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Original scientific paper

Using empirical methods, GIS and bathymetric survey for assessing the siltation of Sidi-Yacoub Dam (northwestern Algeria)

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The silting of dams is a critical issue that requires immediate solutions through a participatory approach involving diverse territorial stakeholders. This approach aims to mitigate sediment inputs and preserve the intrinsic qualities of water resources within dams. In this context, the present study evaluates the siltation rate of the Sidi-Yacoub Dam, located in the Oued El Ardjem watershed, and identifies the primary causes contributing to this phenomenon. The methodology employed combines the analysis of thematic maps with the application of the sedimentation prediction model *Previsioni Interimento Serbatoi Artificiali* (PISA) to calculate various parameters. The annual average of solid inputs reaching the reservoir is estimated at 376.74 m^3/km^2/year, corresponding to an overall siltation rate of 0.46 Mm^3/year. The preservation of this hydraulic infrastructure is critical to optimizing water resource utilization in the region and supporting its economic and social development. This study underscores the importance of integrating empirical methods, Geographic Information Systems, and bathymetric surveys to achieve a comprehensive understanding of siltation dynamics. The findings indicate that the dam experienced a significant loss of approximately 32.22 Hm^3 of capacity between 1985 and 2004, representing an 11.6% reduction in its initial storage volume. These results highlight the urgent need for effective sediment management strategies to ensure the long-term sustainability of water resources in Algeria and other regions confronting similar challenges.

Keywords: siltation, Sidi-Yacoub Dam, geographic information systems, bathymetric survey, sedimentation prediction model

1. Introduction

Dam siltation has emerged as a critical global challenge affecting water resource management across diverse geographical regions (George et al., 2017; Mohafid et al., 2024). This issue, resulting from the gradual sedimentation of solid particles at the bottom of reservoirs, poses significant challenges both environmentally and socio-economically (Owens et al., 2005). This expanded introduction addresses several key aspects of dam siltation, including its impact on water storage capacity, water quality, biodiversity, as well as management strategies and innovative solutions to mitigate its adverse effects (Gonzalez Rodriguez et al., 2023; Schmutz and Moog, 2018).

On one hand, siltation reduces the storage capacity of dams, thereby limiting their long-term effectiveness in water resource management (Gonzalez Rodriguez et al., 2023). The decrease in retention capacity can compromise water availability for irrigation, drinking water supply, hydroelectric power generation, and other essential uses (Yüksel, 2010). This reduction in water reserves can also exacerbate the risk of shortages in regions reliant on dams as the primary source for their water supply (Ehsani et al., 2017). On the other hand, siltation affects water quality by promoting the accumulation of contaminants and nutrients in sediments, which can lead to the deterioration of the aquatic ecosystem and increased risks to human health. Silted dams can also alter natural habitats and disrupt the life cycles of aquatic species, thereby threatening biodiversity and associated ecosystem services (Ong and Orego, 2002; Rashmi et al., 2022; Porto et al., 2023).

Faced with these challenges, dam managers and policymakers are confronted with the need to implement effective management strategies to prevent or mitigate siltation (Wang et al., 2018; Espa et al., 2019). These strategies may include watershed management practices to reduce soil erosion, dredging techniques to remove accumulated sediments, as well as innovative approaches such as regulating water flows to promote natural sediment transport (Paskett, 1982;

Verstraeten et al., 2002; Panagos et al., 2024). In general, dam siltation poses a major challenge for the sustainable management of water resources, with significant implications on environmental, economic, and social fronts. Understanding the causes and impacts of this phenomenon, as well as developing integrated and sustainable management approaches, are essential to ensure the resilience of dam systems and the preservation of aquatic ecosystems on a global scale (Panagos et al., 2024).

In Algeria, the issue of dam siltation is particularly concerning and represents a major challenge for water resource management. With a significant number of dams distributed throughout the country, siltation poses serious problems that affect water supply, agriculture, energy production, and the aquatic ecosystem (Remini and Toumi, 2017; Benkadja et al., 2013; Hallouz et al., 2018). Algeria, facing semi-arid to arid climatic conditions, heavily relies on dams for water resource management (Sarra et al., 2023). These infrastructures are crucial for storing rainwater and river flows, thus providing water for agricultural irrigation, drinking water supply, and hydroelectric power production. However, the progressive sedimentation in these reservoirs diminishes their storage capacity and compromises their long-term effectiveness.

Estimating siltation in dams relies on various models, each with its own methods and applications. Empirical models, such as rating curves that take the form of power functions (Walling, 1977; Jansson, 1996; Asselman, 2000), rely on historical data to establish simple relationships between sedimentation and variables like sediment load and dam storage capacity. Analytical models, like the Meyer-Peter Müller equation, use mathematical equations to estimate siltation based on hydraulic and sedimentological parameters (Huang, 2010).

On the other hand, considering sediment particle size and hydraulic conditions, various empirical and process-based models have been developed to predict soil erosion and sediment deposition in dam reservoirs. Among these, the Universal Soil Loss Equation (USLE) and its modified versions, such as the Modified Universal Soil Loss Equation (MUSLE) and the Revised Universal Soil Loss Equation (RUSLE), are widely utilized for estimating soil erosion rates. These models consider factors such as rainfall intensity, soil erodibility, slope length, and land cover (Zerouali et al., 2024; Ouadja et al., 2022; Wischmeier and Smith, 1978; Renard et al., 1997). They are particularly effective for assessing erosion at the watershed scale and have been successfully applied in diverse climatic and topographic settings. In addition, the Soil and Water Assessment Tool (SWAT) is a comprehensive hydrological model that integrates land use, soil properties, and climate data to simulate sediment yield and transport processes within a watershed (Arnold et al., 1998). Another advanced model, the Water Erosion Prediction Project (WEPP), employs a process-based approach to predict soil erosion and sediment deposition. It considers factors such as rainfall distribution, soil properties, and land management practices (Flanagan and Nearing, 1995). These models offer valuable insights into the dynamics of soil erosion and sediment transport, enabling the formulation of effective sediment management strategies. The choice of an appropriate model often depends on the availability of data, the scale of the study, and the specific objectives of the research (Nistor et al., 2024).

To ensure the long-term maintenance and effective management of artificial reservoirs, dam operators commonly use the Previsioni Interimento Serbatoi Artificiali (PISA) model (Benkadja et al., 2013), which predicts siltation and optimizes dredging operations to preserve storage capacity. This model is based on mathematical equations and numerical simulations that incorporate watershed characteristics and sediment fluxes, while also being enhanced by field data to improve accuracy. This study employs a multidisciplinary approach combining empirical methods, Geographic Information Systems (GIS), and bathymetric surveys to assess siltation in the Sidi-Yacoub Dam, located in northwestern Algeria. The primary objective is to quantify sediment accumulation and its impact on water storage capacity while using GIS to analyze spatial distribution patterns and identify critical deposition zones. Additionally, the study evaluates the effectiveness of bathymetric surveys for siltation monitoring, highlighting their advantages and practical limitations. Based on the findings, sediment management and reservoir maintenance strategies will be proposed to ensure infrastructure sustainability. This research provides a comprehensive analysis of siltation dynamics in the Sidi-Yacoub Dam while offering actionable recommendations applicable to other regions facing similar water resource management challenges.

2. Study area and database

The Oued El Ardjem basin is located in northern Algeria between parallels 35° and 36° North and meridians 1° 15′ and 1° 45′ East (Fig. 1), and is situated in the Ouarsenis Massif, which is part of the Tellian Atlas mountain range located between the Cheliff plain to the north and the parallel of Tiaret to the south. Several cities and villages are situated in the Oued El Ardjem Basin, covering a total area of 910 km^2, including Ramka, Bordj Bounaama, and Lardjem. The outlet of the basin is located in Sidi-Yacoub, south of the Cheliff, and it flows from the southeast to the northwest. Figure 1 illustrates the location map of the Oued El Ardjem Basin (ANBT,2017 Ouadja et al., 2021). Figures 1a and 1b represent the elevation and contour maps of the Oued El Ardjem basin, respectively.

The entire basin exhibits generally rugged terrain. The Oued El Ardjem serves as the main watercourse of the basin, originating in the Ouarsenis mountains before flowing into the Oued Cheliff, with a total length of 384 km. The rocks found in the watershed are of sedimentary origin, dating from the Triassic to the Miocene periods. Quaternary deposits are located along the wadis or in the alluvial plains, typically composed of gravelly materials. Recent alluvium is

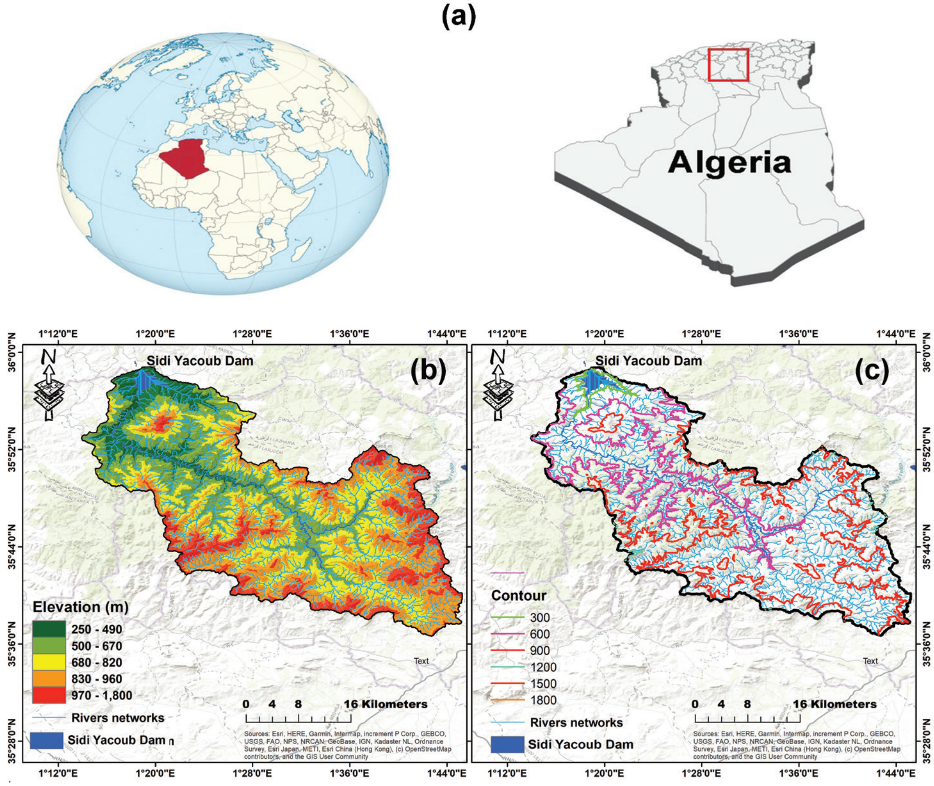

Figure 1. (*a*) Geographic location of the Oued El Ardjem basin, (*b*) Elevation, and (*c*) Contour maps, as well as the location of the Sidi-Yacoub Dam

limonous. The recorded geological formations are as follows: marly limestones (44%), marly-limestone formations (17%), marls (16%), limestone or marly sandstones (9%), flysch and molasse (8%), marly-sandy formations (3%), evaporites (2%), limestones (<1%), and loose deposits with medium texture (<1%).

The Oued El Ardjem basin has altitudes ranging from 250 to 1828 meters. The Oued El Ardjem river, originating from the northern slopes of the Ouarsenis massif in the Tellian Atlas, drains the basin to the Sidi-Yacoub dam, which was constructed with an initial capacity of 285 Hm^3. Slope is a critical factor in assessing soil erosion, as it directly influences runoff velocity and soil detachment. To evaluate erosion risk effectively, slopes are commonly classified into categories based on their steepness: 0–3°, 3–7°, 7–15°, 15–25°, 25–35°, and greater than 35°. Gentle slopes (0–3°) typically experience minimal erosion, while moderate slopes (3–15°) are more vulnerable due to increased surface runoff. Steeper slopes (15–35° and above) significantly accelerate water flow, thereby increasing the

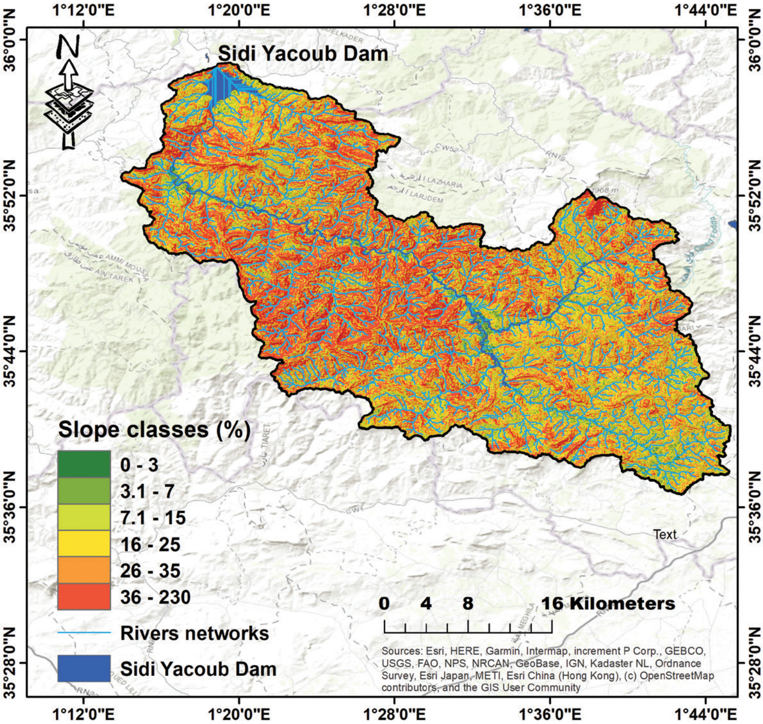

Figure 2. Slope map of the Oued El Ardjem basin.

potential for severe soil erosion and loss. This classification is essential for identifying high-risk areas and implementing targeted soil conservation practices.

In the Oued El Ardjem basin, the dense hydrographic network is largely attributed to the presence of steep slopes, which range from 3% to 50% (Fig. 2). The steepest areas are primarily located upstream, particularly in the mountainous regions to the south, west, and southeast. In contrast, the gentlest slopes are found downstream, near the dam basin in the northern sub-basin. Notably, the sub-northwest basin (Ramka region) features extremely steep slopes. Across the rest of the basin, slopes typically range from 10% to 30%, contributing to varying degrees of erosion potential.

2.1. Sidi-Yacoub dam

The Sidi-Yacoub Dam is an earth dam featuring a watertight clay core, constructed between 1981 and 1986. Standing at a height of 95 meters and reaching a crest elevation of 272 meters, it is equipped with four water intakes spaced 8.5 meters apart, corresponding to the depth of the Sidi-Yacoub Valley. Located at the confluence of two rivers, with the Lardjem Oued as the primary source, the dam forms an important left-bank tributary to the Cheliff River. Its reservoir, with a capacity of 280 Hm^3, supplies water for both irrigation and potable use.

Originally budgeted at 500 million dinars, the initial cost of the dam later increased by 200 million dinars upon re-evaluation. Geographically, the dam site is defined by a latitude of North 33° 98′ and a longitude of 1° 32′, adhering to international geographic coordinates with the prime meridian passing through Greenwich. Situated approximately 1 km northwest of the village bearing its name, the Sidi-Yacoub dam lies within the gorges of the Oued Lardjem. The nearby town of Chlef is approximately 28 km to the north, accessible via the local road W42, which traverses the right flank of the gorges (ANBT, 986).

The selection of the dam site followed extensive studies, favoring a location with optimal morphology. The gorge's bottom measures 60–90 meters in width and extends approximately 430 meters in length. The dam's axis is strategically positioned to accommodate upstream and downstream cofferdams within the gorges. The gorge's right side exhibits a concave shape, contrasting with the convex relief observed on the left side (ANBT, 2004).

The climatic characteristics of a basin are crucial for understanding the hydrological behavior of its rivers. Indeed, the abundance, duration, and variations in the intensity of precipitation during periods when the soil is not protected by vegetation can have a significant impact on the physical environment and lead to erosion processes. In this study, data from 1985 to 2013 were used to characterize precipitation in our study area. Figure 3 depicts the rainfall map of the Oued Ardjem basin (ANBT, 2017).

Land use plays a critical role in the erosion process, significantly influencing whether erosion is exacerbated or mitigated. It determines the level of soil protection, with vegetation cover being a key factor in reducing erosion. Vegetation cover absorbs the kinetic energy of raindrops, covers a significant portion of the soil, and slows down runoff or maintains good soil surface porosity. On one hand, plant cover shields against the impact of rainfall, thereby prolonging soil permeability and reducing runoff volume. On the other hand, the litter layer absorbs a substantial amount of runoff energy, while also supporting mesofauna, which further influences infiltration rates (Roose and Sarrailh, 1990). Figure 4 illustrates the land use in the watershed.

Land use in the Oued El Ardjem basin is predominantly characterized by sparse vegetation, which covers 286.4 km^2 (31.5%), followed by rainfed croplands at 269.8 km^2 (29.6%). Together, these two categories account for 61.1% of the total basin area, reflecting the region’s dependence on natural vegetation and agricultural activities. Closed needle-leaved evergreen forests (134.2 km^2, 14.7%) and closed to open shrubland (110.9 km^2, 12.2%) are also significant, indicating the presence of forested and transitional vegetation types. Smaller areas consist of croplands integrated with vegetation (64.2 km^2, 7.1%) and forest-shrubland/grassland (26.1 km^2, 2.9%). Water bodies (7.5 km^2, 0.8%) and bare areas (6.1 km^2,

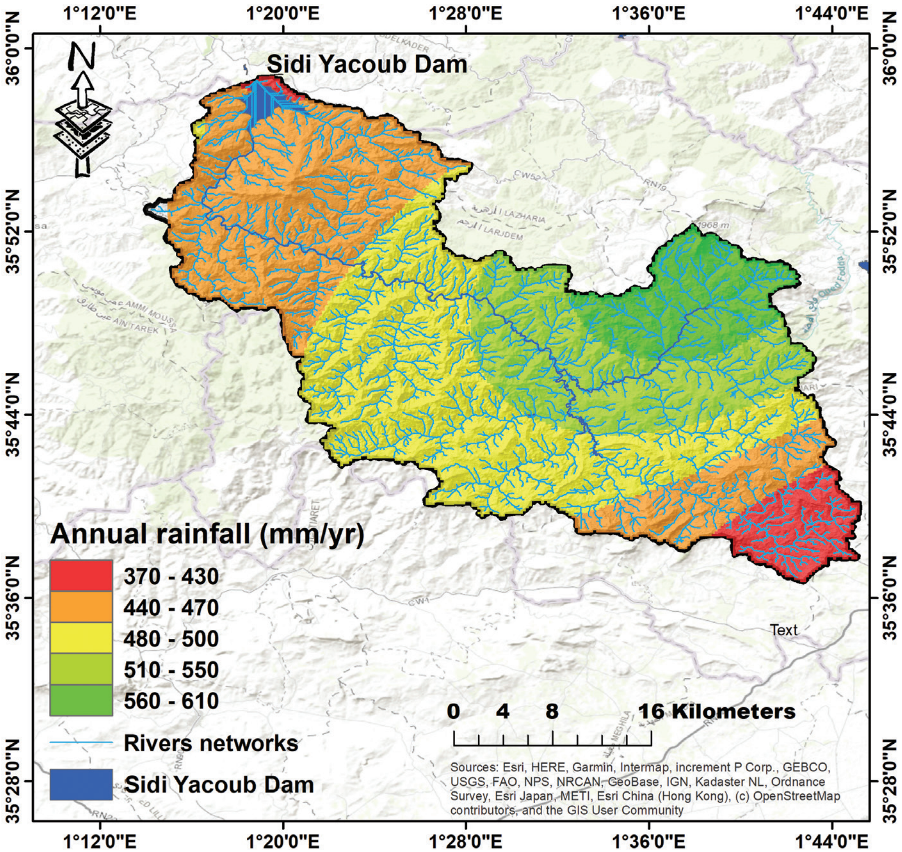

Figure 3. Mean annual rainfall map of the Oued El Ardjem basin.

0.7%) occupy minor portions of the landscape, while vegetation/croplands (0.5 km², 0.1%) and closed broadleaved deciduous forests (0.3 km², 0.0%) are negligible. This distribution underscores a diverse ecosystem centered on vegetation, agriculture, and forested regions. These findings highlight the importance of managing land-use practices to mitigate erosion, preserve ecosystems, and maintain water quality.

2.2. The dam reservoir

The largest portion of the catchment area is characterized by Normal marine facies (Mf), covering 327.93 km², representing 35.26% of the total area. These deposits typically signify sedimentary formations formed under normal marine conditions (Fig. 5). Upper Cretaceous marine (Cu) deposits encompass a substan-

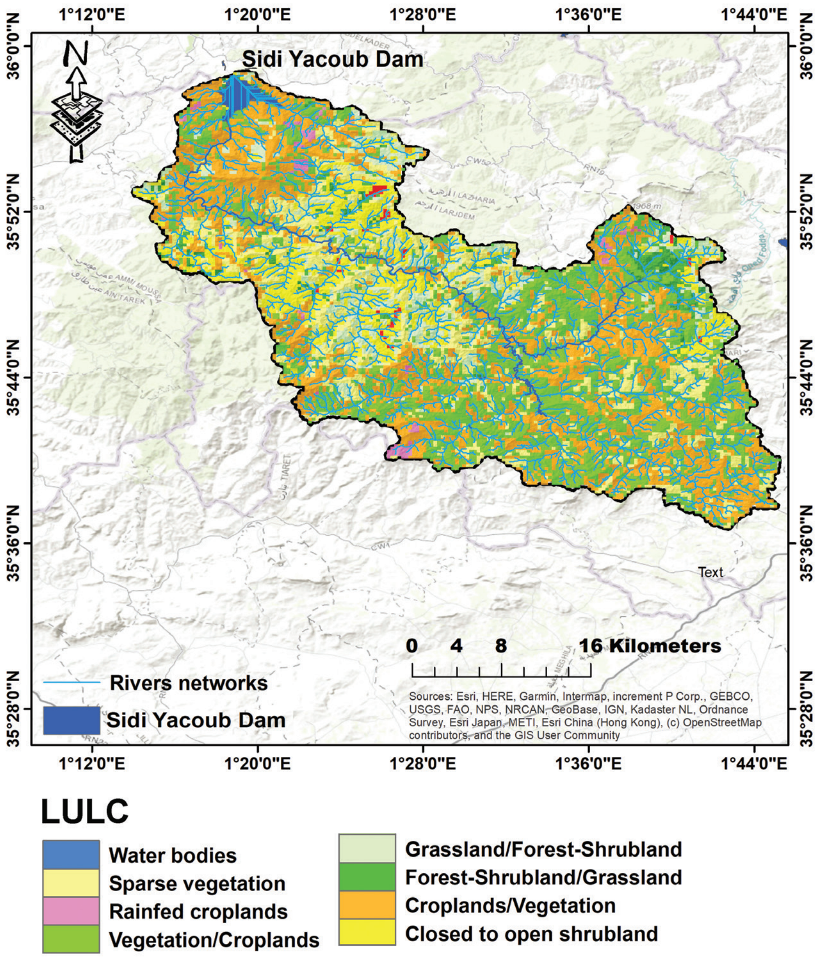

Figure 4. Land Cover Map of the Oued El Ardjem basin.

tial area of 434.28 km^2, constituting 46.69% of the catchment area, indicating geological formations from the Upper Cretaceous period formed under marine conditions. Lower marine Miocene (Ml) deposits occupy 79.71 km^2, accounting for 8.57% of the catchment area, suggesting sedimentary formations from the Miocene epoch formed under marine conditions. Middle Cretaceous (Cm) deposits cover a smaller area of 17.13 km^2, representing 1.84% of the catchment area, signifying geological formations from the Middle Cretaceous period. Marine Triacea (T) deposits span 38.14 km^2, comprising 4.10% of the catchment area, indicative of sedimentary formations from the Triassic period formed under marine conditions (Fig. 5). Lower marine Eocene (El) deposits cover 33.24 km^2,

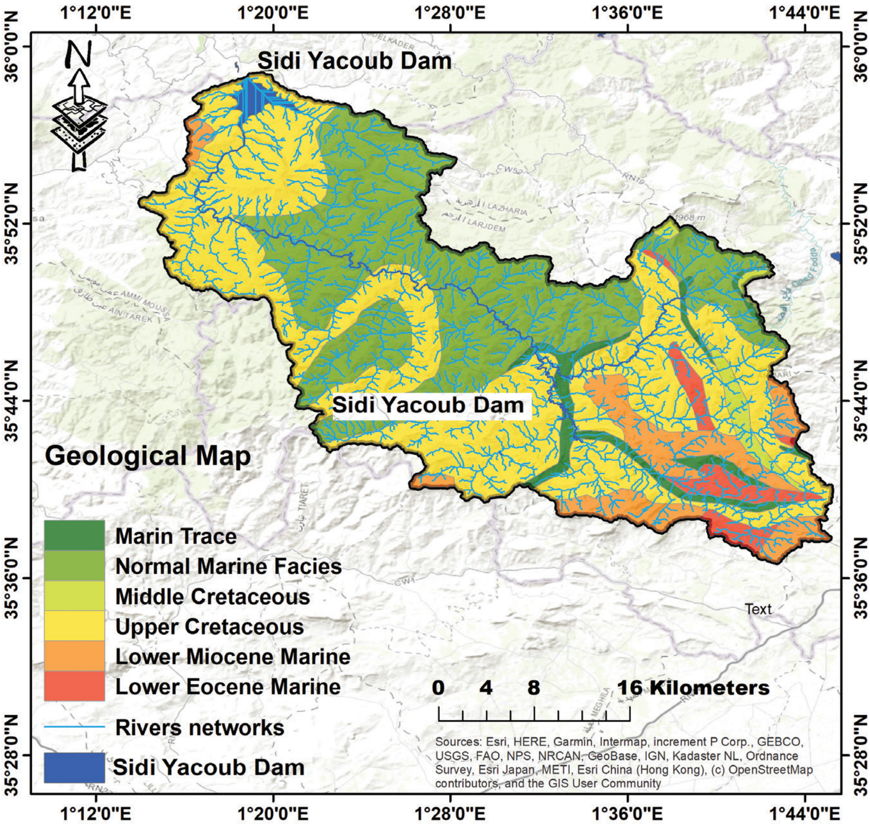

Figure 5. Geological map of the Oued El Ardjem basin.

accounting for 3.57% of the catchment area, suggesting sedimentary formations from the Eocene epoch formed under marine conditions. This analysis underscores the diverse geological composition of the Sidi-Yacoub catchment area, shaped by various sedimentary formations from different geological epochs.

The dam reservoir contains a total original volume of 285 Hm^3, the normal reservoir (RN) has a shoreline elevation of 264 m and the highest water level elevation (PHE) is 267.5 m. Capacity as of March 20, 2004 was 251.89 Hm^3 and the greatest water surface area was 931.80 ha. Figure 6 shows a map of the plan of the reservoir and represents the various transitions of the water in the Sidi-Yacoub reservoir (ANBT, 2004; Ouadja et al., 2021).

The Sidi-Yacoub dam was constructed as an earthen embankment with a watertight core, filters, protective drains, and both upstream and downstream embankments. The watertight core, composed of clay, is situated vertically in

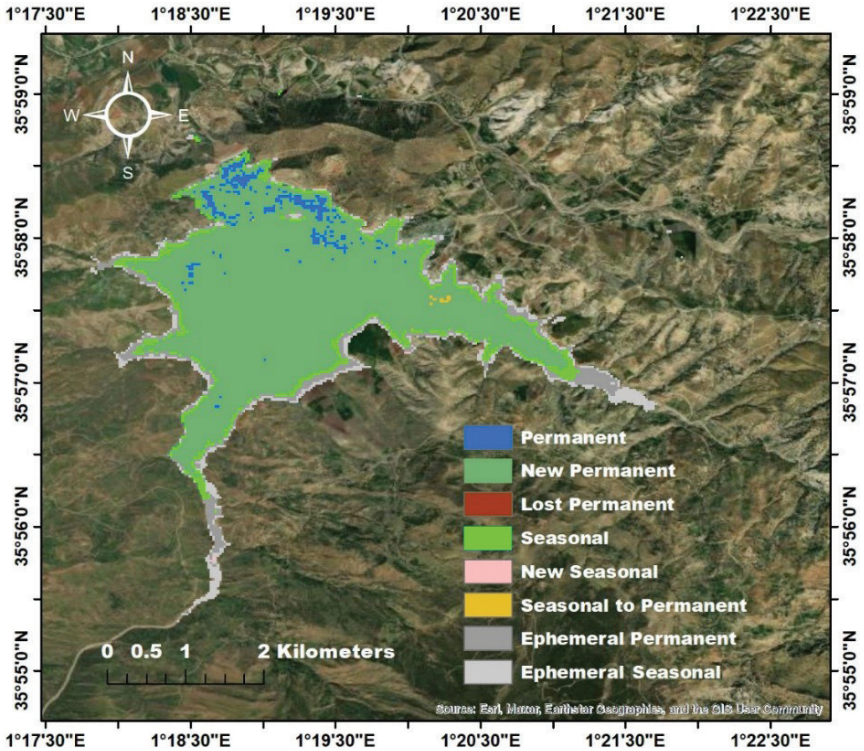

Figure 6. The Water Transitions map of the Sidi-Yacoub Reservoir.

the central section of the dam to enhance seismic safety measures. Surrounding the clay core are filters, positioned both upstream and downstream, consisting of materials adhering to precise particle size requirements. Additionally, the embankments are comprised of semi-permeable materials with carefully graded granulometry to facilitate controlled seepage (ANBT, 2017).

Water surfaces change over time, transitioning between different states based on climatic variability, hydrological dynamics, and human intervention. In this study, we analyzed these transitions using long-term satellite observations, identifying several categories: the emergence of new permanent and seasonal water bodies, areas that remained consistently water-covered, and regions where previously permanent or seasonal water was lost. Additionally, the analysis captures transformations between water states, for instance, seasonal water becoming permanent or ephemeral water disappearing entirely. To distinguish these states, we used temporal profiles, which provide monthly observations for each pixel, enabling the detection of water presence, absence, or data gaps. These profiles are instrumental in identifying significant hydrological changes, such as the gradual filling of a reservoir or the desiccation of a water body. Seasonality profiles further differentiate changes resulting from natural seasonal patterns from those due to more permanent transitions. As illustrated in Fig. 6, the classification includes categories such as "Permanent" (consistent presence over multiple years) and "New Permanent" (recently established, long-term water presence), based on consistent temporal criteria rather than visual appearance alone. Therefore, while the Sidi-Yacoub Reservoir appears full in static imagery, only areas that meet the strict thresholds for long-term presence are classified as permanent. This approach ensures a more objective, data-driven representation of water surface dynamics.

3. Databases

Data processing is conducted on a multi-software platform comprising ArcGIS 10.8, Excel 2016, and SAGA GIS. This setup enables the creation of a comprehensive database and facilitates data manipulation, updates, visualization, and tabulation. Table 1 provides an overview of the documents and software used in this process.

Table 1. The datasets used for the PISA modeling.

Datasets	Data sources	Year of release
Topographic data (Shuttle Radar Topography Mission SRTM)	Image Shuttle Radar Topography Mission (SRTM) of resolution 30 m obtained from the website: Earth explorer USGS (https://earthexplorer.usgs.gov/)	2000
Soil map	Digital Soil Map of the World (2019) https://www.fao.org/geonetwork/srv/en/metadata.show	2019
Land cover map	Landsat 8 ETM+ satellite image of 25/03/2019 with 30 m resolution, obtained from the website: United States Geological Survey (https://earthexplorer.usgs.gov/)	2019
Climatic data	The National Agency of Hydraulic Resources (ANRH)	1985–2013
Bathymetric data	Reservoir depth measurements HYD/CTSYSTEMS (ANBT)	2004

4. Methods and materials

4.1. Estimation of siltation using empirical formulas

Several empirical formulas exist for calculating sediment yield, each differing based on the author's perspective and the specific parameters considered, such as rainfall and characteristics of the study region (*e.g.*, mountainous areas, plateaus, semi-arid climates, tropics). In this study, the most applicable formulas were selected.

4.2. Fournier formula (1960)

Fournier (1960) developed a model to predict sediment yields at the outlet of a river regardless of its geographical location, using data from 104 watersheds from various regions around the globe. The formula is as follows:

$$E = \frac{1}{36}\left(\frac{P_m^2}{P_{an}}\right)^{2.65}\left(\frac{h^2}{s}\right)^{0.46}, \tag{1}$$

where E - mean annual specific sediment yield (t km^{-2} year^{-1}), P_m - mean monthly rainfall of the wettest month (mm), P_{an} - mean annual rainfall (mm), h - mean watershed elevation above sea level (m), and S - watershed area (km^2).

4.3. Gavrilovic's formula (1972)

The Erosion Potential Method (EPM) model, developed in the 1950s by Gavrilović in Yugoslavia, aims to assess the risks of soil water erosion and propose practices to limit soil loss. Successfully applied in alpine watersheds in Italy, this model has demonstrated its effectiveness. The empirical EPM model is based on mathematical laws applied using factors calculated and determined through field observations and laboratory analyses. The EPM model relies on the combination of water erosion factors, including precipitation, temperature, soil erodibility, soil protection, types of erosion, and slopes. Soil losses are quantified by the equations developed by Gavrilović (1972). The method used is the Gavrilović equation, known by the acronym EPM, which accounts for different types of erosion, unlike the majority of models that consider only one aspect of erosion. This model has been widely applied in Eastern Europe, Switzerland, Italy, and Iran (Bagherzadeh et al., 2011).

In this study, we applied this model to quantify erosion in the Sidi-Yacoub sub-watershed. All necessary data regarding the model parameters and the similarity of the physical conditions of the watershed were available. The application of the EPM model requires the integration of various parameters into a GIS. This coupling allows for the rapid and efficient assessment of soil losses and the estimation of the impact of each factor and their interactions. Erosion is expressed as the product of the above-mentioned factors. These parameters have been studied using remote sensing and field data, then integrated into the GIS.

The equation is given by the following expression:

$$E_S = 3.14 T P_0 \sqrt{Z^3} \tag{2}$$

where
E_S – Watershed erosion (t/km^2/year), T – Temperature, where $T = \sqrt{\frac{t_0}{10}} + 0.1$, t_0 – mean annual temperature (°C), P_0 – mean annual rainfall (mm), and Z – soil erodibility coefficient (0.01 to 1.5).

4.4. The Sogreah formula (1969)

The Sogreah formula, developed in 1969 from data collected from 27 watersheds in Algeria, including 16 that feed reservoir dams, establishes a relationship between sediment yields (denoted as A in t km^{-2} year^{-1}), annual flood runoff (R in mm), and watershed permeability (a). This formula is discussed in the works of Meddi et al. (1999) and El Mahi et al. (2012). The values used for the parameters R and a are weighted averages based on their respective coverage within the watershed. The equation is as follows:

$$D_S = aR^{0.15} \tag{3}$$

where Ds – specific erosion (t km^{-2} year^{-1}), a – permeability coefficient, and R – annual runoff (mm).

$$R = P_{an} + D_m \quad , \tag{4}$$

$$D_m = \frac{P_{an}}{\sqrt{0.9 + \left(\frac{P_{an}}{L}\right)}} \tag{5}$$

$$L = 300 + 25\,T + 0.5\,T^2 \,, \tag{6}$$

where P_{an} – mean annual rainfall (mm), D_m – annual runoff deficit (mm), T – mean temperature in Celsius (°C), and a is an empirical parameter that varies with the degree of watershed permeability, ranging from highly permeable to impermeable terrain. Degradation can be estimated by the following formulas:

- $8.5 < D_S < 74$ – high permeability a,
- $75 < D_S < 349$ – moderate permeability a,
- $350 < D_S < 1399$ – low to moderate permeability a,
- $1400 < D_S < 3199$ – low permeability a,
- $3200 < D_S$ – impermeable a.

4.5. Estimation of siltation using PISA model

The Prediction Model for Siltation in Artificial Reservoirs (PISA) is a statistical parametric model of multiple linear regression designed for assessing sedimentation in reservoirs. It has been formulated to be easily and rapidly applicable, without the need for data collected directly in the field, but rather from input variables obtained from traditional mapping and analysis of time series of hydrological variables. PISA has been utilized in 42 water resource projects (hillside reservoirs) in Italy by Bazzoffi et al. (1996, 1997, 1998), Bazzoffi and Van Rompaey (2003), Ouechtati and Baldassare (2011) in Tunisia, and Benkhadja et al. (2013) in Algeria.

The PISA model is based on climatic, morphological, and physical parameters of a watershed, which can provide a prediction of the average annual sedimentation rate in artificial reservoirs expressed in $m^3.km^{-2}$ of sediment. It allows for an indirect estimation of soil erosion upstream of the dam. The model is given by the following relationship:

$$Y = 4259334 - 1.3898A + \\ 102.9576(SER)0.5 - 9.84435PEN - 0.31\bar{P} + 116.718D \tag{7}$$

where Y is the Sedimentation index expressed by the annual volume of wet sediments deposited into the reservoir per unit area of the watershed ($m^3\,km^{-2}$), A is the watershed area (km^2), SER is the erodible surface corresponding to the cultivable surface added to 1/16 of the non-cultivable agroforestry surface (km^2), PEN is the average slope of the watershed ($m\,m^{-1}$); A is the mean annual precipitation (mm), and D is the drainage density ($km\,km^{-2}$).

The formula for the erodible surface corresponding to the cultivable surface added to 1/16 of the non-cultivable agroforestry surface (km^2) is given as:

$$SER = Sc + \left(\frac{1}{16}\right) \tag{8}$$

where A is the cultivated surface area, referring to agricultural land (km^2), and Snc is the non-cultivated agroforestry surface area (km^2). For this study, Sc, Snc, and SER were estimated to be 386, 544, and 420 km^2, respectively.

The method presented in this section involves isolating the hydrographic network and calculating the drainage density (D) for the watershed.

$$D = \frac{\sum L}{A}, \tag{9}$$

where $\sum L$ is the total length of the river (km); and A is the watershed area (km^2). For this study, $\sum L$ and A were equal to 1,132.81 km and 930 km^2, respectively, and D was estimated to be 1.21 $km\,km^{-2}$.

Computing the slope (SER) of a surface mathematically requires elevation data to represent the terrain. The slope at any given point on the surface is typically calculated as the rate of change in elevation per unit distance. In this study, the slope map was generated using the ArcGIS Toolbox.

The PISA model offers several advantages, particularly through its formulation for use during the construction phase of a dam in regions with limited or no hydrological data. Another key benefit is its flexibility, as it can be applied to watersheds of various sizes–unlike the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978), which is constrained to small field hillslope scales. Although the USLE is widely used for predicting soil erosion, it presents limitations at larger or more heterogeneous scales. Specifically, it is designed for small, relatively uniform areas and does not account for complex

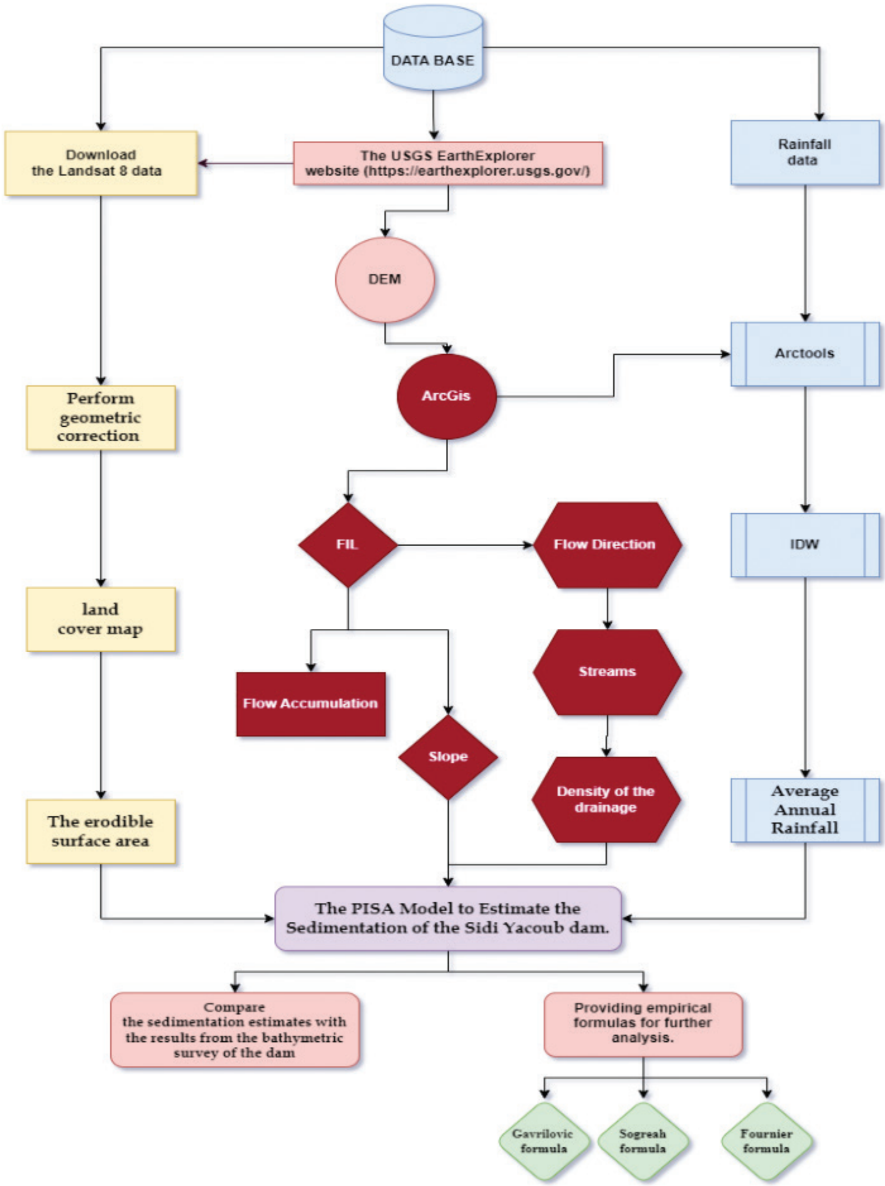

Figure 7. The flowchart used in this study.

terrains, short-term erosion events, or processes such as gully erosion and mass wasting. Moreover, the USLE simplifies soil properties, assumes uniform slopes, and may not fully capture dynamic land management practices or the impacts of climate change. It also overlooks sediment transport and deposition. To enhance its global applicability, it would require adaptations, including finer-resolution spatial data, climate projections, and considerations of various erosion processes. Additionally, the PISA model can be effectively employed during the reservoir operation phase to support proper management measures. These measures help reduce sediment inflow at the dam, mitigate related environmental impacts (Bazzoffi and Baldassarre, 2000; Bazzoffi and Van Rompaey, 2003), and restore the reservoir's original capacity (Ouechtati and Baldassarre, 2011). In its first application in Algeria, Benkhadja et al. (2013) assessed sedimentation using the PISA model, offering a significant contribution to sediment management in the region.

For the first time, PISA was applied in Algeria when Benkhadja et al. (2013) assessed sedimentation in the K'sob Dam, part of the K'sob River watershed, using the model. The final result from the model application was $Y = 1{,}822$ m^3 km^{-2} per year, equivalent to an annual specific erosion of 2,915 t km^{-2}. This study confirmed the reliability of the PISA model for estimating soil losses and dam sedimentation in a semi-arid area. In Tunisia, Ouechtati and Baldassarre (2011) evaluated the sedimentation of the Siliana and Lakhmess dams located in the Siliana watershed. The sedimentation index estimated using the PISA model for the watershed was 1,356.6 m^3 k^{-2} year^{-1}. Integrating dam sedimentation volumes into sediment volume calculations indicates a clear trend towards an increase in actual soil losses. Thus, they observed, for the Siliana dam, compatibility between the estimates derived from the PISA model and field measurements. Figure 7 is a flowchart that explains the procedures used in this study.

5. Results

5.1. Empirical formulas

Table 2 presents the results obtained from applying three distinct sedimentation estimation formulas: the Fournier Formula (1960), Gavrilovic's Formula, and the Sogreah Formula (1969). Each equation offers a unique approach to estimating sedimentation rates based on specific input parameters and mathematical formulations.

For the Fournier Formula (1960), the parameters used were $P_m = 67$ mm, $P_{an} = 419$ mm, $H = 745$ m, and $S = 930$ km^2. Based on these inputs, the calculated sedimentation rate was $E = 273$ t km^{-2} year^{-1}, with an annual sediment yield of 0.20 H m^3 year^{-1}. Developed by Fournier in 1960, this formula offers a methodology that considers various factors influencing sedimentation processes, including precipitation and watershed characteristics.

In the case of Gavrilovic's Formula, the parameters $P_{an} = 419$ mm, $T = 25$ °C, and $Z = 0.6$ were utilized. Applying these values resulted in a sedimentation rate of E = 1,713 t km^{-2} year^{-1}, corresponding to an annual sediment yield of

Table 2. Results of siltation estimation at Sidi-Yacoub Dam using empirical formulas.

The Fournier Formula (1960)					
P_m (mm)	P_{an} (mm)	H (m)	S (km^2)	E (t km^{-2} year^{-1})	E (Hm^3 year^{-1})
67	419	745	930	273	0.20
The Gavrilovic's formula (1972)					
P_{an} (mm)	T_0	Z	E_S (t km^{-2} year^{-1})	E_S (Hm^3 year^{-1})	–
419	25	0.6	1713	1.23	–
The Sogreah formula (1969)					
a	P_{an} (mm)	R (mm)	A (t km^{-2} year^{-1})	As (Hm^3 year^{-1})	–
700	419	383.93	1709	1.22	–

1.23 H m^3 year^{-1}. Gavrilovic's Formula, known for its comprehensive approach, considers factors like temperature and elevation to enhance the accuracy of sedimentation predictions, making it suitable for diverse geographical contexts.

Similarly, the Sogreah Formula (1969) offers insights into sedimentation rates with parameters $a = 700$, $P_{an} = 419$ mm, and $R = 383.93$ mm. This formula yields a sedimentation rate A of 1708.98 t/km^2/year and an annual sediment yield (As) of 1.22 H m^3 year^{-1}. Developed by Sogreah in 1969, this formula integrates parameters such as soil characteristics and rainfall patterns to estimate sedimentation, making it particularly applicable in hydrological modeling and watershed management studies. These findings underscore the calculated sedimentation rates and annual sediment yields derived from the specific parameters provided for each formula. Despite variations in input parameters and formulations, the results demonstrate a notable consistency in estimating sedimentation using Gavrilovic's and Sogreah's models.

5.2. Estimating the siltation rate using bathymetric surveys

Estimating the siltation rate using bathymetric surveys provides crucial insights into the gradual accumulation of sediment within dam reservoirs over time. In 1986, an initial study conducted by the GRAĐEVINSKI INSTITUT ZAGREB Yugoslavia (1983) revealed that the reservoir of the dam originally boasted a total volume of 285 H m^3, with a standard retention level set at 264 meters (ANBT, 2004).

Fast forward to 2004, a bathymetric survey carried out by the HYD/CTSYSTEMS company recorded a significant water loss volume of 16 H m^3 since the dam's initial filling in 1985. This substantial loss reduced the reservoir's volume to 252.85 H m^3. Notably, during the survey, a sediment elevation of approximately 10 meters was observed between the curve of the year of filling and 18 years later, indicating progressive siltation within the dam reservoir.

The recorded data provides valuable insights into the surface area and capacity of the dam at different retention levels. At the normal retention level of

264.00 meters, the dam's surface area spans 879.18 hectares, with a corresponding capacity of 252.84 H m^3. Comparatively, at the PHE level (267.5 meters), the surface area expands to 931.8 hectares, accommodating a capacity of 284.01 Hm^3 (ANBT, 2004).

Examining the capacity curve, referenced from the year of dam filling in 1985, reveals a substantial reduction in capacity over time. Specifically, the dam's capacity has decreased by 33.16 H m^3, representing an 11.59% loss to 2004. This decline in capacity underscores the ongoing challenge posed by sedimentation within the reservoir, necessitating continual monitoring and management strategies to mitigate its impacts.

Overall, the evolution of capacity loss within the dam reservoir, particularly at the normal retention level, highlights the importance of regular bathymetric surveys in assessing siltation rates and informing effective sediment management practices. Such monitoring efforts are essential for maintaining reservoir functionality, preserving water storage capacity, and safeguarding downstream ecosystems and water resources. The evolution of the capacity loss of the dam reservoir at the normal retention level (264 m) is summarized in Tab. 3.

Figure 8 provides a visual representation of the reservoir's capacity evolution shown as changes in water level elevation over time. Following the bathymetric survey conducted in 2004, the current capacity (2017) of the reservoir stands at 227.72 H m^3. This assessment reveals an average annual capacity loss of 1.79 H m^3 $year^{-1}$ from 1986 to 2004, highlighting the gradual reduction in storage capacity attributed to sedimentation.

An intriguing observation from Fig. 9 is the depiction of surface area evolution corresponding to water level elevation changes. The current surface area of the reservoir, as determined by the bathymetric survey, measures 879.18 hect-

Table 3. Comparison of volume and area at Normal Retention Level (RN: 264.0 m).

Volume			
	1985 HIDROELEKTRA	2004 HYD/CTSYSTEMS	2017
Capacity (H m^3)	285	252.85	227.72
Capacity loss (H m^3)	-	32.15	57.28
Year number	-	18	32
Annual capacity loss (H m^3)	-	1.79	1.79
Area			
	1985 HIDROELEKTRA	2004 HYD/CTSYSTEMS	2017
Surface (ha)	925	879.18	843.72
Surface loss (ha)	-	45.82	81.28
Number of years	-	18	32
Loss (ha $year^{-1}$)	-	2.54	2.54

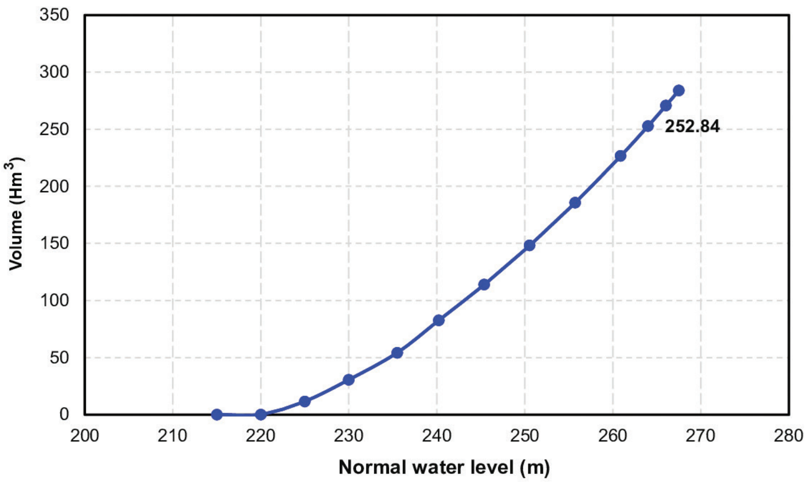

Figure 8. Reservoir capacity curve based on bathymetric surveys of 2004.

ares. Analysis of the data indicates an average annual surface area loss of 2.54 hectares per year during the period from 1986 to 2004.

The bathymetric survey campaign conducted at the Sidi-Yacoub dam in the Wilaya de Chlef played a pivotal role in enabling the ANBT to effectively monitor the evolution of siltation levels within the reservoir. This comprehensive analysis serves as a crucial tool for the rational and precise management of the

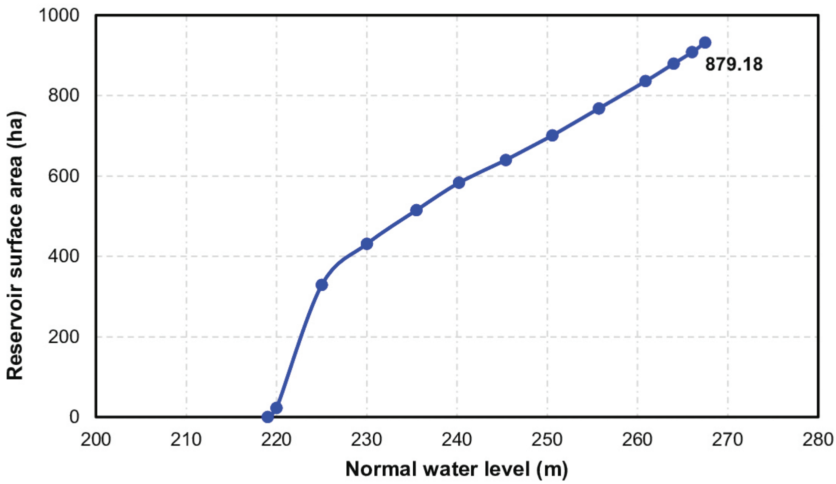

Figure 9. Evolution of the water surface area of Sidi Yacoub dam reservoir.

dam's capacity. The consortium of companies, HYDRODRAGAGE-C.T.SYSTEMS, undertook a terrestrial topographic survey covering 487.20 hectares of exposed areas within the reservoir, complemented by a bathymetric survey spanning 444.60 hectares. Consequently, the total surveyed area encompasses 931.8 hectares, with approximately 56% surveyed through terrestrial methods and 49% through bathymetric survey techniques (ANBT, 2004).

Since its filling in 1986, the Sidi-Yacoub dam has experienced a notable loss of approximately 33.15 Hm^3 in volume by September 2004, equating to around 11.6% of its initial capacity of 285 Hm^3. This corresponds to an average annual loss of approximately 1,790,000 m^3/year. The primary outcome of the survey lies in the estimation of capacity and surface area at both the PHE and RN levels, providing crucial insights into the reservoir's current state and aiding in strategic decision-making regarding its management. The primary result obtained is the estimation of the capacity and surface area at the PHE and RN levels, which are represented in Figs. 8 and 9.

5.3. Estimating the siltation rate using the PISA model.

To estimate the siltation rate using the PISA model, several parameters need to be determined, including the erodible surface area and characteristic surfaces within the Sidi-Yacoub watershed. The calculation of these parameters involves utilizing GIS software, such as ArcGIS, and satellite imagery data.

The erodible surface is defined as the area susceptible to degradation under the influence of both natural and human factors. Within the Sidi-Yacoub watershed, characteristic surfaces are grouped into cultivated and non-cultivated categories. Cultivated surfaces typically include areas used for agriculture, while non-cultivated surfaces comprise relatively dense wooded areas, such as forests, with limited human intervention. Utilizing ArcGIS software and the pre-classified land cover map (30-meter resolution, April 2019) downloaded directly from the USGS Earth Explorer platform (https://earthexplorer.usgs.gov/), characteristic surfaces within the watershed were delineated. The map, part of a standardized USGS dataset (*e.g.*, NLCD or MODIS MCD12Q1), was clipped to the watershed boundary and reclassified as needed for analysis. For this study, the cultivated surface (*Sc)*, non-cultivated surface (*Snc*), and total erodible surface (*SER*) were estimated at 386 km^2, 544 km^2, and 420 km^2, respectively. Additionally, parameters such as the length of the river network (L) and the total area of the watershed (A) are essential for model calculations. In this case, L was determined to be 1,132.81 km, and A was 930 km^2. Furthermore, parameter D represents the mean distance between drainage networks and was estimated at 1.21 km km^{-2}.

By inputting these parameters into the PISA model, the siltation rate within the Sidi-Yacoub watershed could be estimated. This model enables the assessment of potential siltation impacts, aiding in the development of strategies for effective sediment management and watershed conservation. After calculating each parameter constituting the PISA model, the annual siltation index of our watershed can be easily defined. Therefore, we present the results in Tab. 4.

To convert sediment volume to weight, a sediment density of 1.3 t m^{-3} was assumed. This density value is commonly used in sedimentation studies and represents the average density of sediment deposits. Given that the siltation

Table 4. Determination of the siltation rate of the Sidi-Yacoub dam based on PISA model

Year	Watershed area, A (km^2)	Erodible surface, SER (km^2)	Average slope of the watershed, PEN (grades)	Mean annual precipitation, Pan (mm)	Drainage density, D (km km^{-2})	Sedimentation index, Y (m^3 km^{-2})	Y(t)
1985	930	420	14.92	572.05	1.21	1,060.44	821,839.40
1986	930	420	14.92	398.08	1.21	1,114.37	797,201.77
1987	930	420	14.92	509.76	1.21	1,079.75	772,435.28
1988	930	420	14.92	496.22	1.21	1,083.95	775,438.04
1989	930	420	14.92	533.40	1.21	1,072.42	767,192.66
1990	930	420	14.92	497.15	1.21	1,083.66	775,231.49
1991	930	420	14.92	451.86	1.21	1,097.70	785,275.72
1992	930	420	14.92	378.51	1.21	1,120.44	801,542.23
1993	930	420	14.92	337.70	1.21	1,133.09	810,593.99
1994	930	420	14.92	396.49	1.21	1,114.86	797,555.88
1995	930	420	14.92	381.82	1.21	1,119.41	800,809.18
1996	930	420	14.92	379.80	1.21	1,120.03	801,255.38
1997	930	420	14.92	489.08	1.21	1,086.16	777,021.47
1998	930	420	14.92	472.77	1.21	1,091.21	780,637.48
1999	930	420	14.92	404.36	1.21	1,112.42	795,809.76
2000	930	420	14.92	362.52	1.21	1,125.39	805,088.58
2001	930	420	14.92	288.68	1.21	1,148.28	821,464.02
2002	930	420	14.92	383.60	1.21	1,118.86	800,413.69
2003	930	420	14.92	355.94	1.21	1,127.43	806,547.80
2004	930	420	14.92	370.04	1.21	1,123.06	803,420.91
2005	930	420	14.92	337.48	1.21	1,133.16	810,641.99
2006	930	420	14.92	391.73	1.21	1,116.34	798,611.18
2007	930	420	14.92	557.15	1.21	1,065.06	761,924.68
2008	930	420	14.92	453.36	1.21	1,097.23	784,941.99
2009	930	420	14.92	473.06	1.21	1,091.13	780,575.13
2010	930	420	14.92	399.92	1.21	1,113.80	796,794.70
2011	930	420	14.92	383.71	1.21	1,118.82	800,389.18
2012	930	420	14.92	460.36	1.21	1,095.06	783,390.64
2013	930	420	14.92	460.72	1.21	1,094.95	783,310.84
2014	930	420	14.92	380.68	1.21	1,119.76	801,061.25
2015	930	420	14.92	368.42	1.21	1,123.56	803,780.14
2016	930	420	14.92	320.30	1.21	1,138.48	814,451.68
2017	930	420	14.92	394.35	1.21	1,115.53	798,030.64

index data for the Sidi-Yacoub watershed ranged from 1,060.43 to 1,148.28 $m^3\,km^{-2}\,year^{-1}$, with an average of 1,107.75 $m^3\,km^{-2}\,year^{-1}$, we can calculate the corresponding sediment weight using the assumed density.

For example, let's take the average siltation index of 1,107.75 $m^3\,km^{-2}\,year^{-1}$. Using the assumed sediment density of 1.3, we can calculate the sediment weight per unit area per year as follows:

Sediment weight = Volume × Density = 1,107.75 $m^3\,km^{-2}\,year^{-1} \times 1.3\ t\,m^{-3} \approx$ 1,439 $t\,km^{-2}\,year^{-1}$

This calculation yields an approximate sediment weight of 1,439 tons per square kilometer per year. The variation in the siltation index of Sidi-Yacoub, as indicated in Fig. 10, reveals fluctuations in sedimentation rates 1985–1986, 1989–1990, and 2008–2009 exhibited the lowest siltation rates (Fig. 10). These variations are attributed to fluctuations in annual average precipitation, with high precipitation contributing to strong siltation indices and low precipitation associated with weak siltation indices. Such insights are vital for understanding the dynamics of sedimentation within the watershed and guiding effective sediment management strategies.

The histograms presented in Figs. 11 and 12 provide a comparative analysis of the specific degradation obtained from two sedimentation estimation models: the PISA model and the Sogreah model, and the PISA model and the Gavrilovic model, respectively. According to the data provided, the specific degradation obtained by the PISA model for the period 1985–2017 was 47,500 $t\,km^{-2}$. Conversely, the specific degradation calculated by the Sogreah model for the same

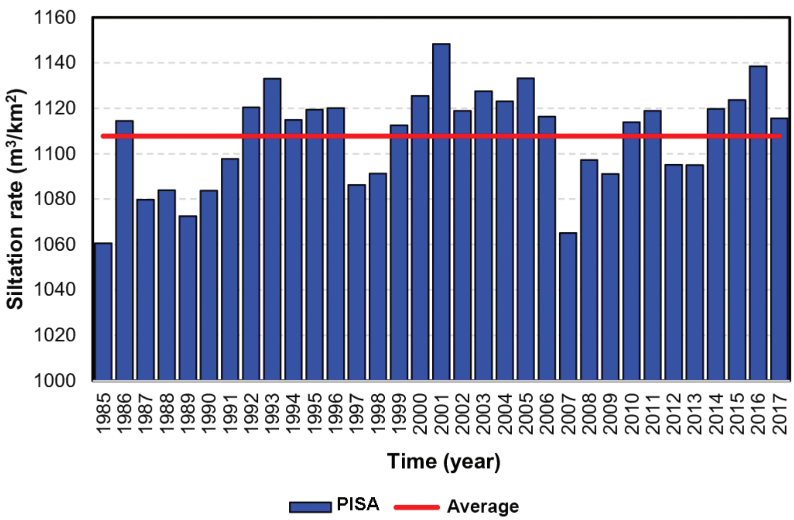

Figure 10. Estimating the siltation rate using the PISA model.

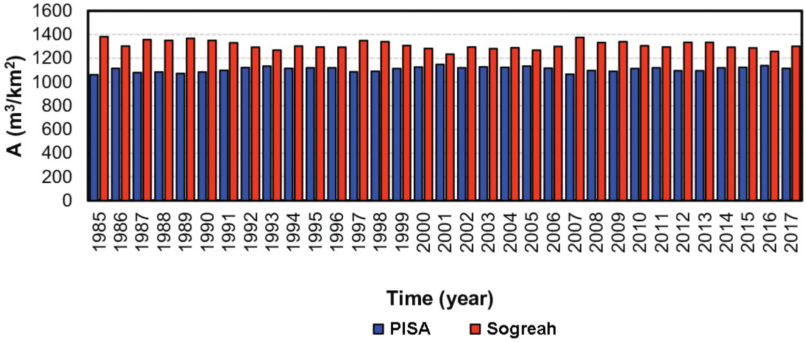

Figure 11. The specific solid deposit by the PISA and Sogreah models.

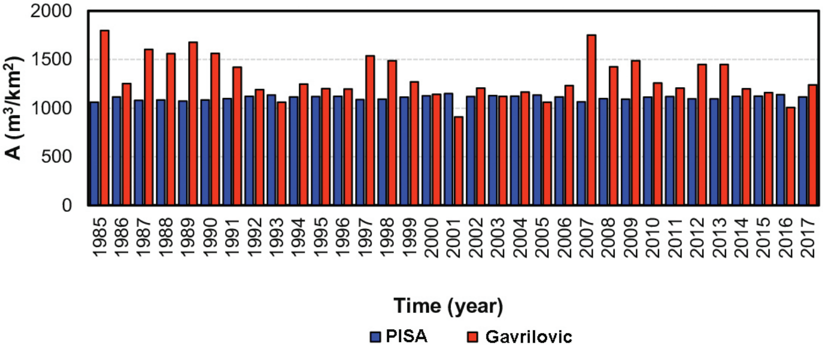

Figure 12. The specific solid deposit by the PISA and Gavrilovic models.

period was 58,000 t km^{-2}. Comparing these values, we observe that the specific degradation obtained by the Sogreah model was approximately 1.22 times larger than that obtained by the PISA model. This differrence highlights variations in the estimations provided by the two models. Such comparative analysis is essential for understanding the strengths and limitations of each model and for making informed decisions regarding sediment management and reservoir capacity planning.

The quantification of sediment transported to the outlet (Sidi-Yacoub dam) consists of adding each sediment rate produced by this watershed. The difference between the PISA model and the actual measurements was calculated by formula (12), and the results obtained are presented in Tab. 5:

$$\Delta = \frac{Y' - Y}{Y} * 100\% , \tag{10}$$

Table 5. Deviation in values of siltation assessed by the PISA model and the bathymetric survey (1985/2004).

Basin	Y (m^3 km^{-2})	Y (H m^3)	Y' (H m^3)	Δ (%)
Sidi Yacoub	22 132	20.58	32.22	−36.13

where Δ is the deviation of siltation between the PISA model and the bathymetric survey in percent (%), Y' is the Siltation of the dam between 1985 and 2004, measured by bathymetric survey (H m^3), and Y is the siltation of the dam between 1985 and 2004, estimated with the PISA model (H m^3).

The deviations between the PISA model and other siltation estimation methods for the periods 1985–2004 and 1985–2017 highlight notable discrepancies in the results. From 1985 to 2004, the PISA model estimated siltation behind the Sidi-Yacoub Dam at 20.58 H m^3, whereas a bathymetric survey recorded a higher value of 32.22 H m^3—a difference of −36.1%. This finding indicates that the PISA model underestimated the siltation rate by 36.1%. During the period 1985–2017, the siltation estimated using the Sogreah formula was 22.02% higher than the PISA model's estimate, and the Gavrilovic formula's estimate exceeded the PISA model value by 22.67%. These discrepancies suggest that, despite providing useful insights, the PISA model tends to underestimate siltation rates compared to bathymetric surveys and empirical formulas.

These results illustrate the differences in sediment estimations between the PISA model and empirical formulas over the period 1985–2017. The deviations indicate discrepancies between the model predictions and the empirical measurements, highlighting the need for further refinement or adjustment of the models for improved accuracy in estimating sedimentation levels. Figure 13 presents the soil erosion risk map based on the PISA model for the Oued El Ardjem basin, indicating that most of the basin is at high to very high risk of erosion. Figure 14 provides a comparative analysis of sedimentation estimates for the Sidi-Yacoub Dam from 1985 to 2004, derived from various methods, including the PISA model, the Fournier formula, the Sogreah formula, the Gavrilovic formula, and bathymetric survey measurements. The PISA model estimated sedimentation at 20.58 H m^3, significantly higher than the 6.15 H m^3 estimated by the Fournier formula. The Fournier formula yielded the lowest estimate among all methods, substantially underestimating sedimentation relative to the other models and the bathymetric survey. The Sogreah and Gavrilovic formulas produced comparable results, estimating sedimentation at 24.44 H m^3 and 24.75 H m^3, respectively–slightly higher than the PISA model's estimate and in close agreement with each other. However, the bathymetric survey reported the highest sedimentation volume at 32.22 H m^3, highlighting significant discrepancies between empirical models and actual measurements. These differences may reflect inherent limitations or inaccuracies in the models, underscoring the value of bathymetric surveys in providing more accurate and reliable sedimentation data.

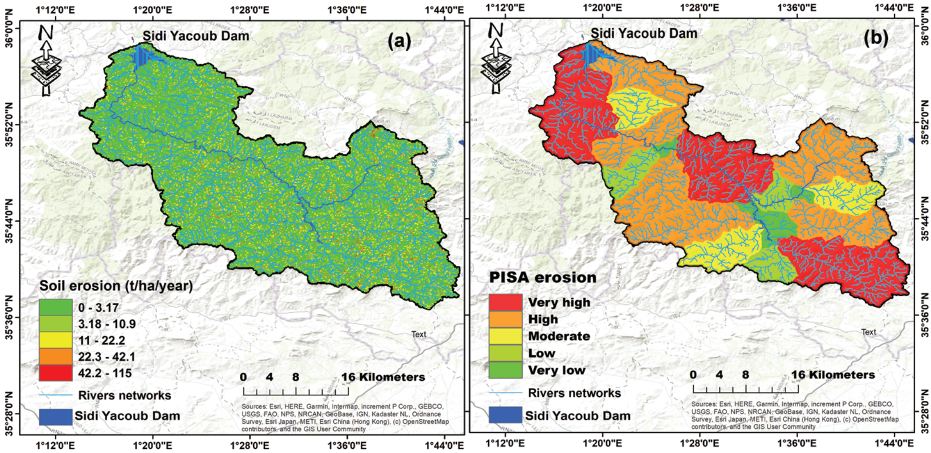

Figure 13. Comparative soil erosion maps of the Oued El Ardjem basin based on the PISA model. (*a*) Distribution of erosion potential with values ranging from 0 to 115, showing areas from very low to very high erosion risk and (*b*) Categorized erosion risk levels from very low to very high, providing a simplified visual interpretation of erosion potential across the basin.

Overall, the comparison highlights variations in sediment estimation results obtained from different methods. While the PISA model provides a higher estimation compared to the Fournier formula, the Sogreah and Gavrilovic formulas yield estimations closer to each other but slightly higher than that of the PISA

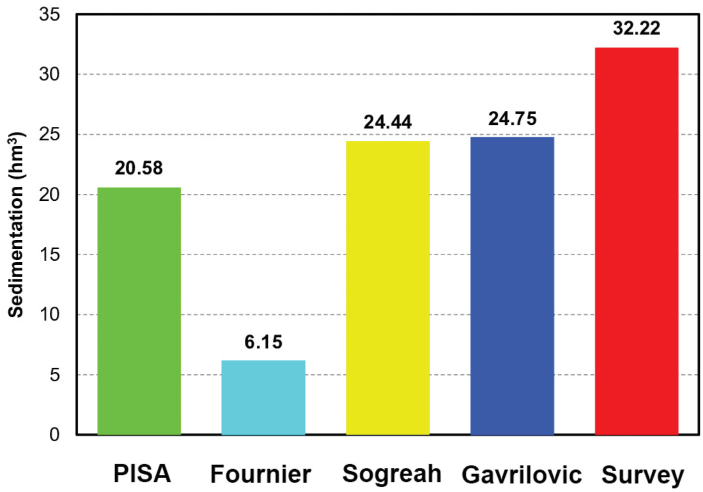

Figure 14. Histogram comparing sedimentation estimated by the PISA model, empirical formulas (Fournier, Sogreah, and Gavrilovic), and bathymetric survey for the period 1985–2004.

model. The bathymetric survey measurement indicates the greatest sedimentation, suggesting potential discrepancies between modeled estimations and actual measurements. These differences underscore the importance of continued refinement and validation of sedimentation modeling approaches to improve accuracy and reliability in estimating sedimentation levels.

6. Discussion

This study assessed the siltation rate of the Sidi-Yacoub Dam through a multidisciplinary approach integrating empirical methods, GIS, and bathymetric surveys. The findings yield critical insights into reservoir sedimentation dynamics and underscore the sediment management challenges faced by dams in Algeria and other semi-arid regions with similar conditions. Between 1985 and 2004, the Sidi-Yacoub Dam experienced a substantial capacity loss of 32.22 million cubic meters (H m^3), corresponding to 11.6% of its initial capacity of 285 H m^3. This reduction is primarily attributed to sediment accumulation, with an average annual siltation rate of 1.79 H m^3 $year^{-1}$. Such results align with observations of other dams in Algeria and comparable semi-arid contexts, where soil erosion and high sediment yields from surrounding watersheds contribute to persistent siltation challenges. Bathymetric analysis further confirmed this progressive process, revealing a sediment elevation increase of approximately 10 meters during the 1985–2004 period. This ongoing loss in storage capacity directly affects water availability for irrigation, potable water supply, and hydroelectric power generation, highlighting the urgent need for effective sediment management strategies to safeguard the dam's long-term functionality.

Furthermore, the study compared results from several empirical models (Fournier, Gavrilovic, Sogreah) and the PISA model against bathymetric measurements. Notable discrepancies emerged, underscoring the limitations of these empirical approaches and the need for local calibration to enhance the accuracy of siltation estimates. For instance, the PISA model estimated a siltation rate of 20.58 H m^3, which was 36.1% lower than the 32.22 H m^3 recorded by bathymetric surveys. This underestimation may be attributed to the complex nature of erosion and sedimentation processes within the watershed, as well as the variability of climatic and hydrological conditions that may not be fully captured by the model. Similarly, the Fournier formula, which yielded a considerably lower estimate of 6.15 H m^3, appeared less suitable for the Sidi-Yacoub watershed because it does not account for critical factors such as slope and soil characteristics. In contrast, the Gavrilovic and Sogreah formulas—both incorporating parameters like temperature, rainfall, and soil permeability—produced estimates closer to the bathymetric data, at 24.75 H m^3 and 24.44 H m^3, respectively. However, these models still slightly overestimated siltation relative to the bathymetric measurements, with deviations of 22.67% and 22.02%. Such discrepancies highlight the importance of tailoring sedimentation models to local conditions and the potential advantages of employing more sophisticated models that integrate a broader range of data inputs.

The study also explored the influence of climatic factors and land use on siltation rates. Annual variations in rainfall emerged as a key driver of sediment input to the reservoir, with high-rainfall years (*e.g.*, 1998–1999 and 2001–2002) corresponding to elevated siltation rates, while drier years (*e.g.*, 1985–1986 and 2008–2009) exhibited lower rates of siltation. This finding underscores the role of intense rainfall events in accelerating soil erosion and transporting sediments into the reservoir. Regarding land use, the analysis revealed that 45.43% of the watershed comprises bare soil, substantially increasing the risk of erosion. In contrast, vegetated areas, covering 46.3% of the watershed, function as natural buffers that mitigate soil erosion. These results highlight the necessity of land management strategies such as reforestation, soil conservation, and sustainable agricultural practices to reduce erosion and sediment inputs into the reservoir.

The implications of these findings for sediment management in the Sidi-Yacoub Dam and similar systems are far-reaching. The ongoing loss of capacity due to siltation not only undermines the sustainability of water resources but also endangers the socio-economic activities dependent on these dams. Consequently, effective sediment management strategies are critical to mitigate the adverse impacts of siltation. Such strategies may include sediment dredging—albeit costly—to restore reservoir storage capacity; watershed management interventions, such as reforestation, terracing, and grazing control, to reduce soil erosion; and flow regulation measures designed to facilitate downstream sediment transport, thereby decreasing accumulation within the reservoir.

7. Conclusions

This study aimed to estimate the foreseeable siltation of the Sidi-Yacoub Dam reservoir by employing empirical formulas and bathymetric data to assess reductions in its initial capacity. Between the dam's commissioning in 1985 and September 2004, it experienced a substantial capacity loss of approximately 32.22 H m^3—an 11.6% decrease from the initial 285 H m^3. This reduction primarily stems from sediment accumulation at an average annual siltation rate of 1.79 H m^3 $year^{-1}$. The findings provide a comprehensive understanding of the reservoir's sedimentation dynamics and highlight the urgency of adopting effective sediment management strategies. Nevertheless, potential remains for refining and improving the assessment of annual specific degradation rates.

New methodologies, including the integration of spatially distributed climatic data and the incorporation of both morphological and climatic parameters, show promise in enhancing the precision of siltation rate estimates. Of particular note, application of the PISA model to the Sidi-Yacoub Dam yielded noteworthy yet somewhat inconsistent results. The PISA model estimated a siltation volume of 20.58 H m^3, corresponding to a specific erosion rate of 1,107.75 m^3 km^{-2} year^{-1}. However, a pronounced deviation emerged when comparing this figure with bathymetric data, which indicated 32.22 H m^3—reflecting a discrepancy of –36.13%. By contrast, the Sogreah model deviated by –24%, demonstrating closer alignment between its estimates and empirical measurements.

These discrepancies underscore the limitations of existing empirical models in accurately estimating siltation, particularly under complex, watershed-specific conditions such as those observed at the Sidi-Yacoub Dam. Consequently, further research and the development of more advanced sedimentation modeling approaches remain essential. Such efforts will facilitate more precise assessments and, in turn, more effective management of reservoir capacity and water resources, especially given evolving climatic conditions and land use patterns. Effective sediment control is vital to the long-term functionality and sustainability of dams, and ongoing improvements in both modeling and management strategies will help ensure that water resources remain available for crucial uses, including irrigation, drinking water supply, and power generation.

Supplementary materials – Not applicable.

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SAŽETAK

Korištenje empirijskih metoda, GIS-a i batimetrijskog istraživanja za procjenu zamuljivanja brane Sidi-Yacoub (sjeverozapadni Alžir)

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Zamuljivanje brana je ključno pitanje koje zahtijeva hitna rješenja kroz participativni pristup koji uključuje različite teritorijalne dionike. Ovaj pristup ima za cilj ublažiti unos sedimenta i očuvati intrinzična svojstva vodnih resursa unutar brana. U tom kontekstu, ova studija procjenjuje brzinu zamuljivanja brane Sidi-Yacoub, smještene u slivu Oued Lardjem, i identificira primarne uzroke koji doprinose ovom fenomenu. Korištena metodologija kombinira analizu tematskih karata s primjenom modela predviđanja sedimentacije Previsioni Interimento Serbatoi Artificiali (PISA) za izračun različitih parametara. Procijenjeni godišnji prosjek krutih tvari koje dospijevaju u akumulaciju iznosi 376,74 $m^3\,km^{-2}\,god^{-1}$, što odgovara ukupnoj stopi zamuljivanja od 0,46 $Mm^3\,god^{-1}$. Očuvanje ove hidraulične infrastrukture ključno je za optimizaciju korištenja vodnih resursa u regiji i podršku njezinom gospodarskom i društvenom razvoju. Ova studija naglašava važnost integriranja empirijskih metoda, geografskih informacijskih sustava i batimetrijskih istraživanja kako bi se postiglo sveobuhvatno razumijevanje dinamike zamuljivanja. Nalazi pokazuju da je brana pretrpjela značajan gubitak kapaciteta od približno 32,22 H m^3 između 1985. i 2004. godine, što predstavlja smanjenje od 11,6% u odnosu na početni volumen. Ovi rezultati naglašavaju hitnu potrebu za učinkovitim strategijama upravljanja sedimentom kako bi se osigurala dugoročna održivost vodnih resursa u Alžiru i drugim regijama koje se suočavaju sa sličnim izazovima.

Ključne riječi: zamuljivanje, brana Sidi-Yacoub, geografski informacijski sustavi, batimetrijsko snimanje, model predviđanja sedimentacije

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