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REVIEW

Mapping Land at Risk of Marine Submersion in the Coastal Alluvial Plains of Eastern Tunisia: A Review

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ABSTRACT

Tunisia's coastal alluvial plains are fragile areas exposed to occasional disturbances (including storms, submersion, and floods) and serious imbalances, such as rising sea level, erosion, and salinisation of soils. Their sensitivity tends to increase under the impact of strong anthropogenic pressures: population growth, rapid urbanisation, and concentration of economic activities. With the acceleration of climate change and the associated rise in sea level, these areas are facing a new challenge. At the interface between land and sea, scattered across these coastal alluvial plains are wetlands that are predisposed to marine submersion due to a combination of factors. Diachronic analysis of cartographic documents has made it possible to produce geodynamic maps. These were used in the current study to assess sea level rise and flooding, as well as their impact on the future development of coastal alluvial plains, particularly during exceptional weather and sea conditions. The findings show that a poor understanding of the mechanisms specific to these environments has often resulted in short-sighted sectoral approaches to land use planning. Sabkhas and lagoons alone account for more than half of all submerged areas. Coastal wetland ecosystems will be threatened by changes in living conditions, as the rather saline biocenosis will be transformed into a euryhaline lagoon biocenosis.

Keywords: Coastline; Alluvial Plains; Wetlands; Sea Level Rise; Marine Submersion

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1. Introduction

The low-lying coastal alluvial plains of eastern Tunisia are particularly interesting sites for analysing the risk of marine submersion due to several predisposing geomorphological factors: morphological diversity, erosion, and the sediment crisis of sandy beaches [1–6]. During coastal storms, extreme marine water levels are often higher due to low atmospheric pressure and wind. In addition to this surge phenomenon, breaking waves on the coast also have an impact. On natural beaches, wave run-up is a function of the slope of the beach and the characteristics of offshore waves [7–10]. Visible signs of rising sea levels and erosion have been observed since the 1980s, reflected in the retreat of sandy beaches, the submergence of coastal areas by sea intrusions, and the exposure of strategic urban infrastructures, particularly ports [4, 6, 11–16].

In Tunisia, the Urban Development Plan, a land use plan, seems to have been overtaken by the expansion of urban areas and the real evolution of cities. The coastal wetlands in Tunisia are part of the DPM (The Maritime Public Domain) and are also governed by law no. 95-73. This law states that the Public Maritime Domain is made up of the Natural Public Maritime Domain (the shoreline, lakes, and lagoons communicating naturally with marine waters, exclusive fishing zones, and exclusive economic zones) and the Artificial Public Maritime Domain (roadsteads, ports, and artificial islands). In turn, the Territorial Planning and Urban Planning Code, promulgated by law no. 94-1223 and reformulated and supplemented by law no. 2003-78, specifically regulates the Development Master Plans and the formalities for drawing up and approving Urban Development Plans. Article 25 of this code, which is the first legislative document to address the concept of the coastline, stipulates a minimum setback from the limit of the DPM (The Maritime Public Domain) of 100 metres in areas not covered by an Urban Development Plan and 25 metres in areas covered by an Urban Development Plan. This distance may be modified in areas affected by marine erosion or whenever coastal protection is required. By law, any temporary occupation of the DPM (The Maritime Public Domain) gives rise to fees payable to the public treasury by the occupier in accordance with the laws and regulations in force.

However, the regulatory framework for urban development favours building within the perimeter of the lagoon environment. The Urban Development Plans, most of which were drawn up 20 years ago, include options for guiding urban development in lagoon areas. Examining the Urban Development Plans of the municipalities of Greater Tunis, Cap Bon, and Greater Sousse reveals that in some cases (Hergla, Gammart, Korba, Maâmoura, and Tazarka), the urban planning alternatives favour urban expansion on the shores of lagoons and coastal sabkhas.

Under conditions of global change (global warming and a relative rise in the average level of sea water), the risk of flooding of Tunisian coastal alluvial plains is set to increase [6, 17–21]. Sabkhas and maritime marshes will be the environments most directly affected by the impact of sea level rise [1–5, 21–32]. This implies a possible reduction in the space available for inhabitants and a probable risk for economic activities. Successive IPCC reports [18, 19, 24, 25] have highlighted these potential risks, which must be taken into account in management plans for Tunisia's coastal fringe. In this study, the mapping of land at risk of marine submersion and the assessment of the impacts of submersion on the coastal alluvial plains of Tunisia are based on the IPCC scenarios [19], local hydrodynamic data, and a Geographic Information System (GIS) modelling approach. The mapping tool used is an effective tool for modelling and mapping a possible rise in sea level, as well as quantifying sensitive areas.

2. Materials and Methods

2.1. Study Area

Tunisia's coastline is bordered by varied terrain in terms of geology, topography, and hydrography. The northern coastline is bordered by rugged relief, and it is only from the Bizerte Lake system onwards that the morphology becomes relatively open and partly bordered by alluvial plains [4, 23]. Tunisia's coastal alluvial plains were formed by the accumulation of alluvial sediments deposited by wadi flooding, and are often dotted with wetlands [13, 16, 33–38]. The susceptibility of the southern part of the eastern coast to subsidence explains the expansion of sabkhas and lagoons (**Figure 1**). These wetlands, considered to be buffer zones, are the first line of natural defence against marine storms and flooding. They are often flooded during exceptional or even ordinary rainfall events and submerged during marine storms. The

flood expansion zones of these wetlands and flood plains are now largely urbanised areas, where the soils have mostly lost their capacity to absorb water and the ecosystems have been modified. By occupying these areas, humankind has for a long time significantly altered their morphology, leading to a deterioration in water quality and impacting biodiversity. However, these environments are now highly coveted [14, 21, 25, 26, 34].

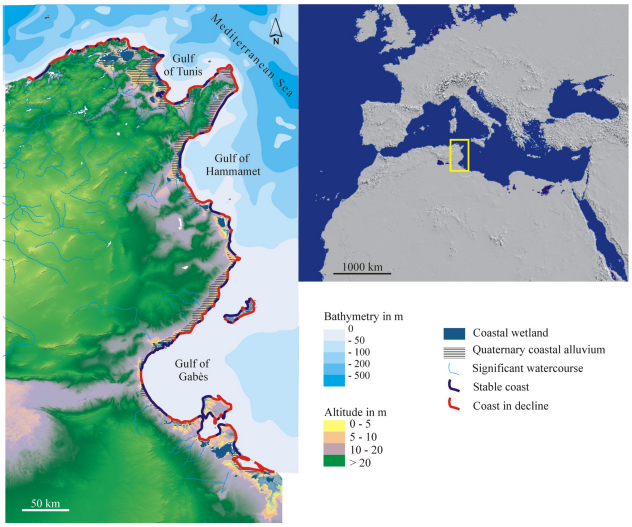


Figure 1. The study area.

Sources: [4, 27]; SRTM Worldwide Elevation Data; production: W. Chouari.

2.2. Methodology for Processing and Analysis of Cartographic Data

Cartographic representation of coastal alluvial plains is challenging due to their generally flat and monotonous topography. The lower areas of these plains are occupied by wetlands, with the average altitude of the banks of these wetlands not exceeding 10 m. In some cases, the bottoms of the wetlands are located a few tens of centimeters below sea level.

Forecast mapping of lands at risk of marine submersion in the coastal alluvial plains of Tunisia can be done using existing documentation: topographic maps (at a scale of 1:50,000 from 1902 and 1922 and 1:25,000 from 1982), old or recent aerial photographs, images taken from Google Earth, and satellite images (Thematic Mapper images of 30 m resolution). The stereoscopic interpretation of aerial photographs and images from Google Earth allows analysis of the territory as a whole. This approach is associated with field observations, which are carried out with the objective of completing, verifying, and updating the information obtained from cartographic documents.

Topographic maps, aerial photographs, and images taken from Google Earth were corrected and georeferenced in the UTM projection system, Datum WGS 1984, in accordance with a methodology classically used in coastal photo interpretation. This method is based on the application of polynomial correction models calculated from landmarks (invariable points such as road intersections, buildings, etc.) common to the different images and the reference document. The margins of error remaining after the correction were estimated by calculating the differences from one date to another in the position of elements considered invariable (buildings, ruins, etc.). The uncertainty at the coastline level was between ±0.5 and 1 m. The aerial photographs, geometrically corrected and georeferenced, were then integrated into a Geographic Information System.

However, these documents are not capable of restoring detailed topography, especially the slight differences in altitude observed at the level of low coasts which play a major role in the process of submersion of low coastal lands. Indeed, the generally flat and monotonous topography poses a cartographic problem [1, 7–10]. To resolve this problem in the study of the Tunisian coastline, the method initially involved measuring dynamic morphological parameters. Photograph interpretation was used to reconstruct the kinematics of the dune cord. The altimetry of the sites was obtained by conducting GPS topo-morphological surveys, combined with analysis of hypsometric data. From this information, we calculated digital terrain models to reproduce the height differences in as much fine detail as possible. The topo-morphological surveys were connected to the Tunisian geodetic system, and the digital terrain model was constructed with the Arc GIS software using the kriging interpolation method. The altitudinal reference frame used was therefore refined compared to that recommended in the 1:25,000 maps (**Figure 2**).

The boundary with the sea is the coastline and the altimetric boundary on the internal side is the 10 m NGT (General Levelling of Tunisia) curve. The marine zone corresponds to the area covered by marine saltwater. The surface hydrographic elements include coastal wetlands (e.g. sabkhas, lagoons, chotts, and maritime marshes). The coastal strip brings together the beaches, dunes, and dune strip. Particular attention was paid to the various existing surface and

linear hydraulic structures (including dykes and breakwater) that are likely to play a role in the dynamics of marine storms [1, 31].

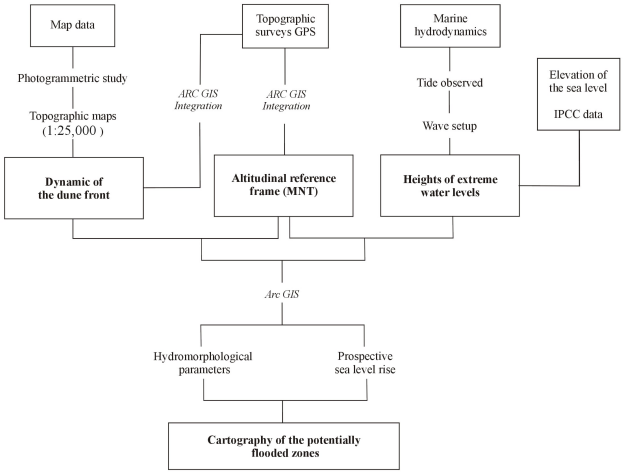


Figure 2. Flowchart of the method recommended for mapping potentially submersible alluvial plains; production: W. Chouari.

The Total Water Level (TWL) is linked to an elevation of the water body due to a combination of physical processes linked to meteorological and astronomical phenomena. The mean coastal water height relative to the reference level includes the following factors: sea level rise; tide level; the atmospheric surge created by the wind which pushes water masses towards the coast and depressions, which have an inverse barometer effect; and wave surge or set-up, which is a local elevation of the body of water towards the coast due to breaking waves. In addition, the shore jet or swash (masses of water projected towards the top of the foreshore by the breaking of waves) contributes to the mean coastal water height [8–10].

$$TWL = \eta + Ss + R_{2\%} + \Delta SLR \quad (1)$$

where: TWL: total water level;

ŋ: predicted astronomical tide;

Ss: storm surge;

R2%: 2% exceedance wave run-up height;

ΔSLR: trend in the mean sea level between time projections of SLR.

In order to integrate the impact of climate change, we used IPCC (2013) [21] projections to assess current and future (2100) characteristic sea levels. The annual mean sea level increase was linearly integrated into the dataset used to calculate the maximum shoreward elevation of water. Vulnerability to coastal submersion was assessed using two modelling methods: static and hydrodynamic models, which solve the mass and momentum equations [8]. The static (also known as bathtub, planar surface projection models) method for representing overtopping flows uses a calculated Extreme Total Water Level (TWL) based on Stockdon et al. [10]. This mapping approach, based on a static model, is used in the USA [8]. In France, the Coastal Risk Prevention Plan recommended this approach for coastal communities to develop their own risk management plans. This static approach simply compares water and land elevations and assumes that flooding occurs instantly when water levels exceed backshore elevations. In Morocco, Hakkou et al. [9] assessed the coastal flooding risk of the Kenitra coast (Moroccan Atlantic). Total water levels are empirically calculated and statistically analysed, taking into account the tide data, wave run-up and projected IPCC sea level rise. However, this approach does not consider the flows, the time necessary to flood the vulnerable zones, and the effect of coastline retreats.

3. Rising Sea Levels and a Hypothetical Increase in Extreme Events

As was strongly emphasised at the recent United Nations Climate Change Conference (cop27), climate change is one of the major global issues to be addressed in the coming years. All the climate change hypotheses acknowledge an increase in the frequency and severity of meteorological calamities and water-related risks affecting the Mediterranean [21, 22, 28]. This is confirmed by the relative rise in sea level, the hypothetical increase in the frequency of storms and simultaneous marine submersion in the lowest coastal areas [1, 2, 12, 17, 23, 29,30].

Coastal alluvial plains are areas that attract major urban, tourist, industrial, agricultural, fishing, and port activities [27]. These areas have suffered the impact of strong demographic growth, particularly as a result of heliotropism and the exodus of rural populations to coastal areas, which are particularly sensitive to flooding and marine submersion.

3.1. Tunisia's Coastal Alluvial Plains: Sensitivity Exacerbated by Land Use Patterns

Two-thirds of the population lives in eastern Tunisia, where 73% of the country's inhabitants live in less than a third of the country's territory (**Figure 3**).

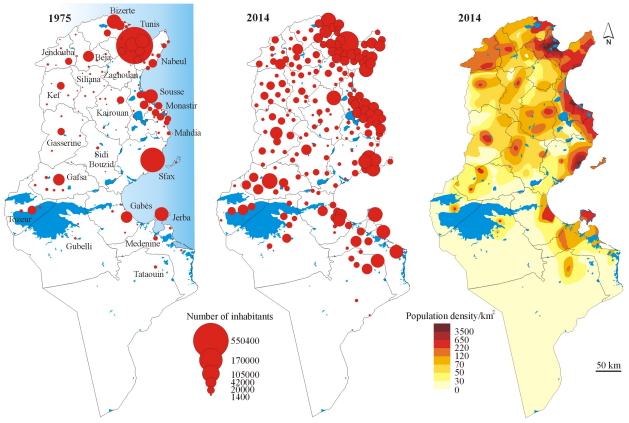


Figure 3. Population distribution and density in Tunisia (1975–2014); production: W. Chouari.

The population density exceeds 120 inhabitants per km2 in the coastal delegations, and in some areas there are more than 3,000 inhabitants per km2 (Tunis, Nabeul-Hammamet, Sousse, and Sfax). Demographic projections indicate that population density will continue to rise in the coastal delegations. Massive urbanisation since the 1970s has accelerated this increase, and urban growth has favoured settlement in more fragile and vulnerable areas. Building development has spread out, particularly on the outskirts of towns along the main roads and towards wetlands or the coast.

With a high concentration of relatively efficient infrastructure (e.g. roads, railways, ports, airports, and communications networks), over 80% of industrial activity is concentrated in the main industrial hubs along the coast (Bizerte, Tunis, Sousse-Monastir, Sfax, and Gabès). There are 1,257 ha of industrial zones along the coast, while the total surface area of Tunisian industrial zones is 1,410 ha [27].

From the 1970s onwards, large and very extensive tourist areas were created. The hotel infrastructure first expanded close to the coastal towns and villages (such as the northern suburbs of Tunis, Nabeul, Hammamet, Sousse, Monastir, Houmet Essouk, and Zarziz) and then spread out in all directions, mainly towards the sandy beaches. At the current rate, in a few decades, the entire Gulf of Hammamet will be occupied by hotels (including Hergla Marina and the Essalloum tourist area). According to estimates, the artificial coastline stretches for 201 km, with current or planned projects set to extend it to over 230 km [4, 27].

The impact of holidaymakers on coastal geomorphological units must also be taken into account, as evidenced by the trampling of dunes and the compaction of temporary wetlands drained by vehicle traffic and parking [1, 14, 26, 29–32]. In Tunisia, these wetlands have often been regarded as unhealthy environments that needed to be "cleaned up" at all costs.

Tunis was built at the expense of marshy lagoon lands, and a post-independence urban sprawl developed very rapidly on the banks of the sabkhas and along the north and south coasts of the capital. The peri-urban area fragmented in the 1980s, and the 1990s reinforced this trend, encompassing other borders, including development on the banks of the lagoon and sensitive areas on the banks of the sabkhas (Ariana and Radès sabkhas) and the Garâas (Garâa Ben Ammar) [29, 30] (**Figure 4**).

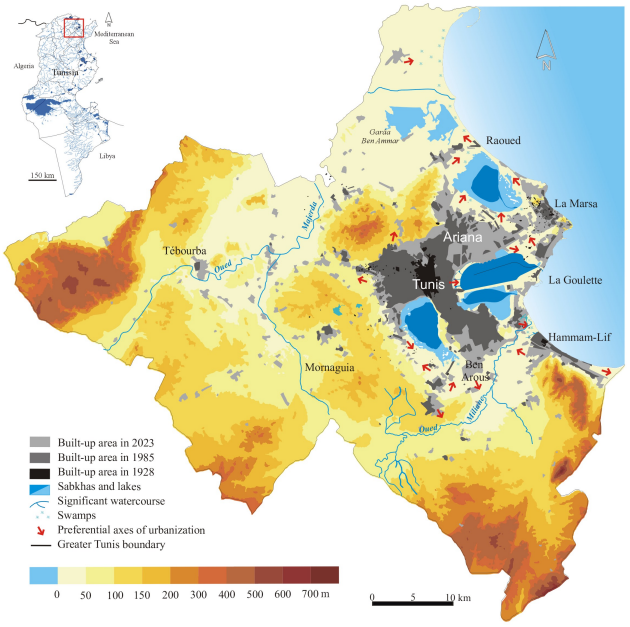


Figure 4. Extension of the Tunisian urban area towards the wetlands and the coast.
Sources: 1:50,000 topographic maps from 1928, 1:25,000 topographic maps from 1985, and Landsat images from 2023; production: W. Chouari.

On the eastern coast of the Cap Bon peninsula, the most spectacular reduction in surface area has been that of the Korba lagoon. Between 1960 and 1987, the southern banks of this body of water were filled in to provide 30 ha of building land for the expansion of the town of Korba towards the coast. Similarly, the bottom of the old Menzel Témime lagoon was filled in with waste from the town, and an entire residential district was built to the south-east of the town at the expense of a 14 ha lagoon and the bordering dune. Today, the area has only a few metres of beach, which is completely submerged during the stormy season.

Another example is the expansion of the villages of Ramla and Ouled Bou Ali in the Kerkennah Islands. These villages are now separated by sabkhas that are increasingly being eaten away by buildings. This land is unproductive and can be flooded during high tides and particularly during marine storms. Urbanisation–wetland–agriculture conflicts are multiplying along the shores of wetlands, and the impact of high salinity destabilising the buildings is more pronounced in the neighbourhoods on the shores located in the lowest areas (**Figure 5**).

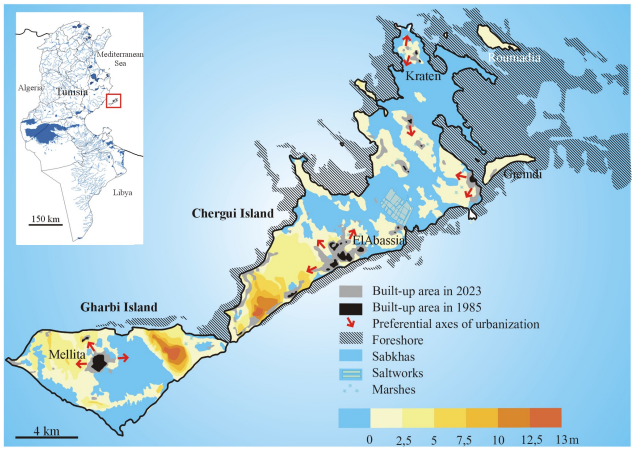


Figure 5. Urban sprawl in the Kerkennah Islands towards the wetlands and coastline.
Sources: 1:25.000 topographic maps from 1985 and Landsat satellite images from 2023; production: W. Chouari.

In Sfax, over 80% of industrial activity is concentrated in the main industrial zones along the coast. The built-up area is spreading like an oil slick, and urban construction along the main roads has put pressure on coastal wetlands and watercourses, threatening their natural balance, especially through solid and liquid waste (**Figure 6**).

The rapid development of the eastern sector of Jerba Island has altered the natural landscape and contributed to an ecological imbalance. It should also be remembered that the construction of hotel units, in particular Dar Jerba and Tanit, has necessitated large areas of sabkhas to be sealed off.

In addition, the significant drop in the water table and the intrusion of saltwater from the sea have reduced the percentage of freshwater in the water supply to these wet depressions. This phenomenon is particularly problematic in island areas, where freshwater resources are already very limited. Hydrological parameters directly affect the physico-chemical properties of water, nutrient availability, oxygenation, substrate salinity, sediment chemistry, and pH [11, 14, 17, 24].

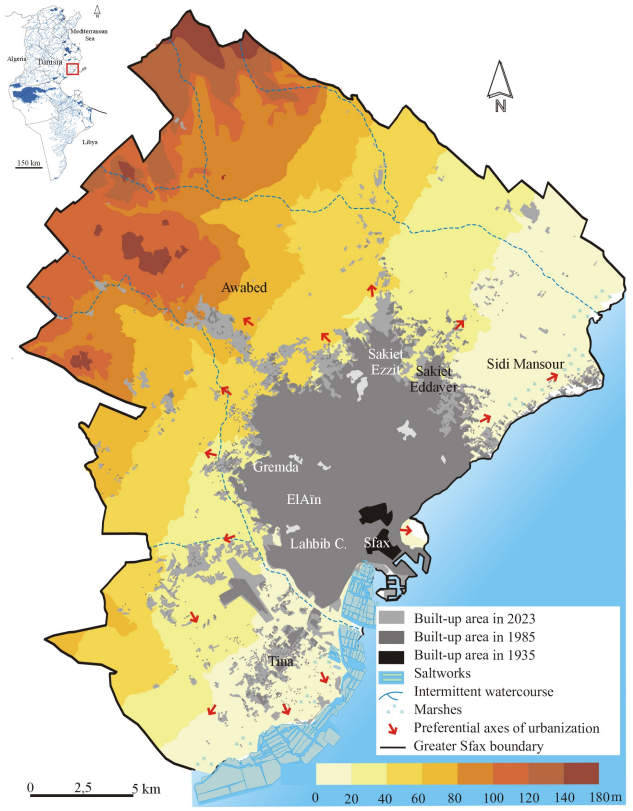


Figure 6. Preferential axes of urbanisation in Greater Sfax.
Sources: Aerial photographs from 1935, 1:25,000 topographic maps from 1985, and Landsat 2023 images; production: W. Chouari.

On the whole, built-up areas, whether residential or commercial, located in flood-prone areas on the banks of wetlands or directly on the seafront, are expanding and becoming denser. Tunisia's coastal wetlands, because of their accessibility, their benefits for the local population, and the immense importance of their biological wealth, are subject to strong human pressure.

3.2. Coastal Alluvial Plains Sensitive to Relative Sea Level Rise

On a global scale, the average sea level has risen by 10 to 15 cm since the end of the 19th century [20]. Depending on the models used, scientists estimate that by 2100, sea levels could rise by an average of +29 to +110 cm, depending on the minimum or maximum global warming assumptions [20]. This rise in sea level is perhaps the most certain outcome of global warming, amplifying sea surges during coastal storms (**Figure 7**).

Several studies claim that the global climate change underway will lead to a significant rise in sea level above the upper limit proposed in the IPCC scenarios [11, 21]. In Tunisia,

the acceleration in the relative rise in sea level has been taken into account in all the assessment reports published by the IPCC[18, 19]. The climate scenarios constructed by the IPCC on the basis of past and present climate trends predict a rise in sea level of 13 to 59 cm by 2100, in accordance with greenhouse gas emission scenarios. There are three possible values to choose from when making assumptions about the sea level rise by 2100: the minimum risk assumption of 38 cm, the median assumption of 50 cm, and the maximum risk assumption of 55 cm.

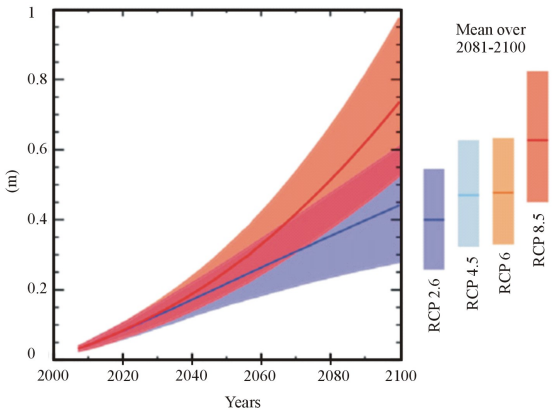


Figure 7. Projection of global sea level rise from 2000 to 2100.
Source: Based on the IPCC AR5 report and temperature projections for different emissions scenarios[39].
Note: IPCC projections are reported for two different emissions: very high emissions (red, RCP 8.5 scenario) and very low emissions (blue, RCP 2.6 scenario).

The Tunisian coastline also contains several indicators of the rise in sea level during the 20th century. These indicators are diverse, but precise measurements are still relatively rare or non-existent.

In Tunisia, the rise in relative sea level is also corroborated by evidence from archaeological sites (building remains at Sidi Erreis, Gammart, Carthage Salammbô, Sallakta, the Kerkennah Islands, and Jerba; tombs at Mahdia; ruins at Sidi Mechreg). In ancient times, sea levels were lower than they are today on all of Tunisia's coastline, as shown by the permanent and widespread submergence of the coastal quarries exploited in Roman times[13, 15, 16, 40]. This minor transgression since Antiquity is probably eustatic in origin. Its amplitude varies between 0.2 and 1.5 m because, depending on the location, local tectonic behaviour has increased or decreased it. As a result, it is possible that the coast retreated during the historic period.

Tide gauges also estimate that the average water level of the Mediterranean Sea rose by 1.5 cm per decade between 1891 and 1950[15]. Tide gauge readings from the ports of Sfax and La Goulette have confirmed previous observations, revealing a rise in sea level at a remarkable rate since the beginning of the 20th century (**Figure 8**).

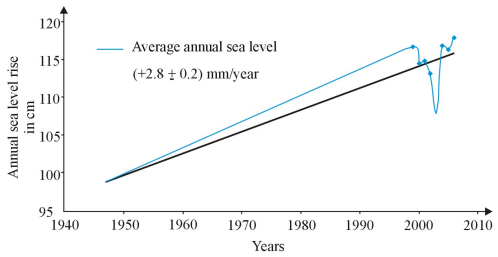


Figure 8. Average annual sea level in the port of Sfax.
Sources: [6]; production: W. Chouari.

The average sea level in the port of Sfax rose by an average of 17 cm over 60 years between the first and last data collected (1946 and 2006) to reach a value of 116 cm, indicating an annual rise of 2.8 ± 0.2 mm per year.

Furthermore, according to Jabnoun and Harzallah[41] the level of the Mediterranean is characterised by high interannual and decadal variability. This behaviour has been shown to be linked to the North Atlantic Oscillation (NAO) through its effect on atmospheric pressure and local changes in the wind field. The same authors provided an estimate of the sea level trend along the Tunisian coast, based on tide gauge observations and model simulations. The available observations were adjusted to the sea level in the Atlantic. The sea level rose at an average rate of 1.5 mm per year from 1889 to 2015 (127 years), corresponding to 19 cm over this period. For the period 1946–2006, the sea level rise is estimated at 9.2 cm. This trend is very close to the global sea level trend, estimated at 1.5 mm per year for the period 1901–1990[33] (**Figure 9**).

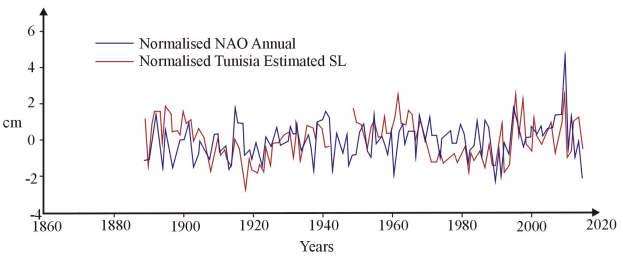


Figure 9. Red: sea level drift along the Tunisian coast. Blue: inverse of NAO index for January (upper) and annual (lower) values. Both series are centred and normalised.
Source: [41].

For the recent period 1980–2015, the results show that the sea level is rising at a higher rate of 3.0 mm/year. However, this rather high rate can be partly attributed to decadal oscillations corresponding to the transition from negative to positive phases over the period 1980–2015.

Climate change could lead to a rise in average sea level and is likely to be accompanied by stronger and more frequent storms.

3.3. An Area Exposed to Storms and Marine Submersions

Direct or atmospheric climatic hazards affecting eastern Tunisia include heavy rainfall, storms, tornadoes, and hail. Tornadoes are fairly rare, but some do affect the coast during the transitional seasons. One or two tornadoes are recorded each year between the Gulf of Gabès and the Gulf of Hammamet, causing occasional damage. In addition, a certain number of meteorological conditions are required for the recording of intense and exceptional rainfall with high accumulations. Predicted climate change is also expected to accelerate atmospheric circulation, increasing the frequency and intensity of storms. These storms are frequently associated with surges, i.e. exceptional rises in sea level lasting several hours. The extreme water levels caused by low barometric pressure and strong winds are generally higher than expected during coastal storms. This surge is compounded by the effects of wave breaking, which also depends on the slope of the beach and the characteristics of the waves offshore [10].

Several storms have hit the Tunisian coast, contributing to beach erosion and the submergence of coastal plains and wetlands. Four major events marked the 19th and 20th centuries: January 1831, December 1931, January 1951, and January 1981 [32]. January 1981 was an exceptionally stormy month in the Bay of Tunis, with several storms in quick succession, particularly on the 8th, 16th, 20th, and 21st. The storm of the 20th was particularly strong and caused the most damage to public and private property. During this episode, the marked drop in atmospheric pressure was accompanied by violent winds gusting to almost 140 km/h, causing a rise in sea level and waves 1.5 m high. The highest water level on 21 January 1981 is estimated at +0.90 m NGT (the reference level considered is the zero of the General Levelling of Tunisia since all the topographic maps are given with this reference level) and caused flooding at the bottom of the Gulf of Tunis. This episode caused beaches to shrink by around 50 m, flooded farmland for several months, and destroyed seaside amenities. Fences collapsed, and even several houses collapsed over a distance of more than 15 km [3, 12, 30, 32] (**Figure 10**).

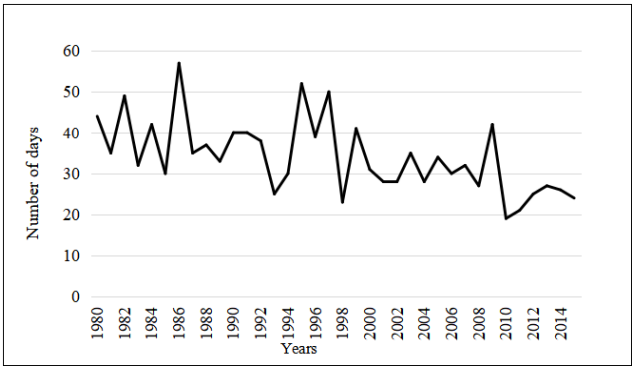


Figure 10. Occurrence of marine storms from 1980 to 2020 at the Tunis-Carthage station (wind speed > 100 km h^{-1}).

Source: [3].

Other major, but not exceptional, events have also prompted much debate in the press and media, as well as exchanges of photos and even videos on social networks. Two marine storms hit the coasts of the Tunisian Sahel on 10 March 2012 and 27 November 2022. The effects of these storms were felt along the region's various shores. Unfortunately, these storms have not been measured by specialist services and their geomorphological consequences have not been published. However, attention is often focused on the damage to seafront facilities at Kantaoui and Rejiche (**Figure 11**).



Figure 11. (**a**) At Kraten in the Kerkennah Islands, on the night of 26 to 27 November 2022, violent winds blew, pushing the sea over the dykes and encroaching on houses, fields, and roads. (**b**) At Sidi Abdelhamid in Sousse Sud, during the storm of the night of 26 to 27 November 2022, the sea wall built to counter the rising waters failed to block the breaking waves. Mixed waste was transported by sea currents and piled up along the coast.
Source: https://nawaat.org/2023/01/04/changements-climatiques-kerkennah-un-archipel-en-sursis/.

During these events, seawater advances inland, often

resulting in a significant loss of beach sediment. Tunisia's sandy beaches are increasingly vulnerable due to their fine grading, and morphogenic events can lead to breaches in the bordering dunes, through which seawater invades natural and/or developed areas. This submersion is the result of repeated erosion of the dune base by storm tides, flooding the upper beach. Often the problem stems from a lack of sediment, which causes the beach to recede and sink, making the base of the dune more vulnerable to the action of the shore jet. When the dune cordon is eroded and the sandy beach falls below extreme sea levels, submergence occurs. The areas most sensitive to these phenomena are generally those considered to be low lying and urbanised.

Streets, tracks, and footpaths running perpendicular to the shoreline also encourage the advance of the sea. Accumulations of material resulting from the destruction of buildings on the seafront or the redevelopment of dumpsites attract attention because of their volume and their highly heterogeneous and chaotic appearance. Unfortunately, in addition to the disadvantage of fixing the shoreline and disrupting the sediment exchanges that take place within the beach profile, the built-up areas adjacent to the shoreline prevent it from adapting to the changes imposed by a marine advance linked to rising sea levels.

Combined with the thinning of the barrier beaches, the rise in sea level may lead to an increase in maritime incursions during storms in low-lying coastal plains and wetlands, and at the same time make it increasingly difficult for water to drain out to sea. The duration of soil immersion, which has been recorded to last several days in the lowest-lying areas, may be extended.

These coastal areas are particularly interesting for analysing the risk of flooding, as they combine multiple predisposing factors: erosion of beaches and cliffs, morphological variability, and sediment crisis on beaches.

4. Potential Flooding of Tunisian Coastal Alluvial Plains

In coastal Tunisia, the estimated maximum rise in sea level by 2100, combined with the human occupation of the coastline, the shortage of river sediments evacuated to the sea, and the scarcity of dykes capable of coping with rising sea levels, means that it is reasonable to assume that vast areas currently located at around 1 m above sea level will be partially flooded unless drainage and protection systems are adequately developed.

4.1. Submergence Scenarios for Coastal Alluvial Plains at the Bottom of the Gulf of Tunis for 2100

The effects of future relative sea levels on the alluvial plains at the bottom of the Gulf of Tunis, from the Ghar El Melh lagoon in the north to the southern suburbs of Tunis in the south, have been assessed on a fine-grained scale. These plains are characterised by their high economic and ecological value, the presence of agricultural, tourist, and urban activities, and protected wetlands. The area is potentially prone to coastal flooding because of its very low topography and because it is affected by significant subsidence [17], which accentuates the local effect of rising sea levels linked to ongoing climate change.

Sensitivity to potential marine flooding is assessed using two modelling methods: static models and hydrodynamic models that solve the mass and momentum equations [8]. Static models are widely used to assess the impact of storms and sea level rise. They are based on a simple comparison between the extreme water level and the altimetry of the coastal alluvial plain. Thus, the method used in the mapping of submersible land is based on the cross-referencing of geomorphological data, a digital terrain model, and extreme sea levels for different scenarios proposed for Tunisia by the IPCC [18, 19] for the current century [1, 2, 6–10, 39]. Four submersion hazard classes were considered: (Z1) zones between −1.1 and 1.04 m; (Z2) zones between 1.05 and 1.42 m; (Z3) zones between 1.43 and 1.54 m; (Z4) zones between 1.55 and 1.59 m above sea level. These thresholds correspond to exceptional sea levels due to large surges induced by exceptional gales under the various IPCC scenarios (**Figure 12**).

Sabkhas and lagoons alone account for more than half (53.2%) of all submerged areas. The remainder (46.8%) is spread over other low-lying areas, essentially alluvial plains and agricultural areas adjacent to coastal lagoons. These areas extend mainly into the Majerda delta plain, which is already very low lying. The coastal margins of this plain are often less than 1 m high, which has facilitated the expansion of wetlands such as lagoons, chotts, and sabkhas (the Ghar El Melh lagoon and its annex, the Sidi Ali El Mekki lagoon,

the Kalâat Landlouss sabkha, the Sidi Bahroun sabkha, and the former mouth of the Majerda wadi "Foum El Oued") (**Table 1**).

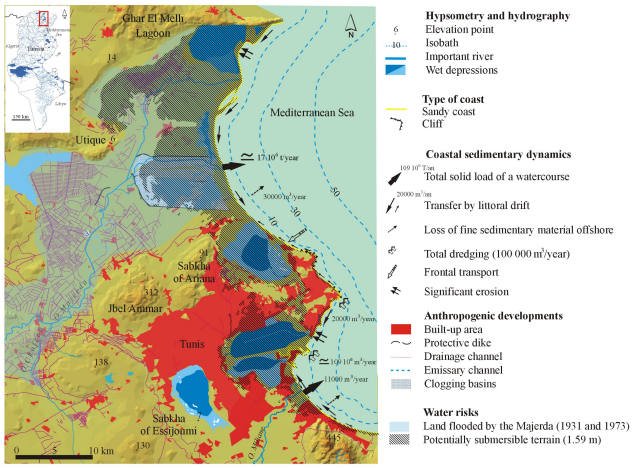


Figure 12. Map of potentially submersible land at the bottom of the Gulf of Tunis in the event of a rise in sea level (exceptional maximum sea level due to large surges induced by exceptional gales according to the various IPCC scenarios) [18, 19].
Sources: Digital Elevation Model, 1:25.000 topographic maps from 1985; production: W. Chouari.

At the bottom of the Gulf of Tunis, the width of the dune was measured by varying the elevation of the water level in the three scenarios defined according to the extreme sea levels associated with the different return periods. The disappearance, even partial, of the dune would result in the submergence of the area behind it. Furthermore, the current DPM limits do not take into account the rise in sea level expected over the next few years. If this were to occur, part of the boundary would simply be annexed to the sea. Mapping of the coastal sabkhas showed that they were partially flooded in the current situation and would be totally flooded at a level of +1.04 m with the opening of the new graus. Simulation of a 55 cm rise in sea level shows that almost all the sabkhas of Sidi Bahoun, Kalâat Landlouss, Ariana, and Radès would be submerged, drifting towards new lagoon systems that are largely open to the sea, which would change the nature and dynamics of the ecosystem and destabilise it. Even in a voluntary scenario, the low-lying alluvial plains would be flooded. The predicted relative rise in sea level by 2100 will radically alter the current morphology, potentially flooding up to around 247 km^2 of coastal alluvial plains at the bottom of the Gulf of Tunis. This delimitation in fact gives the minimum space at risk, as it does not account for the impact of marine erosion that will occur in the meantime, as well as the impact of subsidence, which has increasingly been confirmed by geologists.

On the other hand, the cartographic results show a low sensitivity of the sections protected by a sufficiently wide dune cordon and in a state of fattening (such as Borj Cédria, Medfoun, Gdhabna, and Gigthi). The dune cordon often acts as the first natural barrier against marine submersion. Demonstrative cases were reported in the eastern part of the Skanès coast, at various points on the Chatt Mariem coast, and at El Menchia after the storm of 10 March 2012, showing the importance of sediment exchanges between the various coastal environments and spaces, from the foreshore to the catchment areas of the wadis and adjacent coastal areas. In the sections of the coastline not yet lined with hard structures, the reconstruction of the beach in terms of both width and thickness after the storm was achieved in the context of migration of the entire beach-dune system, providing remarkable confirmation of the conveyor belt principle [20].

4.2. Impact of Sea Level Rise on the Future Development of Coastal Wetlands

The evolution of coastal wetlands in the face of climate change is still difficult to predict. It will most likely reduce the morphological stability of water bodies. The boundary between scenarios of clogging and those of submergence is already being blurred, is very narrow, and still subject to uncertainty. On the one hand, accelerated erosion will encourage flooding of the wetland lido. On the other hand, increasingly dry climatic conditions favour more solid terrigenous inputs (soil degradation and erosion on the slopes), while a probable increase in marine storms could favour marine inputs and migration inland from the lido.

The trend of evolution from an open lagoon to a sabkha is observed in the sabkha of Soliman. Ruiz et al. [42] confirmed that the surface area of the permanent water body had shrunk by up to 30%, despite being fed by freshwater. This is also the case for other coastal sabkhas in Tunisia, such as the Ariana and Bou Zid sabkhas [30]. The same scenario applies to the Korba and Sidi Ahmed Ben Daouad (Maâmoura) lagoons on the eastern coast of Cap Bon.

For a scenario of rapid sea level rise and a stable sedimentation rate, the evolution of the environment tends towards an open environment. There are signs to suggest that

Table 1. Distribution of submerged land at the bottom of the Gulf of Tunis for different scenarios proposed by the IPCC [18, 19, 21] (production: W. Chouari).

Zones	Type of Land Use	Area in km²	Surface Area (%)	The Area Added in km²	The Area Added in % of the Total Area
Z1 (–1.1 m to 1.04 m)	Sabkhas	45.23	20.70	-	-
	Lagoons	80.45	36.82	-	-
	Wadi mouths	0.31	0.14	-	-
	Agricultural land	76.52	35.02	-	-
	Urban areas	15.98	7.31	-	-
	Total	218.49	100	-	-
Z2 (1.04 m to 1.42 m)	Sabkhas	48.15	21.02	2.92	27.67
	Lagoons	81.41	35.54	0.96	9.09
	Wadi mouths	0.42	0.18	0.11	1.04
	Agricultural land	82.32	35.94	5.80	54.97
	Urban areas	16.74	7.30	0.76	7.20
	Total	229.04	100	10.55	100
Z3 (1.42 m to 1.54 m)	Sabkhas	49.71	20.66	1.56	13.57
	Lagoons	81.56	33.90	0.15	1.30
	Wadi mouths	0.49	0.20	0.07	0.60
	Agricultural land	89.56	37.23	7.24	63.01
	Urban areas	19.21	7.98	2.47	21.49
	Total	240.53	100	11.49	100
Z4 (1.54 m to 1.59 m)	Sabkhas	50.23	20.26	0.52	7.12
	Lagoons	81.72	32.97	0.16	2.19
	Wadi mouths	0.51	0.20	0.02	0.27
	Agricultural land	95.25	38.43	5.69	77.94
	Urban areas	20.12	8.11	0.91	12.46
	Total	247.83	100	7.3	100

Source: Proposed by the IPCC [21–24]; production: W. Chouari.

this dynamic is taking place in certain lagoons, such as the Foum El Oued and Ghar El Melh lagoons [40]. However, although some areas of erosion have been detected, hindsight is not sufficient to state with certainty that this trend will continue in the long term (**Figure 13**).

The Ghar El Melh lagoon is in fact a complex of wetlands covering an area of 30.2 km². It is part of a very low accumulation coastline and comprises three units: the main "El Bhira" lagoon, the Sidi Ali El Mekki lagoon, and the El Ouefi sabkha. The eastern part of the wetland is the most disturbed compared with the rest of the lagoon complex. When the new port of Ghar El Melh was built in 1974, sedimentary disturbances and a decline in orchards occurred [43]. With a rise in sea level of 1.04 m, the Ghar El Melh wetland would be transformed into a bay. On the other hand, lands such as the sabkhas, which are currently repugnant, could be transformed into environments permanently occupied by seawater or even veritable lagoons. This is also the case for the sabkha of Sidi Bahroun (**Figure 14**).

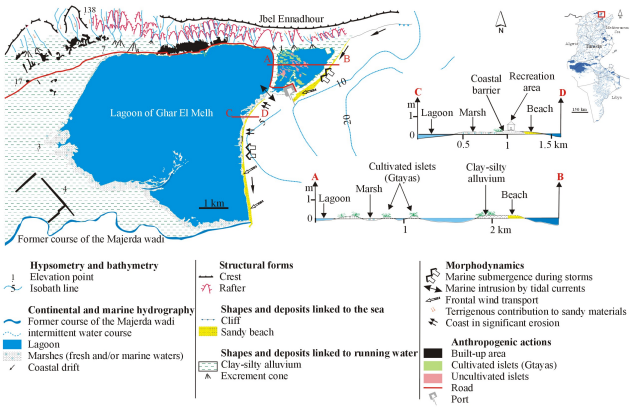


Figure 13. The Ghar El Melh lagoon: disrupted sediment dynamics along the shoreline, a heavily modified lido morphology, a lagoon system threatened by maritimisation, and a threatened heritage culture.

Sources: [4]; Landsat image, 2023; production: W. Chouari.

The coastline at the bottom of the Gulf of Hammamet

will feel the impact of rising sea levels, particularly through the string of sabkhas and the alluvial plain that border it, as well as through its many sandy beaches, especially those bordered or occupied by built-up areas. Even now, the sabkhas are heavily influenced by marine waters, which can reach them through gaps in the coastline. W. Chouari [2], studying the repercussions of a rise in sea level on the wetlands at the bottom of the Gulf of Hammamet, showed that the episodic opening of breaches during storms would have a significant morphogenic effect. Indeed, the acceleration of the rise in sea level and the increased frequency of storms would increase the risk of fragmentation of the dune cord separating the wetlands from the sea (**Figure 15**).

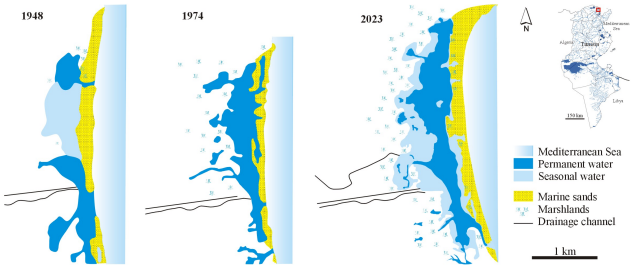


Figure 14. Changes in the morphology of the Sidi Bahroun sabkha between 1948 and 2019.

Sources: [4]; Aerial photographs, 1948 and 1974 and extract from Google Earth, 2023; produced by W. Chouari.

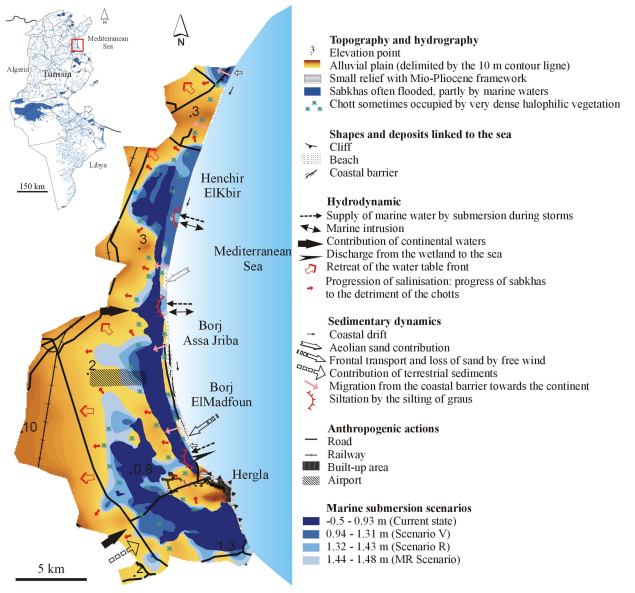


Figure 15. Wetlands at the bottom of the Gulf of Hammamet: morphological dynamics and potentially submersible areas—a future state in 2100 for the various scenarios proposed by the IPCC [18, 19].

Sources: Digital Elevation Model; production: W. Chouari.

In addition, the loss of beach sediments will increase, given that during storms, significant quantities of solid matter displaced by waves in the sabkhas through submersion or the opening of breaches or the widening of graus cannot be recovered. All these factors accelerate the retreat of sandy beaches (**Figure 16**).

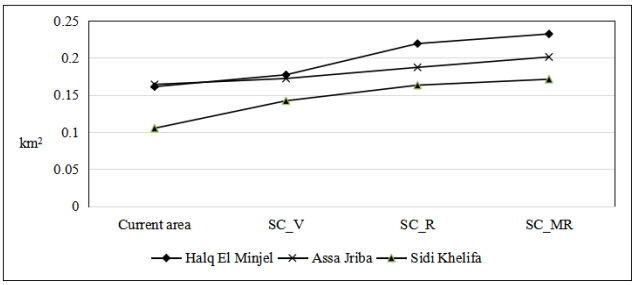


Figure 16. Extension of wetlands (future state in 2100) at the bottom of the Gulf of Hammamet for the different scenarios proposed by the IPCC [18, 19].

Source: Produced by W. Chouari.

The shores of the Kerkennah Islands also show abundant signs of erosion, despite the low energy of the waters that bathe them, due to their shallow depths and the strong expansion of the shoals. The wetlands that are frequently adjacent to them are often sites of expansion at the expense of the low-lying land that borders them. According to Etienne [11], the sabkhas of the Kerkennah Islands predate the palm grove, as can be seen particularly well at the Henchir Salem sabkha, to the north-east of the village of Melitta. The dead palm trees around the sabkha bear witness to its expansion. The surface area of the sabkhas in the Kerkennah Islands increased between 1984 and 2011 from 4,164 ha to 4,900 ha, an increase of 736 ha (15%) over 27 years. In 1984, the sabkhas represented 26.6% of the Islands' surface area and had expanded to 31.4% by 2011. Sabkha-type environments, now regularly flooded and impassable for several months at a time each year, contain remnants of important ancient forms of occupation. In addition, non-halophilic plants have been found in wet depressions and areas affected by the tide [40]. The wetlands, scattered along the low-lying coastal areas of the Kerkennah and Jerba islands, are influenced by regional climatic and marine variations (rising Mediterranean waters), as well as by the effects of tourism and urban development. The disruption of these exoreic systems and their conversion into endorheic systems under the influence of human disturbance is leading to the rapid loss of coastal ecosystems and the formation of sabkhas. These sabkhas allow only low, salt-tolerant vegetation to grow. The spread

of these environments obviously reflects a loss of arable and nutritious soil, increasing the food and economic vulnerability of local populations. In turn, brackish groundwater has a significant corrosive effect on human constructions (**Figure 17**).

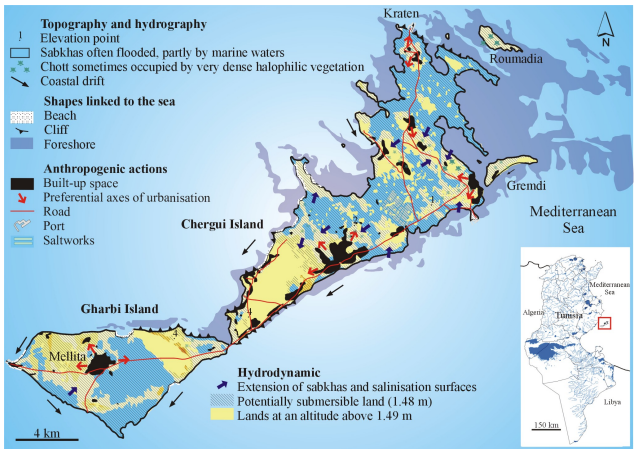


Figure 17. Wetlands of the Kerkennah Islands: risks associated with water and environmental change.

Sources: Etienne [11]; Landsat image, 2023; production: W. Chouari.

On the other hand, the wetlands of eastern Tunisia have also been subject to numerous artificial sealing operations. Claims on lagoons and sabkhas are sometimes made by public authorities carrying out various development activities on reclaimed land (such as residential estates, transport infrastructure, tourist resorts, and industrial zones). They can also be made by people wanting to extend their homes. Some wetlands have even disappeared (sabkhas of Menzel Témime, Kelbou, and Ben Ghyadha), while others will soon do so if nothing is done to save them (e.g., sabkhas of Kélibia, Lebna, and Sousse).

5. Conclusions

All the IPCC reports [18–23] confirm that rising sea levels will affect the coastal system in terms of coastal erosion, temporary coastal flooding, and permanent coastal flooding, particularly in low-lying coastal areas, leading to a loss of biodiversity and ecosystems and/or a change in their functions. In Tunisia, sabkhas, lagoons, maritime marshes, and wadi mouths seem to be the environments where the ecological consequences will be most apparent. These coastal wetland ecosystems will be threatened by changes in living conditions linked to the intrusion of seawater. Some of the marshy areas with halophilous vegetation that border the alluvial plains on the outer side are less than 1 m above sea level and will be submerged.

The intrusion of seawater into the water table will undoubtedly be amplified. The interface between fresh and saltwater will move inland, raising the piezometric level. However, to date, decision-makers in Tunisia have placed little emphasis on the links between climate change and the rational use of low-lying coastal alluvial plains.

Given the current occupation of the coastal zone and the increasing pressure on land, environmental changes linked to marine submersion are a major source of risk that must be taken into account in the development and management plans for the coastal strip. Over the coming decades, therefore, the issue of sensitivity to submersion is likely to become central to the management of these dynamic areas.

However, the uncertainties associated with the estimates of future sea level rise envisaged by the IPCC scenarios temporarily prevent any definitive conclusions from being drawn about the future of coastal wetlands. Tunisian ecosystems have adapted to alternating dry and wetter years. If there is less water, the wetlands will become much poorer. Their survival will depend on the availability of fresh water. The hydrogeomorphological dynamics are slowed down and the regeneration capacity of wetlands is strong.

The reduction in wetlands is mainly due to the accelerating pace of urbanisation and the construction of major facilities and infrastructure along the coast. However, the impacts of climate change on wetlands will only be felt in the long term (projections covering a window of less than 100 years). Nevertheless, the acceleration in sea level due to climate change should be highlighted, as it will most likely modify coastal morphology and transform wetlands. The effects of accelerated sea level rise will lead to both the creation and destruction of wetlands. Sea level rise will have an impact on the coast, coastal wetlands, and neighbouring water tables, particularly by increasing their salinity. Climate change and the increase in human activities are increasing the sensitivity of coastal areas due to impacts linked to agriculture, water quality, and the services provided by coastal ecosystems. Predicted climate change would exacerbate beach erosion, salinisation of agricultural soils, and flooding of low-lying coastal wetlands.

Wetlands provide services to society, both in terms of

biodiversity and the quality and quantity of water resources. These natural and man-made wetlands essentially maintain the ecosystem in place. However, changes to these environments, particularly as a result of human activity in recent decades, have led to major modifications to their functions, posing major management problems. Their natural or artificial destruction would endanger other adjacent systems (alluvial plains, groundwater, and rivers) or those located downstream (e.g. schorres, slikkes) while reducing their productivity, thus causing the disappearance of the populations that live there. This is why it is vital to protect them and use them according to their potential. Managers are invited not only to delimit wetlands, but also to evaluate their function to carry out effective protection, maintenance, or restoration actions.

The economic (growing urbanisation, tourism, and industrial development), ecological (significant marine biodiversity in coastal waters and lagoons), heritage (preservation of the rich bird life), and landscape issues at stake all require the implementation of a comprehensive and integrated approach to the risk of marine submersion, including risk prevention. The problem of dune barrier erosion and the risk of submersion is no longer posed in simple environmental terms but leads to political decision-making which coastal managers must deal with. It is a matter of assessing the risk incurred in the most relevant way possible before intervening in the field. Forecasting an evolving trend constitutes a very useful preliminary approach for the development of a rational development plan for a coastal area. Without solutions to these problems, the Tunisian coastline will lose its rich assets and parts of its beaches. These perspectives require a global reflection on the Tunisian coastline, its assets, constraints, and risks, and the means at its disposal to drive the planned change from a perspective of sustainable development.

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