Ekológia (Bratislava) - Journal of the Institute of Landscape Ecology, Slovak Academy of Sciences Vol. 44, No. 2, p. 147–159, 2025
DOI:10.2478/eko-2025-0017

LONG-TIME DYNAMICS IN A NORTH AFRICAN COASTAL RAMSAR SITE, THE SIDI BOUGHABA LAKE

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Received: 4 January 2025 / **Accepted:** 30 May 2025

Abstract

Moukrim S., Tellal J., Lahssini S., Boudjaj A., Rhazi M., El Madihi M., Ben Bammou M., Moukrim M., Saber E.-R., Wahby I., Rhazi L., Grillas P.: Long-time dynamics in a north African coastal Ramsar site, the Sidi Boughaba Lake. Ekológia (Bratislava), Vol. 44, No. 2, p. 147–159, 2025.

Coastal wetlands host a large part of the world's biodiversity and provide various ecosystem services with a known economic value. However, they experience many pressures due to anthropogenic and natural drivers, causing periodic changes in their structure and functioning. Earth Observation provides opportunities for monitoring water surface dynamics and understanding the impacts of different drivers on wetland degradation. This study had two objectives: to assess the spatiotemporal dynamic of the Sidi Boughaba Lake surface area (Mediterranean and North African coastal Ramsar site, Morocco) over 38 years (1984–2021) and to identify natural and anthropogenic drivers of this dynamic, mainly land-use and land-cover changes and policies. This work focused on the use of multiple datasets based on remote sensing images within a cloud-based computing platform. Time series of satellite images were classified and used after a series of processing procedures to assess the land use and land cover and water extent dynamics. Results reveal that over 38 years, the lake shows intra- and inter-annual variations, including significant losses of permanent water impacting its dynamic and extent. Those trends call into question the urban and agricultural policies adopted. Pressure on resources and the regressive trend recorded in the dynamic of the lake are likely to increase further in future years if effective protection measures are not implemented. The results of this study help authorities, civil society, and decision makers to make decisions and call for action to protect these areas and maintain their capacity to provide ecosystem services and address global concerns such as biodiversity conservation and climate change mitigation.

Key words: water transition, land use, land cover, urban extension, remote sensing, Google Earth Engine, Morocco.

Introduction

Coastal wetlands are known in the North African and Mediterranean region for their high levels of biodiversity, with many endemic species of plants and animals (Hammada et al., 2004; Ramdani et al., 2001a,b). They play an important role in the local ecosystem by providing a variety of important ecological, economic, and cultural benefits (Ait Kacem et al., 2022; Costanza et al., 1997; Nogueira et al., 2022; Schuerch et al., 2018; Xu et al., 2020), including (i) critical habitats for a variety of plant and animal species (migratory birds, fish, and shellfish); (ii) key sources of water, food, and fuel for local communities; (iii) natural buffers against storm surges and floods, helping reduce the impact of these events on coastal communities; (iv) water quality improvement by filtering pollutants, reducing erosion, and stabilizing shorelines; (v) climate change mitigating by sequestering carbon; and (vi) economic benefits, including fisheries, salt and plant biomass, recreation, ecotourism, etc. Despite their importance, these wetlands are facing significant direct and indirect threats from a range of human activities, including urbanization, agriculture, alteration of hydrologic regimes, water management practices, pollution level increase, and infrastructure development (García et al., 2010; Geijzendorffer et al., 2018; Li et al., 2020; Poudel et al., 2013). Coastal wetland degradation and loss is a significant issue, with impacts including the reduction of water quality, loss of biodiversity, and increased flood risk (Schuerch et al., 2018).

Comprehensive studies of coastal wetland trends and dynamics can be challenging to conduct due to the complexity of these ecosystems and the lack of long-term data for tracking changes over time. However, Earth Observation (EO) provides opportunities for periodic and systematic monitoring of these areas and has become an important source of data for monitoring water surface dynamics (Geijzendorffer et al., 2018; Guelmami, 2024; Pekel et al., 2016). EO also offers opportunities to understand the impacts of human activities on wetland loss/degradation and the effects of land use and land cover (LULC) change in the surrounding area including their catchment, which have been identified by many authors as having a significant impact on the dynamics, extent, and ecological functions of these ecosystems (Li et al., 2019).

In this context, the availability of open access satellite images has created new development opportunities for wetland monitoring. Specific indices have been developed (Pekel et al., 2016; Smith, Baker, 1981), and the recent development of cloud-based geospatial analysis platforms (e.g., Google Earth Engine) allows the integration and processing of large datasets. The use of satellite imagery and other remote sensing techniques provides a better understanding of changes over time in the extent of surface waters and LULC, serving as indicators for hydrological dynamics and anthropogenic impacts, respectively (Bouziani et al., 2023; Pekel et al., 2016; Sogno et al., 2022; Tottrup et al., 2022; Weise et al., 2020). This valuable information contributes in the effective management and conservation of these ecosystems. Also, these satellite-based methods have the advantage of being inexpensive and allow for large-scale data collection (Tariq et al., 2021; Tregubov et al., 2021).

Coastal wetlands are an essential component of the country's natural resources but continue to face significant challenges that threaten their existence and ecological health (Nogueira et al., 2022). To ensure their long-term sustainability, there is a need to implement effective management and conservation strategies that address the challenges facing these ecosystems and promote their health and resilience. In this context, this study aims to detect, assess, and analyze the spatiotemporal dynamic of the water surface of the Sidi Boughaba Lake between 1984 and three different years (2019, 2020, and 2021) and to investigate the drivers that affected its extent and dynamics. This will improve our knowledge and understanding of these valuable ecosystems and inform conservation and management efforts to protect and ensure their sustainability for future generations and meeting international commitments.

Material and methods

Study area

The Sidi Boughaba Lake is a permanent, brackish/freshwater coastal wetland of the Moroccan Atlantic coast installed behind a stabilized dune cordon of a few tens of meters wide. The lake is located next to the mouth of the Sebou River in the northern part of the Rabat-Salé-Kénitra Region (Fig. 1), within 34.212 and 33.254 north and 6.664 and 6.692 west in a subhumid with warm winter bio-climate (Benabid, 1982). It is oriented from N–NE to S–SW (Fig. 1) and has been recognized in the Ramsar list since 1980 over an area of 650 ha. It extends for 5.5 km in length, with a variable width reaching 350 m and a depth varying between 0.5 and 2.50 m. The genesis of this environment dates back to 6520 ± 110 before the present (Reille, 1979). Although the geomorphological origin of the site remains unspecified, the lake's configuration strongly implies its previous existence as a meandering river arm. This notion gains further support from pollen analyses conducted by Reille (1979), which underscore the presence of historical vegetation typically associated with freshwater lakes, including species from the *Myriophyllum* genus. While the lake's salinity has experienced variations over the past century, as documented by Elkhiati et al. (2004), its primary water source remains the groundwater table, as highlighted by Cherkaoui and Boucharfa (2003).

This lake is surrounded by a natural Mediterranean thermophilic vegetation composed mainly of *Juniperus phoenicea* along with different arborescent species, in particular, *Populus alba, Pistacia lentiscus*, *Eucalyptus sp.*, *Tamarix gallica*, *Olea europaea*, *Chamaerops humilis*, *Myrtus communis*, *Retama monosperma*, etc (Atbib, 1979). This lake adjoins the vast Maamora forest (Benabou et al., 2022a), which represents the largest lowland cork forest in the world (Benabou et al., 2022b). However, this once-prosperous area, which provides a wide range of ecological, environmental, and socioeconomic services—such as supporting a rich algal flora and traditional fishing and representing as an important area for fauna and a breeding site for regionally rare and globally threatened water birds and for staging migrant birds (e.g., *Fulica cristata*, *Netta rufina*, *Aythya nyroca*, *Oxyura leucocephala, Anas strepera*, *Aythya ferina*, *Anas platyrhynchos,* and *Marmaronetta angustirostris*) (Ait Kacem et al., 2022; Cherkaoui et al., 2013)—is witnessing an increasing degradation process similar to most Mediterranean coastal wetlands (Grillas et al., 2021).

For a detailed land-use change analysis and socioeconomic impact assessment, a surrounding area including the sub-watershed that drain into the lake was defined as specified in Fig. 1 (yellow color). This perimeter was chosen to have a sufficiently broad vision of land occupation in the territory and thus to analyze the various transitions and changes in the LULC from 1984 to 2021.

Data source, data processing, and analysis framework

The overall approach is outlined in Fig. 2. It consists of using multiple datasets based on remote sensing images (Landsat archives, Sentinel, CHIRPS rainfall, Global Surface Water [GSW]), in addition to the location of the study area in order to clip the used images. Moreover to classify satellite images, localization of field plot within well-known land use has been used to train classification algorithm. The datasets will be detailed as follow.

Time series of Landsat satellite images (245 elements including only images where the cloud cover percentage is less than 5%) covering the time frame steps 1984–2021 were classified and used after a series of pre-processing and processing procedures, such as radiation correction, cloud removal, image clipping, and calculations of normalized indices—namely, Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI)—which are dimensionless and vary between -1 and +1. The NDVI and NDWI correlating with vegetation productivity (Bannari et al., 1995; Reed et al., 1994) and water cover (Gao, 1996) were used to assess the LULC and water extent, respectively.

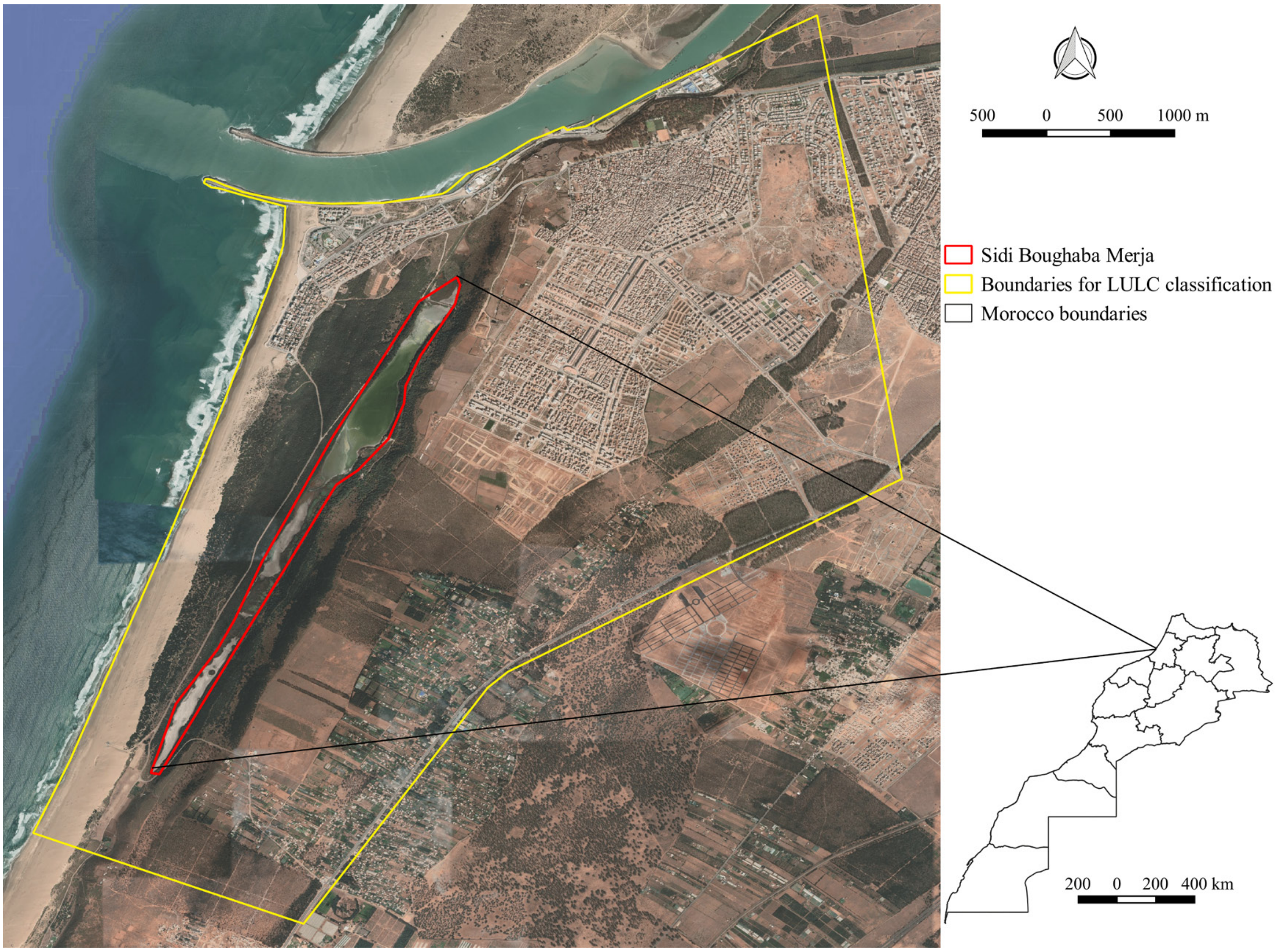

Fig. 1. Location of the Sidi Boughaba Lake and the surrounding area for LULC classification (Google Earth imagery © 2024 Google).

The Global Surface Water dataset, developed by the European Commission's Joint Research Centre (ECJRC) within the scope of Copernicus Program framework, was used. It is one of the first datasets attempting to capture the dynamism of surface water extent using Landsat 5, 7, and 8 imageries (Pekel et al., 2016). This dataset expresses various global surface water characteristics with approximately 30-m spatial resolution and for over more than 37 years back. It presents water surface distribution, including water occurrence and transitions.

In order to determine the precipitation trend in the study area, the data acquired during 38 years (from 1984 to 2021) from CHIRPS dataset were used. Mann-Kendall test (Kendall, 1975) and Sen's method (Sen, 1968) were performed in order to determine, respectively, the annual rainfall trend and its magnitude.

All datasets underwent processing in Google Earth Engine (GEE), a powerful cloud computing platform that grants access to a vast collection of satellite images and geospatial data spanning approximately 40 years and encompassing the global scale. Moreover, GEE offers a comprehensive suite of tools that significantly streamline their utilization, visualization, correction, calibration, analysis, and processing, leveraging Google's impressive computing capabilities (Gorelick et al., 2017; Patel et al., 2015). GEE relies on the use of complex algorithms, including "expert systems" which are an applied branch of artificial intelligence, visual analytics, and evidential reasoning (Gorelick et al., 2017). Indeed, GEE provides a user-friendly interface that allows researchers and analysts to easily visualize and interact with the Earth's surface and its diverse datasets. By using specific scripts, users can perform a wide range of analyses, such as monitoring water surface coverage, masking snow cover, conducting change detection analysis, and creating captivating time-lapse visualizations, among many other applications. For the specific case of land classification, GEE is well suited to iteratively build supervised classification processes by including a variety of different data into a single model. Several classifier for supervised classification prevails, such as Random Forests (RF) (Breiman, 2001), Classification and Regression Trees, and Support Vector Machine (Nery et al., 2016; Tassi, Vizzari, 2020). Researchers reported that higher accuracy was achieved when using the RF classifier algorithm (Belgiu, Drăguţ, 2016).

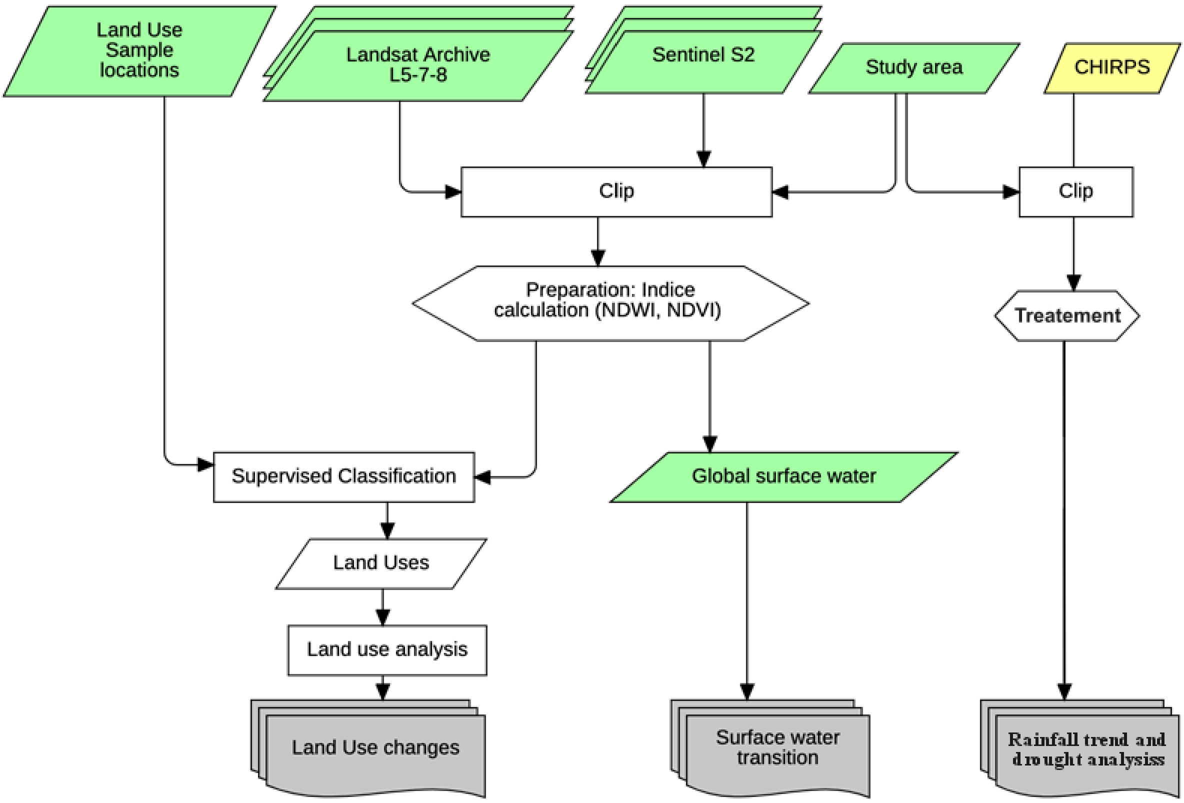

Fig. 2. Flowchart of overall approach: rectangles and parallelogram represent, respectively, processing and datasets (green used datasets and yellow primary datasets); gray represent output used for assessing surface water and driving forces explaining transitions.

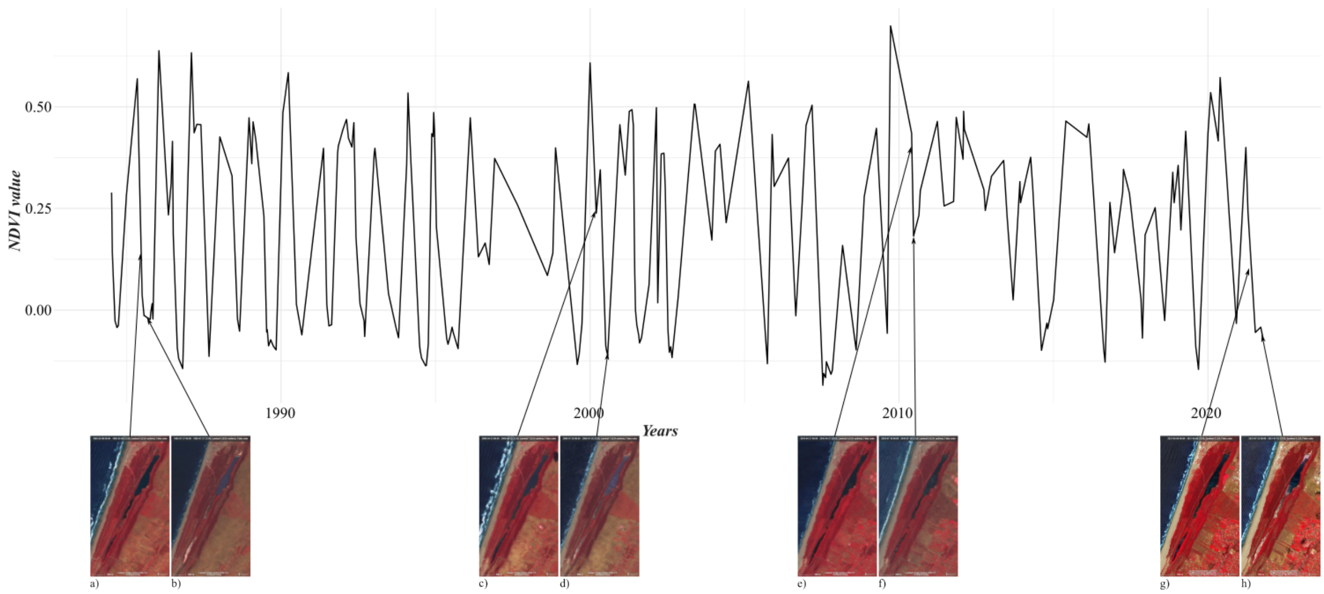

Fig. 3. Temporal evolution of NDWI showing the water state of the Sidi Boughaba Lake between 1984 and 2021. Satellite images (a–h) illustrate surface areas of water bodies through a widely used false-color composite that utilizes near infrared, red, and green bands. This composite was principally used to assess and distinguish water (represented by dark color) from other components of the landscape (indicated by red colors). (a) Landsat 5 image (05/08/1985), (b) Landsat 5 image (07/27/1985), (c) Landsat 7 image (04/23/2000), (d) Landsat 7 image (07/28/2000), (e) Landsat 5 image (04/27/2010), (f) Landsat 5 image (07/16/2010), (g) Sentinel-2 L2A image (05/06/2021), and (h) Sentinel-2 L2A image (07/25/2021) (source of satellite images: ESA archive).

Water class transition

The Sidi Boughaba Lake water transition maps were generated using the Global Surface Water dataset (Pekel et al., 2016). These maps provided detailed and spatially explicit information regarding the observed changes in water occurrences over time. The dataset classifies water occurrences into three major classes (not water, seasonal water, and permanent water). The transition maps illustrate the state changes within these classes between the initial observation period in 1984 and the later periods at the end of the record, specifically for the years 2019, 2020, and 2021. In instances where water was not present at the beginning or the end of the time series but was detected in some intervening years, it is referred to as "ephemeral water." Depending on the hydrological behavior and by tracking the intra- and inter-annual patterns of these "ephemeral" events, this category has further included two additional classes: "ephemeral permanent water" (not water replaced by permanent water that subsequently disappears) and "ephemeral seasonal water" (not water replaced by seasonal water that subsequently disappears). The two ephemeral water classes were also helpful for computing and spatializing the maximum water extent in the study area. The spatial water transition maps highlighted the changes between 1984 and the 3 years (2019, 2020 and 2021), within the border of the studied Ramsar site, between 11 classes of water occurrences (not water, permanent, seasonal, new permanent, new seasonal, lost permanent, lost seasonal, seasonal to permanent, permanent to seasonal, ephemeral permanent, and ephemeral seasonal).

LULC and LULC change

Changes in water surface area may be influenced not only by climatic conditions but also by significant anthropogenic factors, particularly LULC and LULC change (Guelmami et al., 2023; Mehrani et al., 2023; Moukrim et al., 2023; Rifai et al., 2018). Analyzing LULC in the surrounding area of the Sidi Boughaba Lake provided a comprehensive overview of land-use patterns and helped identify the main changes that have occurred. The Landsat data archive was used to perform multiple land-cover monitoring at medium spatial resolution (30 m). Satellite images were selected based on the quality assessment band flags to minimize the effects of clouds and clouds' shadows. Simultaneously, the spectral bands were selected for classification and calculation of indices. Some indices (NDVI and NDWI) (Bannari et al., 1995), which are helpful for land-use classification, were calculated and added to the bands. Data processing methodology to obtain the classification maps was achieved using Random Forests. This algorithm is an ensemble learning method that involves the use of multiple individual decision trees. Each individual decision tree has several nodes. The final result is determined by the majority of votes in the tree, and each end of a tree represents a given decision (Breiman, 2001). The RF algorithm was chosen since it is qualified as one of the best performing models to produce a highly accurate classification (Breiman, 2001). For training data, the composite Sentinel images for 2021 and Landsat images for 1984 were used.

Faced with the difficulty of distinguishing the spectral signature between different classes, we proceeded to group arboriculture and forests land use into a class called *high-dense vegetation* "D_1". We also have retained a class called *low-dense vegetation* "D_2" which groups annual and perennial herbaceous crops and forage (irrigated or pluvial) in a single class. The *bare land* (*BL)* class groups together areas with very low vegetation index values. *Built-up lands* (*Bu*) represent man-made land surfaces, infrastructure, and residential land uses, and *Water* (*W*) represents surface water extent. These groupings allowed us to have five classes with a more distinctive spectral behavior in the different satellite images used, facilitating different analyses. For LULC result validation, visual interpretation of satellite data from Google Earth Pro and ESA archives in addition to other collected samples on the field was adopted.

Within the potential LULC maps developed for the 2 years of monitoring (1984 and 2021), it was possible to generate a LULC change map. This land-cover transitions map was used to quantify the long-term LULC dynamics and derive statistics corresponding to each group/class change at 30-m spatial resolution (El Madihi et al., 2023).

Results

Overview of the inter- and intra-annual lake water dynamics

The analysis of the temporal evolution of NDWI and satellite images covering the temporal horizon retained in this work showed changes in water levels and extent (Fig. 3). The values of the NDWI index vary temporally (monthly and annually), and the values recorded are low (between -0.185 and 0.699, with an average that does not exceed 0.190), which testifies the water coverage variability of the Sidi Boughaba Lake over several temporal ranges.

Generally, the lake extent fluctuates seasonally and inter-annually following the rainfall pattern. The average extent of the site gradually rises and decreases, respectively, during winter and summer period. Figure 3a–h highlights those inter-annual variations in water extent. During the study period, the lake has experienced periods of maximal water extent (Fig. 3c,e,g) and minimal extent water over few or several months (Fig. 3d–h). However, during the second decade of the 21st century, it was noted that periods of lake dryness rapidly set in and continued for several months, despite Mann-Kendall and Sen tests on annual rainfall data in the Lake Sidi Boughaba highlighting a significant ($P < 0.05$) positive trend in annual rainfall ($Z = 1.99$, $Q = 4.4$) during the study period (Fig. 4).

Water class transition in the Sidi Boughaba Lake

Through the utilization of GEE with the implementation of various scripts, it was possible to generate water transition maps between the initial date 1984 and the three last years of monitoring (2019, 2020, and 2021). These maps offer valuable insights into the changes occurring between different water classes (Fig. 5). Conversions and changes in state do not describe what happened in the intervening years, so an unchanging (no water, permanent, seasonal) water surface means that the seasonality at that particular point was the same in the first and last years it was observed and not necessarily that it was stable throughout.

To sum up, Fig. 5 presents the spatial visualization and the representativeness of each water class transitions, expressed both

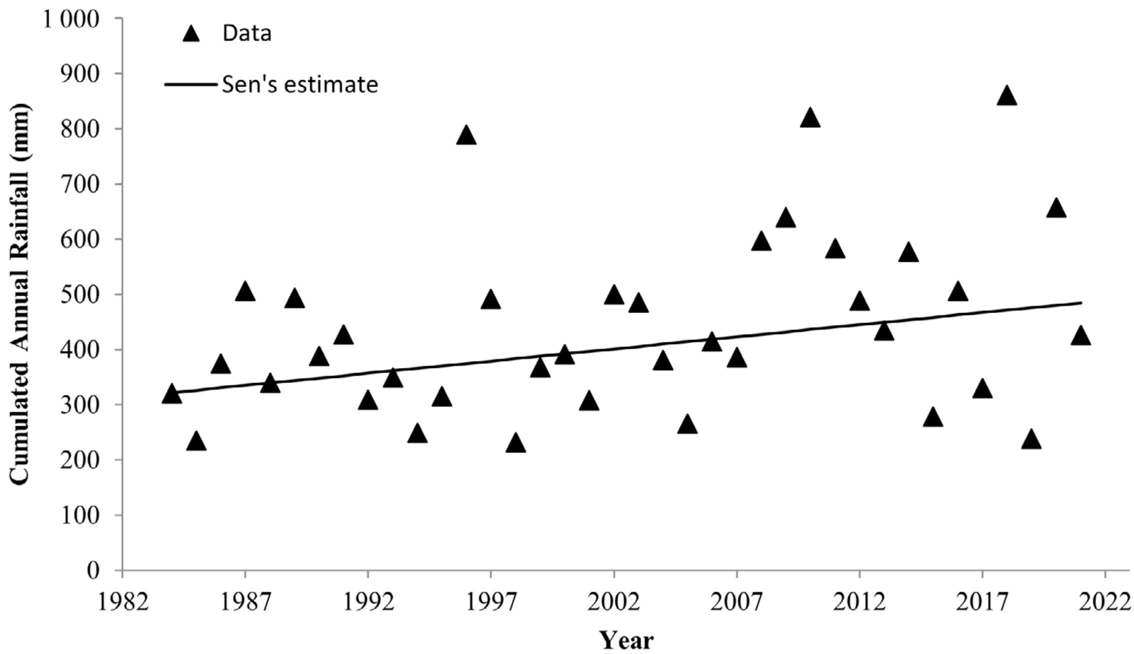

Fig. 4. Annual time series and trend statistics using Sen's slope estimator from 1984 to 2021 for the study area.

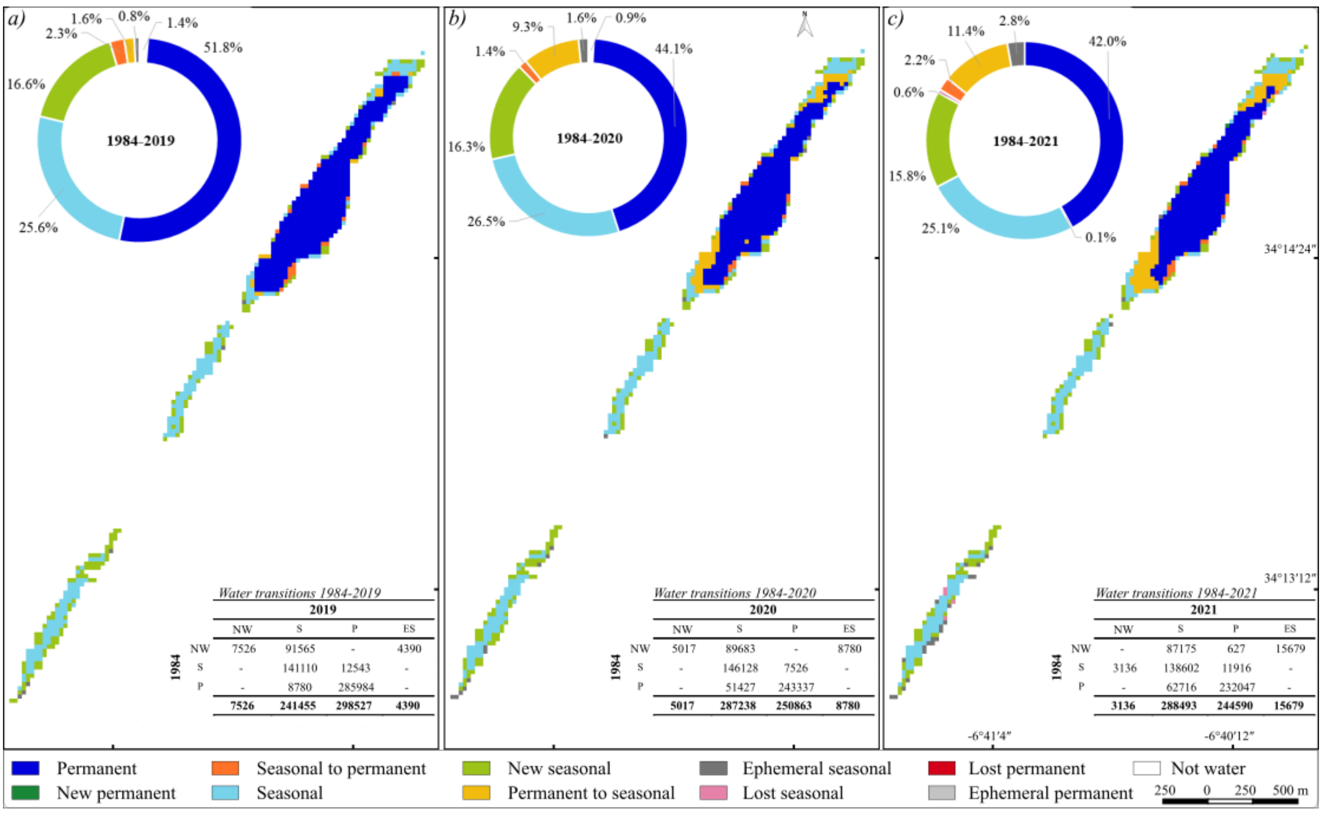

Fig. 5. Spatial visualization of water transition and summary of transition class areas (in percent and in m^2) in the Sidi Boughaba Lake between 1984 and (a) 2019, (b) 2020, and (c) 2021. Note: NW - not water; S - seasonal; P - permanent; ES - ephemeral seasonal.

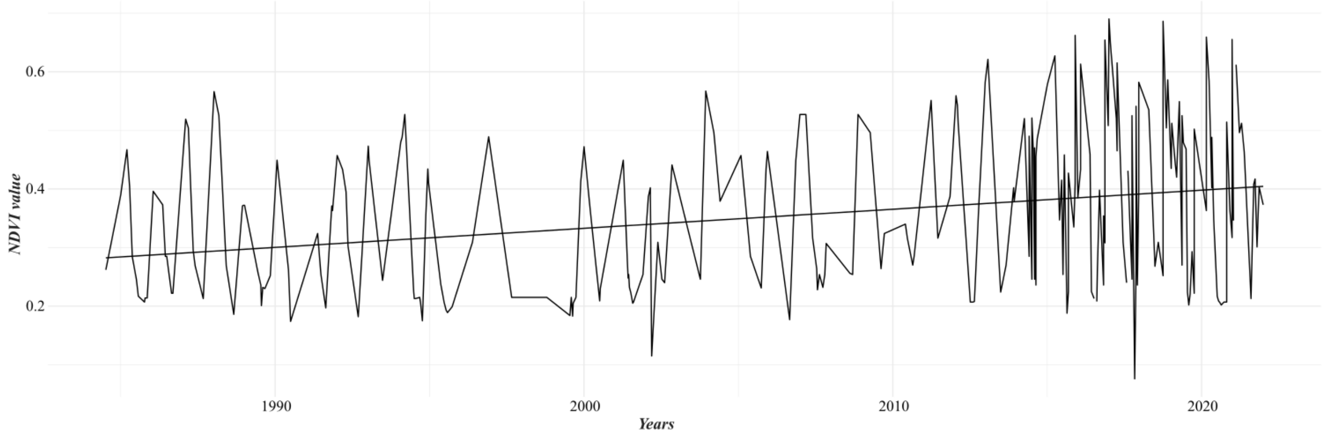

Fig. 6. Global trend of the NDVI value between 1984–2021 in the surrounding area of the Sidi Boughaba Lake.

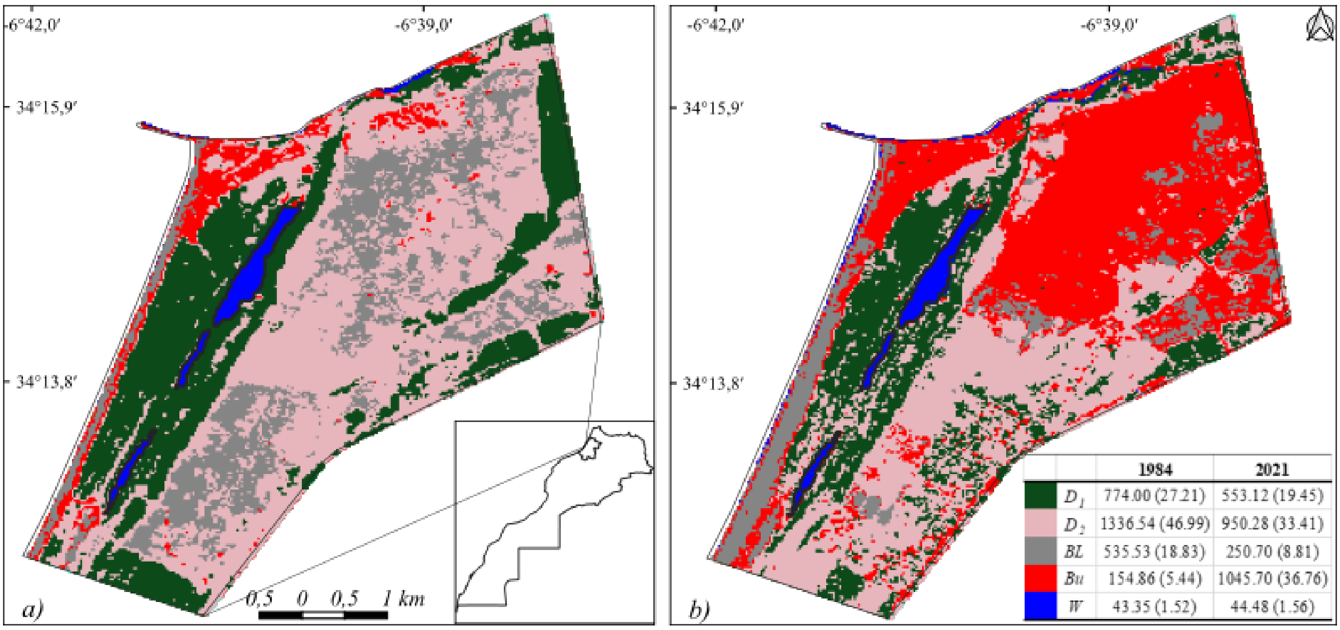

Fig. 7. Land-use classification: (a) 1984 and (b) 2021. Table showing the area (ha) and percent (between brackets) of each category. Note: D_1 - high-dense vegetation; D_2 - low-dense vegetation; *BL* - bare land; *Bu* - built-up lands; *W* - water.

as a percentage and in terms of area (m^2). The analysis of these water transition classes revealed the maximum extent of detected water in the lake, covering an approximate area of 551,898 m^2. Substantial part of water extent (22.6, 29.6, and 32.9%) underwent various transitions between the different selected dates (respectively, between 1984 and 2019, 2020, 2021). Notably, an important area experienced a transition from not water to seasonal water (approximately 16% for the different dates) or ephemeral seasonal water (less than 2.8%).

The seasonal class has not changed much, while the permanent water class has shown a significant drop from 52% (2019) in water extent to 42% (2021). An extensive transition from the permanent to the seasonal water class was recorded (especially after 2019) on approximately 10% of the global surface mainly in the center part of the Sidi Boughaba Lake. On the other hand, the transition from seasonal to permanent water was noted in very restricted areas (less than 2.2%).

LULC classification and changes

LULC in the surrounding area of the Sidi Boughaba Lake, based on the use of NDVI as proxy variable, over the past 38 years was analyzed over different time steps. Fig. 6 shows the global trend of the NDVI mean over the study area. Index values vary over time (intra- and inter-annually) with an annual mean ranging between 0.205 and 0.455.

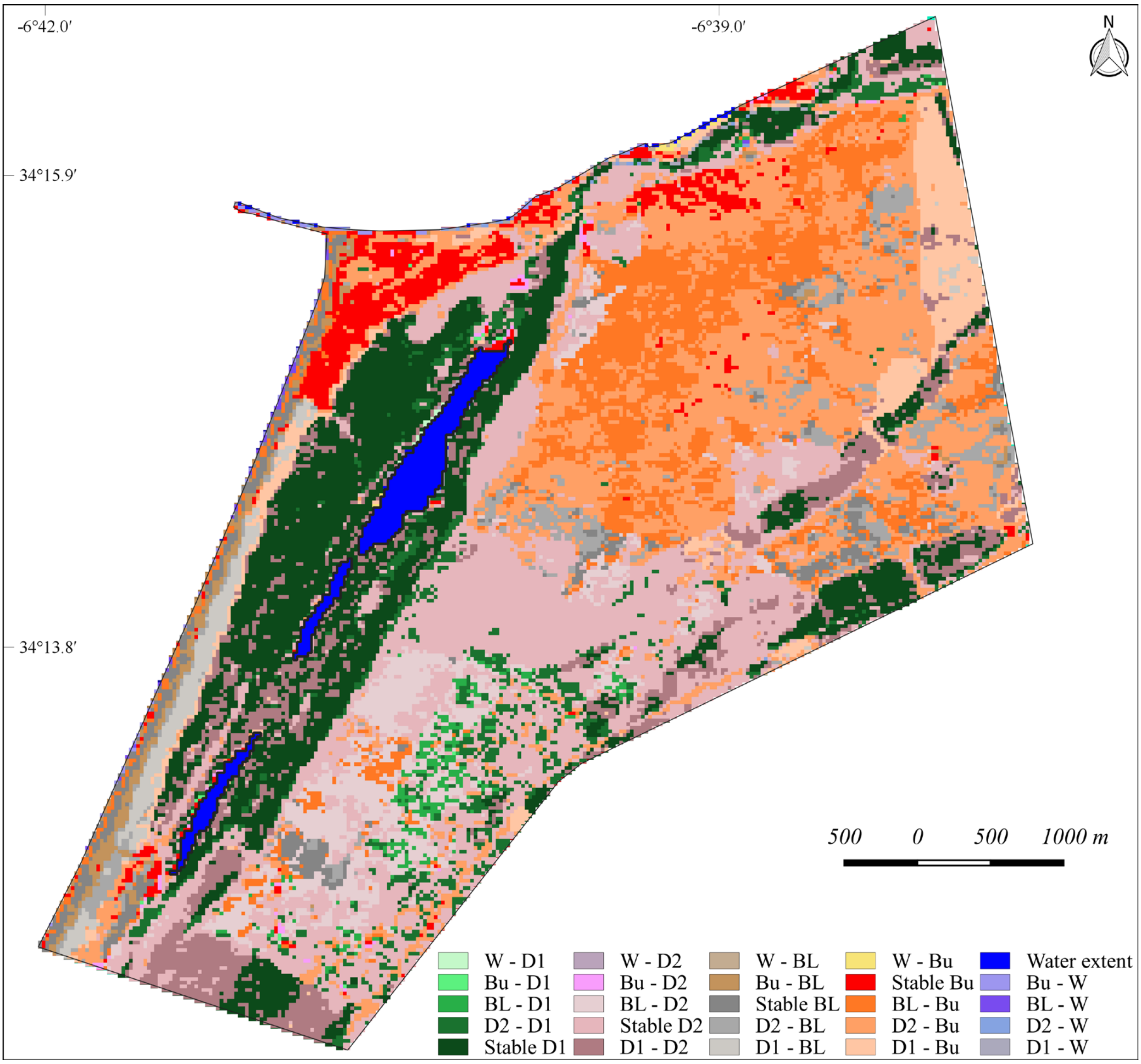

Fig. 8. Spatial visualization of land-use changes in the surrounding area of the Sidi Boughaba Lake from 1984 to 2021. Note: D_1 - high-dense vegetation; D_2 - low-dense vegetation; BL - bare land; Bu - built-up; W - water.

The LULC classification and accuracy assessment were performed in the surrounding area for the 2 years: 1984 and 2021 (Fig. 7). The overall accuracy for the LULC maps was generally high (above 79%). The results of this classification show the dominance of the "low-dense vegetation" class (47%) in 1984 and "built-up lands" class in 2021 (36.8%). Analysis of classification results showed that positive and negative evolution trends were recorded and represented by expansions and reductions in the area of the different classes between the two dates. According to these results, we note that the "Bu" class increased from ~5.5 to ~36%. Following the process of urbanization, other land-cover types exhibited a large decline. The "D_1" class decreased from 27.2 to 19.4%. The "D_2" gradually went down from 47 to ~33.4% and the "BL" area decreased gradually from 18.8 to 8.8% (Fig. 7).

Overlying those maps (Fig. 7a,b) allowed for the development of the LULC change map between the two dates which spatially visualize different changes (Fig. 8). Also, the transition matrix (Table 1) highlighted changes in land-cover classes and quantified these changes from and to each of the five land-cover classes through cross-tabulation of the changes between the two dates. Spatial analysis of the LULC changes reveals landscape dynamics on which all classes were affected by different dynamics (Fig. 8). The initial land uses that have not been affected by changes in cover in each class are 52.7% (409.12 ha), 43.3% (579.29 ha), 14.3% (76.33 ha), and 69.3% (108.10 ha), respectively, for the "high-dense vegetation," "low-dense vegetation," "bare land,"

Table 1. Transition matrix showing LULC change in the surrounding area of the Sidi Boughaba Lake between 1984 and 2021 (area in '*ha*' and percent changes are provided in '*brackets*').

LULC Classes		Unit	*2021*				
			D_1	***D_2***	***BL***	***Bu***	***W***
1984	***D_1*** (1)	*ha* *(%)*	**409.12** **(14.38)**	211.47 (7.43)	40.64 (1.43)	108.97 (3.83)	3.82 (0.13)
	D_2 (2)	*ha* *(%)*	115.66 (4.07)	**579.29** **(20.37)**	90.87 (3.19)	548.47 (19.28)	2.25 (0.08)
	BL (3)	*ha* *(%)*	25.59 (0.90)	150.62 (5.30)	**76.33** **(2.68)**	280.16 (9.85)	2.84 (0.10)
	Bu (4)	*ha* *(%)*	1.45 (0.05)	6.03 (0.21)	35.47 (1.25)	**108.10** **(3.80)**	3.80 (0.17)
	W (5)	*ha* *(%)*	1.31 (0.05)	2.87 (0.10)	7.40 (0.26)	-	**31.77** **(1.12)**

Notes: (1) – High-dense vegetation; (2) – low-dense vegetation; (3) – bare land; (4) – built-up; (5) – water. On the diagonal, the bold numbers represent unchanged LULC area from 1984 to 2021 and their corresponding percentages.

and "built-up." The most significant conversions concerned the transition from low-dense vegetation and bare land to built-up lands (respectively, 41 and 52.3% of the initial D_2 and BL classes) and from high-dense vegetation to low-dense vegetation (27.3% of the initial D_1 class). Other conversions have been recorded from bare land to low-dense vegetation (28.1% of the initial BL class) and from low-dense vegetation to high-dense vegetation (8.7% of the initial D_2 class).

Discussion

The objective of this work is to capitalize on open access data from different datasets to analyze the spatial and temporal transition of water in a North African coastal wetland and investigate the natural and anthropogenic drivers that affected its extent and dynamics, mainly LULC in the surrounding areas, to ensure their management and sustainability. In this research, the analysis of annual rainfall showed the direction and magnitude of its trend. Despite the fact that a positive significant trend in annual rainfall is recorded (Fig. 4), which is illustrated also by the development of some transitions to seasonal and ephemeral seasonal waters (Fig. 5), several authors have already reported an increase in aridity and droughts in the study area (Challi et al., 2021) and in Morocco (Driouech et al., 2010; Sebbar, 2013). In addition, while our analysis shows a positive trend in rainfall, this should be interpreted within broader climate change contexts affecting North African wetlands. Beyond precipitation quantity, changes in rainfall patterns, timing, and intensity significantly impact the hydrological regime of the Sidi Boughaba Lake. Rising temperatures increase evapotranspiration rates, potentially accelerating water loss despite the modest increase in rainfall.

The analysis of the temporal evolution of the NDWI (Fig. 3) showed low values (ranging between -0.19 and 0.52) and their temporal (monthly and annual) variation. Such values could be explained by low and variability of water extent over several temporal ranges. In this context, Ramdani et al. (2001b) highlight that there are no outflow or inflow surfaces in the lake, and the water level and extent are related to rainfall. The southern part of the site usually dries out and the water level can drop by 1 m by late summer with a large extent reduction, but it recovers its adequate level of filling during wet seasons (Ramdani et al., 2001b). Unfortunately, this observation seems no longer valid during last years. The lake returns to its adequate level during the wet season but the water level drop by early summer, and it was noted that periods of lake dryness rapidly set and continued for several months (Fig. 4).

In this sense, comparison of water transition maps produced (Fig. 5) highlights the significant amount of water areas that have experienced transitions between the different selected dates, allowing us to identify which part of the lake is more affected by these transitions than others. Consequently, the northern and peripheric parts of the lake are the most affected by these transitions compared to those existing in the southern and central parts. According to these results, the lake dryness is becoming more and more pronounced, especially since the permanent water class shows a significant decrease from one year to another, mainly in favor of the seasonal class.

Certainly, climate can have impacts on the structure and functioning of many natural wetlands in Morocco and North African and Mediterranean region, as highlighted by different authors (Grillas et al., 2021; Sebbar, 2013) and others countries (Asgher et al., 2021). However, other authors have noted that socioeconomic changes have led to mechanisms of degradation in the coastal wetlands, and many indicators (pedologic, soil erosion, hydrologic, plants richness, and composition) reflect these trends (Chouari, 2021; Lachhab et al., 2022). In the context of this study, the positive trends in the amount of precipitation and the subsequent decrease of the lake water extent over the period of study indicate that there is an anthropogenic contribution to the dynamic of this Ramsar site, a hypothesis that has been addressed and refined in some sections of this work.

Anthropogenic impact: Changes in LULC

An exceptional demographic growth has been recorded in Morocco, with the country's total population increasing by almost 70% between 1984 and 2021, with an annual growth rate of 1.44% (HCP, 2014). The areas that show a high rate of population growth are in the coastal region, which has experienced urban expansion and large socioeconomic development (Rhinane et al., 2012). This evolution has been accompanied by an increasing demand for urban extension (El Mahrad et al., 2020; Loulad et al., 2023) and water pumping, illustrated mainly by a large land-use change occurring in the surrounding areas during recent years. As LULC has been deemed important in determining the environmental impacts of anthropogenic land-use and conversion (Majumdar, 2020), LULC classification was performed in the surrounding area of the lake for two dates 1984 and 2021 (Fig. 7a,b) and a LULC change map was developed (Fig. 8). This change map helps understand the main changes occurred over the timeframe in a landscape that has been undergoing rapid transformations.

The analysis of the dynamics of change in the study area highlighted different evolution processes that took place, including a regressive trend in the two vegetation classes and a progressive trend in the built-up class. The *Bu* class in 2021 has increased significantly from the year 1984 (from 155 to 1046 ha). Such trends could be largely explained by increasing anthropogenic pressure with remarkable urbanistic development. These results align with those observed by Rifai et al. (2018) in the Tahaddart Ramsar wetland (Northwest Morocco), where a significant decline in natural habitats was also noted. In that region, natural vegetation was largely replaced by built-up areas and bare land, revealing similar anthropogenic pressures to those identified in this study. Another process was noted during the field trips in the study area that concerns the development of agricultural systems. This conversion is accompanied by transition to permanent irrigated agriculture and nurseries extension as promoted by the introduction of the strategy *Green Morocco Plan* for agricultural sector (Sraïri, 2021). Irrigation development associated with pumping in the aquifers (Bahir et al., 2018), which are generally in hydraulic communication with the lake, reduces the underground water flows supplying this coastal Ramsar site.

To sum-up, the effects of climate change, on the one hand, and human population growth and its increasing consumption (expansion of urban areas and development of intensive agriculture), on the other hand, have recently increased the stress on natural resources (Alexander et al., 2015; Asgher et al., 2021; Garnett et al., 2013), with main consequence of excessive water exploitation and degradation of natural resources in the coastal area. The recent and ongoing regressive dynamics of the Sidi Boughaba Lake highlight a concerning phenomenon observed at the national and regional scales (Gardner, Finlayson, 2018; Muller et al., 2022; Rifai et al., 2018). This affects the ability of these natural areas to provide ecosystem services and respond to global concerns such as biodiversity and climate change mitigation (Geijzendorffer et al., 2018).

While natural factors may contribute to explain some traits of the regressive dynamics of natural environments, human-induced activities are the main trigger for the transformations that natural areas are currently undergoing (Guelmami et al., 2023; Loulad et al., 2023; Moukrim et al., 2023; Rifai et al., 2018; Sayad, Chakiri, 2010). In the study area, the dynamics and changes in land use have shown the magnitude of the disturbances generated (Fig. 8). The pressure on resources and the regressive trend recorded in the dynamic of the lake are likely to increase further in future years if effective protection measures are not implemented, especially in the context of proven global change (Grillas et al., 2021; Leberger et al., 2020; Moukrim et al., 2022).

Ecological consequences and management implications

The observed changes in water extent and LULC patterns in the Sidi Boughaba Lake carry extensive ecological consequences that extend beyond the physical landscape transformation. Permanent water body loss directly limits habitat availability for aquatic species, particularly during prolonged dry periods (Grillas et al., 2021). Simultaneously, the conversion of natural vegetation to built-up areas and agricultural land threatens plant biodiversity, including some species adapted to the unique conditions of North African coastal wetlands. These shifts in vegetation not only reduce biological diversity but also compromise ecosystem services, such as water filtration, carbon sequestration, and flood regulation. Furthermore, water quality deterioration, exacerbated by agricultural runoff containing fertilizers and pesticides from the surrounding agricultural land, additionally threatens the lake's ecological integrity and its capacity to support diverse biological communities that characterize the Ramsar sites of global importance (Gardner, Finlayson, 2018; Rhazi et al., 2001; Xu et al., 2020).

In light of these results, urgent and targeted management interventions are essential to ensure the long-term sustainability of the Sidi Boughaba Lake. Failure to act decisively might severely threaten the site's ecological integrity and even compromise its Ramsar status. The findings of this research provide critical insights that can be used to create evidence-based conservation strategies to protect this valuable ecosystem for future generations (Geijzendorffer et al., 2018; Guelmami, 2024). Some of the key recommendations include establishing well-defined buffer zones to limit urban development, implementing strict regulations on groundwater pumping for agricultural purposes, and promoting sustainable water management practices throughout the sub-watershed. Restoration interventions should be strategically focused at the northern and peripheral sides of the lake, which our analysis has identified as particularly vulnerable to ecological transitions and degradation. An integrated sub-watershed management approach that addresses both surface and groundwater dynamics would help maintain hydrological balance. These interventions need to be complemented with sensitization activities among local communities and stakeholders to instill collective responsibility for wetland conservation. The implementation of such measures requires coordinated action among governmental agencies, conservation organizations, and local communities to address the complex challenges facing this valuable ecosystem (Geijzendorffer et al., 2018).Haut du formulaire

Such collaborative programs will help achieve the objectives expected from the nomination of this natural area as a Ramsar site, enable the country to honor its international commitments (Finlayson et al., 2020), and serve as a model for protecting other coastal wetlands in the North African region that face similar challenges.

Conclusion

Due to the lack of relevant in situ data, this study has demonstrated the usefulness of combining multiple datasets based on remote sensing images and cloud-based computing platform to explore the spatial and temporal dynamics of water in coastal wetlands and investigate the natural and anthropogenic drivers that affected their recovery capacity. The results highlight intra- and inter-annual variations in the Sidi Boughaba Lake over the study period, including significant losses of permanent water between 1984 and 2021. The water transition maps produced have improved our understanding of the extent of water areas that have experienced transitions and have allowed us to identify which part of the lake is more affected by these transitions. Changes in the dynamic and water extent of the Sidi Boughaba Lake are mainly the result of the combined effects of natural and anthropogenic factors, including climate variability and urban expansion/agricultural policies that have led to serious consequences for surface water resources in the surrounding area. Therefore, measures to reduce pressure and protect this natural resource for future generation are necessary. The results of this study demonstrate the sensitivity of coastal wetlands to global change, which calls for policy choices that are consistent with the carrying capacity of these natural spaces and address threats facing these valuable ecosystems. To further support these findings, future research directions are recommended, including biodiversity assessments, methodological improvements incorporating higher resolution imagery and regional climate modeling, and the integration of community-based social research. These multidisciplinary approaches would deepen understanding of wetland dynamics and inform conservation strategies for the Sidi Boughaba Lake and other similar coastal wetlands in North Africa.

Acknowledgements

The authors would like to acknowledge anonymous reviewers and editor for providing helpful comments and suggestions. They thank the Moroccan Forest Department (especially Mrs. Hayat Mesbah) for the logistic support. This work was supported by BiodivRestore Program (RESPOND Project) funded by the Ministry of Higher Education, Scientific Research and Innovation of Morocco (MESRSI).

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