Public Disclosure Authorized

Disappearing coasts:

Coastal erosion and its costs in the Maghreb

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Summary

This report investigates coastal erosion in the Maghreb part of the Middle East and North Africa (MENA) region focusing on: (a) understanding recent trends and hotspots of coastal erosion in Algeria, Libya, Morocco, and Tunisia, (b) quantifying the asset destruction costs from historic coastal erosion, and (c) piloting forecasting (10 years and 20 years into the future) of coastal erosion in selected locations. The report creates original data using high resolution Earth Observation data using 50m resolution segments along the coast instead of 500m as is done in global evaluations, along with statistical temporal change detection. It then uses economic valuation techniques to estimate the economic costs related to these physical changes of the coasts.

The Maghreb is the second most coastally eroding region, following South Asia (where especially the low-lying Bangladesh delta is disappearing at rapid speeds). The average annual coastal erosion rate of 0.07 meters, is surpassed significantly especially in Tunisia, which has average coastal erosion rates of 0.70 meters per year, and Morocco, which has rates of 0.14 meters on the Mediterranean coast and 0.12 meters on the Atlantic coast. These are country averages, and certain hotspots in these countries are disappearing at faster rates, of several meters per year. Hotspot examples analyzed from Tunisia in the report include beaches on Djerba, Hammamet, and Soliman. For these locations, more than half of the beaches have already disappeared.

Coastal erosion has many negative consequences, and this report focusses on two: the effects on the destruction of coastal assets (such as land and buildings), and the effects on tourism revenues. For the asset destruction cost quantification, damages to coastal land and near-shore assets (buildings) are monetized using local data on property prices in Algeria, Libya, Morocco, Tunisia. The estimated annual asset destruction cost from coastal erosion amounts to the equivalent of 2.7% of GDP in Tunisia, 0.7% in Libya, 0.4% in Morocco, and 0.2% in Algeria. The reductions in tourism revenue from coastal erosion in the Maghreb, are discussed by bringing in survey evidence from other coastal areas around the world, where tourists were interviewed about their propensity to return (if the beaches would continue to erode) and their willingness-to-pay to stop erosion. The conclusion is that some of the hotspot beaches that have already been more than half disappeared may still attract tourists, although the question in the face of continued coastal erosion trends is 'for how much longer.'

In order to detect and analyze local hotspots of coastal erosion along Morocco's and Tunisia's sandy coastlines, a novel dataset that uses high-resolution satellite imagery has been created that is both comprehensive yet very detailed. Its comprehensiveness allows for the assessment of erosion processes all along the coastlines of the two countries and makes the identification of coastal erosion hotspots possible. Using more granular segmentations of the coast than previous studies then enables zooming in on these hotspots and studying the site-specific developments and their drivers. The report illustrates the merits of this novel dataset by assessing the changes in the coastal landscape at several touristic beaches that were subject to severe erosion in the past decades. The precise nature of the dataset is then utilized to study shoreline changes not only retrospectively but also for predicting future erosion and the expected position of the shoreline. Furthermore, the rich structure of the analysis employed is also exploited to study the effects that different protective structures had on the parts of the coast they were intended to protect. Similarly, the merits of the novel dataset in these regards are illustrated with case studies.

An extension of the aforementioned analysis for other countries in MENA is ongoing and will provide policy-makers with valuable information that is a crucial prerequisite for taking appropriate steps to combat coastal erosion. The focus of this report is on the part of uncovering the extent and the associated costs of coastal erosion in affected countries. A soon to be published MENA flagship report titled "Blue Skies, Blue Seas" then sheds light on how to bring about blue skies and blue seas in the region, discussing promising ways to combat the erosion of MENA's coasts.

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1 Coasts and their importance for the Middle East and North Africa (MENA)

"*If no measures to combat erosion are undertaken, sandy beaches will inevitably be lost, with cascading effects on the economy and the wellbeing of the local populations, particularly those dependent on tourism*." (Snoussi et al discussing coastal erosion in Morocco, 2017)

MENA's coastline stretches almost 25,000 km and every single country in MENA has a coast with different seas/oceans bordering them. The MENA region is bordered by the Atlantic Ocean, the Mediterranean Sea, the Red Sea, as well as the Arabian Sea and various Gulfs. The Western and Eastern Mediterranean coasts have been populated for millennia and include some of the world's most ancient cities, while the North Atlantic has Morocco's largest city on its shoreline. The Gulfs are also characterized by heavy ship traffic and several large, rapidly growing and densely populated cities are scattered along its coast. While no country is landlocked, the length of their coastlines vary considerably. Jordan has less than 30 kilometers of shoreline with the Gulf of Aqaba which provides it with access to the Red Sea, while Saudi Arabia has more than 7500 kilometers and Egypt and Iran almost 6000 km.

Coasts are home to large parts of the population in MENA. Globally, more than 40% of people live within 100 km of the coast and this number is set to increase further. In MENA, this share is almost 50% in 2020 and it is estimated that total coastal population will be increasing by about 18% until 2035 (Maul & Duedall, 2019). The share of the population living within 100 km of the coast varies strongly across countries, from around 6% in Iraq over 30% in Saudi Arabia (despite being the country with the longest coastline in the region) and more than 80% in Tunisia and Oman, to 100% in Malta, Kuwait, Lebanon and Qatar. For the majority of MENA countries, the respective capital city is located near or next to the coastline. Besides the capitals, other major cities and economic centers are located at the coast (e.g. Alexandria in Egypt, Jeddah in Saudi Arabia) but smaller towns and villages cluster along it as well. Increasing urbanization pressures and partly uncontrolled migration to coastal urban centers have exacerbated the share of the population potentially affected by coastal erosion (Ahizoun et al. 2009; Anfuso et al. 2011). Population growth also brings development leading to changes to the natural environments and habitats that provide natural erosion protection such as wetland 'sabkha' (Chekirbane et al., 2013, Amrouni et al., 2019).

Given the concentration of settlements along them, the coasts of MENA are also major hotspots for economic activity. The concentration of human settlements along the coasts also brings a concentration of economic activity. This phenomenon is especially prevalent in certain countries. For example, in Morocco, where around two thirds of the population lives nearby the coast, more than 90% of industries have their operations at the coastal zone and coastal tourism, largely dependent on intact beaches, is a major contributor to the national economy (Snoussi et al, 2009). Apart from these sites, cultural and natural sites alike are located at the coasts, threatened by coastal erosion processes (Trakadas, 2020). Similarly, in Tunisia more than 83% of industrial firms are located in specialized industrial zones along the coast of Sahel, a region approximately stretching from Bizerte to Sfax[1], and 90% of the country's total economic output is achieved in near-shore areas.[2] A state-of-the-art port complex drives Djibouti's US$2 billion city-state economy and the city-states of Kuwait, Bahrain, Qatar or the United Arab Emirates (UAE) are also heavily dependent for their existence on their coastal locations (AFED, 2009). In Egypt, the city of Alexandria at the Mediterranean hosts about 40% of the country's industrial capacity as well as being an important summer resort (El-Raey, 2010). Regional transportation hubs such as ports and other economic centers are located in low-laying coastal areas all around MENA (Schäfer, 2013), where sea level rise and coastal erosion poses major threats to them.

[1] https://oxfordbusinessgroup.com/overview/forging-ahead-uneven-growth-industry-subsectors-remains-challenge

[2] https://www.kfw.de/stories/environment/climate-change/coastal-protection-tunisia/

In some MENA countries, large shares of the population are dependent on marine resources that are threatened by further environmental degradation. The fishing industry is of economically significant in some MENA countries including Morocco, Yemen and Oman. In Morocco, for instance, fisheries and connected industries contribute around 2.3% to national GDP and create employment for almost 700,000 people (directly and indirectly) in 2014. Furthermore, around three million people depend on fisheries for their livelihoods.[3] Morocco's fish production in terms of capture fisheries dominate the region with about 40% of the four megatons of fish landed every year being caught by Moroccan fishermen (OECD-FAO, 2018). Furthermore, the large coastal areas are important to the livelihoods of hundreds of thousands of people in MENA, with many of them vulnerable and poor, which often rely on small-scale fisheries and aquaculture that have been increasing substantially in recent years (Sieghart et al, 2019; OECD-FAO, 2018).

For several countries in MENA intact beaches and coastal zones are vital for their attractiveness to tourists. Some countries in MENA rely heavily on their beaches and associated recreational services in order to attract international as well as domestic tourists. For example, Djerba island at the Southern end of the Tunisian shoreline, accounts for around a quarter of all international tourists arriving in Tunisia (Carboni et al., 2014) and tourism there is focussed strongly on its coastal assets to attract tourists (Widz and Brzezinska-Wojcik, 2020). Similarly, in Egypt coastal zone tourism has grown significantly in the past decades, bringing about economic benefits to host communities but also increasing environmental pressures (Abel-Latif et al, 2012). Losing the natural assets represented by beaches can have severe adverse effects on the tourism sector by diminishing the number of tourists or threatening tourism-related infrastructure.

The first part of this report analyzes the human and economic effect of coastal erosion in some of the most affected countries in MENA in the Mediterranean: Tunisia, Morocco, Algeria and Libya. An assessment of the direct costs of coastal erosion to land and built assets for Algeria, Morocco, Tunisia and Libya reveals that even though these estimates include only a part of the overall costs arising due to a degradation of the coastline of these countries, the economic impact of coastal erosion is substantial.

The second part draws on a novel dataset to assess the coasts of Morocco and Tunisia in more detail, identifying hotspots of coastal erosion, forecasting shoreline changes and evaluating the impact of different protective measures. This part documents some of the proceedings of an ongoing cooperation with the National Oceanographic Center of the United Kingdom and the European Space Agency. It analyzes the specific local erosion dynamics in Morocco and Tunisia in more detail by employing high-resolution satellite images and sophisticated procedures that properly account for phenomena such as the breaking of waves as they approach the shore to avoid misclassification issues. This makes the identification of local hotspots of coastal erosion at a very detailed scale possible. Additionally, models are employed to forecast future changes to the shoreline and retrospective evaluation of the effects of different human interventions in the coastal landscape is exemplified.

2 Erosion of MENA's coasts and its economic costs

This section provides an overview of historical changes of MENA's coasts before turning to the costs associated with this erosion. The direct economic costs of coastal erosion are estimated in Section 2.2 for four selected countries. Section 2.3 discusses the implications of coastal erosion for tourism revenue.

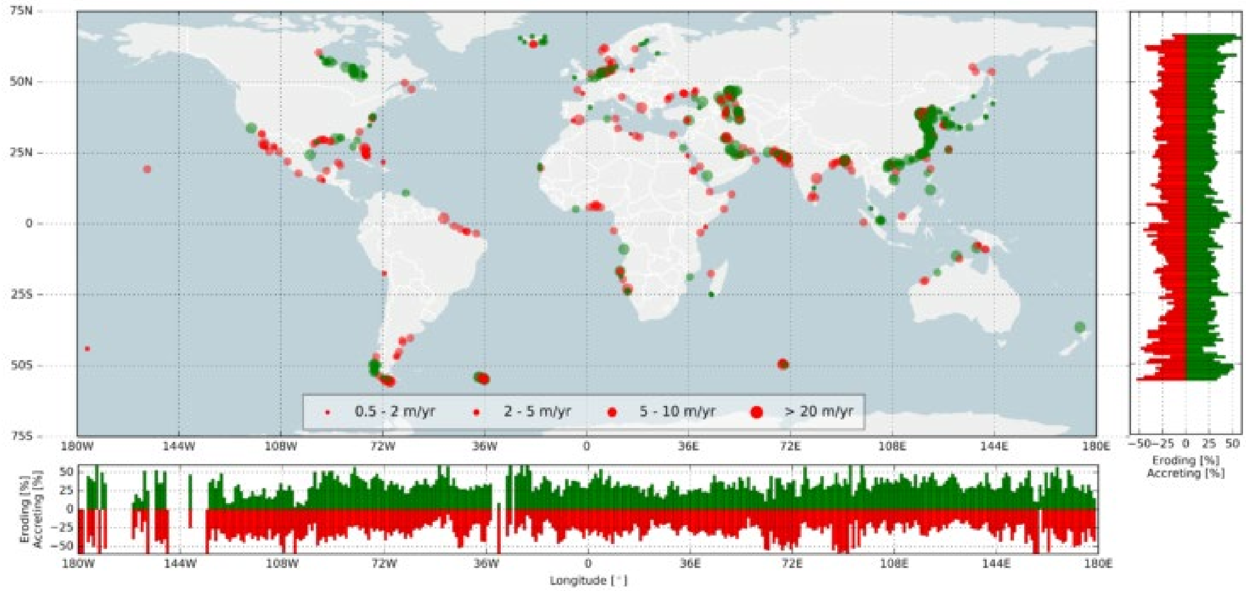
[3] http://www.fao.org/blogs/blue-growth-blog/morocco-a-maritime-fishing-nation-works-to-develop-its-aquaculture-sector/en/

2.1 Historical changes of coasts in MENA

Changes in coastlines and the gradual disappearance of beaches are processes that take place all over the world, however with regional variation. Changes in coastal shorelines are a pervasive process, taking place in almost any part of the world with access to the seas. However, the specific dynamics of these processes play out quite differently across regions and countries. Shorelines and beaches can accrete (gain area), erode (loose area) or stay stable over time. In a global analysis, satellite images for equally-sized segments (so-called transects) along the shoreline were analyzed and average changes of sandy coastlines were calculated for the period from 1984 to 2016 (Luijendijk et al, 2018). In Figure 1 below, red dots denote erosion hotspots and green ones those where accretion is prevalent, with the size of the dots indicating the severity of these processes. Globally, Asia has seen some of the most severe changes in coastal changes, both in the form of accretion (mainly in East Asia) and erosion (mainly in South Asia). In the Middle East and North African (MENA) region, the Southern Mediterranean coast is characterized by more severe erosion, while the coasts at the Gulfs have seen high rates of accretion in the past decades.

Figure 1: Constantly changing coastlines

Eroding and accreting beaches



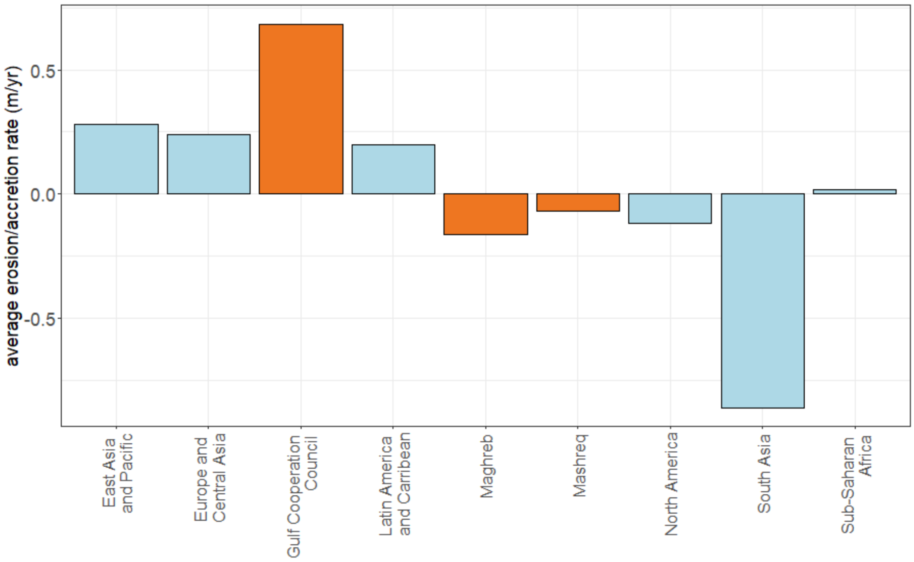
Source: Luijendijk et al (2018)

The sources of coastal erosion are manifold and depend on shoreline characteristics as well as their utilization. There are a number of factors that drive coastline change which are often split into human-induced factors (coastal subsidence, coastal protections, tourism infrastructure or land reclamation) and natural physical forcing elements (e.g. storm events, sea-level rise, sediment transport) (Sytnik et al., 2018). Coastal areas with different tidal dynamics and wave energy incidences demonstrate unique coastal morphologies (Hayes & FitzGerald, 2013). Fluvial and alongshore sediment transports are major morphodynamical processes which determine the shape of the coastline (Sytnik et al., 2018) and often determine how the coast is divided into management cells when implementing a holistic management scheme. Human interventions, such as ports or groins, intervene in the hydrodynamic processes along the shoreline. Often, they stabilize areas by sediment build up in one location but starve the sediment and intensify the erosion rate at other locations.

In a global comparison, Maghreb's coasts are the world's second fastest receding, falling short of South Asia only. Computing average net erosion rates MENA's sub-regions shows that Maghreb and the Mashreq region have seen their beaches and coasts erode in the past decades, while GCC's coasts have accreted substantially. As can be seen in Figure 2 below, comparing these average erosion rates to regions worldwide reveals that the net erosion of Maghreb's coasts is only topped by the massive erosion rates of South Asia's shorelines. In Maghreb, beaches were retreating by an average of 15cm per year in the period 1984-2016, while Mashreq's beaches retreated by around 7cm per year. On the other hand, GCC shorelines, especially the ones located at the Arabian/Persian Gulf and the Oman Gulf, experienced substantial accretion rates, totaling almost 70cm accretion of its beaches per year.

Figure 2: The Maghreb is the second fastest coastally eroding region

Net coastal erosion by region, average rate from 1984 to 2016



Source: Authors based on Luijendijk et al, 2018

Note: The Maghreb region comprises Algeria, Libya, Malta, Morocco and Tunisia. The Mashreq region includes Djibouti, Egypt, Iraq, Iran, Jordan, Lebanon, Syria, West Bank and Gaza as well as Yemen. The GCC refers to the high income Gulf countries of the Mashreq region, namely Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates.

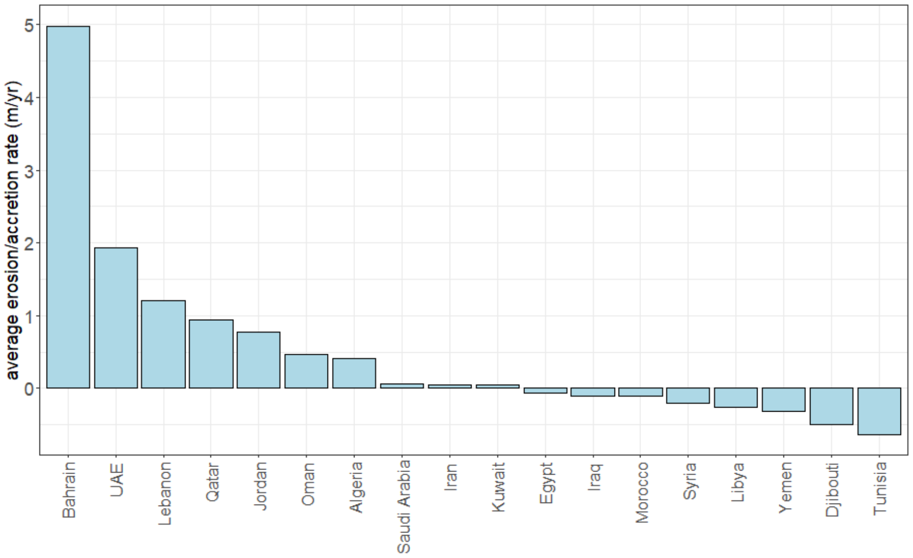
Coastal erosion also varies substantially across countries in MENA. The regional comparison presented above masks some heterogeneities with respect to retreating shorelines. For example, within the Maghreb region, Tunisia, Libya and Morocco face net erosion of their beaches, while in Algeria accretion dominates, as can be seen in Figure 3. GCC countries such as Bahrain, the UAE, Qatar and Oman have experienced severe accretion rate, owing largely to land reclamation and coastal development projects, while Saudi Arabia's vast coastline has been staying rather stable on average. The coasts of the poorest countries in the MENA region, Yemen and Djibouti, have been retreating as well, with around 30 and 50 centimeters per year on average.

At the Mediterranean basin, North African countries have seen the most severe erosion rates. North African countries are especially at risk to coastal erosion as they lie within the transitional zone between subtropical temperate and continental climates that are exposed to forecasted climate change effects (Amrouni et al., 2019). The average sandy beach shoreline retreat 12cm per year on the Atlantic coast of Morocco, 14 cm on the Mediterranean coast of Morocco, and 70cm on the coast of

Tunisia. It has been found also elsewhere that Moroccan coastlines are migrating landward and beaches are shrinking (see Snoussi et al, 2017). Similarly, Libyan coasts have seen distinct net erosion retreating around 27cm per year. While Algerian coasts showed overall accretion, locally, parts of their beaches have shown relatively high erosion rates as well.

Figure 3: Tunisia is facing the fastest rate of coastal erosion, followed by Djibouti and Yemen

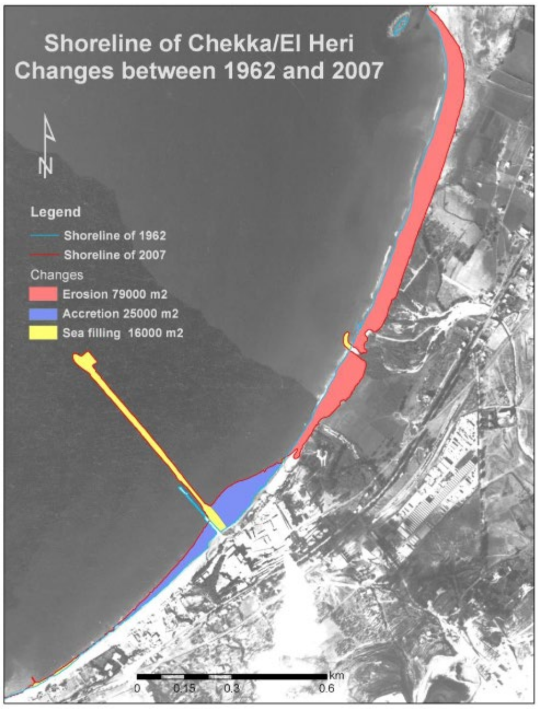
Net coastal erosion by country; average rate from 1984 to 2016



Source: Authors based on Luijendijk et al, 2018

Coastal dynamics are also highly dependent on local characteristics. This is exemplified in Figure 4 below, which shows changes at a beach near Chekka/El Heri at the Northern part of the Lebanese coast. Here, most parts of the beach experienced severe erosion with a maximum retreat of 81 meters in the period 1962-2007 (Abou-Dagher et al, 2012). Simultaneously, however, other parts of the beach have been accreting in this period, mostly due to blocked sediment transport caused by a jetty built perpendicular to the sandy beach, with accretion reaching a maximum of 94 meters.

Figure 4: Shoreline changes in Chekka/El Heri, Lebanon, between 1962-2007



Source: Nader (2015)

Getting an overview of coastal erosion at a national scale while also being able to determine the situation at specific hotspots is important, requiring comprehensive yet granular analyses of countries' coastlines. To gain an understanding of the state of a country's coast comprehensively studying the coastline on a large scale is important. Simultaneously, once certain erosion hotspots are identified, deriving detailed insights in the specific dynamics and drivers of changes in the coastal landscape hinge on the granularity of observations, both on a spatial and temporal scale. This necessary combination motivated the analysis carried out in cooperation with the National Oceanographic Center of the United Kingdom that will be laid out in more detail in Section 3. The very granular yet comprehensive analysis involving high-resolution satellite images allows for the assessment of the state of coasts on a large (e.g. national) scale to identify specific erosion hotspots, while simultaneously enabling in-depth study of site-specific dynamics and their possible drivers.

2.2 The cost of coastal erosion due to the destruction of land and built assets

Given that the coasts in various countries in MENA have already eroded severely, one does not have to wait for Sea Level Rise to continue to create challenges to coastal communities. Coastal erosion is already happening, has been happening for at least some decades now, and is threatening coastal communities, livelihoods, and ecosystems. Here, the threat that coastal erosion poses to homes and livelihoods is assessed, the human exposure to coastal erosion is analyzed and an estimate of the economics of coastal erosion for some countries in MENA is established. The costs of coastal erosion are potentially even larger than the conservative estimates provided here. Large parts of the tourism industry are threatened by coastal erosion, a sector that, directly or indirectly, contributes about 14% of value-add to GDP in Tunisia[4] and almost 19% to GDP in Morocco (Kasmi et al, 2020). Given that international experiences have shown that large parts of certain tourist groups has reported that they

[4] https://english.aawsat.com//home/article/1840766/tunisia-13b-tourism-revenues-expected-2019

would not return if beaches were disappeared or reduced (see e.g. Tarui et al, 2018 for Hawaii; Uyarra et al, 2005 for Barbados; Raybould et al, 2013 for Australia), unchecked coastal erosion presents a worrisome development for the tourism sector in such countries. Thus, a concise overview of sources for additional, indirect costs is given in the next section.

Quantifying the direct costs of the degradation amounts to estimating the adverse effects to physical assets like buildings as well as the value of land lost. The average erosion rates are extracted from the global dataset on historical shoreline changes from 1984 to 2016 already mentioned above (Luijendijk et al, 2018). Following previous studies on the quantification of the economic effects of coastal erosion (see e.g. Croitoru et al, 2019) we focus on areas in countries that are subject to land loss.[5] In other words, we do not value the accretion of areas. This is largely because whereas with coastal erosion the economic effects are always negative as territory is lost, with coastal accretion, they can be negative or positive. For example, accretion near a harbor's entrance may hinder ships from entering the port and lead to siltation of pathways, necessitating dredging works to maintain them. Similarly, when rivers are used for the shipment from the ocean to inland destinations, accreted areas can block the entrance of them. Furthermore, even when accreted land is not detrimental by itself, it remains unclear whether it can be used for development or recreational purposes. Conversely, accreted land, as a result from land reclamation projects of coastal development projects, as we have seen in several Gulf countries, are obviously generating economic value. In Libya, Morocco and Tunisia, more than half of the coastline is subject to coastal erosion, lower shares are reported for Algeria. Tunisia is the country with the highest rate of erosion for eroding sections, which are losing 2.4 meter a year on average, followed by Algeria with 2.1 meter a year erosion, though for a smaller part of the coastline. For Libya and Morocco, the historical erosion rates are lower with around 0.9 meters per year.

Given these erosion rates and information about the length of the eroding coastline, the average amount of eroded area per year is calculated. This information is provided in the final column of Table 1. These figures serve as a measure of yearly land loss due to coastal erosion in the countries under scrutiny. The amount of area lost due to coastal erosion per year ranges from 90 hectares in Algeria to almost 250 hectares in Tunisia. The subsequent calculations of yearly direct costs arising from shore retreat are based on these values.

Table 1: Eroded coastal area in Maghreb countries

Country	% of coastline subject to erosion	% of coastline urbanized	Long-term Erosion	
			Rate (m/yr)	Area (Ha/year)
Algeria	29%	14.5%	-2.1	-90.5
Libya	55%	7.0%	-0.9	-100.1
Morocco	54%	6.6%	-0.9	-139.9
Tunisia	59%	15.0%	-2.4	-247.3

Source: Authors based on Luijendijk et al (2018)

In order to quantify the value of land lost, the unit price of coastal land per square meter in these countries was assessed, based on market data and, where available, official statistics.[6] Prices of land near the coast differ substantially based on its location. Urban prices for coastal land exceed the ones

[5] This also leads to the differences in values for coastal erosion reported in Table 1 and the ones depicted in Figure 3 in the previous section.

[6] The various sources are either online property portals (such as avito.ma, mitula.ma, homeintunisia.com, opensooq.com with various country domains) or official sources where available (mainly in Morocco).

of rural areas considerably, due to the limited space in cities following high rates of urbanization and exuberant demand for nearshore properties within them.[7] Table 2 shows the result of these assessments. Urban land is most expensive in Morocco, while being comparatively lower in Algeria. Rural land prices are not as dispersed, ranging from USD20 per square meter in Morocco and Algeria to USD30 in Libya. The present value of annual rents for the next 30 years is then used as an estimate of the value of land. Some assumptions had to be made for the calculation of the present value of land. The rent-to-price ratio of land was assumed to be 8 percent with rents increasing by 8 and 5 percent for urban and rural land, respectively. To account for agglomeration effects in coastal regions, average urbanization rates as estimated by the United Nations for the 30 years were used. Finally, a standard rate of 3 percent was used for discounting future rents foregone by erosion of coastal areas.

Table 2: Coastal land prices for Maghreb countries (US$/m^2)

Country	Urban	Rural
Algeria	350	20
Libya	480	30
Morocco	650	20
Tunisia	450	25

Source: Authors based on rapid price assessment

The distinction between prices of land due to its location necessitates the classification of eroded land due to its land use. We used the European Space Agency's Global Land Cover database[8] to determine the share of urban areas on the total coastline. Column 2 in Table 1 provides the results of this exercise. More than 15% of Tunisia's and 14.5% of Algeria's coasts are urbanized respectively. For the other countries the share of urbanized coastal area is lower, with 7% in Libya and 6.6% in Morocco.[9] To estimate the value of built housing assets destroyed per year, estimates for the average replacement costs of buildings for coastal districts, adapted from data for twelve countries in the MENA region (Dabbeek & Silva, 2020). The number of dwellings, buildings and population is identified on a very fine scale and estimate the economic value based on geographical location and physical characteristics. Aggregating these data for coastal districts in the four countries under investigation allows for the estimation of the value of lost assets due to coastal erosion.[10]

Table 3: Direct economic costs of coastal erosion

	Algeria	Libya	Morocco	Tunisia
Buildings lost (US$ million)	3	1	8	29
Land lost (US$ million)	310	272	425	1,078
Total (US$ million)	**313**	**273**	**434**	**1,107**
Total (% of GDP)	**0.2%**	**0.7%**	**0.4%**	**2.8%**

[7] It should be noted that it would be preferable to further distinguish between agricultural land and building plots in the case of rural land. However, additional to price data constraints, determining the relative shares of these types of land on total rural coastal area proved to be hardly possible. While the land use dataset of the ESA provides a distinction for already built-up areas and ones that are explicitly used for agricultural purposes, it is not possible to determine whether a certain plot of bare land is dedicated as a building plot or not. Given these difficulties and the often not clear-cut rules for land classification in these countries, we refrain from drawing such distinctions and use a composite price for rural areas.

[8] http://www.esa-landcover-cci.org/

[9] The share of urban areas are calculated for the whole coastline, not only for the parts that are subject to erosion. The limited information for land prizes did not allow for such a differentiation.

[10] Note that these estimates do not take infrastructure costs (e.g. lost roads) explicitly into account.

Source: Authors.

Direct costs of coastal erosion in the countries considered are high and amount to a substantial portion of GDP. Table 3 provides the estimates regarding average yearly direct costs arising from coastal erosion processes based on values for lost land and buildings upon it. The estimates show that in Maghreb countries coastal erosion entails substantial direct costs, ranging from USD273 million per year in Libya to more than USD1.1 billion per year in Tunisia. Relative to the gross domestic product, in Algeria the damages amount to about 0.2% of GDP, in Morocco to about 0.4% of GDP, in Libya to about 0.7% of GDP and in Tunisia to about 2.8% of GDP.

The estimates provided here are very conservative as they are not taking into account losses in adjacent properties. Near-shore properties derive part of their value from their proximity to the sea and hence may be affected indirectly in a sense that their value will be reduced even if erosive forces do not directly destroy them (Scott et al, 2012; Pompe & Rinehart, 1995; Fraser & Spencer, 1998). A detailed study on erosion management strategies at the East Coast of the US finds, using a hedonic price model, that the value of property is substantially lowered if located in a high-erosion zone (Landry et al, 2003). The negative effect of beach retreatment on property values diminishes with distance, implying that properties that are near but do not necessarily border the shore can be affected through negative spill over effects arising from erosion processes (Rinehart & Pompe, 1994). These effects are not included in the estimates of direct costs presented above, hence they should be viewed as rather conservative assessments of the overall costs due to coastal erosion in the countries under scrutiny.

The effects on developments such as ports or industrial sites as well as on ecosystems are most likely substantial but also hard to quantify. Besides destroying buildings, coastal erosion also impairs the human developments along the coast such as ports or industrial sites. Furthermore, it has also detrimental effects on the coastal ecosystem, destroying the habitat of coastal flora and fauna. These specific effects are not captured in the analysis above as it would require detailed modelling of effects and costs of coastal erosion along these developments and natural habitats, a task that is hardly possible at a national or regional scale.

Climate change will increase direct costs that arise from coastal erosion in the future. The impacts of climate change such as a higher probability for extreme weather events and advancing sea level rise will exacerbate coastal erosion and its effects. Hence, the costs due to this phenomenon will also most likely increase in the future unless suitable steps are taken to combat it and protect human developments where possible.

Nonetheless, this empirical assessment shows that shore retreatment is a substantial threat and entails significant costs for the affected regions. Advancing sea level rise and a higher probability for extreme weather events due to the effects of climate change will most likely culminate in even higher costs in the future. Immediate action should thus be seen as indispensable, both to mitigate direct costs now and in the future with their associated impacts on coastal populations, many of which are dependent on intact shores for their basic income.

2.3 Reduction of economic revenue generated from coastal areas

Coastal erosion is an existential threat to tourism, a sector than contributes significantly to economic output in Maghreb countries. Probably the largest share of the costs of coastal erosion, especially in the long-term, will be by reducing revenues resulting from touristic activities in impacted areas.[11] Foregone revenues from tourism activities are a severe threat, especially for countries for which "blue" tourism represents a large part of their revenues. Tourism is of major importance to the economy of many countries in MENA, with several countries having more than 10 percent of GDP from the sector. For example, both Tunisia and Morocco are heavily dependent on their tourism sector, which to a large part builds on the existence of beaches. In Morocco over 12 million international visitors were recorded in 2018, with receipts received totaling more than $9.5 billion (around 8% of GDP) according to data from the United Nations World Tourism Organization (UNWTO) and tourism activities account for more than half of export in services. Considering indirect economic impacts, tourism and its value chains accounted for 18.6% of GDP and 16.4% of employment in 2017 (Kasmi et al, 2020). In Tunisia, economic activity connected with the tourism sector amounted to 14.2% of GDP in 2018, offering job opportunities for more than two million Tunisians.[12] Receipts received from international tourists alone contributed over $2.3 billion to the economy, representing around 6% of GDP in 2018 and more than 90% of the country's recorded bed nights were spent in coastal areas (Jeffrey & Bleasdale, 2017). Hence, the threat posed by the disappearance of beaches due to coastal erosion should be recognized.

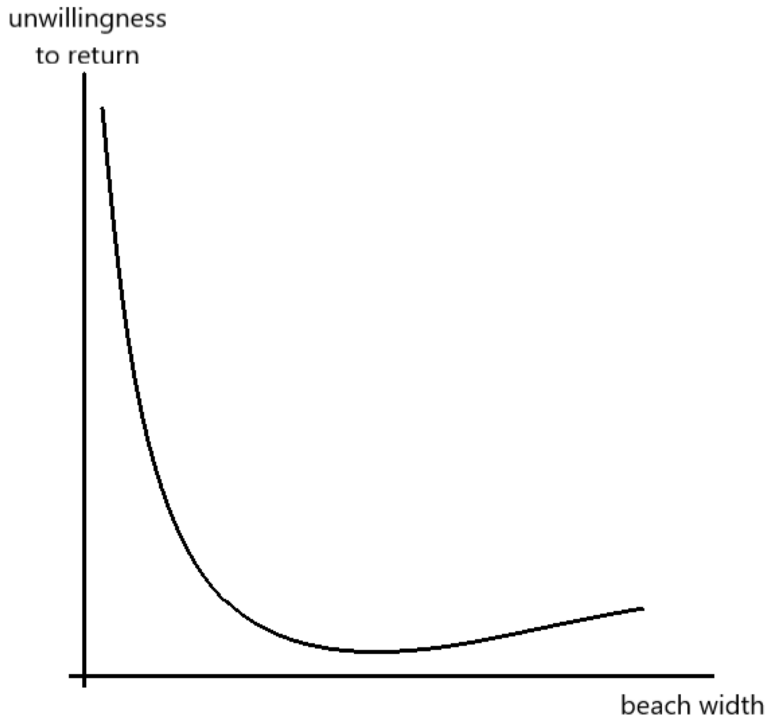
Tourists primarily visiting the coasts of MENA could decide not to return should beaches disappear. There are several drivers that could drive negative indirect effects. In the extreme case, disappearance of beaches could lead to total losses should tourists decide not to visit the affected areas at all anymore. For example, for some tourist groups a majority of respondents to a survey conducted in a Hawaiian town stated that they would not consider staying in a hotel should the nearby beach completely erode (Tarui et al, 2018). Similarly, more than three quarters of surveyed tourists in Barbados were unwilling to return for the same price should beaches largely disappear; this was associated with a 46% decrease in tourism revenues. Other environmental features also drive the willingness of tourists to return in nearby Bonaire, with again more than three quarters of them not willed to return for the same price should corals bleach (Uyarra et al, 2005). For two stretches along the Australian coast, large parts of tourists stated that major erosion events would lead them to switch to other destinations; losses equated to more than USD75 million per year (Raybould et al, 2013). Hence, the retreatment of beaches could lead to severe economic losses, especially in regions that are primarily visited for their beaches as is the case in many coastal tourism destinations in countries in MENA.

The propensity of tourists to visit a certain location decreases due to beach retreatment, but not necessarily in a linear fashion. There is broad consensus that the retreatment of beaches is lowering the willingness of tourists to return to locations that are primarily relying on beach recreation, with the extreme case of visitors not returning should a beach erode completely (as discussed above). For example, in a survey carried out at beaches in Delaware, United States, around two third of visitors stated that a reduction of a beach's width to a quarter of its current size would worsen their experience and a third indicated that they would reduce their number of visits (Parsons et al, 2013). Similarly, for Californian beaches it was found that visits to beaches are negatively related with losses in beach width due to coastal erosion, however in a non-linear fashion and differing by main activity of tourists coming to the beach. For beaches that are narrower than 20 meters, a reduction in width is associated with much larger decreases in the propensity of recreational visitors to come back than when initial beach width is larger than 20 meters (Pendleton et al, 2012). In Barbados it was found that tourist's aversion to return is especially strong for beaches with a width of less than 8-10 meters (Schuhmann et al, 2016).

[11] Ghermandi and Nunes (2013) provide estimates for the value of recreational services for near-shore locations on a global scale and show that these vary with the accessibility, development and touristic amenities like the existence of beaches or coral reefs.
[12] https://english.aawsat.com//home/article/1840766/tunisia-13b-tourism-revenues-expected-2019

However, interestingly beaches can also be too wide, with long ways to the sea decreasing visitor's utility (Parsons and Massey, 2003; Pendleton et al, 2012). A similar non-linear relation can also be found for the speed of erosion, where surveys reveal that higher rates of beach retreatment lead to a disproportionate reduction in consumer surplus, and hence propensity to revisit, compared to slower retreatment rates (Huang et al, 2011). These findings imply that the relationship between the unwillingness to return of tourists and the beach width can be thought as approximately having a shape like the one depicted in Figure 5.

Figure 5: Stylized relationship between beach width and unwillingness to return



Source: Authors.

Interventions that increase beach width such as beach nourishment are often viewed more positively than other ones that mitigate coastal erosion. Beach nourishment refers to the filling of a certain beach with sand or similar sediment to restore the width (or area) lost to coastal erosion. It has been found in studies that large parts of surveyed persons respond positively to such interventions. In a large-scale survey in North Carolina almost half of respondents were in favor of beach nourishment to increase beach width, which is estimated to lead to more trips taken to the beaches with the aid of an econometric model (Whitehead et al, 2008; 2010), with results being confirmed by other studies (Landry & Liu, 2009; 2011). On the other hand, some interventions may decrease the propensity to return. Beachgoers tend to take fewer trips to those beaches with sand dunes and jetties. When presented with different levels of erosion, a study on beaches in New Hampshire and Maine found that erosion leads to 1.36 fewer trips per resident. The introduction of an erosion control program that prevents the stated erosion would attenuate the aggregate impact; however, respondents would take 1.01 fewer trips because of it. Hence, erosion control can be desirable but the potential negative impacts on the beach environment can offset the benefits of decreased erosion (Huang et al, 2011).

Having intact beaches is an important determinant for the prices hotels can charge. In coastal districts a higher share of open or flat coastlines (i.e. beaches) is a significant determinant for higher accommodation prices (Hamilton, 2007). In a similar spirit, hotel prices at Costa Brava in Catalonia of those having a beach awarded with the Blue Flag certification in their vicinity are more than 10% higher on average (Rigall-I-Torrent et al, 2011). Blue Flag certification indicates that the beach and sea water quality meets certain standards and that beach management also fulfills specific environmental standards. Both Morocco and Tunisia are part of this program and efforts to extend its scope are ongoing in order to accommodate to changing attitudes of tourists. Revenues for hotels in the vicinity of retreating beaches are likely to decrease, as the amenity value for tourists decreases if the beach quality deteriorates.

One way to estimate the indirect cost of coastal erosion is by asking individuals about their preferences with regards to avoiding the erosion of beaches and asking them to monetize them. A common way how this states preference issue is addressed in the literature is to utilize surveys to determine what is called the "willingness-to-pay" (WTP) of both residents and tourists to preserve beaches. This measure reflects the amount of money that these people would be willing to pay for beach-saving initiatives such as beach nourishment or building offshore safeguards. The reasoning behind these studies is that, while such measures can be quite costly (also varying with respect to the region) ex-ante, ignoring those possibilities may lead to much higher ex-post costs induced by sea level rise and costal erosion (Darwin and Tol, 2001). The nature of these surveys, which build to certain extent on the attachment of respondents to the region under scrutiny, limits their practical use to small geographical units such as individual beaches or beaches on a certain island. However, their importance with regard to informing policymakers about possible sources for financing of such precautionary measures is not negligible and some lessons can be drawn from such analyses. They can also be used to assess different threats for the attractiveness of assets like beaches. For example, one such study found that beach retreat has a diminishing influence of beachgoers utility of beachgoers on average and that the WTP to avoid beach retreat is higher than for beach closure due to jellyfish outbreaks or the loss of seagrass in the surrounding water (Enriquez & Bestard, 2020).

Studies have shown the potentially high losses of touristic revenue stemming from coastal erosion in MENA. For example, tourists visiting Djerba Island in Tunisia would be willing to contribute over €5 million a year for a project aimed at reducing coastal erosion (Dribek and Voltaire, 2017). This figure implies that beach preservation measures to reduce coastal erosion may be financed largely by contributions by tourists[13] and also measures the value that tourists attribute to intact beaches. Hence, considering that most of the Djerba's tourism is focussed on its coastal zone (Widz and Brzezinska-Wojcik, 2020) an erosion of its beaches may in fact eradicate tourism altogether, implying huge potential revenue losses. While this may seem like a local example for costs of beach retreatment, it should be noted that Djerba hosts around 25% percent of international tourists visiting Tunisia (Carboni et al., 2014), exemplifying its important status for the Tunisian tourism sector as a whole. For a similar region in Morocco, the Tetuan coast with its main touristic beaches, Benkhattab et al. (2020) find that total eroded surface in the period from 1958-2018 amounted to approximately 490 ha. Building on these numbers and the projections about beach retreatment in the future, Flayou et al. (2017) estimate that lost revenues to the economy due to the retreatment of these beaches alone could accumulate to USD190 billion in the next few decades.[14]

[13] The authors also calculate the willingness-to-pay for the project residents of Djerba residents and found similar values per capita. As the number of residents (around 30,000) is tiny in comparison of tourists visiting Djerba (more than one million per year), the contributions of tourists are the lion's share of overall contributions.

[14] It should be noted that the authors compute these highly detrimental effects to the local tourism sector by means of benefit transfers of WTP values from another source and assume a complete disappearance of the

Other approaches that quantify the economic effects of coastal erosion also highlight large potential losses to the local economy. They may use information on the attributes of beaches like their width, land value and characteristics of hotels located nearby (e.g. room price) to directly estimate reductions of land values and revenues due to coastal erosion in the framework of hedonic price regressions. Using such an approach, the decrease in beach width due to coastal erosion in Rethymnon on the Greek island Crete could lead to revenue losses amounting to around EUR18.5 million in the next ten years due to the progressing retreat of a single beach (Alexandrakis et al, 2015). The impact of sea level rises on beach tourism in Sahl Hasheesh and Makadi Bay, Red Sea in Egypt were valued to lead to expected losses in revenues that could exceed USD350,000 per day in 2050 (Sharaan et al, 2020). Similar studies show beach surface reduction to have a decisive negative impact on the overall image of tourist destinations, decreasing the number of arrivals and hence reducing receipts received from them (Scott et al., 2012; Raybould et al., 2013; Bitan and Zviely, 2019).

Hence, direct losses due to coastal erosion are only a fraction of total losses to the economy, not considering the impact on tourism or marine activities as well as ecosystems. Considering the evidence on indirect losses attributable to coastal erosion, the analysis on direct costs of coastal erosion presented in the previous section provides only a very conservative estimate about the actual costs of this phenomenon in MENA countries. Accounting for lost future revenues, accruing mainly in the tourism sector, is crucial for assessing the real costs of coastal erosion, also with respect to potential losses in tax revenues. Furthermore, coastal erosion processes can also impair the revenues generated in ports and near-shore industries dependent on intact coasts. Another important point to consider is that ecosystems may be permanently damaged from coastal erosion, which can be important income sources, such as for fisheries. However, quantifying the effects on these sectors is extremely challenging and out of the scope of this report.

3 A novel dataset on changes of the coasts in Morocco and Tunisia

The efficient identification of coastal erosion hotspots requires fine-scale investigations of the coast on a large scale. However, the respective coast segments that are under threat of eroding also have to be observed at a level that is as granular as possible. This section presents the findings of such a detailed analysis that was carried out for the coasts of Morocco and Tunisia in cooperation with the National Oceanographic Center of the United Kingdom. In order to accurately determine the extent of coastal erosion of certain hotspots, for this analysis only high-resolution satellite photographs were used. Additionally, the width of analyzed segments along the shoreline is considerably lower compared to previous studies. These granularities in the analysis process allow for more precise assessments of hotspots of coastal erosion along the whole coastline under scrutiny. The first subsection provides an overview of changes in the coasts of Morocco and Tunisia, identifying regions that gained or lost area in the last decades. The next subsections then demonstrate the merits of using high-resolution satellite photos to conduct a detailed study of the coastal landscape. Section 3.2 assesses changes of certain Tunisian beaches that exhibited severe rates of erosion in the past and were defined as priority areas given their importance as touristic destinations. Section 3.3 exemplifies the forecasting possibilities of the analysis carried out. Section 3.4 then illustrates the effects that different protective measures have on the coast they are intended to protect.

beaches, a process that varies for the different beaches under scrutiny and may in fact take several decades. Nonetheless, these findings highlight the potentially huge amounts of losses that could result from coastal erosion for touristic regions.

3.1 Identifying coastal erosion hotspots in Morocco and Tunisia

While coastal erosion takes place globally and at national scales, understanding the specific drivers of coastal erosion at a local scale is important. While the analysis above provides an estimate of the costs of coastal erosion at a national scale for the four MENA countries under scrutiny, it is important to note that changes in the shoreline are highly case-dependent, with erosion and accretion site often closely together, sometimes even at the same beach (see Section 1). These local differences require large-scale, yet granular analyses of shorelines to cover a country's coastline comprehensively to identify coastal erosion hotspots, while also allowing accurate assessments of the dynamics at a more local scale.

Small-scale differences can make a difference; hence, higher resolutions of coastlines are preferable. It is clear, that aggregate national indicators can hide a lot of the heterogeneity within countries, where some local areas are eroding as others are accreting. Similarly, analyses using finer resolutions for the identification of these processes at shores can provide important insights of historical processes as well as help quantifying erosion rates that can be expected in the future. Hence, to better understand regional and local erosion rates in North African countries, a cooperation with the National Oceanographic Center of the United Kingdom and the European Space Agency has been put forward to better understand the distribution of coastal erosion along the coast (NOC, 2020). This task was achieved by employing higher resolution spatial images, where 50m segments as opposed to the 500 meter segments of the coast from Luijendijk et al (2018) were used. Furthermore, in contrast to Luijendijk et al (2018), the analysis carried out by the National Oceanographic Center accounted for issues related to possible misclassifications of shorelines due to white-water, a phenomenon that occurs from breaking waves as they approach the shore and is one of the largest error sources in shoreline classifications (Pardo-Pascual et al, 2018).[15] The analysis was carried out for coastal erosion in the time period 2000-2020, providing estimates for a more updated timeframe than Luijendijk et al (2018). A background paper (NOC, 2020) provides more details on the methods used, the implementation of the various verification steps and other technical details.

There is also temporal variability in coastal erosion processes, with aggregate statistics potentially masking them. Additionally, to the specificities of different geographical locations, coastal erosion processes, such as the response of sandy beaches to sea level rise, are also temporally variable (Cooper et al, 2018). Given that shorelines are constantly subject to changes – whether they are induced by human development or natural forces - regular monitoring on a granular spatial scale is important to consider variabilities in all dimensions in order for policy-makers to be able to make informed choices based on accurate and timely evidence. The nature of the analysis carried out by the National Oceanographic Center allows for considering the long-term historical changes of the coastlines at a very granular spatial scale but also a detailed analysis of changes in erosive processes over time. Using this information not only can policy-makers base their decisions on current developments along the shore, but also already implemented protective measures can be evaluated with regards to their effectivity in curbing the threat of coastal erosion to human developments and their potentially unintended side-effects.

For Tunisia and Morocco, these detailed analyses already allow for more accurate identification of the local hotspots of coastal erosion, with more countries to follow. In a first step, the National Oceanographic Center carried out detailed analyses of the coasts of Tunisia and Morocco; two countries in MENA whose coasts are threatened by coastal erosion and for which beach tourism and

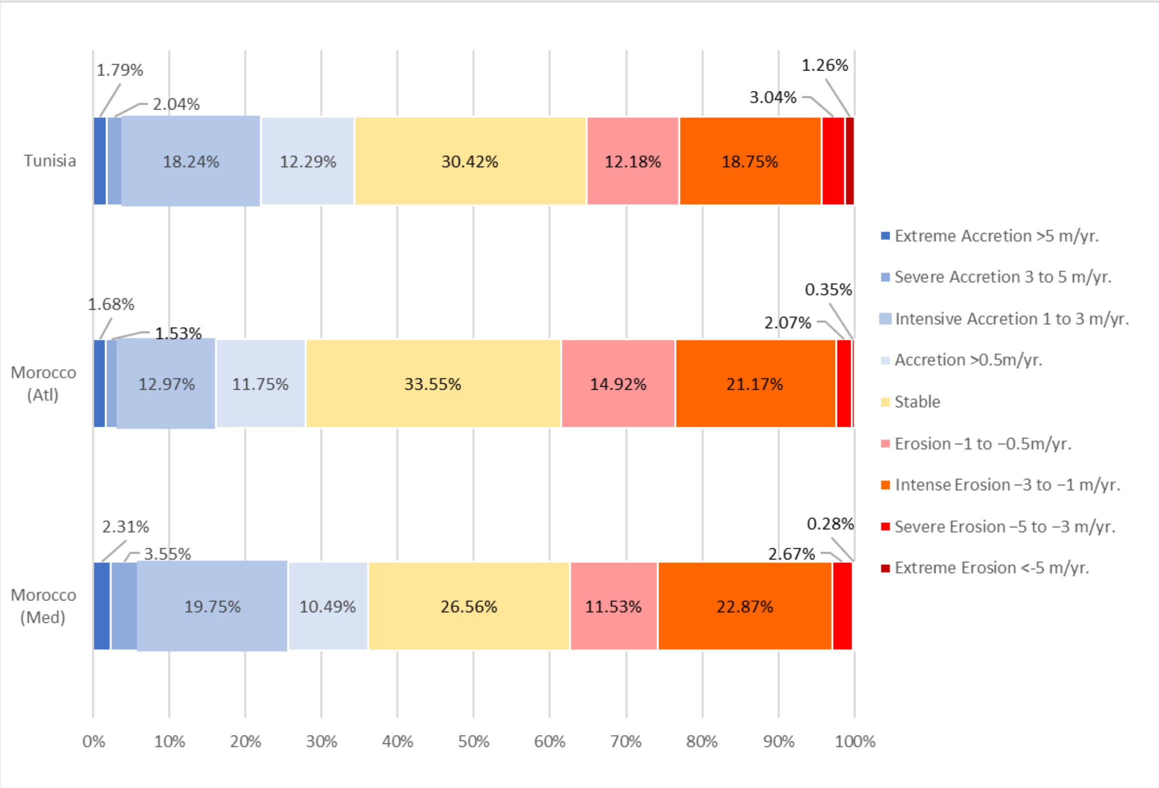
[15] It should be noted that the analysis by the National Oceanographic Center does not involve a in-situ assessment of shoreline changes, i.e. the results are not verified on-site.

coast-related activities play a very large role in their economic mix. North Moroccan statistics are split into Atlantic/Mediterranean at the Ksar es-Seghir port, as it was expected that there may be a difference in the nature of shoreline evolution due to hydrodynamic processes at the coast. The analysis has shown that coastlines facing the Mediterranean have lower sandy coastlines; with Morocco showing 75% and Tunisia 85%, whereas the Atlantic side of Morocco's coastline demonstrates a near-complete sandy composition at 96%.

Comparing the shares of coastlines undergoing changes shows that more areas erode but also that changes in the coastal landscape are heterogeneous. An overview of the different forces shaping the coastlines of Tunisia and Morocco can be gained by comparing the percentage of areas undergoing different shoreline dynamics (Figure 6). For both countries eroding areas (i.e. ones loosing at least 0.5 meter per years in the past decades) are exceeding the ones that experienced varying degrees of accretion. Tunisia illustrates a relatively evenly balanced shoreline change for each category but more than 35% of Tunisia's beaches are eroding. Around 38% of the Atlantic Moroccan coast is eroding to some degree, with about 28% accreting. On the Mediterranean coast of Morocco classes of erosion and intensive erosion are 4% more than the respective classes of accretion. Overall, it is characterized by more balanced, but also more dynamic erosion patterns, with only around one quarter of the shore remaining stable (i.e. average changes between ±0.5 meters per year) in the past two decades.

Figure 6: Shoreline changes are very heterogeneous within Tunisia and Morocco

Proportion of accreting, eroding and stable shoreline by country/region



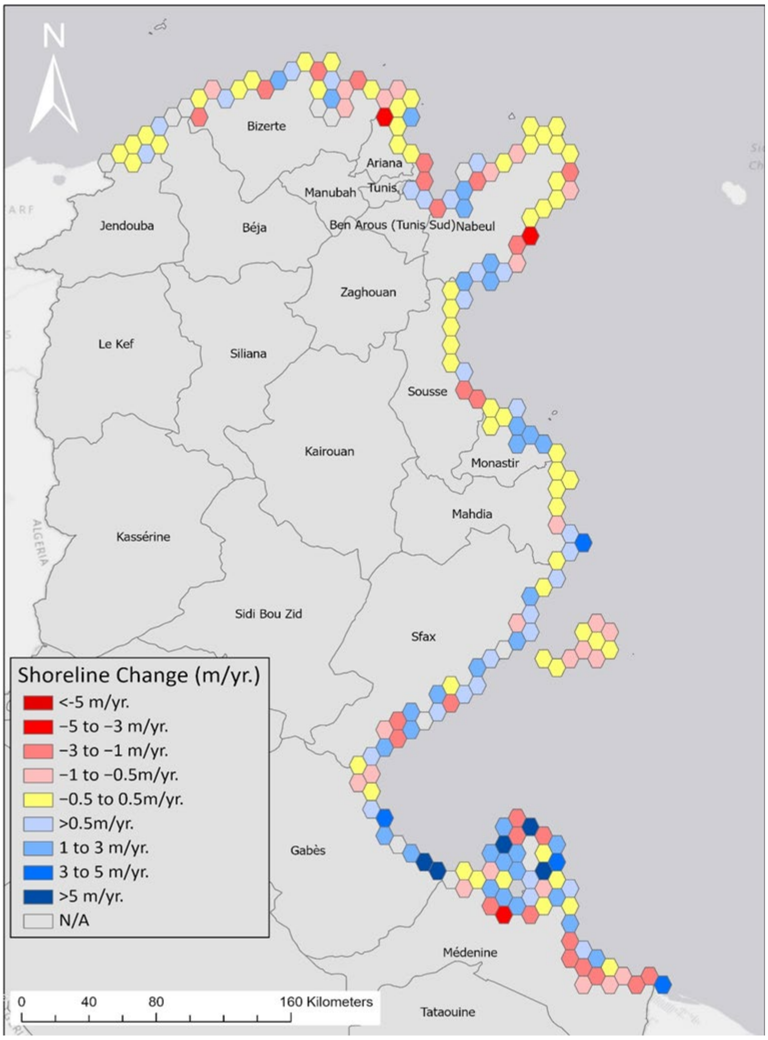
Source: Authors.

The detailed analysis of Morocco's and Tunisia's shorelines allows for assessing the effects of coastal erosion more closely. In the following paragraphs illustrations of the shoreline change are provided. In the figures to follow the data of the individual 50m transects are presented by aggregating the data to hexagons to better visualize the data.[16] The colors of the individual hexagons indicate the change predominant in certain regions, with red hexagons indicating erosion and blue ones accreting areas. Yellow hexagons denote relatively stable parts of the shoreline.

Coastal erosion in Tunisia: As indicated above, shoreline changes are hugely varied within countries and this is also the case in Tunisia (see figure 7), for which 85% of the coastline was identified as being sandy. Intensive erosion, i.e. beaches receding by more than 2 meters per year, is mainly happening in seven main areas with Utique in Bizerte and Korba in Nabeul. The highest accreting areas are located along the coast of Sfax, Gabes and Medenine, the latter of which frequently experience extreme or severe accretion. Whilst the state of shoreline change is mixed, there appears to be more erosion occurring in the North, with more accretion in the South.

Figure 7: Many beaches in Tunisia are eroding

Hotspots of coastal erosion



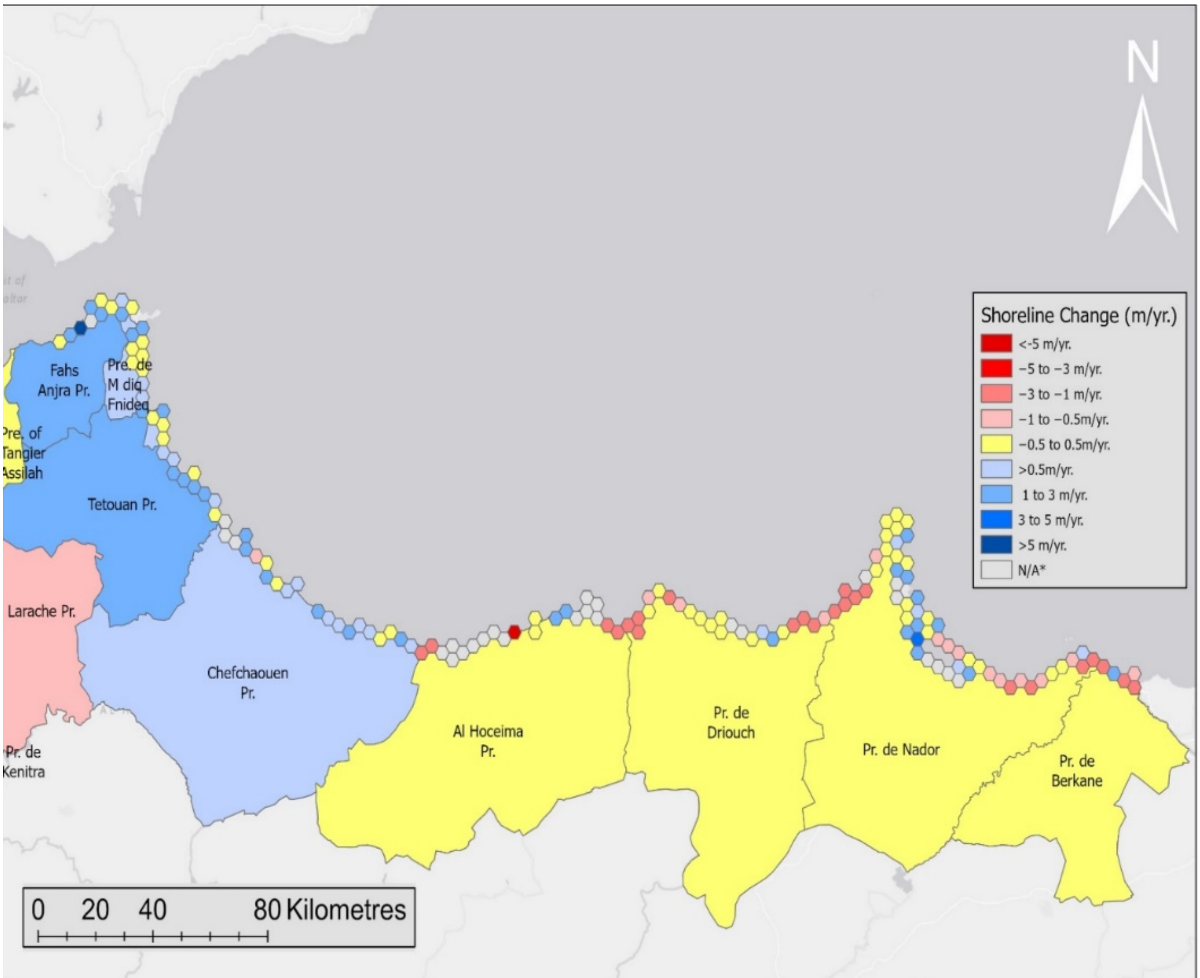
Source: Authors.

[16] Hexagons represent the shape and direction of the coastline whilst reducing sampling bias (Sahr et al., 2003). After experimentation, a 15km^2 hexagon was deemed suitable for Morocco and 50km^2 for Tunisia, to summarize a mean shoreline change rate over the three areas.

Note: Tunisia shoreline change rates aggregated to about 50km^2 hexagons.

Erosion of Morocco's Mediterranean coast is characterized by the influence of human structures. On Morocco's Mediterranean coast, intensive accretion is occurring in the Fahs Anjra and Tetouan Provinces (Figure 8). Anthropogenic developments such as Northern Africa's largest port, Tanger-Med, a 1.6km^2 long strip of development on the northern tip of Morocco, are likely to have a significant and potentially ongoing effect on shoreline change rates. A further possible source of change relates to the hydrological cycle and the rates of river flow deposition at estuarine locations. This has not been investigated but these are inherently variable systems which may experience significant interannual and decadal variability. In spite of this, it seems unlikely since there are numerous studies on the threat of the Moroccan coastline due to sea level rise (Snoussi et al., 2008; Snoussi et al., 2009; Kasmi et al., 2020). Further along the Mediterranean coast of Morocco, erosional processes become more dominant. The largest sections of erosion are occurring on either side of the Driouch Province in the Al Hocaeima bay Port and surrounding the Port Nador West Med. A combination of mis-registration issues and coastal infrastructure developments are resulting in the severe accretion rates within the lagoon at Nador. However, along the outer coast of Nador intensive erosion is occurring. The coastline is migrating landward and the beaches are insidiously shrinking, posing a threat to their sustainability.

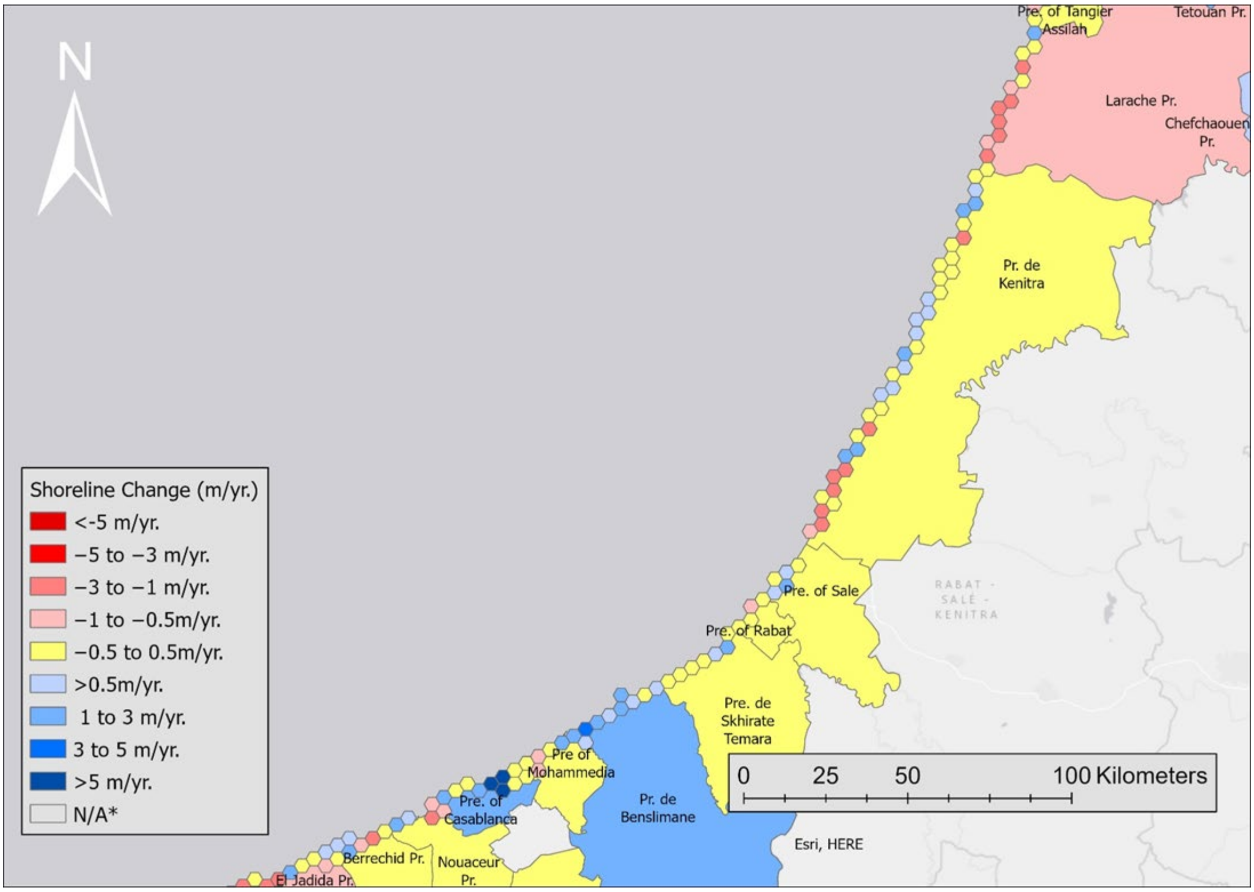
Figure 8: Shoreline changes along the Mediterranean coast of Morocco
Hotspots of coastal erosion



Source: Authors
Note: Morocco Mediterranean shoreline change rates aggregated to about 15km^2 hexagons.

Large parts of the Atlantic coast of Morocco are also eroding. Along Morocco's north Atlantic coastline, erosion is common in the Larache and El Jadida Provinces (Figure 9 below). Intensive erosion is also occurring in regions of Kenitra and Nouaceur,. Pockets of severe or extreme accretion can be found around the port in Casablanca and the headland at Mohammedia, Guelmim Oued Noun, but accretion is also dominant across the northern Mediterranean tip of Morocco. Larache is a coastal town on the south-west side of Tanger-Tétouan-Al Hoceïma where a mix of morphological processes are occurring with reports of considerable sand mining activities.[17] Investigations into the shoreline change rate along the Tetouan coast using aerial photographs showed the shorelines retreated by an average of 58.4m over a 60-year period (Benkhattab et al, 2020). With the boundaries of intensive erosion ranging from -1 to -3 meters per year, erosion appears to be increasing; in another 60 years it is projected to retreat by a further 60 to 180m.

Figure 9: Shoreline changes along the Atlantic coast of Morocco
Hotspots of coastal erosion



Source: Authors.

Note: Morocco Atlantic shoreline change rates aggregated to about 15km^2 hexagons.

[17] https://coastalcare.org/2015/10/the-sand-thieves-of-larache-northern-morocco

3.2 Zooming in on selected hotspots of coastal erosion in Tunisia

More than a third of Tunisia's sandy beaches are under threat from coastal erosion, with some experiencing erosion of several meters per year. Around 35% of Tunisia's sandy coastlines are eroding at a rate of more than 0.5 meters per year (see Figure 6 above). Given their importance for the tourism sector as well as the threat coastal erosion poses for them, this report identified and defined three beaches in Tunisia as priority areas. These beaches were among those parts of the coast that experienced the starkest reductions in the recent past and are threatened by further retreat in the future. However, it should be stressed that this also holds for many other beaches in Morocco and Tunisia, making timely action to combat their retreatment indispensable.

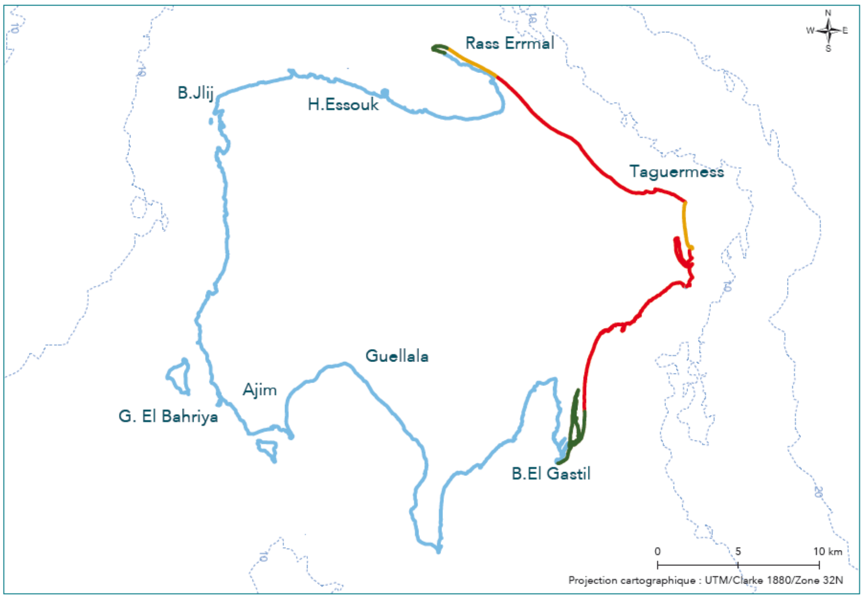
One such beach that is declared a hotspot for erosion is located in Hammamet Bay, south of the capital in central-east Tunisia. Coastal erosion at the Hammamet beach contributed to the loss of 24,000 square meters of beach area in the span of thirteen years between 2006 to 2019 with a loss rate of 3-8 m/year (see figure 10). These high rates of erosion are in large parts caused by the rapid urbanization on the coast of Hammamet that hinders natural sediment from flowing to the shoreline. Coastal erosion manifested by shoreline retreat along with the rapid urban growth has also negative effects on groundwater aquifers and vegetation coverage as it made aquifers exposed to seawater intrusion (Amrouni et al, 2019).

Figure 10: Coastal erosion Hammamet beach, Tunisia

Source: Authors
Note: in orange is the beach as of 2019 and in green is the beach as of 2006

Important beaches of Djerba island, a major tourist destination, also have been on the fast retreat. Figure 11 below shows that large parts of the eastern shoreline of Djerba island, a highly touristic island that hosts around a quarter of all international tourists visiting Tunisia (Carboni et al, 2014), have been eroding in the past decades (as documented for example in Oueslati, 2015).

Figure 11: Coastal erosion at the East coast of Djerba island, Tunisia

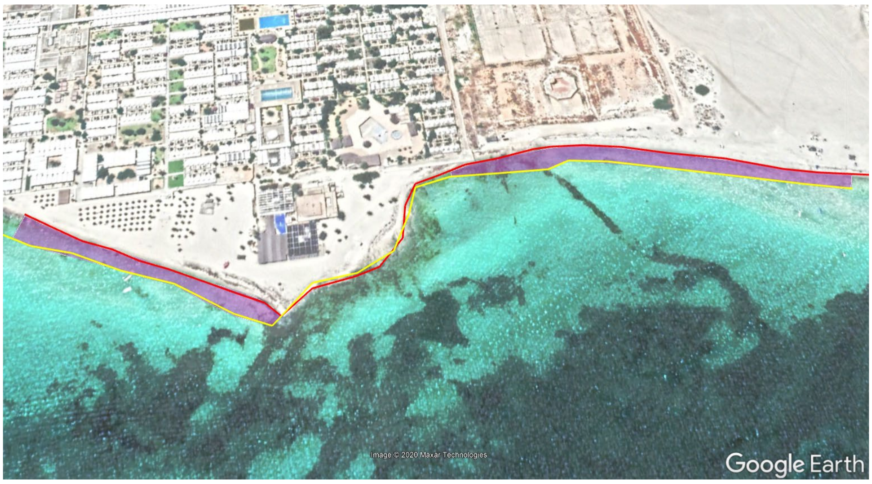


Source: Oueslati et al (2015)

Note: Red parts of the coastline denote areas experiencing erosion, green parts are accreting and yellow parts are rather stable.

Specific locations on Djerba have massively lost beach area in the last decades. Such a location is the beach at Dar Djerba that has lost an area of around 6,900 square meter in the period from 2003 to 2018 (see Figure 12). This potentially has negative repercussions for the nearby tourist resorts deriving most of their amenity for tourists from intact beaches and threatens the local economy that is heavily dependent on tourism overall. The advanced state of beach retreatment and its effects on coastal resorts has also been impressively observable for certain site, e.g. for the oceanfront of the Les Sirenes hotel (Figure 13). Since the 1990s the beach on front of the hotel has basically disappeared and progressing coastal erosion has damaged parts of the resort, leading to the abandonment of it. Between 2006 and 2018, the beach lost approximately 3,500 square meters of its area, implying a loss rate of around 300 square meters per year.

Figure 12: Coastal erosion Dar Djerba, Tunisia



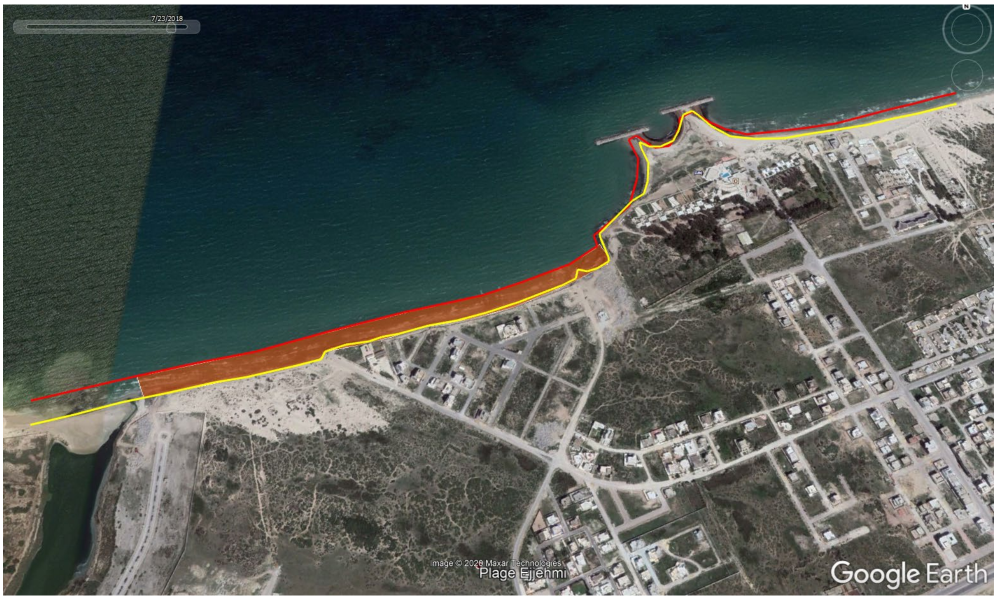
Source: Authors
Note: Yellow line is the shoreline as of 2003 and red line the shoreline as of 2018

Figure 13: The Les Sirenes Hotel in Djerba, Tunisia

Source: Ameur Oueslati & authors.

Soliman, a village southeast of Tunis, has also seen its beach retreat in the recent past. The Soliman beach has retreated at a pace of around 3.5 meters per year between 2004 and 2018. Over the course of 14 years, this amounted to an area lost of around 4.3 hectares, the equivalent of more six football fields. The protective measures that can be seen in Figure 14 below had distinct effects on the sediment transport alongshore and contributed to the erosion dynamics as will be laid out in the next section. The three examples of priority areas in this section represent a few among many such beaches that retreated, highlighting the threat that coastal erosion poses for MENA's beaches.

Figure 14: Coastal erosion Soliman beach, Tunisia



Source: Authors
Note: Yellow line is the shoreline as of 2018 and red line the shoreline as of 2004

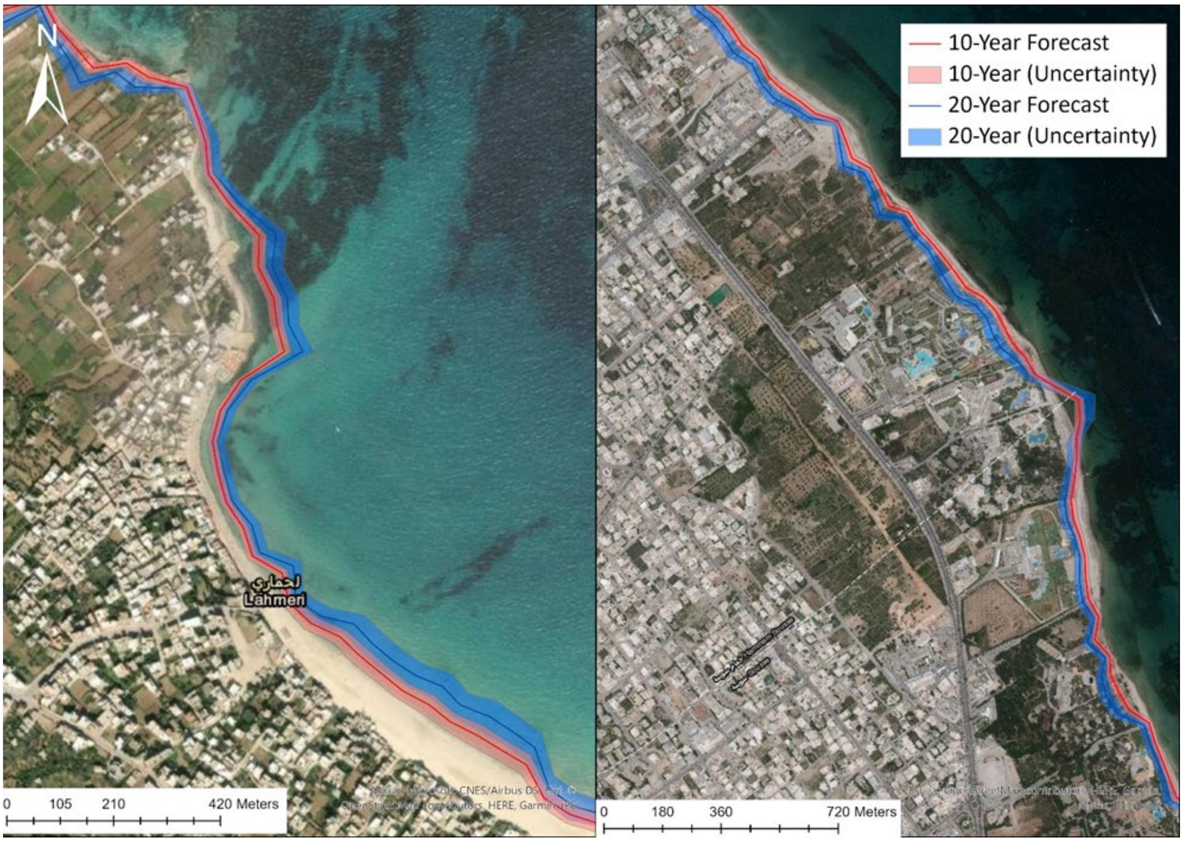
3.3 Forecasting future shoreline changes at coastal erosion hotspots

With the aid of high-resolution aerial photographs and predictive models, future shoreline changes can be forecasted accurately. The high resolution of satellite images and the innovative methodologies used to correct for possible misspecification problems in the present study allows for more accurately forecasting future shoreline changes at a very granular level. The forecasts presented here are derived using a Kalman filter, which predicts shoreline changes beginning in the first year (2000) and uses the periods for which observations are available (2000-2020) to iteratively minimize the error of the forecast. This way it improves the forecasts by updating the rate and uncertainty surrounding it on the fly using the historical data. Predictions for future changes (i.e. out-of-sample forecasts) are thus more reliable, even though a linear relationship is still assumed.

These forecasts can then be used to assess future shoreline changes, both in the form of erosion and accretion, at a local scale and for policy-relevant timeframes. Having analyzed historical changes at a granular scale allows to accurately forecast future changes of the shoreline at very specific sites. Furthermore, with the aid of the predictive model mentioned above forecasts can be obtained for periods that are most relevant for current policy-makers as opposed to long-term studies on sea level rise and its consequences for coastlines. Such predictions of the shoreline are illustrated below at a local scale (Figure 15). Two cases are present showing severe/extreme accretion and erosion in Tunisia, namely in Lahmeri (left panel) and Hamman Sousse (right panel). The red and blue line show the changes in the shoreline that can be expected in ten and twenty years, respectively, with the shaded areas indicating the uncertainty around these forecasts.

Figure 15: Forecasting shoreline changes in Tunisia

Shoreline change forecast of the mean high-water line.



Source: NOC (2020)

Note: Left = accreting areas in Lahmeri, Tunisia. Right = Eroding areas in Hammam Sousse, Tunisia. Shaded areas denote the 95% confidence intervals of forecasts.

Accurate forecasts such as these can help in designing suitable responses and allow policymakers to make decisions based on more reliable evidence than previously possible. The case of Hamman Sousse shown above highlights the threat of future aerial loss due to coastal erosion for near-shore human developments. The granularity of the forecasts can be achieved due to the high resolution of the satellite photos used and the fine scale that was chosen to partition the shoreline into segments. This brings about advantages for the reliability of these forecasts for policy-making decisions. For example, when considering the forecasts for Hamman Sousse one can clearly see that certain parts of the coast are expected to erode less than others. In fact, a certain part of the beach is predicted to be accreting in the next two decades, probably due to site-specific dynamics in sediment transport and wave dynamics. This highlights the advantage of using granular data on the erosion of specific sites as opposed to using for example expected rises in sea level alone to model the changes in coastlines. Such analyses are valuable to assess the effects of rising sea levels due to climatic changes on a large scale for different scenarios. However, they are essentially considering only one of the multiple possible sources for coastal erosion and model these effects often for a distant point of time (e.g. the year 2100). The utilization of historical data on erosion of specific sites to forecast future changes implicitly incorporates the many different forces that shape the shoreline evolution. Hence, this also allows for more accurate predictions for short- and medium-term timeframes. Such detailed information regarding the erosion dynamics are valuable for policy-makers having to decide which parts of the shore to protect and how. Such decisions are associated with substantial costs depending on the specific strategy, making accurate information on near-term shoreline evolution an important factor to determine the most efficient choices.

3.4 Monitoring & Evaluation: the effectiveness of coastal infrastructure interventions

The detailed nature of the analysis also allows for the retrospective evaluation of different protective measures in order to enhance decision processes for future investments. The granularity of the analysis conducted allows for the comparison with of the effects different protective measures had on coastal erosion processes. Analyses like that are crucial pre-cursors for the design and implementation of future measures that aim to combat coastal erosion at specific sites. This is illustrated here with the example of Soliman beach, which is located in the gulf of Tunis, southeast of Tunis (see figure 16 below). This coastline, in particular, has seen strong rates of coastal erosion through time. To face the effects of the erosion, in the late 1980s, early 1990s infrastructure projects were implemented in the form of breakwaters to protect the natural and urban developments along the coastline (Saïdi et al, 2012; Marzougui & Oueslati 2017). The initial set of breakwaters that were built in 1989 and 1990 for coastal protection have been replaced by a coastal groins-system in 2018 for further protection (see figure 17). This changed coastal flow and sediment transport dynamics with distinct effects on coastal erosion processes at the Soliman beach.

Figure 16: Geographical location of Soliman beach, Tunisia

Source: World Bank staff (2021)

Figure 17: Changes in the coastal protection of Soliman beach, Tunisia

Breakwaters (1990 – 2018)	Groin system (2018 – Current)

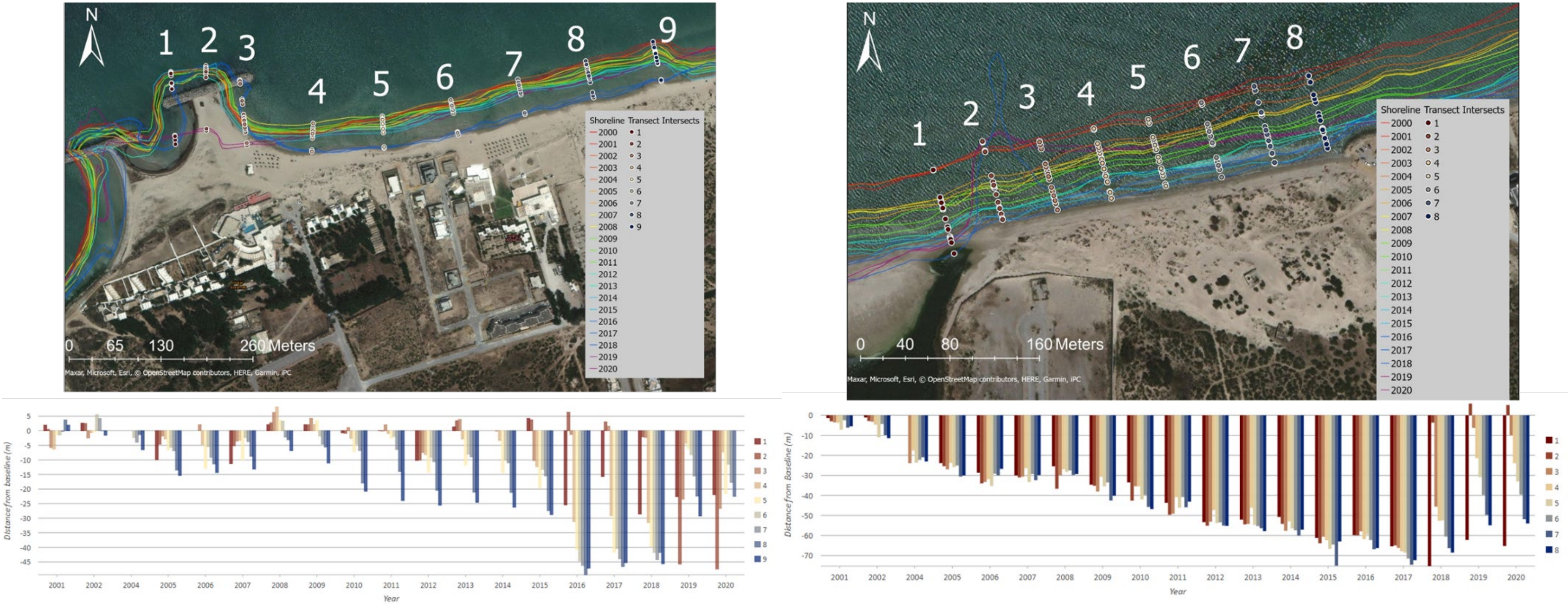
Source: NOC (2020)

Different protective measures at Soliman beach came with significantly different patterns of coastal erosion over time. The coastal breakwaters were replaced by a set of coastal groins late 2018. Considering the area where the two breakwaters were replaced in the lower left corner of Soliman beach, the left panel of Figure 18 below reveals the shoreline changes of this particular area in more detail. The upper part of the figure shows the coastline as of May 2017, i.e. before the replacement of the breakwaters, overlaid with the position of the shoreline in the last two decades, indicated by the differently colored lines. The lower panel then shows the erosion/accretion patterns for each of the transects which are located at different parts of the coast as marked in the upper panel of Figure 18 below. As can be seen from the bar chart in the lower part, especially transect 5 to 9 experienced severe erosion over the years up to 2018. Following the replacement of the breakwaters in 2018, transect 2 shows severe erosion which reflects the removal of the structures. What is more interesting are the changes in transects 5 to 9 in which an immediate and large reversal of the erosion that has been occurring in the years before the introduction of the groins. A similar picture emerges for a part of the shoreline further downstream (right panel of Figure 18), where the construction of groins (in transect 2) also substantially reduced erosion patterns and led to accretion in the affected areas in the years 2018 to 2020, especially so in transects upstream relative to the structure (i.e. transects 3-8). The case study also highlights the importance of the temporal dimension inherent to the issue posed by coastal erosion. Considering that erosive processes may accelerate, decelerate or reverse over time, either through human intervention or by natural forces, regular and detailed evaluations of them is important for policymakers to make informed choices with respect to the implementation of protective measures.

Responses to coastal erosion hence require regular and site-specific monitoring and analysis of the coastline, should be tailored to the local specificities and incorporate the claims of all possible stakeholders affected by them. The example described above demonstrates the developments and regeneration of the Soliman beach following the introduction of the groin system that altered sediment transportation over time. Careful planning is necessary to incorporate possible effects of different structures and select the ones that have the desired effects once implemented. The range of different possible measures (be it hard defense solutions like groins, soft solutions such as beach nourishment or nature-based solution, e.g. the re- or afforestation of marsh or mangroves) should be considered. Simultaneously, the possible spillover effects of measures on other parts of the coastline necessitate the incorporation of the various stakeholders along the coast in the planning process in an integrated manner. Hence, a pre-evaluation of adaptation policies should include feasibility and environmental impact assessments in an Integrated Coastal Zone Management (ICZM) process to minimize adverse side-effects of them, as in some instances poorly informed adaptation measures may cause more damage than 'doing nothing' (Hoggart et al, 2014).

Figure 18: Changes in erosion at Soliman beach after replacing breakwaters with groins

Coastal line changes 2000-2020



Source: NOC (2020)

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