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Article

Fine Spatial Scale, Frequent Morphological Monitoring of Urbanised Beaches to Improve Coastal Management

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Abstract: Between 1959 and 2010, a coastline retreat of 2.4 m/year and erosion of up to 174 m were recorded around Turbo, in northern Colombia. This degraded coastal system is the result of a poorly planned coastal defence scheme, combined with a lack of formal technical methodologies for diagnosis and monitoring. The coastal system cannot provide the protection services required by the local community. From 2017 to 2019, the group monitored urban beach profiles in a small area close to the town of Turbo, in the wet and the dry seasons, as part of a coastline analysis to identify morphodynamic trends in the area. The results show a net shoreline accretion of up to 30 m and positive sedimentary accumulation of up to 45.8 m^3/m. To the north of the study area, sediment accumulation is evident at the Turbo River Delta. The 34 coastal protection structures in the study area have a high k index (~0.7), suggesting that they are the main drivers controlling the trend of sediment accumulation. The correlation of geomorphological, oceanographic, and anthropic variables related to the presence of coastal structures, is necessary in order to set up efficient coastal protection schemes.

Keywords: coastal erosion; beach accretion; coastal management; k index; Turbo; Colombia; Gulf of Urabá

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1. Introduction

Coastlines are one of the most dynamic and complex environments on the planet, particularly in areas that have been urbanized [1–4]. Examples of morphologic processes at some beaches close to major cities in Latin America are described in Silva et al. [5] where the coastal areas are exposed to modification by natural as well as anthropic phenomena. Erosion processes are the most notable changes on a coastline, and predictions suggest that these processes will intensify on most of the world's coastlines over the coming decades [6,7].

Erosive processes are controlled by natural variables, such as winds, waves, currents, and tides. Intense winds play an important role in transporting the sand from beaches. Wind also determines the power (height and period) and the direction of the waves. During intense events, the waves erode the beaches, moving sediments offshore to submerged banks, from which they may be returned to the beach in periods of low energy waves [5]. Coastal currents also transport beach material put up by the waves. Tides change the level of the sea, exposing sediments to the actions of waves and wind [8].

Healthy coastal ecosystems require fluxes of energy, matter, and organisms to be balanced [9]. Although the coastline is constantly changing, in the short term, this does not necessarily imply erosion or sedimentation processes [10]. Understanding the sedimentary balance allows us to measure these processes in the medium and long term. A coastal system is in equilibrium when the amount of material that comes into the system is similar to that which leaves it. Processes of coastal erosion and/or sedimentation occur when the system has lost and/or gained sediment [11,12].

On the other hand, erosive processes can also be the result of urbanization near the coastline, sand extraction from the beaches, and/or inadequate coastal protection structures. In these cases, the erosion can induce social and economic problems for the local communities [13–15]. According to Rangel-Buitrago et al. [16], close to 90% of the structures built in Colombia have not been successful in protecting the coast from erosion.

Over the last 70 years, there has been considerable coastal erosion on the 500 km coastline of Antioquia (Colombia) on the Caribbean Sea (Figure 1). A major change occurred in the 1950s when the river Turbo was diverted, shifting its mouth to the north out of the bay. This changed the circulation patterns adjacent to the coastline, causing a decrease in the sedimentary supply to the beaches in the south [17], while around Punta Yarumal, accretions of up to 1.4 km^2 were recorded [18]. Studies suggest that sediment transport is mainly governed by the climatic seasons: in the dry season, the sediments come from the north, and in the wet season, from the south [19].

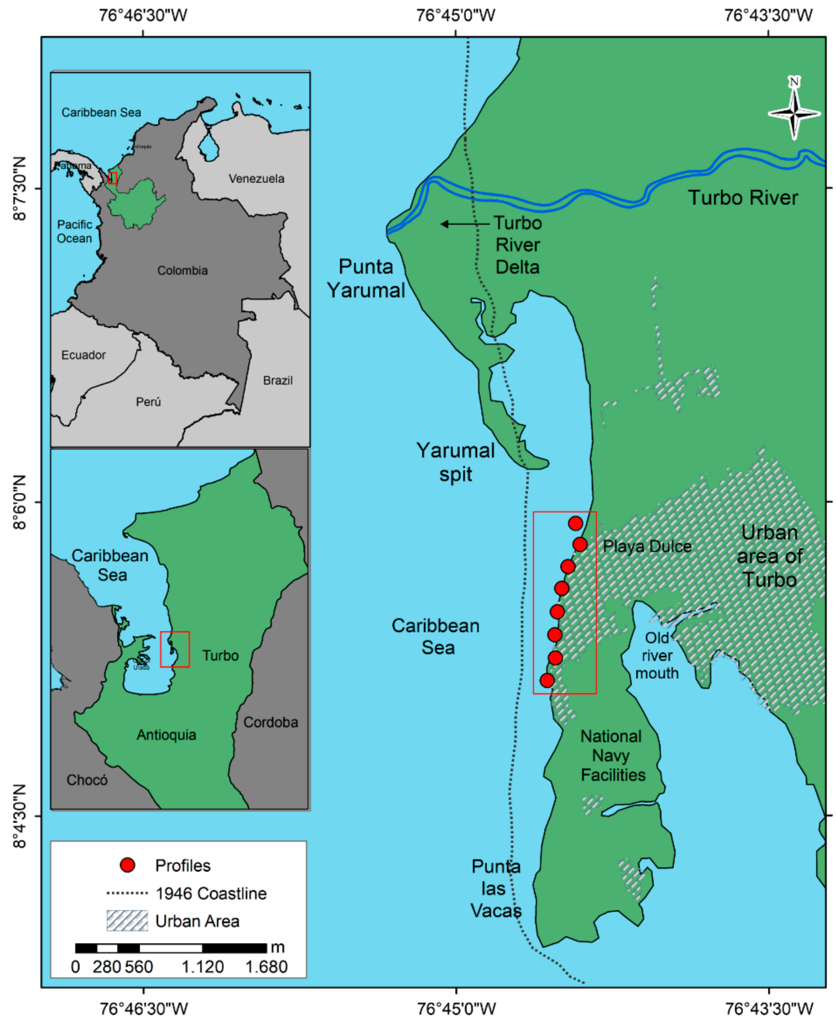

Figure 1. Location of Antioquia, Colombian Caribbean.

The evolution of Yarumal spit has been governed mainly by three factors. First, the transport of the accumulated sediments carried by the river Turbo. Second, the interruption of sediment transport to the south, due to the formation of the Turbo River Delta. Third, the modifications of the coastal currents due to the interaction of the incident waves with the discharge from the river Turbo. Therefore, the spit acts as a sand bar, obstructing the sediment transport to the south [20]. Around Punta Las Vacas, in the south, erosion is induced because (a) the sediment is trapped in the delta, and (b) there is strong wave energy in the area that does not allow sediment to feed the coastline [19].

One of the more problematic areas is in the vicinity of the urban beach of Turbo, where rates of coastline erosion of 2.4 m/year were measured with a coastline regression of 174 m in some places [21]. To save the coast and increase some beach areas, protection structures were built, some perpendicular and some parallel to the coastline, mainly wall-band groins [22]. However, studies have suggested that the erosive processes here are actually due to these structures; the use of inappropriate materials, the closeness of the structures, and the lack of their maintenance [17,22].

Since coastal processes are highly dynamic, behaviour on a small scale (of the order of meters) is not accurately inferred from measurements on the large scale (hundreds of kilometres). In the study area, a few coastal analyses on a large spatial scale are available [19,20,22], as well as local studies in the order of a few kilometres [17], but these do not reach the fine spatial scale required to characterize the beach processes. For fine temporal scale studies, the topographic profiles of the beach and the coastline must be carried out frequently and in different climatic seasons [23]. Fine temporal and spatial scale measurements give an accurate morphological analysis of this coastline, which can provide important information for decision-making in this remote area [10]. On the other hand, although coastal morphodynamics are mainly controlled by the interaction of natural processes, coastal protection structures do modify some coastal processes [24]. Determining the anthropogenic impact of such structures makes it possible to evaluate how much they influence the evolution of the coastline.

In this work, changes to the Turbo urban coastline are described from the measurement of beach profiles (2017–2019), recorded coastline evolution (2014–2019), and characterization of the coastal structures found there. For the coastline evolution and hard structures impact, an index was used with the information recorded. It is worth noting that the technical criteria used for the design and construction of most of the coastal protection structures in the study area are not documented. Similarly, little is known regarding the historical conditions of the coastline before these interventions. It has therefore not been possible to define the efficiency of the protection structures on the coast of Turbo, Colombia.

2. Materials and Methods

2.1. Study Area

The study area is 2.2 km of urbanised beaches in the district of Turbo on the Gulf of Urabá, in the west of the Colombian Caribbean Sea. The gulf is around 80 km long and 25 km wide, with an average depth of 20 m, and a maximum of 70 m [25].

The Gulf of Urabá has two climatic seasons, the dry season, December to March, with trade winds from the north and northeast, and a wet season, August to November, with winds from the southeast [26]. In the wet season, gusts of up to 20 m/s occur, with mean values around 2.5 m/s [27]. In January, the dry season, the average wind speed is 4 m/s [28]. The wave characteristics in the gulf are also a function of the seasons, in the dry season, the swell comes from the northeast, with heights of 0.2–0.4 m, while in the wet season, the waves come from the southeast, generated by local winds with mean significant wave heights of 0.1 m. In the gulf, the wave energy and direction are transformed, due to the bathymetry, the geomorphology of the Atrato River Delta, and local winds [20,26].

The river Turbo flows from the western Abibe mountains to the Gulf of Urabá and transports around 73,000 t/year of sediment, producing a huge delta [17]. From January to April the average load is 100 t/day and from May to December, 300 t/day. According to [27], the fresh water, with its huge load of sediment, flows from west to east of the gulf. The sediment transported is a mixture of mud and fine sand.

Coates et al. [29], suggest a rapid uplift in the Central American Isthmus, with respect to the Atrato basin, in NW Colombia, due to the interaction of the South American and Caribbean plates. In the Turbo river, sedimentation and compressive tectonics has produced subsidence, with a mean value of 5 mm/year [30]. This phenomenon deforms the coastal environment and could affect the dynamics of coastal currents and waves and generate erosion on the beaches.

The study area is the urbanised coast of Turbo (Figures 2 and 3), from the north of Playa Dulce to the edge of the naval facilities, approximately 2.2 km, divided into seven segments and delimited by eight beach profiles (Figure 2). In the first two segments (Playa Dulce), there are no coastal protection structures, and the beach has an approximate width of 800 m, due to beach nourishment carried out in 2016 [20,31,32]. From profile 3, south, the beach narrows with considerable interventions that established 34 coastal protection structures [33,34].

Figure 2. Location of the urban beaches of the Turbo (Antioquia). The red dots show the location of the eight beach profiles. The red lines show the delimitation of the segments.

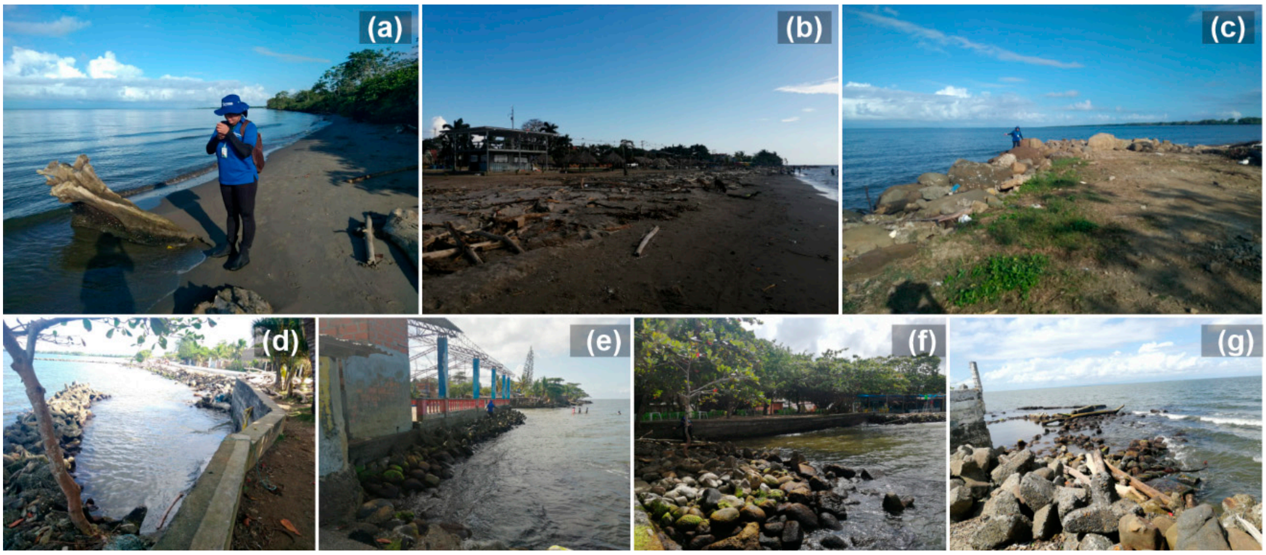

Figure 3. Beach and coastal protection structures in the study area: (**a**) Segment 1; (**b**) Segment 2; (**c**) Segment 3; (**d**) Segment 4; (**e**) Segment 5; (**f**) Segment 6; (**e**) Segment 7.

2.2. Methods

For the present study, seven field campaigns were carried out between 2017 and 2020 (Table 1). The coastline and beach profile measurements were performed in the two seasons, over three consecutive years. The coastline monitored has eight reference points (located at a distance of 220 m), and the analyses were carried out in seven sections. The profiles were linearly spaced, following Larson and Kraus [35] (see Figure 2).

Table 1. Dates of the campaigns and climatic season respectively.

Campaign	Date	Climatic Season	Measurements
1	January 30 (2017)	Dry	Coastline and beach profiles
2	November 18 (2017)	Wet	Coastline and beach profiles
3	May 07 (2018)	Wet	Coastline and beach profiles
4	November 01 (2018)	Dry	Coastline and beach profiles
5	April 24 (2019)	Wet	Coastline and beach profiles
6	December 16 (2019)	Dry	Coastline and beach profiles
7	January (2020)	Dry	Protection structures

2.2.1. Sedimentary Balance

To determine the sedimentary balance (m^3/year), the area under the curve obtained for each of the beach profiles was calculated, according to the methodology proposed by Castelle and Harley [36]. The beach profiles were measured following the description in Appendix A (see Table 1). For each profile, the measurements were compared with those of the previous campaign. The medium-term balance was calculated as the sum of positive values (accumulation) and the subtraction of negative values (erosion).

2.2.2. Changes to the Coastline Position

The changes of the coastline were calculated according to the methodology proposed by Botero et al. [37], during six field campaigns. These measurements were made between 2017 and 2019 (see Table 1), using the measurements of 2014 and 2015 as a basis [38,39].

In each campaign, and around the time of high tide, points were taken every meter at the sea-sand boundary. The coastline measured between profiles 1 and 8 was approximately 1500 m. In profiles 1 and 8, the measurement extended 300 m to the north and south respectively. To analyse the changes in the coastline, the End Point Rate (*EPR*) and the Net Movement of the coastline (*NSM*) were calculated, based on the following expressions:

$$EPR = \frac{D_m}{T_{LA} - T_{LR}} \tag{1}$$

$$NSM = L_A - L_R \tag{2}$$

where D_m is the mean distance (m) calculated between the oldest and the most recent coastline, and T_{LA} and T_{LR} are the time elapsed between them, respectively. The difference between LA and LR is the distance between the oldest and most recent coastlines (similar to D_m). Positive values of *EPR* and *NSM* indicate an advance of the coastline, and negative values indicate retreat.

2.2.3. Anthropic Impact

Following Correa and Vernette [22], a characterization of the coastal protection structures was made to identify: the horizontal geometry, the height above sea level (at each campaign), the geographical location, the type of structure, and its material. Using a GPS, the initial and final coordinates of each structure were recorded, and then its length was calculated.

A drone was used to obtain an orthorectified mosaic. The flight plan was design based on the coastline, with an extension of 30 m seaward, and 500 m landward. The spatial resolution of the mosaic was 1 cm/pixel. The horizontal geometry of each structure was measured, and this information was compared with the field measurements. The *k* index of the structures was calculated for each segment [40] to define the anthropic impact using the following categories: Minimum 0.0001–0.1; Average 0.11–0.5; Maximum 0.51–1.0; and Extreme > 1. The *k* index is the relationship between the linear sum of the lengths of the structures in the segment (l) and the total length (L) of the segment (Equation (3)):

$$k = \frac{l}{L} \tag{3}$$

3. Results

3.1. Sedimentary Balance

The sedimentary balances for each segment are presented in Figure 4. This figure shows the segments and their associated profiles and the calculation of the balance (accumulation +, and losses −) between each campaign. It should be taken into account that measurements were not made for some profiles in certain campaigns, due to adverse weather conditions.

In general, the greatest sedimentary accumulations were in segments 1 to 3. Profile 3 shows the highest accumulation in campaigns 3 and 5, with 46 m^3/m and 44 m^3/m, respectively. Accumulations are also seen in profile 7; 12 m^3/m, 16 m^3/m, and 28 m^3/m, for campaigns 3, 5, and 6, respectively. Sedimentary losses were found between campaigns 3 and 4, at profiles 1, 3, 5, and 7, with 27 m^3/m, 16 m^3/m, 3 m^3/m, and 2 m^3/m, respectively.

3.2. Coastline Changes

In Figure 5, the coastlines measured in the campaigns are shown. For easy comparison, four zones were obtained joining profiles 1 and 2, 3 and 4, 5 and 6, and 7 and 8, respectively. The analysis of the coastline evolution was carried out based on the EPR and NSM calculation (Table 2).

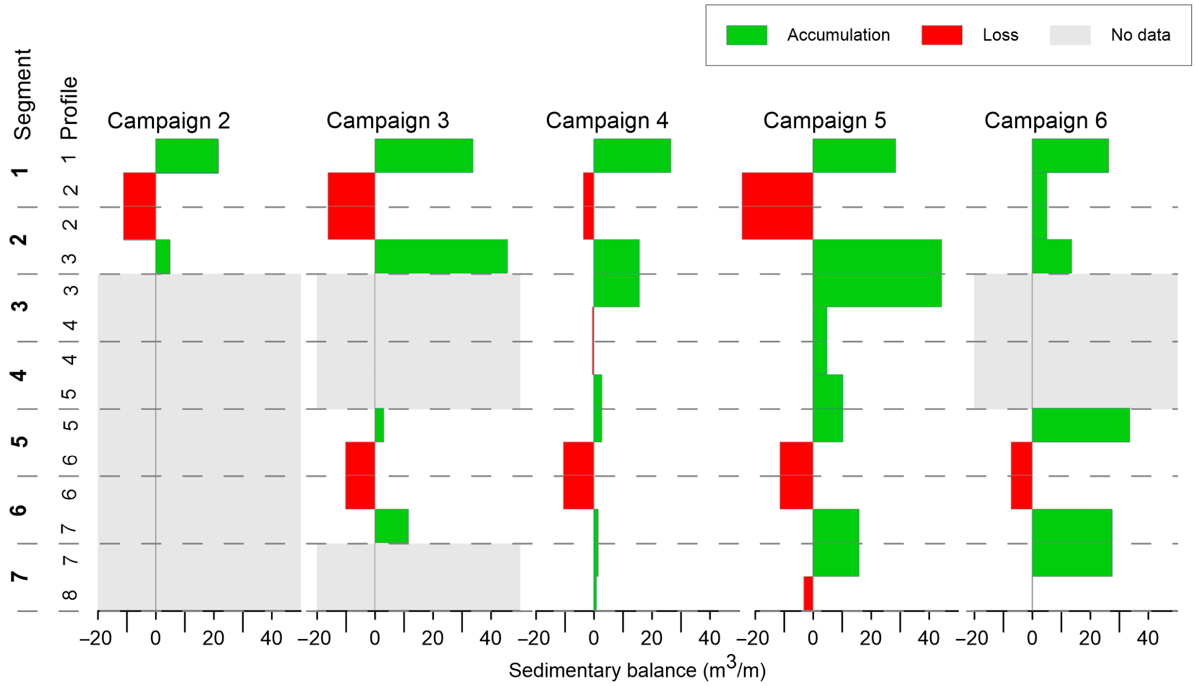

Figure 4. Sedimentary balances for each segment. The balances are shown as the accumulation (+) in green, and losses (−) in red, between each of the campaigns.

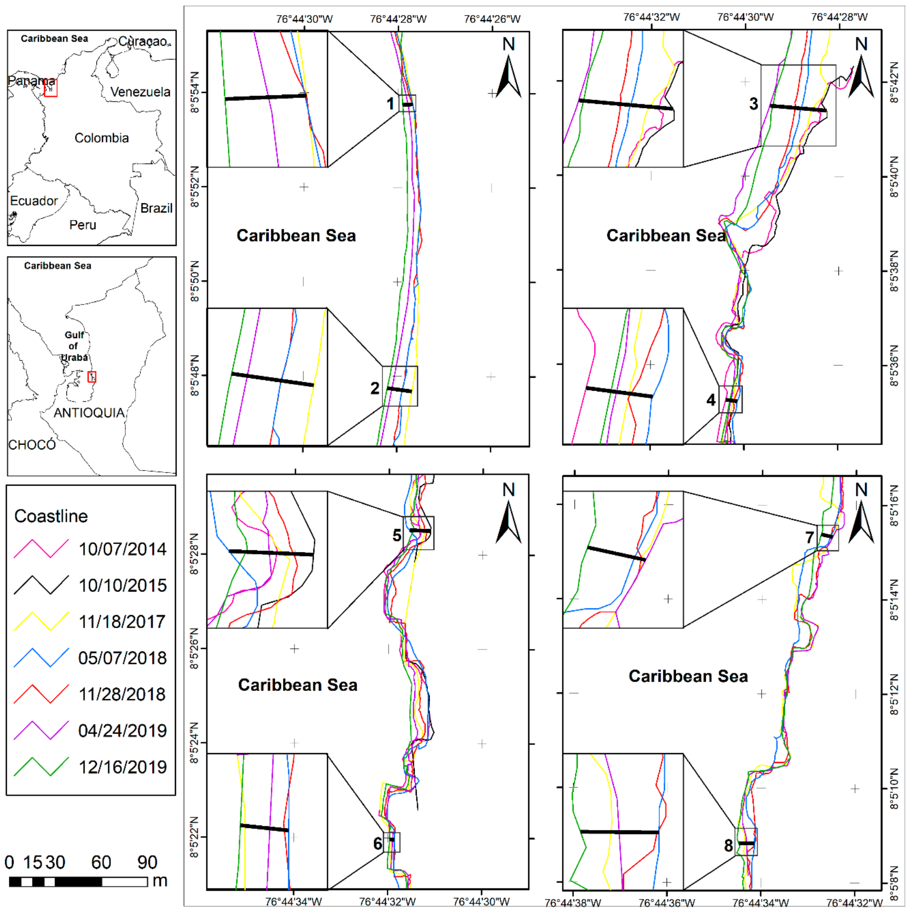

Figure 5. Coastline changes for the urban beaches of Turbo, 2014–2019.

Table 2. Net Movement (NSM) and End Point Rate (EPR) for each profile.

Profiles	NSM (m)	EPR(m/year)	Process
1	6.7	3.2	Accretion
2	16.2	7.8	Accretion
3	29.9	5.8	Accretion
4	−2.9	-0.6	Erosion
5	5.0	1.0	Accretion
6	0.3	0.2	Accretion
7	7.2	3.5	Accretion
8	4.0	1.9	Accretion

The values in Table 2 show that accretion (coastline advance) occurs in all the profiles, except profile 4. The profiles with the highest NSM and EPR values are in the north, suggesting a more rapid advance than in the south. However, in the southern sector, profile 7 stands out as having high values of coastline advance.

3.3. The k Index

The results of the *k* index calculations are presented in Table 3, taking into account that 34 coastal protection structures were identified. As mentioned before, segments 1 and 2 do not have protection structures (k = 0). The longest segment analysed is segment 7 (296 m), while segment 5 (284 m) has the maximum number of structures (9 with a total length of 369 m). Segments 4 and 5 have the highest *k* index (1.3). Segments 3 and 4 have three structures each. However, the length of the protection structures in segment 3 is half that of segment 4 (k = 0.6). On the other hand, segments 6 and 7 have eleven structures each, with a *k* index of 1.1 and 0.9, respectively. The characteristics of each structure are detailed in Appendix B.

Table 3. Values of the *k* index in each segment analysed.

Segment	Segment Length (m)	Number of Protection Structures	Protection Structures Length (m)	*k* Index
1	185.1	0	0	0
2	205.8	0	0	0
3	227.7	3	126.9	0.6
4	230.4	3	301.2	1.3
5	283.2	9	368.2	1.3
6	223.5	11	246.5	1.1
7	295.2	11	251.8	0.9

4. Discussion

In the north of the study area, specifically in segments 1 and 2 where the *k* index is zero, the results show a net advance of the coastline. These findings coincide with the results of Correa and Vernette [22], indicating that this section has no coastal protection structures and that it has net accretion, mainly associated with the delta of the Turbo River. This river deposits a considerable volume of sediment, mainly the result of anthropic activities, such as changes in land use, and deforestation inland [31,41]. Molina [20] noted, in 2009, an advance of up to 160 m in the Punta Yarumal sector. Advances in this section are similarly described by Alcántara et al. [17], who evidenced intense progradation towards the south of Punta Yarumal (Playa Barajas, now Playa Dulce), with rates of up to 464 m/year for 2009 to 2015. Following these trends, it is expected that there will be a progressive accretion of sediments in the Punta de las Vacas area, trapping the sediments that should reach the southern areas [17].

The patterns of sediment deposition in the north change according to the climatic season. The intra-annual dynamics of Punta Yarumal are as follows: during the dry season (December—April) when the swell and strong winds from the north occur [42], the spit evolves in a north-south direction, inducing erosion to the north (Playa La Martina) and sediment accumulation in the south (Playa Dulce). The swell could be generating north-south coastal currents that transport the sediment from the mouth of the Turbo River. On the other hand, during the wet season (May—November) the opposite occurs. The weak waves, generated by local winds coming from the south, produce low-intensity longitudinal transport to the north. Therefore, the evolution of Punta Yarumal is south-north with erosion in the south, which does not balance the sediment transport occurring in the dry season. The behaviour of some segments could be explained by the transverse sediment transport from the submerged sand bars [20,43]. Thirty-four coastal protection structures have been built on the coastline studied, with an average length of 1.3 km (59% of the coastline). Most of these structures are groins (built from pentapods), seven are retaining walls and 12 are revetments [34]. Most of these structures were considered to be temporary and were built without technical studies [22].

The results of the k index for segments 3 to 7 (see Table 3) suggest that the anthropic interventions are the principal driver affecting sediment transport. In these segments, the sediment variations are affected by the state of the structure, rather than on seasonal oceanographic conditions. In the dry season, the sediment from the river Turbo does not seem to have a significant influence on these segments. On the other hand, in the wet season, the southerly direction of the waves produces a little accumulation in these zones. At profiles 5 and 7, an accumulative impact was evident (positive trend), due to the presence of the protection structures. The details of the accumulative balances of each profile are presented in Appendix C.

In regions close to Antioquia, major coastal damage can also be seen. In the department of Córdoba, south of here, according to Rangel et al. (2010), around 150 protection structures have been built on the 134 km coastline, while in the department of Bolívar, north of here, there are 289 structures on a coastal stretch of 44 km. Municipalities such as Arboletes (13 km of coastline) and Necoclí (92 km of coastline) have 38 and 52 coastal protection structures, respectively. However, as seen on the urban beach of Turbo, the relation between these structures and the recovery and formation of beaches seems to be minimal, or null. In some areas, the structures have allowed the coastline position to be conserved but have caused imbalances in sediment transport in adjacent areas, increasing and/or generating erosive processes.

Regarding anthropic factors, the k index is a quantitative assessment of this influence on a segment of the coast [44]. In order to identify the changes produced on the coastline by building protection structures, it is necessary to carry out an adequate diagnosis to know the initial conditions of the area before intervention [9], as well as the characteristics and the dimensions of the structures. In this sense, although the k index does not take into account aspects of dynamics (currents, waves, or sediments), it is considered as a complementary indicator of the degree of impact of the protection structures on the coastline since it allows the shoreline modifications related to these structures to be quantified [45].

In Rodella [46], based on Williams and Micallef [47] and Cifuentes [48], environmental, social, and geomorphological variables were analysed, such as beach width, erosion, and high anthropic intervention, which have an impact on the development of tourist activities. Their results explain that eroded beaches have a lower physical carrying capacity since the space available for the establishment of recreational facilities and activities is less. Likewise, anthropic interventions affect the visual perception of a coastal ecosystem. These results are consistent with the evidence from sections 1, 2, 3 and 7 of the beaches at Turbo, where there are the highest accretion values, these are the beaches most frequented as spas and where the majority of tourists will visit.

In the study area, and in general, on the Colombian Caribbean coast, most of the protection projects have been carried out without any previous studies and with no institutional control. This results in significant alterations to the coastal system, with protection provided in some areas, and sedimentary imbalances occurring in others [49]. Our results suggest that the structures in the area near Turbo have interrupted sediment transport along the coast, causing a severe deficit in the sediment balance south of the Turbo urban area, agreeing with Correa and Vernette [22]. In recent years, the northern area of Turbo has seen a net advance of the coastline, associated with the accretion process on the spit at Punta Yarumal. Our results show that these sediments reach sections 1 to 3. According to several authors, considerable volumes of sediment from the Turbo River Delta are deposited in the Gulf of Urabá, due to processes within the river basin arising from changes in land use and high rates of deforestation [31,41].

The identification of the drivers that induce erosion on urbanized beaches is generally inadequate, because of the complex relationships between natural and anthropic variables. However, Pereira et al. [50] showed that the main anthropic impacts have a direct relationship with infrastructures, such as breakwaters and seawalls. Traditional engineering designs for coastal protection structures often modify the dynamics of the ecosystems, possibly resulting in their isolation, and therefore in a reduced ability to provide ecosystem services [24], perhaps even reaching a point of no return at which coastal ecosystems can no longer be restored [51]. The more interventions there are on a beach, the more necessary it is to perform morphological measurements at a fine spatial scale (metres) and to quantify anthropic indices. Until now oceanographic, climatic, and morphological characterizations have been carried out at a large scale (kilometres). This has prevented progress in understanding erosive problems. Our results suggest that a fine spatial scale methodology, carried out at an acceptable frequency, in different climatic seasons: wet and dry, during consecutive years), gives a more accurate morphological analysis of this coastline. This can become an input for the design of suitable medium and long-term projects to control and mitigate erosion. On the other hand, the assessment of ecological benefits is also important to evaluate coastal natural and anthropogenic processes [52]. These inputs can be used to carry out more coordination between public and private actors and therefore to serve in the protection of natural resources, the improvement of economic and tourist activities, and in the integrated management of coastal zones [46].

5. Conclusions

From the geomorphological point of view, the beaches of the Turbo area can be divided into two sectors, those of the north, where there are no coastal protection structures, and those in the south, each with several coastal protection structures, mostly revetments and groins.

The measurement of topographic profiles of the beach and coastline carried out at a fine spatial scale, frequently and in different climatic seasons (wet and dry), allowed the detailed analysis of morphological processes. This showed that the trends seen in other, large-scale studies are quite the opposite of what occurs in certain segments. The variability in the rates of sedimentary balance depends on the climatic seasons. In the dry season, there is an accumulation of sediments in the north (where there are no protection structures), probably due to the energetic waves from the north that produce north-south coastal currents and transport the sediment from the delta of the river Turbo. In the wet season, coastal transport is limited and south-north. Some of the observed sediment probably comes from the submerged sand bars.

The beach sections studied that have coastal structures showed a negative or neutral sedimentary balance, suggesting that their morphological behaviour is modulated by the presence of the structures and, in turn, by the coastal dynamics. Using the k index, the level of the anthropization of the area was identified. However, in order to quantify the impact of natural and anthropic variables, it is necessary to simultaneously measure oceanographic and morphological variables, as well as evaluate other indices that account for the degree of influence of both the natural and anthropic phenomena.

It is hoped that this work can be used as a preliminary guide for the diagnosis of this coastline, considering both natural and anthropic conditions, thus assisting in the formulation of integrated management of the coastal zone. The development of indicators that more accurately reflect the influence of climatic, oceanographic, and anthropic variables are needed.

It is also clear from these results that, in terms of regulations, there is a need to develop laws that allow for adaptive solutions and to ensure that they are fully enforced. The actions and/or infrastructure to be deployed should contribute to the protection and sustainable use of the coastal zone. Investment in monitoring should lead to better diagnoses of coastal problems and in the medium and long term, this will provide savings compared with the short-term decision making that has been a feature of this coastline.

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Appendix A

The measurement of the beach profiles was carried through topographic surveys with differential GPS and Total Station, based on Huang et al. [53]. This technique provides information at a fine scale, which is why it is recommended in areas with considerable interventions [23]. To ensure that the profiles were measured in the same direction in all campaigns, the azimuth of each was established using a compass. The profiles were measured from the back of the beach, following a line perpendicular to the coastline, up to a depth of one meter (for safety). The elevations of the level water at the profiles were corrected using the tidal forecast information for the Colombian Caribbean Sea [54]. Figure A1 shows the measured profiles.

The northern segments, profiles 1 and 3 (Playa Dulce), have beach widths of 50–220 m, while in profiles 4 to 8 (southern zone) the widths are less than 5 m. It is worth noting that in the first segments no coastal protection structures were registered, while in the segments further south the anthropic interventions are very evident (Figure 1).

In the first campaign, profile 1 had a beach width of 65 m, while in later campaigns this increased up to 100 m. In the beach zone, there was a gentle slope, while in the intertidal zone there was an inclination of approximately 45°.

In profile 2, a berm was evident from the back of the beach area, for the next 200 m in all the campaigns. The longitudinal variation of the berm remained stable in campaigns 1 to 5, but in campaign 6 its width grew to 215 m.

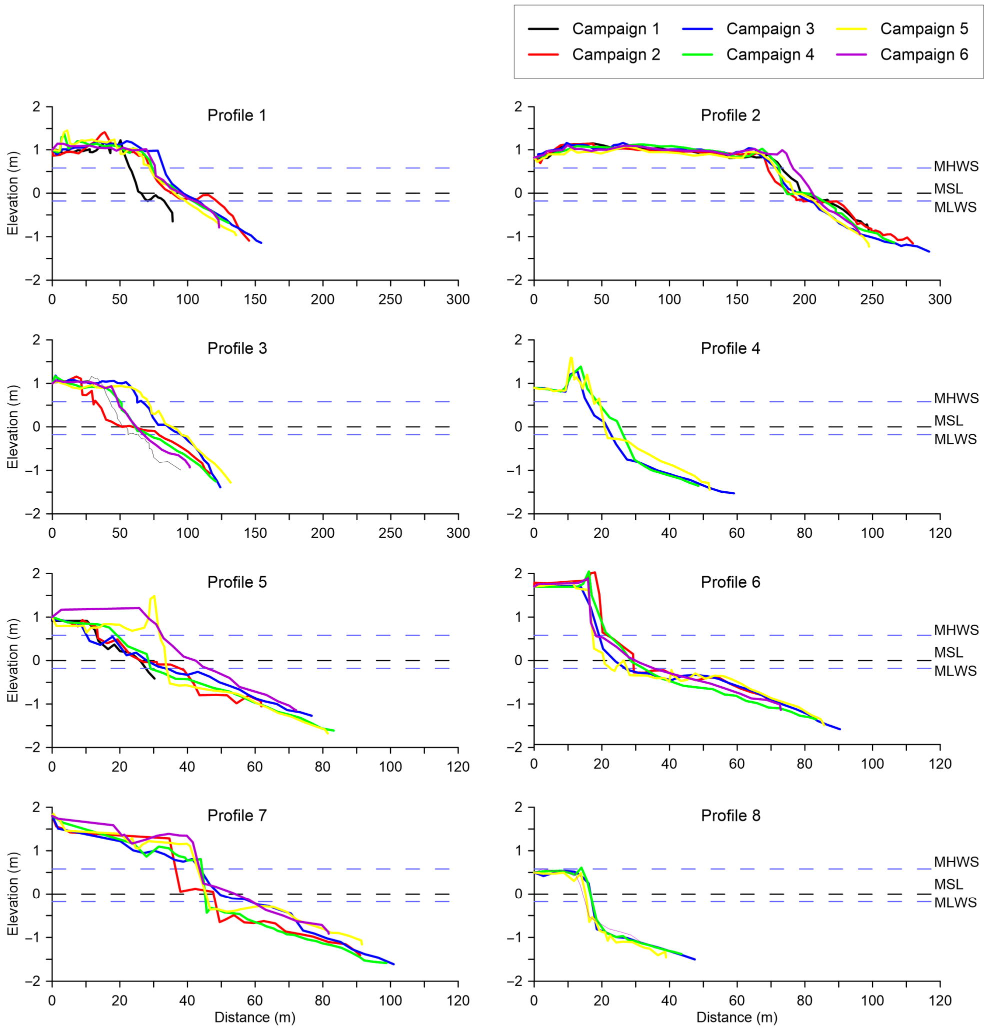

Figure A1. Beach profiles measured the coloured lines show the measurements from each campaign. High Tide Maximum Live Equinox (PMVE), Mean Sea Level (NMM), and Low Tide Minimum Live Equinox (BMVE) are shown for reference.

In profile 3, in campaigns 1, 4, and 6, the profile had a gentle slope from the back of the beach area, for the next 125 m. In campaign 2, there was a "storm scarp" in the beach zone from the back for the next 35 m. In campaigns, 3 and 5, smaller scarps were observed on the profile, forming an irregular slope.

Profile 4 has a rock revetment, from the back of the beach area, for the next 10 m with a height of 1.5 m. Due to the adverse weather conditions in the first and last two campaigns, it was not possible to take measurements on this profile.

In profile 6, from the back to the next 19 m is the road, which runs parallel to the coastline. In general, no significant changes were observed here, and the beach has an average width of 7 m. However, in the submerged zone, from campaign 2 on, the profile eroded notably.

The measurements for profile 7 were taken in a rustic beach club. At the beginning of 2018, beach nourishment was carried out by the municipality, obtaining widths of 38–54 m. In order to maintain this beach, a pentapod revetment was constructed 50 m from the high-water line. Therefore, there is an abrupt change in the slope of this profile between campaigns 1 and 2. In campaigns 3 to 6, the coastline advanced seaward and the beach slope became gentler. In campaigns 3, 5, and 6, sedimentary accumulations were recorded in the submerged area of this profile.

Eighty per cent of the sediments on the beach profiles are of terrigenous origin, mainly coming from the deltas of the Turbo and Atrato rivers [17]. They are mostly composed of lithic to subilitic arenites and mudstones [30]. The break zone along profiles 1 and 2 has some areas with sandy gravel. From profile 3, there are some boulders and basalt-type igneous rocks, which have been introduced to the littoral system in order to counteract the erosive processes [22].

Appendix B

Table A1 presents a detailed description concerning each of the coastal protection structures identified, and Figure A2 shows photographs of each. It is important to note that structures 2, 3, and 13 are included in the *k* index calculation of two segments.

Table A1. Properties of coastal protection structures on the urban beaches of Turbo.

Structure	Segment	Type of Structure	Length (m)	Beach Zone	Condition of the Structure	Approximate Construction Date
1	3	Rock revetment	76.61	Intertidal	Good	2019
2	3 and 4	Rock revetment	242.49	Intertidal	Good	2019
3	3 and 4	Damaged pentapod revetment	70.57	Intertidal	Poor	NA
4	4	Rocky groin	49.83	Intertidal	Good	2019
5	5	Retaining wall	52.56	Intertidal	Acceptable	NA
6	5	Rock revetment	11.30	Subtidal	Good	NA
7	5	Rock revetment	29.45	Intertidal	Good	2019
8	5	Rock revetment	84.57	Intertidal	Good	2019 (reinforced)
9	5	Damaged pentapod groin	40.61	Subtidal	Poor	NA
10	5	Retaining wall	18.71	Intertidal	Acceptable	1985
11	5	Rock + pentapod revetment	40.71	Intertidal	Good	NA
12	5	Seawall + Tires	27.95	Intertidal	Good	NA
13	5 and 6	Rock + pentapod revetment	119.34	Intertidal	Acceptable	NA
14	6	Retaining wall	38.00	Intertidal	Poor	NA
15	6	Rock revetment	26.00	Intertidal	Acceptable	NA
16	6	Retaining wall	16.00	Intertidal	Poor	1986
17	6	Rock revetment	20.71	Intertidal	Poor	1985
18	6	Retaining wall	23.00	Intertidal	Acceptable	1984
19	6	Rock + pentapod revetment	10.55	Intertidal	Acceptable	1984
20	6	Retaining wall	27.00	Intertidal	Acceptable	1990
21	6	Rock revetment	6.24	Intertidal	Good	2002
22	6	Rock revetment	14.00	Intertidal	Good	2002
23	6	Rock revetment	8.00	Intertidal	Good	2002
24	7	Damaged pentapod revetment	54.61	Intertidal	Poor	NA
25	7	Rock revetment	18.44	Intertidal	Acceptable	NA
26	7	Breakwater	13.00	Subtidal	Acceptable	1990
27	7	Rock revetment	44.21	Intertidal	Poor	1990
28	7	Retaining wall	14.00	Intertidal	Good	NA
29	7	Pentapod groin	13.00	Subtidal	Poor	NA
30	7	Retaining wall	54.00	Intertidal	Good	1998
31	7	Pentapod groin	8.00	Subtidal	Acceptable	NA
32	7	Pentapod groin	7.00	Subtidal	Poor	1988
33	7	Retaining wall	10.50	Intertidal	Good	1990
34	7	Retaining wall	15.00	Intertidal	Good	NA

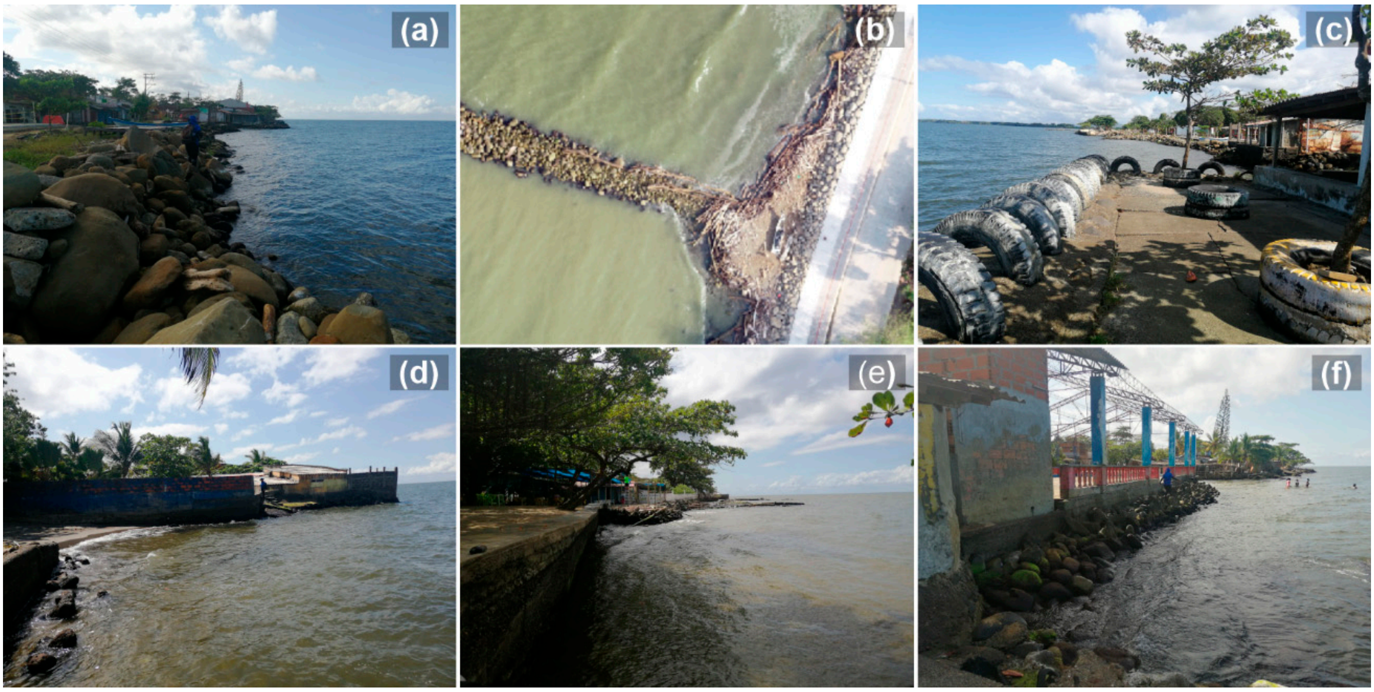

Figure A2. Types of artificial coastal protection structures associated with Table A1: (**a**) Rock revetment (structure 2); (**b**) Rocky groin (structure 4); (**c**) Seawall + Tires (structure 12); (**d**) Pentapod groin (structure 31); (**e**) Retaining wall (structure 20); (**f**) Rock + pentapod revetment (structure 13).

Appendix C

For each campaign, the dynamics in each segment were analysed by comparing the two profiles that delimit it. These results are presented in Figure A3. In profiles 1 and 3, for campaigns 1, 2, and 3, there was an accumulation of sediments (black lines) and sedimentary loss in campaigns 3 and 4. In campaigns 4 and 5, a sediment accumulation was observed and, finally, in campaigns 5 and 6, sedimentary loss was evident, producing an overall trend of equilibrium for the profile (red lines).

The accumulated sedimentary balances for profile 2, campaigns 1 and 3, changed from loss to gain (black lines). In the later campaigns, the behaviour of the profile is backwards, suggesting that the profile is equilibrium. It should be noted that profile 2 is located at the beginning of Playa Dulce, where an artificial sand fill was carried out.

Profiles 4 to 8 have many coastal protection structures. The results suggest a sedimentary accumulation for all campaigns, with a tendency of balance.

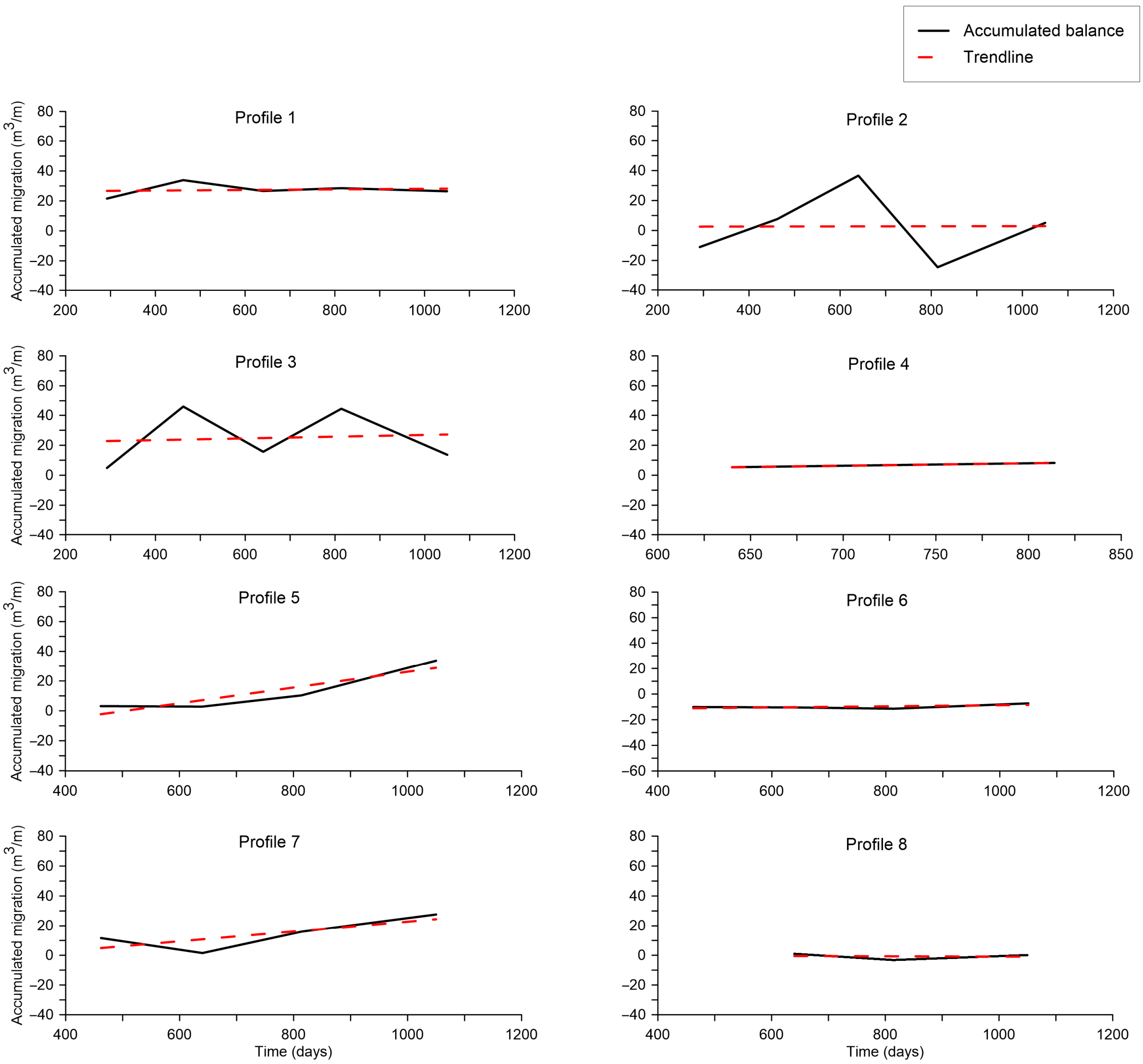

Figure A3. Sedimentary balance for each of the profiles. The dashed red line shows the overall trend.

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