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Dynamics of coastal zone transformation: The Oued Tensift's mouth and Souiria Laqdima beach

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ABSTRACT: This study explores the morphological evolution of the Oued Tensift estuary and the Souiria Laqdima beach over the period 1985–2023, focusing on the impacts of natural and anthropogenic factors, particularly extreme events such as the 2014 floods. By utilizing a combination of diachronic satellite imagery analysis and shoreline mapping through CoastSat software, we identified critical patterns of erosion and accretion, highlighting the vulnerability of these coastal systems to both natural processes and human intervention. The study reveals that coastal changes are not only driven by hydrodynamic forces, such as tidal activity and sediment transport, but are also exacerbated by increasing urbanization near the estuary. The findings underscore the necessity for adaptive and integrated coastal management strategies that consider both immediate risks and long-term environmental pressures, particularly in light of climate change and rising sea levels. Our research offers valuable insights into the complex dynamics governing coastal systems and provides a solid framework for sustainable planning and decision-making to enhance the resilience of these fragile environments.

KEYWORDS: Coastal dynamics, Shoreline evolution, Oued Tensift estuary, Erosion and accretion, Diachronic analysis, Coastal management.

1 INTRODUCTION

Coastal zones, acting as critical interfaces between terrestrial and marine ecosystems, are continuously reshaped by natural forces such as waves, tides, and storms, as well as anthropogenic activities, including urbanization and infrastructure development. These areas are particularly vulnerable to the impacts of climate change, which exacerbate coastal erosion, sediment deposition, and flooding, leading to significant ecological and socio-economic consequences [1]. Recent studies highlight the growing threat of these stressors, particularly in regions like Southeast Asia and North Africa, where both natural and human-driven coastal dynamics converge [2], [3].

The Oued Tensift estuary, located along Morocco's Atlantic coast, represents a dynamic coastal system influenced by both fluvial and marine processes. This study focuses on the Souiria Laqdima beach, which experiences significant sedimentation and morphological changes, partly due to the influx of sediment from the Oued Tensift and the impacts of extreme weather events such as the 2014 floods. Such floods are known to drastically alter coastal geomorphology, with the 2014 event causing widespread deposition and erosion in many parts of the Moroccan coastline [4]. Comparative assessments from similar environments emphasize the role of extreme weather events in accelerating coastal changes [5].

The primary objective of this study is to investigate the diachronic changes in the coastal morphology of the Oued Tensift estuary and Souiria Laqdima beach over the period 1985–2023. Specifically, we aim to document the evolution of the shoreline and estuarine morphology, quantify rates of erosion and accretion, and assess the influence of significant hydrological events, such as the 2014 floods. By combining remote sensing techniques with advanced shoreline mapping methodologies, this study builds on previous research into shoreline dynamics along Morocco's Atlantic coast [6], [7] and elsewhere in similar coastal settings [8], [9]. The findings provide a deeper understanding of the natural and anthropogenic forces driving coastal transformation, contributing to the development of evidence-based coastal management strategies.

Given the increasing risks posed by climate change, sea-level rise, and human development pressures, this research offers critical insights for environmental planners and policymakers. Some studies suggest that integrating local geomorphological data with broader climate models can help design effective adaptation measures [10], [11]. The Oued Tensift and Souiria Laqdima case study underscores the necessity for proactive coastal management strategies that incorporate both global climate models and localized geomorphological assessments to protect vulnerable coastal systems [1], [12].

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2 METHODOLOGY

This study investigates the diachronic evolution of the Oued Tensift estuary and Souiria Laqdima beach, focusing on the period from 1985 to 2023. Our approach is founded on two main axes: first, the transformation of the Oued Tensift river mouth, and second, the movement of the shoreline along Souiria Laqdima beach. We employed satellite imagery and advanced software tools to achieve our objectives.

- **Satellite Image Analysis**

We utilized historical satellite images from Google Earth to track morphological changes at the river mouth over the study period. The satellite images, obtained through the "Show Historical Imagery" feature, provide a diachronic view of the estuary's evolution. This imagery allowed us to detect significant shifts in sediment accumulation and estuary widening, which were then mapped using geospatial software [13].

- **CoastSat Software for Shoreline Mapping**

Shoreline dynamics were analyzed using CoastSat, a Python-based toolkit specifically designed for coastal studies. CoastSat leverages Google Earth Engine and pre-processed images from the Landsat and Sentinel-2 satellites to extract shoreline positions at approximately 10-meter accuracy. By utilizing this software, we were able to map the evolution of the Souiria Laqdima beach's shoreline over a 38-year period. Similar methodologies have been used in studies of coastal dynamics in Morocco and Thailand [6], [12].

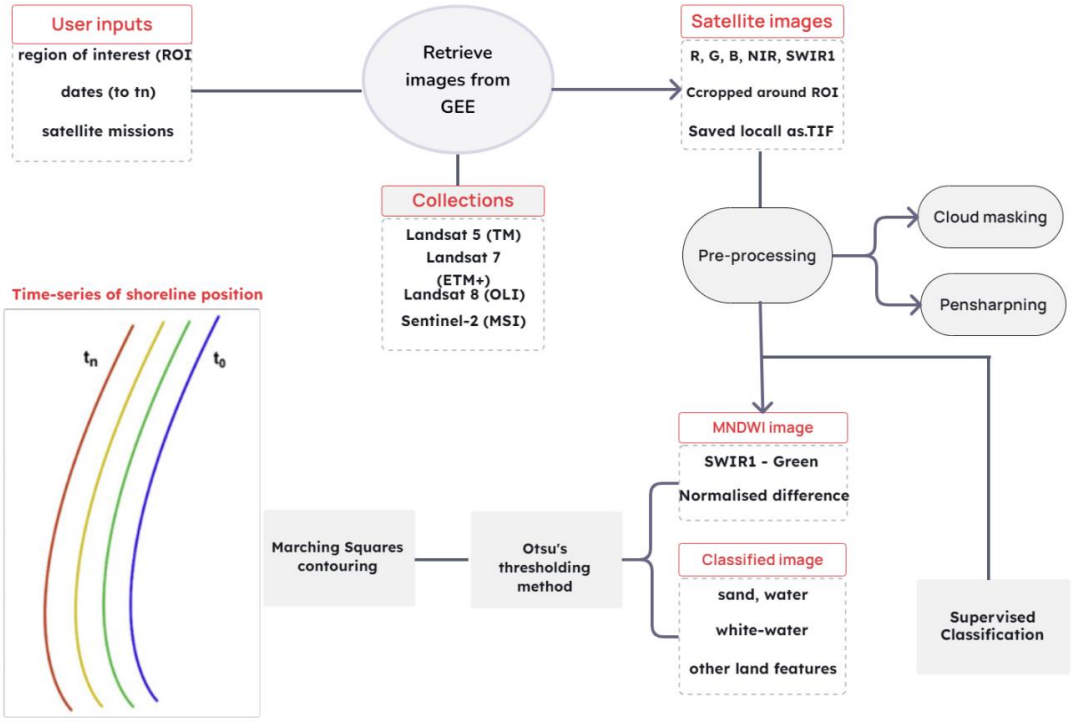

Fig. 1. Flow chart outlining the functionalities of CoastSat. Time-series of shoreline position are obtained over any user-defined region of interest and date range modified [13]

- **Data Integration and Validation**

To validate our findings, we cross-referenced satellite data with hydrological records, particularly those related to the 2014 floods, which were major contributors to sediment movement and coastal transformation [4]. The results were analyzed to quantify erosion and accretion rates across the study area, ensuring consistency with previous studies of shoreline evolution [8], [9].

3 STUDY AREA

The study area is located on the Atlantic coast of Morocco at Souiria Laqdima, with geographic coordinates of 9° 20' 27.33" W longitude and 32° 2' 39.63" N latitude. This coastal stretch extends 6 kilometers and is situated 36 kilometers south of Safi, at the mouth of the Tensift River (Fig. 1). The

northern boundary of the area is marked by the Doukkala Plains, while the northeastern border is defined by the Rehamna region [14]. To the southeast, the plateaus are bordered by the Chichaoua Plateaus, to the south by the Essaouira Province, and to the west by the Atlantic Ocean.

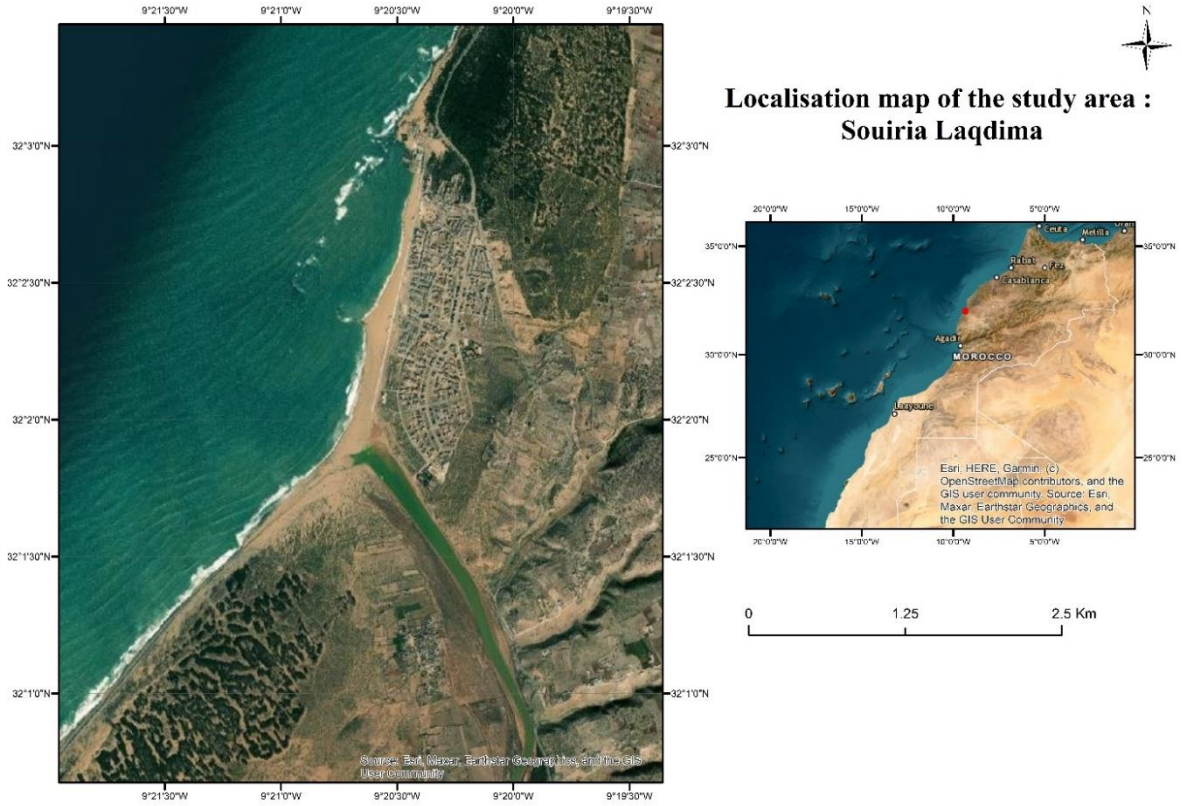

Fig. 2. Localization map of the study area [14]

- **Geological and Sedimentary Characteristics**

The geological formation in this region includes a succession of sedimentary strata ranging from the Paleozoic era to the Eocene epoch. Over these older strata, there are more recent sediments from the Plio-Quaternary era, including conglomerates, sands, and clays, formed due to marine transgressions. The area is part of the western coastal Meseta, a notable geological formation [14] – [16].

The coastline experiences significant accumulation of Quaternary sands from marine deposits, resulting in the formation of large quantities of pebbles transported to the beach from the High Atlas Mountains via the Tensift River.

- **Local Demographics and Urban Development**

Souiria Laqdima, a small coastal town located at the mouth of the Tensift River, has approximately 6,000 inhabitants as of 2023. The town covers an area of about 2.5 km^2. Between 1985 and 2023, the population has increased from around 3,500 inhabitants, with the town expanding from roughly 1.8 km^2 due to urbanization and coastal infrastructure development.

- **Hydroengineering Structures**

In the estuary reach of the Tensift River, hydroengineering structures such as jetties and groynes have been constructed to manage sediment transport and protect the coastline from erosion. These structures play a crucial role in regulating sediment flow and stabilizing the shoreline. Additionally, a small port facilitates local fishing activities and impacts the hydrodynamics of the estuarine zone.

- **Meteorological characteristics**

o Wind

Morocco's wind regime is governed by the presence of two atmospheric circulation systems, which explains the two annual climatic phases: one humid (temperate climate), the other dry (tropical climate). In summer, the wind regime is characterized by northeasterly trade winds. In winter,

lows crossing the Atlantic Ocean from west to east, combined with the formation of secondary lows off the Azores, push the trade winds south of Morocco, where they are replaced by stronger north to northeast winds.

Analysis of the statistical data recorded by the weather station in 2002 reveals a predominance of northeasterly to easterly winds in spring and summer. In winter, on the other hand, west to north-west winds predominate, with a decrease in east to north-east winds.

Wind data recorded at study area station at an altitude of 25m over the periods 1955, 1956 and 1959 to 1964 show that: The most frequent winds are light to moderate (speeds between 2 and 10 m/ s), originating mainly inland (E and NE sectors).

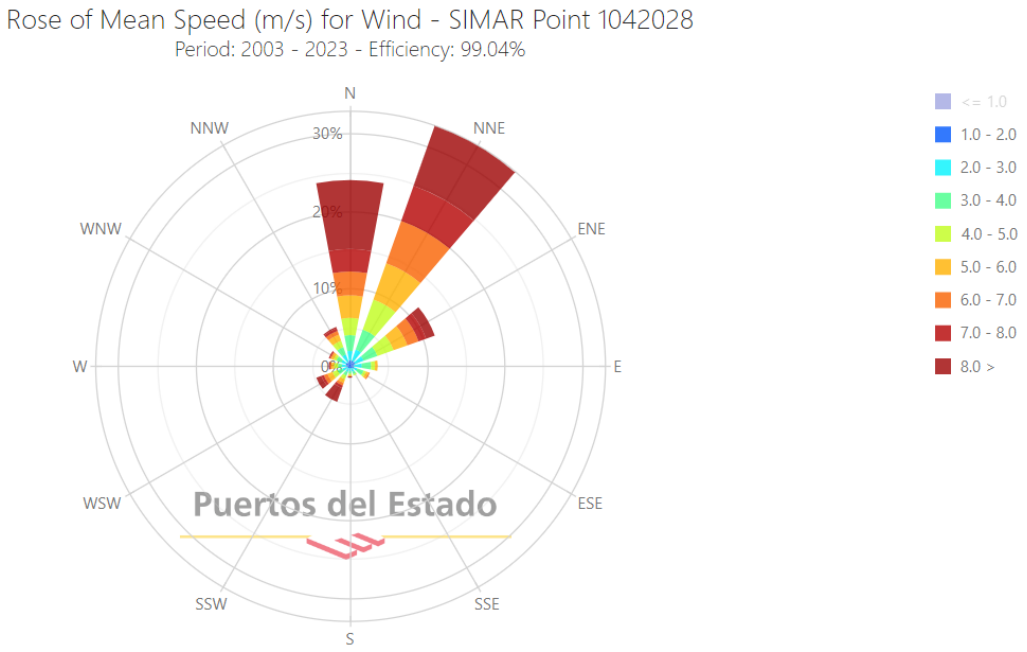

Fig. 3. The wind rose at Ports of the State site

- Swell and waves

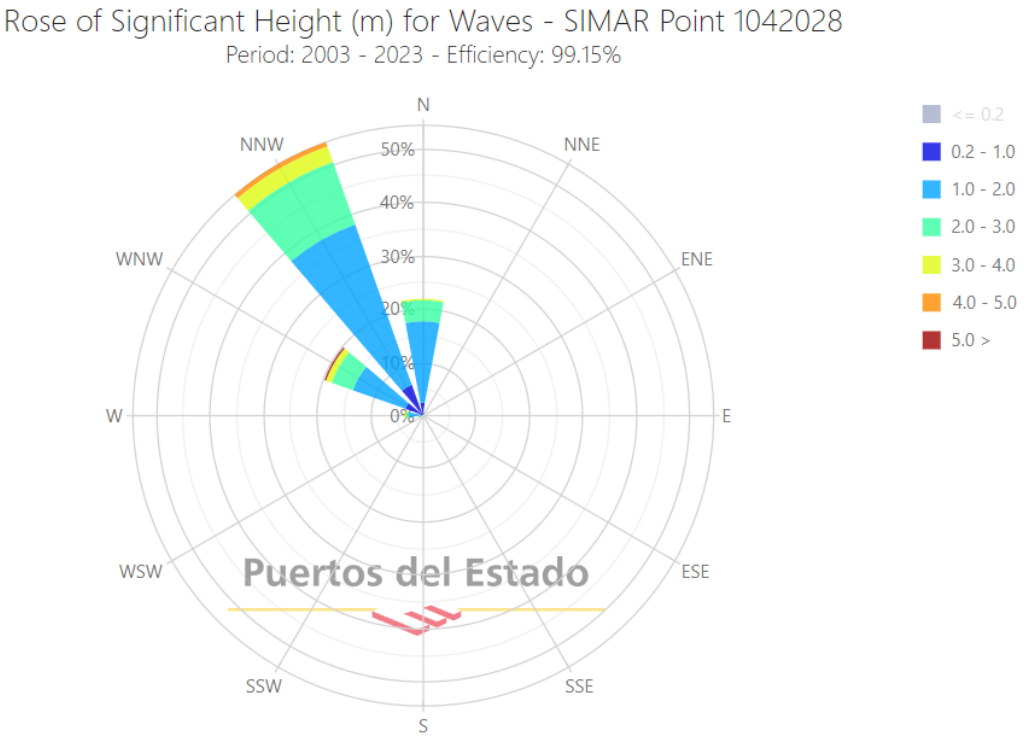

Fig. 4. Rose of Significant Height (m) for waves at Ports of the State site

The swell data recorded off Safi (January 2003-2023 period), show that from the swell direction point of view, incidences from the NNW sector dominate, with frequencies of 58.62% and 31.48% respectively. The other directions are considered secondary (low to very low frequency), with those from the W representing 5.60%, NE and SW having very low frequencies of 2.76% and 0.83% respectively.

- Storm records: November 2014 floods

The flooding of the Oued Tensift in 2014 was a result of severe thunderstorms and heavy rainfall in southeastern Morocco, which caused the river to overflow its banks. The hydrological events of November 2014 were analyzed to understand the origins and impacts of these floods. The primary attributes of the 2014 flood at Talmest, one of the principal monitoring stations of Oued Tensift, are described by [4]. This study analyzed the flood features in Talmest for the years 2008, 2009, 2013, and 2014, comparing the highest flow rates, frequency of occurrence, and geographical impacts of the flooding. The Log-Normal law was used to estimate the maximum flows through statistical and hydrological analyses. Additionally, the maximum annual instantaneous flow was transposed based on the findings of [4].

During the 2014 flood, the average river flow of Oued Tensift was significantly higher than usual, with the maximum flow rate reaching approximately Approximately 2-3 cubic meters per second (m^3/s). The average flow rate under normal conditions is around 1,500 m^3/s cubic meters per second. The flood lasted for 2 to 3 days, with peak flooding occurring over a 24-hour period.

4 RESULTS

The study "Dynamics of Coastal Zone Transformation: A Diachronic Study of the Oued Tensift Mouth and the Evolution of Souiria Laqdima Beach Shoreline (1985–2023) " presents its findings through a series of visual data representations that illustrate the dynamic changes in the coastal zone. A map of the evolution of both the Oued Tensift mouth and the shoreline position highlights significant spatial transformations over the studied period. A Time Series Line Chart provides a detailed overview of how the shoreline distance has shifted over time, revealing key trends and fluctuations in the rate of erosion and accretion. A Scatter Plot with a Trend Line complements this by plotting individual data points while emphasizing the general direction of shoreline change, allowing for a clearer understanding of both immediate variations and long-term tendencies. Additionally, a Bar Chart compares the shoreline distances for each year, offering a straightforward visual comparison of annual shifts. Together, these visual tools collectively underscore the significant morphological changes experienced by the Souiria Laqdima beach, driven by natural and anthropogenic factors, with clear implications for coastal management and environmental sustainability in the region.

- **Evolution of the river mouth's morphology**

The results of the study on the morphological evolution of the Oued Tensift mouth and the adjacent coastal area of Souiria Laqdima from 1985 to 2011 (Fig.5) reveal a gradual and significant transformation. In 1985, the river mouth was relatively narrow, with a small opening into the ocean, accompanied by a narrow beach, indicating limited sediment deposition. However, by 2003, significant changes were observed with considerable widening of the river mouth and beach expansion, suggesting increased sediment deposition, likely due to coastal processes such as longshore drift and variations in river discharge. By 2007, the widening continued, along with increasing urban infrastructure development along the shore. Ongoing sediment accumulation further contributed to beach expansion. In 2009, there was a notable shift in the river's orientation, with a more pronounced curve to the south before entering the ocean, while the beach became more expansive, and urban development intensified. By 2010, the river mouth had stabilized, with significant urban encroachment along the coast, and sediment accumulation appeared stable. In 2011, the configuration remained similar to the previous year, although the beach continued to grow, particularly towards the northeast, suggesting a stable and increased sedimentary environment over time. These results highlight a gradual transformation influenced by both natural processes and human interventions.

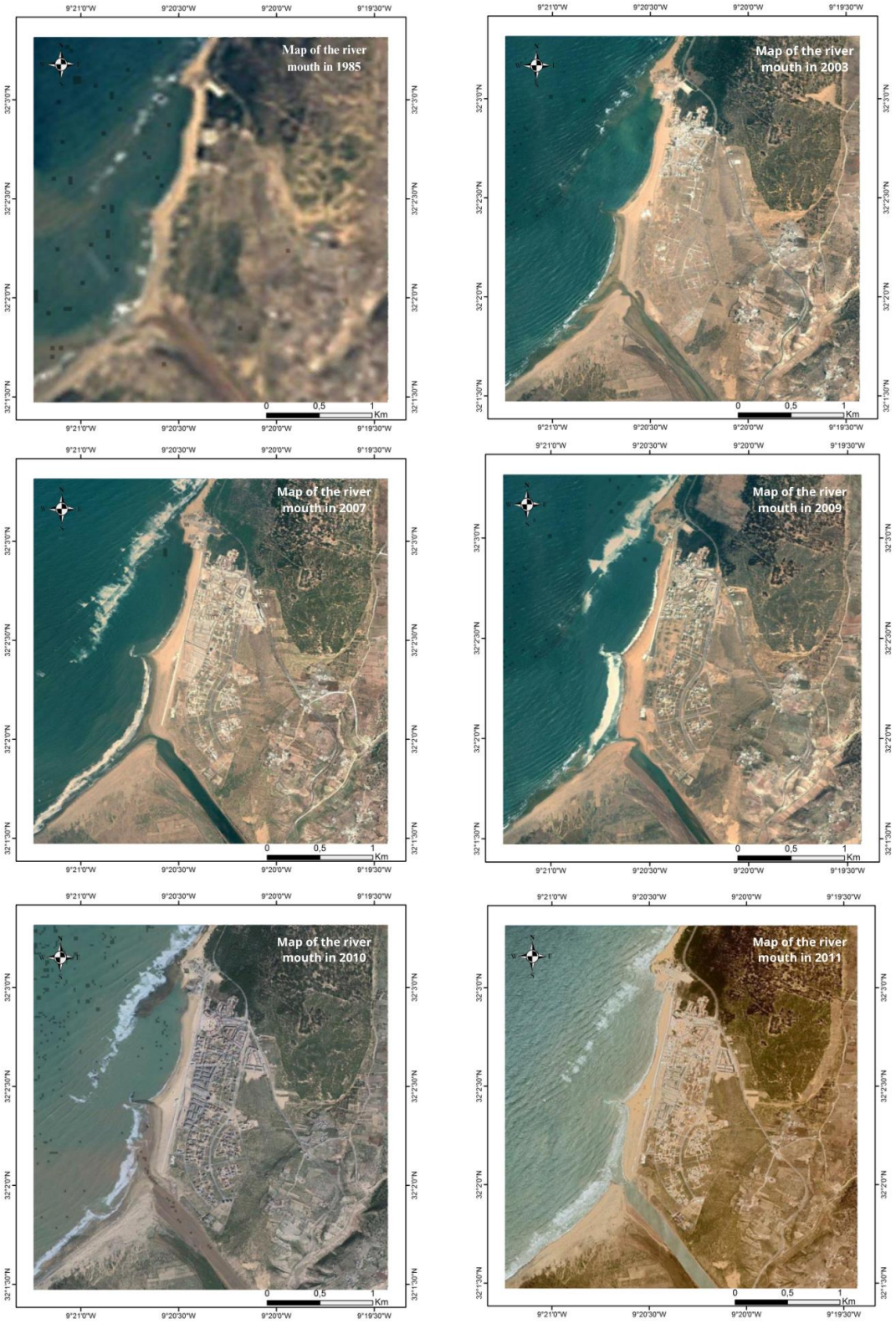

Fig. 5. Set of maps of the Oued Tensift mouth from 1985, 2003, 2007, 2009, 2010, 2011

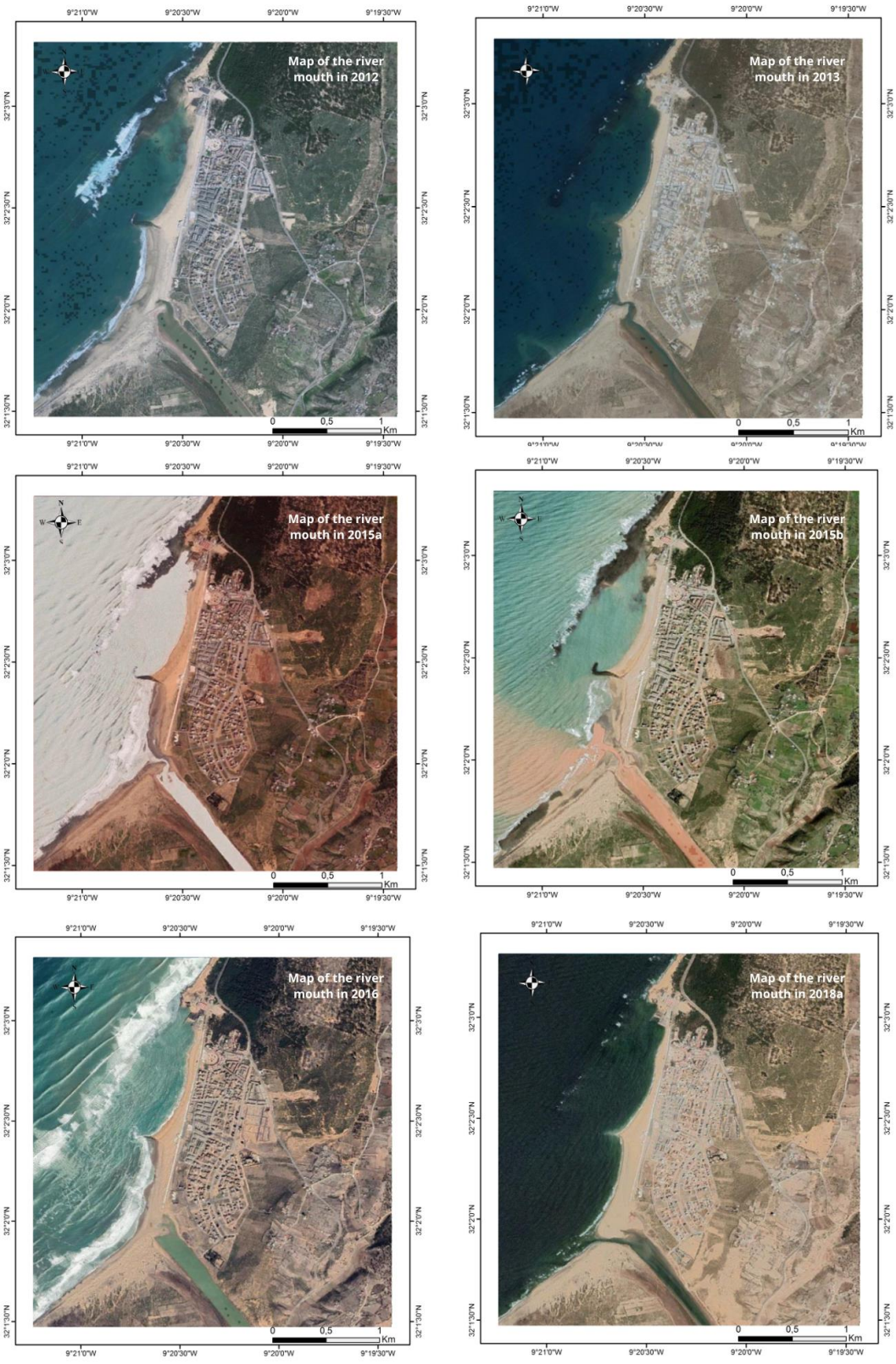

Fig. 6. Set of maps of the Oued Tensift mouth from 2012, 2013, 2015a, 2015b, 2016, 2018a

between 2012 and 2018 reveal significant morphological changes driven by both natural and anthropogenic factors. In 2012, the river mouth exhibited a slight reorientation with a widened channel and clear sediment deposition along the northern section, while the beach continued to expand, suggesting stable sediment dynamics. By 2013, the widening of the river mouth became more pronounced, accompanied by increased sediment accumulation along the beach, reflecting strong depositional processes, potentially influenced by nearby urban expansion. In early 2015, structural modifications at the river mouth were evident, likely due to human interventions to manage sediment flow and river discharge, while the

later part of 2015 showed further shifts in the river mouth, with visible sediment plumes extending into the ocean, suggesting enhanced sediment discharge and beach expansion, particularly towards the north. In 2016, the river mouth stabilized, and the adjacent shoreline remained wide, indicating consistent sediment accumulation. The active coastal processes were highlighted by sediment plumes shaping the river-sea interface, with urban sprawl increasingly posing potential risks to natural sediment flows. By 2018, the river mouth exhibited more stability with well-defined boundaries, and the beach experienced significant expansion, showing a sustained trend of sediment deposition, possibly influenced by coastal structures and nearby urban development. These observations suggest that human activity, alongside natural processes, played a crucial role in shaping the coastal morphology during this period.

Fig. 7. Set of maps of the Oued Tensift mouth for the years 2018b, 2020, 2021, and 2023

The 2018b map (Fig.7) depicts an elongated shoreline with a noticeable demarcation between the river estuary and the ocean, as urban development encroaches nearer to the coast. Coastal currents, represented by arrows, persistently impact the shape and structure of the coastline by transporting sediment. The estuary has undergone noticeable alterations in 2020, characterized by the reshaping of the beach and river path as a result of sediment accumulation. The 2021 map (Fig.7) displays a more constricted entrance, characterized by a high accumulation of sediment towards the northern region, potentially attributed to seasonal occurrences or extraordinary floods. The 2023 map depicts an expanded river mouth and some stabilization of coastal configurations compared to previous years. However, it acknowledges that the movement of sediment along the shoreline, known as longshore drift, still impacts the dynamics of sediment and the shape of the coast.

- **The changing position of the shoreline**

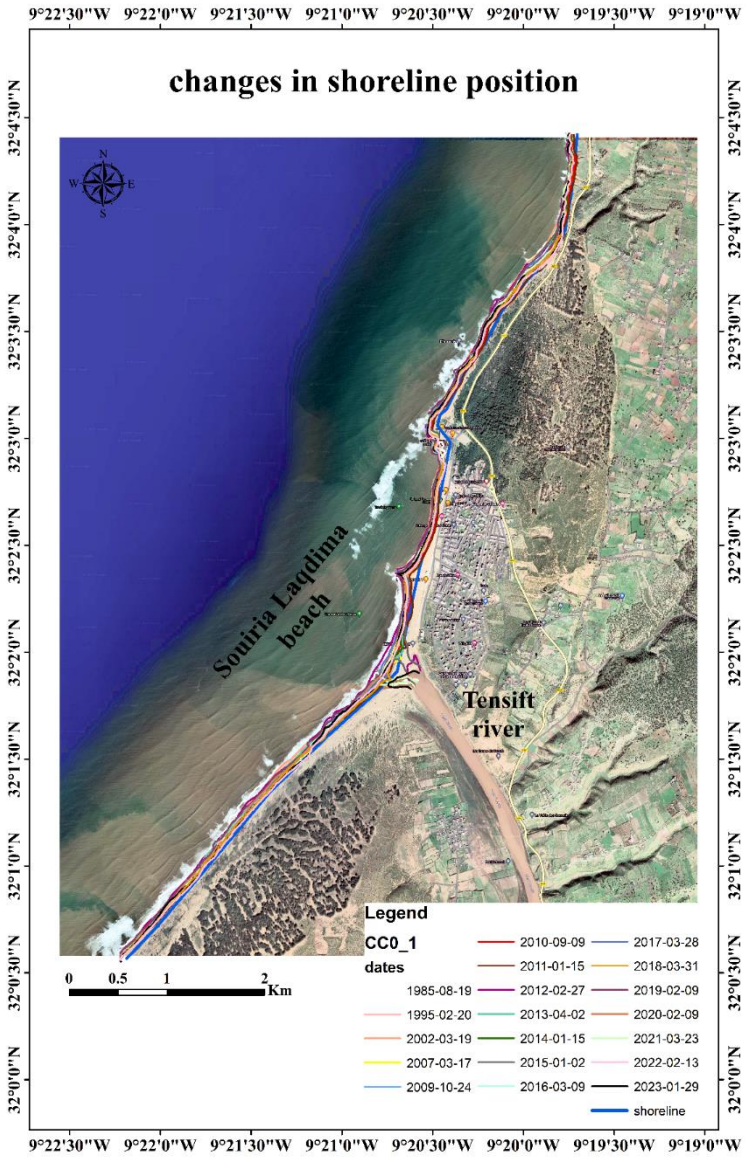

Fig. 8. Map of shoreline position in different years

The analysis of the shoreline position at Souiria Laqdima from 1985 to 2023 (Fig.8) reveals complex coastal dynamics influenced by events such as the Oued Tensift floods in November 2014. From 1985 to 1995, the coastline experienced significant accretion, with a noticeable increase in beach width due to sediment deposition. This trend continued variably until 2010, reflecting consistent sediment influx. However, between 2010 and 2011, there was a brief period of shoreline decrease, suggesting potential erosion or reduced sediment deposition. The years from 2011 to 2012 showed stability, indicating an equilibrium between erosion and accretion. Between 2012 and 2013, both erosion and accretion occurred simultaneously, highlighting the complex nature of coastal processes. Observations from 2013 to 2014, just before the flood, were crucial for understanding previous river dynamics and sediment movement. Post-flood, from 2015 to 2023, the shoreline displayed significant changes. In 2015, there was notable accretion with increased beach width, followed by a dynamic coastline oscillating between accretion and erosion in subsequent years. This alternation reflects interactions between weather conditions, river flows, and human intervention. Stability appeared to return in 2021, yet recent maps from 2022 and 2023 continue to document a complex interplay of erosion and accretion shaping the Souiria Laqdima coastline.

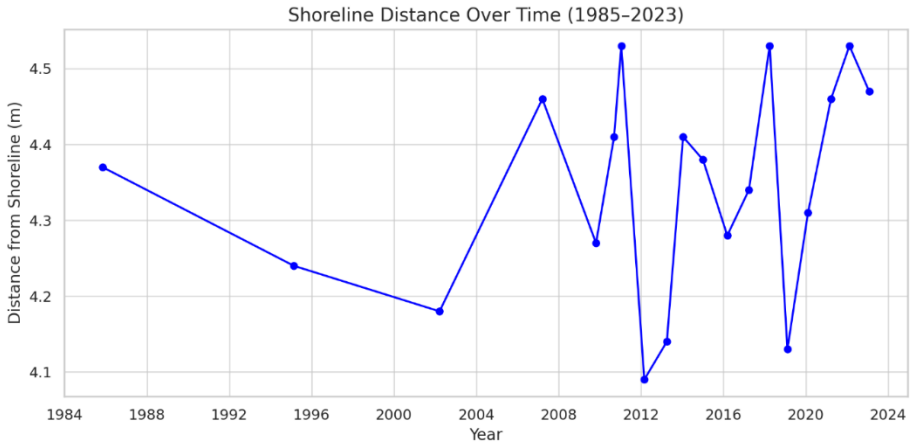

Fig. 9. Distance from shore (1985-2023)

The shoreline distance (Fig.9) has exhibited fluctuations over the years, but a general trend of decline is evident from 1985 to 2023. This suggests a progressive erosion or a gradual retreat of the shoreline over the decades. Nonetheless, there are notable anomalies in certain years where the distance briefly increased.

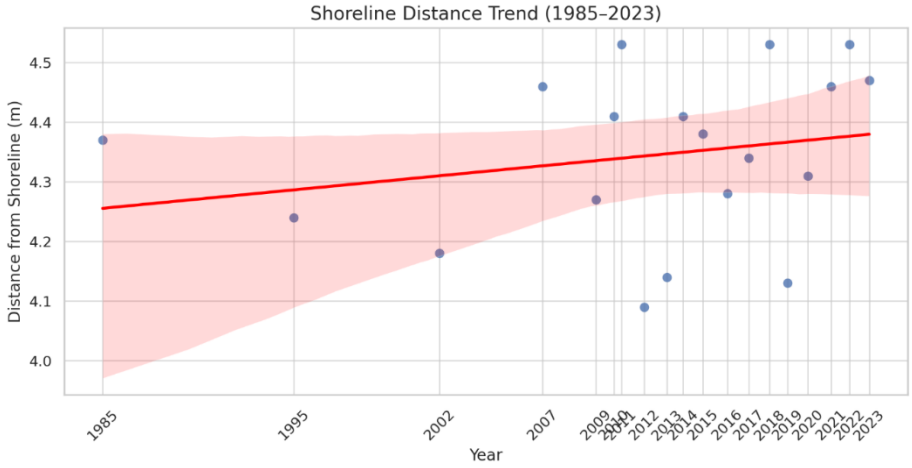

Fig. 10. Distance from shore with linear trend (1985-2023)

The trend line (Fig.10) shows a moderate decline in shoreline distance over the 38-year study period. The regression coefficient, represented by the slope of this line, indicates a consistent annual retreat of the shoreline.

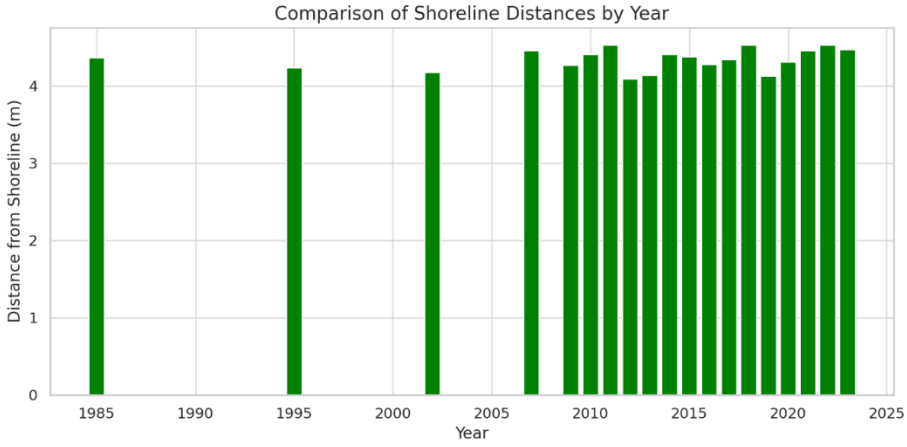

Fig. 11. Comparison of shoreline distances (1985-2023)

Notable peaks are observed in certain years (such as 2007), where the shoreline distance increases compared to previous years (Fig.11).

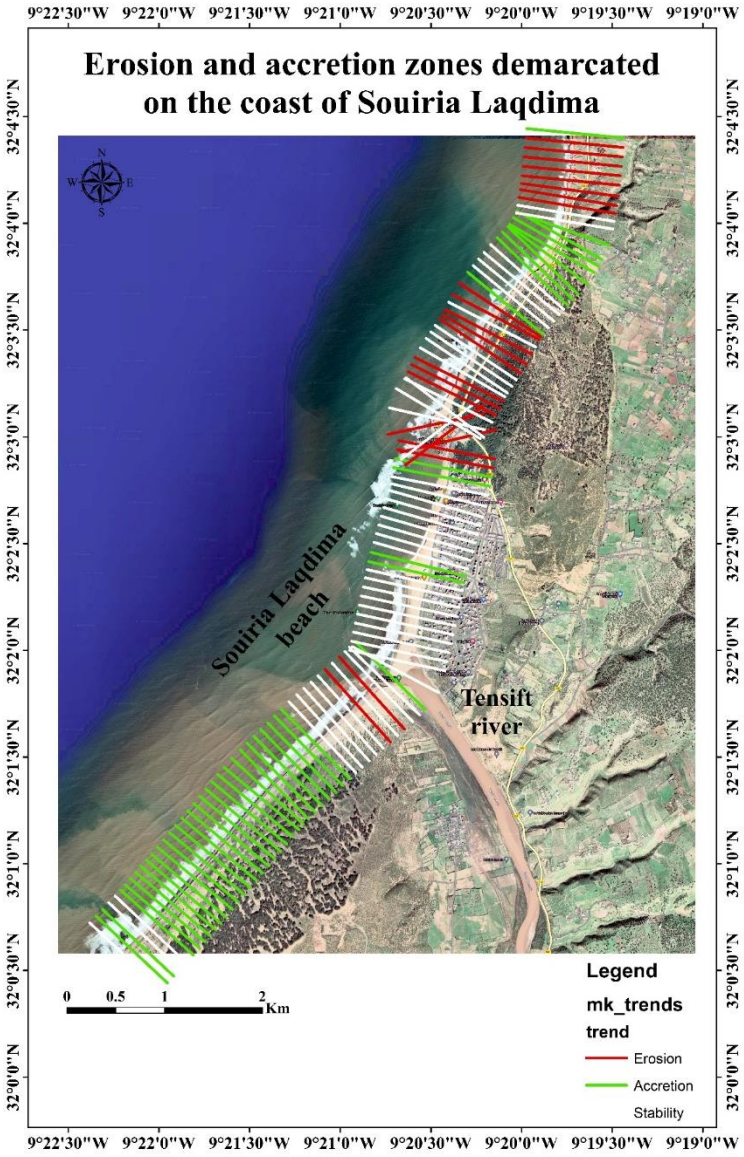

Fig. 12. Erosion/accretion map of Souiria Laqdima beach

The coastal assessment map of Souiria Laqdima (Fig. 11) illustrates a dynamic landscape of erosion and accretion along the shoreline, represented by different colored lines: red lines indicate erosion, symbolizing land loss due to wave action; green lines represent accretion, showing areas where new material is deposited, leading to shoreline advancement; and white lines mark stable zones with little to no observed change. This dynamic is driven by various factors, including wave energy, sediment supply, tides, and human impacts, such as infrastructure development. For example, Sector A may experience accretion due to sediment retention by natural features like the town's port and an artificial groyne, creating favorable conditions for deposition. In contrast, Sector B may suffer from erosion caused by littoral drift, disrupted by artificial structures like the groyne. In Sector C, near the Oued Tensift estuary, a mix of erosion and accretion reflects the complexity of fluvial-marine interactions, with accretion influenced by river sediment deposits and erosion driven by tides and river currents.

5 DISCUSSION

The morphological evolution of the Oued Tensift estuary and Souiria Laqdima beach, as documented between 1985 and 2023, reveals the intricate dynamics of coastal processes that are influenced by both natural factors and anthropogenic activities. Our findings illustrate that this region, like many coastal areas globally, is experiencing pronounced changes in response to both climate-driven events and human interventions. The widening of the Oued Tensift estuary, along with significant periods of both erosion and accretion along the Souiria Laqdima beach, aligns with global trends in coastal transformation, where natural processes such as tidal action, wave energy, sediment transport, and storm events interact with human infrastructure to shape coastal morphology.

The significant sediment accumulation and changes in the river mouth configuration, particularly following the 2014 floods, are indicative of the role that extreme weather events play in coastal transformation. This observation aligns with findings by [4], who highlighted the dramatic impact of the 2014 floods on sediment dynamics along Morocco's Atlantic coast. Similar patterns have been observed globally; for instance, [5] in Southeast Asia identified floods as major accelerators of coastal change, disrupting established sediment transport systems and exacerbating both accretion and erosion. Such events not only deposit massive amounts of sediment but also reshape coastal and riverine landscapes by altering hydrological flows and introducing new sediment dynamics. The consequences of these disruptions extend beyond short-term morphological changes, affecting long-term coastal stability and management strategies.

Furthermore, the role of anthropogenic activities in shaping the Oued Tensift estuary and Souiria Laqdima beach cannot be overlooked. The construction of hydroengineering structures such as jetties, groynes, and sea defenses has undoubtedly altered the natural sediment transport processes. This is consistent with findings by [9] in the Mediterranean, where human interventions have had profound effects on coastal systems, often accelerating erosion in areas adjacent to the protected zones. In our study, the construction of coastal infrastructure has contributed to both stabilization in some areas and erosion in others, a duality also noted by [6] in their assessment of coastal dynamics along Morocco's Atlantic coast. These structures, while intended to prevent erosion and protect urban infrastructure, frequently disrupt natural sediment flows, leading to increased sediment deposition in some areas and sediment starvation in others.

The shoreline changes observed in Souiria Laqdima reflect a complex interplay of accretion and erosion processes, influenced by both natural sediment transport and human activities. Over the nearly four-decade period covered in this study, our analysis shows that periods of shoreline retreat, such as those following the 2014 floods, are often followed by phases of accretion, driven by sediment redistribution from both fluvial and marine sources. This pattern mirrors global observations, where coastlines subject to significant weather events exhibit dynamic behavior, alternating between erosion and recovery phases. [1] emphasized that such variability is becoming more pronounced in the face of rising sea levels and increased storm intensity, factors that are closely linked to global climate change. As climate models predict more frequent and intense storms, the potential for extreme weather events to disrupt sediment balances and drive coastal retreat becomes increasingly concerning.

In this context, the role of coastal management strategies becomes even more critical. Our findings suggest that while coastal infrastructure can mitigate the immediate risks of erosion in certain areas, it often exacerbates problems elsewhere by disrupting natural sediment transport processes. This echoes the conclusions drawn by [8], who argued for integrated coastal zone management (ICZM) approaches that combine localized geomorphological data with broader climate models. The need for such integrated strategies is particularly urgent in regions like Souiria Laqdima, where human development pressures are increasing alongside the risks posed by climate change. Without proactive management, the balance between protecting human infrastructure and preserving natural coastal processes is likely to become untenable, leading to accelerated coastal degradation.

Wind and wave dynamics in the Souiria Laqdima region also play a crucial role in shaping the coastline. The predominance of northeasterly winds in the summer and northwesterly winds in the winter contributes to a seasonal pattern of sediment transport. Our analysis of wind data, supported by meteorological records, shows that these wind regimes influence longshore drift and sediment deposition, with northeast winds driving sediment southward along the coastline. This seasonal variability in sediment transport has significant implications for coastal management, as periods of increased sediment transport may temporarily mitigate erosion but can also lead to sediment deposition in areas where it may contribute to flooding or other hazards. [12] made similar observations in Thailand, where wind and wave regimes significantly influenced coastal sediment dynamics, often in ways that were difficult to predict or control through conventional coastal management practices.

The observed influence of northwesterly swell, which dominates throughout the winter months, further complicates the sediment dynamics in this region. The NNW swell, combined with the existing wind regimes, creates a complex system of sediment redistribution that can exacerbate erosion in certain areas while promoting accretion in others. Our findings indicate that this swell contributes significantly to the erosion of the northern sections of the beach, where the interaction between wave energy and coastal structures results in increased wave reflection and sediment removal. This dynamic is consistent with global observations of coastal erosion, where swell-driven processes are often the primary contributors to sediment loss, particularly in regions with high wave energy, as noted by [1].

Moreover, the role of longshore drift in shaping the coastal morphology of Souiria Laqdima cannot be understated. Our study revealed that longshore drift, driven by both wind and wave action, is responsible for much of the sediment transport observed in this region. This process, which moves sediment along the coast in a predominantly southward direction, has contributed to the gradual widening of the beach in some areas, while leading to erosion in others. Similar findings have been documented in studies of Mediterranean coastlines [9], where longshore drift plays a central role in the redistribution of sediments and the formation of coastal features such as sandbars and spits.

The implications of these findings for coastal management are clear: successful management strategies must account for the complex and interconnected processes that drive coastal change. Simply implementing protective infrastructure without considering its broader impacts on sediment transport and coastal dynamics is likely to result in unintended consequences, such as the exacerbation of erosion in unprotected areas. This underscores the need for ICZM approaches that integrate geomorphological data with predictive climate models, allowing for adaptive management strategies that can respond to both short-term weather events and long-term climate trends. [8] argue that such strategies are essential for preserving the resilience of coastal systems in the face of increasing pressures from human development and climate change.

In conclusion, the diachronic analysis of the Oued Tensift estuary and Souiria Laqdima beach between 1985 and 2023 provides valuable insights into the dynamic nature of coastal systems in Morocco. The interaction between natural processes such as wave action, wind, and sediment

transport, and anthropogenic factors such as coastal infrastructure and urbanization, has created a highly variable coastline that requires proactive and integrated management. Our findings not only contribute to the growing body of literature on coastal dynamics but also highlight the urgent need for sustainable coastal management strategies that address both local geomorphological factors and global climate change. By incorporating high-resolution satellite imagery and advanced shoreline mapping techniques, this study offers a comprehensive framework for understanding and managing coastal change in vulnerable regions like Souiria Laqdima.

6 CONCLUSION

The diachronic study of the Oued Tensift estuary and Souiria Laqdima beach (1985-2023) highlights the complex interaction between natural processes and human interventions in shaping this coastline. The analyses reveal a coastal dynamic influenced by longshore drift, wind and swell regimes, as well as human infrastructure such as dykes and ports. These factors, combined with extreme events like the 2014 floods, have accelerated both accretion and erosion in different parts of the beach. The maps and diagrams included in the study clearly show that while some areas have benefited from significant sediment deposition, others have suffered rapid erosion, underscoring the impact of increasing urbanization and climate change.

The observed coastal morphological changes in this region are comparable to those documented in other parts of the world, where climate change and human intervention significantly alter natural processes. The results of this study underscore the urgency of implementing integrated coastal management strategies that combine local geomorphological observations with global climate forecasts. Only a proactive management approach can ensure the resilience of vulnerable coastal areas like Souiria Laqdima in the face of rising sea levels and increasing urban pressure.

Thus, this research provides a solid foundation for the implementation of sustainable management policies that account for both short- and long-term risks, particularly in the context of climate change, to protect this fragile coastline and the populations dependent on it.

ACKNOWLEDGMENTS

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