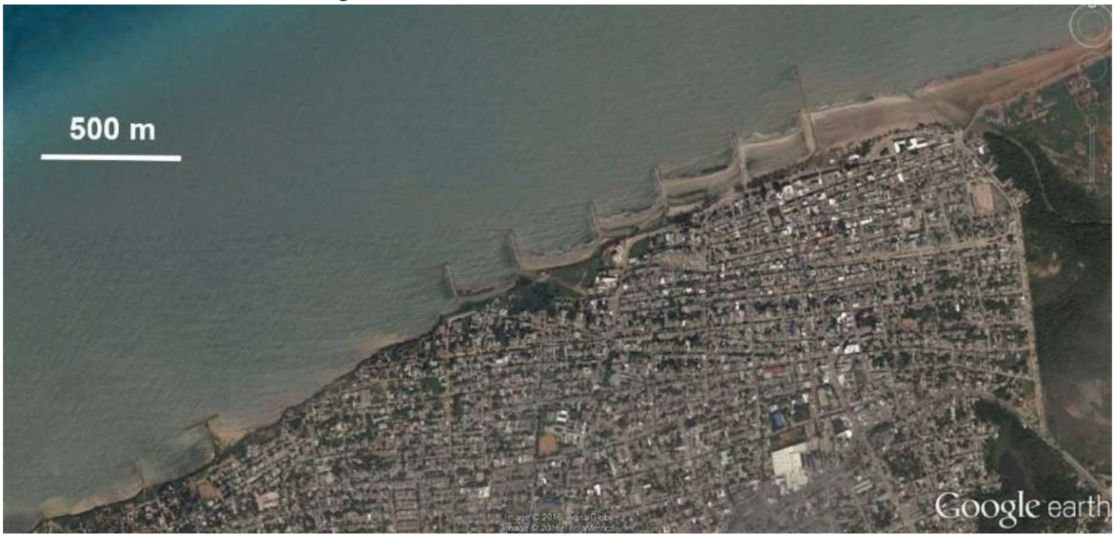
Source: Google Earth, adapeted by Ping Wang.

Longshore Sediment Transport Gradient Induced by Anthropogenic Activities

The Riohacha coastline provides an example of beach accretion and erosion associated with artificial interruption of the persistent westward longshore sand transport. Figure 14 shows the aerial view of the Riohacha coastal line with a groin field. It is apparent that the few, three to be exact, groins at the updrift end have impounded a large amount of sand and resulted in a quite wide beach there (Figure 15). Several small rivers to the east and updrift of the beach contribute to the sand supply. However, the field of these 150-m long groins nearly completely interrupted the westward longshore sand transport and resulted in severe beach erosion along a long and extending stretch of downdrift coast. Figure 16 illustrates the erosion along the beach downdrift of the groin field. In addition, due to the depleted sand supply, the groins downdrift of the east-most three failed to impound any sand.

A rather common situation that tends to develop in association with the installation of groin field is that the beach accretion, in this case rather rapid beach accretion, at the updrift of the first few groins often lead to the conclusion that the structures are successful. Therefore, the groins should be high and long in order to accumulate more sand and create a wider beach, as is the case for the Riohacha beach. Furthermore, more groins should be installed to combat the erosion along the downdrift beach since the ones further updrift have successfully accreted beach. This is likely the reason for the construction of the two groins further downdrift of the original groin field (Figure 14). As illustrated clearly by the photos, the above interpretation of groin success is not correct and construction of more groins does not solve the downdrift erosion problem. Longer groin does lead to wider updrift beach particularly for the case of northern Colombia coast with unidirectional longshore sand transport almost 100% of the time. However, the updrift accumulation occurs at the expense of downdrift erosion. By extending farther into the sea and beyond the surf zone, long groin seriously limits the possibility of the sand that bypassed around the tip of the groin to be deposited on the downdrift beach. Instead, the bypassed sand, if any, is likely deposited farther offshore and does not direct benefit the eroding downdrift beach. Similar sand bypassing patterns around and through a groin were found by Wang and Kraus (2004) in a large-scale laboratory study on interaction of a groin with longshore sand transport.

Figure 14 - Aerial view of the Riohacha shoreline. Note the large amount of sand accumulation at the east- most three groins and little to no sand accumulation at the rest of the groins and erosion further downdrift



Source: Google Earth

Given the persistent westward longshore sand transport at almost 100% of the time along the northern Colombia coast, and along the trade winds dominated tropical coast in general, applications of structures that impound longshore sand transport should be carefully considered. Inducing beach accretion at the updrift side is a relatively simple task. The difficult aspect is to not causing prolonged and irreversible erosion problems along the downdrift coast. Therefore, the structures should be carefully designed to allow reasonable beach accretion at the project site, while also allowing the westward longshore sand transport to be continued, with short-term and recoverable interruption. Importantly, the sand that bypasses the structures should directly benefit the downdrift beach, as oppose to, e.g., being deposited and dispersed in the surf zone or the offshore area (WANG; KRAUS, 2004). Comprehensive and site-specific study should be conducted to support the design of shore- protection structures.

Figure 15 - Large amount of sand accumulation updrift of the first groin. The groin is considerably higher than the beach

Source: Photo by Ping Wang.

Figure 16 - Severe beach erosion downdrift of the Riohacha groin field, exposing a crucial infrastructure to direct wave attack

Source: Photo by Ping Wang

Longshore Sediment Transport Gradient Induced by both Natural and Anthropogenic Activities

Coasta Verde Cienega is located within the greater shadow zone of the Santa Marta headland and at the edge of the secondary shadow zone, as discussed earlier (Figure 9). Compared to the km-19 site further to the west, the waves along this stretch of the coast is much smaller due to the shadowing effect of the Santa Marta headland. Based on wave modeling results as discussed earlier, a wave-height gradient exists along this stretch of the coast due to the secondary shadowing by the headland, although the rate of longshore sand transport should be much smaller due to the lower wave. Beach erosion here has exposed a crucial pipeline along the coast (yellow marker in Figure 17). Various low-profile groins made of sand bags were installed in an effort to control the erosion. Based on field observations, the sand-bag groins have very limited and localized effect.

Figure 17 - Severe beach erosion along the Costa Verde Cienega coast, exposing a crucial pipeline (yellow marker). Note the low-profile sand-bag groin and the earth moving machine at the top of the picture. The earth moving machine was moving sand from the upland to nourish the beach and attempting to control the erosion

Source: Photo by Ping Wang

In addition to the longshore sand transport gradient induced by natural processes as discussed above, anthropogenic activities also played a significant role in the beach erosion at the Coasta Verde Cienega site. The westward longshore sand transport and a transport gradient induced by a long groin is well illustrated at this site by time-series Google Earth photos (Figure 18). A 140-m long groin was installed between January 2011 and May 2012. Rapid sand accumulation east and updrift of the long groin occurred directly after the installation of the groin. By May 2012, the updrift beach had grown to about 35 m landward of the tip of the long groin. Only five months later in October 2012, the updrift of the long groin was filled to the tip of the structure. The impoundment at the groin created a transport gradient at the downdrift, which further contributed to the beach erosion problems caused by the natural wave-height gradient associated with the secondary shadowing of the Santa Marta headland as discussed above. Since the sand has filled to the tip of the groin, bypass around the tip should have occurred and was observed in the field. However, it is not clear if the bypassed sand can reach the downdrift beach since the groin extended quite far from the shoreline. The bypassed sand is deposited about 140 m seaward of the downdrift shoreline. No apparent processes that would transport the bypassed sand in the onshore direction to the downdrift beach were observed in the field. Therefore, similar to the long groins at Riohacha site, the downdrift beach did not benefit from sand bypassing even when the updrift beach reached the tip of the structure.

Figure 18 - Time-series photos at the Coasta Verde Cienega site. Note the installation of a long groin between January 2012 and May 2012. A large amount of sand was impounded rapidly by this long groin

Source: Google Earth

The above two examples from Riohacha and Coasta Verde Cienega, along with numerous other cases along the northern Colombia coast, strongly suggest that caution should be carefully exercised in artificially interrupting the persistent westward longshore sand transport. Impounding the longshore moving sand by engineering structures, many times by groin field, is quite easy to do. The often very rapid beach accretion at the updrift side of the structure may lead to construction of longer and more groins. This can quickly turn into a very destructive practice along the tropical trade winds dominated coast, where longshore sand transport is westward almost 100% of the time. Numerous examples in addition to the three discussed here can be found along the entire Caribbean coast and other tropical coast.

Well-planned regional scale study investigating 1) the source and availability of the sand to the beach, 2) rate of longshore sand transport, and 3) most importantly, existing natural and anthropogenic causes of longshore sediment transport gradient should be conducted before installing structures to impound longshore moving sand. The study should have adequate temporal and spatial scales. Spatially, the study should include a long stretch of beach, particularly along the downdrift coast, to ensure that the downdrift effect induced by the shore protection structures is fully considered over a adequately long period of time. In the case of Riohacha and Costal Verde Cienega coasts, the downdrift effect of the long groins extends up to 5 km based on field observations, although the direct relationship between the structures and beach erosion becomes less directly apparent farther down the coast. However, the influence of the groins cannot be ruled out and is often perceived by local community as the cause of erosion, which may lead to construction of more poorly planned structures, as in the cases of both Riohacha (Figure 14) and Costa Verde Cienega (Figures 17).

Temporally, due to the unidirectional westward longshore sediment transport nearly at all time, the transport gradient caused by natural as well as anthropogenic conditions can persist over a long time. Long-term planning is essential for crucial infrastructures such as highways. The km-19 stretch of the coastal highway provides an alarming example. Judging from the configuration of the highway and the fact that the km-19 section curved substantially seaward, it is likely that the risk of beach erosion and subsequent landward retreat of the shoreline was not considered over an adequate period of time. Other factors must have controlled the design of the curvature. As discussed early, this stretch of the coast is experiencing about 15 m per year landward movement of the shoreline persistently due to the shadowing of the dominant NE incident wave by the Santa Marta headland. The shoreline retreated roughly 120 m landward just between 2009 and 2016. This rapid erosion rate would not have supported the design of the seaward curve of the highway over a long term. It is therefore crucial that the long-term effect of beach erosion be adequately considered. Furthermore, the main cause of the longshore transport gradient, i.e., the erosion, is the wave shadowing by the Santa Marta headland which is almost 40 km away from the site. This highlights the need to understand regional processes.

Figure 19 - Configuration of the coastal highway, note that the road curved significantly seaward at the km-19 section

Source: Google Earth.

CONCLUSIONS

The northeast-southwest trending northern Colombia coast is located in the tropical zone. Its coastal processes are strongly controlled by the northeast trade wind, which blows largely shore parallel. The ocean waves in the greater study area are generated mostly by the trade winds and approach the coast from NNE and NE directions over 95% of the time. This highly oblique incident wave drives a persistent southwestward longshore sand transport. The state of the beach is strongly influenced by this constant unidirectional longshore sediment transport. At locations where this westward longshore sand transport is interrupted, naturally or anthropogenically, beach accretion occurs along the updrift shoreline with a positive longshore transport gradient coupled with erosion at the downdrift with a negative gradient. Along the 600-km studied shoreline, natural interruption of longshore transport is predominantly caused by protruding headland. The longshore sediment transport gradient created by the Santa Marta headland is the main reason of the aggressive erosion about 40-km away that is threatening a major coastal highway. Anthropogenic interruption of the longshore transport along the northern Colombia coast is mainly caused by the construction of groins, as well as some harbors. Numerous groins were constructed due to their local success in creating beach accretion at the drift side. However, severe beach erosion occurs along the downdrift shoreline. Shoreline protection along the northern Colombia coast, and coasts in the tropical area in general, should carefully consider the persistent unidirectional longshore sand transport and should not be misguided by the local updrift accumulation. Adequate spatial and temporal scales must be incorporated in the design of shore-protection measures. Given the fact that easterly trade wind has significant influence along the entire tropic coast, the findings by this study along the northern Colombia coast should be applicable to many other tropical coasts.

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