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Original Article

Impact of climate change on the spatiotemporal variability of a coastal ecosystem in the Tunisian Sahel

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ABSTRACT

Wetlands are some of the most important ecosystems on Earth. Despite their importance for water and carbon cycle regulation, wildlife survival and economic value. Furthermore, wetlands are experiencing rapid degradation due to severe transformations. They have been polluted and declined dramatically as land cover has changed in many regions. Whereas, human activities along with severe climate changes have led to critical loss and degradation of these ecosystems. This study evaluates changes of Halq El Mingel wetland, Tunisia, between 2006 and 2017. Spatial and temporal dynamics of wetland changes were quantified using Landsat and Google Earth images and three radiometric indexes have been calculated; Normalized Difference Vegetation Index, Normalized Difference Water Index and Salinity Index. Results revealed that important spatial and temporal variations are detected for each index.Also, the area of wetland in Hergla city decreased significantly over the last 10 years from 1146.7 ha to 806.6 ha respectively. A notable change is the shrinkage of the wetland area during 2006-2017 period which is linked to the decline of rainfall over the years. This study proposes a methodology to monitor changes in wetland using geospatial technology and thus to support decision-making for sustainable management.

1. Introduction

Wetlands are subject to strong anthropogenic and natural pressures causing their degradation [**Erreur ! Source du renvoi introuvable.**]. Since guidelines publication, several studies have tried to resolve these problems in different countries [2-8] whereas in Tunisia, [1] and [9]. However, in Tunisia, wetlands are defined as « *areas of lakes, sebkha, marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters* » [10] and according to [1] this definition resumes largely the definition of wetlands on the Ramsar Convention, signed in Iran on 2 February 1971. According to [11], these ecosystems can be designated as « *regions with low water levels, often near ground surface, which are covered by active plants during the growing season and water saturation period* ». There are the most valuable landscape elements in the context of assuring ecosystem services [12] because they provide habitat to a large number of animal and plant species [13] ranging from micro-organisms, to invertebrates, reptiles, birds and mammals, as well as trees and all sorts of aquatic plants. Also, they enhance the quality of water [14,15] indeed they are natural filters that purify water and are natural barriers that protect deeper farther lands from the demages caused by natural disasters, such as erosion, storms and floods

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[16]. However, wetlands are among the most degraded ecosystems in the world [17]. According to [18], the world has lost between 64% and 71% of its wetlands in the twentieth century. This loss will likely continue into the twenty-first century. Furthermore, [19] have been listed causes of the wetland ecosystems loss including the pressure for land, excessive land exploitation and the establishment of projects and activities which cause hydrological changes such as the construction of drainage systems (dams, dikes, *etc.*), the deviation of watercourses and the underground pumping. Wetlands play a key role in climate change mitigation [20,21]. In contrast, the Millennium Ecosystem Assessment report mentioned that global climate change is expected to exacerbate the world's loss and degradation of many wetlands. The loss or decline of their species and to harm the human populations dependent on their services [22]. Whereas Halq El Mingel sebkha is a representative Tunisian wetland with its typical alternation of drought phase in summer and flooding in winter. It was presented as a « sensitive site » and since 2011; it was classified as a Ramsar site [23]. His ecosystem plays an important ecological, hydrological and socio-economic role fulfilling various functions and values beneficial to the local population and the environment. Hydrologically, it ensures the regulation of hydrological flows, the mitigation of floods, the effects of erosion and the conservation of surface and ground water resources. It also brings many benefits to society such as fishing, agro-sylvo-pastoral and artisanal activities, outdoor recreation and environmental education, *etc*. [1]. In this paper we investigate the use of Geographic Information System (GIS) and Remote Sensing (RS) tools to *i)* map dynamic wetland from different aspects (seasonal and annual), *ii)* analyse these spatio-temporal changes during 2006-2017, and *iii)* explain the major factors that have driven the observed changes for better mapping, monitoring and managing this area.

2. Materials and Methods

2.1. Study area

Located at 25 Km on North-West of the city of Sousse, Halq El Mingel (35°59'23''N, 010°30'10''E) is a coastal wetland of the Tunisian Sahel (see Figure 1). Theoretically, its permanent surface is about 1450 ha while its surface can reach 2050 ha during wet periods. The depth varies from 0.5 m to 1 m and it is fed directly by Oued Essod [24]. The sebkha is divided into a northern part where water is periodic and a southern one where water is permanent. This segmentation is due to the road linking Sidi Bou Ali to Hergla which interrupts the water exchange between the two parts [23].The climate belongs of the lower semi-arid bioclimatic stage marked with mild winters and yearly mean precipitation of 200 mm. The coldest month is January with an average temperature of 11.5 °C, and the hottest one is August with an average temperature of 28 °C (Table 1).

Table 1. Variation of monthly average precipitation in the region of Sousse 2007- 2017.

Month / Year	JAN	FEB	MAR	AVP	MAY	JUIN	JUIL	AUG	SEP	OCT	NOV	DEC	Average (mm/year)
2007	69.3	224.3	780.3	340.3	122.4	264.8	13	47.8	343.2	490.7	113.1	502.9	276
2008	88.3	97	534.1	84.4	286	211.3	27.6	98.9	681.1	316.5	149.7	143.1	226.5
2009	741.2	243.9	194.9	709.7	130.8	5.3	32.3	135.6	461.4	206.1	104.8	82.2	254
2010	206.6	124	348.7	246.3	226.6	104.8	30.9	20.8	298.2	346.9	403.2	120.9	206.5
2011	261.2	278.3	119.6	249.4	308.1	176.5	81.8	15.2	90.9	445.1	305.2	224.8	213
2012	496.3	534.7	739.6	428.5	147.1	50	38	84.6	530.6	618	323.7	166.9	346.5
2013	356	222.7	232.4	320.1	55.7	6	98.6	275.1	418.9	338.9	257.7	387.9	247.5
2014	276.4	181.7	799.7	188.5	280.2	232.5	90.2	38.7	255.8	477	338.4	494.8	3045
2015	266.5	505.1	407.9	9.5	78.5	11.1	14.1	326.5	288.3	359.1	246.2	133.3	220.5
2016	170.8	83.3	229.3	161.6	137.5	60.7	4.4	10.6	430.4	173.8	260.3	689.3	201
2017	475.5	510.7	136.4	366.8	56.1	419.7	7.8	6.1	153.4	125.3	478.2	312.2	348

(*https://power.larc.nasa.gov/data-access-viewer*)

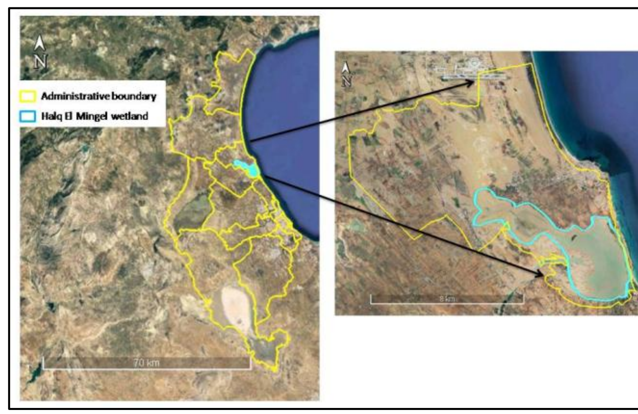

Fig 1. Geographical Localization of the study area (@Google Earth, 2021)

2.2. Methodology

This study presents a specific methodology for the spatio-temporal study of wetlands using RS techniques based on GIS and Google Earth (GE) data. As a first step, two Landsat images were downloaded and corrected. As a second step, three radiometric indexes are calculatedon April 2007 and 2017.And Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Salinity Index (SI) are analysed in order to extract respectively vegetation, hydrological and salinity change. Then, GE images were georeferenced and digitized to derive seasonal and annual changes on the wetland. The management of data and layout of the maps were processed using the Quantum GIS® 2.2. Figure (2) presents the whole flowchart of this research.

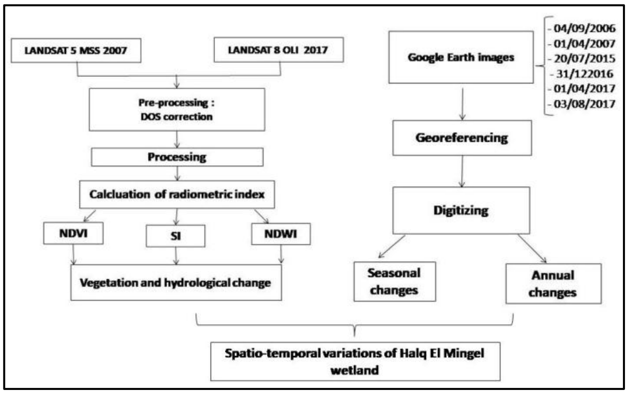

Fig 2. Flowshart of the methodology adopted in this research

2.2.1. Satellite data

The data in form of satellite imagery was acquired from the USGS official website (https://earthexplorer.usgs.gov/) from two Landsat satellites. The first one is Landsat 5 carrying the MSS (Multi-Spectral Scanner) sensor and the second one is Landsat 8 carrying the OLI (Operational Land Imager) sensor. Then images were georectified to Universal Transverse Mercator (UTM) coordinate system, using World Geodetic System (WGS) 1984 datum, assigned to north UTM zone 32 and Path 191 Row 035.

2.2.2. Preprocessing

An atmospheric correction with the Dark-Object-Subtraction (DOS) method is applied to remove or reduce the influence of the atmosphere. This method involves the correction of atmospheric transmittance through optical thickness values at a given wavelength or using the default transmittance values generated from the in situ atmospheric [25,26,27,28,29].

2.2.3. Images processing

Normalized Difference Vegetation Index, this vegetation index is used to track seasonal fluctuations in abundance, density, distribution and vegetation status [30]. NDVI is most commonly applied among vegetation indices [31,32]. The values of the NDVI are theoretically between (-1) and (+1), the negative values corresponding to surfaces other than vegetation cover, such as snow, water or clouds, for which the reflectance in the red is higher than that of the near-infrared.

Normalized Difference Water Index, NDWI can be used to highlight vegetation and water surfaces with positive values [33]. It uses the SWIR band since the water has a peak absorption. Its value increases from dry soil to open water spaces and depends on the percentage of cover in vegetation as it is sensitive to the total amount of liquid water in the leaves [34,35].

Salinity Index, salinization in the semi-arid areas can lead to desertification and land degradation [26,36]. For example, [37] demonstrated that SI is very useful for identifying and delineating saline soils.

Table 2. Details of the radiometric indexes used

Index	**Formula**
Vegetation index	NDVI = (NIR-RED) / (NIR+RED)
Water index	NDWI = (NIR-SWIR) / (NIR+SWIR)
Soil salinity index	SI = SQRT (RED x NIR)

With:

- NIR is the spectral reflectance value acquired in the near-infrared.
- RED is the spectral reflectance value obtained in the red portions of the electromagnetic spectrum.
- SWIR is the spectral reflectance value acquired in the short wave-infrared.

2.2.4. Google Earth Time Series Images

Data extracted from GE imagery was acquired from the GE Pro platform. Four images covering the entire study area were used to map changes in wetland area between 2006 and 2017. Images were georeferenced, mosaicked and converted from geographic coordinate system (latitude/longitude) to projected coordinate system (nothing/easting) using UTM projection in QGIS® 2.2. The image covering within the area boundary was clipped using the digitized area boundary map. Thus, the wetland spatial features extraction was investigated using GE time series images for 2006, 2015, 2016 and 2017 (see Figure 3).

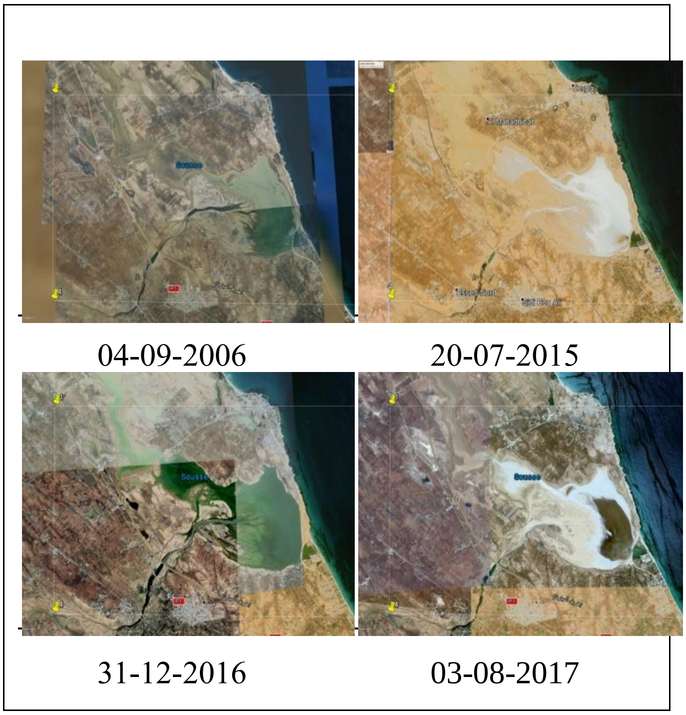

Fig 3. Google Earth Time Series Images used

3. Results

3.1. Radiometric indexes analysis

In 2007, NDVI values ranged from (-1) to 0.1 and reached 0.5 in 2017, with the highest values being around the sebkha. This indicates the high concentration of halophytes that can be explained by the importance of rainfall frequencies recorded before this period (Figure 4).In 2007, the minimum NDWI values for the sebkha range is 0.6, while the maximum NDWI is 0.9. In 2017, NDWI values range from (-1) to 0.9. It is noted that values above 0.7 indicate the presence of water with a larger surface area in 2007 (Figure 5). The SI map of Halq El Mingel in 2007 indicates that SI values ranged from 0.0015 to 0.8 with a high salinity on the south-east side. Besides in 2017, the values are less important with values below 0.133 and the most important salinity is always located on the south-east side (Figure 6). The calculation of the NDWI and SI radiometric indexes from Landsat images made it possible to assess the change in the Halq El Mingel sebkha state during the period 2007-2017. Multi-year changes in vegetation, water level and soil salinity rate were inferred.

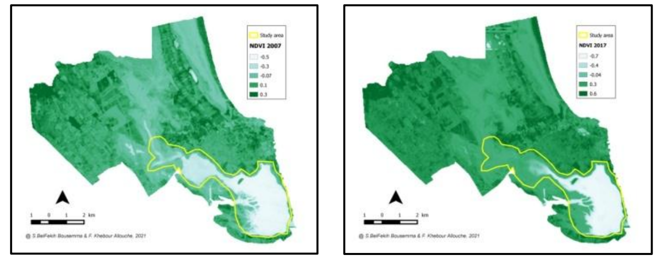
Fig 4. NDVI maps (at left in 2007, at right in 2017)

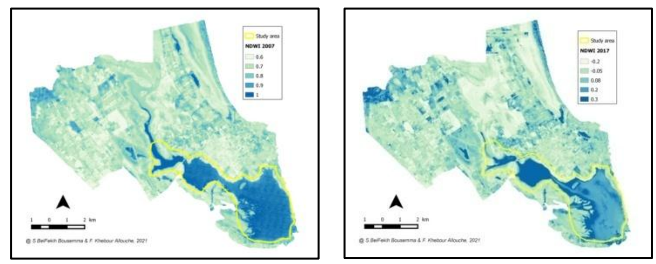
Fig 5. NDWI maps (at left in 2007, at right in 2017)

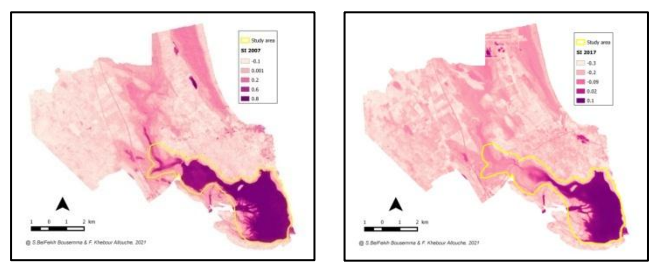
Fig 6. SI maps (at left in 2007, at right in 2017)

3.2. Spatio-temporal Wetland dynamics

3.2.1. Seasonal dynamics

In summer, the precipitation are lucky it is about 6.1 mm (Table 1) so only the permanent surface of the wetland is gorged with water 350.9 ha. In autumn, the surface increased slightly 689.8 ha. Whereas, in winter, it reached the maximum with about 1418.1 ha. In fact, the permanent and periodic parts of Halq El Mingel are both of them water-filled. However, the increase detected is explained by the rainy events recorded in December 2016 (689.3 mm). In spring, the wetland surface has shrunk to be 1146.7 ha, so that it gradually returns to its original form detected in summer, which related to the decrease of rain-water in this season (Figure 7).

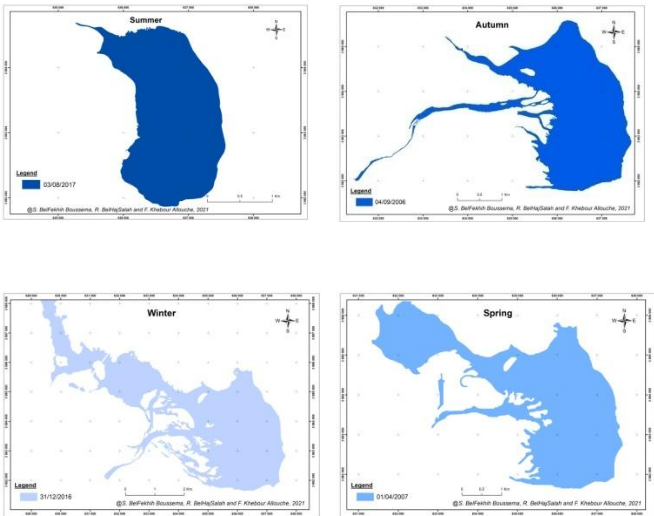

Fig 7. Seasonal variation of Halq El Mingel wetland

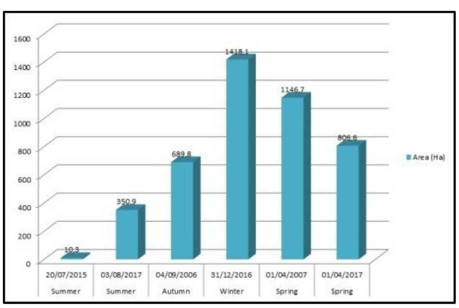

Fig 8. Seasonal variation of the area of Halq El Mingel wetland

3.2.2. Annual dynamics

Biannual

The delimitation of the sebkha shore line in summer (in dry period) respectively for the years 2015 and 2017 revealed a strong variation. In 2015, the shore line was very narrow and the water surface is negligible, about 10.3 ha. But, in 2017 it increased very highly and the growth recorded in August 2017 may be the result of the high rainfall recorded in March 2017. For that, the surface reached 350.9 ha in this period(Figure 9).Figure 10 is the result produced from two Landsat images taken both of them in spring (just in the final of the wet period) respectively for the year 2007 and 2017. It shows that the volume of the sebkha is variable and it has shrunk from 1146.7 ha in 2007 to 806.6 ha in 2017. In the first period (2007), the sebkha was filled with rainwater and the precipitation is about 780.3 mm. Although the precipitation was important in early spring 2017, the volume of Halq El Mingel is less than in 2007. So, it can be explained by the high temperatures recorded in the summer which can reach 42°C. Then the evapo-transpiration exceeds precipitation.

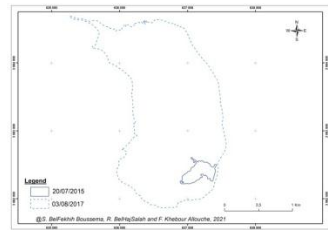

Fig 9. Biannual variation 2015-2017 of Halq El Mingel sebkha shoreline in summer

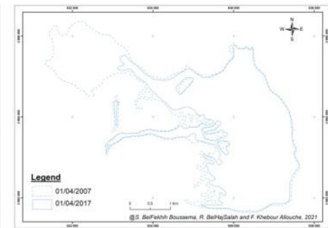

Fig 10. Biannual variation 2017-2017 of Halq El Mingel sebkha shoreline in spring

Multiannual

Figure (11) presents the result of the superposition of GE clips from the years 2006, 2007, 2015, 2016 and 2017. The analysis shows the multi-annual variation of the sebkha surface and changes can be detected from season to season and from year to year. In fact, the wetland variation cannot be predicted; it is highly dependent on hydrological variations, precipitation, anthropogenic impacts.

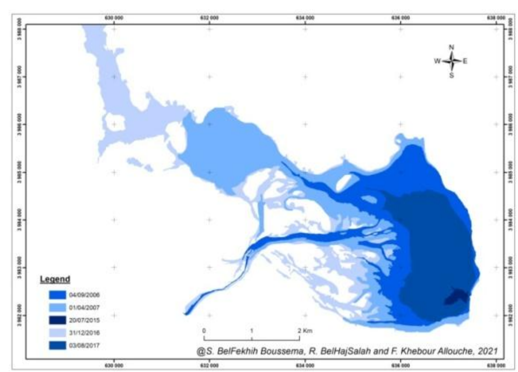

Fig 11. Multi-annual variation of the Halq El Mingel sebkha surface

3.3. Impacts of climate change

The water level of the sebkha changes according to the seasons and years. In the summer, following a high evaporation and in the absence of a wadi supply, the water level of the sebkha decreases. In addition to the rains, there are the contributions of the adjacent sewage treatment plants and wadis in the winter. During this period, the sebkha of Halq El Mingel is also partly fed by marine inputs through Oued Essod. So that, rainfall instability and rising sea levels seriously affected this wetland situation. Global climate change impacts will often exacerbate impacts of other drivers of degradation of wetlands. Based on [22], if exact measures are not taken and joint efforts are not made to protect the climate, it is expected that the Mediterranean region will be more affected in the coming decades: a) warming will increase faster than the global average; (b) precipitation will likely be reduced ; (c) summer heat wave events will become more severe; (d) sea levels will rise faster than before and will increase the frequency of coastal flooding; (e) extreme events such as droughts and floods could intensify; and (f) many wetlands will dry out or become temporary. In addition, global climate change and anthropogenic impact will affect wetland, which creates a serious problem in identifying and quantifying these areas.

4. Discussion

More recent works using modern assessment techniques like GIS and RS technologies to assess and monitor wetlands have been used [2-5,33,38-41]. In Tunisia, technological advances in GIS and RS technologies have provided several services for the protection and conservation of these areas. In addition, they offer powerful tools for data acquisition, spatial analysis, and graphical display [1]. From [42], climate change is one of the most actively considered scientific issues in the world today, because of its potentially far-reaching consequences. [43] confirmed that global climate change through alterations in hydrological regimes had a negative impact on wetland ecosystems. According to [9], water erosion is the main factor in soil degradation in Tunisia. So, irregular rains; vegetation cover degradation; crop management expansion and overgrazing, have only aggravated the situation. For that reason, the changes observed in Halq El Mingel wetland dealing with the seasons and years are explained under climate change and human activities. Mainly, climate change, such as frequent drought, could cause the shrinkage of wetland area; human activities, such as wetland reclamation and water conservancy engineering, are thought to be the reasons for habitat loss, degradation, and threaten the survival of waterfowls [44]. Special care should be given to the development of wetlands. So that water management must be the first concern for any development because of its natural settings.

5. Conclusion

The present study clearly demonstrates the utility of GIS and GE techniques in mapping and monitoring the changes which have taken place in Halq El Mingel wetland from 2006 to 2017. It has been concluded from the analysis that indeed the zone is a "sensitive" area (Ramsar site) that deserves careful management in order to maintain a state-wide ecological balance for both present and future development.

So, it is our belief that the wetland situation will be proved and to enhance the quality of live in these environments for fauna and flora. In the post-revolution period, Tunisia expressed its commitment to protect and preserve national wetlands. In 2019, the General Directory of Forests declared its intention to implement a National strategy for the management of wetlands 2020-2025 with the support of World Wildlife Fund [45]. This study provides useful information for both the communities and the environmental policy-makers. Subsequently, the wetland map assessment can help to underline the wetland depletion and its attendant vulnerability as well as fulfil as a guide for land-use practices.

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