Spatio-economic valuation of sand in the context of shoreline (in)stability in the Senegal estuary (West Africa), integrating DeltaDTM and LiDAR technology

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Abstract

Coastal erosion is an increasing challenge in coastal management, resulting from complex interactions between geomorphological features, marine forcing, and anthropogenic interventions. The growing influence of human development and intervention on estuaries and coastal area evolution has led to a global sediment crisis, particularly in tropical or low-lying deltas (for example, Niger, Senegal, Nile, and Mekong), in contrast to the emerging international sand market. Paradoxically, the economic valuation of sand within the context of ecosystem services is limited, despite the global impact of coastal erosion, particularly on the West African coast. Among these, the transboundary Senegal estuary coast has been experiencing erosional trends coupled with coastal engineering developments in Saint-Louis (Senegal) and along the Ndiago Port (Mauritania) over the past 10 years. Using high-resolution elevation datasets (DeltaDTM and LiDAR) and imagery (Landsat), this study examines sand volumes lost/gained between 2013 and 2023 along the Senegal-Mauritania coast and assesses the economic value of sand as sediment reservoirs/stocks and as an ecosystem regulator (sand transport/redistribution). Results indicate that the Senegal-Mauritania coast accumulated a net sand volume of 1.515 x 10^6 m^3, equivalent to 10,527,000 USD in the market and 5,150,500 USD in production costs between 2013 and 2023. Coastal engineering infrastructure in Ndiago Port (Mauritania) and along the Goxxu-Mbacc-Ndar Toute also significantly impacted sand trapping, causing downdrift erosion. Findings also contribute to the unexplored field of coastal ecosystem services economic valuation in West Africa, offering new insights into the intrinsic value of sand as a reservoir and a vital ecosystem regulator.

Keywords: sediment budget, natural capital, environmental economics, coastal erosion, coastal engineering

1 Introduction

Coastal systems have been experiencing increasing anthropogenic pressure since the beginning of the Anthropocene (Crutzen, 2006 ; Smith and Zeder, 2013 ; Zalasiewicz et al., 2015 ; Elias, 2018 ; Li, 2024). According to the United Nations (2021), 40% of the global population lives within 100 km of the coast, and 90% of this population lives in coastal cities with over one million inhabitants (UNDESA, 2018). In West Africa, the impacts of climate change and anthropogenic interventions on coastal regions are particularly intense, with the low-lying coastal hinterland hosting 31% of the GDP[1] and 51% of the urban population (WACA, 2010). From Nouakchott to Lagos, coastal cities are becoming new erosion hazard hotspots, putting approximately 80 million people living within the coastal fringe at risk. Among them, the transboundary Senegal estuary (Senegal-Mauritania) is mainly composed of medium sand (Ndour et al., 2020 ; Dramé et al., 2022) shaping the Langue de Barbarie spit, known for its 2003 artificial breaching, reshaping the local morphodynamics (Durand et al., 2010 ; Wade et al., 2017 ; Ndour et al., 2020 ; Sarr et al., 2024). The past 10 years have witnessed the development of coastal engineering infrastructure on both sides of the estuaries. A jetty and breakwater were built in Ndiago port (2016-2023), while a riprap seawall (2018-2023) was implemented along the urbanised seaside of Langue de Barbarie to protect coastal communities from coastal erosion and sea flooding (**Error! Reference source not found.**).

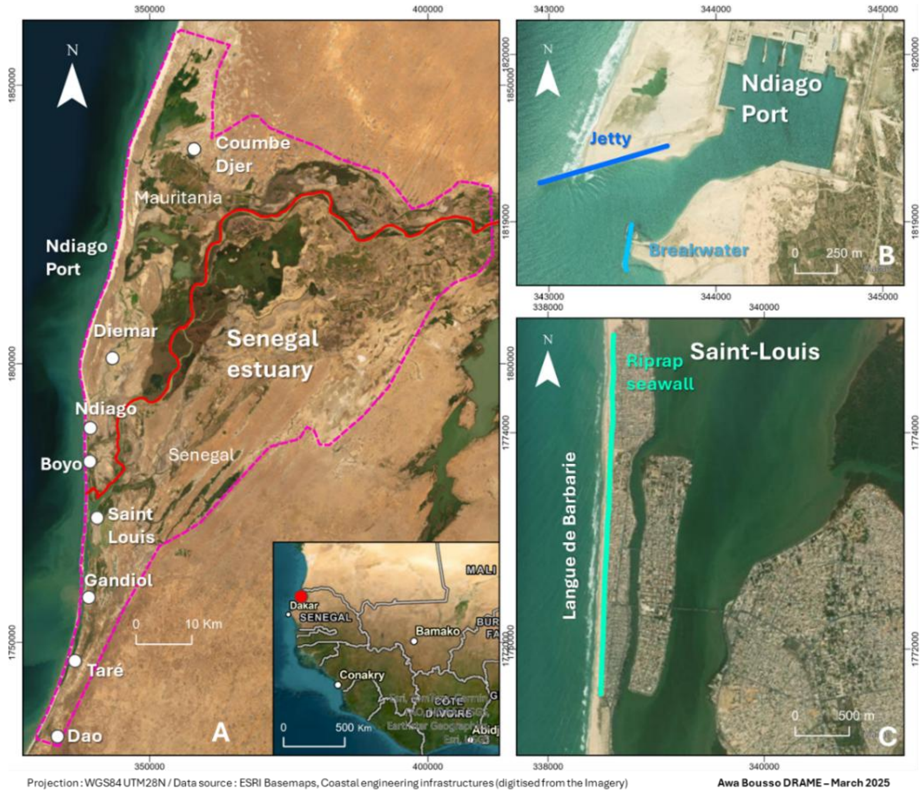

Figure 1 - Study area : A) Location map of the transboundary Senegal estuary coast ; B) Coastal engineering on the Mauritanian coast ; C) Coastal engineering infrastructures on the Senegalese coast

In this sensitive context, sand plays a vital role in maintaining the dynamic equilibrium of the shorelines (Thorn & Welford, 1994). This balance is closely related to sediment budget theories (Rosati, 2005 ; Parsons, 2011) which are widely used in geomorphology to account for sediment deposition and erosion and to better understand their spatial distribution and influence on landform morphodynamics. Sand reservoirs reflect the concept of sources and sinks (Anthony & Julian, 1999 ; Chang-Song et al., 2015). They can be considered as sources when they supply sediments and as sinks when they accumulate these materials. Beyond shoreline stabilisation, sand is also a highly sought marine resource/commodity in the construction industry (Peduzzi, 2014 ; Dawson, 2020), paradoxically encouraging sand mining at unsustainable levels and exacerbating erosion risks. For instance, Steinberger et al. (2010) estimated that between 47 and 59 billion tons of material is extracted annually, whereas Krausmann et al. (2009) evaluated sand and gravel mining to be between 68% and 85% of the extracted aggregates. However, sand mining is known to cause sediment deficits, directly favouring coastal erosion (Moyés Polo 2000 ; Magoon et al. 2015 ; Kurt 2016 ; WACA 2019 ; Leal Filho et al. 2021). This global situation is also due to an emerging international sand market (Gavriletea, 2017 ; Bendixen et al., 2021), despite raising environmental protection frameworks. Despite its critical role, the economic valuation of sand as a coastline stabiliser remains limited, potentially due to challenges in quantifying its indirect benefits or the dominance of extractive perspectives in valuation research. Assessing sand

[1] GDP = Gross domestic product

economic valuation through the lens of shoreline stability is therefore not just an ecological concern but a major economic challenge for low-lying West African coastal systems such as the Senegal-Mauritanian shoreline of the Senegal estuary.

2 Methodology

Shoreline change analysis was performed to assess net shoreline mobility before calculating sand volumes eroded or accumulated over the 2013-2023 period. This study covers a period of 10 years, from October 2013 (01/10/2023) to August 2023 (02/08/2023). October 2013 corresponds to 10 years after the 2003 breach, and August 2023 was chosen to be consistent with the available sand production costs. The steps are presented in Figure 2 and are detailed in the following sections.

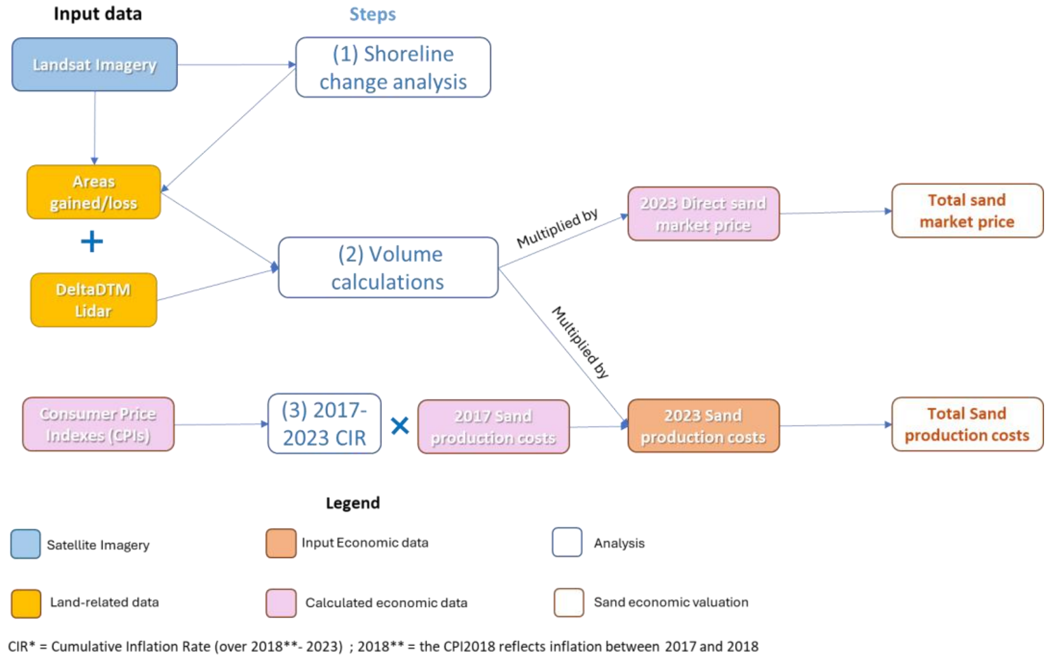

Figure 2 - Methodology overview

2.1 Coastal erosion dynamics

Landsat imagery was accessed from the USGS Earth Explorer, covering 10 years, from October 2013 to August 2023, on a monthly basis. In the Senegal estuary coast, particularly along the Senegal-Mauritania border, the dense urbanisation reaches the waterline (e.g. Goxxu Mbacc, Guet-Ndar and Ndar Toute), while the Ndiago Port buildings are directly implemented on the coast. In contrast, the rest of the Mauritanian side of the estuary coast is uninhabited, leaving a large beach width that does not exist in the aforementioned zones.

The emergence of artificial intelligence in coastal geomorphology in recent years allows for the extraction of coastlines and the calculation of changes over different timescales to become more numerous in the recent period. Models such as BeachTools perform shoreline analysis from a wet/dry line made from polygons representing the beach and vegetation (Zarillo et al. 2008), but do not have a georeferencing tool to correct the image projection. Similarly, CoastSat (Vos et al., 2019) works on rectilinear coasts and does not consider wavy shorelines alternating between small headlands and bays, such as the Senegal Estuary coast. Other shoreline extraction techniques use high-resolution satellite images. For example, the Landsat Toolbox for Shoreline Extraction computes the Normalised Difference Vegetation Index (NDVI) before classifying land and sea categories to create shore boundaries (Liu et al., 2017), while the high-resolution extractor from Maglione et al. (2014) used the coastal blue wavelength in Band 1 and the NIR2 wavelength in Band 8 of Worldview 2 and 3 imagery to extract shore boundaries from the Normalised Difference Water Index (NDW and NDVI indexes. However, high-resolution imagery (≤ 0.5m) was not available for the study area. Additionally, using near-infrared (NIR) to distinguish the limit between water bodies and land is a widely used methodology (Barsi et al., 2014).

Consequently, the shorelines and riverside of the Langue de Barbarie were hand-digitised monthly for each period using the instantaneous water line mentioned in Boak and Turner (2005). A total of 688 shorelines were digitised using the Near-Infrared Band (NIR). Considering the micro-landforms of the Senegal-Mauritania coast, shorelines were manually extracted to respect micromorphology and ensure quality control. Moreover, a 200m transect spacing was defined to cope with the shoreline morphology covering a long stretch of the Senegal estuary coast (Senegal-Mauritania). Shoreline change analysis was performed in the 4th version of the Digital Shoreline Analysis System (DSAS v4) (Thieler et al., 2009) using cross-shore transects at 200m equidistance. On the one hand, the Linear Regression Rate (LRR) was used as an indicator of the annual erosion rate to monitor coastal erosion using the 688 shorelines. On the other hand, the Net Shoreline Movement (NSM) represents the distance between "*the oldest and youngest shorelines for each transect*" (Thieler et al. 2009), hence October 2013 (Landsat 8, 01/10/2013) and August 2023 (Landsat 8, 02/08/2023). The rates were analysed and plotted in a Python environment.

2.2 Volume calculations

By definition, volume is the product of the area and elevation. To calculate the volumes gained/lost, we intersected the areas between the 2013 and 2023 shorelines (Figure 3). Areas were automatically generated using ArcGIS Pro (Shape_Area field). Areas were converted to lines and merged with cross-shore transects (line features) previously used to calculate the total shoreline retreat (NSM) in 2013-2023. Second, the sign of the Linear Regression Rate (LRR) indicator, previously calculated over 2013-2023 was used to determine areas gained or lost for each polygon owing to spatial jointures based on the transect identification number (Transect_ID field). Third, elevation values (Z) were extracted from DeltaDTM, a high-accuracy digital elevation model accessible from the TU Delft online repository. DeltaDTM offers an absolute vertical uncertainty of 0.45m and a (horizontal) spatial resolution of 30m (Pronk et al. 2024). The DeltaDTM raster was converted into points. Similarly, a LiDAR dataset produced by Egis & Deltares (2019) in 2019 was used. This dataset had a vertical accuracy of ± 0.15m. The volumes gained or lost ($V_{L/G}$) were calculated using the product of the area lost/gained ($A_{L/G}$) and elevation (Z), as indicated in Equation (2):

$$Sand_{VOL} = A_{L/G} \times Z \qquad (equation\ 1)$$

$$V_{L/G} = A_{L/G} \times Z \qquad (equation\ 2)$$

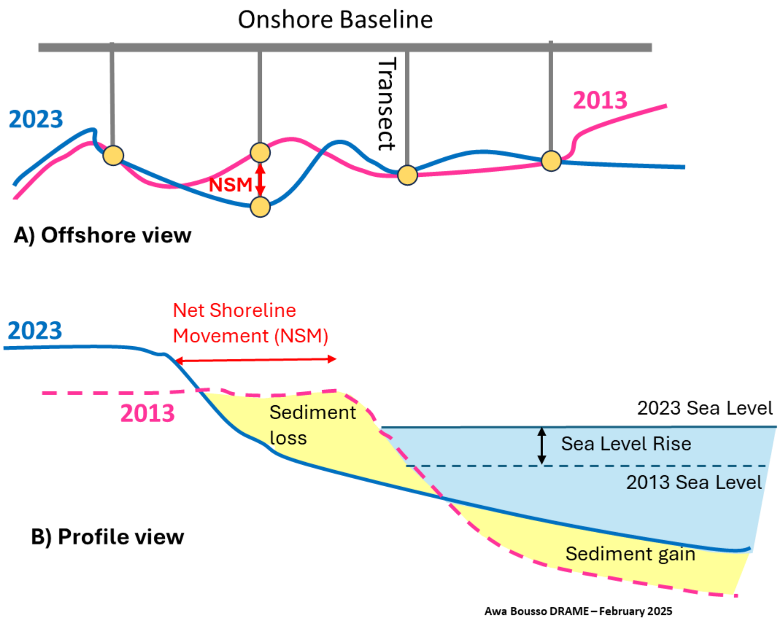

Figure 3 - Volume loss / accumulation

2.3 Sand economic values

Sand plays a crucial role in shoreline stabilisation, providing essential ecosystem services to coastal communities. Ecosystem services encompass the provision, protection, regulation, and cultural benefits that societies obtain from ecosystems (Costanza et al., 1997 ; Costanza, 2000 ; Millennium Ecosystem Assessment, 2005). Many studies have recognised the ecosystem services that sand provides to humans (Asabonga et al. 2017; Hackney et al. 2020; Rangel-Buitrago et al. 2023), including protection from waves, raw material supply for industries, species habitat, tourism, and shoreline stabilisation. Furthermore, ecosystem service valuation echoes the notion of total economic value developed by Pearce and Warton (1993), presenting their utilitarian or non-utilitarian value (Figure 4). The Total Economic Value (TEV) is a comprehensive framework that captures the full array of benefits provided by ecosystem services and environmental resources, including both market and non-market values (Figure 4). It acknowledges that natural resources have intrinsic value beyond that reflected in market transactions. In this study, we focused on the economic value of sand within the framework of coastline stabilisation, as shown in Figure 4.

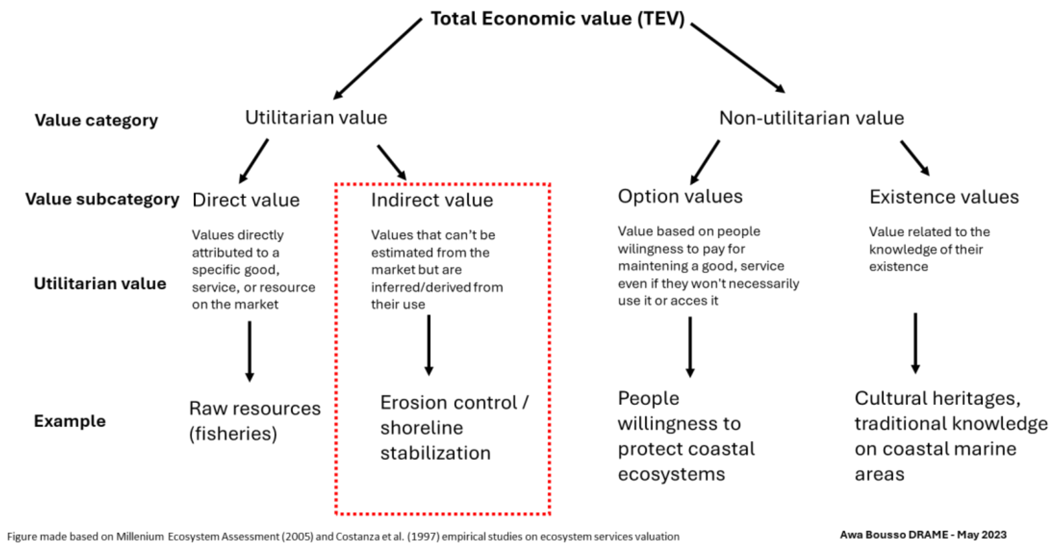

Figure 4 - Total Economic value applied to coastal areas

Different approaches have been developed by the Millennium Ecosystem Assessment (2005) and Costanza et al. (1997) to quantify ecosystem services, ranging from direct market valuations to revealed preferences and stated prices. We applied them to shoreline management in the context of the Senegal-Mauritania coast and summarised them in **Error! Reference source not found.**. According to Richardson et al. (2015), the benefits transfer approach refers to "*the use of existing data or information in settings other than for what it was originally collected*." This methodology estimates the economic value of ecosystem services by applying existing econometrics from a study site to a similar environment in which data may not be available. Based on the data availability outlined in **Error! Reference source not found.**, we used a benefit transfer approach to apply the national price of sand market value and production cost to the overall Senegal-Mauritania coast.

Table 1- Existing methodological approaches to valuate ecosystem services (adapted to the Senegal estuary coast)

Approach	Valuation method	Description	Adaptations in our case of sediment valuation	Data availability
Direct market valuation	**Market price**	**Based on the service or good price/cost in the market**	**Price of sand on the market**	**Yes – National value from 2015 on the ANSD online database**
	Replacement cost	Cost induced by the replacement of sand (e.g. beach nourishment)	Price of sand to replace sand eroded/gained on beaches. Replacement costs depend on factors such as sand grain size, extraction method, transportation, engineering studies, and placement, rather than just the cost of sand production itself.	Not available
	Avoided cost	Potential costs related to socio-economic damages induced by the absence / lack of sand	Cost savings from preventing socio-economic damages, such as erosion or seaflood damages, due to coastal protection (e.g., sand dunes, beach nourishment).	Not available
	Production approaches	**Added value created from an ecosystem service to increase it**	**Price of sand based on production costs (e.g. equipment used, human resources)**	**Yes available (national level) from the ANSD (2020) study on sandmining**
Revealed preference	Travel costs	Costs spent to benefit/enjoy the ecosystem service (implicit value of the service)	Tourists travelling to Saint-Louis coastal areas to enjoy sandy beaches and seascapes.	Not available
	Hedonic pricing	Additional value / Increase in property values due to the presence of sandy beaches to the initial price people are willing to pay for the same service (getting sand) in similar markets.	Coastal properties near have higher prices compared to similar properties without such access.	Not available
Stated preference	Contingent valuation	Survey-based method based on hypothesis, valuation scenarios	People willingness to pay for sand conservation / protection	Not available

The direct sand market price is used as a proxy to represent the in-situ value of sand on the beach, with all the benefits it brings to coastal ecosystems. As direct replacement cost data are unavailable, this study used sand production costs to estimate the costs associated with its replacement. Sand production costs are used as a proxy for the **partial** value to produce and replace eroded sand (from quarries) but without having the same characteristics as marine/natural sand. Comparing the market prices and production costs of sand as a natural resource allows us to better understand the intrinsic value of sand (market value) and replacement (production) costs. The benefits were calculated from the difference between the sand market value and the sand production costs. According to the Millennium Ecosystem Assessment (2005), humans take advantage of "*the **benefits** obtained from the **regulation of ecosystem processes***". This approach aims to emphasise the role of regulatory services, also known as sand transport/distribution processes, in the coastal ecosystem, which cannot be replaced (benefits).

On the one hand, the sand market value was collected from the Senegalese National Statistics Agency (ANSD, n.d.) and is only available from April 2015 onwards. We selected the sand market price in August 2023 ($S_{DM-Aug2023}$) to remain consistent with sand production costs from August 2017. On the other hand, the ANSD estimated sand production costs in 2017 during a survey conducted between July 2017 and August 2017. The study, "*Etude monographique sur l'extraction de sable au Sénégal (EMSAS)*", evaluated the human resources needed to produce sand, as well as the equipment (trucks and excavators), transportation costs, and licence costs. As the ANSD sand production costs were estimated for August 2017, we updated them to reflect 2023 prices. This requires estimating the total inflation between 2017 and 2023. Annual inflation is measured using the Consumer Price Index (CPI), which is widely used by multiple financial organisations (UK House of Commons 2009; OECD 2025; US Bureau of Labor Statistics, 2025), and is equivalent to the *Indice Harmonisé des Prix à la Consommation* (ANSD, 2019).To assess total inflation over multiple years (2017-2023), economists use the Cumulative Inflation rate (CIR) to account for annual price increases (Jones and Wilson, 2006 ; Kurniasari et al., 2023). The CIR method has been proven to be robust for predicting building materials in Nigeria (Oghenekevwe et al., 2014) and Sudan using inflation data from the Sudan Central Bank (Elkhider et al., 2020). We applied this method to calculate the 2023 sand production costs ($S_{PROD-Aug2023}$) based on the 2017 sand production costs($S_{PROD-Aug2017}$) obtained from the ANSD study. As specific CPIs for equipment, transport, fuel, goods, or human resources used by the ANSD to calculate sand production costs in 2017 were not available, the general CPI from 2018 to 2023 was used to calculate the Cumulative Inflation Rate between 2017 and 2023, assuming that it affects all goods and services in Senegal, including those needed to produce sand. Table 2 CPIs used in this study are presented in Table 2. It should be noted that the 2018 CPI refers to inflation between 2017 and 2018 (CPI_{2018}). The Cumulative Inflation Rate (CIR) formula (Oghenekevwe et al.

2014 ; Bansilal 2017 ; Elkhider et al. 2020) was applied to obtain the 2023 updated unitary sand production costs in 2023 ($S_{PROD-AUG2023}$), as shown in Equation (5).

$$CIF_{Aug2017-Aug2023} = (1 + CPI_{2018})(1 + CPI_{2019}) \ldots (1 + CPI_{2023}) \quad (equation\ 3)$$

$$CIF_{Aug2017-Aug2023}(\%) = (CIF - 1) \times 100 \quad (equation\ 4)$$

$$S_{PROD-AUG2023} = CIR_{Aug2017-Aug2023} \times S_{PROD-Aug2017} \quad (equation\ 5)$$

Table 2 - Cumulative inflation calculations from annual Consumer Product Indexes (CPIs)

Year	CPI in %	Source	Comments
2018	0.5	ANSD (2019)	The CPI is the only provided metric by the ANSD. Specific CPIs on human resources, goods and equipment variables used in the sand production evaluation are not available.
2019	1.0	ANSD (2020b)	
2020	2.5	ANSD (2021)	
2021	2.1	ANSD (2022)	
2022	9.7	ANSD (2023a)	
2023	5.9	ANSD (2024a)	
Cumulative Inflation (2017-2023)	**23.04**		**See the methodology**

Consequently, the volumes previously calculated were multiplied by the unitary sand market value ($S_{DM-Aug2023}$) and its unitary production cost ($S_{PROD-AUG2023}$), using the following formulas:

$$Sand_{MK} = \left| A_{L-G} \times Z_e \times S_{DM-Aug2023/\mathrm{m3}} \right| \quad (equation\ 6)$$

$$Sand_{PROD} = \left| A_{L-G} \times Z_e \times S_{PROD-Aug2023/\mathrm{m3}} \right| \quad (equation\ 7)$$

Table 3 summarises the unitary sand market values and sand production costs used in this study. Calculations were performed using ArcGIS Pro to capture spatial variations along the Senegal-Mauritania coast. The final sand economic values (market- and production-based) were mapped in ArcGIS and sectorised to detect the amount of money saved or lost resulting from volume. This perspective might not fully capture the social, ecological, and cultural dimensions of the economic value of sand, but it provides a partial estimation based on one service: erosion control or shoreline stabilisation.

Table 3 - Summary of input economic parameters for sand economic valuation

Parameter	2017	2023	CIR (2018-2023)	2023 Input (USD)	Source	Comments
Sand production cost in 2017	1,606 Fcfa	1,982 Fcfa	23,04 %	3.40 USD	ANSD (2020)	Currency rate on 17/07/2023: 1 XOF = 0.001713 USD
Sand market price in 2023	-	4,175 Fcfa	-	6.95 USD	ANSD (n.d.)	Currency rate on 15/08/ 2023 : 1 XOF = 0.001667 USD This data is **only available from April 2015 monthly**. August 2023 has been chosen to match the sand production cost, which gives a sand value in August 2017.

The unitary direct market price of sand is plotted below to capture the variations in the sand market value over time. The price of sand in the market is relatively stable, with an annual rate of change of 0.0016 (slope in Figure 5), which indicates minimal price variation. However, there has been a sharp increase in sand market prices since 2020. This abrupt change may be associated with a decrease in sand production and an increase in sand demand. This change can be attributed to the COVID-19 pandemic, which impacted all industries, including mining and construction. This hypothesis is confirmed by Hatoum et al. (2021), who reported productivity losses in the building industry, mining site shutdowns, and labour shortages. A similar pattern was also reported by the Senegal National Statistics Agency, underlining a decline of -71.3% in the Building and Public works industries in 2020 and a progressive recovery since 2022-2023 (ANSD, 2025).

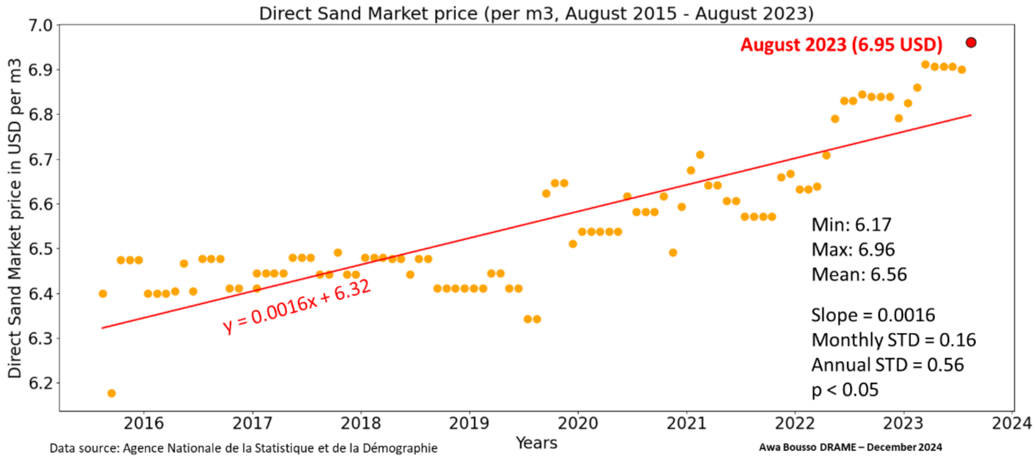

Figure 5 - 2023 Direct Sand market value over 2015-2023

2.4 Uncertainty calculations

The uncertainty of the economic value of the volumes gained/lost, based on both the sand market and sand production, is primarily determined by volume. The volume was obtained from the area gained/lost (field shape_area value in ArcGIS Pro) and elevation datasets. To calculate the overall uncertainty, we applied the standard error propagation method (Wang and Iyer, 2005 ; Hengl et al., 2010 ; Nourbakhshbeidokhti et al., 2019) using the square root of the sum of the squared individual uncertainties. This approach accounts for the cumulative effect of multiple error sources, thereby ensuring a more accurate estimation of the overall uncertainty. In our study, this implies an uncertain association with elevation and area.

First, the area uncertainty was based on the shoreline mapping error, which includes tidal corrections and pixel errors, as proposed by Fletcher et al. (2012). Tidal corrections were equivalent to the average tide levels in Saint-Louis when the satellite images were captured in October 2013 and September 2023. It should be noted that there are no tide data in Saint-Louis or other coastal cities along the Senegal-Mauritania coast. Therefore, we used the tides collected from the SHOM (2025) prediction services at the Saint-Louis station instead of those observed at the Dakar station, which is far from the study area. The area uncertainty was computed using the error propagation approach (Equation 8).

$$\Delta a = \sqrt{(E_T)^2 + (E_P)^2} \quad (equation\ 8)$$

Second, regarding the elevation uncertainty (E_Z), we mainly used the DeltaDTM absolute vertical uncertainty of ± 0.45m (Pronk et al. 2024) for the entire coast except for the Langue de Barbarie. As the 2019 Egis and Deltares (2019) LiDAR dataset was used with the DeltaDTM for the Langue de Barbarie, we assumed that they had an equal spatial distribution. Therefore, a specific elevation uncertainty for the Langue de Barbarie (Δz_{LB}) was computed using an equal weight for Lidar ($\Delta z_{LiDAR} = 0.15$m) and DeltaDTM ($\Delta z_{DeltaDTM}$ 0.45m) as shown in Equation (9):

$$\Delta z_{LB} = \sqrt{(0{,}5 \times \Delta z_{LiDAR})^2 + (0{,}5 \times \Delta z_{DeltaDTM})^2} \quad (equation\ 9)$$

When applied to volume uncertainty, the error propagation principle yields Equation (10), which includes both elevation and area relative uncertainties. Consequently, the total volume uncertainty ($\Delta_{v-SNMAU}$) was calculated using Equation (11) for the entire coast except for the Langue de Barbarie spit whose total volume uncertainty (Δ_{v-LB}) was calculated using Equation (13)

$$\left(\frac{\Delta v}{v}\right)^2 = \left(\frac{\Delta a}{A}\right)^2 + \left(\frac{\Delta z}{Z}\right)^2 \quad (equation\ 10)$$

$$\Delta_v = V \times \sqrt{\left(\frac{\sqrt{(E_T)^2 + (E_P)^2}}{A^2}\right) + \left(\frac{\Delta z_{SNMAU}}{Z}\right)^2} \quad (equation\ 11)$$

The simplified version of the total volume uncertainty (Equation 12) was adapted to reflect the general uncertainty of DeltaDTM (Equation 13) and the specific uncertainty for Langue de Barbarie, which used both LiDAR and DeltaDTM (Equation 14):

$$\Delta v = V \times \sqrt{\frac{(E_T)^2 + (E_P)^2}{A^2} + \left(\frac{\Delta z}{Z}\right)^2} \quad (equation\ 12)$$

$$\Delta v\ (SNMAU) = V \times \sqrt{\frac{(E_T)^2 + (E_P)^z}{A^2} + \left(\frac{\Delta z_{DeltaDTM}}{Z}\right)^2} \quad (equation\ 13)$$

$$\Delta v\ (LB) = V \times \sqrt{\frac{(E_T)^2+(E_P)^z}{A^2} + \left(\frac{\Delta z_{LiDAR}}{Z}\right)^2} \quad (equation\ 14)$$

In the above Equation, (E_Z) represents the uncertainty, (E_T) tidal corrections and (E_P) pixel error. Tidal corrections (E_T) were equivalent to the average of both tide levels in Saint-Louis when the satellite images were sensed in October 2013 (01/10/2013) and August 2023 (02/08/2023). As tide data in Saint-Louis or other coastal cities along the Senegal-Mauritania coast are not available, we used the tides collected from the SHOM (2025) prediction services at the Saint-Louis station.

The analysis of direct sand market prices over 2015-2023 (Figure 5) indicated a very low slope (0.0016), which was considered negligible and not associated with uncertainties in our study. Likewise, the potential uncertainty of sand production costs directly arises from the CPIs calculations by the ANSD and has not been considered in this study. This implies that the total uncertainty of sand valuations based on the direct market price ($\Delta TV_{\ DM-Aug2023}$) and sand production costs ($\Delta TV_{\ PROD-Aug2023}$) primarily depends on volume uncertainty. The uncertainty of sand market price and sand production costs was used with both general uncertainty (for the entire Senegal-Mauritania coast, $\Delta v\ (SNMAU)$ and the Langue de Barbarie ($\Delta v\ (LB)$ as its volume comprises DeltaDTM and lidar data. They are equal to the absolute values of the product of the volume uncertainty and the unitary sand direct market price ($S_{DM-Aug2023}$) or unitary sand production cost ($S_{PROD-Aug2023}$) as shown in Equations 15 and 16.

$$\Delta TV_{\ DM-Aug2023} = |\ \Delta v\ \times\ S_{DM-Aug2023}\ |\ (equation\ 15)$$

$$\Delta TV_{\ PROD-Aug2023} = |\ \Delta v\ \times\ S_{PROD-Aug2023}\ |\ (equation\ 16)$$

3 Results

3.1 Elevation variations

The Senegal-Mauritania coast is mainly low-lying, with a decreasing north-south gradient from Coumbe Djer to the mouth (Figure 6). The Mauritanian coast is slightly higher (slope = 2.1%) than the Senegalese coast (slope = 1.6%) with respective elevation averages of 2.2m and 1.15m (Figure 6A,B). Unsurprisingly, the maximum elevation (5.6m) is located in Mauritania between Ndiago Port and Diemar. The northern Langue de Barbarie is the lowest area on the coast, with an average elevation of 1.1 m and a maximum of 2.3m in Guet-Ndar. The southern spit had a higher average elevation (1.8m) than the northern spit, but greater differences in elevation (STD = 0.67).

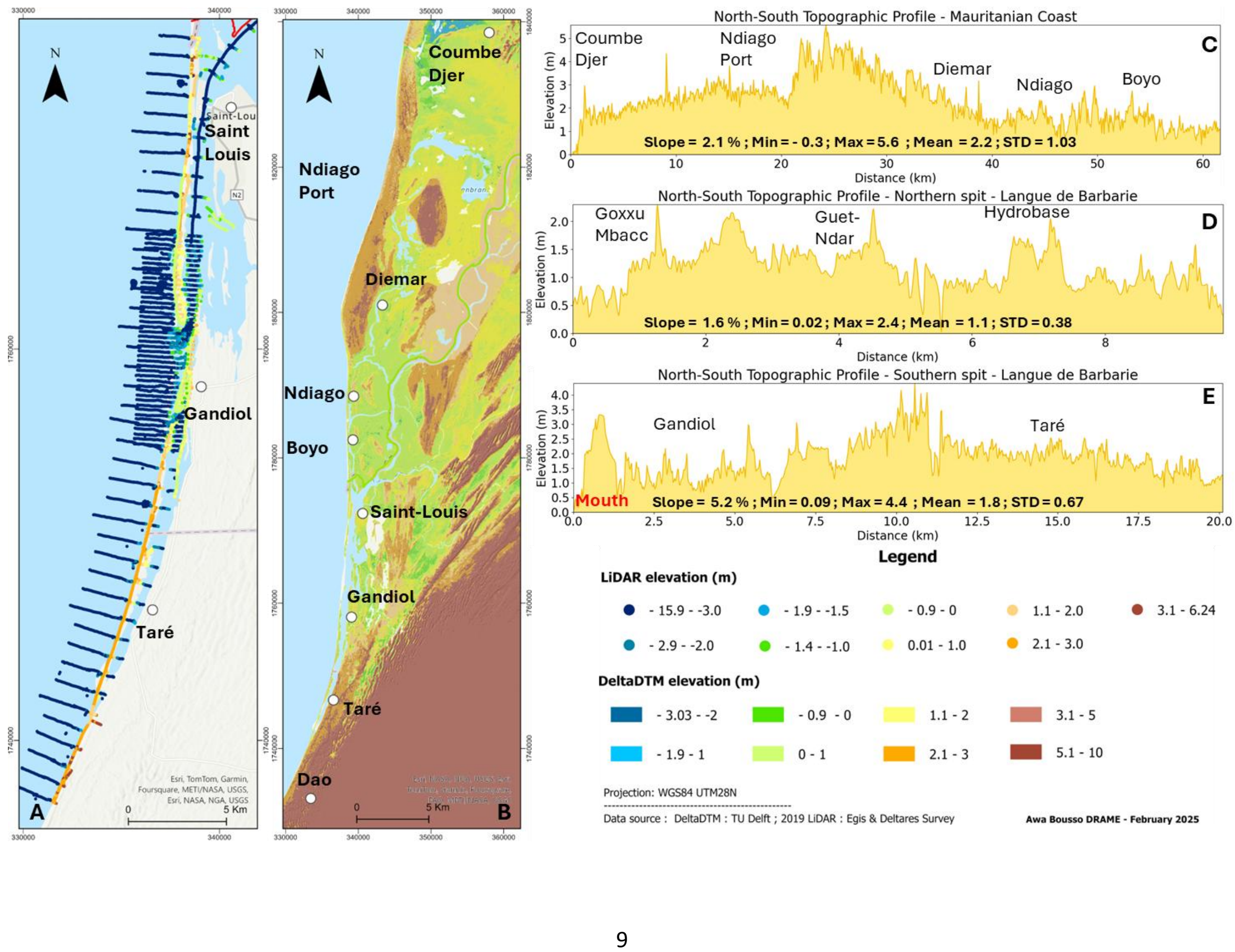

Figure 6 – Elevation map of the Senegal-Mauritania coast: A) DeltaDTM ; B) Lidar ; C) Topographic profile of the Mauritanian Coast ; D) Topographic profile of the northern segment of the Langue de Barbare ; E) Topographic profile of the southern segment of the Langue de Barbarie

3.2 Shoreline change analysis

The Linear Regression Rate (LRR) and Net Shoreline Movement (NSM) measure the distance between the earliest and most recent shorelines. The findings show that the Senegal-Mauritania coast experienced alternating areas of erosion and accretion (Figure 7). An uncertainty of ±1.2 m/y was calculated for the LRR. The Mauritanian coast was more stable than the Senegalese side during–2013-2023 period with a predominant accretion pattern. For example, Coumbe Djer and Diemar-Ndiago appear as the most stable areas of the Mauritanian coast (Figure 7A, B), recording respective rates estimated at 1.5 m/y ± 1.2 and 1.9 m/y ± 1.2 (LRR), resulting in an average shoreline accretion of 25.9 m and 21.6m (NSM, Table 4) over the 2013-2023 period. Maximum net shoreline progradation was observed in the Ndiago port area (Figure 7A, B), reaching 259.7m at an annual rate of 24.7 m/y (Table 4). This was due to the development of the Ndiago Port (2017-2021) (République Islamique de Mauritanie 2021) alongside a northern jetty (**Error! Reference source not found.**), which favoured sediment accumulation northward. This port is part of the Mauritanian coastal development plan that aims to regain control over southern Mauritania, which is inhabited by only a few sparse villages (Ministère de l'Environnement de la Mauritanie 2017). Ndiago-Boyo is the only portion of the Mauritanian coast presenting an erosional trend (-1.4 m/y ± 1.2) and a net shoreline retreat of -18.6m, contrasting with its riverside gaining sediments.

Conversely, the Senegalese coast presented more variability with alternate erosion and accumulation patterns. Despite some erosion hotspots, Goxxu Mbacc-Hydrobase (Saint-Louis) displayed a stable coastline (LRR = -0.6 m ± 1.2 /y ; NSM = -0.2m), reflecting the impact of a 3.5 km riprap seawall built on the seaside of the Langue de Barbarie (**Error! Reference source not found.**) during the 2018-2023 period. This coastal engineering infrastructure was built to protect the coastal communities of Langue de Barbarie from erosion and winter seaflooding due to energetic winter swells, as reported by the National Weather Agency (ANACIM, 2018 ; ANACIM, 2021 ; ANACIM, 2023 ; ANACIM, 2025). Local newspapers reported a winter-swell-induced episode on 19 November 2018 affecting Guet-Ndar coastal communities, damaging houses, and injuring some inhabitants (Ndarinfo, 2018 ; Walf Group, 2018 ; France24 Observers, 2018). Unsurprisingly, the mouth of the Senegal Estuary was the most dynamic zone, recording both maximal erosion and accretion (Figure 7, Table 4). The northern segment of the mouth prograded at a mean pace of 0.1m/y ± 1.2 for a net accretion of 32.0 m, whereas the southern one lost -14.8 m/y ± 1.2 corresponding to an average shoreline retreat of – 177.4m. These trends reflect the progressive shoreline adjustments to the 2003 artificial breaching through alternating cycles of erosion/accretion, where the northern spit elongates southward, while the southern segment erodes, moving landward to Gandiol and forming a closed lagoon.

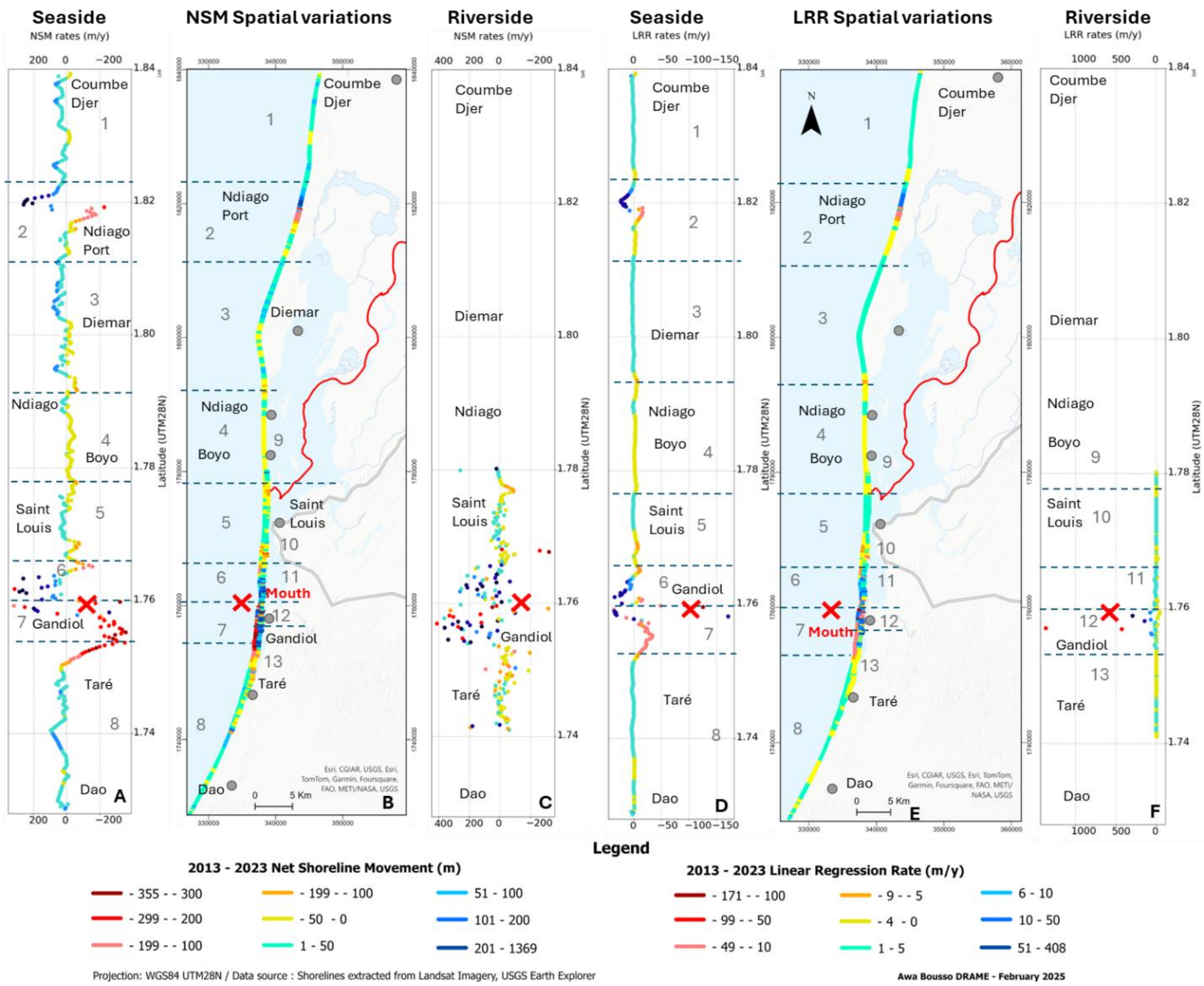

Figure 7 - Coastal evolution of the Senegal-Mauritania coast over 2013-2023: A) Seaside NSM ; B) NSM Spatial variations ; C) Riverside NSM ; D) Seaside LRR ; E) LRR Spatial variations ; F) Riverside LRR

Table 4 – 2013-2023 Net Shoreline Movement (m) and Linear Regression Rates (m/y) – Senegal-Mauritania coast

			Net Shoreline Movement (NSM) in m						**Linear Regression Rate (LRR) in m/y**			
Area	**Zone**	**Name**	**Length (km)**	**Min (m)**	**Max (m)**	**Mean (m)**	**STD**		**Min (m/y)**	**Max (m/y)**	**Mean (m/y)**	**STD**
Seaside	1	Coumbe Djer	17.4	-23.0	77.4	25.9	24.2		-2.1	5.6	1.6	1.5
	2	Ndiago Port	11.6	-226.5	259.7	12.4	105.6		-15.5	24.7	1.4	9.7
	3	Diemar - Ndiago	18.8	-49.7	80.1	21.6	31.8		-5.3	4.0	1.9	1.9
	4	Ndiago – Boyo	17.6	-61.8	39.3	-18.7	21.6		-4.8	2.3	-1.4	-1.7
	5	Goxxu Mbacc – Hydrobase (Saint-Louis)	8	-75.3	39.0	-0.2	31.8		-6.4	2.4	-0.6	3.0
	6	Mouth – North LB	9	-321.4	318.1	32.0	132.9		-125.3	36.7	0.1	23.8
	7	Mouth – South LB (Gnayam)	7.8	-355.7	252.7	-177.4	160.3		-171.4	36.6	-14.8	31.7
	8	Open Coast (Gnayam –Dao)	24	-11.2	96.0	28.7	23.3		-0.7	5.3	1.6	1.6
Riverside	9	Ndiago – Boyo, riverside	3.2	-77.9	256.3	6.9	71.6		-3.1	1.7	0.1	1.2
	10	Goxxu Mbacc – Hydrobase (Saint-Louis), riverside	13.4	-320.8	157.2	-12.4	65.6		-21.7	8.2	0.3	3.3
	11	Mouth - Northern LB (Gandiol)	7	-316.5	321.9	81.1	118.8		-41.6	296.3	14.6	52.8
	12	Mouth – South LB (Gandiol - Taré)	3.2	-98.1	271.4	111.6	125.6		-16.5	1369.7	93.5	341.1
	13	Southern LB (Taré)	16.8	-355.7	408.8	24.8	122.6		-4.8	426.8	8.2	49.6

3.3 Sand volumes variations

The volume calculation results showed a pattern similar to that of the shoreline change analysis. In Mauritania, Coumbe Djer and Diemar-Boyo are still among the zones loosing less sand than rest of the coast, with sand volumes gained of 0.844 x 10^6 m^3 (± 3,750) and 1.198 x 10^6 m^3 (±5,680)(Figure 8A, Table 5). Unsurprisingly, the area around Ndiago port accumulated a maximum of 2,172,399 m^3 (±13,930) during 2013-2023 and only lost (-1.062 × 10^6), resulting in a net sand balance of 1.11 × 10^6 m^3 (±13,930) (Figure 8A,B, Table 5). This reflects the impact of the jetty on the northern area of the port (**Error! Reference source not found.**B), inducing sedimentation of 1.158 × 10^6 m^3 (± 191,720), and the southern breakwater (**Error! Reference source not found.**B), where -0.435 × 10^6 m^3 (± 18,170) was eroded. Ndiago-Boyo is the main erosion hotspot of the Mauritanian coast, losing 0.474 × 10^6 m^3 (± 3,560) (Figure 8C, Table 5), and the longshore drift is redistributed to the Senegalese coast.

As a result, the northern portion of the Langue de Barbarie (Goxx Mbacc – Hydrobase) accumulated 48,920 m^3 (±1,960). Within this zone, specific locations, such as Goxxu-Mbacc-Guet-Ndar, gained 59,200 m^3 (± 2,100) from 2013-2023 (Figure 8D, Table 5), illustrating the impact of the 2018-2023 riprap seawall (Figure 1C)**Error! Reference source not found.**. However, the downdrift areas experienced a conjunctive effect between the seawall and mouth. Since the 2003 breach, the mouth of the Senegal estuary has been framed by the northern and southern segments of Langue de Barbarie. The mouth displayed an overall erosive pattern, with the southern tip losing 2.5 times more sand (− 2.188 × 10^6 m^3 ± 21,800) than its northern counterpart (− 0.804 × 10^6 m^3 ± 13,840). Lastly, the open coast is the only area on the Senegalese coast that experienced accretion (1.779 10^6 m^3 ± 3,800, Figure 8F, Table 5) which falls within the same magnitude as the Mauritanian coast. This observation illustrates the impact of coastal engineering pressure and mouth hydrodynamics on the sand accumulation processes.

In comparison, the riverside has a less dynamic pattern, displaying erosion along the Langue de Barbarie. The significant difference in magnitude between the seaside and riverside is proportional to the wave and river energy. Interestingly, the southern spit segment framing the mouth gained 73,000 m^3 ± 6,840, and Taré-Dao lost 494,120 m^3 ± 2,770 (Table 5) which surely moved landward in a closed environment (Figure 8 E). This localised riverside growth confirms the previous accumulation trend, indicating a landward movement of the southern Langue de Barbarie with the mouth tip (111.6m progradation, at 93.5 ± 1.2, Table 5) and the rest of the spit (Taré 24.8m, 8.2m/y ± 1.2, Table 5), framing a closing lagoon in Gandiol (Figure 8E).

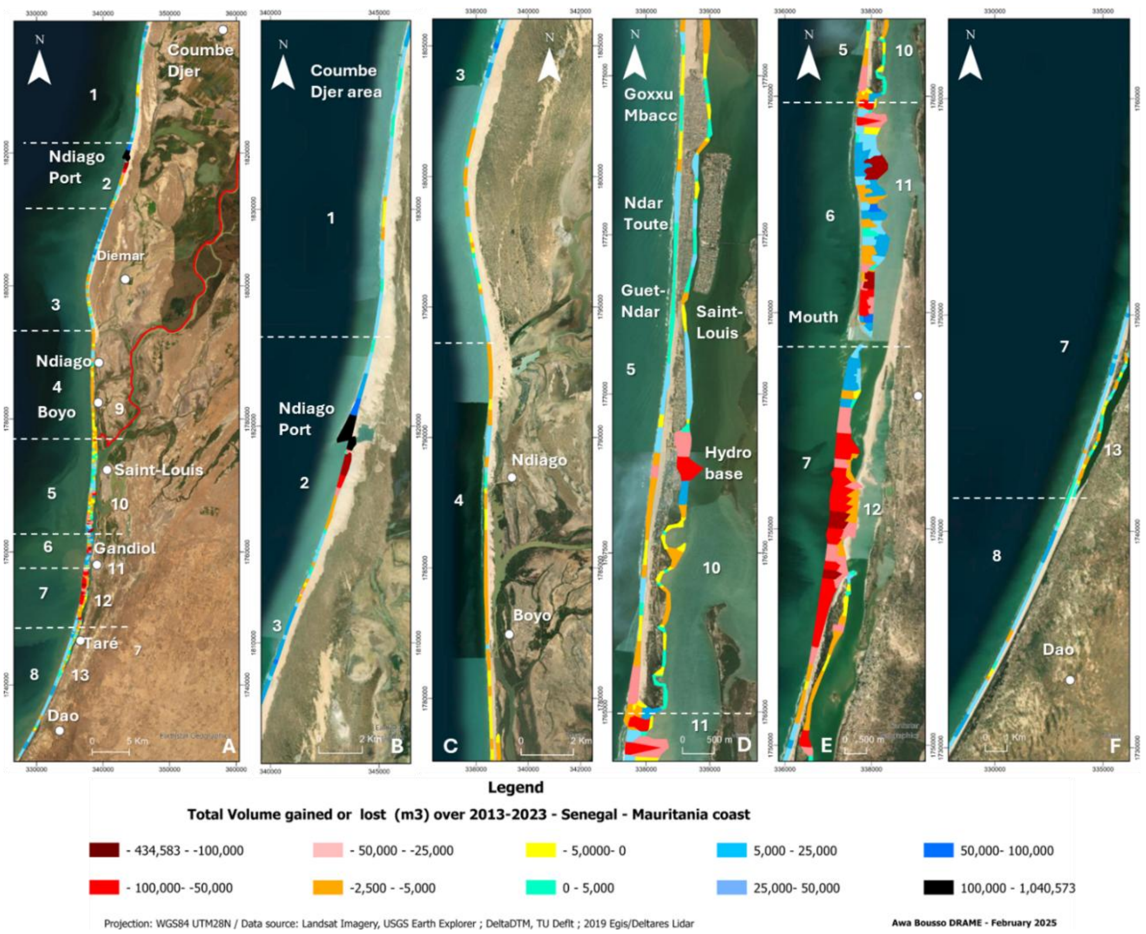

Figure 8 - Total Volume gained or lost in the 2013-2023 period - Senegal-Mauritania coast : A) Overall coast ; B) Ndiago Port ; C) Ndiago-Boyo ; D) Saint-Louis ; E) Mouth ; F) Open Coast (Dao)

Table 5 - 2013-2023 Volumes gained/lost - Senegal-Mauritania coast

Area	N°	Name	Volume gained (m^3)	Volume lost (m^3)	Total / Balance	Min	Max	Mean	STD	Average uncertainty
Seaside	1	Coumbe Djer	0.92 x 10^6	-70,915	**0.844 x 10^6**	-2.519 x 10^4	3.671 x 10^4	9,486	9,555	3,750
	2	Ndiago Port	2.172 x 10^6	-1.062 x 10^6	**1.110 x 10^6**	0.435 x 10^6	1.041 x 10^6	19,480	159,505	13,930
	3	Diemar - Ndiago	1.488 x 10^6	-0.290 x 10^6	**1.198 x 10^6**	-2.359 x 10^4	5.50 x 10^4	11,860	9,323	4,574
	4	Ndiago – Boyo	0.135 x 10^6	-0.610 x 10^6	**-0.475 x 10^6**	-2.325 x 10^4	2.386 x 10^4	-4,609	8,534	3,560
	5	Goxxu Mbacc – Hydrobase (Saint-Louis)	0.162 x 10^6	-0.113 x 10^6	**4.892 x 10^4**	-2.724 x 10^4	1.65 x 10^4	1,087	8,741	1,960
	6	Mouth – North LB	0.764 x 10^6	-1.568 x 10^6	**- 0.804 x 10^6**	-0.296 x 10^6	6.23 x 10^4	-10,178	-1,353	13,840
	7	Mouth – South LB	0.221 x 10^6	-2.409 x 10^6	**-2.187 x 10^6**	-0.128 x 10^6	4.61 x 10^4	-41,277	40,812	21,800
	8	Open Coast (Dao)	1.835 x 10^6	-55,093	**1.770 x 10^6**	-1.412 x 10^4	4.31 x 10^4	14,588	10,992	3,800
		Total - Senegal-Mauritania Coast	**7.692 x 10^6**	**-6.177 x 10^6**	**1.515 x 10^6**	**-0.434 x 10^6**	**1.041 x 10^6**	**2,334**	**54,557**	**7,337**
Riverside	9	Ndiago – Boyo, riverside	0	-3.921 x 10^4	**-3.921 x 10^4**	-8.66x 10^3	-0.112 x 10^6	-4,901	2,954	5,320
	10	Goxxu Mbacc – Hydrobase (Saint-Louis) riverside	0.260 x 10^6	-0.375 x 10^6	**-0.115 x 10^6**	-7.80 x 10^4	3.342 x 10^4	- 1,233	13,883	2,900
	11	Mouth - Northern LB (Gandiol)	3.753 x 10^4	-0.165 x 10^6	**-0.127 x 10^6**	-0.144 x 10^6	2.0 x 10^4	-15,945	-3,713	10,224
	12	Mouth – South LB	7.327 x 10^4	-2.76 x 10^2	**7.299 x 10^4**	--2.75 x 10^2	3.27 x 10^4	12,165	12,835	6,842
	13	Southern LB (Taré-Dao)	9.933 x 10^4	-0.587 x 10^6	**- 0.494 x 10^6**	-9.983 x 10^4	1.33 x 10^4	-5,429	13,786	2,770
		Total - Senegal-Mauritania Banks	**0.282 x 10^6**	**-0.987 x 10^6**	**-0.705 x 10^6**	**-0.144 x 10^6**	**3.342 x 10^4**	**-3,396**	**16,908**	**3,332**

3.4 Sand economic valuation

Sand economic value from a reservoir / stock perspective

When analysing the economic value of sand as a reservoir/stock, the direct sand market price was used as a proxy for the total intrinsic value of sand, while production costs served as a proxy for partial replacement costs, as these costs were unavailable. To recall, replacement costs would include sand production costs based on the grain size needed, extraction method, engineering studies, and transportation to the beach for recharging.

The findings show that the overall Senegal-Mauritania coast had a net volume of $1{,}515 \times 10^6$ m^3 ± 10,550 USDD, corresponding to a sand market value of 10,528,000 (± 51,000, Figure 9A) in the 2013-2023 period and a production cost of 5,150,400 USD ± 24,950 (Figure 310A). As previously shown, the Mauritanian coast stores more sand than the Senegalese coast of the Senegal Estuary. Similarly, the gain previously identified in Ndiago Port is worth a market value of 7,717,000 USD ± 96,800 on the market and 3,555,200 USD ± 47,400 if it needs to be produced (replace). In both cases, these amounts reflect the value of sand trapped by coastal engineering infrastructure in the zone. The most expensive sand loss was noted in Ndiago-Boyo and was valued at -3,295,300 ± 32,400 on the market and -1,614,000 ± 12,100 as produced goods.

On the Senegalese side of the Senegal Estuary, the seaside of the Langue de Barbarie (Goxxu-Mbac-Hydrobase) gained 4.892 × 10^4 m^3 in 2013-2023, corresponding to a market price of 340,000 USD ± 14,500 (Figure 9A, D, Table 6) and 166,300 ± 7,100, respectively (Figure 310A and D, Table 6). The volume lost in the mouth region was the greatest along the Senegalese coast, with a significant volume eroded in the southern spit framing the mouth, reaching -15,204,600 USD ± 74,120 (market price, Figure 9A, E, Table 6) and -7,438,230 USD (production cost, Figure 310A, E, Table 6), indicating that sand values of 1,520,500 USD and 700,100 USD were lost annually in the 2013-2023 period. Specific attention was paid to the riverside of the Langue de Barbarie, with the southern segment (Dao) losses equivalent to the economic value of sand moving landward (-3,434,100 ± 19,275 sand market in A,F, Table 6; -1,680,00 ± 13,690 production cost, Figure 310A, F, Table 6) and shaping the Gandiol closing lagoon. Taken together, the sand market values were greater than the sand production costs in all areas. This indicates that the intrinsic value of sand has a greater environmental value than that of artificial replacement. The value of natural sand is tied to its specific physical properties (e.g. grain size and skewness) and transport processes, which cannot be replicated by quarry-sourced sand. To further the analysis, the benefits are analysed in the following section.

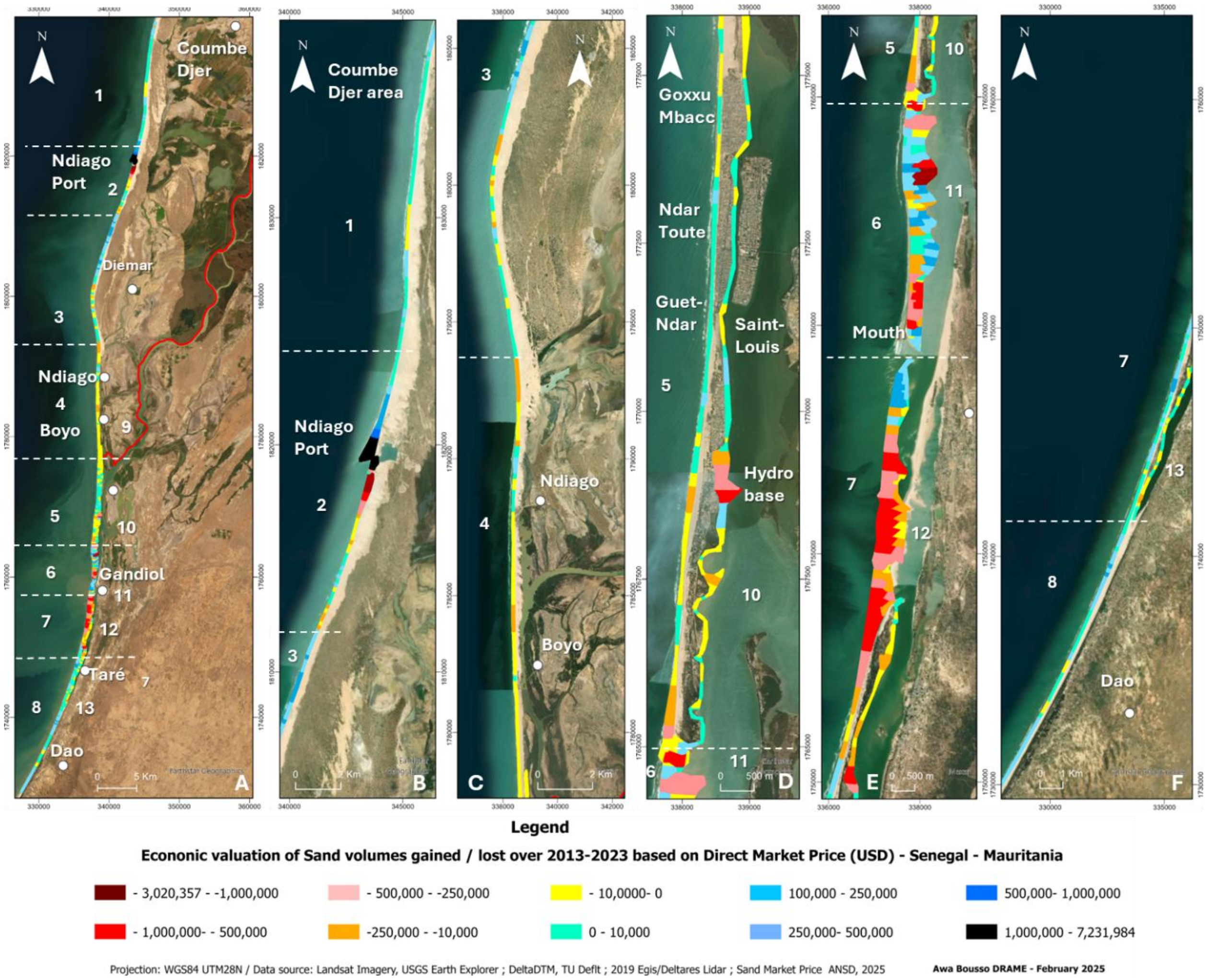

Figure 9 – Sand economic valuation based on direct market price over 2013-2023 - Senegal-Mauritania coast : A) Overall coast ; B) Ndiago Port ; C) Ndiago-Boyo ; D) Saint-Louis ; E) Mouth ; F) Open Coast (Dao)

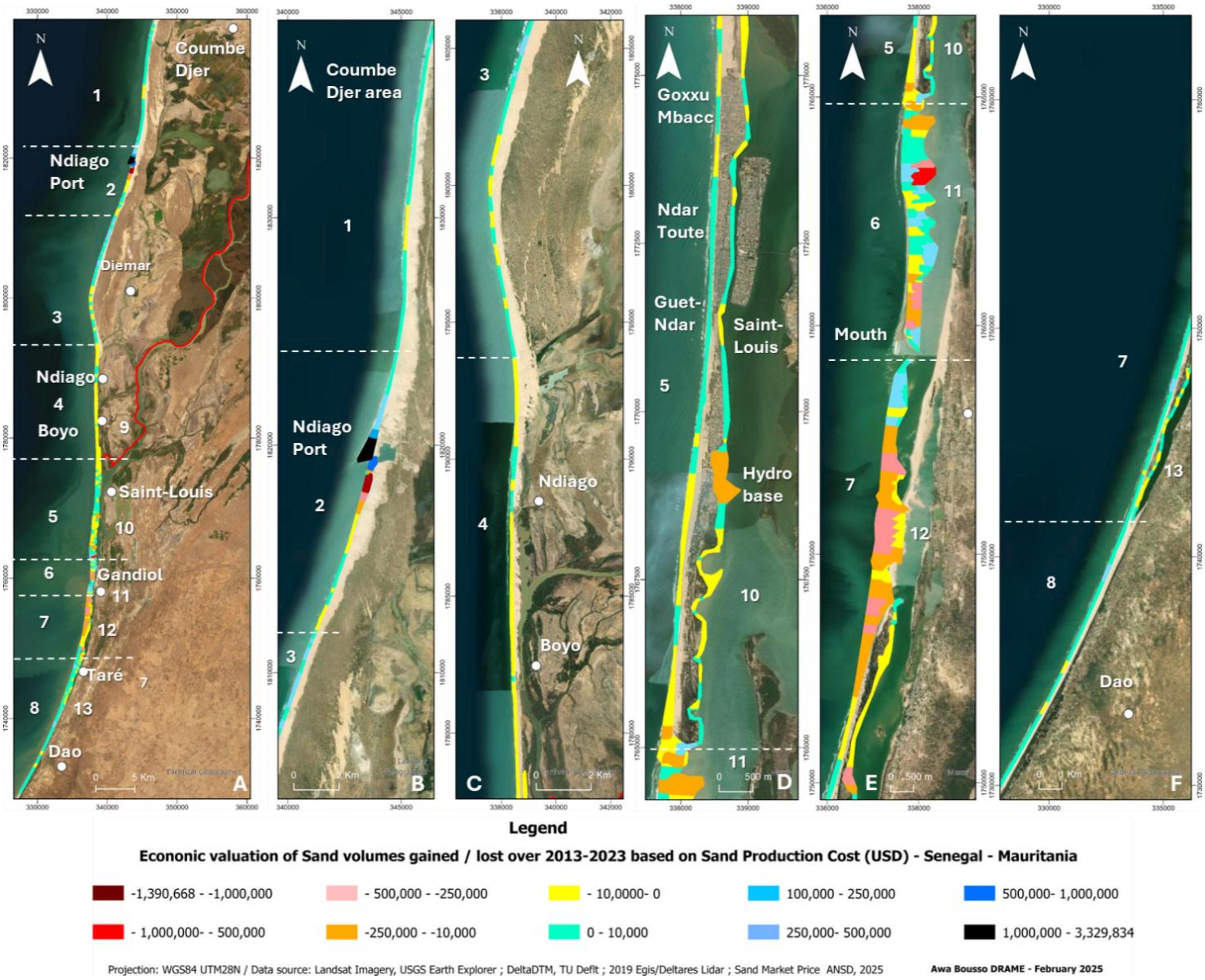

Figure 310 - Sand economic valuation based on sand production cost over 2013-2023 - Senegal-Mauritania coast : A) Overall coast ; B) Ndiago Port ; C) Ndiago-Boyo ; D) Saint-Louis ; E) Mouth ; F) Open Coast (Dao)

Table 6 - 2013-2023 Sand Economic valuation of volumes gained / lost over 2013-2023 - Based on Market Price and Production costs - Senegal-Mauritania coasts

Area	N°	Name	Net Volume (m^3)	Volume Uncertainty (m^3)	Net direct-Market Price (USD) in 2023	Net - Production Cost (USD) in 2023	Benefits (USD) in 2023	Uncertainty of the Net Direct Market price (USD)	Uncertainty of the Net Production price (USD)
Seaside	1	Coumbe Djer	**0.844 x 10^6**	3,750	5,868,130	2,870,740	2,997,390	26,070	12,750
	2	Ndiago Port	**1,110,380**	13,930	7,717,140	3,775,290	3,941,850	96,830	47,370
	3	Diemar - Ndiago	**1.198 x 10^6**	4,570	8,325,300	4,072,810	4,252,490	31,800	15,550
	4	Ndiago – Boyo	**- 0.475** x 10^6	3,560	-3,299,120	-1,613,960	-1,685,160	24,720	12,100
	5	Saint-Louis	**4.89** x 10^4	1,960	339,970	166,315	173,650	14,500	7,100
	6	Mouth – North LB	**-0.804** x 10^6	13,840	-5,588,750	-2,734,100	-2,854,700	96,170	47,000
	7	Mouth – South LB	**-2,188** x 10^6	21,800	-15,204,600	-7,438,230	-7,766,400	151,510	74,120
	8	Open Coast (Dao)	**1.780** x 10^6	3,800	12,369,900	6,051,460	6,318,450	26,370	12,900
		Total - Senegal-Mauritania Coast	**1.515** x 10^6	**7,340**	**10,527,960**	**5,150,370**	**5,377,600**	**52,000**	**24,950**
Riverside	9	Ndiago – Boyo, riverside	**-3.921** x 10^4	5,320	-272,540	-133,330	-139,200	37,000	18,100
	10	Saint-Louis, riverside	**-1.15** x 10^4	2,900	-799,210	-391,000	-408,230	20,100	9,800
	11	Mouth - Northern LB (Gandiol)	**-1.275** x 10^4	10,220	-886,560	-433,700	-452,850	71,000	34,760
	12	Mouth – South LB	**7.3** x 10^4	6,840	507,300	248,180	259,130	47,550	23,260
	13	Southern LB (Taré-Dao)	**-0.494,** x 10^6	2,770	-3,434,100	-1,679,990	-1,754,100	19,275	9,430
		Total - Senegal-Mauritania Banks	**-0.703** x 10^6	**3,330**	**-4,885,110**	**-2,389,840**	-2,495,270	**23,160**	**11,330**

Sand economic value as an ecosystem regulator – Valuation from a benefit perspective

The Millennium Ecosystem Assessment (2005) defined Regulating Ecosystem Services (RES) as "*the **benefits** obtained from the **regulation of ecosystem processes***". In the framework of this research, these benefits reflect the economic value of sand transport and (re)distribution processes, which act as coastal ecosystem regulators that contribute to shoreline stabilisation. Furthermore, it should be noted that, in the economy, direct market prices include production costs and benefits. The benefits were calculated based on the difference between the economic value of sand based on the direct market price and sand production costs. The most significant positive benefits were noted in Mauritania, particularly in Diemar-Ndiago (4,252,500 USD, Table 6), the Ndiago Port area (3,941,850 USD, Table 6), and Coumbe Djer (2,997,400 USD, Table 6). However, the benefits identified in the Ndiago Port (3,941,850 USD, Table 6) are an economic valuation of the artificial impact of coastal engineering infrastructure trapping sand rather than natural coastal sediment transport. Conversely, the greatest negative benefits were primarily on the Senegalese coast of the estuary, especially in the mouth region (total of -11,219,450 USD, Table 6) which depicts the economic value of combined marine and fluvial sediment transport and redistribution processes leading to erosion. In the same context, accumulation processes at the southern spit tip shaping the mouth and closing the Gandiol Lagoon are estimated at 259,130 USD (Table 6), while the riverside of the Langue de Barbarie (-1,754,100 USD, Table 6) indicates the value of transport processes moving sand landward, reducing the inlet area. The benefit value ranges imply that replacing the existing sand reservoirs alongshore would not necessarily restore the environmental benefits lost, such as natural beach nourishment, or potential positive cascade effects in sediment (re)distribution. Except for the dynamic mouth area, areas with the most significant losses, such as the Ndiago-Boyo or the riverside of the southern Langue de Barbarie (Dao) corridors, may indicate that coastal solutions, such as beach nourishment, may not be cost-effective. Simultaneously, areas presenting the highest positive benefits (Coumbe Djer, Diemar-Ndiago) could be considered more balanced and effective ecosystem regulators (sand transport and (re)distribution processes) and more suitable for beach nourishment.

Nevertheless, the results of the economic valuation of sand should be interpreted cautiously. They only represent an indirect value of the shoreline stabilisation service that sand provides to humans and have been calculated from existing data (LiDAR and DeltaDTM). The full value of sand services would also include other variables, such as safeguarding coastal properties, flood protection, and habitat for species, which could not be valued because of a lack of data.

4 Discussion and Conclusion

To our knowledge, this study is the first to offer an economic valuation of sand within the framework of shoreline stabilisation in West Africa. By leveraging high-accuracy elevation data (LiDAR and DeltaDTM), this study provides a comprehensive assessment of the intrinsic value of sand as a reservoir/stock (market price and production cost) and ecosystem regulator (sand transport processes and benefits). These values were built on sand volumes eroded or accumulated between 2013 and 2023, which were estimated from shoreline change analysis.

4.1 Coastal erosion

Resulted evidenced different erosion/accretion patterns along the Senegal and Mauritania coasts of the Senegal estuary. Accretional trends predominate the Mauritanian coast, notably around Coumbe Djer (LRR=1.5 m/y± 1.2, NSM=25.9 m), Diemar-Boyo (LRR = 1.93 m/y ± 1.2, NSM = 21.6 m), and at Ndiago port (LRR=24.7 m/y, NSM=259.7 m), where coastal engineering infrastructures trapped sand northward and caused downdrift erosion. In contrast, erosion dominated the Senegalese coast, particularly the mouth region (north LB tip LRR = 0.1 m/y ± 1.2 ; overall NSM = 32.0 m, south LB tip LRR = -14.8 m/y ± 1.2; NSM = -177.4 m), southern Langue de Barbarie (LRR = -14.8m/y ± 1.2 ; NSM = 177.4m). These mouth dynamics are natural responses to this behaviour. The mouth undergoes cycles of widening and narrowing until it returns to its initial pre-breach position, driven by the southward elongation of the northern segment of the Langue de Barbarie. Moreover, the urbanised Langue de Barbarie (Goxxu Mbacc – Hydrobase) appears to be stable (LRR = -0.6 m/y± 1.2 ; NSM = -0.2m), underlining the effect of the 2018-2023 riprap seawall. These findings are aligned with Sarr et al. (2024) studies on the 2012-2022 coastline changes in Saint-Louis, who reported -1.5 m/y ±1.4 in the north Langue de Barbarie (-0.1 for Goxxu-Mbacc-Hydrobase), 14m/y ±1.4 in the mouth region, and 1.3 m/y ±1.4 in the southern Langue de Barbarie. They also match Ndour et al. (2018) research over the 2003-2016 post-breach period showing the southward accretion of the northern Langue de Barbarie at a pace of 3.71m/y while the downdrift segment presented erosive (-4.4m/y, -3.71m/Y, -2.7 m/y) and accumulation sectors (2.32m/y, 3.13m/y). However, our findings differ from our analysis focused on the 2013-2023 period, covering both the Mauritanian and Senegalese sides of the estuary, including the riverside. Our research is also different because we considered both the linear regression rate (LRR) and net shoreline movement (NSM), which is more coherent with volume calculations. Moreover, we observed the landward of the southern Langue de Barbarie (LRR = 93.5 ± 1.2, NSM = 111.6m), whose tip transforms the inlet into a lagoon near Gandiol. This closing process and the widening/narrowing cycles of the mouth support the last recovery phase of the inlet-barrier dynamics (Fitzgerald et al. 2000 ; Zăinescu et al. 2019) after experiencing external disturbances (e.g. artificial breaching in 2003).

4.2 Volumes and Sand economic value

Furthermore, the economic valuation of the volumes gained/lost reflects the shoreline change patterns. Our investigations found that the Senegal-Mauritania coast gained a net sand volume of 1.515×10^6 m³ (± 10,550), which corresponds to a market value of 10,528,000 USD (± 50,992) and a production cost of 5,150,367 USD (± 24,950). The areas with the highest net sand volume gains and economic benefits were Diemar-Ndiago (1.198×10^6 m³ ± 4,580), Ndiago Port (1,110,400 m³ ± 13,930), and Coumbe Djer (844,335 0.844×10^6 m³ ± 3,750). They correspond to respective market values of 8,325,300 USD ± 31,900, 7,717,150 USD ± 96,830; and 5,868,130 USD ± 26,100 and production costs of 4,072,800 USD ± 15,553 ; 3,775,290 USD ± 47,400, and 2,870,740 USD ± 1,380. As a result, Diemar-Ndiago, Ndiago Port, and Coumbe Djer recorded net benefits of 4,252,490 USD, 3,941,50 USD, and 2,997,400 USD, respectively. In contrast, the most severe sand losses occurred along the Senegalese coast, particularly in the mouth zone and southern riverbank of the Langue de Barbarie. The northern limit of the mouth lost 803,150 m³ (± 21,780), corresponding to a market value of -5,588,750 USD (± 96,170) and a production cost of -2,734,100 USD (± 47,000), resulting in negative benefits of -2,854,700 USD. Similarly, 2,187,700 m³ (± 21,800) was eroded in the southern limit of the mouth, with market and production values of -15,204,600 USD (± 151,500) and -7,438,230 USD (± 74,120), respectively, generating negative benefits of -7,766,400 USD. In addition, the southern riverine area of Langue de Barbarie lost 494,120 m³ (± 2,770), with a market value of -4,888,100 USD (± 23,160) and production costs of -2,389,840 USD (± 11,330), resulting in negative benefits of -2,638,850 USD. Such severe losses underline the value of sediment transport processes and the need for localised coastal management solutions. However, one exception to this pattern was observed in Goxxu-Mbacc-Hydrobase (Saint-Louis), where a net volume of 48,920 m³ ± 1,960 (market value = 340,000 USD ± 14,500, production cost = 166,300 USD ± 7,100, benefits = 173,650 USD) was accumulated owing to the riprap seawall protecting this urbanised and densely populated area.

Although uncertainty calculations included 3 variables, such as tidal corrections, pixel error influencing shoreline position (Fletcher et al., 2012), and the vertical accuracy of the elevation datasets, the latter may still limit the precision of the estimates. DeltaDTM has an absolute vertical uncertainty of ± 0.45m (Pronk et al. 2024), while the Lidar covering the Langue de Barbarie has a lower uncertainty of ±15 cm or ±0.15m (Egis & Deltares, 2019). Despite these limitations, these elevation datasets provide significantly better accuracy than the global SRTM DEM, with a vertical accuracy of ±9.76m (Farr et al., 2007). Furthermore, sand market valuations use direct market prices and are not associated with uncertainties. In addition, 2023 sand production costs were estimated using the 2017 initial costs from the National Statistics Agency (ANSD, 2020a) and updated using the cumulative inflation rate, necessitating the annual consumer product index from 2018 to 2023, as sand production costs were surveyed only in 2017. Although estimated on a national scale, their potential uncertainties are respected in terms of production and valuation of these estimates. This can constitute a limitation as CPIs specific to variables used in sand production costs, such as licencing costs, trucks, mechanical diggers, transport, and human resources, were not available.

The literature on sand economic valuation in the context of shoreline stabilisation has not been studied in Africa. The existing literature mainly focuses on sand mining from an anthropogenic perspective and is limited. It either provides rough volumes from field surveys and modelling, but not necessarily economic estimates, or provides sand valuation in a different context than coastal or marine environments. For instance, the longshore drift current provides a better understanding of the volumes transported alongshore. Our volume calculations fall within the same range as those of Sadio et al. (2017), who estimated that the longshore drift transported 611,000 m³/y on average in 1984-2015. They are also similar to those from the SOGREAH (1994) study, which reported a decreasing north-south volume between 600,000 and 700,000 m³/y. As mentioned above, studies on coastal sand volumes eroded or accumulated in West Africa primarily focus on sand mining and do not include economic valuation of sand or sediments. In comparison, the sand volume annually trapped in the Ndiago Port (115,580 m^3/y ± 19,170 in this study) was smaller than the 700,000 $m^3\ y^{-1}$ accumulated at the Lomé Port breakwater (Togo) from 2018 to 2023 (Lawson et al., 2023). This difference is due to a more energetic longshore sediment supply in the Gulf of Guinea, as evidenced by Ndour et al. (2018), who compared Senegal and Mono estuary recovery from breaches. Similarly, Jonah et al. (2015) assessed sand mining volumes from field surveys at the Amoakofua and Mbofra Akyinim sites (Elmina-Cape Coast-Moree, Ghana), which was estimated at 285,376 m3 between November 2010 and November 2012. They indicated that the average erosion rate of the Cape Coast was −0.85m/y between 2005 and 2012. Rates of −4.35 m/y and -4.25m/y were recorded at the Mbofra Akyinim and Amoakofua mining sites, respectively.

Only one study on sand economic valuation in West Africa was found, and it was not on shoreline management but on traditional sand mining in a lake in Benin. Djihouessi et al. (2017) examined the economic value of traditional dredged sand in Lake Nokoue (Benin, area of 190m²) in the context of sand as a habitat for fisheries and sand (sedimentation) as an indirect source of flooding and replacement costs. They valued the sand economic value in Lake Nokoué at 2.44 million USD per year. It is important to note that their input data were obtained from field surveys conducted from November 2016 to April 2017. Our study is different and brings a new approach, as it focuses on the shoreline and uses GIS to offer a spatialised valuation of sand covering both the Mauritanian and Senegalese sides of the Senegal Estuary. It also offers a market-based and production-based valuation of the sand volume gained/loss to capture the benefits as a proxy of the process variability along the shore. Moreover, the context is different, as they worked on a closed system of a lake, whereas we considered the Senegal-Mauritania coast of the Senegal Estuary. Nokoue Lake experiences traditional sand dredging, whereas our study focused on the natural processes causing coastal erosion/accretion. Under other latitudes, Ramesh et al. (2022) studied the economic valuation of Indian coastal sandy dunes, including provisioning services (water), regulation services (carbon and disturbance regulation), cultural services (recreation), and supporting services (medicinal value). Using a benefit transfer approach based on economic valuations in different places worldwide (the Netherlands, East Japan, Mexico, Spain, South Carolina in the US, and Ireland), they estimated the value to be 5,713,683,259 USD for an area of 32,445 ha. The benefit transfer approach is similar to our study, but we used sand market price, production costs, and inflation provided by the Senegalese National Statistics Agency, not those from foreign countries, as these authors did. In Israel, Bar et al. (2016) used a contingent valuation method to assess population perceptions and willingness to pay for dune conservation.

In the context of marine/natural resources, sand volume variations along the Senegal-Mauritania coast are natural capital moving beyond the nature-based Senegal-Mauritania border, following a source-sink (interconnectedness) pattern. Natural capital is a multidimensional concept that refers to renewable and non-renewable resources, ecosystem services, and ecological processes that support life (Ghofrani et al., 2020 ; Ncube & Arthur, 2021 ; Fairbrass et al., 2025). Consequently, coastal erosion raises questions regarding the paradox between the global sediment crisis (Bravard, 2018; Filho et al., 2021) and the emerging international sand market (Gavriletea, 2017) fuelled by sand mining. Future research avenues could include assessing the cost-benefits of all ecosystem services, including habitat for species, protection against flooding, nutrient transport, carbon sequestration and recreational value.

4.3 Recommendations for policy-making

This spatial-economic evaluation framework can inform future Environmental Impact Assessments (EIAs) and coastal development permits. This study recommends implementing a transboundary management plan based on the sediment budget approach to ensure long-term (dynamic) equilibrium and integrated coastal zone management. It also proposes:

- Taking into account the importance of proactive conservation policies (e.g. protecting the existing sand reservoirs), over-reactive restoration (replacing sand), or coastal engineering developments
- A benefit-based ranking system can help identify priority zones for coastal protection based on nature-based solutions which have proven to be the most efficient for similar sandy coastal environments (Vacchi et al., 2020 ; Van der Meulen et al., 2023 ; Glueck et al., 2024). For instance, areas with highly positive benefits (Coumbe Djer, Diemar-Boyo) could serve as targeted locations for beach nourishment, whereas areas with negative benefits could be more suitable for other alternatives. Replanting the local *Casuarina equisetifolia* (filaos) on the shore and mangroves on the banks could serve as a more suitable, cost-effective, and long-term nature-based solution to this problem. The efficacy of filaos in shoreline stabilisation has also been demonstrated locally (Ndiaye et al., 1993 ; Ngom et al. 2016). Additionally, they existed in the Langue de Barbarie in 1928 (Conseil Général du Sénégal, 1928) before increasing coastal urbanisation.
- Moving beyond the anthropocentric approach, such strategies could also include less populated sand reservoirs, such as Ndiago-Boyo, which is the only erosional sector on the Mauritanian coast and a primary sand supply source for accumulation in the adjacent Goxxu Mbacc-Hydrobase area.
- Closely monitor areas undergoing morphodynamic changes, such as the closed Gandiol Lagoon, to better understand their shifting sediment dynamics and potential impacts on shoreline stability.
- Develop a circular use of dredged sand in the Ndiago port and the mouth of the Senegal River.
- Enforcing more frequent and stricter field control measures against illegal sand mining is crucial for mitigating further losses.

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References

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