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Assessing the role of riverbank erosion in reservoir siltation using remote sensing: Case of the Ibn Battouta Dam

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ABSTRACT

In Morocco, research on dam siltation has largely concentrated on upstream watershed erosion, often disregarding reservoir bank erosion. This study aimed to bridge this gap by analyzing the morphological evolution of the banks of the Ibn Battouta Dam, located in the western Rif region, over a 40-year period. Remote sensing and GIS data were used to achieve this goal. Two sets of satellite images were analyzed: Landsat images (1984-2014) and high-resolution Sentinel-2A images (2015-2024). The Normalized Difference Water Index (NDWI) has been applied to extract water surfaces and analyze the shoreline changes. A reference digital elevation model (DEM) was constructed to represent the topography prior to dam construction, enabling a comparison between the theoretical and observed reservoir contours. Bathymetric data collected in 2013 and 2020 were incorporated to enhance the precision of our analysis. The results highlight significant modifications along the banks, primarily caused by erosion and sediment accumulation, with influencing factors including tributary inflows, soil composition, and prevailing winds. Morphological changes were quantified using the S-segment method based on the elevation difference (Δh) and slope angle (α) along the maximum gradient. The findings confirm progressive bank degradation, emphasizing the need to include bank erosion processes in dam siltation assessments.

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1. INTRODUCTION

Water is a vital resource that has been a central concern in Morocco's politics for several decades. Owing to its increasing scarcity and the pressures exerted by climatic hazards such as recurrent droughts and floods, sustainable management of this resource has become a national priority (Bennouna, 2020). This challenge is even more complex in countries where agriculture plays a key role (World Bank, 2024). Therefore, it is imperative to ensure a stable water supply to support agriculture as well as the industrial and tourism sectors.

To address this growing vulnerability and to better regulate water availability, Morocco adopted an ambitious dam construction policy as early as the late 1960s. The aim was to store water during periods of abundance to cope with future droughts. This strategy has enabled the country to have 152 large dams, offering a storage capacity of 19.9 billion m³, according to the General Directorate of Hydraulics (2023). However, despite this infrastructure, major challenges remain, notably the silting of reservoirs, which compromises their efficiency.

Water erosion is a pressing global environmental challenge that poses a significant threat to natural resources by degrading soil and inducing dam siltation (Ed-Dakiri et al., 2022). It involves the displacement of soil particles by runoff and is a major driver of reservoir sedimentation (El Mokaddem et al., 2019). This process is exacerbated by increasing rainfall erosivity patterns, especially in vulnerable regions, such as Europe and North Africa, highlighting the role of climate-related factors in accelerating soil degradation (Panagos et al., 2015). Morocco's climate is characterized by substantial spatiotemporal variability in both yearly and seasonal rainfall, partly because of its extratropical location, making it prone to various large-scale fluctuations. Moreover, the country's large topography, characterized by the Rif and

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Atlas Mountains, has a considerable impact on its climatic conditions (Borrelli et al., 2020; Gumus et al., 2023). These climatic characteristics intensify erosion and increase sedimentation in water reservoirs, thereby challenging water management efforts.

Silting of dams reduces their storage capacity by approximately 0.5%-1% per year, or approximately 75 million m³ annually (Choukri et al., 2019; Schleiss et al., 2016). This progressive loss hampers reservoir operations and threatens essential services, such as drinking water supply, irrigation, power generation, and flood control (Hilgert et al., 2024; Lawmchullova & Rao, 2024; Skariah & Suriyakala, 2021). In addition sediment trapping triggers adverse downstream effects, including intensified erosion, ecosystem disturbances, and altered flow regimes (Kondolf et al., 2014; Maavara et al., 2020). In semi-arid regions, siltation interferes with soil–water interactions and groundwater recharge, especially under declining rainfall conditions (Luo et al., 2023).

This issue is directly linked to the degradation of natural resources, particularly in developing countries. Therefore, the management of watersheds facing climatic hazards is a crucial issue, especially in arid and semi-arid regions, such as Morocco (Maurya et al., 2023; Messaoudi et al., 2025).

In northern Morocco, particularly in the Rif region, water erosion presents a critical risk for soil degradation and dam sedimentation (Ed-Dakiri et al., 2024). The average annual soil loss in this region ranges from 30 to 60 metric tons per hectare, resulting in an annual siltation of water reservoirs of 125 million m³ and a consequent 0.5% yearly reduction in their storage capacity.

The Ibn Battouta Dam, essential for the potable water supply of Tangier, exemplifies this issue. Its storage capacity has decreased from 43 million m³ in 1978 to only 30.1 million m³ by 2020 (Department of Water Research and Planning, 2024). This decline has been attributed to the high sedimentation rate caused by water erosion in the Tleta watershed. Sediment transport in riparian environments is a complex phenomenon influenced by various natural and anthropogenic factors. Flood events, particularly in the Tleta watershed, have accelerated sediment transport and redistribution (Ockelford et al., 2020).

Moreover, dams interrupt the longitudinal transport of sediments, leading to upstream accumulation and alterations in downstream erosion processes (Serra et al., 2022). This dynamic justifies a reassessment of the sediment sources contributing to the silting of the Ibn Battouta Dam, considering not only the upstream inputs but also the morphological changes downstream. Beyond Morocco, similar issues have been observed globally: sediment retention by dams has been shown to increase coastal and downstream erosion (Mosaid et al., 2024). Human infrastructure, such as dams and ports, has modified sediment flows and disrupted morphological processes (Laïbi et al., 2014). Therefore, it is essential to consider downstream erosion and update the existing studies by integrating recent technological advances and new data.

The study of watershed morphology and erosional processes is essential for understanding the impact of climate change on the hydraulic infrastructure (Lu et al., 2021). Modern remote sensing techniques, such as satellite imagery and digital elevation models (DEMs), enable a detailed analysis of morphological changes, particularly erosion and sediment deposition. The integration of geospatial data into GIS software facilitates the assessment of hydrogeomorphological parameters and improves our understanding of erosional processes that contribute to sedimentation (Hema et al., 2022; Rai et al., 2018).

Although several studies have been conducted on the Tleta watershed, they have mainly focused on upstream erosion, which is considered the primary source of sediment. This approach has led to neglecting downstream erosion, which can play a significant role in sediment accumulation. Thus, updating the current knowledge is necessary, considering recent technological advancements and the newly available data.

Our study falls within this framework and aims to reassess the erosional processes downstream of the watershed. Using modern remote sensing tools and multi-source data, we analyzed morphological changes around the Ibn Battouta Dam reservoir. By comparing images taken during different periods, we identified areas particularly affected by shoreline degradation to better understand the full range of erosional processes that influence the watershed.

Understanding these erosional dynamics is essential for addressing the challenges of sustainable water resource management in Morocco. Combating dam sedimentation is a priority to ensure water security and guarantee a long-term water supply. This study assessed the contribution of riverbank erosion to the siltation processes of the Ibn Battouta Dam by integrating shoreline dynamics analysis with multitemporal satellite imagery and bathymetric surveys.

2. MATERIALS AND METHODS

Located in the extreme northwest region of the Rif Mountain ridge, the Tleta watershed covers an area of 177 km² (2021). As shown in Figure 1, national and regional roads strategically connect Tangier, Tétouan, and Larache. It has an average altitude of 171 m and a slope of up to 16%. This watershed, drained by the Oued Kebir and its tributaries, feeds the Ibn Battouta Dam, whose initial capacity of 43.6 million m³ dropped to 30.11 million m³ in 2020 owing to sedimentation caused by erosion. Under a subhumid Mediterranean climate, the region receives an average annual rainfall of 750 mm, concentrated between October and March (Sabir et al., 2019). However, heavy rain frequently causes flooding and accelerates soil erosion. Geologically, the watershed consists of marl and schist formations, which, owing to their fragility, facilitate sediment transport toward the dam. Similar conditions have been observed in other Mediterranean watersheds, where marly and schistous formations contribute significantly to the sediment yield because of their low cohesion and high erodibility (Rodrigo-Comino et al., 2018). The distribution of vegetation is largely influenced by lithology and soil type. On marl substrates and clay-textured soils, the predominant vegetation formations include tall and dense matorral, low and sparse matorral, and very sparse Erme zones. In contrast,

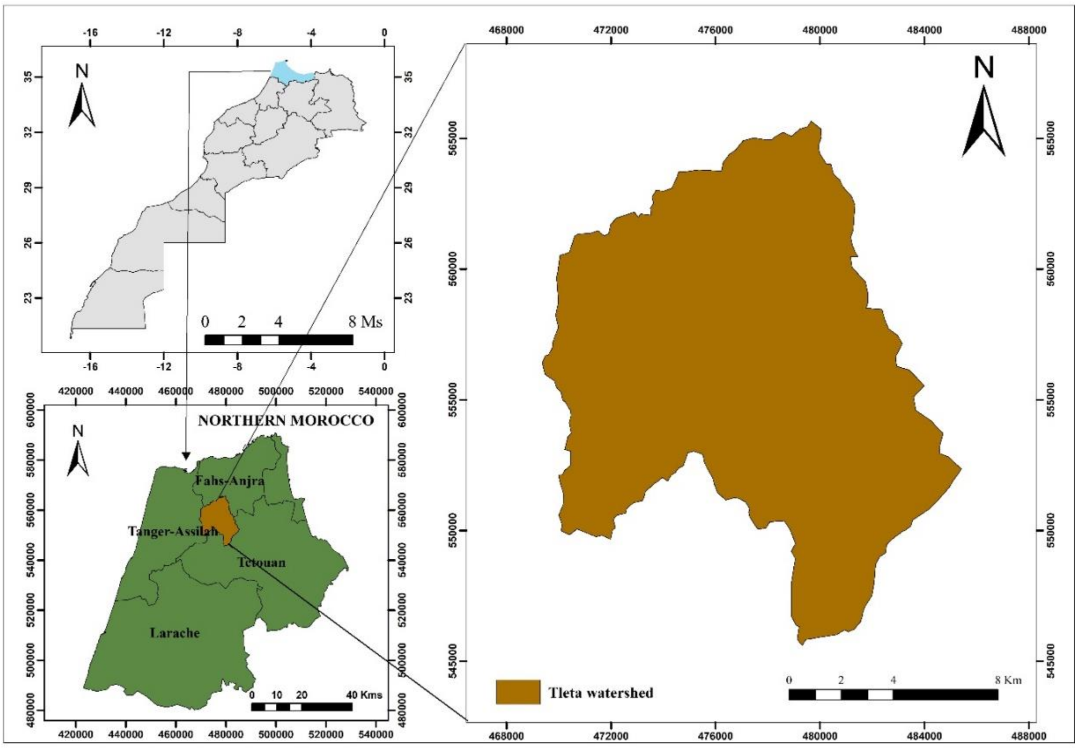

Figure 1. Geographical location of the Tleta Watershed

sandstone substrates are dominated by matorral formations, primarily resulting from cork-oak forest degradation (Ezzine et al., 2011).

These characteristics render the Tleta Watershed hydrologically dynamic but vulnerable, thus requiring appropriate management to preserve its water resources and mitigate the impact of sedimentation on hydraulic infrastructure.

2.1. Data acquisition and preprocessing

The data used in this study were mainly spatial and exogenous. They included hydrometric and bathymetric data from the 2013 and 2020 campaigns provided by the Directorate of Research and Water Planning (DRPE). In addition, LANDSAT satellite images have been used too. These images were captured by the TM, ETM+, and OLI sensors of the Landsat 5, 7, and 8 satellites, covering the period 1984-2014. Finally, Sentinel-2 images captured by the MSI sensor were used, covering the period 2015-2024. The acquisition dates and corresponding hydrometric status of the Ibn Battouta reservoir are summarized in Table 1.

The combined use of Landsat and Sentinel satellites offers key advantages for this study. Landsat, with its TM, ETM+, and OLI sensors, provides a historical series of images since 1984, essential for analyzing long-term changes around the Ibn Battouta reservoir. Sentinel-2, with a spatial resolution of 10–20 m, effectively extracts the distribution of terrestrial surface water (Wang et al., 2018). Moreover, its high revisit frequency is crucial for the dynamic monitoring of water bodies and for detecting changes (Ogilvie et al., 2018).

This approach not only enables the tracking of morphological changes around the reservoir's shores but also demonstrates the significant impact of spatial resolution on the accuracy and relevance of the results. The integration of Landsat and Sentinel data has been widely used for water resource management, offering valuable insights into hydrological dynamics and the impacts of climate change (Donchyts et al., 2016; Pekel et al., 2016).

The Google Earth Engine (GEE) was used to process satellite data, particularly to identify and extract water surfaces from satellite images, as it allows automatic, large-scale, and parallel operations. This facilitates the processing of vast amounts of data over extensive geographical and temporal scales (Ravanelli et al., 2018).

ESRI ArcGIS 10.8 software with its extensions was utilized for spatial analysis, including the creation of digital elevation models (DEMs), slope mapping, and overlaying various spatial layers to assess the sediment volumes deposited in the reservoir. The use of GIS for hydrological modeling has proven effective in assessing sedimentation risks, optimizing land-use planning, and supporting decision-making in water resource management (Van Westen, 2013).

2.2. Extraction of the actual water surface

The actual water surface of the Ibn Battouta reservoir was extracted using satellite images available via the Google Earth Engine. Sentinel-2 (2015-2024) and Landsat 5, 7, and 8 (1984-2014) data were preprocessed to remove clouds, cirrus, and shadows using pixel-quality information (QA60 for Sentinel and QA_PIXEL for Landsat). The Normalized Difference Water Index (NDWI) was calculated to identify aquatic surfaces, allowing for the precise delineation of the reservoir's water surface. NDWI is computed using green and near-infrared (NIR) bands to identify water bodies. Open water areas had positive values, whereas soil and terrestrial vegetation areas had values less than or equal to zero (Eq. 1).

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \quad [1]$$

Table 1. Dates of images and hydrometric status of the Ibn Battouta reservoir

Acquisition Date	Sensor	Resolution (m)	Elevation (m)	Volume (mm^3)
18/08/1984	TM	30	44.27	15.077
20/09/1999	ETM+	30	37.85	2.026
06/06/2001	ETM+	30	46.75	29.112
22/04/2002	ETM+	30	47.66	33.388
06/07/2003	TM	30	47.09	29.489
06/01/2007	TM	30	40.70	7.276
28/04/2007	TM	30	41.03	8.046
01/07/2007	TM	30	40.14	6.129
06/07/2009	TM	30	46.63	26.352
23/08/2009	TM	30	45.32	21.040
27/11/2009	TM	30	42.85	12.813
20/04/2010	TM	30	47.81	31.594
07/06/2010	TM	30	47.09	28.356
09/05/2011	TM	30	48.02	32.565
16/10/2011	TM	30	43.64	15.218
17/07/2013	OLI	30	46.66	26.481
19/09/2013	OLI	30	44.79	19.092
26/02/2014	OLI	30	45.46	21.576
01/05/2014	OLI	30	45.69	22.474
10/09/2015	MSI	10	40.03	10.051
29/11/2015	MSI	10	41.13	6.758
25/03/2016	MSI	10	43.52	12.775
21/09/2016	MSI	10	38.60	2.754
30/12/2016	MSI	10	44.54	15.941
12/04/2017	MSI	10	46.10	3.744
11/07/2017	MSI	10	44.25	15.013
12/01/2017	MSI	10	44.60	16.136
23/06/2018	MSI	10	47.69	27.770
15/11/2018	MSI	10	45.98	20.917
10/03/2019	MSI	10	47.39	26.494
29/10/2019	MSI	10	41.30	7.120
21/02/2020	MSI	10	40.82	6.412
22/12/2020	MSI	10	38.79	2.949
03/01/2021	MSI	10	45.68	19.823
18/04/2021	MSI	10	47.81	28.290
20/07/2022	MSI	10	46.67	23.558
23/09/2022	MSI	10	45.22	18.206
28/04/2023	MSI	10	44.94	17.257
02/02/2024	MSI	10	41.84	8.351
14 /07/2024	MSI	10	46.26	21.968

Source: Loukkos Hydraulic Basin Agency, Morocco

2.3. Extraction of the theoretical water surface

To differentiate shoreline variations caused solely by water level fluctuations from those resulting from morphological transformations due to erosion or progradation caused by the lake's tributaries, it was necessary to create simulated surfaces based on a DEM that predates the formation of the lake (Fig. 2). These surfaces, also known as theoretical surfaces, represent the contours of the lake in the absence of topographic changes.

The DEM was generated by digitizing contour lines and elevation points from a topographic map. The resulting DEM was used to estimate the terrain shape before dam construction and served as a baseline for comparison with actual data. Figure 3 presents a series of detailed comparisons in which the actual and theoretical water surfaces are overlaid on each satellite image.

2.4. Development of recent bathymetric DEMs and estimation of sediment deposits

The creation of a recent bathymetric DEM from the collected bathymetric data allowed for the estimation of sediment deposits in the dam reservoir. As shown in Figures 4 and 5, the process began with the processing of bathymetric data and continued with the calculation of the altimetric variable Z based on the reference elevation (44.5 m NGM) and the measured water depth, according to the relation Z = (reference elevation - depth) in meters (NGM). The (x, y, z) points were then converted from Excel to ArcGIS as a shapefile, after which the bathymetric DEM was created

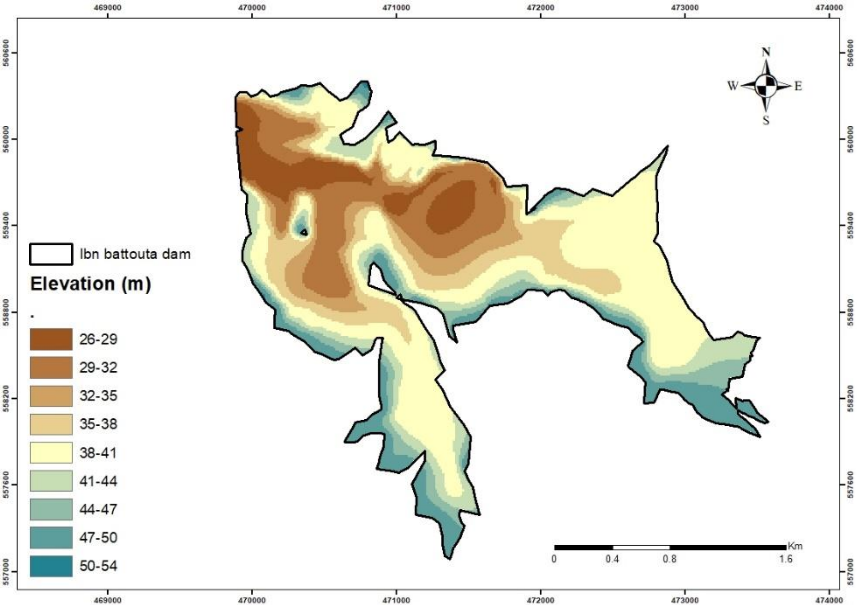

Figure 2. Reference digital elevation model (DEM) of the Ibn Battouta dam (1965)

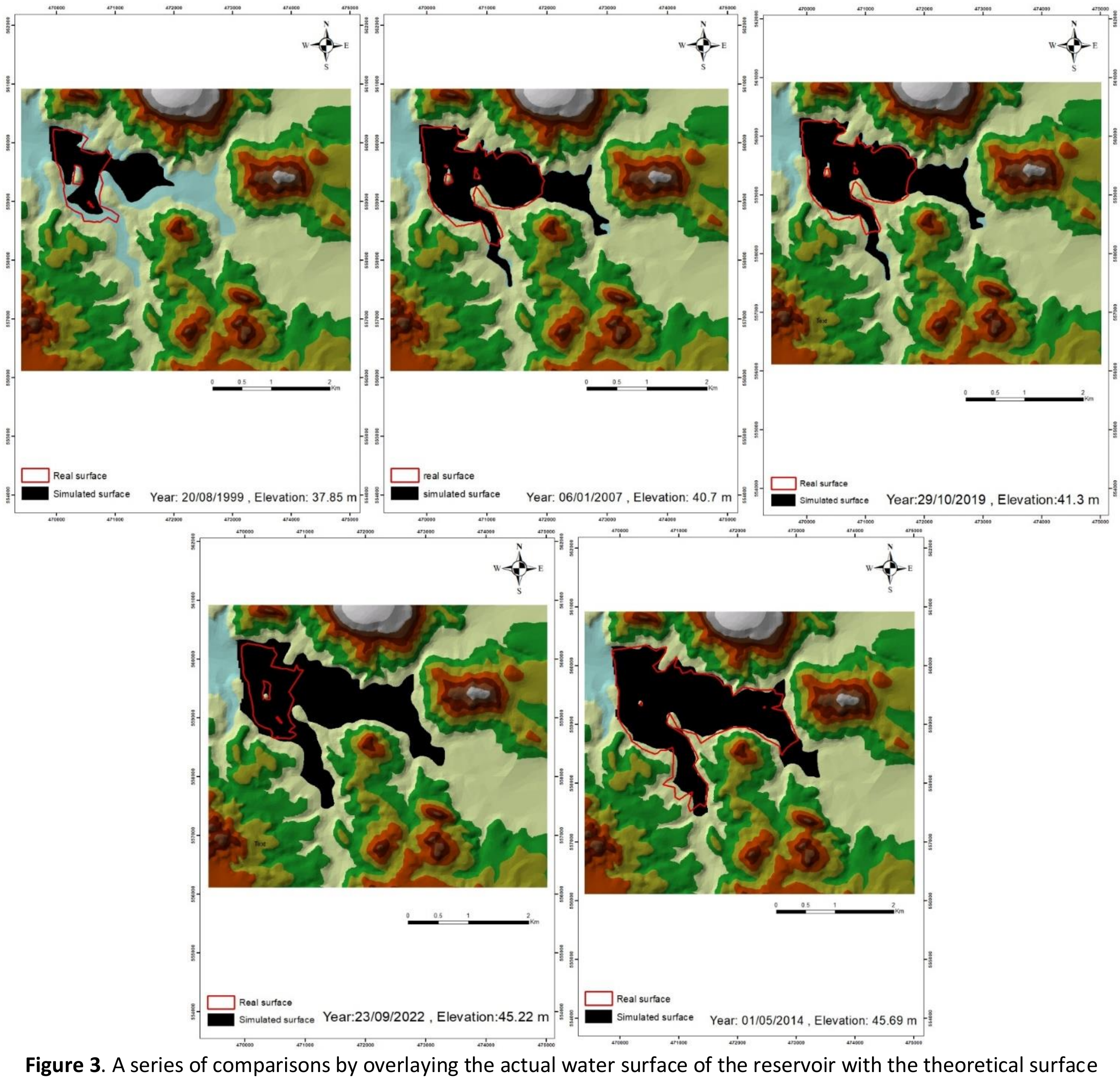

Figure 3. A series of comparisons by overlaying the actual water surface of the reservoir with the theoretical surface

through interpolation using the natural neighbor method available in the *Spatial Analyst* toolbox. The resulting DEM was subsequently used to generate slope maps in ArcGIS, which highlighted areas characterized by steep gradients and highly irregular topography. The DEM was generated from digitized contour lines (10 m intervals) of a 1:50,000 topographic map, resulting in a grid with a spatial resolution of 30 m.

2.5. Change detection methodology

As illustrated in Figure 6, the effect of water-level variations on planimetric changes was quantified by calculating the planimetric variation segment "S," which is a function of the elevation difference (Δh) and slope angle (α). Segment "S" is calculated using Equation 2.

$$Si = \Delta h \times \cot \alpha i \quad \text{...[2]}$$

This calculation helps detect significant planimetric variations when the slope angle (α) is below a specific threshold, as determined using Equation 3.

$$\alpha = \tan^{-1}\left(\frac{Eq}{px/2}\right) \quad \text{...[3]}$$

where Δh represents the variation in the water level, Eq is the contour interval derived from the topographic map, Px is the pixel size, and α is the slope angle.

In this study, the contour interval used to construct the digital terrain model (Eq. 3) was 10 m, which represented the minimum altimetric value in our analysis. The denominator (Px/2) also corresponds to the minimum value (5 m in this case), below which the planimetric change recorded by a pixel is negligible.

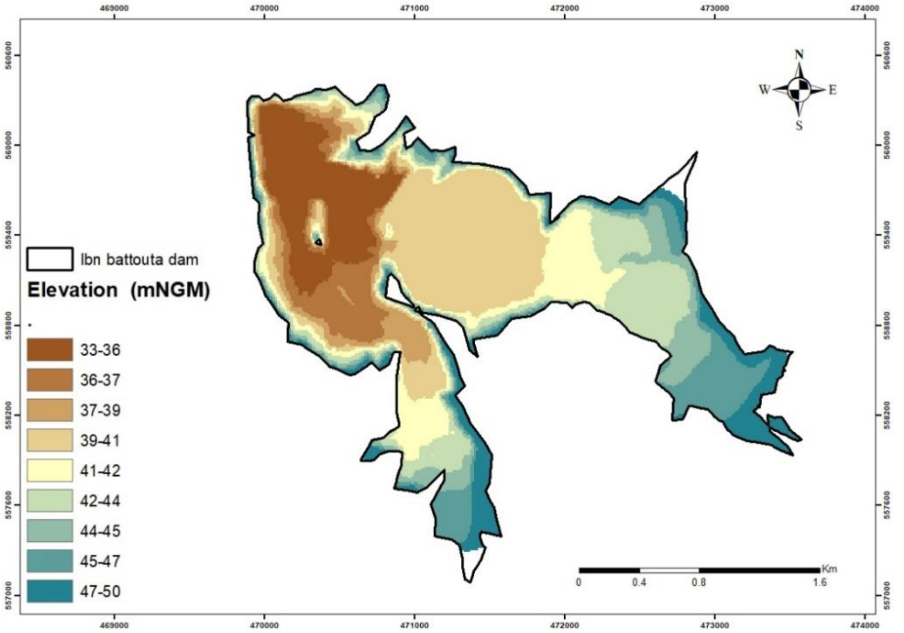

Figure 4. Bathymetric digital elevation model of the Ibn Battouta dam (2013)

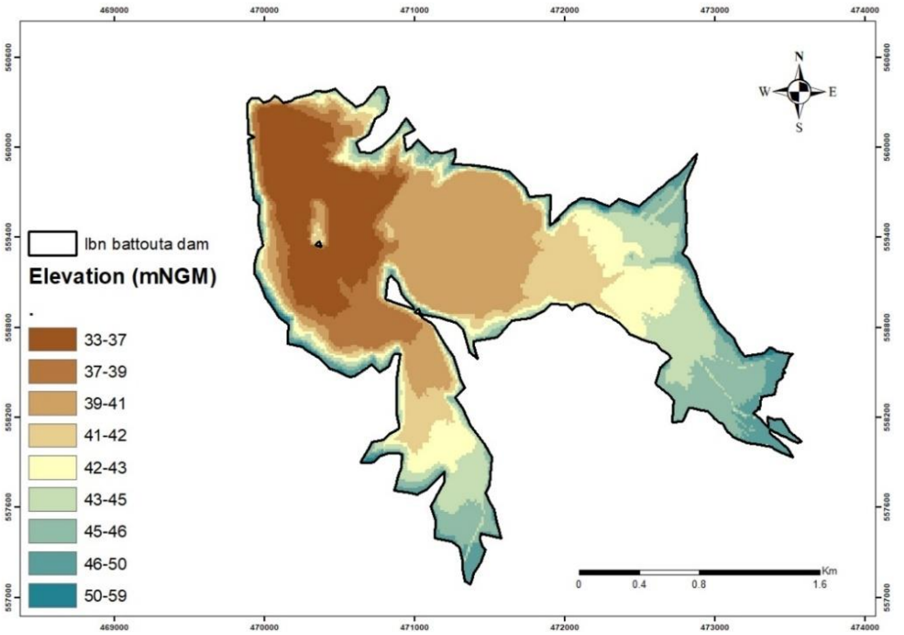

Figure 5. Bathymetric digital elevation model of the Ibn Battouta dam (2020)

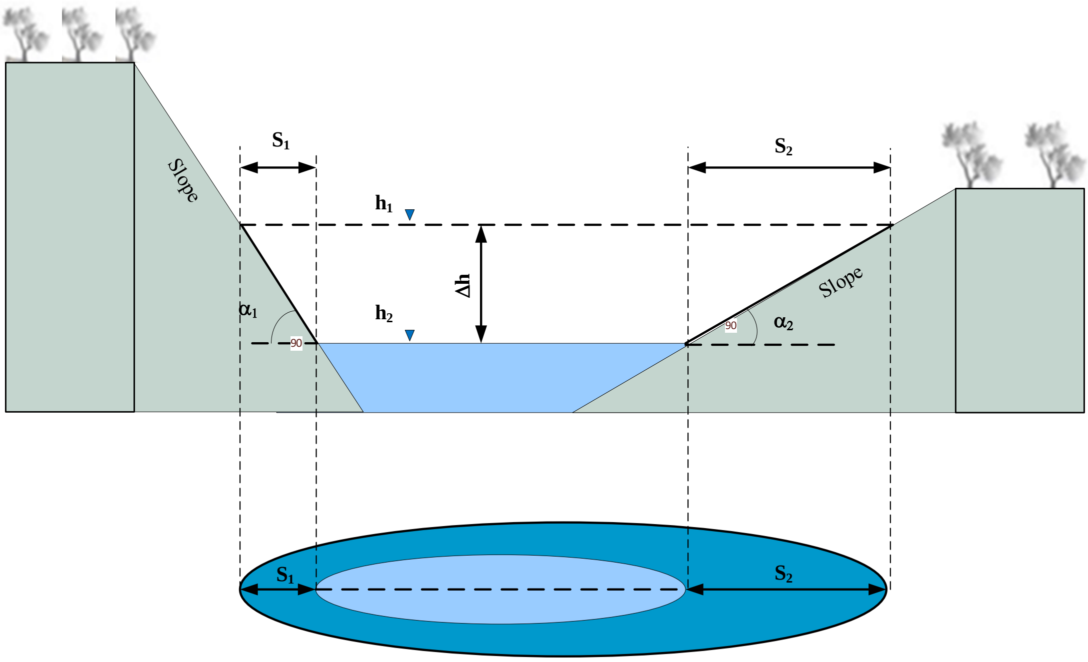

Figure 6. Diagram showing the effect of water level height variations on planimetric changes (Lo Curzio et al., 2013)

By applying the formula for calculating the segment of planimetric variation to our data, the planimetric displacements detected from the images became significant when the slope angle (α) values were below the threshold value, and Δh was equal to or greater than the value of the contour interval (Eq).

3. RESULTS

This study monitored the morphological evolution of the shores of the Ibn Battouta dam reservoir and highlighted the changes that occurred between 1984 and 2024. To this end, the Normalized Difference Water Index (NDWI) was used via the Google Earth Engine platform to enable the accurate mapping of water contours over the decades.

In parallel, a Digital Elevation Model (DEM) developed from contour lines extracted from a topographic map enables the analysis of morphological variations within a detailed geomorphological framework.

3.1. Extraction of Water Surface Using NDWI

The water surface contours of Ibn Battouta Dam were extracted using the Normalized Difference Water Index (NDWI) on the Google Earth Engine (GEE) platform, covering the period 1984-2024.

This index effectively enhanced the contrast between water bodies and the surrounding land surfaces, thereby enabling the precise identification of flooded areas.

To assess the accuracy of the extracted surfaces, we compared the results from Landsat (1984-2013) and Sentinel-2A (2014-2024) imagery with reference surfaces derived from the contour-surface scale established during the 2013 bathymetric survey provided by the Hydraulic Basin Agency of Loukkos.

Table 2 summarizes the average accuracy assessment of water surface extraction derived from both Landsat and Sentinel-2A imagery. These values were obtained by averaging the absolute and relative errors calculated for each observation date within each satellite dataset. The resulting absolute and relative errors are listed in Table 2.

Table 2. Comparison of mean errors between Landsat and Sentinel-2A

Satellite	Mean Absolute Error (km^2)	Mean Relative Error (%)
Landsat	00.20	06.06
Sentinel-2A	00.08	02.09

The Mean Absolute Error (MAE) represents the average difference (km^2) between the extracted and actual water surface areas, regardless of the error direction (overestimation or underestimation). The Mean Relative Error (MRE) expresses this difference as a percentage of the actual water surface area and provides a measure of relative accuracy. By comparing these averages, Sentinel-2A outperforms Landsat with smaller absolute and relative errors. This indicates that Sentinel-2A provides more precise and reliable water surface delineation results, mainly because of its higher spatial and spectral resolutions.

3.2. Spatio-temporal evolution of the water surface

The overlay of all extracted polygons over time resulted in a map showing the spatial variability of the water surface between 1984 and 2024 (Fig. 7). These variations were primarily related to fluctuations in hydrometric elevations recorded during the image acquisition dates (Fig. 8).

3.3. Comparison between actual and theoretical surfaces

The actual water surfaces were extracted directly from the satellite images. In parallel, theoretical surfaces were estimated using a reference Digital Terrain Model (DTM) and water elevation data, assuming no morphological changes since the construction of the dam. The comparison (Fig. 10) shows that the theoretical surfaces are consistently larger than the observed surfaces. This overestimation was observed across almost all observation dates, with differences generally ranging between 0.1 km² and 0.4 km² and occasionally reaching up to more than 1 km² during certain periods.

This consistent bias indicates that the theoretical model tends to overpredict the water surface extent compared with the actual measurements derived from bathymetric data.

3.4. Extreme events and hydrometric context

Two extreme cases were identified in this study. On August 20, 1999, the minimum surface area was recorded at an elevation of 37.85 m, corresponding to an extended drought period. On May 9, 2011, the maximum surface level reached 48.02 m following periods of heavy rainfall and runoff.

3.5. Sediment Deposition and Morphological Change

To better understand the dynamics of sediment deposition in the Ibn Battouta Dam reservoir, we used bathymetric data collected during the two most recent bathymetric surveys conducted in 2013 and 2020. By comparing these data with the initial Digital Elevation Model (DEM) of the site, we produced maps that accurately identified the areas where sediments had accumulated at the bottom of the reservoir.

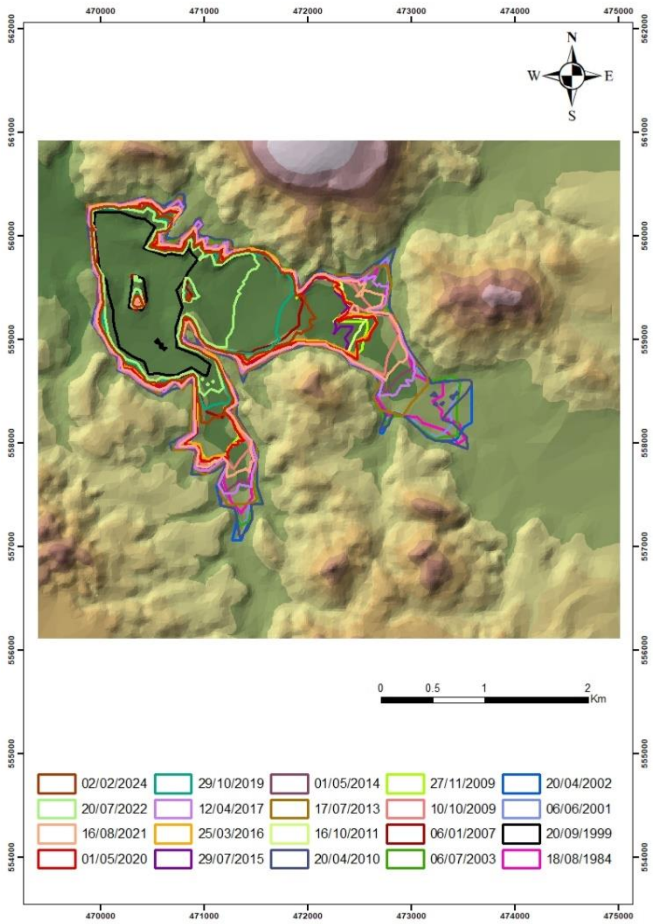

Figure 7. Water surface variation of the reservoir for the 1984-2024 period

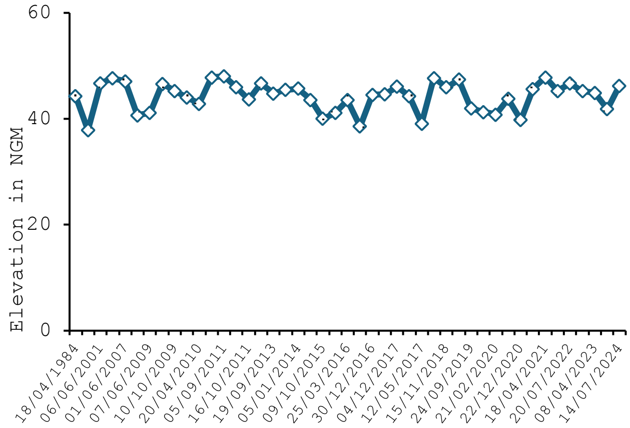

Figure 8. Variation of the dam elevations during the 1984-2024 period

This comparison allowed for the visualization of changes in the underwater morphology of the reservoir, highlighting the areas most affected by sedimentation.

To analyze sediment dynamics, we performed a differential analysis by subtracting the 1965 DTM from the 2013 and 2020 bathymetric models (2013-1965 and 2020-1965) and subtracting the 2013 model from the 2020 model (2020-2013) to quantify long-term and recent sediment deposition, respectively. This allowed us to generate detailed maps highlighting sediment accumulation and erosion zones.

Between 1965 and 2013, sediment deposits reached +23 m, mainly in the center and north of the reservoir. Although less significant, shoreline erosion resulted in elevation losses of up to -12 m.

From 1965 to 2020, sedimentation intensified in the southwest basin (+17 m), while erosion increased along the northeast, southeast, and southwest shores, resulting in losses of up to -12 m (Fig. 11).

3.6. Planimetric change detection (2015-2024)

Geomorphological validation was performed by quantifying planimetric changes between 2015 and 2024 using Sentinel-2A data with a resolution of 10 m. This analysis allowed the detection of subtle variations in the water surface footprint.

The slope angle (α) was calculated to be 63.43°using the elevation difference (Δh = 5.13 m). The planimetric displacement of the shoreline was approximately 2.57 m, suggesting that minor geomorphological changes (<5 m) were not detectable given the resolution limits (Table 3).

4. DISCUSSION

The results of this study highlight a significant reduction in the water surface and storage capacity of the Ibn Battouta reservoir, confirming the persistent issue of siltation affecting Moroccan dams. Similar observations were reported by El Boukhari et al. (2020) at the Hachef Dam, which is also located in northern Morocco, where sediment accumulation was found to severely compromise water storage efficiency and operational lifespan. These findings underscore the broader trend of accelerated reservoir silting across the country, largely attributed to soil erosion within upstream catchments and insufficient sediment management strategies.

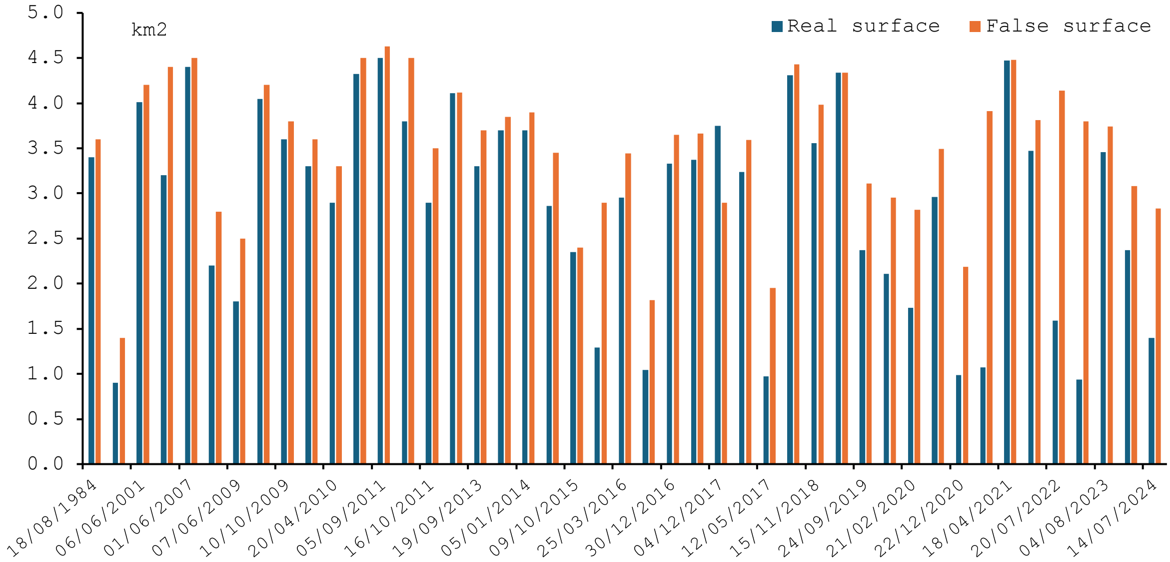

Figure 9. Actual and theoretical surfaces of the dam during the 1984-2024 period

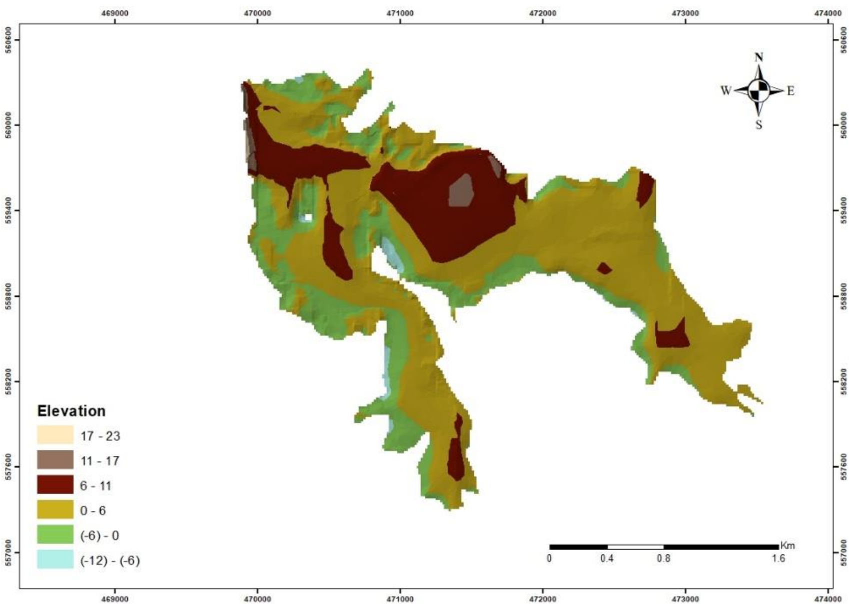

Figure 10. Map of deposition and erosion areas (2013-1965)

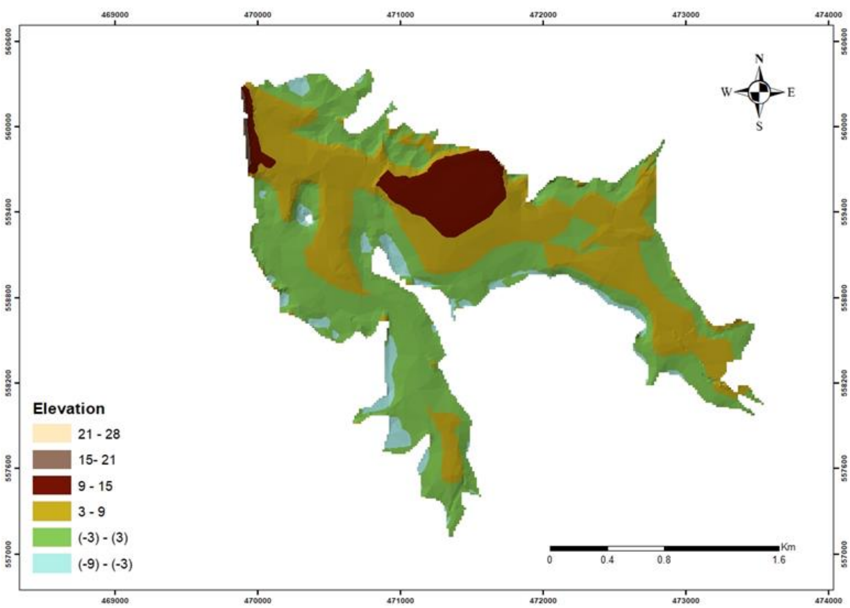

Figure 11. Map of deposition and erosion areas (2020-1965)

Table 3. Water elevation changes over time at Ibn Battouta Dam

Date	Elevation (m)	Δh (m)
9/11/2015	41.13	5.13
14/07/2024	46.26	

The analysis of water surfaces extracted using the Normalized Difference Water Index (NDWI) made it possible to assess the effectiveness of satellite imagery in detecting water bodies. By comparing the results obtained from Sentinel-2A and Landsat, we evaluated the accuracy of the extractions in terms of absolute and relative errors expressed in square kilometers.

The results confirm the reliability of satellite-based remote sensing, particularly the use of the Normalized Difference Water Index (NDWI), for accurately detecting and monitoring surface water dynamics (Gao et al., 2016). Among the analyzed datasets, Sentinel-2A imagery demonstrated superior performance over Landsat, primarily because of its higher spatial resolution (10 m) and enhanced spectral sensitivity. The use of the Multispectral Instrument (MSI) sensor on Sentinel-2A enables improved mapping of inland water bodies, increasing the global water surface mapping resolution from 14.25 m to 10 m (Verpoorter et al., 2014). This enhancement provided more detailed and precise imagery. Additionally, the high-frequency acquisition of high-resolution data makes it possible to create dynamic surface-water maps. These maps can distinguish between permanently and temporarily inundated water bodies. This approach provides a clearer and more up-to-date understanding of the evolution of water surfaces (Toming et al., 2016). These improvements resulted in lower absolute and relative errors in surface extraction, making Sentinel-2A particularly well-suited for precise hydrological monitoring (Fig. 12).

A long-term analysis conducted over a 40-year period (1984-2024) revealed substantial temporal and spatial variability in the reservoir water surface (Fig. 9). According to Figure 7, it is evident that the variation in the shape and size of the polygons is primarily attributable to differences in the hydrometric water levels, which range between 35.85 and 48.02 meters. This significant surface variation between the images was particularly noticeable in the upstream part of the reservoir, suggesting that the main tributaries bring in sediments that contribute to deposition and alter the morphology of the reservoir.

These fluctuations were strongly correlated with hydrometric data, suggesting that changes in water levels are largely driven by seasonal and interannual variations. Although hydrological variability explains most of the observed fluctuations, the results also suggest that geomorphological changes affect the shape and depth of the reservoir. These transformations may reflect cumulative sediment deposition, gradual delta formation, and shifting inflow channels, which are processes commonly reported in Mediterranean reservoirs exposed to intense erosion and irregular rainfall.

The overlap of the polygons shown in Figure 7 sometimes makes it difficult to visualize the planimetric variations of the water surface in the reservoir. This complexity arises from the fact that, during the analyzed period, several hydrometric levels are similar, making it harder to distinguish the changes

One of the most critical drivers of siltation in reservoirs is riverbank erosion, particularly along the tributaries that feed into them. Riverbank erosion is a geological process by which soil and sediment are detached and transported from riverbanks into the watercourse, leading to changes in the morphology of banks and adjacent areas (Saadon et al., 2021). This process can occur at varying speeds, sometimes resulting in landslides or collapses, and is influenced by multiple factors: (1) Fluctuating water levels: Seasonal and interannual variations increased bank saturation and promoted collapse; (2) Wave action: Wind-driven waves generate hydraulic pressure and directly dislodge bank material; (3) Tributary inflows: Concentrated flows at confluence intensify shear stress and accelerate erosion; (4) Bank geometry and material: Steep banks composed of unconsolidated soils erode faster, especially when vegetation cover is sparse (Mohd Rosli et al., 2024).

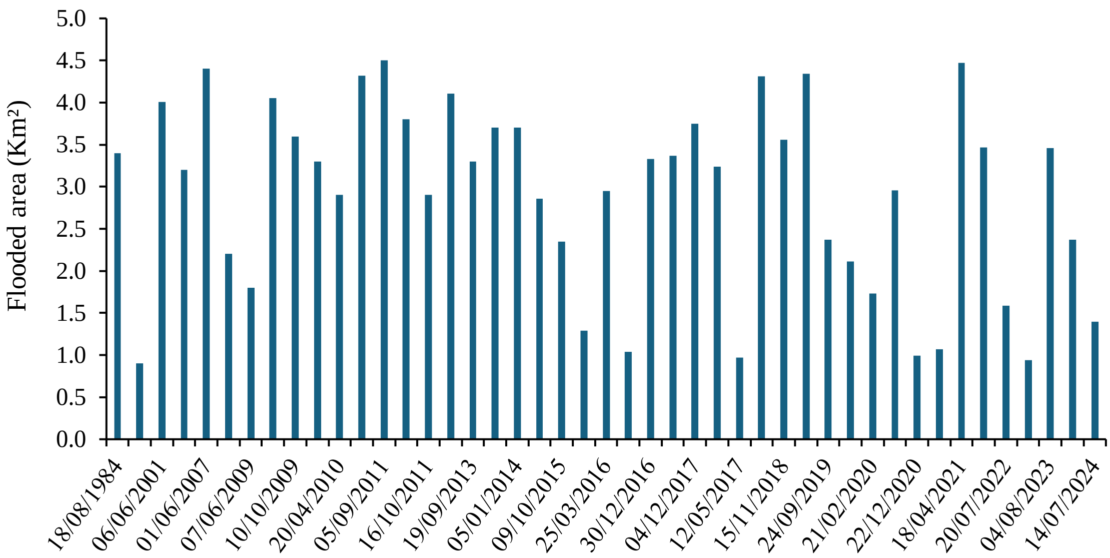

Figure 12. Variation of the water surface of the reservoir for the 1984-2024 period

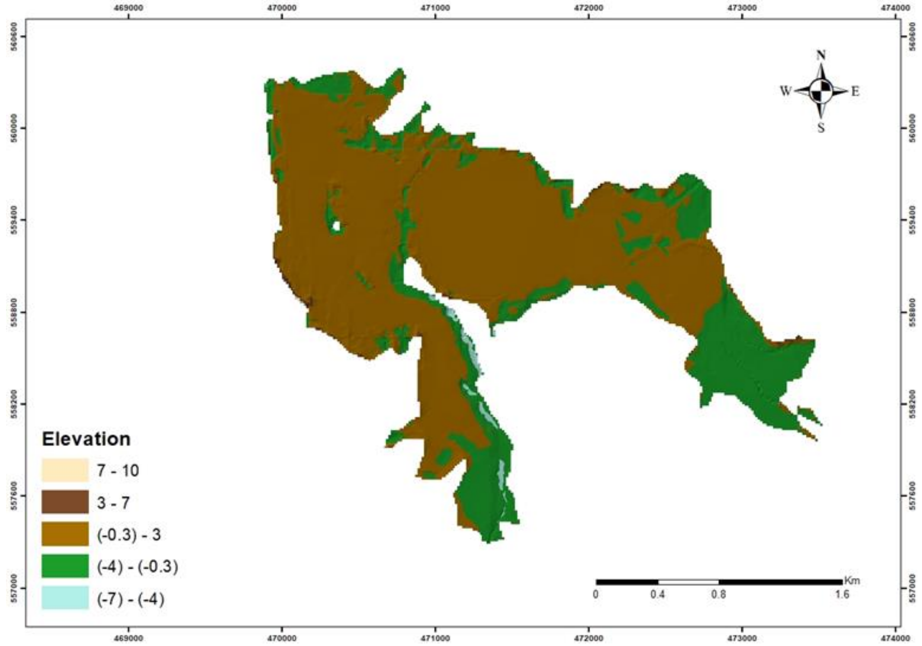

Figure 13. Map of deposition and erosion areas (2020-2013)

Spatial asymmetry is evident, as erosion is more pronounced along the southeastern and northeastern banks, likely due to a combination of stronger tributary inflows, steeper slopes, and weaker lithology. Conversely, the northwestern zones showed higher sediment accumulation, indicating the downstream deposition of eroded materials.

The retreat of riverbanks caused by wave action, rainfall-triggered slope failures, and insufficient vegetation cover leads to the direct introduction of eroded soil into the reservoir. These sediments tend to accumulate rapidly at river mouths, reducing water depth and significantly accelerating reservoir infilling. The observed spatial mismatch between the theoretical (simulated) and actual water surface areas highlights zones of concentrated sedimentation that are often aligned with areas prone to persistent erosion. The sediment distribution maps (Fig. 13) further confirm a consistent pattern of shoreline retreat and sediment deposition, indicating an alarming and ongoing trend.

By subtracting the 2013 DEM from the 2020 DEM, a more detailed analysis of the recent evolution of sediment deposits was obtained. This shorter time frame reveals contemporary trends, such as an increase in the sedimentation rate or, conversely, stabilization of deposits. This recent comparison helps to detect rapid or recent changes in the dynamics of sediment accumulation.

The map for the most recent period showed more moderate elevation differences, ranging from -7 m to 10 m. Areas with elevations between 3 m and 10 m indicate recent deposits, although of a lower magnitude compared to the previous period. The deposition zones were more scattered, which may suggest a more homogeneous redistribution of sediments or a reduction in sediment input in some parts of the reservoir.

The comparison between the 2020 and 2013 DEMs highlights the significant accumulation of sediments in several areas of the reservoir. Deposits are particularly concentrated in the northwestern region, where a marked increase in elevation (7-10 m) indicates intense sedimentation.

Bank erosion is especially pronounced in the southeastern and northeastern zones of the reservoir, where a notable decrease in elevation indicates significant erosion during this period.

The observed water level change of 5.13 m at the Ibn Battouta reservoir between November 9, 2015, and July 14, 2024, corresponds to a shoreline displacement of approximately 2.57 m, calculated from a slope angle of 63.43°. This displacement, which exceeds the detection limits of satellite imagery and DEM resolution, confirms the occurrence of measurable geomorphological changes. These findings align with the patterns of sediment deposition and riverbank erosion identified in the DEM comparisons and satellite-derived water surfaces, demonstrating that the reservoir underwent significant morphological evolution over the analyzed period.

Such measurable changes highlight the value of high-resolution, multitemporal monitoring tools, such as GEE, which can provide detailed datasets to support effective reservoir management strategies, particularly for agencies like the Loukkos Basin Water Agency. In practice, these datasets can guide management decisions in several key areas: (1) The early detection of erosion hotspots enables targeted interventions, such as riverbank reinforcement or revegetation; (2) The quantification of sediment volumes aids in predicting reservoir infilling rates, helping schedule dredging or sediment management programs; and (3) Scenario analysis: Simulating water level fluctuations can forecast areas at risk of erosion and optimize reservoir operations to minimize sediment mobilization.

By integrating satellite-derived NDWI data with hydrometric and geomorphological information, water authorities can adopt evidence-based strategies to maintain the reservoir capacity, reduce siltation rates, and improve long-term water resource sustainability.

5. Limitations and recommendations

Despite the valuable insights provided by this study, several limitations should be acknowledged. First, satellite imagery (Landsat and Sentinel) is subject to temporal and spatial resolution constraints and cloud cover, which may affect the accuracy of the water surface extraction and shoreline delineation. Second, bathymetric data were only available for 2013 and 2020, preventing a continuous temporal analysis of sedimentation trends and limiting the ability to capture seasonal or annual variations. Third, minor uncertainties may arise from image preprocessing, DEM interpolation, and geometric correction steps. Future studies should integrate more frequent bathymetric surveys, higher-resolution imagery, and field validation to improve the accuracy, robustness, and reliability of sediment estimations. Additionally, integrating NDWI-based analysis with machine learning shoreline extraction or LiDAR-derived topography could further improve spatial accuracy and detection sensitivity.

Based on these findings and considering the above limitations, we recommend the following actions to support sustainable sediment management and preserve the capacity of the Ibn Battouta reservoir. First, continuous satellite-based monitoring should be implemented to track water surface and sediment dynamics. Second, the structural reinforcement of vulnerable riverbanks should be prioritized to reduce erosion and sediment input into the reservoir. Third, the ecological restoration of degraded upstream areas, including vegetation rehabilitation, will help stabilize soils and limit further sediment transport. These interventions are necessary to maintain reservoir storage, ensure operational capacity, and promote long-term sustainability of water resource management in the region.

In summary, acknowledging these limitations and implementing the proposed recommendations will strengthen sediment management strategies and ensure the sustainable functioning of the Ibn Battouta reservoir and similar Mediterranean watersheds.

5. CONCLUSION

This study monitored the morphological evolution of the Ibn Battouta reservoir and assessed sedimentation trends from 1984 to 2024. The actual water-surface contours were extracted from satellite data, and the theoretical surfaces were determined using a reference Digital Elevation Model (DEM). The overlay of these datasets highlighted significant changes over time, revealing progressive reservoir shrinkage and significant sediment accumulation. These changes are mainly attributed to sediment contributions from tributaries and shoreline degradation, which play a crucial role in the gradual silting of the dam. The results of this analysis underscore the major impact of erosion and sedimentation processes on the functional capacity of reservoirs. Shoreline degradation is a significant source of sediment that substantially contributes to siltation. These findings emphasize the need for sustainable and proactive management of reservoir shores. Measures such as shoreline stabilization, reforestation, and watershed management should be considered to limit the sediment input and preserve the long-term functionality of the Ibn Battouta dam.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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