World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

MORPHOLOGICAL RESILIENCE CAPACITY AND SEDIMENT BALANCE OF A BEACH RESTING ON PRECAMBRIAN BASEMENT IN SAN-PEDRO: HIGH-FREQUENCY ALTIMETRY MONITORING

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World Journal of Advanced Research and Reviews, 2026, 32(01), 1769–1776

Publication history: Received on 12 September 2026; revised on 22 October 2026; accepted on 24 October 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.32.1.2678

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ABSTRACT

In a context of significant coastal erosion along the San Pedro shoreline, this study looks at the morphological and sedimentary dynamics of a Precambrian bedrock beach affected by tidal cycle variations. The goal is to understand how the beach responds to marine forces, to measure sediment reshuffling, and to assess its resilience to erosion. To do this, high-frequency elevation monitoring was carried out on two contrasting beach profiles, one located in the hollow of the beach crescent and the other on its crest. This method made it possible to observe, at short intervals, topographic changes and sediment movements over several tidal phases. The results reveal a rapid alternation between accretion and erosion, with a general tendency for accretion during ebb and erosion during flood. The trough of the crescent profile retains more sediment than the crest, showing the influence of morphology on sediment dynamics. The amplitudes of reworking are lower in February than in April, reflecting an increased sensitivity of the coastal system during periods of strong wave action. Most monitored points show morphological resilience above 60%, although this capacity varies depending on the position on the foreshore and the intensity of the sea. In conclusion, despite relatively good short-term resilience, San Pedro beach remains subject to ongoing structural erosion. This study thus contributes to a better understanding of morphodynamic processes in Precambrian bedrock areas and provides useful information for preventive measures for vulnerable coastal areas.

Keywords: Altimetric Monitoring, Tidal Cycle, Beach Crescent, San Pedro, Côte d'Ivoire.

1 INTRODUCTION

In Côte d'Ivoire, the coastline has been undergoing a worrying regression for several decades [7]. The infrastructure and socio-economic activities installed along the sea are visibly impacted [3]. The San Pedro sector, located in the southwest of the country, has a particular geological configuration because it belongs to the Precambrian basement domain. It is characterized by rocky outcrops, dead cliffs and narrow beaches compartmentalized by capes and creeks [2]. This morphology contrasts with that of the sandy beaches observed in the center and east of the Ivorian coast. It directly influences sedimentary exchanges [7], the circulation of hydrodynamic energy and the response of beaches to marine forcings [6]. This response, often considered in theoretical predictions of the future position of the coastline, has often been overestimated because of the failure to take into account the self-resilience capacity of beaches. In this context, the concept of morphological resilience appears central [1]. It refers to the ability of a beach to regain, after a disturbance, a configuration close to or identical to its initial state (Masselink et *al*, 2003). This property depends on the nature of the sediments, the slope of the foreshore, the geometry of the beach profile, the intensity of the waves and the tidal regime [1] and [4]**.** The analysis of the sediment balance at the scales considered, for its part, makes it possible to identify the phases of fattening and erosion, to quantify the transfers of matter and to understand the mechanisms of adjustment of the coastal system in the face of hydro-sedimentary variations [7]. The San Pedro coastline is a privileged field of study to examine the dynamics of a beach in the Precambrian basement domain subject to active marine forcings. The interactions between the tide, the morphology of the beach crescents and the redistribution of sediments are still insufficiently documented, even though they condition the short- and medium-term stability of the coastline. In such an environment, the use of high-frequency altimetry monitoring makes it possible to observe topographic variations with great precision and to highlight sedimentary rearrangements at the scale of a tidal cycle. It is with this objective in mind that the present work is inscribed. It specifically aims to know the amplitudes of sedimentary movements, to evaluate the associated sedimentary fluxes and to assess its resilience capacity (Figure 1).

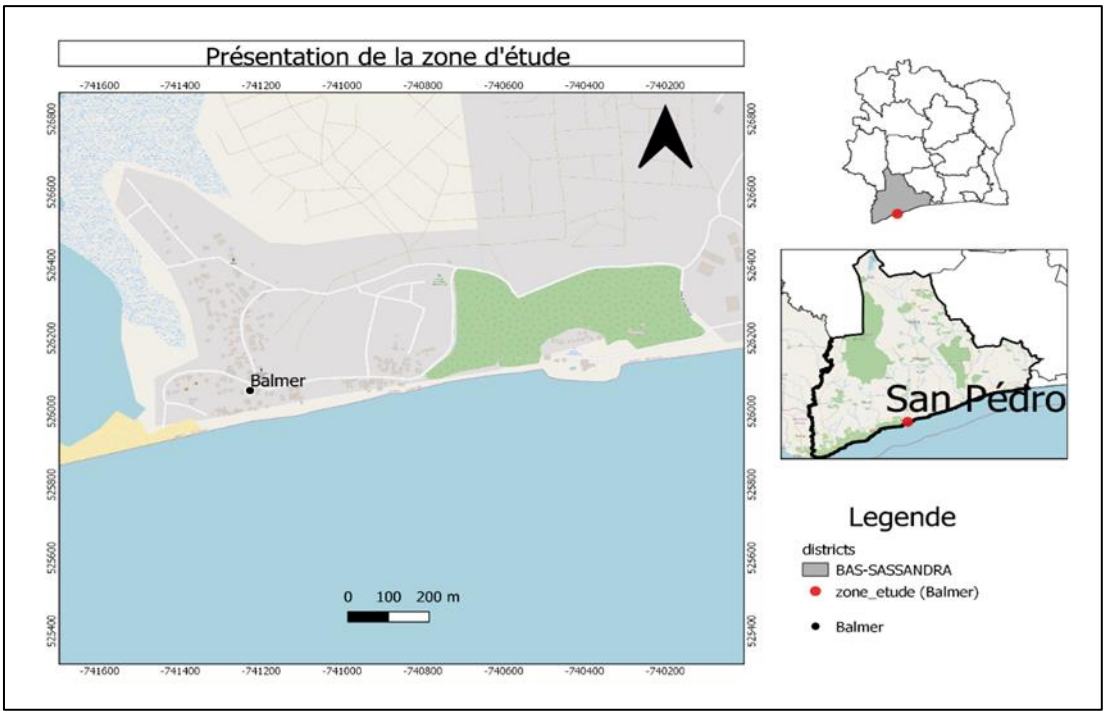

Figure 1: Study area

2 METHODOLOGY

The methodology is based on the study of morphological resilience and sediment balance based on continuous altimetry monitoring of transversal beach profiles, located in two morphologically contrasting sectors. Metal stakes were installed along the profiles and their apparent heights were recorded every 5 minutes during a tidal cycle. The successive variations made it possible to calculate the instantaneous (RrI) and cumulative (RrC) resulting rearrangement. The comparative analysis of the profiles then made it possible to estimate the resilience capacity (Figure 2).

2.1 Instantaneous Resulting Reshuffle (RrI)

It is the difference in dimension between two consecutive surveys of the height of the stake at a given point.

$$RrI(t+1) = Hp(t) - Hp(t+1)$$

2.2 Cumulative Resulting Reshuffle (RrC)

$$RrC\ (t) = \sum_{t}^{1} RrI$$

2.3 Effective reshuffling or maximum amplitude

This is the difference between the maximum and minimum stake height. It is obtained by:

$$Re = Hpmaxi - Hp\ mini$$

2.4 Envelope curve

It is the curve that joins all the maximum amplitudes on the one hand and all the minimum amplitudes of the tracking points on the other hand.

2.5 Resiliency of a beach point

It expresses as a percentage the ability of a point to return to its initial altimetry position after a tidal cycle. It is expressed by: $Cr = \left(1 - \frac{\text{Rrif}}{\text{Re}}\right) * 100$

With RrIf= Final instantaneous resulting reshuffle.

2.6 Incoming and outgoing sediment flow

The ability of the beach to erode or fatten sediment is expressed every two hours in a trapezoidal section 4 m high. The bases are represented by the changes in the elevation levels of the points designated in the section. The fixed distance between these points represents the height. The trapezoid area formula is applied to the tracking points every two hours. $S = (\frac{B+b}{2}) * h$ (With s=surface, B=large base, b=small base, and h= height

Figure 2: Study site in San Pedro and location of elevation monitoring points.

3 RESULTS AND DISCUSSION

3.1 Envelope Curve

3.1.1 Tidal cycle of 11/02/2026

The sedimentary movements observed on the two profiles during the cycle of 11/02/2026 are reflected by the amplitudes of the RrI and the RrC. On profile A, the variations range from -14.1 cm to +13.42 cm, while on profile B, they vary between -14.3 cm and +13.42 cm.

These two envelopes therefore have very similar amplitudes, occupying almost identical vertical columns (Figure 1). The position of the profile, whether it is located on the crest or in the hollow of the beach crescent, does not lead to any significant difference in the intensity of sedimentary movements. As a result, neither of the two profiles differs significantly from the other.

tidal cycle of 17/04/2026

The sedimentary movements of the cycle of 17/04/2026, like those of 11/02/2026, adopt a funnel shape: the envelope of the points at the top foreshore is narrowed, while those at the middle and bottom foreshore widen (Figure 1).

On profile A, the displacements are in a vertical column ranging from -30.5 cm to +30.3 cm. On profile B, they range from -26.3 cm to +40 cm.

The envelope of movements is therefore wider on profile B, located in the hollow of the crescent beach, which underlines the influence of morphological position on the intensity of movements (Figure 3). The maximum is reached on this profile B, with a remarkable value of +40 cm recorded between points B9 and B11.

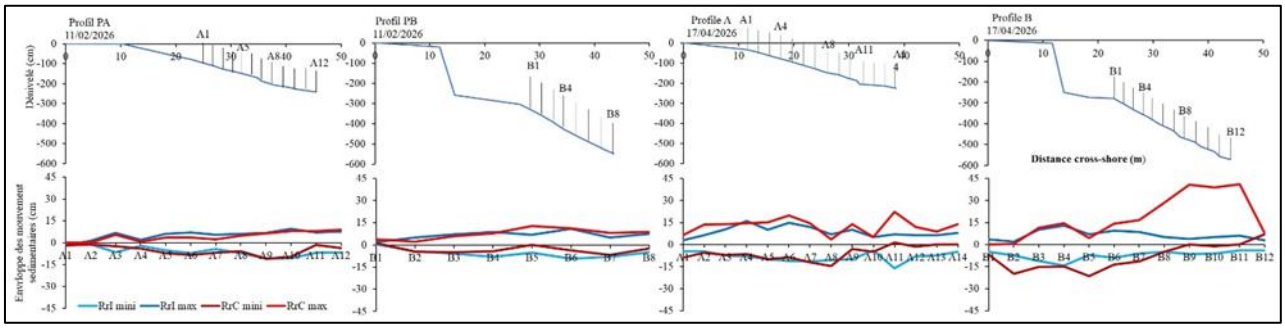

Figure 3: Envelope curve of sedimentary movements in the tidal cycles of 11/02 and 17/04/2026.

3.2 Amplitudes of RrI and RrC

3.2.1 Tidal cycle of 11/02/2026

The RrI and RrC curves have an upward trend from the upper foreshore to the lower foreshore (Figure 3). At all points, the RrI values are mostly larger than those of the RrC. This reflects an alternating action of positive and negative values of wave action in order to minimize their accumulation over the duration of the monitoring. The RrI values are between 2.4 and 20.3 cm. Those of the RrC are between 2.2 and 17.6 cm. (Table I). The amplitudes are therefore more or less identical from one profile to another.

3.2.2 tidal cycle of 17/04/2025

The shape of the RrI and RrC curves no longer rises from the top to the bottom of the foreshore as in the cycle of 11/02/2026. The curves increase from the top foreshore to a certain level and decrease. The inflection point between the two trends is not at the same level on the profiles and on the type of curve. The values of the RrI vary between 7.5 and 27.1 cm and that of the RrC vary between 6.6 and 41.1 cm. Unlike the tide of 11/02/2026, the amplitudes of the RrC are mostly greater than those of the RrI at all the points studied (Figure 3). The cycle of 17/04/2026 reveals the particularity of either a gradual accumulation of the same type of algebraic value over the duration of the follow-up or a strong asymmetry between negative and positive values so as to allow an accumulation of a trend. This cycle also turns out to be more energetic than that of 11/02/2026 and also shows a differentiation in morphological behavior according to the geometry of the range. Profile B, in fact, concentrates the highest amplitudes of RrC (Figure 4).

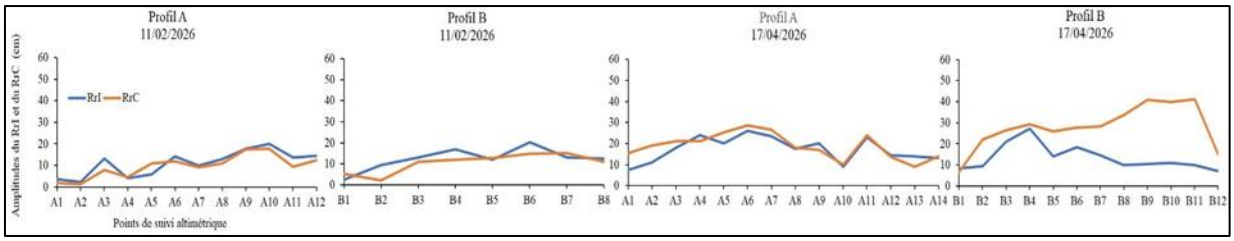

Figure 4: Evolution of the amplitudes of sedimentary movements along the foreshore

3.3 Maximum Amplitudes of Sedimentary Motions

The amplitudes of sedimentary movements are expressed by curves with an ascending pace from the top to the bottom of the foreshore for the cycle of 11/02/2026. The cycle of 17/04/2026 shows an ascending part from the upper foreshore, then another descending part towards the lower foreshore. The places of change in trend do not take place at the same places on the profiles (Figure 5). The maximum reworked amplitude over the two tidal cycles is 41.1 cm, obtained on the RrC curve of profile B during the cycle of 17/04/2026. On analysis, the amplitudes of 17/04/2026 are significantly greater than those of 11/02/2026. Thus, the sedimentary movements follow a certain regime.

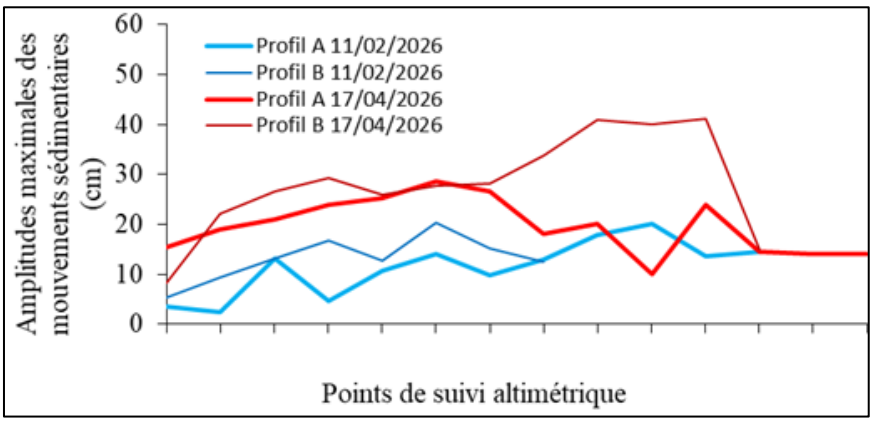

Figure 5: Variability of the reworked maximum sedimentary amplitudes in the tidal cycles of 11/02/2026 and 17/04.2026/

3.4 Beach resilience capacity in the tidal cycle

3.4.1 Tide of 11/02/2026

The histograms of expression of the final resulting rearrangement are small compared to those of the actual rearrangement which reflect the maximum amplitudes reworked in the tidal cycle (Figure 6). These small histogram heights indicate a good capacity of the point to restore its initial altimetry level at the beginning of the monitoring. The sedimentary resilience capacity in the tidal cycle is thus expressed is greater than 60% at each of the points of the profiles. Only the A1 and B1 points on the upper foreshore present histograms of the same height for the Re and the Rrf. They thus express 0% resilience capacity after the duration of the monitoring. They thus express their inability to return to their initial altimetry positions after a tidal cycle. This situation is linked to the low rate of submersion at these points.

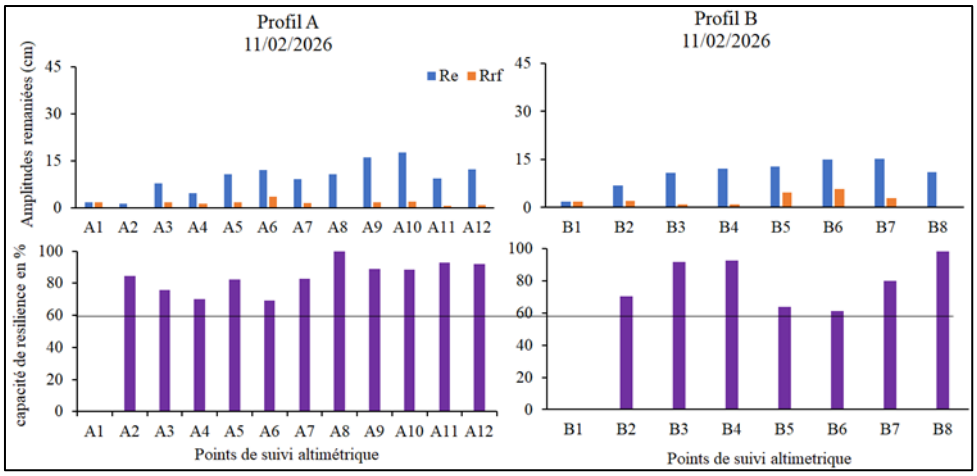

Figure 6: Expression of the resilience capacity of the points of profiles A and B in the tidal cycle of 11/02/2026.

3.4.2 Tide of 17/04/2026

The resilience capacity of half of the monitoring points is less than 60% (Figure 7). This same range had expressed a resilience capacity of more than 60% on all the monitoring points except the first point located further up the extreme high foreshore. This configuration confers a status of resilience capacity backed by a hydrodynamic regime. The February period has a weaker dynamic with a good resilience capacity of more than 60% of all the points in the range. Conversely, the April period offers a stronger dynamic with a poor resilience capacity of all the points of the beach.

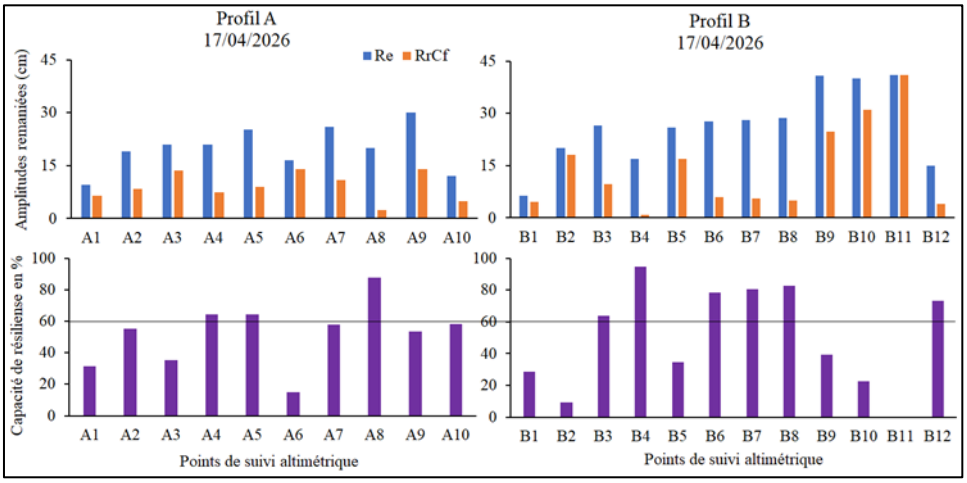

Figure 7: Expression of the resilience capacity of the points of the A profile in the tidal cycle 17/04/2026

3.5 Surface sedimentary flow in and out of a beach section.

3.5.1 Tidal cycle of 11/02/2026

Out of 6 states (08:00, 10:00, 12:00, 13:55, 16:00, 18:00) studied during the monitoring period on 11/02/2026, 4 states have higher surface sedimentary fluxes than outflows (Figure 8). Two states have outflows that are larger than the inflows. These two states reveal an erosion suitability of the range. These are the states of 08:00 (BM+01 H 34 min) and 12:00 (PM- 01 H 55 min). The sum of the inflows in the duration of the monitoring is also greater than that of the outflows (Figure 8). The range shows more suitability for deposition in the tidal cycle and this is also confirmed in the end.

3.5.2 Tidal cycle of 17/04/2026

Out of 6 states (08:00, 10:29, 12:00, 14:00, 16:45, 18:00), studied over the duration of the monitoring, 3 states show greater inbound sedimentary surface flows than the outflows (Figure 8). These states reveal an ability of the beach to fatten on their date. A state where the outflow is greater than the inbound and a state of absence of movement. The sum

of the inflows in the duration of the monitoring is also greater than the sum of the outflows. The beach therefore shows a good ability to fatten in the tidal cycle. The sum of the inflows and outflows at the end of the monitoring is greater at the tide of 17/04 than the tide of 11/02/2026. Thus, the variability of sediment dynamics highlighted in the vertical amplitudes of sedimentary movements is also confirmed in longitudinal sedimentary transport.

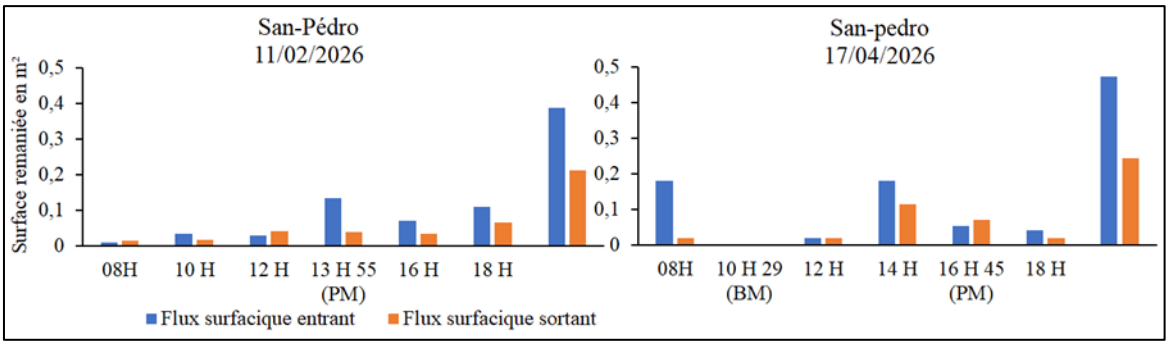

Figure 8: Surface sediment flow in and out of a beach section in the tidal cycles of February 11 and April 17, 2026.

4 DISCUSSION

The question of the variability of sedimentary amplitudes as a function of dynamic seasons was addressed by [6] on the beaches of Port-Bouët and Assoindé in a sedimentary basin. These authors had pointed out that on the same beach the heights of the sedimentary amplitudes generally increase with the significant height of the swell. Thus, they had found greater amplitudes in July where the dynamics are greater than in December in Assouindé. This observation is the same on the coast of San-Pedro where the beach rests on the Precambrian basement. The scientific discussion on the morphological resilience of the beach studied in San Pedro indicates a restoration capacity of more than 60% in February when the dynamics are low and a resilience capacity down by 60% in April when the dynamics are stronger. The resilience capacity is thus delayed in more dynamic periods. This is in line with the conclusions of the work of [7] et [2] [3], [10] who describe persistent structural erosion on the San-Pedro coastline. [7] highlighted a worrying regression of the Ivorian coastline linked to marine forcings and port infrastructure. In this study, the small-scale analysis of the erosion process by observation of the sedimentary flow in and out of a long shore coastal portion gives the advantage to the suitability for deposition. The erosion discussed by [7] is approached from a frontal point of view. In this study, erosion is considered from a lateral point of view. [2] [3] insist on the geological particularity of the Precambrian basement of San Pedro and on the compartmentalization of beaches by capes and creeks, which explains the variability of sedimentary flows observed. [7] emphasize the importance of sedimentary exchanges and energy circulation, confirming that the crescent configuration of the beach directly conditions the resilience of the coastline. [8] studied the port coastal perimeter of San Pedro from 11 transverse profiles and report a seasonal alternation with erosion between May and August and fattening between November and February, results that corroborate the observations where the rearrangements are less significant in February and peak in April. Gbessi (2018) showed that the annual rate of coastline retreat varied from 0 to 2.41 m/year between 2009 and 2012, with peaks reaching 3.5 m/year in 2011 during exceptional swells, which confirms that episodes of strong marine unrest amplify sedimentary imbalances, as observed during the April 2026 cycle presented in this work. Thus, the results of the study are in line with the work of Yacé, Hauhouat, Yao and Gbessi where San Pedro beach shows a notable but insufficient morphological resilience in the face of chronic erosion, and the crescent beach morphology as well as the seasonal variability of swells must be taken into account in any sustainable management strategy of the Ivorian coastline.

5 CONCLUSION

The study of San Pedro beach highlights a coastal dynamic where the seasonal variability of the swells governs the sedimentary processes: seasonal variability is decisive, with low amplitudes of reshuffling in February and much stronger in April. The sedimentary amplitudes vary between -14.3/+13.42 cm in February and between -30.5/+40 cm in April. The morphological resilience is generally good and reaches more than 60% in the tidal cycle for the less dynamic season. The increase in swell dynamics weakens this tidal resilience, which drops below 60%, thus showing less ability of the beach to restore the initial altimetry level. The sedimentary flows entering every two hours in a coastal portion are mostly greater than those outgoing, so that their accumulation in the tidal cycle always remains greater than the outgoing cumulation. Thus, the portion studied shows an ability to be deposited in the tidal cycle.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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