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**Morphological Evolution of the Water Body and Hydrodynamic and Sedimentological
Study of the Moulay Bousselham Lagoon, Morocco**

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Abstract

The Moulay Bousselham lagoon, located on Morocco's North Atlantic coast, stands out due to the interplay between freshwater sources (the Nador Canal and Oued Drader) and the marine waters of the Atlantic Ocean. This interaction governs the transfer of dissolved elements, particles, and sediments throughout the lagoon's sectors. To investigate the lagoon's hydro-sedimentary behavior, a granulometric analysis of surface sediments was performed using a laser method that relies on light diffraction and scattering.

The analysis of the obtained results, along with the sample descriptions, reveals that mesokurtic granulometric curves are the most prevalent. The application of the Passega test indicates that the dominant mode of sediment transport is uniform, pelagic, and graded suspension, reflecting a calm, undisturbed environment. Near the channel and the mouths of Oued Drader and the Nador Canal, there is notable variation in sediment fractions, with both fine ($d < 63 \mu\text{m}$) and coarse ($63 \mu\text{m} < d$) particles. The dominant facies are parabolic, indicating deposition under relatively swift currents. The lagoon basin is mainly composed of clayey silts. The sedimentological analysis further reveals that coastal erosion-derived sediments are influenced by dynamic processes primarily driven by currents, which are closely linked to winds and tides. These currents are stronger in shallow areas and weaker in deeper parts of the lagoon.

Key words: Satellite images. Granulometric analysis, Sedimentary facies, Passega test

1. Introduction :

Wetland ecosystems are crucial to humanity, offering essential services such as water purification, biodiversity preservation, and coastal protection (Karim et al., 2019). Currently, over 50% of the world's population lives in coastal areas, where land meets the sea. This has led to intense urbanization in recent decades, concentrating socio-economic activities such as tourism, agriculture, and marine exploitation along coastlines. These developments have placed excessive pressure on natural resources, leading to overexploitation and an acceleration of coastal erosion (Cai et al., 2009).

Lagoons and estuaries are prominent examples of littoral ecosystems. These environments are often considered delicate due to their relatively young geological age, dynamic nature, and high productivity. As a result, they face significant challenges in balancing resource use and conservation. Conflicts are likely to arise between development demands and the need to preserve natural resources, emphasizing the importance of a solid understanding of lagoon structures and functions to implement effective management and conservation strategies (Bazaïri et al., 2003).

Approximately 34% of the world's coastlines are sandy, and around 80% of these are retreating at varying rates, from a few millimeters to as much as 10 meters per year (Cai et al., 2009; Rise & Klose, 2004). Both natural forces and human activities have heightened the vulnerability of these coastal areas. Human interventions disrupt the natural sediment movement, diminishing the sedimentary deposits that sustain beaches and lagoons. As a result, these ecosystems can no longer naturally replenish their sediment stocks (Bruun, 2019; Hammar-Klose, 2000). Lagoons

require substantial sediment input to form and maintain their structure. They are commonly found in deltaic environments such as the Medjerda, Ganges, and Mississippi river deltas. The development of coastal lagoons is closely linked to past glacio-eustatic sea-level changes, which coincide with ice sheet formation and retreat. Coastal lagoons are some of the most productive ecosystems worldwide (Dezileau et al., 2016; Kelley et al., 1998). Based on geomorphology, coastal lagoons can be classified into leaky, restricted, or closed systems, depending on their hydrodynamic connection with the coastal ocean (Kjerfve & Magill, 1989).

In leaky coastal lagoons, tidal currents predominantly influence flow dynamics, often masking residual currents caused by freshwater inflows or wind-induced density gradients. Conversely, restricted lagoons experience pronounced stratification, which results from river inputs and thermal variations. Mixing in these systems is primarily driven by wind and tidal action (Davidson, 2014). These hydrodynamic processes enable lagoons to act as natural sinks for organic and inorganic materials, accumulating sediments over time.

At a geological timescale, lagoons are transient landscape features. Their existence is influenced by factors such as relative sea-level rise due to glacial cycles, local tectonic movements, and sedimentary processes. Studies suggest that approximately 64-71% of the world's wetlands had already disappeared by the beginning of the 20th century (Davidson, 2014). Wetland degradation is primarily driven by sedimentation and infilling, which compromise their capacity to store water and significantly deteriorate water quality (Zedler & Kercher, 2005; Bowen & Johnson, 2017). The rapid accumulation of silt, a phenomenon observed in many areas, threatens the ecological and economic services provided by wetlands (Dezileau et al., 2016).

The Moroccan coastline spans over 180 administrative communes, accounting for about one-seventh of the country's total land area. In many coastal regions, real estate development has already increased pressure on dune systems, accelerating coastal erosion and raising the risks of flooding and damage to property and infrastructure (Ennouali et al., 2023). While human activities remain a significant driver of change, climate change is anticipated to exacerbate existing issues and introduce new hazards. Although the ecological significance of coastal lagoons is well-recognized, there is a distinct gap in the literature concerning long-term hydro-sedimentary studies specifically targeting the Moulay Bousselham Lagoon. Previous research has largely focused on the impacts of urbanization, agriculture, and climate change on coastal systems but has not comprehensively examined their effects on the lagoon's sediment dynamics over extended periods.

This study addresses this gap by employing a novel approach that integrates satellite imagery analysis from 1987 to 2017 with detailed granulometric data to assess sediment transport and deposition across various depths and locations in the lagoon. The combination of large-scale monitoring with fine-scale sediment analysis provides a holistic understanding of the lagoon's morphological evolution, capturing both broader changes and localized sedimentary processes. The findings will help identify the primary factors influencing sediment distribution and accumulation, offering insights crucial for sustainable coastal management strategies. This

study thus fills a critical knowledge gap in understanding North African coastal lagoon dynamics and informs conservation efforts aimed at mitigating environmental degradation.

The Moulay Bousselham Lagoon is recognized under the Ramsar Convention on Wetlands of International Importance, which Morocco adopted in 1980 (BIDET J.C., 1977). The lagoon's significance lies in its unique interaction between continental freshwater inflows and marine waters, resulting in complex sedimentary dynamics. These dynamics govern the movement and deposition of dissolved elements, particles, and sediments within the lagoon. The Merja Zerga Lagoon is fed by two main water channels: the Nador Canal in the southern part, which receives water from various sanitation groups along the Sebou River's right bank, and the Oued Drader to the northeast, which drains a sub-catchment area of 318 km² (B, 1977; BIDET J.C., 1986; ORMVAG, 1994). Taky et al. (2009) described the interconnected nature of the drainage system, which comprises quaternary canals that collect excess water from agricultural fields before discharging it into the Merja Zerga Lagoon. This hydrological connectivity is essential for understanding the lagoon's sedimentary and ecological dynamics (Bazaïri et al., 2003).

The primary objective of this study is to investigate the hydro-sedimentary mechanisms governing the Moulay Bousselham Lagoon. By analyzing the evolution of its water body morphology through satellite imagery and granulometric studies of surface sediments collected at various depths and locations, the study aims to characterize the nature of these sediments and elucidate the factors influencing their transport and deposition. A statistical and granulometric analysis will provide insight into the natural particle flow dynamics within the lagoon system, thus enhancing our understanding of its sedimentary processes.

2. Study area

Historical Context

According to popular belief, the story of the Moulay Bousselham Lagoon is tied to its namesake, Moulay Bouselham, or "man with a selham" ("man with a coat"), who is said to have come from Egypt before settling in the Merja Zerga region. He died during the Battle of the Three Kings in 1578 at Oued al-Makhazin. The area has since been home to several other saints, with at least seven recognized today (MAP, 2012).

Geographic Location

The Moulay Bousselham Lagoon is situated along Morocco's northern Atlantic coast, within the coastal fringe of the Gharb alluvial plain, located between latitudes 34°47'N 6°13'W and 34°52'N 6°14'W **Fig. 1**. It occupies a tectonic depression oriented in a north-south direction and is surrounded by hills that rise to less than 200 meters, primarily in the southeast (Lalla Zohra Hills) and northeast (Jaaidi et al., 2015). The lagoon features a straight shoreline aligned NNE-SSW along its western edge, with a sandy beach bordered by sandstone cliffs formed through the erosion of consolidated coastal dunes (Ennouali et al., 2023).

The Gharb basin, which encompasses the Moulay Bousselham region, is positioned between two significant structural formations: the Meseta and the Rif. The depression holding the lagoon is tectonic in origin, located in the northern part of the Gharb Plain and extending into the

Western High-Rharb. This area is geologically linked to a productive zone and exhibits signs of tectonic weakness and subsidence, as highlighted by geophysical research (Combe, 1969).

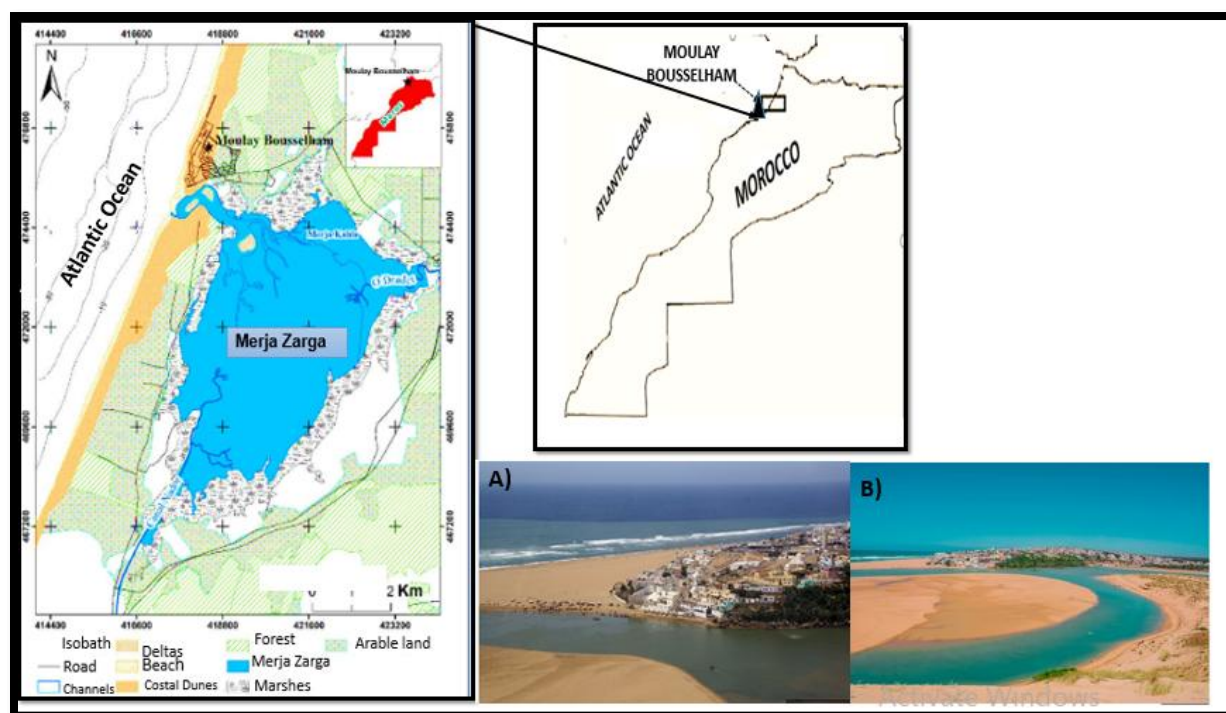


Fig. 1: Map showing the location of the study area,(A): the lagoon pass.(B) Main lagoon channel

Coastal Dynamics

The coastal dune series varies significantly from south to north, serving as a critical barrier between the lagoon and the ocean. This barrier is interrupted at Moulay Bousselham by a gully. The subsidence in the region contributes to unique coastal morphology, with dune alignments gradually sinking towards the east-west axis. Older geological formations behind the coastline are being replaced by newer deposits near the passes, resulting in a relay of progressively younger materials. This shift is particularly evident as ancient consolidated dunes gradually disappear within the barrier beach, contributing to a westward movement of the coastline. Additionally, subsidence results in an inland receding coastline, characterized by sandy beaches to the south and calcarenite bars visible at low tide to the north (Benmohammadi et al., 2007; Carruesco, 2018).

Lagoon Characteristics

Moulay Bousselham Lagoon is roughly elliptical in shape, covering approximately 35 km², with a length of 9 km from north to south and a maximum width of 5 km from east to west (BIDET J.C., 1977). The lagoon consists of three primary zones:

1. Fluvial Zone: Includes the mouths of the Drader Wadi to the east and the Nador Canal to the south (Arabe et al., 2015; Carruesco, 2018; El Jihad et al., 2014).
2. Merja Kahla: A shallow, triangular area in the north, covering about 3 km².

3. Merja Zerga: Located in the south, this zone spans 27 km² and reaches depths of up to 5.5 m.

The pass zone Fig. 1 is further divided into two sections: the inner pass, where the waters of Wadi Drader and the lagoon breach the consolidated dunes, and the outer pass, which connects the lagoon to the ocean. The coastal zone features a dynamic beach and shifting dunes, with the southern beach forming a coastal arrow.

To the north of the gully, a rocky bar runs along the coast, while the gully itself, averaging 357 m in width, experiences strong tidal currents. The gully's position and continuity are influenced by ocean swells, which can obstruct it, as well as tidal currents that help keep it open. Since 1928, the gully has gone through cycles of opening and closure due to human intervention and natural silting processes (SOGREAH, 2011).

Geological Setting

Moulay Bousselham Lagoon is situated within the Gharb basin, lying between the Meseta and Rif structural formations. The tectonic depression that accommodates the lagoon is located in the northern Gharb Plain, characterized by tectonic weakness and subsidence (Lecoz, 1964). Here, a thin Meso-Cenozoic layer rests upon a Paleozoic basement featuring folded and faulted zones (MICHARD, 1976). The region underwent tectonic deformation during the Pleistocene epoch, resulting in the formation of domes and basins (BIDET J.C., 1977). Tertiary sedimentation included marly-sandy deposits from the Miocene and detrital materials from the Pliocene. The lagoon's present depression formed during a significant tectonic phase in the Middle Villafranchian (LACOTE, 1984), surrounded by hills and dunes. The adjacent soils, primarily sandy and calcareous, reflect changes in sea level and climatic variations over the Quaternary period (Ennouali et al., 2023; LACOTE, 1984).

4. Presentation of the problem:

The Merja Zerga Lagoon is highly vulnerable to pollution and desertification, largely due to human activities and the prevailing semi-arid climate. It experiences significant runoff and sediment input from surrounding areas, resulting in water salinity levels that can vary from brackish to hypersaline, depending on rainfall and evaporation rates. Seasonal fluctuations in water levels are common, with partial drying occurring during the summer months. A critical threat to the lagoon's ecosystem is the silting of the channels that connect it to the sea, which could disrupt the entire aquatic environment. To address these challenges, a comprehensive study was conducted to analyze the lagoon's water levels over the past 40 years and to assess its sedimentary hydrodynamics.

5. Materials and Methods :

This study examines the morpho-dynamics of the water body boundaries within the Moulay Bousselham Lagoon, accompanied by a thorough sedimentological analysis. This section outlines the methods and strategies employed throughout the research, detailing a multifaceted approach designed to explore morpho-sedimentary variations. The methodology aims to

identify morpho-dynamic changes in the lagoon's water body boundaries across various geographic and temporal scales.

A. Morphological analyses of the Moulay Bouselham lagoon:

This research utilizes Landsat satellite images covering the years 1987, 1997, 2007, and 2017. The analysis involves georeferencing and digitizing the coastline corresponding to each specific date. The primary approach leverages satellite imagery, recognized as one of the most effective methods for illustrating the lagoon's water level evolution over time. By investigating the historical dynamics of the lagoon, the study seeks to discern trends on a broader historical scale.

The morpho-dynamic analysis heavily relied on a diverse set of Landsat images, necessitating careful consideration during data extraction. Images were selected based on favorable weather and marine conditions, specifically captured during low tide, at the same time of year, and under clear, cloud-free skies. It is crucial to note that satellite-captured images are not conventional photographs but digital records of luminance values stored as raster images.

To ensure the reliability of the data, each image underwent a verification process, which confirmed two essential criteria: the images were captured during low tide and within a specific period (winter) when the lagoon is typically submerged. The verification process also incorporated a tide status system, detailing the location and duration (date and time) of the images to enhance precision and accuracy in the morpho-dynamic analysis of the lagoon.

Table .1 was processed using an appropriate FormMain application (available on CNet) to determine the tidal status. We focused on identifying low-tide times and locating images corresponding to this configuration during the same period of the year as part of our analysis. All the photographs were taken under favorable atmospheric and marine conditions, enabling us to understand the historical evolution of the lagoon's water mass.

Table 1: Images taken to observe the evolution of the lagoon

The dates	SpacecraftID/Sensor	PATH- ROW	Pixel size (m)	Coordinate system/Datum UTM/WGS	Zone	The selected images
08/03/1987	TM (1984-1997)	202, 36	30	UTM/WGS 84	29	Low tide (dead waters)
11/03/2007	L4.5TM	202, 36	30	UTM/WGS 84	29	Low tide (dead waters)
03/03/1997	TM (1984-1997)	202, 36	30	UTM/WGS 84	29	Low tide (dead waters)
02/01/2017	L8 OLI/ TRS	202, 36	30	UTM/WGS 84	29	Low tide (dead waters)

The focus of our study is the mid-term radial development of the coastline over a 10-year period, specifically analyzing the years 1987, 1997, and 2017 (Table 1). This timeframe encompasses various morphogenetic events, including the impacts of storms and human activities. Notably, morphological changes in the pass zone are significantly influenced by

storm systems along the Moroccan coast, particularly during winter months when extreme storms and swells occur.

Being situated in an agricultural zone, the lagoon is heavily impacted by ongoing agricultural development around its various drainage systems. These activities have a direct effect on the hydro-sedimentary balance and water quality of the lagoon, primarily due to nutrient residues such as nitrogen and phosphorus from fertilizers, as well as toxic products from herbicides. To evaluate the lagoon's changes over time, a consensus was reached to conduct research focused on low tide levels. The boundary between submerged sections (indicated as dark blue in aerial imagery) and dry areas of the lagoon fluctuates according to tidal levels, climate conditions, and contributions from water mass particles generated within tributaries.

Previous studies conducted by American scholars (Crowell et al., 2005; Dolan, Tobern & Soderberg, 1991; Thieler et al., 2000) have indicated that discrepancies observed in both images may result in an error margin of ± 8 meters from reality. Consequently, we have adopted a conservative accuracy limit of 10 meters for our reference documentation. The LANDSAT sensors measure energy reflected from the Earth's surface when illuminated by sunlight and are well-regarded for their reliability. In this study, we utilized ArcGIS software to estimate various measurements across the entire area, enabling the digitization and georeferencing of thematic layers. Additionally, attribute tables for these layers were developed to enhance data structuring and analysis.

To ensure consistency and accuracy in our results, it was critical to apply uniform treatment to all images throughout the study. The georeferencing process for the utilized documents relied on two topographic maps: the 2006 topographic map of Moulay Bousselham at a scale of 1:25,000 and the 2005 topographic map of Merja Zerga, also at a scale of 1:25,000. Both maps employed the conical projection system conforming to Lambert Zone 1. Given the high density of tourist developments in the study area, landmarks played a crucial role in minimizing errors during the georeferencing process. Following the georeferencing step, Landsat images from 1987, 1997, and 2007 were overlaid, enabling the digitization of the corresponding coastlines. The same methodology was applied to the satellite images from 1997 and 2017.

The primary aim of this analysis is to assess the sources of uncertainty regarding the quality of the data used, variations in the position of the high water line influenced by tidal fluctuations, and the cartographic processes that may introduce errors related to both the georeferencing of the utilized documents and the digitization of the coastline. The total error (E_T) of this procedure is estimated by equation (1) which sums the error due to digitizing (E_d), the mean square error of georeferencing (E_g) (Table 2), and the error due to variations in the position of the coastline due to oscillations induced by the level of the high tide (E_v)

$$E_T = \sqrt{E_d^2 + E_g^2 + E_v^2} \quad (1)$$

$$E = \frac{\sqrt{E_{T1}^2 + E_{T2}^2 + E_{T3}^2 + \dots}}{\text{time}} \quad (2)$$

The total error (ET) is calculated and annualized (Eq.2) for each period.
Where T :is the time lapse (in years) between the two photographs from which the shorelines are extracted.

Table 2: Estimation of Document Georeferencing Errors.

The Date	Georeferencing Error (Eg)
1987	1m
1997	1m
2007	1.2m
2017	1.12m

To mitigate digitizing errors, our methodology incorporates multiple repetitions of coastline digitization for each date, as recommended by experts (Durand-Delga, 1980; Thieler et al., 2005). In our specific case, the digitization process was performed four times for all datasets. The measured distance between the furthest coastline lines was set at 1 meter for the 1987 dataset, 1 meter for the 1997 dataset, 1.5 meters for the 2007 dataset, and 0.7 meters for the 2017 dataset (refer to Table 2). The variability in digitization observed on screen is attributed to user differences.

Table 3: Estimated (Ed) digitalization errors of different aerial photographs used.

The Date	Estimation of the digitizing error Ed
1987	± 1m
1997	± 1.5 m
2007	± 1m
2017	± 0.7m

In addition to this, the morphological indices employed in this study aided in estimating errors caused by fluctuations in water levels during the times when images were captured (Faye, 2010; Prankevičius & Marcinkevičius, 2017). These authors used the following formula to calculate the margin of error:

$$\Delta d = \Delta h / \tan(\delta)$$

Where d is the margin of error, δ is the slope of the beach, and h is the difference between the maximum and minimum water levels. The tide levels for the dates of the aerial and satellite images were obtained from the SHOM website (shom.fr), ensuring accurate data for our analysis.

B. Sedimentological study

Intertidal areas were sampled using a plastic shovel, while deeper channels were sampled from a boat utilizing a Van Veen bucket. The sampling points were carefully selected in undisturbed locations to ensure minimal disruption from the sampler, with current speeds kept low (approximately <10 cm/s). Each sample's precise location was recorded, including detailed geographical coordinates (longitude and latitude) acquired using a portable GPS device. The recorded coordinates were documented in an Excel file, detailing the X and Y coordinates that

indicate the positions of the samples within the Moulay Bousselham Lagoon. Table 4 summarizes the coordinates of some samples taken and recorded by GPS.

Table 4: Sample Coordinates

Number of samples	Latitude	Longitude
3	34,836764	-6,286708
5	34,834542	-6,285597
6	34,831765	-6,279486
7	34,829542	-6,275042
8	34,830931	-6,271153

1. Laboratory Processing of Samples

Particle size analyses were conducted using laser microgranulometry, a method based on light diffraction and scattering. This technique allows for the analysis of particles ranging from 0.05 μm to 878.67 μm , providing a swift and highly reproducible approach. Each measurement yields the particle distribution (in percentage) across different size classes, categorizing sediment composition into clays (<2 μm), silts (2-63 μm), and sands (63 μm - 2 mm). The computational results are presented in various formats, including granulometric curves and tables, illustrating the sizes (in μm) of the samples relative to their diameters (ϕ).

Additionally, particle size data were analyzed concerning the nature and process of sediment transit and deposition for inclusion in the Passega diagram (Passega, 1957). This diagram delineates various transport modes based on the scattering of points: uniform suspension (SR branch), graded suspension without rolling (RQ), bottom suspension and rolling (PO), and rolling (ON) (Passega, 1957). The obtained data were processed using Gradistat software, which provided the median (most represented particle size class), distribution asymmetry, and particle classification. For each sample, a semi-logarithmic cumulative curve was plotted, representing the cumulative percentage of rejection as a function of the corresponding diameter of the sediment grains (Blott & Pye, 2001).

2. Granulometric Parameters Calculation

From each curve, using an Excel program, we calculated the different granulometric parameters (or indices) based on the method proposed by Passega (1957). These parameters are expressed in Phi (ϕ) and calculated using the following relation:

$$\phi(x) = [-\log(qx)] \times 3,3219$$

where: **qx**: grain size (mm), which corresponds to x % of the cumulative weight Fractiles: represent particle sizes corresponding to cumulative percentages(Wiem, 2017):

1. Quartiles (q25 and q75) represent 25% and 75% respectively. ;
2. Deciles (q10 and q90) represent 10% and 90% respectively.
3. Percentiles (q1 and q99) represent 1 and 99% respectively.

4. Pentiles (q5 and q95) represent 5 and 95% respectively.
 5. Standard deviations (q16 and q84) represent 16% and 84% respectively.
 6. The d60 represents 60%. The four particle size indices determined are: mean, standard deviation, Skewness, and Kurtosis.
- The four particle size indices determined were mean, standard deviation, skewness, and kurtosis.

Average Grain Size

The average grain size (Folk RL, 1957) is defined as:

$$M_z \text{ (in Phi)} = \frac{Q_{16} + Q_{50} + Q_{84}}{3}$$

The average sediment size of the Moulay Bousselham Lagoon is influenced by the energy of the environment and the distance of transport. This allows for the identification of various facies:

Coarse sand and gravel: $M_z < 1\phi$ ($M_z > 500 \mu\text{m}$), Medium sands: $1\phi < M_z < 2\phi$ ($250 < M_z < 500 \mu\text{m}$), Fine sands: $2\phi < M_z < 3\phi$ ($125 < M_z < 250 \mu\text{m}$) and Silts and clays: $M_z > 4\phi$ ($M_z < 63 \mu\text{m}$).

Sorting (Standard deviation)

Sorting is a grain size index that defines the grading of sediments. It depends on the size range of the initial material, sedimentation rate, and the physical characteristics of the current. The standard deviation is determined using the relation:

$$\sigma \text{ (in Phi)} = \frac{(Q_{84} - Q_{16})}{4} + \frac{(Q_{95} - Q_5)}{6.6}$$

Based on its value, different types of sand can be distinguished: Top-ranked sands: $\sigma < 0,35 \phi$, Well-graded sands: $0,35 \phi < \sigma < 0,5 \phi$, Moderately graded sands: $0,5 \phi < \sigma < 1 \phi$, Misclassified sands: $1 \phi < \sigma < 2 \phi$ and Very poorly classified sands: $2 \phi < \sigma < 4 \phi$.

Skewness or asymmetry coefficient (Ski)

Skewness indicates the asymmetry of the particle size distribution curve relative to the Gaussian curve. The asymmetry index varies from +1 to -1, depending on the abundance of fine or coarse grains. Skewness is calculated using the expression:

$$Ski = \frac{(Q_{16} + Q_{84} - 2Q_{50})}{2(Q_{84} - Q_{16})} + \frac{(Q_5 + Q_{95} - 2Q_{50})}{2(Q_{95} - Q_5)}$$

This index helps identify the degree of deviation of the particle size curve from the Gaussian distribution. According to Folk (1966), the following classifications are made as shown in (Table 5).

Table 5: Distribution of Sedimentary Facies by Asymmetry Index (Folk 1966)

Skewness	Ranking
$1 > Sk > 0.3$	Very strong negative asymmetry
$0.3 > Sk > 0.1$	Very strong negative asymmetry
$0.1 > Sk > -0.1$	Near strong negative
$-0.1 > Sk > -0.3$ Sekwness	Strong positive asymmetry
$-0.3 > Sk > -1$	Very strong positive asymmetry

A very strong or strong negative skewness indicates that the sediment was deposited in a turbulent environment and is deficient in fine sediments. A nearly symmetrical frequency curve suggests abrupt deposition without significant reworking. Conversely, strong or very strong positive skewness indicates calm deposition conditions, favoring fine particles.

Inman's acuity index (or Kurtosis).

Kurtosis describes the shape of a probability distribution, similar to skewness. Inman's acuity index (or kurtosis) is defined by (Saidi et al., 2004):

$$K = \frac{(Q_{95} - Q_5)}{\sigma\Phi}$$

The kurtosis of a univariate normal distribution is three (Saidi et al., 2004). Distributions with kurtosis less than 3 are classified as platykurtic, indicating fewer extreme outliers than a normal distribution. Distributions with kurtosis greater than 3 are termed leptokurtic, characterized by more outliers than normal distributions. A mesokurtic distribution has a kurtosis coefficient of 3, similar to that of a normal distribution. The values of K are categorized as follows:

PLATYKURTIC: $0.67 < K < 0.90$, **MESOKURTIC:** $0.90 < K < 1.11$, and **LEPTOKURTIQUE** if $1.11 < K < 1.50$.

The particle size analysis allows us to identify key parameters (mean: Mz, sorting, skewness: SK and kurtosis: K) that characterize the sands forming the different morphological units of the Moulay Bousselham Lagoon and track their evolution.

Finally, we employed spline interpolation with interruptions in ArcGIS software to analyze the distribution of granulometric indices within the Moulay Bousselham Lagoon.

Interpolation serves as a method to predict attribute values at unsampled locations based on data collected from sampling stations throughout the region. This process utilizes localized elevation data surrounding the pixel being interpolated to determine its value.

1. Testing PASSEGA :

Passega (1957) proposed a method for interpreting granulometric data to differentiate deposits formed by various transport modes in both fluvial and marine environments, such as uniform

suspension, graded suspension, and rolling. By applying Passega's method to surface samples from the Moulay Bousselham Lagoon, we were able to identify the primary granulometric facies. This method involves using two characteristic percentiles (D99 and D50) from a sediment grain size curve, plotting them on a double logarithmic scale graph, and comparing their positions with a model (Image CM, where C represents the percentile and M denotes the median) established based on samples with known emplacement conditions. The diagram is utilized to determine sediment transport modes and consists of several sock-shaped segments representing different types of transport (Passega, 1957). The QP segment represents all sediment in graded suspension and rolling, while the ON segment represents sediment transported by rolling.

1. RESULTS AND DISCUSSION

1. RESULTS

A. Morphology of the Moulay Bousselham lagoon.

The analysis of Landsat satellite images from 1987, 1997, 2007, and 2017 covers a significant timeframe, allowing for a comprehensive study of the changes in the Moulay Bousselham Lagoon. The selection of images taken at low tide and during the same period each year ensures consistency in observation conditions. The use of Geographic Information Systems (GIS) proved to be an effective tool for characterizing land use and understanding the natural and anthropogenic influences driving the lagoon's evolution.

A detailed examination of the March 3, 1987 image serves as a ten-year reference for studying changes up to January 2, 2017. The 1987 image depicts a well-supplied lagoon, surrounded by sediment and featuring micro-delta-shaped mouths. The presence of river deltas, such as those from the Canal de Nador and Oued Drader, highlights their significant impact on the lagoon's configuration. Over time, noticeable fluctuations in the size of the lagoon, influenced by climatic conditions, can be observed. Despite being at low tide, the substantial water surface suggests ongoing water input from sources including Oued Drader, Canal Nador, runoff from the lagoon's edges, and groundwater. The presence of micro-deltas at the mouths indicates active sediment transport processes. Meteorological data from 1987 show exceptionally high rainfall, with the Moulay Bousselham region benefiting from its exposure to the Atlantic Ocean, receiving annual precipitation significantly above the national average, around 500 mm per year. These observations underscore the critical role of climatic factors, river inflows, and the complex interaction between the lagoon and its surrounding environment.

Morphological Changes Over Time

March 3, 1997

A detailed analysis of the 1997 image reveals significant changes in the lagoon's morphology compared to 1987. The water level appears noticeably reduced, indicating a variation in levels over the years. The Nador Canal delta is visible, surrounded by sediment, and the Oued Drader delta can also be discerned. Historical meteorological data from 1997 indicate a trend toward

higher temperatures, with daily temperatures ranging from 4.6°C to 18.2°C and an average between 8°C and 12.7°C. Precipitation levels during early to mid-March were relatively low, not exceeding 20 mm, with most days experiencing between 0.2 and 2.5 mm. The overall period was marked by a decrease in rainfall, confirming a relatively dry year. These data suggest that the reduction in the lagoon's water level was influenced by decreased precipitation and higher temperatures.

March 11, 2007

By 2007, significant morphological changes had occurred, particularly in comparison to 1987 and 1997. The lagoon's pass was less developed in terms of size, shape, and position. The lagoon appeared drier, marking a stark contrast to the more humid conditions observed in 1987 and 1997. Historical meteorological data confirm the absence of significant precipitation during March 2007, contributing to the dry state of the lagoon. The lagoon pass's increased proximity to the Atlantic Ocean may have implications for the dynamics of the lagoon's ecosystem, particularly regarding salinity levels and tidal influences. The deltas of the Canal de Nador and Oued Drader had nearly completely emerged, reflecting significant topographical changes. These shifts may be the result of a combination of factors, including sea level variations, river regime changes, and geological modifications.

January 2, 2017

By 2017, the morphology of the lagoon showed substantial changes compared to previous years, particularly 1997 and 2007. The lagoon's surface area had expanded, with a relatively larger water body indicating an increase in size over time. The channels within the lagoon had become more diverse, suggesting an increased utility for irrigation, especially at Merja Zerga. Micro-deltas, such as those of Oued Drader and Canal de Nador, were partially submerged, reflecting ongoing sediment dynamics. The lagoon pass remained in close proximity to the Atlantic Ocean, with distinctive features such as tidal deltas, channels, the littoral spit, and the dune system bordering the south side of the pass. Meteorological data indicated cold weather conditions, with temperatures ranging from -4.4°C to 5°C and very low precipitation levels, not exceeding 0.8 mm. These climatic conditions played a significant role in shaping the lagoon's configuration during this period.

Overall Analysis: 1987-2017

A comprehensive assessment of the Moulay Bousselham Lagoon spanning the years 1987, 1997, 2007, and 2017, based on the superimposition of its water contours, reveals intricate and evolving dynamics driven by a combination of environmental and human factors. The 2007 image showed a less developed lagoon pass compared to 2017, where the lagoon extended further and featured a network of diversified channels(Figure.3) .

One of the major challenges facing the lagoon is water stress, exacerbated by increasing temperatures, decreasing rainfall, and the growing demands of the local population. With only 2% of the lagoon's water supplied by continental sources (Table 6), competition for this essential resource is intensifying. Development and irrigation projects around the lagoon are

contributing to an imbalance between marine and freshwater inputs. The instability of the water level, heavily influenced by the lagoon pass, constitutes a central issue in this study. Human activities, including coastal development, lagoon pass management, and navigation channels, also play a crucial role in the lagoon's evolution. Historical records of pass openings by local residents highlight the ongoing interaction between the community and the ecosystem, emphasizing the importance of an inclusive approach to lagoon preservation. Historical meteorological data, which reveal modest precipitation and temperature variations, underscore the impact of climatic changes on the lagoon (Fig.2). The overexploitation of groundwater, driven by local agricultural needs, further exacerbates water scarcity. According to Bonet and Carlier (1974), approximately 11,106 m³/year of groundwater is extracted to meet these needs, a figure that is expected to increase with the implementation of surface water catchment projects in the Drader region.

The findings indicate that the Moulay Bouselham Lagoon is undergoing a dynamic and continuously evolving process influenced by a complex interplay of climatic, hydrological, and anthropogenic factors. To preserve this vital ecosystem, a balanced management strategy that accounts for climatic conditions, human activities, and water requirements is essential. An integrated approach, incorporating satellite data, climate information, and active community engagement, is critical for ensuring the long-term sustainability of the lagoon.

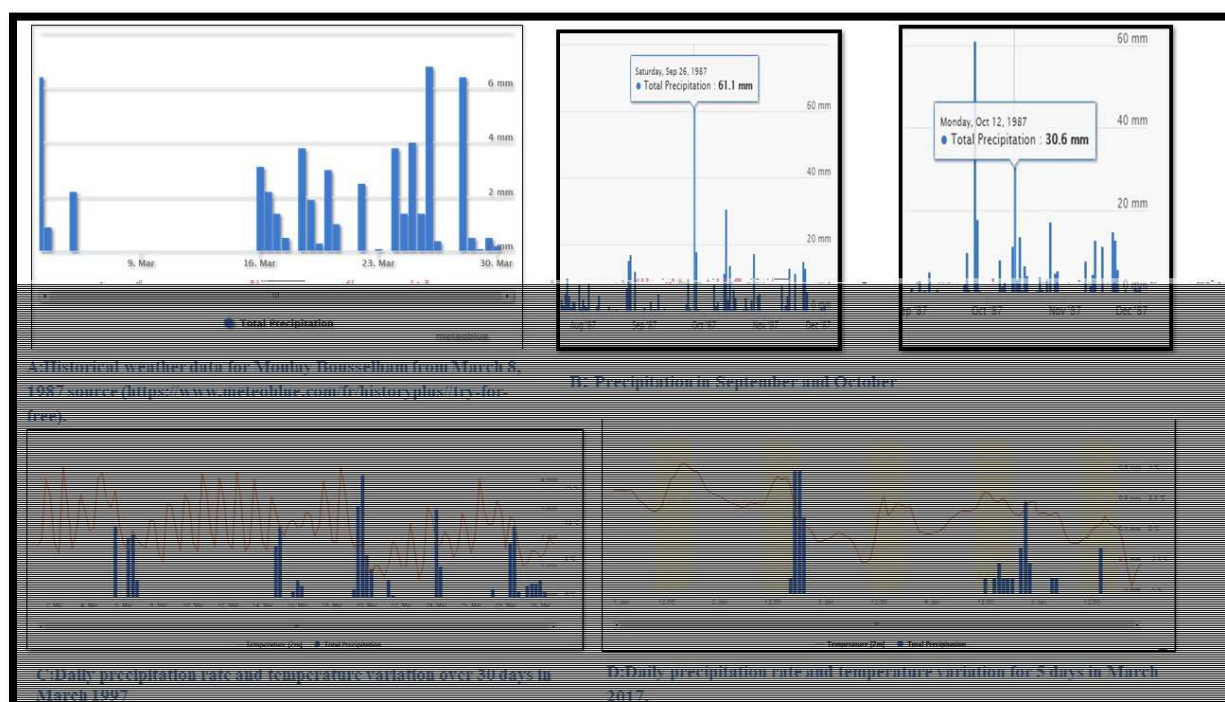


Fig.2: Historical weather data for Moulay Bouselham between 1989 and 2017, source (<https://www.meteoblue.com/fr/historyplus/#try-for-free>).

Table 6: Annual average water inputs to the La Merja-Zerga lagoon system (BENHOUSSA., 2000).

Origin of water	Source	Flow (m ³ /s)	Average volume an/(m ³)	Pourcentage
Continental	Oued Drader	1	31.5 *10 ⁶	0.26%
	Canal de Nador	5	150*10 ⁶	1.22%
	Tablecloths	1.5	34.5 *10 ⁶	0.29%
Oceanic	Moth	200- 600	12 000.11*10 ⁶	98.23%

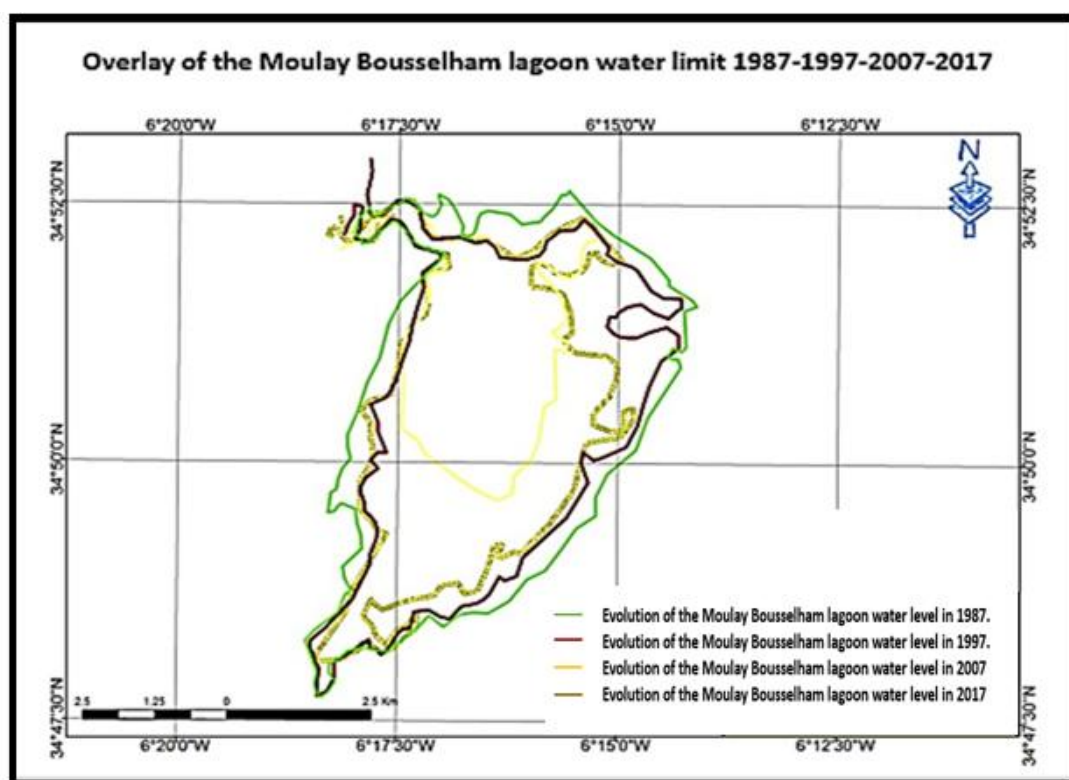


Fig. 3 : Moulay Bousselham lagoon water level superimposition 1987-1997-2007-2017

B. Sediment dynamics of the Moulay Bousselham lagoon basin

To better understand the sedimentary hydrodynamics of the Moulay Bousselham Lagoon, granulometric analysis was performed on 96 sediment samples. Table 7 presents the particle size characteristics, including key parameters such as mean grain size (Mz), sorting, skewness (SK), and kurtosis (K). This analysis characterizes the sediments forming different morphological units of the lagoon and monitors their distribution. The results, generated using

the Gradistat software (Blott & Pye, 2001), include granulometric curves and parameters that enable a comprehensive characterization of the sediment properties.

The particle size distribution for each sample is represented graphically on a semi-logarithmic diagram, where the ordinate indicates the cumulative percentage of rejection, and the abscissa corresponds to the grain diameter. This approach allows for a detailed analysis of the sediment distribution within the lagoon, with specific indices used to facilitate comparisons between samples (Fig.4).

1. Distribution of sedimentary facies

The semi-logarithmic cumulative curves of the sediment samples reveal three distinct facies:

1. **Parabolic Facies:** Characterized by a rapid, turbid current with well-sorted materials, transported by graded suspension with a vertical density gradient within the flow. This facies indicates high-energy transport conditions.
2. **Logarithmic Facies:** Formed by deposition due to excess loading, where the competence of the transport agent is reduced. This facies is associated with uniform suspension, typically resulting from low-density and low-velocity turbidity currents.
3. **Hyperbolic Facies:** Reflects deposition by settling, where transport occurs through pelagic and hemipelagic suspension. The presence of fine silts and clays (<63 µm) is particularly pronounced in this facies, indicating calm and protected environments.

Table 7: Classification of samples by sedimentary facies

samples	Parabolic facies	Logarithmic facies	Hyperbolic facies
	3,11,14,18,21,121,22,24,37,49,43	29, 30, 32,34,54,62	35,44,46,77,79,85,86,90,99,101
	52,55,56,58,61,67,69,71,74,75,76	66,72 N, R, X, Z,80	107,110,111,113 , A9,A15.
	78, I, J, V, P,93,120,105,131,114 ,118, 120, A30, A32, A33,A34,A1,A2,A7,A18,A13, A14, C,E, A26	92,106, 121, 29 30,32, ,34,54,62	
		108,121, A37, A39,A12,A16, A17,A21, A29, A30,F,G,H	

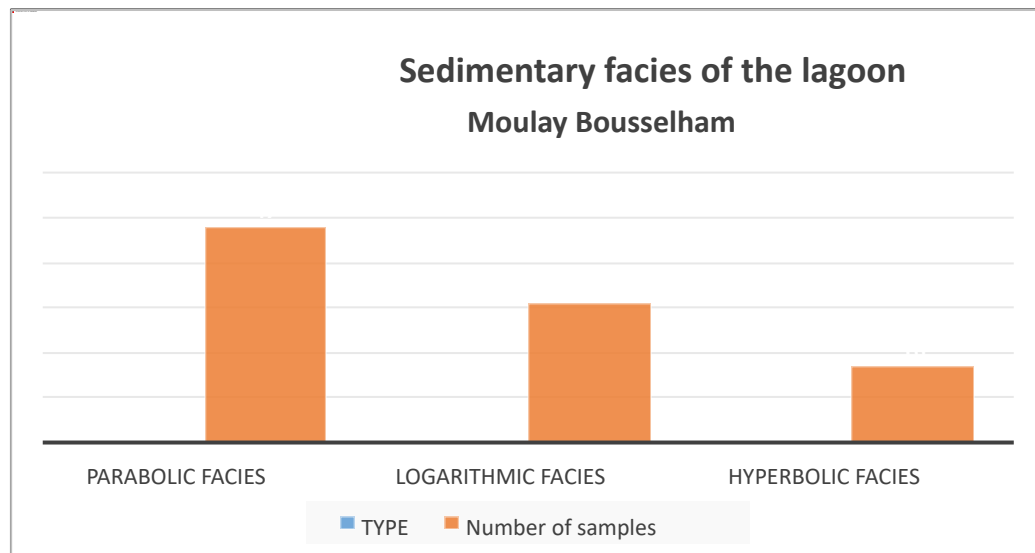


Fig.4: Sediment facies of Moulay Bousselham Lagoon.

II. Granulometric Analysis

1. *Parabolic Facies*

The parabolic facies is the most common, with 51 samples exhibiting characteristics of this type. These sediments, typically well-sorted sands, were formed in high-energy environments, suggesting that deposition occurred under conditions of excess loading. The granulometric curve for Sample No. 3 (Fig.5,6), for example, is distinctive, displaying an S-shaped pattern with a sharp, steep slope. This indicates deposition in a moderately fast stream, where current velocity and sediment transport conditions resulted in the parabolic curve's characteristic concave shape and downward hook towards the coarse fractions. Parabolic facies are prevalent across the lagoon basin and surrounding areas, such as Oued Drader. The dominance of sand suggests turbulent conditions with significant transport energy, primarily driven by rolling and brief saltation.

2. *Logarithmic Facies*

Logarithmic facies, observed in 31 samples, are characterized by cumulative curves resembling straight lines or flattened S-shapes. These sediments, found mainly at the ends of channels (e.g., samples No. 92, 106, 111), and in the intertidal zones, consist of heterogeneous materials, including sands, silty sands, and sandy silts.

The granulometric curve for Sample No. 34 exemplifies this facies, reflecting conditions where transport occurs by uniform suspension due to a reduction in flow velocity (Fig.7,8).

The channel sector exhibits complex deposit textures, influenced by variations in bottom slope and current speed.

3. *Hyperbolic Facies*

Hyperbolic facies, present in 16 samples, are located in calmer zones such as Merja-Kahla and the ends of main channels. Sample No. 157 is representative, with sediments composed predominantly of clayey silts, indicating deposition by settling in a low-energy environment.

These fine-grained sediments reflect transport by uniform suspension, typical of calm, protected areas where particles settle slowly (Fig.9,10).

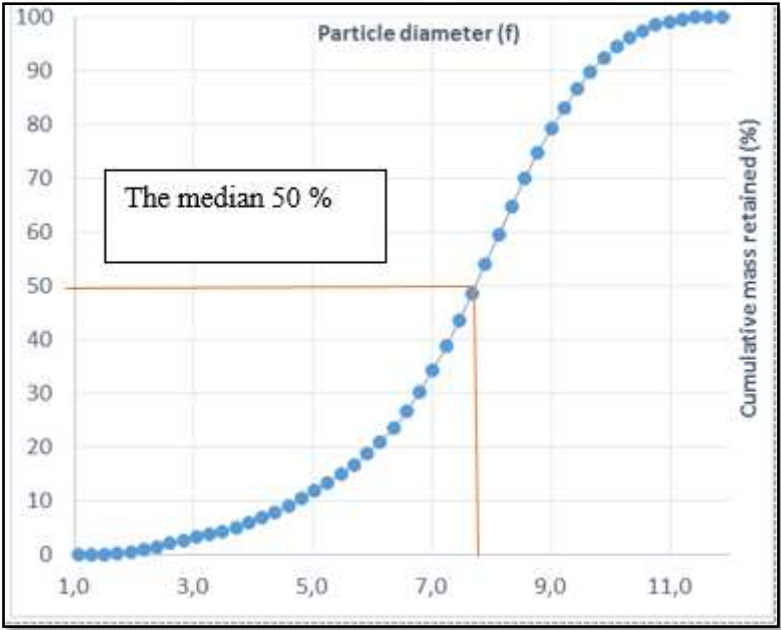


Fig.5: Graph of the cumulative curve for sample N°3



Fig.6: Samples in the channel area

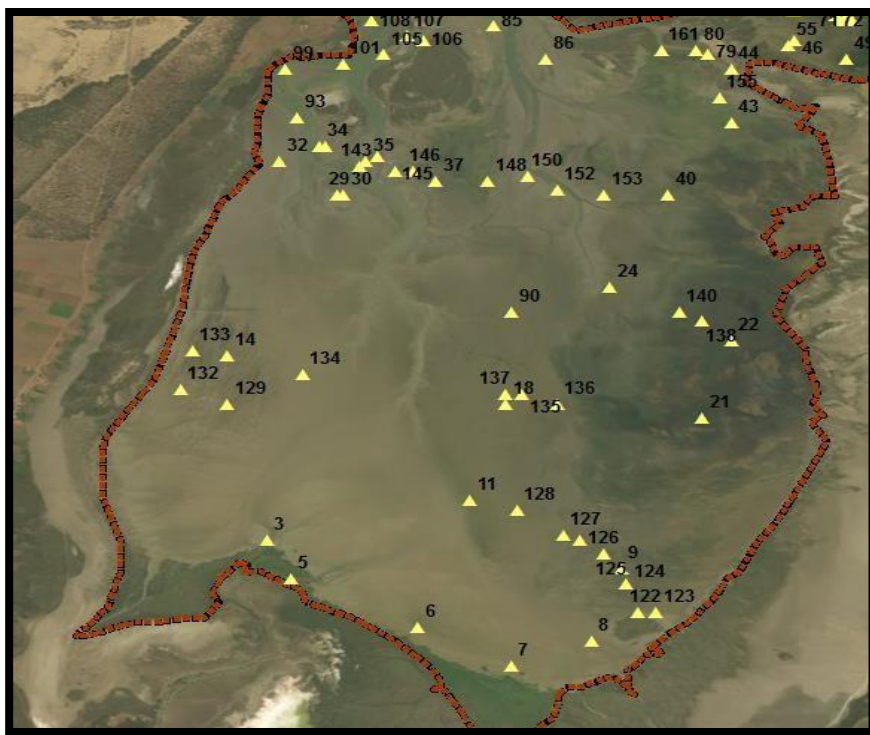


Fig. 7: Sample distribution in the Intertidal Zone

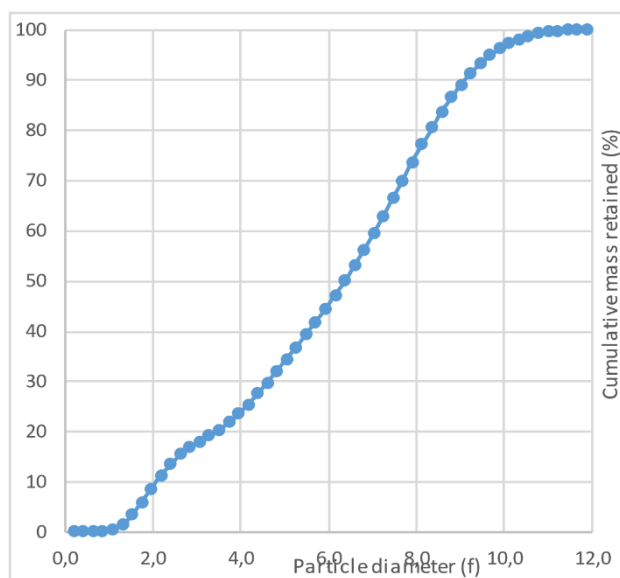


Fig.8: Graphic presentation of sample N°34



Fig. 9: Sample distribution at Merja Kahla

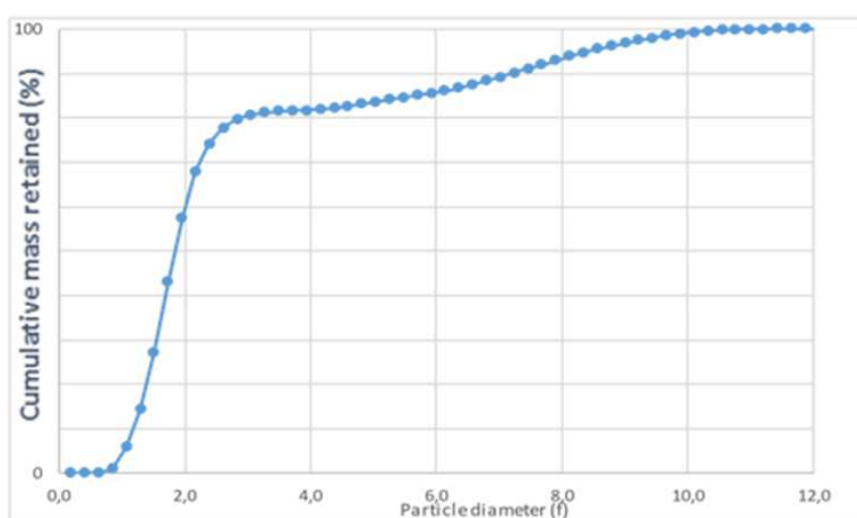


Fig.10: Graphical presentation of the cumulative curve for sample N°157.

III. Granulometric Indices

The granulometric analysis results, calculated using Gradistat, are summarized in Table 8, detailing particle size indices such as mean grain size, sorting, skewness, and kurtosis.

1. Sorting Index (S_o)

Sorting in the lagoon ranges from 4ϕ to 9.96ϕ , indicating that sediments are generally coarse and poorly sorted. High-energy areas, such as the pass, Oued Drader mouth, and Nador Canal, exhibit poorly sorted sediments due to the mixing of fine and coarse grains by strong currents. Conversely, sheltered areas near the Nador Canal show better sorting, where weaker currents allow for selective settling of larger grains.

2. Skewness or Asymmetry Index (Sk)

Skewness values range from 0.1 to 0.3ϕ , indicating positive asymmetry, with finer grains prevalent in low-energy environments. In contrast, coarser grains dominate areas like Canal

the Nador and Oued Drader, where higher skewness values suggest that finer particles are better sorted due to sustained weak currents.

3. Kurtosis (K)

Kurtosis measures the concentration of grain sizes around a central value. In the lagoon basin, kurtosis values indicate a mesokurtic distribution, suggesting moderately graded sediments and a stable deposition environment. Areas near the Nador Canal show leptokurtic distributions, reflecting well-classified sediments resulting from steady currents. In contrast, lagoon channels exhibit platykurtic distributions due to varying energy conditions, such as tidal and seasonal sediment changes.

Table 8: Samples with their indexes and descriptions (see Appendix for other samples).

Samples	MEAN	SORTING	SKEWNESS	KURTOSIS	MEAN:description
3	5,40061236	3,73511935	0,20622245	1,136115392	Fine Silt
5	6,44233126	4,22250625	0,24608774	1,164961609	Fine Silt
6	6,7421037	3,75810638	0,16833097	1,066605938	Fine Silt

The results obtained indicate that the SKEWNESS index of sample N°3 has a strong positive asymmetry towards the fines according to FOLK (1965), which means that the sediment was deposited in a calm environment by decantation. Ze takes sample n°3 as an example (Table 9):

Table 9: Sample No. 3 with indices and descriptions according to FOLK & WARD METHOD; METHOD OF MOMENTS

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic	Geometric	Logarithmic	Geometric	Logarithmic	Description
	mm	mm	f	mm	f	
MEAN :	16.96	5.671	7.462	5.399	7.533	Fine Silt
SORTING (s):	39.10	3.763	1.912	3.736	1.902	Poorly Sorted
SKEWNESS (Sk):	4.603	0.701	-0.701	0.205	-0.205	Coarse Skewed
KURTOSIS (K):	27.53	3.300	3.300	1.135	1.135	Leptokurtic

The sample is poorly classified because the So index equals 3.735, which enabled us to assess the degree of classification; we then deduce that the shape is Leptokurtic from the Kurtosis index. This sample has a low Kurtosis, in other words, it is leptokurtic. This distribution has a high peak as shown below (Fig .11):

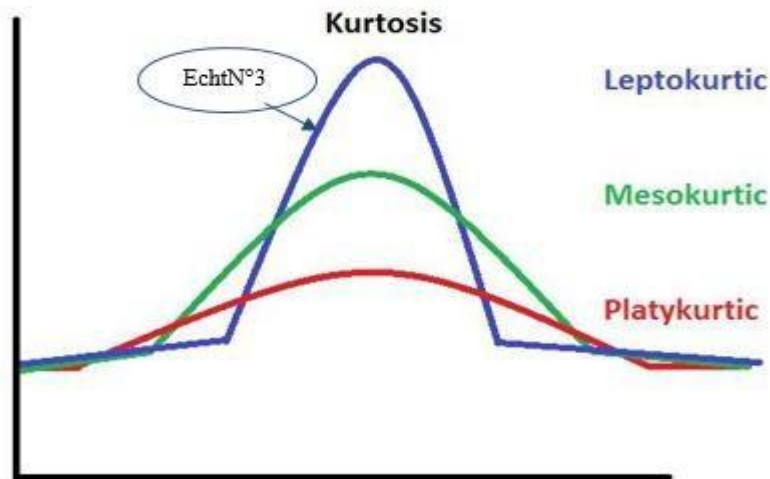


Fig.11: The nature of the curve for Sample N°3

IV. Spatial Interpolation of Granulometric Indices

Using ArcGIS 10, spatial interpolation maps of granulometric indices were created, providing insights into sediment distribution patterns within the lagoon.

Sorting Index Map

The map indicates that sorting values range from 4Ø to 9.96Ø. High-energy zones such as the pass, Oued Drader mouth, and Nador Canal are characterized by coarse, poorly sorted sediments, while calmer areas opposite the Canal de Nador show better sorting (Fig. 12).

Skewness Index Map

The skewness map (Fig. 13) shows a positive asymmetry across the lagoon, with low-current areas exhibiting stronger positive skewness, indicative of calm deposition environments. Negative skewness, associated with fine grain sorting, is observed at Oued Drader and Canal de Nador.

Kurtosis Index Map

Kurtosis varies spatially, with mesokurtic distributions found in stable environments, while leptokurtic distributions near the Nador Canal and pass suggest well-classified sediments under constant currents. Channels with platykurtic distributions indicate more heterogeneous sediment grading due to fluctuating energy levels (Fig. 14).

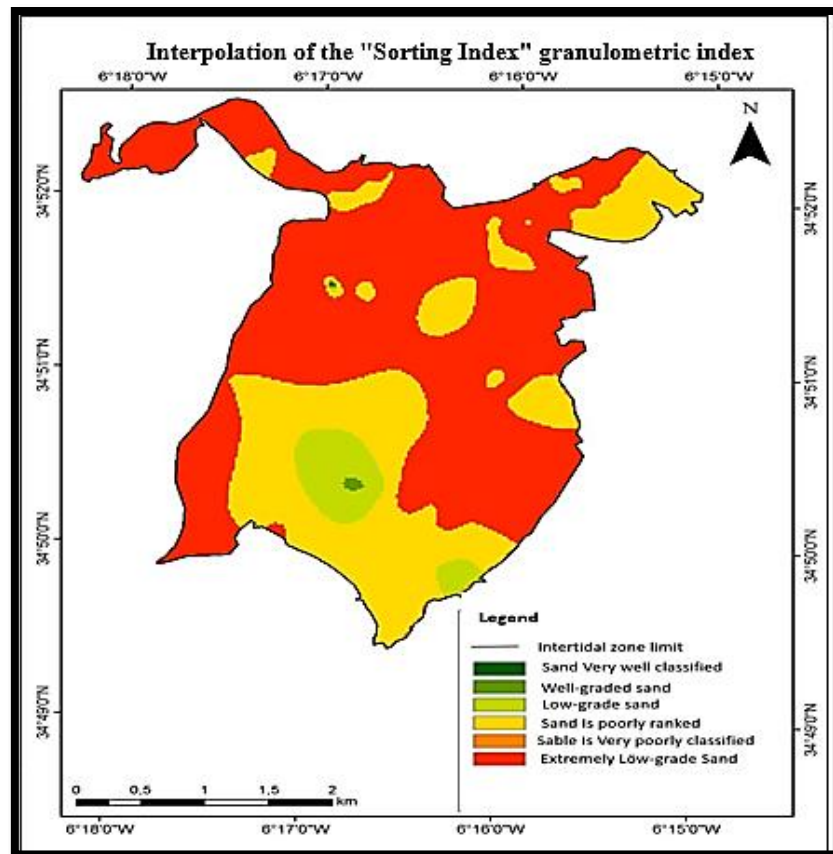


Figure 12: Interpolation of the "Sorting Index" granulometric index

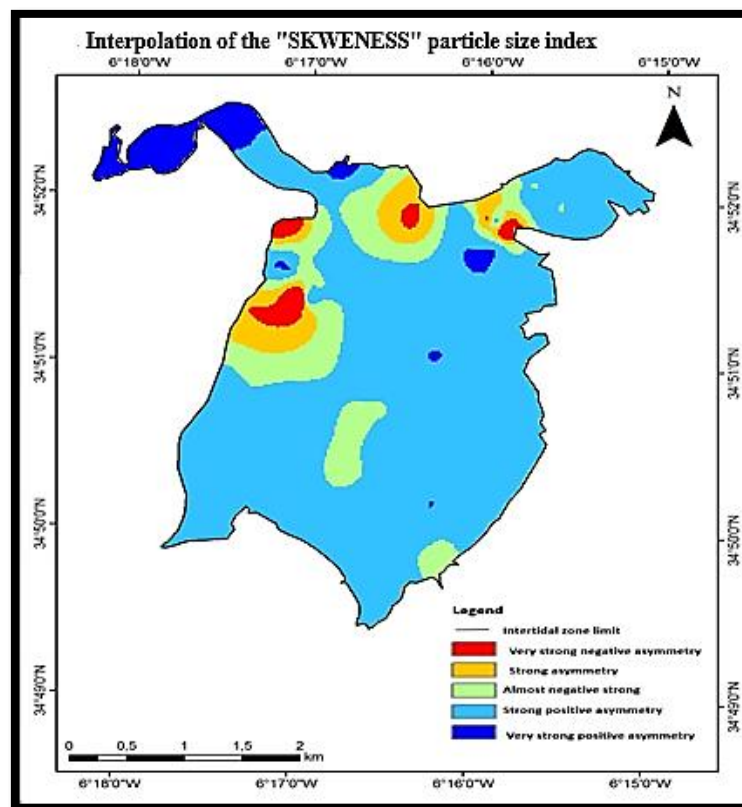


Fig. 13: Interpolation of the "SKWENESS" particle size index

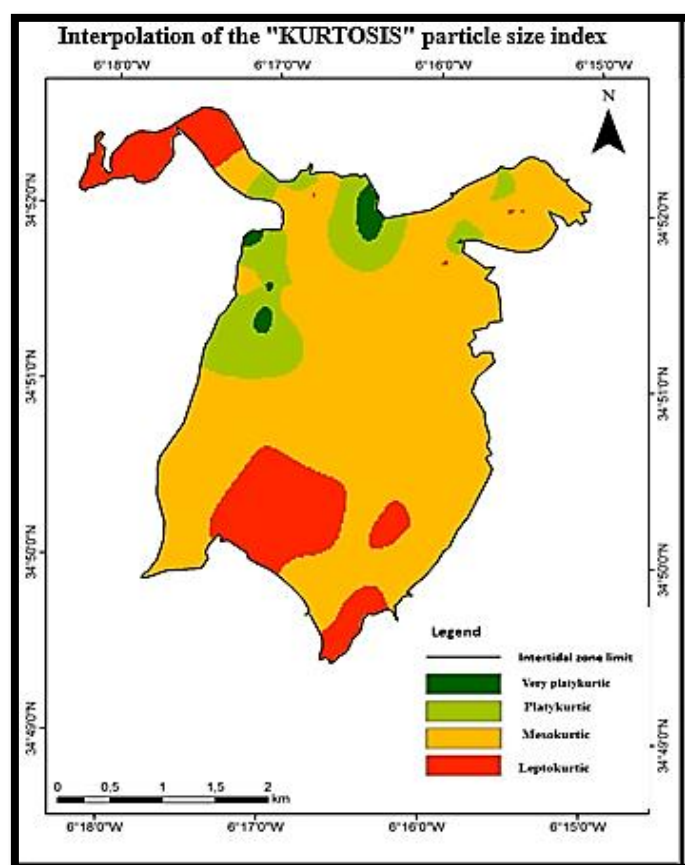


Fig.14: Interpolation of the "KURTOSIS" particle size index

1. DISCUSSION

The fluctuation of the sediment characteristics in the different zones of the Moulay Bousselham Lagoon must be determined by some of hydro-morphological parameters which include hydrodynamic energy, sediment supply and geomorphology. These factors produce complex sedimentary conditions, with differences in grading, skewness, and kurtosis that can be identified at each of them.

Sorting of sediments in the lagoon as expressed by sorting index (4ϕ to 9.96ϕ) depicts the energy levels of the various parts of the lagoon. Sources of high energy include the lagoon pass, the mouth of the Oued Drader, and the Nador Canal where tidal currents and river flows foster a sorting of sediment particle sizes. In these regions, the strong and complex hydrodynamic conditions do not allow sorting of particles according to their grain size, leading to the formation of the poorly-sorted sediments. Due to changes in water velocity and direction, it is expected to

have a combination of different types of sediments resulting to fine-grained and coarse-grained bed layers.

On the other hand, zones near the Nador Canal, which constitute sheltered areas have relatively low energy conditions which facilitate selective deposition of particles. In these zones, larger grains are deposited when smaller currents are encountered, whereas, the fine grains remain in suspension for longer durations and then settle slowly. This differential rilling leads to better sorting since energy levels are appropriate for systematic deposition. This again demonstrates a high energy-low energy model within the lagoon suggesting that, strong current forces play an essential role in the dispersion and distribution of sediments.

The availability of sediment sources plays a vital role in shaping the sedimentary characteristics of the lagoon. The influx of sediments from rivers and channels, such as Oued Drader and Canal de Nador, provides a continuous supply of mixed grain sizes. These inputs contribute to the complex sedimentary dynamics in regions with active sediment supply, where strong currents redistribute materials and create deposits with a wide range of grain sizes. The high rate of sediment supply in these areas results in poorly sorted deposits, as new sediments are constantly introduced and mixed.

In contrast, areas with limited sediment supply, often located farther from direct river inputs or in protected zones, exhibit more uniform sediment characteristics. Here, the deposition process is influenced by the gradual accumulation of finer sediments, leading to better sorting and more consistent particle size distributions. The spatial variability in sediment supply within the lagoon, therefore, creates distinct sedimentary environments, ranging from highly dynamic zones with continuous sediment influx to calmer areas with more stable deposition patterns.

The specific morphological aspects of the lagoon zone, including channels, deltas and intertidal areas also enhance the observed differences in the sediments characteristics. This active waterway has some extremely dynamic sedimentary conditions, including tidal effects and changes with seasons, in the channels. The energy regime in different channel segments may be quite different, with certain sections characterized by strongly expressed energy flow transporting coarser materials while other sections lack the energy required to exert such influence on grain size. This variability influences disposition of the deposit textures a on, based on sand, silt and clay.

Sediment distribution is also influenced by the existence of water deltas: the Oued Drader River and Canal de Nador are two such examples. When particles come into the lagoon from the river, the velocity decreases and they deposit sediments that make deltas with diverse grain sizes. The rich geomorphological structure of the coastal lagoon also results in a heterogeneity of deposition settings in which specific sedentary processes govern distinct zones according to conditions.

Attenuated areas or those parts of the lagoon that are periodically flooded and exposed to external tidal factors are referred to as Intertidal zones. As a result, sediment distribution is cyclic in this environment, particularly for fine-grained particle that becomes re-suspended when there is high tide, before being deposited during low tide. In these areas, sediment is being reworked repeatedly; the sediment distribution follows this energetic balance between sediment input and tidal processes.

The skewness of sediment distributions, ranging from 0.1 to 0.3 Ø, indicates positive asymmetry across much of the lagoon, suggesting that finer grains are more prevalent in low-energy environments. In calm areas, the prolonged suspension of fine particles allows them to

settle more gradually, leading to deposits dominated by fine-grained materials. Positive skewness in these zones reflects a depositional environment where the energy is low enough to allow for the accumulation of finer sediments without significant reworking. Conversely, areas with more dynamic conditions, such as near the Canal de Nador and Oued Drader, exhibit skewness values that indicate coarser grains are more prominent. This pattern suggests that higher-energy conditions favor the rapid settling of coarse particles, while finer sediments are continuously transported away by weak but persistent currents. These variations in skewness across the lagoon highlight the differences in depositional energy and the processes influencing sediment sorting.

Kurtosis values, reflecting the concentration of grain sizes around a central value, vary across the lagoon depending on local energy conditions and depositional environments. Mesokurtic distributions, observed in the lagoon basin, suggest moderately sorted sediments resulting from stable deposition environments. These areas are characterized by balanced conditions that allow for the gradual accumulation of sediments with varying grain sizes, leading to a relatively even distribution.

Leptokurtic distributions, found near the Nador Canal and the lagoon pass, indicate that the sediments are well classified, with a narrow range of grain sizes concentrated around a central value. This pattern is associated with steady currents that consistently transport and deposit similar-sized particles, leading to a more uniform sediment composition. In contrast, platykurtic distributions are common in lagoon channels, where the fluctuating energy levels, influenced by tides and seasonal factors, create deposits with a wide range of grain sizes. The high variability in these areas leads to a flat, poorly classified distribution.

The interplay between hydrodynamic energy, sediment supply, and geomorphology shapes the sediment properties across the Moulay Bousselham Lagoon. High-energy zones exhibit poorly sorted sediments due to constant mixing and reworking, while sheltered areas with lower energy levels show better sorting and more uniform grain sizes. The analysis of skewness and kurtosis provides valuable insights into the depositional environment, with positive skewness and mesokurtic kurtosis indicating stable, low-energy settings, while negative skewness and platykurtic kurtosis suggest dynamic, high-energy conditions.

In summary, understanding the sediment dynamics of the Moulay Bousselham Lagoon requires an integrated approach that considers the diverse factors influencing sediment transport and deposition. Effective management and conservation strategies must account for these complex interactions to maintain the lagoon's ecological balance and ensure the sustainability of its sedimentary environments. By recognizing the role of hydrodynamics, sediment supply, and geomorphology, stakeholders can better address the challenges associated with sediment redistribution and habitat preservation in this dynamic coastal system.

Conclusion

The study of Moulay Bousselham Lagoon reveals key insights into its morpho-dynamic mechanisms and sediment properties. By comparing water level changes and lagoon boundaries over time, the study highlights significant shifts in the lagoon's water surface from 1987 to 2017, influenced mainly by climatic factors such as temperature and precipitation. During this period, the lagoon experienced a reduction in water surface from 1987 to 2007, followed by an increase from 2007 to 2017, partly due to climatic variations and sediment inputs from rivers like Oued Drader and Canal de Nador.

Granulometric analysis of sediment samples collected from the lagoon shows considerable variability in sediment composition. The sediments in high-energy areas like the pass and river mouths are coarse and poorly sorted due to strong currents, which mix fine and coarse grains and hinder effective sorting. In contrast, more sheltered areas, such as near the Nador Canal, exhibit better sorting due to lower hydrodynamic energy.

Statistical metrics such as skewness and kurtosis further describe sediment distribution. Positive skewness indicates a predominance of finer grains in calmer areas, while negative skewness in high-energy zones suggests that coarser grains dominate. Kurtosis reveals a mesokurtic distribution in the lagoon basin, indicating moderate sediment grading, whereas leptokurtic distributions near the Nador Canal and pass reflect more consistent sediment classification.

Overall, the study underscores the complex interplay between hydrodynamic processes and sedimentation in the lagoon. High-energy areas show poorly sorted sediments due to strong currents, while calmer regions have more orderly sediment deposits. Understanding these dynamics is crucial for managing the lagoon's health and mitigating risks such as silting and habitat degradation.

Declarations

1.Funding

This research received no specific funding.

2.Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

3.Code Availability

No custom computer code was developed for this study. The analyses were performed using standard scientific software. Any scripts or processing workflows used during the study are available from the corresponding author on reasonable request.

4.Author Contributions

ZE conceived and designed the study, developed the methodology, performed the data analysis, interpreted the results, prepared the original draft, and acted as the corresponding author. TE contributed to data collection, validation, and manuscript review. FS supervised the research, contributed to the interpretation of the results, and critically revised the manuscript. YF participated in data analysis, validation, and manuscript review. TKW contributed to data interpretation, validation, and critical revision of the manuscript. BZ contributed to the interpretation of the results and critically revised the manuscript. AB participated in validation and manuscript editing. AAM supervised the research, contributed to the interpretation of the results, and critically revised the manuscript. All authors read and approved the final manuscript.

790 **Conflict of Interest**

791 The authors declare that they have no competing interests.

792 **Ethics Approval**

793 Not applicable.

794 **Consent to Participate**

795 Not applicable.

796 **Consent for Publication**

797 All authors have read and approved the final manuscript and consent to its publication.

798 **Use of Artificial Intelligence Tools**

799 The authors declare that no generative artificial intelligence tools were used in the
800 preparation of this manuscript.

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