Sediment Transfer along Pénestin Peninsula Coastline: insights from Photogrammetric analysis and integrated littoral monitoring

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Abstract

While low-lying coastal zones are frequently monitored for the risks associated with sea-level rise and flooding, rocky cliffs are increasingly being scrutinized for their erosive variability and instability. Historically, sediment fluxes have been extensively studied and constrained; however, recent advancements in remote sensing and UAV technology now facilitate more precise quantitative assessments of the volumes of crustal materials involved in these transfers. In this study, we analyze erosion and sediment transport in two sectors of the Penestin Peninsula in South Brittany using high-resolution and high-frequency drone imagery along the coastline. We integrate available aerial photographs, LIDAR data, and newly acquired high-frequency and high-resolution topographic data to perform a detailed photogrammetric analysis of approximately 900 meters of the Mine d'Or cliff. The resulting topographic and morphological differentials at the land-sea interface reveal significant erosion asymmetry between the southern and northern sectors of the beach, primarily influenced by gravitational forces and urban development at beach access points. Quantitatively, since 1952, the southern sector has experienced an average annual retreat of approximately 60 cm, whereas the northern slope has retreated at an average rate of 10 cm per year. Our mapping of the dynamics of coarse and medium sand stocks along the northern coast of the peninsula, spanning the period from 2010 to 2020, indicates that approximately 32,000 m³ of material from cliff erosion has contributed to sediment accumulation on the shore, particularly within the Branzais Marsh. Furthermore, while 10,000 m³ were lost from the beach due to littoral drift transport, approximately 12,000 m³ of sand and gravel were documented in transit to the northern coast. This quantitative analysis underscores the substantial impact of rocky coastal cliff erosion as a major sedimentary source in a context of limited external sediment supply. The sediment stock, made available for transit and

deposition due to local hydrodynamic factors, is notably influenced by a northward longshore drift.

Key-words: Monitoring, Coastal erosion, Cliffs, Aerial photography, Lidar, Drone, Modelling

1. INTRODUCTION

Assessment, monitoring, and evaluation of sediment fluxes and employing state-of-the-art tools and techniques are of paramount importance for rapid, accurate, and comprehensive appraisal of dynamic changes that occur along the coastal zone (Ramkumar et al. 2018a, b; Pian et al. 2018). A range of tools and techniques, including but not limited to field mapping and observation, analyses of aerial photographs and/or satellite images, LIDAR data, or drone surveys, are employed for coastal monitoring and assessment programmes (e.g., Brunier et al., 2016; Le Gall R., 2019; Mathew et al., 2020). These provide measurements of coastal erosion and accretion at different spatio-temporal resolutions (Wheaton et al., 2009; Castella et al., 2019; Cunliffe et al., 2019; Jaud et al., 2019; Laporte-Fauret, Q., 2020). Mapping carried out by CEREMA (Centre for Studies on Risks, the Environment, Mobility and Urban Planning) provides rates of coastal erosion or accretion affecting the southern coastal region of Brittany characterized by rocky cliffs and heterogeneous unconsolidated deposit environments (Figures 1, 2 and 3). Despite substantial efforts to monitor the evolution of northwestern France’s coastline, there is still a lack of quantitative scientific synthesis estimating the volume of sediments involved in these coastal fluxes. In the realm of climate change, there is an urgent need to improve the knowledge of the redistribution of redistribution of materials from coastal erosion at a regional scale in South Brittany at the short- and long-term period (annual to decadal).

Datasets such as aerial or satellite photographs, due to their frequency, resolution, and associated error margins, did not allow for precise discrimination of changes in the coastline at very high resolutions over the past 70 years. However, owing to recent advances in data acquisition (notably LiDAR) and the use of drones in high-resolution campaigns, it is now possible to obtain high-resolution time series of measurements, thus enabling finer (accurate to a few centimetres) monitoring of the coastline.

In south Brittany, the multiple sources of marine and coastal sediments remain equivocal. Firstly, rivers entering the Bay of Quiberon and in the Bay of Vilaine represent the principal source of terrigenous supply in the area. Vilaine's River is the main source of fine sediments that enter the Bay of Vilaine Sedimentary fluxes from the Vilaine river, provide estimation of 0.1 x 10^6 tonnes per year (suspended discharge) (Jouanneau et al., 1999). Moreover, geochemical analyses of the clayey and non-clayey assemblages of the superficial deposits (Lafond, 1961; Bouysse et al., 1966; Gouleau, 1975) suggest a marine origin supplemented by sediment inputs of the Loire River [Barbaroux and Gallene, 1973]. However, the amount of sediment supplied in suspension from the Loire River to the bay of Vilaine remains unknown (Menier et al., 2010). Secondly, the proportion of remobilization of sediments in the whole coastal budget, is at present, poorly assessed despite the ubiquitous erosion along the Brittany coast (Pian et Menier., 2011 and 2018).

In this paper, we monitor the amplitude of erosion and sediment transport in two sectors of the Penestin Peninsula in South Brittany (Figure. 1) using high resolution and high frequency drone acquisitions. We examine how sediment fluxes and their redistribution in the study area help to understand the forcing factors responsible for short-, medium-, and long-term coastline changes.

2. STUDY AREA

The Pénestin Peninsula is bordered to the north by the mouth of the Vilaine River and to the south by the Bay of Asserac (Figure. 1B). This region benefits from significant shelter against weather and marine conditions due to the occurrence of morphological barriers, such as the Quiberon peninsula and neighbouring islands (See, Belle-Île, Houat, and Hoëdic Figure. 1B). This area is better shielded against adverse weather and marine conditions than the coastlines between the the Loire and Gironde rivers (Figure. 1). This protection and mitigating hydrodynamic conditions partly explain the extent and thickness of silty and muddy marine deposits, peculiar to the Vilaine Bay (Vanney, 1977; Menier et al., 2010; Menier et al., 2014; Goubert et al., 2019). However, this setting differs for areas located to the west, between the Laïta estuary and the southern tip of the Quiberon peninsula, where coarser marine deposits are recorded (Menier et al., 2006).

In southern Brittany, the coastline configuration consists of cliffs (47.8%) that are predominantly erosional in nature, while accretionary coasts represent only 23% (Le Roy et al., 2020). These accretionary coasts include sandy dune ridges, notably located between Gâvres and Quiberon peninsula (Figure 2, 3, 4) (Pian et al., 2018; Menier et al., 2019), as well as saline marshes to the east of the Morbihan sector (Le Roy et al., 2020). Compared to the rest of Brittany region, anthropogenically modified coastlines occupy a significant portion (29.1%) of the sector’s coastline (Figure 3). Integrating various criteria such as geology, alteration, land movements, and cavities, le Roy et al. (2020) estimated, that approximately 16% of the cliff coasts are altered, and a voluminous 35.5% are undergoing erosion. The results indicate a very low propensity for erosion over approximately 97.5 km, low over nearly 246.6 km, low to moderate over more than 63.8 km, and finally moderate and high over 0.89 km (Figure 3).

This study focuses on two primary sectors on the western and northern Pénestin Peninsula. Firstly, the Mine d'Or cliff, a sandy cliff with a length of 2 km, and its sandy beach, which is a DYNALIT (https://www.dynalit.fr/) study site.

The cliff has a high propensity for erosion over a relatively short distance (less than 1 km [Le Roy et al., 2020]). The second sector lies between the Halguen point and the Pengrin point (Figure 5), a coastal area located on the southern bank of the Vilaine estuary. This section of the coastline transitions from a rocky cliff coast with some pocket beaches to a sandy accumulation coast (Figures 5, 6 and 7).

To understand the variability in geomorphic features and the dynamics of erosion accretion along this coast, it is necessary to explore the geological, hydrodynamic, and oceanographic settings.

In Brittany, sediment fluxes are highly variable due to the complexity of coastal morphologies and associated subsurface heterogeneity. Compared to other French regions dominated by sedimentary substratum, Brittany offers a wide range of littoral geomorphologies that induce complex local dynamics.

3. REGIONAL GEOLOGICAL, HYDRODYNAMIC AND OCEANOGRAPHIC SETTING

Brittany's rocky cliffs are dominantly composed of metamorphic rocks (mica schists and orthogneisses; Figure 5) belonging to the Vilaine Group (Audren et al., 1971; Brault et al., 2001; Ballèvre et al., 2009 and 2013) of the Hercynian-age bedrock. These rocks may appear locally deeply altered, particularly in the Mine d'Or cliff sector (Brault et al., 2001; Guillocheau et al., 2003) that led to the formation of kaolinite under the influences of the Cenozoic hot and humid tropical climatic conditions and the circulation of hydrothermal fluids through major tectonic faults (Brault et al., 2001; Guillocheau et al., 2003; Van Vliet-Lanoë et al., 2019). This fractured and deformed, highly altered bedrock is overlain by Miocene–Late Pleistocene (Van Vliet-Lanoe et al., 2019) locally deformed fluvio-estuarine sediments. They rest unconformably on the bedrock intervened by an erosional surface (Brault et al., 2001). The Pénestin Formation, predominantly fluvial, fills an erosive paleochannel on the Hercynian micaschists. It comprises three stratigraphic units: the basal unit corresponds to a proximal braided system; the intermediate unit, which is very well preserved and vertically transitions to an internal estuarine system, corresponds to a slightly sinuous distal braided system; and the upper unit corresponds to a distal braided system with numerous evidences of erosion/abandonment (temporary lakes). These three units are arranged in two cycles of base level fall and rise (Brault et al., 2001). These series were interpreted as deposits laid down by a fluvial system within a topographic depression traversed by the paleo-Loire for the basal sedimentary units and by the paleo-Vilaine for the upper units (Brault et al., 2001). The whole sequence is sealed by Quaternary aeolian deposits. In the second sector, towards the Vilaine estuary, the Hercynian bedrock cliffs do not exhibit significant sedimentary cover and/or notable weathering. It may be covered by estuarine silts and/or maritime marshes (Traini et al., 2013; 2015).

The hydrodynamic conditions of the study area appear closely influenced by the geomorphological context. Wave statistics data, derived from measurements conducted by the CEREMA south of Belle-Île Island, indicate that the strongest waves are associated with westward winds (Figure. 8). South of Belle-Île, wave heights range from 4 to 6 m (H_s), with average periods of 6 to 8 s and predominantly originating from the northwest to west. In 90% of cases, H_s is less than 3.5 m with maximum heights of about 5.7 m (Tessier, 2006). The morpho-bathymetry barriers induce refraction in the Bay of Quiberon and the Bay of Vilaine (Traini et al., 2013), directing waves towards the bathymetric gradient. Wave energy thus dissipates from offshore towards the coast but remains active around headlands. In the Bay of Quiberon and the Bay of Vilaine, waves exhibit significant variability of both periods and heights compared to offshore conditions. Average significant wave heights range between 1 and 2 m with average periods of 2 to 5 seconds (Tessier, 2006). Directional wave measurements were conducted on the Four Plateau, off the coast of Pointe du Croisic, indicating principal directions between 235° and 255°. Measurements were also taken off Belle-Île from May 1985 to October 1990 using an omnidirectional buoy (Latteux and David, 2001), recording significant wave heights exceeding 24 hours of 5.9 m with a period of 12 seconds. Given the bathymetric configuration and coastal morphology of the bay, these wave heights do not reach the estuary (Traini et al., 2013; Traini et al., 2015). Their amplitudes and directions are attenuated and deflected by the islands and rocky shallows along their path (Figure 8.A). Wind data (from 1951 to 1980) show prevailing winds coming mainly from the west in 340 out of 1000 observations (Latteux, 2005). Between 1975 and 1997, wind speeds from the western and southern sectors increased by 26.68 cm/s ± 7.76 and 22.53 cm/s ± 7.76, respectively (Pirazzoli et al., 2004). From 2005 to 2018, wind directions generally remain east-west oriented (Figure 8.B). Tides are semi-diurnal with a range of 4-5 m. General currents off the coast of southern Brittany stably flow toward northwest in winter and with less stability toward southeast in summer. Tidal currents are moderate, ranging from 0.25 to 0.4 m/s at maximum during mean spring tides, and highly variable. Closer to the coast, currents show much greater vigour in passages between the Quiberon Peninsula and nearby islands (Belle-

Île, Houat, and Hoëdic). These currents are intensified by shallow depths (Pinot, 1974; Vanney, 1977). In mean spring tides, currents reach 0.9 m/s on the Teignouse passage during flood and 1 m/s during ebb (S.H.O.M, 1990). At the entrance of the Gulf of Morbihan, currents reach 2.2 m/s during ebb and 1.8 m/s during flood. In the Vilaine River, velocities reach 1.5 m/s during mean spring tides, both in flood and ebb (S.H.O.M, 1997). Morbihan experiences relatively low tidal ranges compared to the rest of the region. During neap tides, tides can range from 1.7 m (Gulf of Morbihan) to 2.3 m (Pénestin), while during spring tides, they can range from 3.3 m (Gulf of Morbihan) to 6.2 m (Vilaine River). Generally, tidal range (Figure 9.A) decreases from the western end to Quiberon, thenceforth increases to the eastern part of Morbihan. During astronomical tide or average spring tide periods, the Vilaine estuary experiences a macrotidal regime with respective amplitudes of 6.39 m and 4.75 m. In contrast, during neap tides, the tidal range only reaches 2.25 m in amplitude. The Vilaine estuary experiences a mesotidal type of tide during this period (Traini et al., 2013; 2015; Goubert et al., 2019). The highest tidal currents during spring tides occur at the entrance of the Gulf of Morbihan and in passages between the islands of Quiberon, Houat, and Hoëdic. Velocities at the Gulf entrance can exceed 2.50 m/s. At the mouth of the Vilaine estuary, recorded velocities are around 0.5 m/s but can reach over 1.5 m/s maximum in passages between Quiberon and Houat (Figure. 9B).

4. DATA AND METHODS

4.1. Data

Using data acquired from the National Geographic Institute (I.G.N), the Hydrographic and Oceanographic Service of the Navy (SHOM), the Vilaine Development Institute (I.A.V.), and the

Geo Ocean Laboratory (LGO), we made use of numerous aerial photographs, LIDAR data, and we acquired five (5) high-frequency and high-resolution topographic data from surveys conducted using drones between 2018 and 2023 (Table 1). We modelled the erosion processes of the Mine d'Or cliff over approximately 900 metres in length and mapped the dynamics of coarse and medium sand stocks along the north coast of the peninsula, from Pointe de Halguen to the Branzais marsh.

Field observations and analyses were conducted in the region between the southern tip of the Mine d'Or beach and the Branzais marsh (Figure. 1).

4.2. Data Acquisition, Processing, and Analysis

4.2.1. Photogrammetric Analysis

Two aerial drones were used for the observation and photogrammetric data acquisition campaigns. The first mission utilised a DJI Phantom 4 quadcopter, and subsequent missions were conducted with the help of SenseFlyeBee wing (eBee Plus, then eBee X) (Table 2). Photogrammetry is an analytical method that uses the stereoscopy between paired images to reconstruct a three-dimensional structure. Acquired images were then processed using Post-processed Kinematic (PPK) with the use of the Permanent GNSS Network (RGP) from the National Institute of Geographic and Forest Information (IGN). The output images have centimetre-level resolution and an accuracy of about 5 cm. By utilising multiple images of a scene taken from different positions, it was possible to generate a high-quality 3D point cloud AgisoftMetashape software. The spatial data generated (Georeferenced Digital Elevation Model and Orthomosaic) were then integrated into a Geographic Information System (GIS) for storage and analysis.

4.2.2. Creation of Topographic and Morphological Differentials at the Land-Sea Interface

To quantify 2D and 3D morphological changes at the land-sea interface, differential numerical models were produced using lidar and UAV data. These models were decimated to a resolution of 1m for the northern part and 50 cm for the Mine d’Or area to achieve an appropriate compromise between loss of information, efficiency, calculation time and sufficient resolution to reveal morphological changes. These were then analysed using the Digital Elevation Model of Difference (DoD) 3.0 suite on Matlab for better quantification of uncertainty in estimating geomorphological changes from repeated topographic surveys. The use of this suite, combined with probability calculations (Bayes' theorem), refines the estimation of uncertainties for a better understanding of topographic variations. Estimates of overall volumetric variations (at the scale of each differential) are calculated here using a simple integration scheme (DoD 3.0) that multiplies the calculated difference in altitude by the surface area of each cell. In addition, the volumes involved in the displacements of the main sedimentary bodies for the northern part were discretised using the ‘Volume Calculation Tool’ (v. 0.4) on QGIS (v. 3.28.8) associated with a masking layer. For the Mine d'Or sector, it was chosen to separate the "cliff" part from the "beach" part with an average cliff foot used at Z = 4.5 m (IGN69 elevation).

4.2.3. Analysis of Aerial Photographs and Coastal Line Monitoring

Coastal line monitoring was conducted using ortho-images from IGN and those acquired by LGO (Table 1) and digitized using QGIS and ArcGIS software from the vegetation limit for the lower parts to the top of the cliff for the upper parts. These different polylines were then analysed using the DSAS (Digital Shoreline Analysis System) solution in the GIS (ArcGIS) to calculate evolution rates.

5. RESULTS

5.1. Morphological Evolution of Coastal Areas in the Pénestin Peninsula

5.1.1. The Western Coastline of the Pénestin Peninsula: The Mine d'Or Cliff and Beach

5.1.1.1. Observations from aerial photographs and drone surveys

By utilising a set of four aerial photographs provided by IGN and a drone mapping from 2020, we were able to create a detailed map of the summit of the Mine d'Or cliff over a distance of 2 km (Figures 10, 11 and 12). Data collected between 1952 and 2020 reveal a significant retreat of the cliff summit, estimated between ten (10) meters and over thirty (30) meters along strike. This retreat is not uniform across the study area. The region located between the beach access at the centre of the cliff (Figure 12) and the southern tip of the cliff, over approximately 900 metres, exhibits pronounced erosion, locally reaching up to 40 metres of net retreat, averaging at about 60 cm/year. Figure 13 illustrates the differential balance of this retreat along the 2 km of the cliff, confirming observations drawn from comparative analysis of aerial photographs. Results obtained from the same dataset and for the same period highlight significant erosion between the central part of the cliff and the southern region. Average retreats of about 20 meters, locally reaching 40 meters, are recorded, with an erosion average of about 30 cm/year. Rock-lined regions, particularly beach access points, seem to act as protective barriers against coastal erosion, although it they do not prevent the overall erosional nature of the area (Figure 12).

5.1.1.3. Contributions of Drone Surveys (between 2018 and 2021):

Four (4) differential DTMs were generated (Fig. 10) to cover the entire Mine d'Or cliff and beach. These models produce a high-resolution dataset, facilitating the precise distinction of areas prone to erosion or accretion. We first analysed different surveys conducted between

2018 and 2021 (Figure 13). It was followed by an examination of morphological and topographic differential models, using LiDAR data acquired by SHOM in 2010, as well as a drone survey conducted by our laboratory in 2020. These analyses covered a ten-year observation period.

Drone surveys conducted between 2018 and 2021 provided high temporal information and helped to conduct comparative analysis at an annual frequency (Figure 13). In the figure, red and blue triangles indicate accretion areas and erosion sectors, respectively.

While the overall erosion intensity was high between 2019 and 2020, differential digital terrain models (Figure 13) reveal areas prone to both accretion and erosion along the cliff. Volumes produced by gravitational erosion between 2018 and 2019 are approximately 1624 m^3 and 4333 m^3 for the period between 2020 and 2021. From our analysis, the Mine d'Or cliff can be divided into two (2) distinct segments. The northern portion of the cliff is characterised by a dominance of accretion, whereas, the southern segment is more prone to erosion.

For the northern coastal section, eroded materials accumulate at the base of the cliff, contributing to the widening of the beach. These deposits may also occasionally be supplied by sediment particles from the littoral drift of the southern sector of the Mine d'Or beach. The upper part of this segment is colonised by vegetation, mainly consisting of phragmites. Belonging to the grass family, this vegetation plays a role in stabilizing the base of the cliff, taking advantage of this new gravitational substrate. Reeds thrive in wet environments characterized by waterlogged and poorly oxygenated soils, benefiting from regular freshwater input from aquifers in the subsurface before resurfacing at the interface between bedrock and upper geological formations. The geological formations composed of weathered materials and unconsolidated siliciclastic sediments of the Cenozoic Era appear easily remobilized (Figure 14).

Regarding the southern coastal section (Figure 14), the eroded materials appear to originate from the cliff summit that reaches a height of about 15 to 20 meters, with slopes of 70 to 80°, composed of kaolinized weathered materials and unconsolidated sediments (Figure 10.A.1). The weathering products enrich the base of the cliff, playing a protective but short-lived role. Indeed, these are subsequently remobilized by waves and associated currents, then redistributed either seaward or transported by littoral drift towards the north of the beach.
The differential digital terrain model, constructed for the period from 2010 to 2020 (Figure 13), underlines the erosive sections of the cliff. Approximately 36,000 m^3 of materials have been eroded, contributing to beach nourishment. The southern segment of the cliff has undergone the most significant impacts along about 900 meters (Figures. 10.A.1 and 13). Although the northern cliff section has been relatively less affected by erosion, signs of retreat are locally noticeable, particularly near the beach access from La Source, as well as in heavily gullied sectors north of the cliff (Figures 10A and 10.2 and 12).

5.1.2. The Northern Coastline of the Pénestin Peninsula: From Halguen Point to Branzais Marsh

From Halguen Point to Scal Point, the reflective rocky coastline is characterised by a series of indentations in the form of small pocket beaches that trap subangular gravel to pebble-sand-sized grains of siliciclastic and carbonate shell fragments. These bioclasts seem to be sourced from adjacent mudflats and shellfish fragments from aquaculture farms located in the vicinity (Figures 7 and 15) and accumulate in substantial quantities. Along this coastline, the shell deposits form local-scale beach crescents under certain wave conditions. To the east, in the Branzais Marsh area, near the Ménard dunes, littoral ridges retreat on the eroded shore in the form of storm wash-over fans.

From Camaret Cove to Pengrin Point, while the littoral ridge is composed of a wide variety of siliciclastic and carbonate sediments, aerial photograph analysis showed that a portion of sediment material is in transit from the western sector of the Pénestin Peninsula towards the estuary. Indeed, the external morphology of sediment bodies observed in aerial photography series from 1952 to the present, from west to east (Figure 15), reveal a succession of sandy spits and sandy ridges with asymmetrical morphologies, prograding inland toward the estuary. Temporal series analysis evidences significant morphological changes along the coast (Figure 16) with paramount variations in magnitudes of areas in progradation/accretion and/or erosion (Figures 17 and 18). Since 1952, there has been a progressive establishment and migration of sandy spits, such as the one located within Camaret Cove (Figure 15, 16, 18). Across the area, displacements of around 50m (70 cm/year) are observed for both the progradation/accretion and erosion processes. The fronts of the former salt marshes, abandoned for over 100 years, are affected by a dramatic retreat with breaches welcoming progressive infilling of mixed materials, in transit from the western sectors, during normal hydrodynamic episodes, and accelerated by storm deposits (Figures 16 and 17).

Sandy ridges and associated beaches present on this southern section of the external estuary (Figure 1 and 4) were quantitatively analysed with emphasis on the volumetric estimation of material in transit or accretion from the Halguen Point sector towards the Branzais Marshes over a 19-year period (2001–2020). These beaches exhibit morphologies indicating active sediment transport where coalescing crescent forms are observed (Figure 18). Mixed siliciclastic and carbonate sediment fluxes fluctuate between 4000 and 10,500 m^3, indicating a constant dynamic. The accretion amplitude has been measured at over 17,500 m^3 of deposited material in Camaret Cove and approximately 16,000 m^3 in the eastern part of the Branzais Marshes.

6. DISCUSSION

6.1. Morphological Changes of Mine d'Or Cliff

The morphological changes of the Mine d'Or Cliff exhibit an erosional asymmetry between its southern and northern sectors. Since 1952, the southern sector has experienced an average annual retreat of approximately 60 cm, concomitant with accretion of about 10 cm/yr in the northern sector. This disparity can be explained by the steepness of the cliff faces over an expanse of roughly 900 metres, as well as the significant height of the cliffs, which reach around 20 metres, thus increasing the risk of mass wasting and slope failure (Pierre and Lahousse., 2006.; El Khattabi, et al., 2018).

Among other factors influencing erosion, the anthropogenic developments made at beach access locations play a predominant role (Diouf et al., 2021). The diffraction effect of waves and their erosive impact by scouring (Figure 12) are observed on both sides of the rocky area (Komar, 2011). Thus, the ripraps used near the protective structures seem to generate erosive and regressive effects at the base of the cliff due to wave refraction effects (Figure 14.B). This erosion actively contributes to sediment supply to the beach, fostering a constant sediment flux close to the shoreline. The sands and gravels resulting from this erosion constitute a significant source of siliciclastics, thereby contributing to the replenishment of sediment stocks on the beach.

However, the sandy prism thus created, though beneficial, is dependent on littoral drift. This factor is responsible for the transport and remobilization of sands and gravels, especially slope toe collapses, towards the northern sector. The sediment migration from south to north explains the variation in sediment prism thickness, ranging from approximately 0.5 to 1 metre in the south to over 2 to 3 metres in the north (Figure 14).

This difference in sediment supply creates a buffer zone on the beach, attenuating the impact of hydrodynamic agents. Consequently, debris clears more rapidly on the southern sector over about 900 metres, where erosion has been most intense over the past 70 years.

Although this dynamic contributes to maintaining a stable volume of sediment particles on the beach, it has negative consequences for the geomorphological configuration of the cliff by accentuating erosion at its base. But this volume of sediment is not lost. In the long term, it positively contributes to the accretion of the coast between Halguen Point and the Branzais Marshes along the southern bank of the Vilaine estuary.

6.2. Factors Controlling Cliff Erosion

In all geomorphic processes, gravity is, of course, a widely prevalent and dominant cause. However, spatial variability in cliff erosion suggests multiple and complex mechanisms. Factors that could give positive feedback on cliff erosion are lithology, ground/interstitial water circulation and content, as well as slope. In the south, the lithological composition is characterised by kaolinized clays and highly weathered micaschists. Groundwater circulation exerts additional pressure on the mass, likely the cliff toe, to collapse faster (Pierre and Lahousse., 2006.; El Khattabi, et al., 2018).

The beach appears to play a more protective role north of the cliff than in the south. With greater width and thickness, it acts as a barrier, dissipating wave energy before it reaches the cliff, thus reducing coastal erosion. However, future sea level rise could restrict the beach's width, diminishing its effectiveness and intensifying wave erosive action on the cliff. This could lead to the remobilization of collapsed sediments, increasing sediment stocks in transit towards the southern bank of the Vilaine estuary. Since 1950, the SHOM provides information suggesting that this rise tends to accelerate. It was about 0.88 mm/year at the beginning of the 17th century, and it now reaches 2.75 mm/year. These figures follow global trends of sea level rise, according to a report released in September 2019 by the Intergovernmental Panel on Climate Change (IPCC), projecting it could reach 1.10 meters by 2100 if greenhouse gas emissions do not decrease. Even in the most optimistic scenarios, the sea level would rise by a minimum of 40 centimetres by 2100, thus active as negative feedback on the protective role of the north of Penestin’s beach barrier.

6.3. Morphological Changes in the Sandy Accumulation Coast

This coastal area, sheltered by the Halguen promontories, experiences only refracted waves. This sector records sediment movements laterally along the coast of up to 15 m per year over the last decade (Traini et al., 2015) and particularly active transverse movements (Figures 16 and 18). The construction of the Branzais dike halted coastal retreat (100 m), which was occurring before 1958 (Figure 7). While it appears that some parts of the sand ridges of the "Ménard Dunes" (Traini et al., 2015) are stabilised, since 2001, coastal retreat has remained very active in this region, raising questions about the vulnerability of the Branzais Marshes to sea level rise. The mixed material of siliciclastics and carbonates invaded the salt marshes through the establishment of temporary flood deposits associated with stormy weather events (Figure 17; Traini et al., 2015)

These observations and initial quantitative measurements reveal significant rapid changes along this coast, demonstrating a coastal dynamic of erosion and accumulation. River flow, waves, and tides are the three main hydrodynamic factors controlling the shape and distribution of sediments in estuaries (Boyd et al., 1992; Dalrymple et al., 1992). These parameters are influenced by climate conditions. The Vilaine estuary is subject to a temperate oceanic climate regime.

The presence of a littoral sand drift of up to 15 m/year near the Menard Dunes indicates perpendicular to oblique wave incidence. Thus, the Vilaine estuary appears to trap sandy sediments along its southern bank through the south littoral drift, which are either remobilized or dispersed on the salt marshes in the form of carbonate storm deposits and by the construction of shingle ridges. A similar phenomenon is also observed along the northern bank (Traini et al., 2015).

The siliciclastics and carbonates are partly supplied by products resulting from the erosion of the Mine d'Or cliff, especially the siliciclastics. The biological component originating from anthropogenic (mussel and shellfish farming) activities remains only localised.

In the context of rising sea levels, the increased frequency of flooding events reinforces the erosion of salt marshes by degrading the physical properties of the foreshore. Waves and tidal surges in the context of rising sea levels, reinforced since the construction of the Arzal dam located 8 km upstream from the mouth of the Vilaine (Figure 1C; Traini et al., 2015), further inundate the salt marshes at every tide. Estuarine dams near mouth with large discharge interval reduced these circulations (Figueroa and Son, 2024). Winds blowing towards the land, as well as a sea level rise of approximately 100 mm since the construction of the dam, have contributed to the increase in water level.

The three phenomena (tidal surge, wind wave, and sea level rise) combined enhance lateral erosion of salt marshes in the estuary. Despite heavy sediment accumulation on the lower parts of the intertidal mudflats, the sandy nature of the upper parts still favours erosion. This situation illustrates an adaptation to the post-sea level rise water level and not a consequence of the dam on the river.

6.4. Synthesis of Sediment Fluxes from the Mine d'Or Site to the Branzais Marshes During the Period 2010-2021

A sediment flux assessment (Figure19), conducted over a 60-metre-wide strip, represents the volumes involved between 2010 and 2020. In the area of the Mine d'Or cliff, between the rocky plateau of Demoiselles and Pointe du Lomer, approximately 32,000 m^3 of materials sourced from cliff erosion have contributed to sediment accumulation on the beach. Volumes lost on the beach due to littoral drift-related transport are estimated at about 10,000 m^3, totalling volumes involved in the order of 42,000 m^3.

In the northern sector, between Pointe de Halguen and the Branzais marshes, approximately 12,000 m^3 of sand and gravel were measured in transit to the coast. Over a strip of about 60 meters, the cumulative volumes involved over the same period are estimated at around 41,000 m^3.

Although it may appear surprising to have similar volumes within the two studied sectors, cliff erosion annually supplies the coastal system of the North Peninsula of Pénestin with approximately 4,000 m^3 per year, a natural replenishment that helps preserve the beach as a buffer zone. Sedimentary dynamics continue northward and towards the accumulation coast of the left bank of the estuary. This sink zone is characterised by alternating sectors of accretion and erosion, which are, according to Traini et al. (2015), partly redistributed towards the Vilaine estuary.

6.5. Coastal Erosion and Potential Threats to Human Developments

Coastal change in the area influences the stability and evolution of the coastline, which houses essential infrastructure such as dense urban areas, roads, and the coastal path of the municipality of Pénestin.

Recent changes in the coastline have necessitated extra security measures for beach access, relocation of parking areas, retreat of the coastal path, and signalling of the risk of cliff collapse by the municipality's services. The southern bank of the Vilaine estuary is an area located near the center of the municipality that could be exposed in the medium term if breaches in the coastal barrier of the Branzais marshes were to intensify in the next 50 years. On this same coast, floods during stormy events have already been observed, and these events are projected to become more frequent in the future (IPCC Report). Understanding coastal processes, particularly contemporary coastal retreat models as a proxy for future models, is therefore crucial to inform coastline management in the municipality of Pénestin (Figure 20).

6.6. Advantages and Disadvantages of Drones and Lidar Data and Analysis of High-Resolution Coastal Dynamics of a Cliff Coast and an Accumulation Sandy Coast

The use of drone surveys in this study has proven to be an effective tool for measuring short-term erosion dynamics along both the sandy accumulation coast and the cliff coast. Photogrammetric analysis of image data acquired by drones generated orthomosaics, estimated shoreline positions (Figures 13 and 14), and elevation models (Figure 18), providing quantitative information on coastal geomorphological evolution. Drone surveys offer fine spatial resolution and precise measurements of shoreline position at high temporal frequencies, allowing for the quantification of coastal changes (Pian and Menier, 2011; Cunliffe et al., 2019).

Lightweight drones represent a cost-effective option for deployment in the field, requiring simply trained and properly equipped personnel. Their ability to provide high temporal resolution in surveys far exceeds that of traditional remote sensing methods, such as satellite observations or aerial surveys (Casella et al., 2016; Stow et al., 2004; Yang et al., 2020). The high temporal frequency offered by drone surveys enables obtaining quantitative information on erosion processes, thus offering a deeper understanding of their evolution over time and space. These quantitative data are particularly valuable as they can be directly linked to physical parameters, unlike more traditional proxies, such as the apparent cross-sectional area of detached cliff blocks or the appearance of sand banks extracted from time-lapse photography (Barnhart et al., 2014; Cunliffe et al., 2019).

However, the spatial capabilities of drones are limited by safety and regulatory constraints, as well as their range and size. Combined with other environmental measurements such as wave field and sea surface temperature, these spatial observations could be effectively used to assess and improve numerical models of coastal erosion on various time scales (Wobus et al., 2011; Pian and Menier, 2011; Barnhart et al., 2014; Casella et al., 2014; Pian and Menier, 2019).

7. CONCLUSIONS

This study shed light on the significant role of rocky coastal cliff erosion in contributing to sediment dynamics within the Penestin Peninsula in South Brittany. Through the integration of high-resolution drone imagery, aerial photographs, LIDAR data, and detailed topographic surveys, we conducted a comprehensive photogrammetric analysis of the Mine d'Or cliff. Our findings reveal a pronounced asymmetry in erosion rates between the southern and northern sectors of the beach, with the southern sector experiencing a more rapid annual retreat. The quantified erosion rates and sediment transport data underscore the substantial volume of material—approximately 32,000 m³—derived from cliff erosion and its critical contribution to sediment accumulation along the shore, particularly in the Branzais Marsh.

The observed sediment dynamics, driven by local hydrodynamic factors such as the northward longshore drift, highlight the complex interplay between coastal erosion and sediment redistribution. This study emphasizes the importance of considering rocky coastal cliffs as major sedimentary sources in regions with low external sediment supply. The insights gained from this research contribute to a deeper understanding of coastal geomorphology and offer valuable information for coastal management strategies aimed at mitigating erosion impacts and preserving coastal ecosystems. The application of advanced remote sensing technologies will continue to enhance our ability to accurately assess and manage coastal environments in the face of ongoing climatic and anthropogenic pressures.

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LIST OF FIGURES

Figure 1: Location map of the study area with highlighting the two analyzed sectors: the first comprising the Mine d'Or cliff and its beach, and the second extending from Pointe de Halguen to the Branzais marshes, where Lidar data analysis and drone campaigns were conducted.

Figure 2: Topo-bathymetry map of the coastal lithologies of South Brittany. It is based on the extraction of geological information (lithology and age) from the harmonized 1:50,000 scale geological maps of the BRGM database, supplemented by field studies. The layer was produced for the report titled "Characterization of the geomorphology of the coastline, vulnerability to erosion, and inventory of storms in the Morbihan department" (Leroy et al., 2020; https://geobretagne.fr/geoserver/brgm/wfs).

Figure 3: Topo-bathymetry map highlighting the national index of coastal erosion of south Brittany. This indicator corresponds to a quantification in cm/year (positive for the advancement and negative for the retreat of the coastline over the considered period) of the sensitivity of the coastal line to erosion. Its calculation is based on the measurement of the change in position of a coastal marker (high tide line, vegetation limit) consistent between recent orthophotographs (between 2005 and 2014) and older ones (between 1920 and 1957) over a period of more than 50 years. The indicator is not calculated when a structure replaces the natural coastline. It does not extend into estuaries and generally does not cover the ends of sand spits. (Source : cerema ; https://geolittoral.din.developpement-durable.gouv.fr/wxs).

Figure 4: Topo-bathymetry map of south Brittany showing the main siliclastic deposits (sandy beach and dunes) and the longshore drifts.

Figure 5: Topo-bathymetry context of the Pénestin peninsula and the Vilaine estuary (Sources: SHOM, IGN). Two topographic cross-sections are presented to illustrate the steep gradients on both side of the peninsula.

Figure 6: Simplified geological map of the marine and continental formations of the Pénestin Peninsula. The study area is characterized by a Hercynian-age substrate/basement, heavily altered, fractured, and faulted, overlain on the Mine d'Or cliff sector by Cenozoic sedimentary deposits (Guillocheau et al., 2003; Van Vliet-Lanoë et al., 2019).

Figure 7: Spatial distribution of sedimentary environments in the Vilaine estuary. The figure shows the spatial distribution of sedimentary environments constituting the current estuary above mean sea level. Mudflats represent the main feature (80%) of the estuary. Salt marshes and coastal ridges complement the landscape with 17% and 3% of the estuarine surface, respectively. Note that coastal ridges are absent in the inner estuary. (Modified from Traini et al., 2015).

Figure 8: A. Wave rose 2018-2022 from data collected by the Four buoy of the CANDHIS network and B. Maximum daily wind roses for the Arzal station from 2000 to 2005 (Source: Meteo France).

Figure 9: A., Tidal characteristics: at the top, maximum tidal range for a coefficient of 120 and tidal current at maximum flood for a coefficient of 95; B., Maximum tidal current speeds for a coefficient of 95 and tidal current at maximum ebb for a coefficient of 95 (Source: data.shom.fr).

Figure 10: A. Location of a selection of 5 coastal photographs of the Pénestin peninsula; A.1. Photograph illustrating altered formations (Kaolin; whitish colour) of Vilaine micaschists in the southern sector of the Mine d'Or cliff. This cliff, with a length of about 2 km and a height

ranging from 10 to 20 meters, is subject to very frequent landslides, more specifically over 900 meters between the central part of the cliff (known as La Source) and the south of the cliff (facing the Les Demoiselles rocks). From the top of the cliff, landslides originate affecting the heavily weathered and friable geological formations under the effect of meteoric water infiltration (Brault et al., 2001; Schroëtter, 2013); A.2. Photograph illustrating deep ravines affecting the loose sediment layers of Cenozoic age in the northern sector of the Mine d'Or cliff. These ravining phenomena are caused by the combined action of winds and rains. All these gravitational deposits feed the foot of the cliff and thus participate in the fattening of the beach and nearby environments when remobilized by swells and associated currents; A.3 Aerial view of Pointe du Halguen, showing pocket beaches between rocky points to the north of the Pénestin Peninsula. The coast is characterized offshore by vast rocky plateaus visible at low tide, transitioning laterally to mudflats where the presence of mussel farming areas can be seen; A.4. Photograph illustrating a sandy bank located near the Camaret cove. This bank appears partly vegetated at the top, however, the dynamics along the coast of sandy deposits migrating towards the interior of the Vilaine estuary are clearly distinguished (Traini et al., 2015); A.5. Photograph of the Branzais marshes, located north of the town of Pénestin, on the south bank of the Vilaine estuary. This maritime marsh faces a muddy intertidal flat, through sandy deposits of silico-clastic and carbonate nature, whose sources can be distal and proximal. Distal sediment sources come from geographical sectors located to the west, more specifically in line with the cliff and the beach of the Mine d'Or. The proximal sources are the tidal and subtidal mudflats of the estuary facing the marsh, where quartz and carbonate particles are remobilized and carried during tides and extreme events at the coast.

Figure 11: Time series of aerial photographs from 1952 to 2020 and an extract from a 1947 military map of the Mine d'Or cliff and its beach. The Mine d'Or cliff is bordered by two rocky

formations, Les Demoiselles to the south and Pointe de Lomer to the north. The inset at the bottom of the figure illustrates the coastline pointed out from the aerial photographs where a retreat of about 50 meters is observed to the south and about ten meters to the north.

Figure 12: Schematic representation of the retreat of the Mine d'Or cliff obtained from the analysis of the 1952 aerial photograph and the 2020 drone survey (Table 1).

Figure 13: Three differential terrain models for the Mine d'Or sector for the following years: 2018, 2019, 2020, 2021. More pronounced erosions are observed on the southern sector of the cliff, especially between 2019 and 2020, leading to beach build-up.

Figure 14: Drone photographs of 4 sectors of the cliff in 2020 illustrating both erosion at the top of the cliff (A), the role of rocks and associated erosive processes (B), the presence of caves (C), and heavily kaolinized landslide at the foot of the cliff (D). E. Differential terrain model for the Mine d'Or sector between 2010 and 2020. Cliff retreat on the southern sector is confirmed and appears to be more than 5 meters over 10 years.

Figure 15: Extract from time series of aerial photographs from 1952 to 2020 from the Camaret cove to Pointe de Pengrin. Black arrows indicate examples of migrating sediment bodies, prograding bodies, and accretion, such as the one originating from the 2000s north of the Camaret cove. Blue arrows illustrate erosive sectors since 2013 at the former salt marshes, now abandoned. Yellow arrows illustrate the installation of salt marshes with the presence of Salicornia sp. in the Branzais marshes.

Figure 16: Schematic representation at the land-sea interface of movements along the coast: accretion, erosion, and sediment transit between Pointe de Halguen and the Branzais marshes. Accretion processes during bank formation can reach over 40 meters, and retreats of the coastline exceeding ten meters or more are also observed.

Figure 17: A. 2007 photograph of the Branzais salt marsh and the former salt exploitation (see figure 4 for location). B. 2021 photograph showing the rate of coastal erosion in front of the former salt marshes over approximately 50 meters. C. The photograph shows storm deposits contributing to the progressive filling of the channels associated with the salt marshes.

Figure 18: Differential balance between 2001 (Lidar) and 2020 (drone survey) illustrating sediment fluxes in transit and/or accretion along the coast between the Camaret cove and the Branzais marshes.

Figure 19: Evaluation of eroded and transported volumes over the period from 2010 to 2020 between the southern sector of the Mine d'Or cliff and the Branzais marshes. This analysis was carried out over a strip with a width of 60 meters, representing the area where coastal movements are most significant. Between the Les Demoiselles sector and Pointe du Lomer, approximately 32,000 m³ of materials from the cliff contributed to sediment accumulation on the beach, while erosion of the latter is estimated at about 10,000 m³, totalling 42,000 m³. In the northern sector, a little over 12,000 m³ of sand and gravel were measured in transit towards the interior of the estuary (left bank). Regarding the measurement of total volumes in the area between the pocket beaches sectors of Pointe de Halguen and the Branzais marshes sector, a cumulative volume of approximately 41,000 m³ was estimated.

Figure 20:A. Conceptual representation and historical evolution of erosion, accretion, and sediment transit observed from the analysis and processing of terrain numerical models in our study area from the Mine d'Or cliff to the Branzais marshes between 2010 and 2021. Longitudinal movements (black arrows) indicate sediment transit from the Mine d'Or beach towards the south bank of the estuary. This sediment transit along the coast will be interrupted at Pointe du Scal (see figure 4 for location) and then redistributed in the main

channel of the Vilaine estuary. The main controlling factors of these evolutions are dependent on meteorological hazards, associated and under the combined action of tides and waves. B. It is possible to draw a coastline line by 2100 that inexorably approaches the first inhabited houses located in the southern sector.

LIST OF TABLES

Table 1: Data type, date, origin for the two sectors of our study: Mine d'Or cliff and the left bank of the Vilaine estuary mouth.

Table 2: Photographs and main characteristics of the drones used for surveys on the coast of the Pénestin Peninsula. A. DJI Phantom 4 drone; B. The fixed-wing aircraft (SenseFlyEbee Plus then eBee X), benefiting from high autonomy, and allowing the acquisition of very high-resolution quality. C. Principle of using photogrammetric software.

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