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Numerical Modelling of the Evolution of Sedimentary and Topo-Bathymetric Transit Rates: The Case of the Beaches of Rufisque on the Small Senegalese Coast

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ABSTRACT

This study seeks to estimate by a numerical approach the average rate of sediment transit along the sandy beaches of Rufisque on the small Senegalese coast, and to study its longitudinal variability as a function of this beach. The transit estimation approach is based on the long-term analysis, between 1985 and 2021, of the topo-bathymetric evolution of the seabed. By using remote sensing methods and Geographic Information Systems, the quality of the bathymetric data allows the implementation, and during each period, of a Digital Depth Model (DEM). The superposition of two Numerical Depth Models allows the calculation of the volumes of sand corresponding to the surfaces in erosion or accretion, of the sediment balances and by deduction of the average rates of sediment transit. The method used in this work shows that as a function of the behavior of the beaches, which are more or less dissipative and reflexive, the average rate of longitudinal transport by the coastal drift is inversely proportional to the dissipation capacity of the wave energy of the beach. During the study period, the Rufisque sector recorded significant erosion at the level of cells 1, 2 and 4 with respective average rates of -3.56,103 m3/year, -4.18,103 m3/year and -3,67,103 m3/year, while at the level of cell 3 a positive sediment balance was recorded, meaning an accumulation with an average rate of +1.13,103 m3/year.

Keywords: Digital Depth Model, sedimentary transit, morphodynamic index, remote sensing, GIS.

1. INTRODUCTION

The dynamics of coasts and coastal massifs is one of the main environmental problems facing coastal areas in the world and in West Africa [1]. Senegal, a coastal country located in the extreme part of West Africa, is also subject to this evolution [2], the factors of which can be intrinsic or external and strongly impacted by the activity of the local populations. Thus, coastal erosion largely disturbs the environmental balance and leads to losses of surface area that can be deplorable. As a result, it is now necessary to have a better understanding of the factors responsible for erosion on the coast in order to preserve it and the infrastructure built on it. This will also protect tourism activity since most of the attractive sites and dedicated accommodation (hotels) are located there. Digital Depth Models (DSMs) allow the calculation of areas or volumes, the determination of various indices such as slope inclination and orientation, as well as the visualization of three-dimensional structures [3]. The objective of this study is, on the one hand, to estimate the average rates of sediment transit by diachronic analysis of the morphological evolution of the bottom of the small coast, and on the other hand, to study the longitudinal variability of coastal transits as a function of beach behavior.

2. General context and study areas

In the current context of global climate change, coastal erosion remains a process that results from both natural and human factors and consequently affects the environment and socio-economic activities. The Senegalese coastline represents an area of strategic interest from a demographic, economic and environmental point of view. Natural environments, in a relatively preserved state of conservation, produce vital resources for the Senegalese population [2]. Coastal and marine resources play an important role in the Senegalese economy, whether it is fishing or tourism. As far as geological characteristics are concerned, the Rufisque area belongs to the domain of the small coast of Senegal characterized by sandy coasts and dunes but also marl-limestone facies with undifferentiated limestone. The dunes, through the sand reserve they represent, are thought to play an important role in the dynamic balance of the beaches they border. (figure 1).

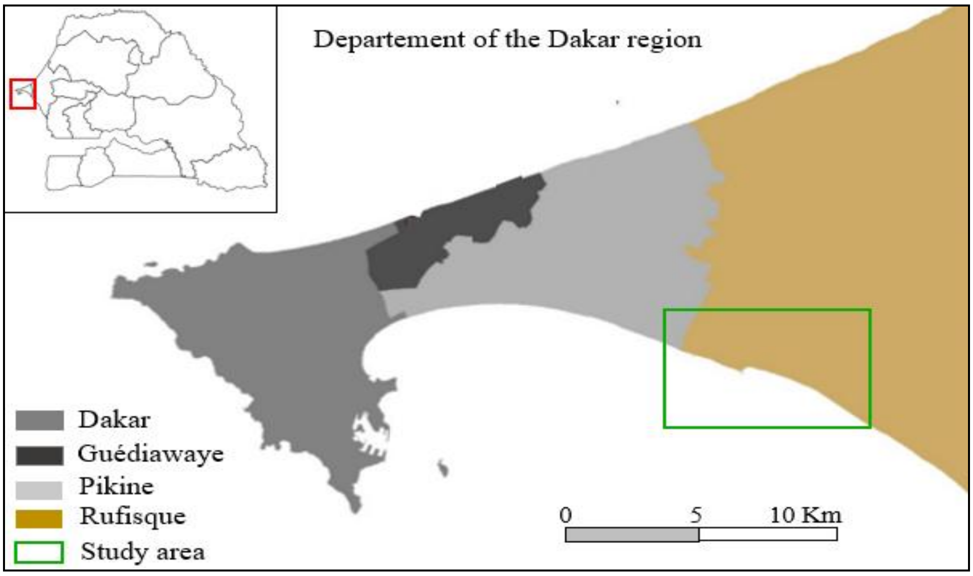

Figure 1: Location of study areas

3. Methodological approaches

The present work consists purely in calculating sand volumes corresponding to the surfaces in erosion or accretion, sediment budgets and by deduction of the average rates of sediment transit by a numerical approach.

3.1. Estimation of sediment transit

The estimation of sedimentary transits is based primarily on the identification of sedimentary cells, between which longitudinal transport is organized, within the framework of a system closed at its two ends as well as towards the land and the open sea [4]. The land boundary is materialized by the coastline and the marine boundary corresponds to the closing depth. Secondly, at the scale of each sedimentary cell (or coastal drift), the assessment of the sediment balance, depending mainly on the sedimentary movements induced by the longitudinal transit, is based on the construction and superimposition of two multi-date Numerical Depth Models (DEMs) resulting from the computer processing of bathymetric data, using the Arc-GIS software, allowing the calculation of the volumes of sand corresponding to the surfaces in erosion and/or accumulation. In this work, the coastal drift cell corresponds to a coastal compartment that contains a complete sedimentation cycle including a source zone (of erosion), an area in dynamic equilibrium and then an accretion zone. The study area is subdivided into four (4) cells. The first cell, which extends from Toubab Dialao to Sendou, is separated by the cape of Nditarh from cell 2, the limit of which is Bargny Guedj. The Thiawlène dike separates cell 2 and cell 3 which extends from Rufisque East to Rufisque West. The Rufisque landing is the boundary between cell 3 and cell 4 that extends from the Rufisque West fishing wharf to Diokoul southwest of Rufisque (figure 2). The mobile or free boundaries, most frequently found on open coastlines, correspond to instabilities or morphological responses to a variation in a component managing sedimentary transit [5].

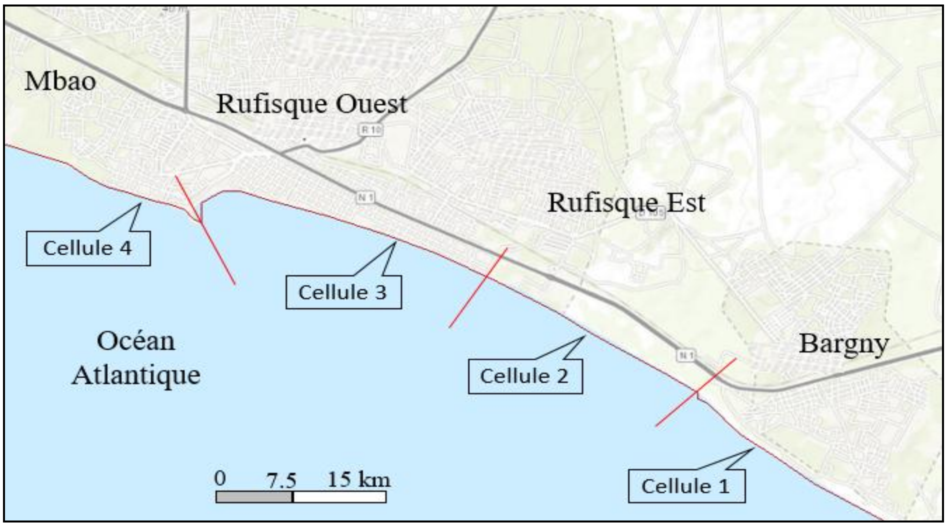

Figure 2: Sedimentary cells identified

Like the concept of sedimentary cell, the concept of closure depth is an essential condition to be taken into consideration in coastal morphodynamics when it comes to establishing a sediment balance. Several methods are often proposed to estimate the depth of closure. For our case study, W.A. Birkemeier's empirical formula is used to determine the depth of closure (Equation 1).

$h_f = 1.57 H_{so}$ **Equation 1**

With hf: closing depth

Hso: extreme annual significant swell height which is around 2.4 m according to Fall et al [6]. A value of -4m is chosen as the closing depth of the coastline studied. Since the coastal kinematics of these areas are dominated by erosion and in order to ensure that the evolution of the foreshore is included in the analysis, the contemporary land boundary would correspond to the ancient coastline (figure 3). However, for this contemporary shoreline, an altimetry attribute of about -1.8 m is affected.

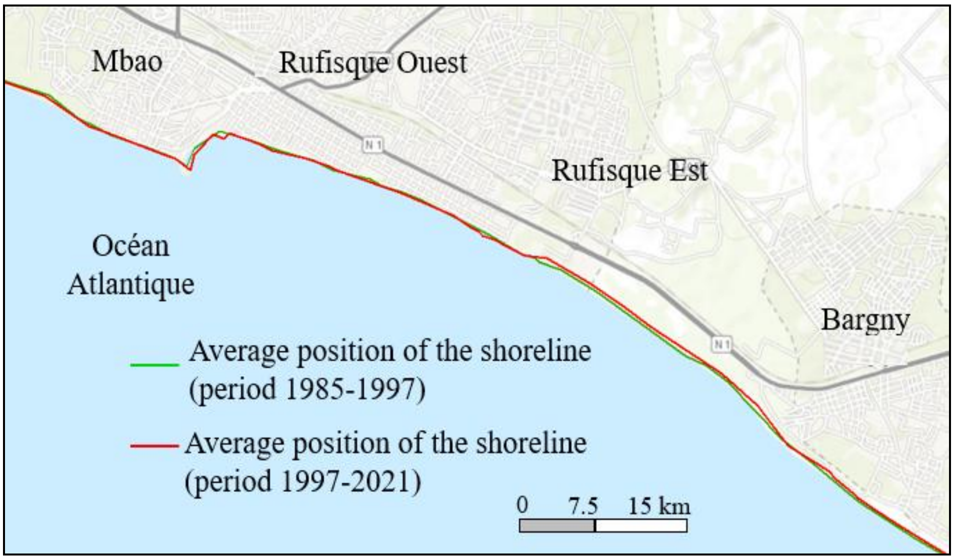

Figure 3: Average position of the shorelines

The bathymetric data used for this study come from the computer processing with the Qgis software and Arcgis of the Digital Elevation Models (DTMs), obtained through the United States Geological Survey (USGS) online portal and downloaded Pléiades images.

3.2. Morphodynamic characterization of the beaches

The physical behaviour of a beach can be characterised by the degree of reflection or dissipation of wave energy. L.D. Wright and A.D. Short [7] propose a conceptual model of a beach comprising six morphodynamic states, two extreme typologies, the reflexive beach and the dissipative range, and four intermediate states presenting both reflective and dissipating elements. This model, designed for microtidal environments, is an interesting approach to visualize beaches in a morphodynamic spatio-temporal continuum, without having hydrodynamic and topometric data. Indeed, this morphodynamic approach is based on a certain number of indices integrating simple parameters synthesizing the sedimentological, hydrodynamic and topographical characteristics of the beaches. The most commonly used indices are the member replication parameter (ζb; [8]) or the Iribarren number (Equation 2), the parameter of the scaling of the bar (ε; [9]) (Equation 3) and dimensionless fall velocity (Ω; [10]) (Equation 4).

$\xi_b = \text{tang}\,\beta/(H_b/L_0)^{0.5}$ **Equation 2**

The range is said to be dissipative when ξb < 0.4, reflexive when ξb > 2, and intermediate when 0.4 < ξb < 2 [8] (Fredsoe and Deiga.

$\varepsilon = 2\pi^2 H_b/gT^2\text{tang}^2\beta$ **Equation 3**

The range is said to be dissipative when ε > 20, reflexive when ε < 2.5 and intermediate when 2.5 < ε < 20 [9].

$\Omega = H_b/T\omega_s$ **Equation 4**

The range is said to be dissipative when Ω > 6, reflexive if Ω < 1 and intermediate when 1 < Ω < 6 [10].

The variables composing the expressions of these indices are Hb: height of the swell at breaking (in m); T: period of the swell (in s); H0: height of the offshore swell (in m); L0: wavelength of the offshore swell (in m); β: slope of the beach (in degrees); g: acceleration of gravity (9.81 m/s) and ωs: sediment fall velocity (in m/s). The height of the waves at breaking is estimated using equation 5.

$H_b = H_0\,[0{,}563/(H_0/L_0)^{0.2}$ **Equation 5**

The wavelength of the offshore swell is estimated by: L0 = gT2/2π. The average slope of the beach is derived from the MNP relating to the ancient period. The median diameter of sediment (D50) in the foreshore is generally around 0.18 mm [6]. The rate of sediment fall (Equation 6) is evaluated using a simple formula that is widespread in the literature (Soulsby 1997).

$$\omega_s = \upsilon/d\ [(108{,}03+0{,}78d_*3)^{0.5}-10{,}39]$$

Equation 6

where d* is the dimensionless sediment diameter expressed by d* = [(s-1) g/υ2]1/3d and s = ρs/ρ, where υ: kinematic velocity of water (10–6 m2/s), d: sediment size (D50, in m), ρs: sediment density (2650 kg/m3) and ρ: water density (1025 kg/m3). All of these measured or estimated parameters used for the calculation of the indices are reported in Table 1.

Table 1: Measured or estimated data used in the calculation of morphodynamic indices.

Cells	Ho(m)	Hb(m)	Lo(m)	D_{50}(mm)	β (deg)	T(s)	ω_s(m/s)
1	2,45	3,4	108,15	0,197	0,76	13,21	0,018
2	2,44	3,35	98,4	0,198	0,45	13,19	0,021
3	2,37	3,2	102,43	0,198	0,83	14,01	0,020
4	2,13	3,8	132,12	0,20	0,64	13,87	0,021

4. RESULTS AND DISCUSSIONS

The Numerical Depth Model of evolution (Figure 4), which makes it possible to spatialize the difference in depth in the foreshore of Rufisque during the periods 1985-1997 and 2009-2021, reveals sub-areas where the depth has either decreased or increased or, on the contrary, has remained stable. These variations, which are due to sedimentary displacements induced mainly by sediment transit, correspond respectively to zones of erosion, stability or accumulation. During these study periods, the Rufisque sector recorded significant erosion at the level of cells 1, 2 and 4 with average rates of -3.56,103 m3/year, -4.18,103 m3/year and -3.67,103 m3/year respectively, while at cell 3 a positive sediment balance was recorded, meaning an accumulation with an average rate of +1.13,103 m3/year (table 2).

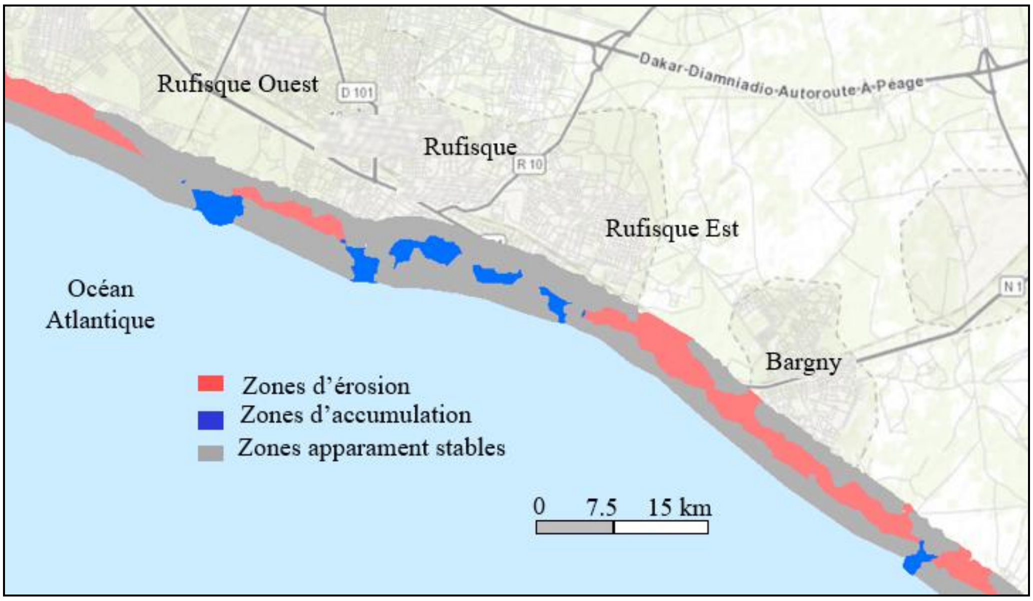

Figure 4: ***Digital Depth Model of evolution of the nearshore zone***

Table 2: Sediment budgets of the beaches and transport rates (10^3 m^3/an)

Cells	Trend of evolution	Average transit rate
Cells 1	Erosion	- 3,56
Cells 2	Erosion	- 4,18
Cells 3	Accrétion	+1,13
Cells 4	Erosion	- 3,67

The three morphodynamic indices (ζb, ε and Ω) show at the levels of cells 1, 2 and 4 (Table 3) that these ranges have a reflexive behaviour. The slope, from the breaking zone to the top of the swash zone, is very low. The energy of the waves is therefore not absorbed, but reflected by the top of the beach. At the level of these cells, we have an absence of sandbars. The slope is gentle and the waves break over a great distance. On the other hand, the berm is very developed, because the stock of sand usually found in these bars is integrated into the berm. On the other hand, at the level of cell 3 (Table 3), the range has a more or less important dissipative behaviour. It is structured by a system of linear bars with little markings on which the waves break several times, hence its dissipative character. This type of beach effectively dissipates wave energy with a morphology that is very different from reflective beaches.

Table 3: ***Morphodynamic characterization of the beaches according to the ζ_b, ε and Ω indices.***

Cells	ζ_b	ε	Ω
Cells 1	0,027	1324,76	24,1
Cells 2	0,043	1065,17	24,7
Cells 3	0,056	987,17	19,15
Cells 4	0,072	1061,34	21,43

Monitoring the evolution of transit rates along the ranges as a function of the Iribarren number (ζb) and the bar staggered index (ε) clearly shows that the transit rate increases as dissipation decreases between cell 3 and 2. Thus, the magnitude is greater at the level of cells 1, 2 and 4. At the level of these cells, the beach has a plunging or swelling type of breaking (reflexive beach), on the other hand on cell 3 the breaking of the beach is of the slippery type (dissipative beach).

5. CONCLUSION

In this study, the exploitation of the data is based on a precise evaluation of interpolated MNPs as a support to calculate sediment budgets and to deduce the average transit rates along the beaches of the study site. Estimating sediment transit by comparing MNP is an interesting method and the average transit rate evaluated is sufficiently reliable. Indeed, this rate is quite comparable to those evaluated either by an empirical formula (LCHF) or by the topographical method along the coastal strip studied or along certain neighboring beaches treated in the literature. The morphodynamic characterization adopted is a very good tool for analyzing and conceptually modeling the functioning of certain beaches in the sectors studied. Indeed, this morphodynamic approach based on the analysis of the mutual adjustments between the slope, the size of the sediments and the hydrodynamic characteristics of the waves, has made it possible to characterize the behavior of the beaches and to explain the longitudinal variability of the volumes carried by the coastal drift from one beach to another. At the level of cells 1, 2 and 4, the sector has a sedimentary deficit reflecting significant erosion, on the other hand at the level of cell 3 the balance is positive presenting accretion. Longitudinally, there is a passage from one dissipating domain to another more or less dissipating. This transition is accompanied by changes in the characteristics of the waves during the break, an important aspect in sedimentary dynamics because of the difference in energy and the capacity of transport.

Declaration by Authors

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