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Expanding Level of Coastal Armouring: Case Studies from Different Countries

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ABSTRACT

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Concreting the natural shoreline by use of traditional hard protective structures, as well as by port/harbour developments is commonly known as coastal armouring. Over the recent decades the expanding level of coastline hardening and its adverse impacts on the environment has arisen as one of the most critical problems all over the world. Therefore, our goal in this study was to demonstrate the crucial issue of progressive extent of technogenous coastal occupation by two case studies from different countries in Europe and in South America: Bulgaria and Colombia. To assess direct impact of armouring on the coastline and adjacent areas two case areas were selected for detailed investigation: an 18 km long coastline of the large Varna Bay (Bulgarian Black Sea coast) and 349 km long littoral of the Cartagena municipality (Caribbean coastline of Colombia). An indicative coastal segmentation of the both case sites by geomorphologic and engineering criteria was first implemented in GIS environment. As well as, for quantitative assessment of the influence of all maritime structures (port and coast-protection) on the studied coasts the coefficient of technogenous impact K was explored. A GIS methodology was applied for data processing, mapping the natural landforms/structures and to evaluate the technogenous impact on the both coastlines. The identified high extent of impacts due to built hard defence structures along the selected study areas in Bulgaria and Colombia could be considered as indicative of the large technogenous occupation of the coasts and the increasing level of shoreline armouring as a global issue.

ADITIONAL INDEX WORDS: *coastal defence, technogenous impact, geomorphic segmentation, Bulgarian Black Sea coast, Caribbean Sea of Colombia*

INTRODUCTION

Coastline armouring, e.g., the protection of coasts by the use of hard defence structures, is a very common engineering solution against erosion and waves (Griggs, 2005; Charlier *et al*., 2005). Hence, coastal armouring involves traditional onshore structures, i.e. seawalls, rip-raps, dikes/revetments, but also port and harbour developments. During the past decade, the expanded level of coastal armouring, with its associated negative influence on the environment, has arisen as one of the most critical problems all over the world. The increasing of coastal armouring has been accompanied by a crescent concern on the cumulative impacts of protection structures and the artificial stabilization of natural coastline. Often, there are a number of adverse influence, including disturbance of cross- and long-shore sediment transport, and associated downdrift beach reduction, accelerated bottom erosion in front of structures, restricted public access to the beach, potential risks for bathers, anaesthetic visual effects on the seaside landscape, etc. (Griggs, 2005; EEA, 2006; Stancheva and Marinski, 2007).

In this context, the main objectives of the present research are directed to: analyse the various types of port/coast-protection structures, assess the increased extent of technogenous occupation and their impacts in two different countries in Europe and South America, i.e., Bulgaria and Colombia. Therefore, two case areas were selected in each country for detailed investigation: an 18 km long coastline of the large Varna Bay (Bulgarian Black Sea coast) and a 349 km long littoral of the Cartagena municipality (Caribbean coastline of Colombia). Geomorphologic and engineering criteria were first utilized to obtain an indicative coastline segmentation of both sites by use of GIS tools. Second, the coefficient of technogenous impact (K) after the methodology of Aybulatov and Artyukhin, (1993) was explored to quantitatively assess the influence of all maritime structures (port/coast-protection) on the both studied coasts.

GENERAL PRESENTATION OF SELECTED STUDY AREAS

Varna Bay (Bulgarian Black Sea Coast)

Traditional hard protective structures, such as seawalls, dikes and solid groins have been widely used since the 1980s in an attempt to cope with erosion/landslide processes at the Bulgarian Black Sea coast. As a result, about 10% of the entire 412 km long coastline has been armoured and this practice is still ongoing: rubble-mound dikes have been constructed as a common solution to protect the coast and public/own infrastructures (Stancheva *et al.,* 2010). Indeed, port and defence structures are not regularly constructed along the Bulgarian coast and there are parts with heavily occupied coastline: an illustrative example is the coast of the large Varna Bay (Stancheva, 2010).

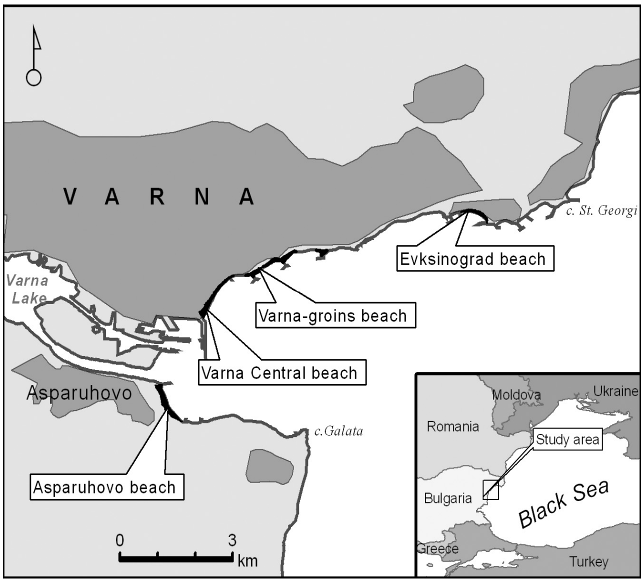

Figure 1. Locator map of Varna Bay.

The bay of Varna is situated at the northern part of the Bulgarian Black Sea coast between cape St. Georgi on the north and cape Galata on the south (Fig. 1). The adjacent coastline is almost 18 km long, being ESE oriented and it mainly consists of sandstones, marls and clays (Peychev and Stancheva, 2009). Two wave energy fluxes with opposite directions determine the long-shore sediment transport along the investigated coast (Fig. 1): the first one, named Evksinogradski, starts at cape St. Georgi and flows south-westward; the second one, named Asparuhovski, begins at cape Galata wand flows westward (Dachev and Cherneva, 1979). Both capes of St. Georgi and Galata are the zones of fluxes divergence while the western part of Varna Bay (the Asparuhovo beach) is the zone of their convergence. This way, the large sand spit, named Asparuhovska, had been developed over the Holocene at that site and thus dividing the Varna Lake from the sea (Fig. 1).

There are few sand beaches in the bay of Varna (Fig. 1): natural Evksinograd beach; Varna-groins beach (artificially created in the fields of groin system); Varna-central beach (formed in the re-entrant angle between the 1 km long harbour mole and coastline); and natural Asparuhovo beach (a remaining part of the former Asparuhovska sand spit).

The biggest Bulgarian Black Sea town of Varna and famous tourist centre is located in the study area. Here, vast deals of urban/land activities, harbour infrastructures and recreational developments are concentrated. A large number of ports/harbours and coast-protection structures have been built along the coast of the bay. The placement of such structures started in 1906 with the construction of the 1 km long mole of Varna harbour and the old navigational channel in the south-western part of the studied area. In 1976 a new navigational channel was dug to serve the deeper-draft generations of vessels on their way to the port of loading, located in the lake of Varna (Fig. 1). As a consequence, the length of the large Asparuhovo beach was reduced by 800 m.

Further, installing of hard defence structures to cope with cliff retreat was in particular enlarged during the 1980s. First a 3 km long coastal dike or embankment as road connection was built. As a result the shoreline was artificially moved seaward with about 40 m and thus creating a new land territory on the former water-area. Few years later, a number of impermeable concrete groins with T-, Y- and Γ-shapes and extended seaward about 100-120 m, were constructed at many sites along the coast. Then, the so called Varna-groins beach has been artificially created between compartments of the groin system by few sand nourishment projects (Fig. 1). On the other hand, since the construction of the aforementioned groin system, the Evksinogradski alongshore sediment flux has been interrupted, which in turn has stopped the sand supply to the following, e.g., in south direction, Varna-central beach (Fig. 1). In addition, the constant dredging activities in the deep-water navigational channel are other type of negative technogenous impact on the coast of Varna Bay. Typically, such works remove the sediments because their effects are similar to sand mining (Magoon and Treadwell, 2009). Moreover, two navigational channels have "trapped" both alongshore sediment fluxes and thus caused disturbance to the natural beach recovery in the study area.

Cartagena Municipality (Caribbean Coastline of Colombia)

Progressive erosion had started to affect the 1,760 km long Caribbean coastline of Colombia over the past century (Correa *et al.,* 2005). In response to this ongoing coastline retreat, since the 1970s, numerous and different protection structures have been emplaced along the coastal zone.

The Municipality of Cartagena de Indias, also known as "La Ciudad Heroica" (the Heroic city), is a large seaport at the north coast of Colombia. Founded in 1533, it was the major centre of early Spanish settlements in South America (Fig. 2). The coastal area is about 348 km long and the metropolitan area has a population of 1,240,000 inhabitants, which are particularly concentrated in the city of Cartagena (DANE, 2010). In fact the Cartagena Municipality occupies about 21% of the Caribbean territory and it is the fifth largest urban area in Colombia. It represents an important centre of economic activities in the region and a popular tourist destination.

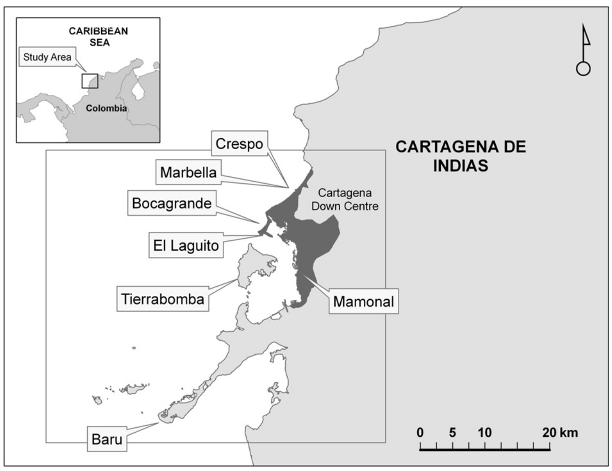

Figure 2. Locator map of Cartagena Municipality.

Interaction among tectonic, climatic and oceanographic processes in the study area has resulted in actual coastal settings, characterized by different geomorphologic units: i) dissipative beaches and barrier islands composed by sand sediments of terrigenous and carbonate origin; ii) marine terraces and cliff sectors, formed by Tertiary sandstones; iii) coastal plains associated with fluvial-marine sedimentary processes, and iv) coastal lagoons with mangrove swamps.

Coastal morphology is characterized by a sediment deficit resulting in erosion problems. In detail, the erosion processes were caused by the construction in 1936 of the jetty of Bocas de Cenizas. This structure favoured the impounding of the Magdalena River supplies into a submarine canyon (Martinez *et al.,* 1990), located in front of Barranquilla (north of the investigated area), and works as a barrier to the natural sediment transport approaching from the northeast. A few decades ago the evident coastal erosion and the interest in preserving the historical and cultural patrimony of the study area have motivated the local decision-makers to implement different protection measures. However, these engineering works have been carried out without any specific plan and without any assessment of their potential impacts.

DATA AND METHODS USED

Different sources of coastal data are used in this joint study:
i) for the Varna Bay (the Bulgarian study case), data from 1:25,000 scale topographical maps, field measurements with GPS "Garmin 12" (carried out in May 2007) and satellite images (freely gained from Google Earth, http://www.digitalglobe.com/) and QuickBird satellite images (which have a resolution of 0.75 m);
ii) for the Municipality of Cartagena (the Colombian study case) data from satellite images (DigitalGlobe map), Base Map cartography (from Agustín Codazzi Geographic Institute –IGAC-Colombia, at 1:25,000 scale), and field observations.

Geographic Information System (GIS) methods have been applied for data processing and mapping the coastlines, and to assess the technogenous impacts. For the case of the Varna Bay, all estimations and analysis were implemented in metric Projected Coordinate System WGS_1984_UTM ZONE_35N. For the case of the Cartagena Municipality, the Ground Control Points (GCP_s) for document registration have been obtained from the geo-referenced 2010 satellite image and all the information was presented in Projected Coordinate System UTM_Zone18.

Mapping or indicating the main geomorphic landform types (beaches/dunes and cliffs) and human modifications of the coastline (port and coast-protection structures) is a key part of identifying those areas which are more sensitive to various coastal risks. Such indicative typology or segmentation would help to highlight the state of the coastline and to form the primary base for vulnerability assessment, very useful in any coastal decision-making process (Anfuso and Martinez del Pozo, 2005; Sharples, 2006). Various types of segments indicated along the coastlines of both case areas were then combined in two major groups using geomorphologic and engineering approaches:

i) Landform coastal segments, presented by natural or artificial sand beaches and erosion cliffs;

ii) Technogenous coastal segments, presented by port/coast-protection structures and navigational channels.

All natural landforms and port or coast-protective structures were mapped as line segments, as the waterward perimeter of the cross-shore structures (such as groins, port/harbour moles, etc.) was also mapped as linear features.

For quantitative assessment of human impacts on the studied coastal areas, the so called coefficient of technogenous impact K was used (Aybulatov and Artyukhin, 1993):

$$K = l / L \qquad (1)$$

where l is the total length of all maritime structures (groins, moles, seawalls, dikes, channels and permeable bridges) and L is the entire length of the study coastal section. According to this methodology the extent of technogenous impact could be then classified as *minimal* at K=0.0001-0.1; *average* when K=0.11-0.5; *maximal* at K=0.51-1.0 and *extreme*, when K > 1.0.

RESULTS AND DISCUSSION

The Case of Varna Bay

A tremendous construction of hard stabilisation structures, mostly dikes and solid impermeable groins, has been implemented over the last few decades at the coast of Varna Bay. On the base of 2007 data from satellite images and GPS field survey, an indicative GIS-based segmentation of the studied coastline was produced (Fig. 3).

A number of 53 various types of segments (landforms and technogenous objects) comprising a total length of 24,57 km, were identified along the studied coastline. This total length of landform segments and technogenous segments exceeds the entire coastal length (18 km) between the capes of St. Georgi and Galata due to the included waterward parts of all ports and cross-shore defence structures. Coastal landforms, such as cliffs and natural or artificial beaches account a number of 18 individual segments with total length of 8,895 km. On the other hand, a number of 35

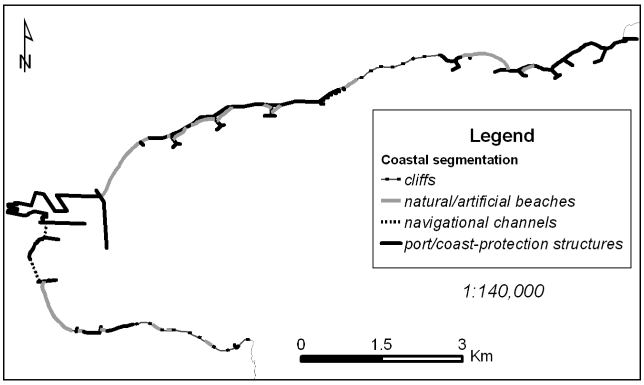

Figure 3. Coastline segmentation of Varna Bay.

technogenous segments (both port and coast-protection structures) with total length of 15,676 km were indicated along the coast of Varna Bay. These ones include both cross- and long-shore structures: two harbour moles, two navigational channels, eighteen impermeable solid groins, two large coastal dikes, a few embankments, seawalls and permeable bridges.

The results show that the eroding cliffs comprise a length of 2.9 km, and both natural and artificial sand beaches have a length of 6.0 km. At the same time the total length of armoured coastline (including only dikes, seawalls, revetments, etc. and harbour onshore developments) is almost 10 km. There are some sites with beaches and structures serving as their backshore borders, such as Varna-groins beach. In detail, there are: one 3 km coastal dike which works as a road connection, and a system of three solid groins and artificial beaches created between their fields. At the end, it was found that 56 % of the entire 18 km long coast of Varna Bay have already been armoured by concreting the natural shoreline.

The coefficient of technogenous impact K for this study area was estimated as a ratio between the total length of all port/coast-protection structures and the entire length of the coastal section: K =15,676 km / 17,880 km = 0.88. This value defines the extent of technogenous influence as maximal and this section as one of the most affected and occupied by human structures along the Bulgarian Black Sea coast. Indeed, the needs to protect the coast at most erosion-prone areas have in particular been proclaimed by the increasing inhabitants in coastal zone and the needs arisen then to save their properties. In fact, such high extent of heavily developed and armoured coastline corresponds to the high number of population in the study area. As the area is an important community centre and attractive tourist destination, the number of local residents/tourists has increased by 318 % over the 1934-2001 period (Palazov and Stanchev, 2006). As a result, at present the Varna Bay is one of the most populous sites along the Bulgarian coast. This habitation growth had also significant impact on the coastline morphology because the higher population concentration required a larger number of protection measures to be implemented for reducing coastal hazards. The applied defence methods, i.e. the building the long dike and solid groins had locally stopped the erosion only at the very place of structures emplacement. In fact, after installing the 3 km coastal dike the active cliff retreat was halted, but the sediment supply incoming from the land was impeded. This in turn has disturbed the sand delivery to the adjacent beaches around the study coast.

Instead of soft protection alternatives, the construction of hard stabilisation structures, such as groins, dikes and seawalls, have been assumed as a common solution to prevent the Bulgarian Black Sea coastline. Although numerous defence measures taken along the coast, the progress of adverse erosion processes show that the problems related to them have not been solved yet (Stancheva and Marinski, 2007). At present, there are many cases of usefulness and ad-hoc structures along the coast, which are partially broken or being in disrepair state. Their effects are now resulting in downdrift erosion, reduction of sandy beaches and degradation of natural resources.

The Case of Cartagena de Indias Municipality

Hard coast-protection structures, in particular groins and breakwaters of calcareous blocks, have been built over the past 50 years at the Cartagena de Indias coastline. Since the study area is very large, a more detailed segmentation of one smaller section of the Cartagena down centre is demonstrated as an example in Figure 4.

Along the coastline of the whole study area, the landforms and technogenous segments present a total length of 349 km. By one hand, landforms, i.e., cliffs and natural and artificial beaches, comprise a total length of 251,27 km. On the other hand, the technogenous segments (both port and coast-protection structures) present a total length of 102,17 km.

In detail, a total amount of 276 (both cross- and long shore) structures with a length of 39.8 km was observed at the 349 km long investigated coast. Most common human structures are harbours and ports, which have a total length of 19,5 km or they constitute 44% of the total length of all structures. Within the Cartagena Bay, human constructions include also industrial developments (oil refineries at Mamonal), commercial activities (Bosque), military uses (Manzanillo) and tourist activities (Manga, Pegasos, Bocagrande and El Laguito). One hundred groins, with a total length of about 4 km, were observed between Castillogrande and Crespo. They were emplaced in the 1970s to control coastal erosion along most important sandy beaches, such as El Laguito, Bocagrande, Las Tenazas and Marbella (Fig. 4).

As major reasons for rising beach erosion could be considered the decrease of sediment input from the rivers solid discharge and sediment impounding in the northern area due to natural processes (Correa, 1990). In fact, the construction of the first few groins had not mitigated the negative effects of severe erosion at this section. Conversely, over the time they have produced downdrift erosion

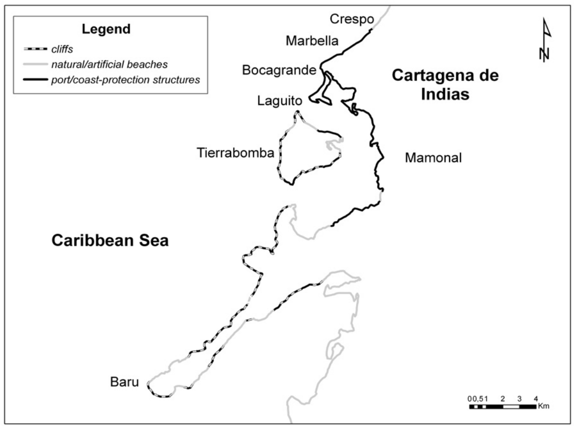

Figure 4. Coastline segmentation of Cartagena Municipality.

and new structures have been continuously constructed downdrift. These groins are impermeable and made of blocks of calcareous rocks obtained from Tertiary rocks extracted in near quarries, with an average cost of 20 €/m^3. Presently, the groins have locally stopped erosion creating a swash aligned coastline with a typical “zig-zag” shape.

A number of twenty-two breakwaters, with a total length of 1.7 km, were observed in the study area. They have been constructed with blocks of calcareous rocks and have been used to protect and enlarge the urban beaches between Crespo and Bocagrande (Fig. 4). By contrast with ineffective groins structures, these breakwaters have properly functioned and have enlarged backing beaches by creating well formed “tombolos”, with occurrence of slight erosion problems downdrift. Only one jetty is observed at the mouth of a coastal lagoon (Cienaga de la Virgen) which was artificially connected to the sea fifteen years ago to solve euthrophization processes. Few promenades, three historical fortifications, with total length of 0.9 km, and thirty-nine seawalls, with total length of 9.5 km, were constructed along the coast of Manga Island and the historical town of Cartagena. More recent developments, i.e. promenades, have been built in Manga and Bocagrande during the past two decades. Modern seawalls have been constructed to protect the urban areas from severe storms and floods coinciding with unusual high tide conditions annually recorded in September and October. A long fence was built at Crespo to stop landward sand migration which affects vehicle circulation in a backing avenue. Last, two shrimp pools were observed in the southern part of the area.

For the Cartagena de Indias Municipality, K value of 0.11 was obtained considering the total length of human structures of 39.8 km, corresponding to 276 structures, and the coastline length (349 km). After the applied classification, the extent of technogenous impact in the area belongs to the "averaged" class ($0.11 \leq K < 0.5$).

The total length of long-shore coastal protection structures and port/harbour developments has a value of 31.96 km that is 80% of total length of the armoured coastline (e.g., the value obtained considering both long- and cross-shore protection structures). In detail, the long-shore protection structures (seawalls and breakwaters) represent c. 39% and ports and harbours the 61% of the recorded value of 31.96 km. Most part of protection structures were built along Cartagena down centre coastline to stop erosion processes and respond to the growth of population, which increased about 300,000 inhabitants in the past five years, and the enhance of tourist demand, which increased about 10% in the last year.

CONCLUSIONS

Through the two selected studies at the Bulgarian Black Sea coast and Caribbean coastline of Colombia this paper was aimed to demonstrate a critical issue of the coastline armouring. In this way the results from the both case studies could be considered as indicative for the progressively increased level of technogenous occupation as a global issue. Potential implications of coastline armouring include numerous adverse effects: loss or damage of the natural landforms; irreversible coastline modifications; interruption or reduction of sediment input from the eroding cliffs to the adjacent beaches; aggravation of erosion processes downdrift; loss of valued sand material from the beach and shallow water-area during construction of the structures; negative visual impacts, lost access for swimmers to the water-area and potential risks for people's life.

With constantly growing coastal habitations, there is no doubt that much more protection measures would be required. Therefore, in future, we should manage our coastlines in conditions of dominant technogenous occupation and respectively modified coastal features and processes. Since the traditional hard defence methods applied so far had more damaging than protective effects there is now a need for using soft prevention alternatives according to the modern guidelines for coastal planning.

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