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D2.2/D3.3 -Coastal Erosion in Monastir

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D2.2/D3.3 - Coastal Erosion in Monastir

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Short summary	Identification of hazard prone areas caused by coastal erosion in the city of Monastir based on a review of literature and through consultations of Municipality Monastir and APAL Tunis	
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Abbreviations

APAL	Agence de Protection et d'Aménagement du Littoral
DPM	Domaine Public Maritime
DTM	Digital terrain model
GMSL	Global Mean Sea Level
INM	Institute National de la Météorologie
SLR	Sea Level Rise
WV3	World View 3

1. Introduction

Urban disaster risk is a growing problem driven by two megatrends of global change: urbanization and the increasing frequency and intensity of climate-related extreme events. Coastal cities are additionally confronted with sea level rise, land subsidence and coastal erosion. Combined with high levels of societal vulnerability, these trends increase disaster risk and associated loss of life, land and economic damage. Tunisia faces major risks among the European neighbourhood countries, given its rapid population growth and almost 80% of its urban areas concentrated along the Mediterranean Sea.

Against this background, the Tunisian "Ministère de l'Equipement de l'Habitat et de l'Aménagement du Territoire" plans to develop a national urban Risk Information and Analysing System (RIAS) to assess the impact of these hazards and reduce their effects. Its implementation, however, faces several major challenges including the lack of relevant geospatial data for urban risk analyses as well as an insufficient understanding of the underlying drivers, current hotspots and possible future scenarios of urban disaster risk. To support this process, the UD-RASP project uses the city of Monastir as a pilot case, representative of Tunisian coastal urban areas faced with similar environmental hazards.

Coastal zones are located on the interface between land and sea and are highly dynamic and complex natural systems. Any change in the properties of land or sea leads to a significant physical and socio-economic impact.[1] Coastal areas are under constant stress from land-based sources like river flooding, or sea-based sources like waves and storm surges. The resulting erosion of the coast is a global phenomenon that is driven by various processes and environmental factors that act together in the morphologically dynamic coastal environment. The main natural drivers are sea level rise, storms, winds, near shore currents as well as the beach face. Furthermore, coastal erosion is influenced by anthropogenic drivers such as coastal engineering, dredging, river regulations and dams. Due to the impacts of climate change, with Sea Level Rise (SLR) as a key factor, coastal erosion has accelerated and is now a major challenge for coastal areas around the world.

As a step towards the assessment of risk for the city of Monastir this report focuses on the past, current and future situation of coastal erosion in the region. Scientific as well as grey literature is reviewed to gain understanding of the local processes. An analysis of the major influencing factors of the coastal erosion risk is conducted. During the whole process, stakeholders are consulted to benefit from local expert knowledge and ensure an up-to-date account of the current situation. Finally, an outlook into future developments and challenges in the study area is given.

2. Coastal Erosion

In this chapter, the underlying processes and influencing factors of coastal erosion are explained. Furthermore, climate change is introduced as a driving factor of the acceleration of coastal erosion on many coasts. In a further step the phenomenon is examined in its role as a natural hazard. Finally, the general situation of coastal erosion in Northern Africa is presented, using Tunisia and Morocco as an example.

[1] Özyurt and Ergin (2009)

2.1 Processes and influencing factors

Under equilibrium conditions, a very delicate balance exists between the processes that erode the beach by carrying away material, and the ones that move material to the shore during the process of accretion. This process is driven by surface waves and determines the shape of the shore. The shore profile is generally determined by a certain level of wave activity, local topography and sediment grain size.[2]

Erosion occurs whenever there is no balance between the transport of material away from the shoreline and deposition of new material onto the shoreline. The erosion and accretion of coastal landforms is natural process that undergoes periodic cycles on timescales ranging from days to years.[3] It is defined as "…the physical removal of sediment by wave and current action".[4] It can also be defined as "…the loss of coastal lands due to the net removal of sediments or bedrock from the shoreline."[5] During the process of erosion, a coastal zone loses its sub-aerial land part, like beaches, dunes, bluffs or cliffs. The removal of material is driven by the action of waves and currents, mass wasting processes on slopes as well as subsidence.[6]

All types of coasts are affected by coastal erosion, however the primary erosion mechanism depends on the geomorphology of the coast.[7] Beaches are eroded when waves or currents remove material from the shore. As a consequence, the beach becomes narrower and lower in elevation. The eroded material is then carried offshore and deposited in large sandbars. Over the course of time, the sediment is transported back to the shore by the waves. On coastal headlands erosion leads to undercutting of cliffs and steep slopes. The process furthermore contributes to mass wasting processes with the development of cracks and subsequent rockfalls. Heavy rainfall events can enhance the soil saturation and lead to a reduction in shear strength of the soil which leads to a higher susceptibility to slope failure.[8]

Apart from coastal geomorphology, the sea level is an important factor influencing coastal erosion. It varies on timescales that range from hours to centuries and on spatial scales from less than 1km to global. The height changes vary from a few millimetres to more than a meter. Sea levels change in reaction to fluctuations in water temperature or transfer of water between oceans and continents and ice sheets. It also varies during the redistribution of water during the tides and changes in the oceanic and atmospheric circulation.

Another factor are weather events like storms that can lead to a sediment transport off the coast. Coastal storms, storm surges, flooding and tsunamis lead to much higher water levels and an increased intensity of waves and currents due to storm winds and atmospheric pressure. Wave conditions and currents play a major role in shaping the coastline as they influence sand transport and serve as a

[2] Australian Department of Climate Change (2009)
[3] Van Rijn (2011)
[4] Klein and Nicholls (1998)
[5] Woolfe (2017)
[6] Woolfe (2017)
[7] Klein and Nicholls (1998)
[8] Woolfe (2017)

major cause of erosion and accretion. . In contrast to changes in sea level, which cause a slow erosion process, storm events provoke short, but very intense erosion on the coast. Depending on the characteristics of the storm, significant erosion rates of several meters per event can occur.[9] Consequently, the associated storm surge or tsunami inundation can affect landforms that are usually not influenced by erosion.[10]

Anthropogenic influence is another factor that has a significant impact on the disposition of landforms to erosion. The construction of coastal structures like breakwaters or seawalls can result in an alteration of coastal sediment transport pathways. Subsequently, the erosion and accretion patterns in the affected landscapes can change. The removal of sediment by dredging or sand mining is another driver of erosion. By reducing the amount of energy dissipated from incoming waves the erosion can be increased. The regulation of rivers can lead to a reduction in the supply of sediments, therefore causing coastal erosion as well.[11]

2.2 Impact of Climate Change on Coastal Erosion

Natural and human induced climate change is likely to modulate the rates and patterns of coastal erosion in the future.[12] Climate related drivers (2.1) will undergo the most significant change, which will lead to a modification in future erosion patterns. Of the many factors influencing costal erosion like sea level, currents, winds and waves, each one of them is affected by climate change.[13]

Among these factors the sea level and the predicted rate of its rise is one of the most important elements of climate change and subject to much scientific and public debate. It poses a serious threat to settlements and economic activities located along coastal regions.[14] One key driver of climate change induced SLR are increases in ocean warming which leads to a thermal expansion of seawater. The second main factor is the water input of melting glaciers and ice fields.[15] It has been proven in multiple studies that the global mean sea level has risen in the course of the 20th century. That trend is predicted to accelerate during the 21st century.[16] The mean rate between 1901 and 2010 was 1.7 (1.5-1.9) mm/yr^{-1} with an increase to 3.2 (2.8 to 3.6) mm/yr^{-1} between 1993 and 2010. [17] Several models predict that the SLR in the 21st century will exceed the rate observed during 1971 and 2010.[18]

Coastal systems and low-lying areas are expected to be increasingly influenced by submergence, coastal flooding and coastal erosion as a result of SLR.[19] A rising sea level causes the shoreline to recede inland by promoting offshore transport of sediment.[20] As the sea level rises the beach seeks to maintain an equilibrium of the beach profile. To maintain that equilibrium during the course of SLR,

[9] Beatley, et al. (2002)
[10] Woolfe (2017)
[11] Woolfe (2017)
[12] Niang et al. (2014)
[13] Wong et al. (2014)
[14] Dasgupta et al. (2009)
[15] Linham and Nicholls (2010)
[16] Gutierrez et al. (2011)
[17] Rhein et al. (2013)
[18] Church et al. (2013)
[19] Wong et al. (2014)
[20] Wong et al. (2014), Linham and Nicholls (2010)

sediment is removed from the shoreline and subsequently deposited offshore so that the nearshore zone gains elevation that is equal to the rise in sea level. Consequently, the volumes of the eroded and deposited material are equal.[21] It has to be considered that local and regional differences in relative SLR and temperature, the occurrence and response to climate change effects will vary around the globe. The impacts of climate change on coastal erosion patterns will be site specific and largely determined by local factors.[22] Apart from SLR, the occurrence of storm surges will have a significant impact on coastal zones.[23] The destructive effect of the phenomena will grow as climate change may lead to an increase in extreme wave heights and the intensity of storms.[24]

2.3 Coastal Erosion as a natural hazard

Coastal areas are globally characterized by rapid economic development and population growth, which lead to increased exposure of coastal infrastructure, assets and activities.[25] The process of coastal erosion has always existed, but it is now accelerated due to human activities.[26] This natural process turns into a risk as soon as it affects human activities or infrastructures. As a high global percentage of the population lives in coastal areas that are vulnerable to coastal erosion there is an increasing need adapt to its effects on the people, the built environment and infrastructure.[27]

Several methods for the hazard assessment of coastal erosion have been developed. Various factors have to be considered as they subsequently determine the assessment method. The form and composition of coastal landforms and the presence of barrier islands as well as reefs in the offshore area are factors that define the processes to be considered. Sandy beaches and rocky shores exhibit different characteristics that influence the analyses.[28] The spatial and temporal scale of the analysis has to be adapted according to the scale of the study area. Additionally the time scale of the analysis has to be defined in advance. At a short, inter-annual time scale the coastal behaviour across seasonal weather cycle has to be considered. For long-term, decadal time scales, climate variability should be incorporated.

It is crucial for coastal communities to consider the risks of climate change in their urban planning in order to reduce the risk from those impacts. Without adaptation the currently eroding beaches, sand dunes and cliffs will erode even further under the influence of increasing SLR. [29] Proactive planning has to become a focus, as it reduces the need for a reactive response to the damages caused by the impacts of climate change. The priority of these protective planning measures is to protect the people, property and infrastructure.

Adaption techniques are a broad set of processes that provide the knowledge, experience and equipment to reduce the effects of coastal erosion. These technologies aim to decrease the

[21] Linham and Nicholls (2010), Bruun (1962)
[22] Klein and Nicholls (1998)
[23] Woth et al. (2006)
[24] Linham and Nicholls (2010)
[25] Lenton et al. (2009)
[26] Van Rijn (2011)
[27] McLaughlin et al. (2002)
[28] Woolfe (2017)
[29] Wong et al. (2014)

consequences of shoreline erosion, wave damage as well as flooding. The measures can be applied individually or in combination, depending on the specific site. The action can be differentiated into "hard" and "soft" measures.

"Hard" measures present the traditional approach to coastal protection. Solid barriers are built between land and sea in order to prevent any interaction taking place.[30] It involves structures such as sea walls, groins, levees, sea dikes and other barriers. While these measures provide tangible protection to the shore sections they protect, they do not prevent the physical process of erosion. The process is merely transferred from the shoreline to the seabed or to the adjacent coast.[31]

With an increasing understanding of natural shoreline functions a trend to non-structural, "soft" measures has developed. These measures try to supplement and adapt to natural processes. They have a focus on information, capacity building, institutional arrangement as well as policy and strategy development.[32] Examples of these measures are the enhancement of coastal vegetation beach replenishment, dune stabilization with fences and vegetation, habitat restoration, beach nourishment or building of seawalls to reduce erosion and enhance the coast as a barrier to storm surges.[33] Through these measures, the natural landscape as well as the habitat function can be better preserved. They do however require ongoing and regular monitoring, maintenance and engineering in order to ensure effective protection. These additional costs and capabilities have to be considered when selecting the appropriate option.[34]

Currently both types of measures are being applied even though there has been a tendency towards "soft" measures. Generally, "hard" measures are applied to protect urban areas against erosion and flooding. "Soft" measures are more often used on sedimentary coasts, composed of beaches.[35]

2.4 Coastal erosion in North Africa

The coastal zones in northern Africa are densely populated areas with high economic activity. From the 1960s onwards, several coastal areas have begun to develop towards tourism, with the most significant change occurring during the 1980s with an accelerated development of tourism and urbanization. Especially the coastal areas have undergone a rapid transformation and experienced urban and economic growth.[36] Previously uninhabited areas saw an increase in population density. The numbers of ports and marinas increased with a simultaneous building and expansion of port infrastructures.

With regard to natural hazards, the coastal countries of Northern Africa face similar challenges. Anthropogenic drivers and pressures like population growth, economic development and urbanization lead to an increased exposure to coastal risks for human infrastructures and the population.[37] The

[30] French 2001
[31] Nicholls et al. (2007)
[32] Linham and Nicholls (2010)
[33] Snoussi et al. (2009)
[34] Chadwick et al. (2013)
[35] Linham and Nicholls (2010)
[36] Oueslati (2010)
[37] Wong et al. (2014)

natural drivers in relation to natural hazards and to coastal erosion in particular are related to climate change related phenomena like accelerated SLR, increase in extreme storm events and increased inundation of coastal areas.[38]

In Tunisia past developments have disturbed the natural equilibrium of the coastal areas.[39] The country has about 1300 kilometers of coast, of which about 575 kilometers are sandy beaches. These beaches are fragile environments and easily destabilized.[40] Therefore one third of Tunisian coasts consist of erodible beaches. Population growth and densification have resulted in conflicts and degradation.

Hinkel et al. (2015) modelled the annual land loss on Tunisia's coast for the past as well as for future scenarios. Three seal level rise scenarios (with 21st century sea-level rise of 0.3 m, 0.51 m and 1.11 m) as well as three socio-economic development scenarios were assumed. A total length of erodible beaches was calculated with 734.2 km. Figure 1 shows expected annual losses due to sea-level rise. Under the high-sea level rise scenario and without adaptation, sea-level rise is projected to erode about 523 m^2 of land in 2100. Under the low sea-level rise scenario 71 m^2 are lost in 2100.

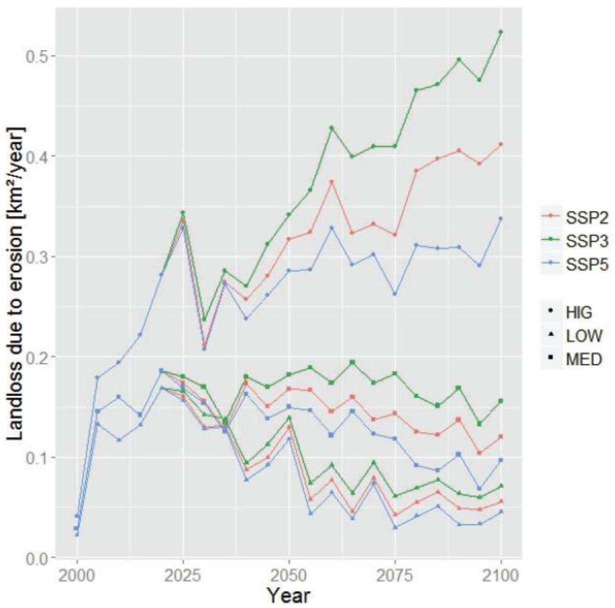

Figure 1: Annual land loss due to erosion until 2100 in Tunisia under three different sea-level rise scenarios[41]

Morocco is another North African country affected by coastal erosion. Its coastal zone expands over 3500 kilometres and borders the Atlantic Ocean and the Mediterranean Sea. About 60 % of the population lives in coastal cities, which host 90 % of the industries. The eastern part of the Mediterranean coast of Morocco has a low topography and a high ecological and touristic value. As a result, the coastal area is physically and socio-economically vulnerable to hazards like sea level rise or

[38] Snoussi et al. (2009)
[39] Oueslati (2010)
[40] APAL (2011)
[41] Hinkel et al. (2015)

coastal erosion. Depending on the scenario, up to 50% of sandy shores in eastern Morocco will be flooded by 2050. Furthermore, significant inundation is expected to occur in coastal areas. Depending on the location, inundation or erosion is the primary issue.[42]

The coastal city of Tangier is the most important socio-economic pole in northern Morocco. The city of Tangier was the first seaside tourism destination in the 1970s Morocco. The coastal area has become increasingly urbanized and tourism has turned into its main economic resource.[43] However, erosion of eastern beaches together with pollution of coastal waters poses a major threat to the touristic sector.[44] Apart from tourist coastal infrastructures, coastal defenses, ports, urban areas, railways and industrial areas are especially vulnerable towards coastal erosion.

To conclude, the coastal countries of Northern Africa are confronted with an accelerated coastal erosion relate which necessitates a detailed assessment of the risk and its future development in the light of climate change.

3. Methodology

3.1 Review of past and current situation

In order to analyse the past and current situation of coastal erosion on the Monastir coast, a literature review was conducted to gather information about the past condition of coastal erosion in the study area. Reports from the "Agence de Protection et d'Aménagement du Littoral" (APAL) were used to gain an understanding of the natural processes. A further focus was set on the implemented and planned protective measures. Additionally to reports from local authorities, scientific literature was reviewed to explore current and future developments in the region, particularly looking at climate change as an influencing factor. Furthermore, interviews with stakeholders were conducted on several occasions. Experts from APAL in Tunis provided valuable information about the current state of the coast in Monastir. During various interviews, the municipality contributed to a detailed understanding of the situation and processes on site. During a field survey that was conducted with the support of the municipality, the current situation was documented. A focus was set on identifying current hotspots of costal erosion and analysing which of the previously planned protective measures have already been implemented.

3.2 Hazard and Exposure Analysis

In the course of the project, GIS analyses were conducted to evaluate the hazard and exposure areas to coastal erosion in Monastir.

3.2.1 Input Data

The input data, used for the analyses have been described in further detail in Deliverable "D1.2". Therefore, only an overview of the data is given in this report (Table 1). Stereoscopic World View 3 (WV3) imagery provided the basis for the subsequent analyses. A digital terrain model (DTM) was furthermore calculated from the WV 3. Additionally, the "Urban" and "Additional" dataset from the

[42] Snoussi et al. (2009)
[43] Anfuso et al. (2010)
[44] Snoussi et al. (2009)

UDRASP Geodatabase were used. The maximum flow velocities, which were calculated in the course of the modelling of the Flash Flood hazard, were also included into the analysis (see Deliverable "D2.2").

Table 1: Input Data for Hazard and Exposure Analysis

Input Data	Source	Date
Imagery 2017 (0.5 m)	EUSI – World View 3 – mosaic	2017
DSM1 & DTM1 (Raster)	IABG, prepared by WV3 imagery	2017
Geodatabase UDRASP (Dataset Urban, Additional)	IABG, prepared by integration of PAU and mapping/updating based on WV3 imagery	2017
Maximum Flow Velocity	DHI, HQ100 precipitation event	2018

3.2.2 Workflow

Before conducting the analysis, the coast of Monastir was subdivided into six coastal segments (Figure 2). The segments are based on delineations that were also used in APAL reports[45]. In Chapter 5, each segment will be discussed separately and an examined regarding its hazard and exposure to coastal erosion.

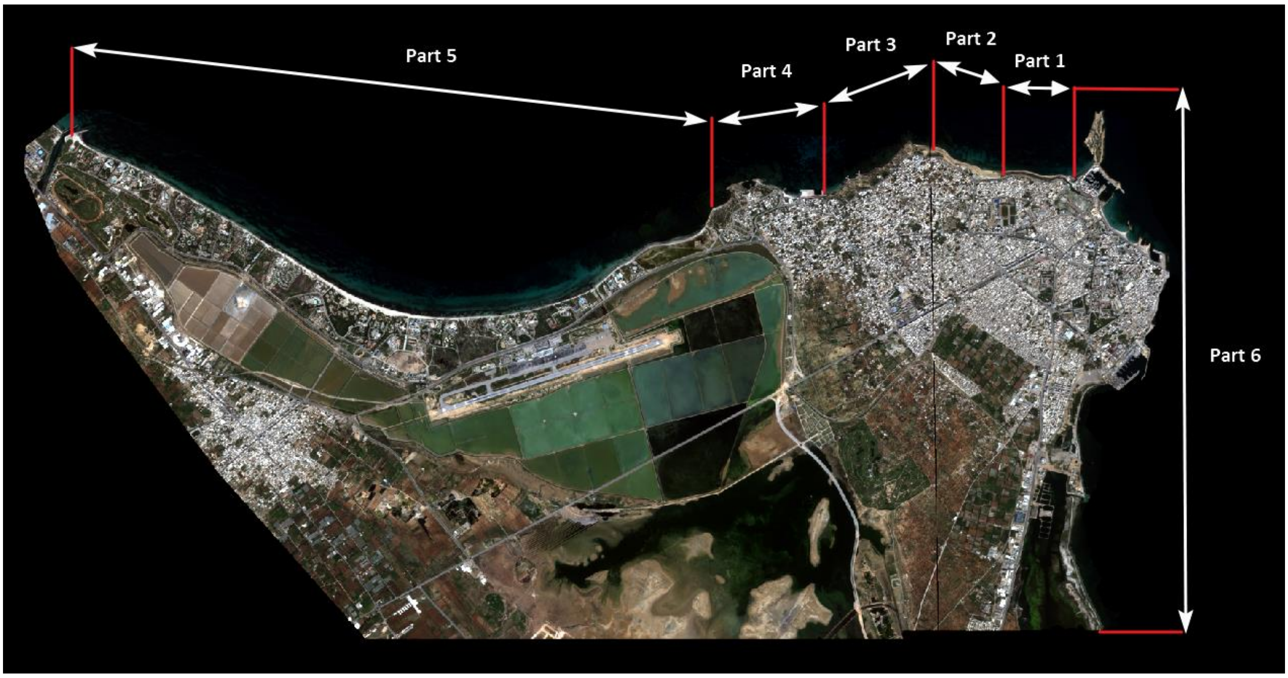

Figure 2: Coastal Segments

[45] APAL (2011b), APAL (2009)

In Figure 3 the workflow for the definition of the hazard area is depicted. To define the hazard due to marine erosion, the area 200 meters inland of the coastline is roughly predefined as a potential hazard area. Furthermore, erosion due to surface runoff is considered by including the terrain situation on the shore. The terrain situation is included by combining the slope information of the DEM with the modelled "Maximum flow velocity" (HQ100). The satellite imagery is inspected, in combination with the terrain situation to manually adapt the boundary of the hazard layer. The predefined 200m Buffer is either maintained or adapted depending on slope and flow velocity. In areas with steep slopes and high maximum flow velocities, the hazard area is expanded, whereas in areas with low slope and maximum flow velocity the 200 m buffer was maintained as a boundary. On several locations, the predefined hazard area is adapted and defined along major roads or other dominant features.

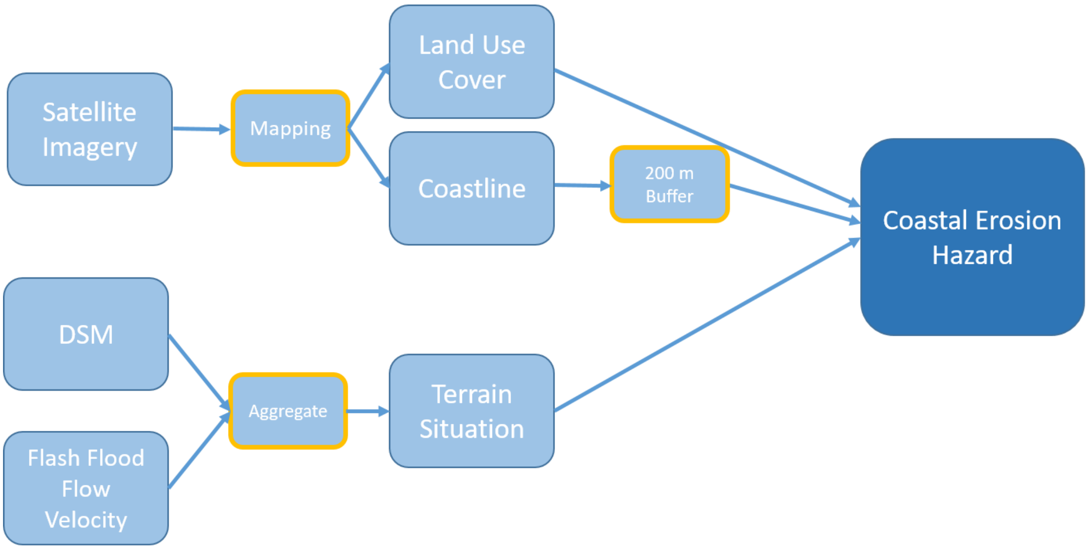

Figure 3: Workflow Hazard Analysis

In next step, the land use inside the hazard area is classified into five categories (Figure 4). The classification is done in close relation to the previously created land use mapping (see Deliverable "D1.2"). Each LUC Polygon is classified according to its status of development. The exposure of each coastal segment is examined and described considering the terrain conditions, LUC-Classes and the development status.

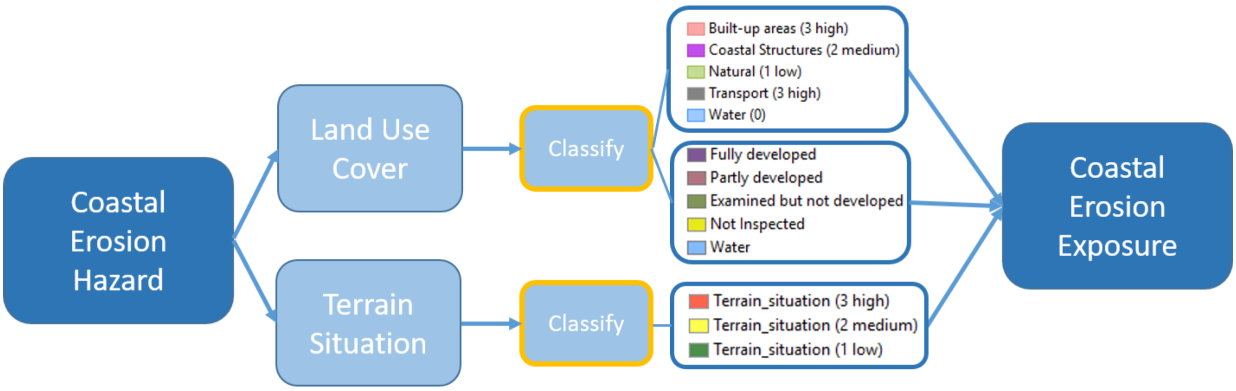

Figure 4: Workflow Exposure Analysis

The results of the GIS analyses are subsequently combined with results of reports by local authorities like the municipality of Monastir and APAL. Furthermore, findings from the field survey are interpreted in order to gain thorough understanding of the coastal erosion processes in the study area and to identify exposed areas.

4. Study Area

This chapter describes the study area of Monastir. An overview of the geography as well as the geological setting, climate and hydrology are given.

4.1 Geography

The coast along the golf of Hammamet has a NW-SE orientation and follows a very straight course until it is abruptly interrupted by the peninsula of Monastir. The city is located on a plateau that tilts to the East and Southeast.[46] The peninsula of Monastir is located in eastern Tunisia about 160 kilometers south of the capital Tunis. It covers an area of about 1020 km^2, being 0.6% of the country's surface.[47] The city has a population of 93,306 (Census 2014). It is located in the eastern Tunisia and adjoins the Mediterranean in the East and West and the municipalities of Sahline and Bembla in the South. The Monastir coast expands over 15 kilometers and is limited by the Hamdoun wadi in the north and the Khniss wadi in the South. The area is located on a plateau, a Sebkha.[48] The Monastir coastline has a total length of approximately 50 kilometers. It stretches from the estuary of the Sidi Abdlahmid Wadi in the Northwest to Ras-Dimas in the Southwest.[49]

4.2 Geology

On a geological scale, Monastir is located in a relatively young area. The bedrock of the Monastir plateau consists of a Neogene formation that is, at the same time, the oldest geological material in the area. The formation is made up of sandy clays from the Miocene and coarse sandstones and calcarenite dating back to the Pliocene. They become visible on the surface on the western and northern edges of the Monastir plateau as well as on the Tefla Wadi. On the entire plateau, the Neogene bedrock is covered with marine deposits from the Quaternary. The area of Khniss and the Sahline consist of a sandy limestone, which is being mined in quarries.[50]

The Peninsula of Monastir is characterized by an alternating sequence of sandy beaches and rocky coasts with sections of steep cliffs in between.[51] The cliffs predominantly consist of alternating Pliocene layers of sandstone and clay. In some lower cliff areas (2-4 m) Pliocene sandstones and quaternary materials dominate. The area generally has a low topography that is interrupted by the mio-plio-quaternary rock at Monastir and the thyrrenic hills of Ksibet el Mediouni as well as collapsed areas around the Sabkha of Sahline. The highest and longest cliff is located in the west, close to the Island of

[46] ARCHIPLAN (2017)
[47] APAL (2010)
[48] ARCHIPLAN (2017)
[49] APAL (2010)
[50] ARCHIPLAN (2017), APAL (2011a)
[51] APAL (2009)

Ghedamsi. It extends towards the west until the old mouth of the Melah wadi. The cliff height ranges between 5 and 20 meters.

The area around Monastir is seismically active, with several active fault lines, the most relevant being the Skanès-Khniss fault line (Figure 5). The monocline runs in a NE-SW direction and is visible on the surface over several kilometers.

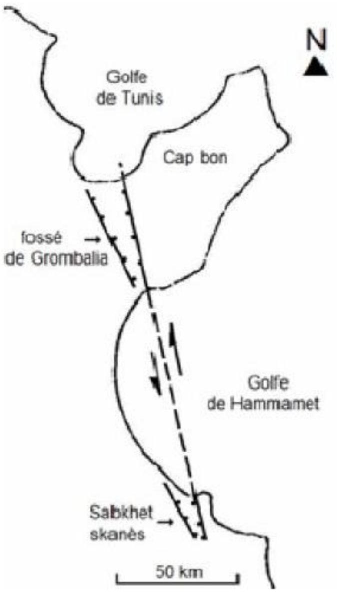

Figure 5: Location of the Skanès-Khniss fault and its extension to the golf of Hammament and the Peninsula of Cap Bon[52]

The Monastir region is located in a “tectonic corner”, which results in an accumulation of pressure. This situation leads to a high frequency of earthquakes in the region. However, the earthquakes mostly remain moderate in intensity, rarely exceeding magnitude 5 on the Mercalli-scale. Therefore, they are not very destructive.[53] Since 1934 all earthquake events have had a magnitude of 5 or lower on the Mercalli scale (Figure 6). The average magnitude of all recorded earthquakes between 1934 and 2005 is 3.35.[54]

[52] APAL (2011)
[53] APAL (2009)
[54] INM (2013)

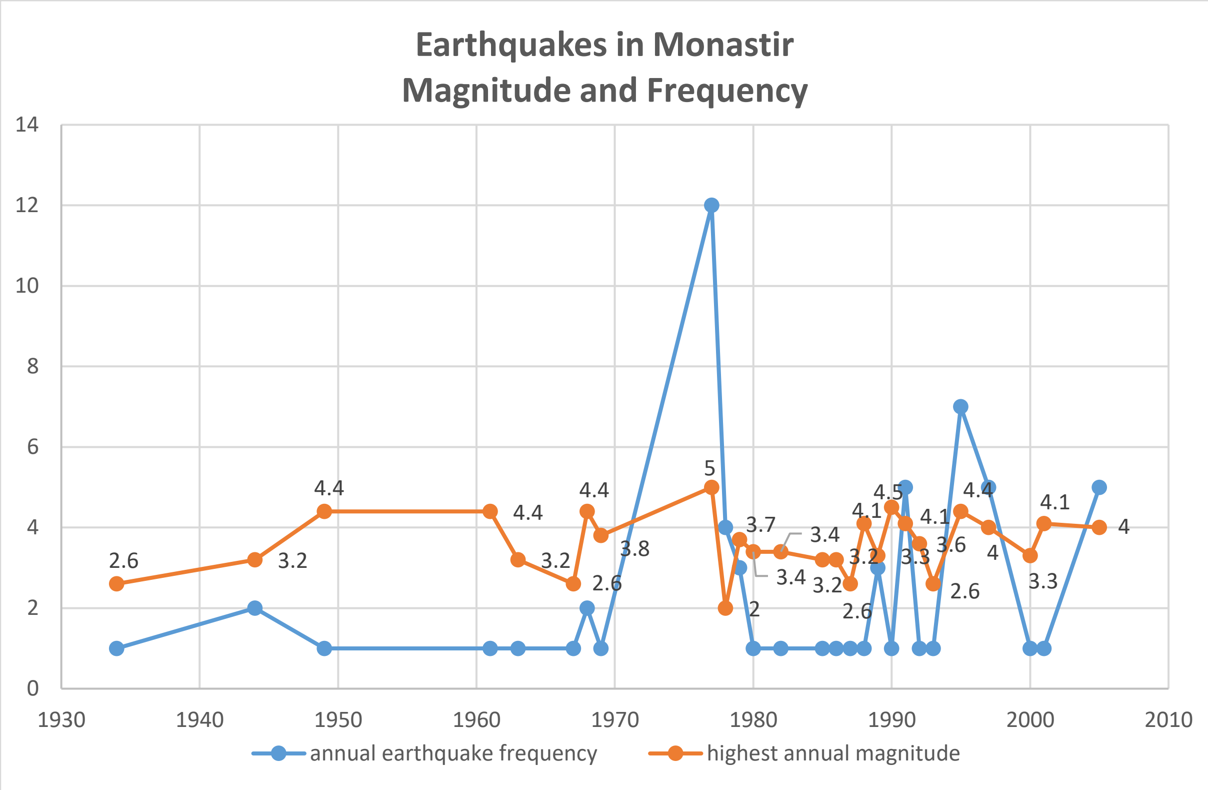

Figure 6: Magnitude and Frequency of Earthquakes in Monastir area (1930-2010)[55]

4.3 Climate

The city is located in a semi-arid area that exhibits mild, rainy winters and hot, dry summers. Average annual rainfall lies at about 300 mm. Short and intense precipitation events occur on a regional scale. They have a high inter-seasonal and inter-annual variability and occur at irregular intervals.[56]

The average monthly temperatures in Monastir range from 12.43°C in January to 27.86°C in July. Mean monthly precipitation is very low during the summer months with values of 6.24 mm in June and 1.99 mm during July. January (46.18 mm), September (45.23) and October (61 mm) exhibit the highest annual amounts of precipitation. The highest mean maximum temperatures can be observed during August (32.83°C) and July (32.38°C). The lowest monthly average minimum temperatures occur during the months of January (8.34°C) and February (8.79°C).[57]

[55] INM(2013)
[56] URAM (2003)
[57] INM (2014)

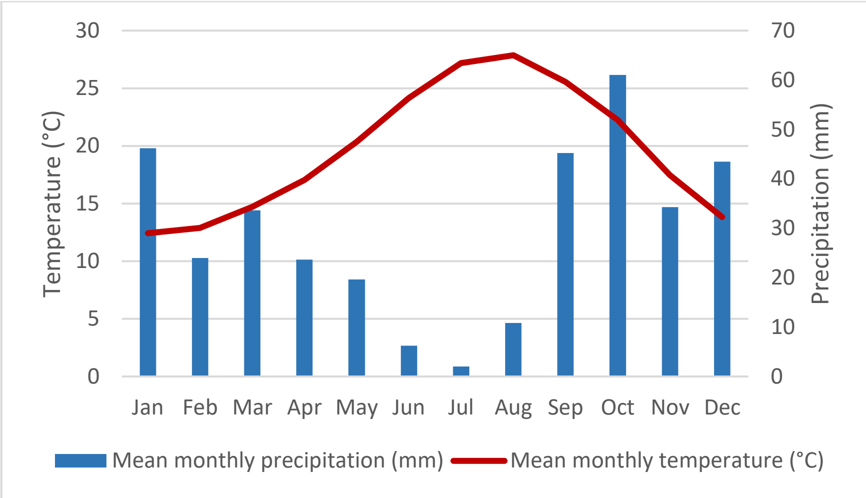

Figure 7: Climate Monastir, Tunisia (Climate station "Monastir-Skanès" (Long: 10.75, Lat: 35,667), Average Data from 1981 to 2014)[58]

4.4 Hydrology

The hydrographic network of the entire governorate of Monastir is largely made up of endorheic basins. The north is divided into the area of the Sidi Abdlahmid wadi and the area of the Maleh wadi, which flows into the sebkha of Sahline-Bembla, a large part of which is artificially diverted towards the Monastir bay via the Khniss drain. Further south, great amounts of water flow into the sebkha of Moknine.[59]

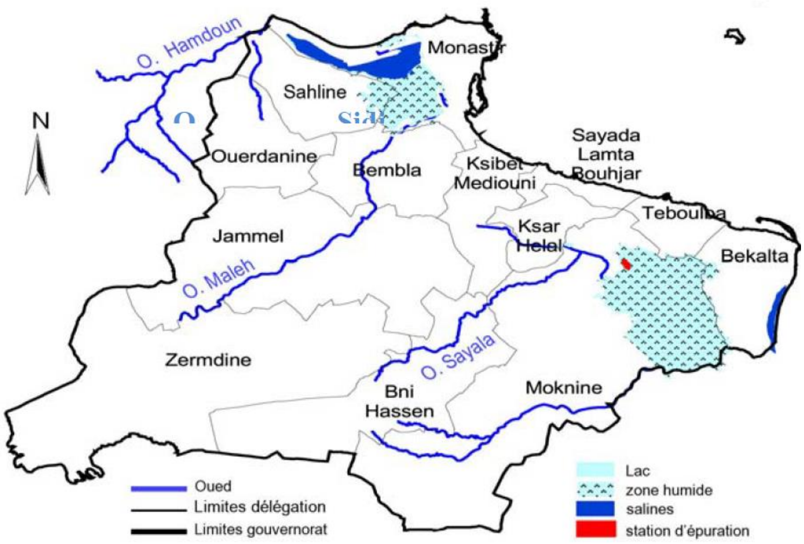

Figure 8: Hydrographic network of governorate Monastir[60]

[58] INM (2014)
[59] APAL (2010)
[60] APAL (2010)

5. Results and Discussion

This chapter presents the results of the hazard and exposure analyses concerning coastal erosion in Monastir. Results from the GIS-analyses (3.2) are presented. The insights are related to findings from the literature survey in order to gain insight into the past situation on the Monastir coast. The development of coastal areas in Monastir is illustrated and implemented adaptive measures are examined. Additionally, findings of a field trip, conducted on May, 16th 2018 are included into the analysis to demonstrate the current local status and identify current hotspots.

5.1 Coastal Erosion in Monastir

In the past, Tunisian authorities and local experts have conducted several surveys in order to analyse erosion processes on the Monastir coast, to identify hotspots and to plan protective measures for the coastal area. The following chapter summarizes results of local studies presents implemented and planned protective measures.

Due to various site characteristics (Chapter 4), Monastir's coast is susceptible to erosional processes. The main factors influencing the rates of coastal erosion in the region are:

- Geology
- Seismicity
- Waves and winds
- Surface runoff

The coast is composed of soft rocks of different geological resistance. The base of the cliffs is constantly being attacked by the sea, leading of the formation of wave-cut notches. That process leads to erosion in the formation rock falls and collapses on the face of the cliff. The coastal cliffs are additionally susceptible to erosion during high intensity precipitation events. Through surface runoff, water can infiltrate into the cliffs through cracks and fissures of the cliffs. That leads the formation of moist reservoirs inside the cliff, which decreases the stability of the slope. The lithology in several parts of the shore is characterized by a high clay content (4.2) which generally has a low water permeability. However, as hydrostatic pressure builds up in the reservoirs water presses into the pores of the clay. As clay has a high swelling capacity under the influence of water, the clay swells and expands. As a result, the lower layers of the cliff become instable. This effect leads to profound chunks of the cliff to glide or break off into the ocean.[61] The just depicted situation illustrates the natural processes that dominate the coastal area. These processes are constantly influenced and altered by anthropogenic changes in the shore are, which will now be described in further detail.

5.2 Part 1

Part 1 of the study area has a length of about 800 meters (Figure 9). It is dominated by steep slopes, but also exhibits gentle slopes in the east. The coastal area is almost entirely covered by protective measures. Longitudinal protection in form of ripraps has been installed. Directly behind these

[61] APAL (2011)

structures a road runs along the coast. On the slope behind the road, drainage of surface runoff has been ensured by the installment of drainage channels leading from the top of the slope into the ocean.[62] Furthermore, the slopes have been coated with soil and vegetation has been planted to prevent surface erosion. The eastern part is dominated by Built-up areas. Due to its steep slopes the area generally is affected by coastal erosion hazard, however the protective measures along the coast have reduced the area's exposure significantly. The road behind the ripraps as well as the Built-up area are identified as the most relevant exposed objects.

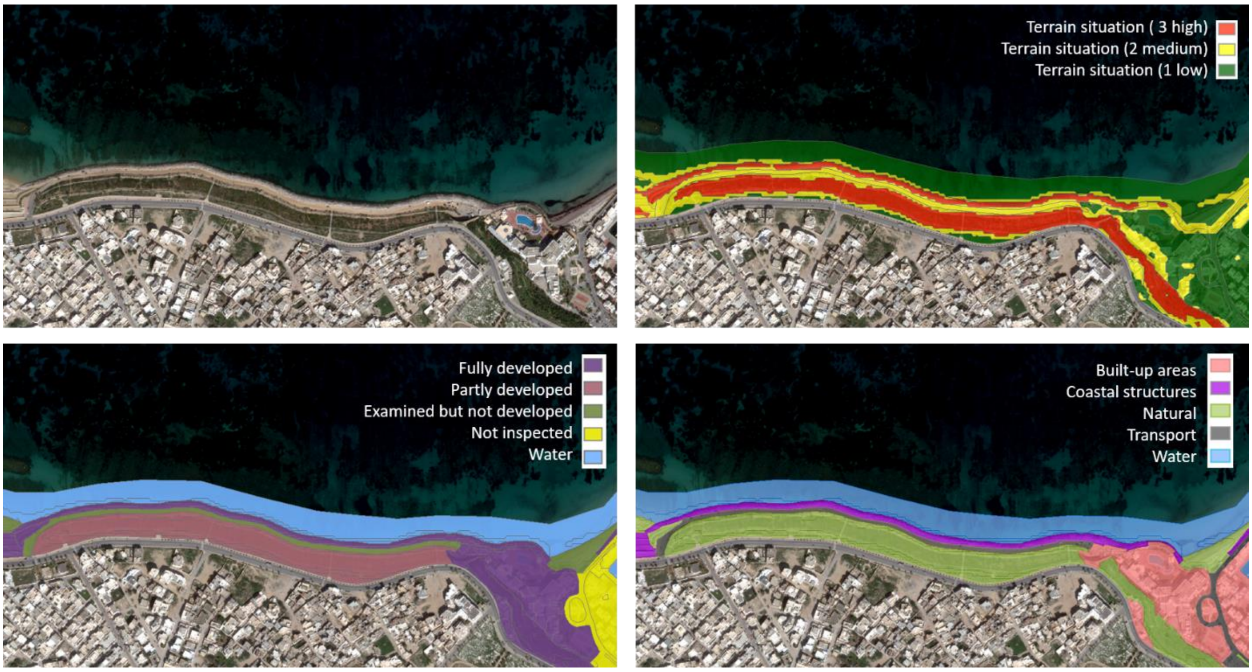

Figure 9: Exposure Analysis, Part 1

5.3 Part 2

Part 2 of the study area (Figure 10) is also dominated by steep terrain with gentler slopes in the east. The whole section has been fully developed in terms of protective measures.

[62] APAL (2010)

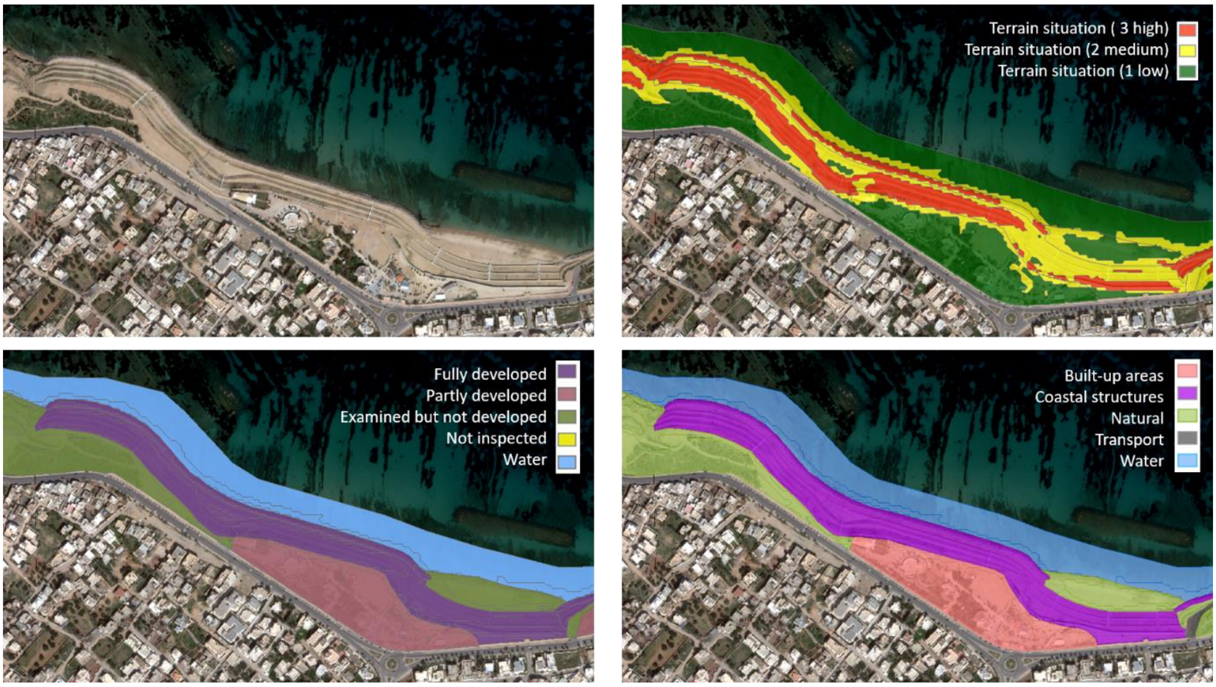

Figure 10: Exposure Analysis, Part 2

In the eastern part, sea walls with drainage channels as well as headland breakwaters have been installed (Figure 11.1). In the western part, ripraps in combination with vertical as well as horizontal drainage channels been constructed (Figure 11.2, Figure 11.3). The municipality confirms, that in this area, the previous erosion has been reduced because of the implemented measures.

Figure 11: Part 2 – 1) Sea Walls 2) Rip Raps 3) Drainage channels

Even though protective measures have been implemented in Part 2, erosional processes affect the area. The slopes of Part 2 area made up of unconsolidated material and have no vegetation cover (Figure 12.1). The artificially deposited material is therefore highly susceptible to erosion through surface runoff (Figure 12.2). The debris that erodes from the slopes is clogging the channels that have been constructed to drain the water. Consequently, the channel's capacity to channel the water in case of intense rainfall is diminished significantly.

Figure 12: Part 2 - 1) Hill erosion due to lacking vegetation cover 2) Blockage of drainage channels through debris accumulation and vegetation growth

5.4 Part 3

Figure 13 shows the third coastal section, which covers more than 30 hectares and exhibits a steep terrain. The morphology of the coastal stretch is dominated by cliffs that range from 5 meters up to 20 meters. This area illustrates the natural coastal processes that take place along the coast if no protective structures are present. The cliffs are currently not developed and are subject to various degradation processes. The slopes in the region are unstable and have collapsed in several areas. Landslides have occurred on a number of locations. Deep gullies run through the slopes, which are occasionally channeled by drainage structures. Small stretches of sandy beaches are located on the shore, which have been subject to accelerated erosion in the past.[63] The only protective action that has been taken area two groins that have been installed in the south eastern part of the segment. Between the two structures, a sandy beach has formed.

[63] APAL (2010)

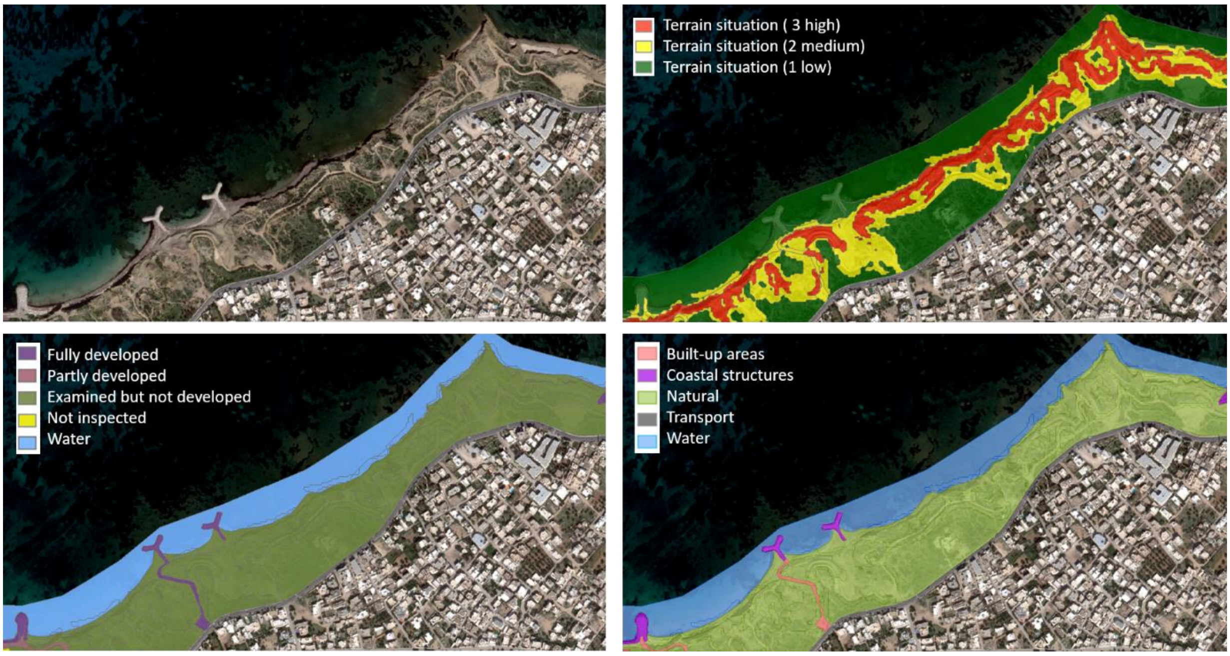

Figure 13: Exposure Analysis, Part 3

In general, Part 3 is highly exposed to coastal erosion. The municipality is currently planning to install protective measures along this segment to stabilize the cliffs and prevent further damage caused by coastal and surface erosion. Water flows from external watersheds will be intercepted at the level of the coastal road. The water will then be channelled through underground drainage pipes and then discharged into the ocean. Interception of all flows from external watersheds at the level of the existing road will allow the drainage of all water arriving at these points. The flow will then be directed through channels and drained into the ocean.

5.5 Part 4

Along the coastal fringe, located between the Skanes Serail Hotel and the former presidential palace (Part 4) the sandy beach at palace level is protected by three breakwaters built in 1967 (Figure 14). The breakwaters offer protection against the waves and have resulted in an accumulation of sediment in the area. West of the former presidential palace another breakwater has protected the shoreline and has also let to an accumulation of material.[64] Part 4 is characterized by shallow terrain and gentle slopes along the coast. The region is dominated by Built-up area that is protected by ripraps that cover the shoreline. The area is highly affected by the hazard due to its shallow terrain, but has a reduced exposure due to the installed protective measures.

[64] APAL (2010)

Figure 14: Exposure Analysis, Part 4

5.6 Part 5

Part 5 (Figure 15) consists of the tourist area with several hotel complexes along the coast. A comparison of the coastline between 1925 and 1988 in the western sector of Dhikla Bay (Part 5) shows an erosional trend, beginning at the mouth of the Hamdoun wadi and extending over 8 kilometers. The average erosion rate lies between 0.48 and 1.24 m/year and is influenced by surges from the North and North-East. Shoreline retreat was less significant in the eastern parts of the bay, with erosion rates, ranging from 0.11 m/year to 0.86 m/year. In the area around the bottom of Dkhila Bay, the shores are accreting, as they are supplied with sediments by the North-South and East-West drifts from adjacent coasts. Accretion rates lie between 0.31 and 0.84 m/year.[65] . This heavily exposed area was undeveloped up until the beginning of the 1960s at the onset of the tourist business. The natural situation is characterized by four areas that lead inland from the shoreline. The sandy beach is followed by the dune area, succeeded by a chott and then a sebkha. The beach had a width varying between 20 and 90 meters. The development of the Skanès tourist area has led to a drastic reduction in the width of the beaches and the dunes disappearing almost entirely in several places. The chott is characterized by a low topography with muddy soils and the presence of halophilic plants. The vast Sebkha of Skanès is strongly influenced by the climate. While it is flooded during the rainy season, its size is reduced significantly during the summer. Today, this coastal fringe has lost its original morphology due to intense urbanization. Since the construction of the Monastir-Skanès airport in 1968 about forty hotel complexes have been constructed and numerous traffic lines, like roads and railway tracks have been created. Numerous hotel complexes have been constructed all along the coast, which several buildings being located within less than 1 meter to the shoreline. Terraces and bars have been constructed on former dunes. APAL calculated the average width of the beaches in the area at less than 15 meters.[66] These developments have led to a weakened sediment budget in large parts of the coast of the area.[67]

[65] ARCHIPLAN (2017)
[66] APAL (2010)
[67] ARCHIPLAN (2017)

Between 1988 and 2000 the rates of erosion and accretion have increased. Erosion has intensified along the coasts of the western part of the bay, with rates between 0.43 and 2.30m/year. Sedimentation on the bottom of Dkhila Bay has accelerated where an advance of the shoreline 0.46m/year to 1.54m/year is observed. The increased erosion in the western sector can be related to the extension of the built-up area in the region. In the eastern part of Dkhila Bay, which is characterized by a wavy coastline, with alternating small bays and caps, the evolutionary trend is reversed compared with the period 1925-1988. The shoreline advances in the bays and behind the Skanès breakwaters, where as it recedes along the caps.

The comparison of the coastline between 2000 and 2016 indicates a slight slowing of coastal erosion in the western sector. The rate of retreat between 0.43 and 2.3 m/year between 1988 and 1996 decreases between 1996 and 2001, with values varying between 0.32 and 2.06 m/year. However, the bottom shore of the bay continues to advance but with a higher speed: 0.46 to 1.54 m/year, for the period 1988-1996 and 1 to 4.5 m/year between 2000 and 2016.[68]

Figure 15: Exposure Analysis, Part 5

At several location measures have been taken to protect the hotel areas (Figure 16.1). Currently, however several touristic structures are located very close to the shoreline that are not properly protected. As a result, these areas are highly exposed to coastal erosion. On various locations, structures like terraces and bars have been damaged by the water (Figure 16.2) and are highly exposed (Figure 16.3, Figure 16.4).

The “Domaine Public Maritime” (DPM) is a regulation by APAL which defines that within 25 meters of the shoreline the construction of buildings is prohibited. Despite the regulation, several structures have been constructed, which demonstrates a need for enhanced enforcement in order to ensure compliance with the DPM.

[68] ARCHIPLAN (2017)

Figure 16: Erosion Processes - Tourist area 1) Sea walls 2)-4) Affected infrastructure

5.7 Part 6

In the North-Eastern Area of the Coast the cliffs are characterized by alternating layers of clay and sandstone (Figure 17). Despite a certain degree of protection through the neighboring islands and shallow waters, coastal erosion has an effect on the area. The area is characterized by slumped material and toppled trees due to dissection by the forces of the waves. The roads that go along the coast in the south of Part 6 have been moved inland several times in the past. [69]

[69] APAL (2011)

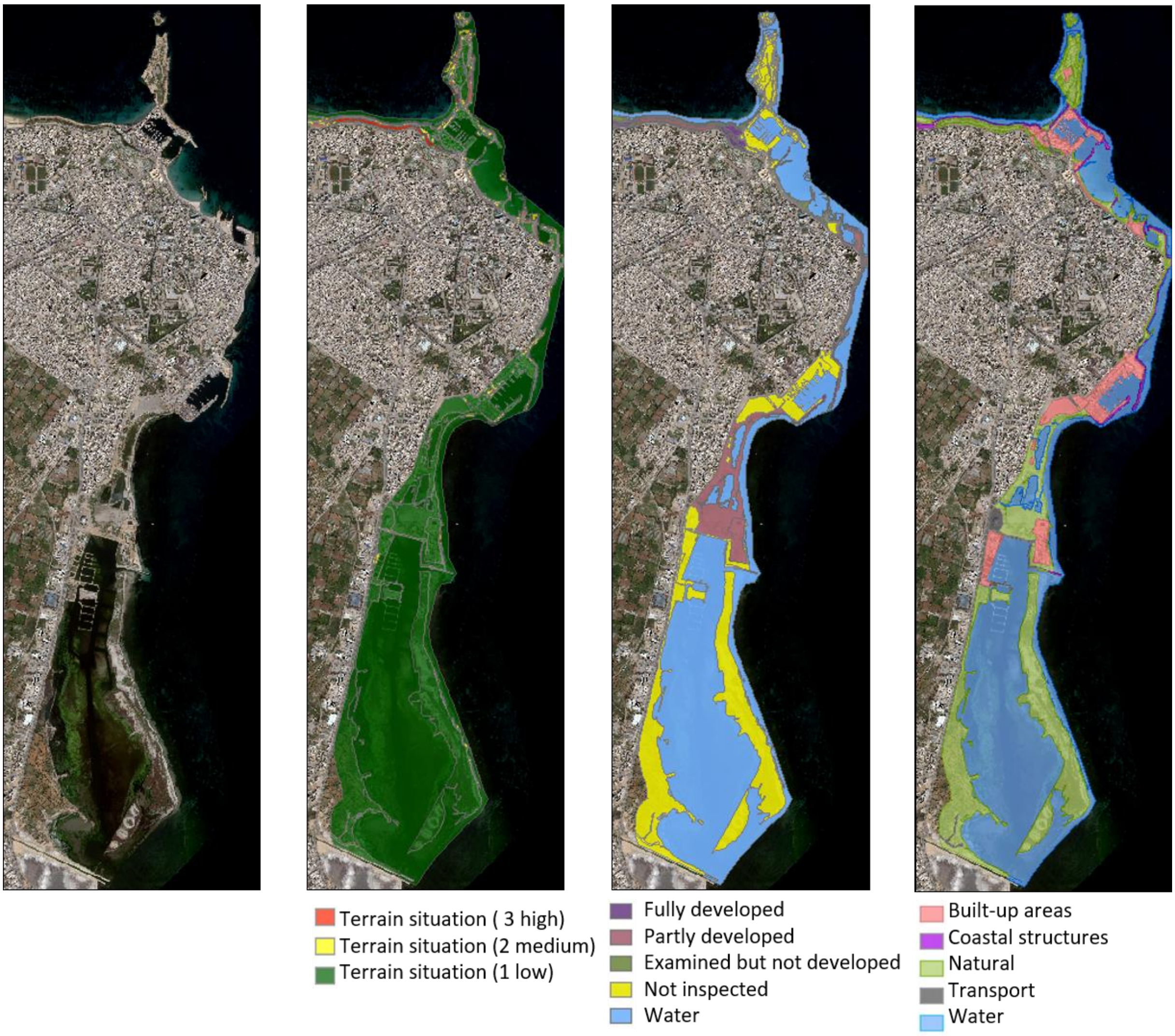

Figure 17: Exposure Analysis, Part 6

Several segments of the eastern coast of Monastir (Part 6) are protected by ripraps as can be seen in Figure 18.

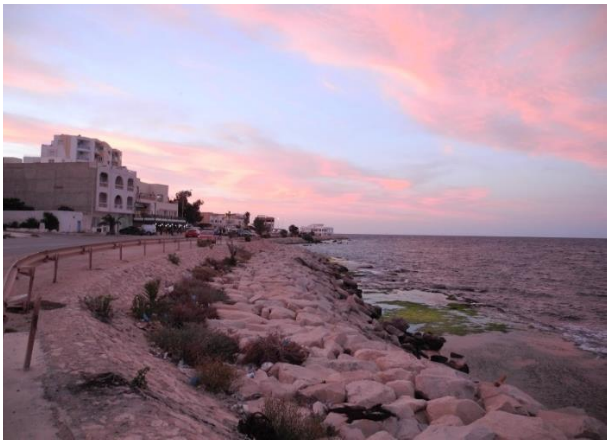

Figure 18: Ripraps in Part 6

5.8 Surface Runoff

During rainfall events, surface runoff becomes the main driver of erosion and has a major impact on cliff erosion on the Monastir coast. The superficial runoff is divided in two types. Firstly, the superficial runoff that comes from beyond the street that runs along the coast. The second type of runoff is the one that occurs between the said road and the ocean.[70]

A significant amount of water comes from external contribution through the watersheds of the area. (Figure 19). This external region covers an area of about 120 hectares spreading over 12 watersheds.

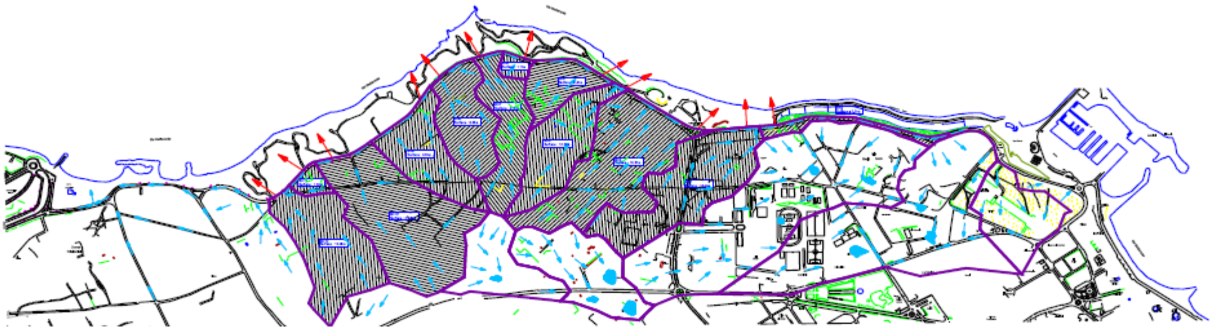

Figure 19: Boundary of watersheds running towards the coast

The drainage of the water is ensured through street gullies and openings in the curbs of the sidewalks, allowing a channelling of the water flow towards the cliffs. Through channels and pipes, the water is transported to the cliff. At the cliff itself, however, there are often not proper drainage system to channel the water into the ocean. This lack of adequate development downstream of the primary drainage structures leads to significant washouts and subsequent collapses at several points of the cliffs. Due to the lack of a secondary system, there is no continuity of superficial flows towards the sea. As a result, natural streams and ravines have formed, which have a negative effect on the stability of the cliff. This situation is an issue is especially apparent in Part 3 of the study area.

In addition to the above-mentioned external input, the cliff is also impacted from water influx that comes from internal drainage systems (Figure 20). They cover a total area of about 30 hectares and are subdivided into 38 elementary basins. Each basin comprises several small streams that contribute to varying degrees to the situation on site.

[70] APAL (2009)

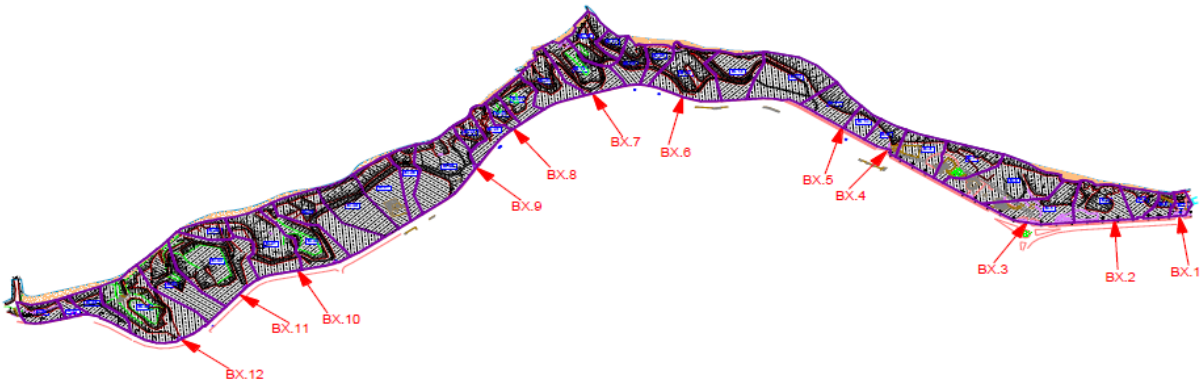

Figure 20: Direction of internal drainage channels to the coast

6. Conclusions and Outlook

In the course of the report a review of coastal erosion hazard in Monastir was conducted. A literature review of local studies has revealed that the shore of Monastir is highly affected by erosion. The main types of processes involve marine erosion through waves and storm surges as well as surface runoff during high intensity rainfall events. The rates of erosion are subject to spatial as well as temporal variations. Touristic activities have developed and expanded since the 1960s and led to enhanced building activities in the area. With accelerated development of the coast, more regions have become increasingly exposed to coastal erosion. Anthropogenic changes have furthermore caused an alteration in the natural processes.

Through these developments a need for adaptive measures has emerged. As a response to the erosion of sandy beaches, rock falls in the cliff areas and other erosional processes, protective measures have been constructed along the coast. “Hard” measures like riprap and groins offer a barrier against the forces of wind and waves. Drainage channels prevent surface erosion during high intensity rainfall events. Furthermore, “soft” measures like the planting of vegetation on the slopes along the coast provide further stability to the coastal area of Monastir.

Nevertheless, further action needs to be taken in order to prevent damages due to erosional processes. The coastline has been protected in Parts 1 and 2. Part 3 is currently not developed, but a project to implement adaptive measures are already in motion. Furthermore APAL is currently conducting studies to evaluate the current status of the beaches in Part 5 in order to plan future actions.

Presently unprotected areas have to be further examined regarding their exposure to erosion hazard and exposure. Especially Part 5 and Part 6 require further inspection in order to ensure the efficiency of current protective measures and to examine areas that have not been developed regarding their exposure to coastal erosion.

Existing protective infrastructure has to be monitored and maintained to ensure a proper function of the implemented measures. Even though protective measures have been taken in Part 2, their efficiency is drastically reduced, as the lack of vegetation cover on the slopes leads to soil erosion.

For future planning, climate change and its effects on the coastal environment has to be taken into account. With an increase in frequency and intensity of storm events, the coasts of Tunisia and Monastir in particular will be exposed to a further increase in coastal erosion.

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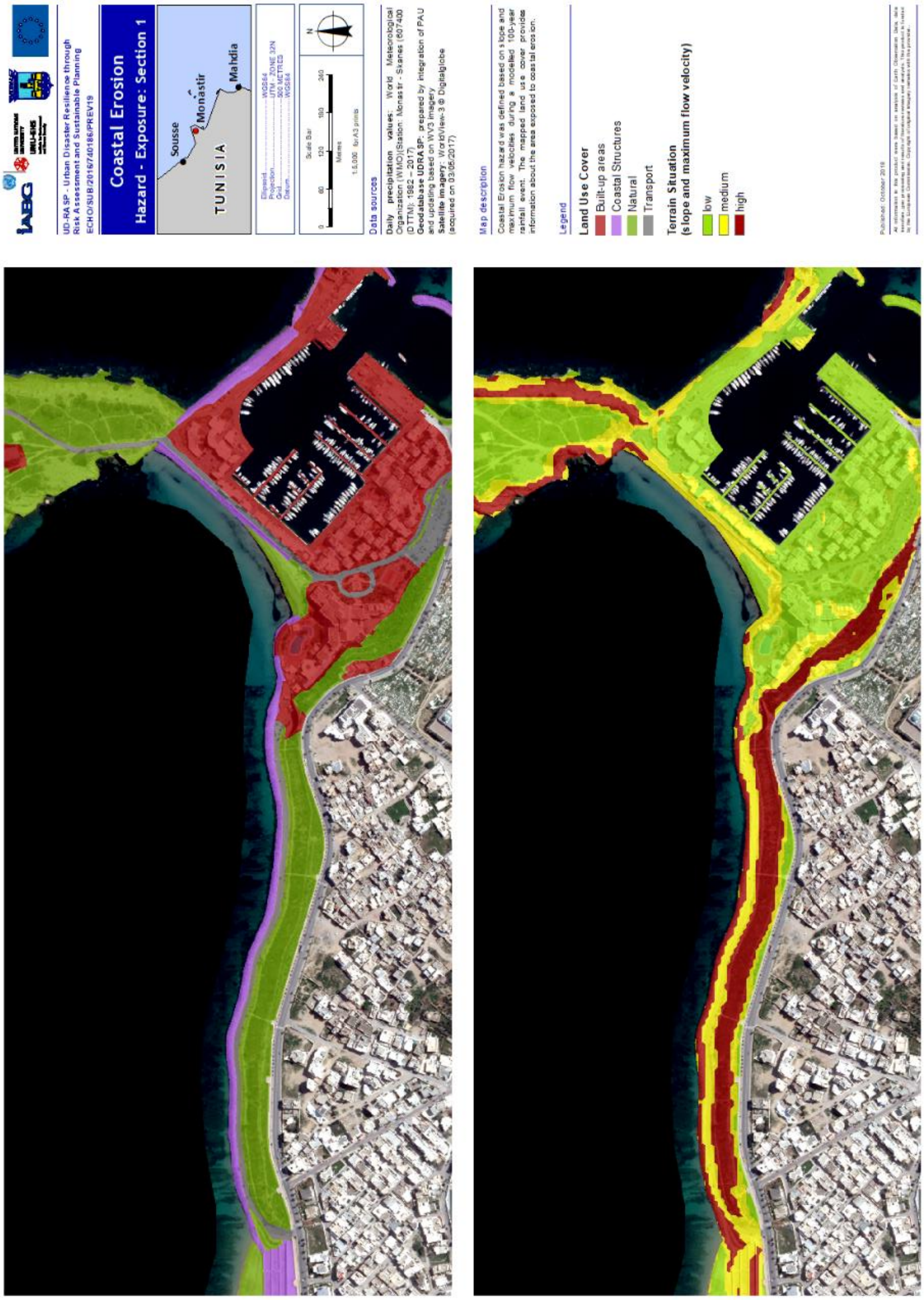
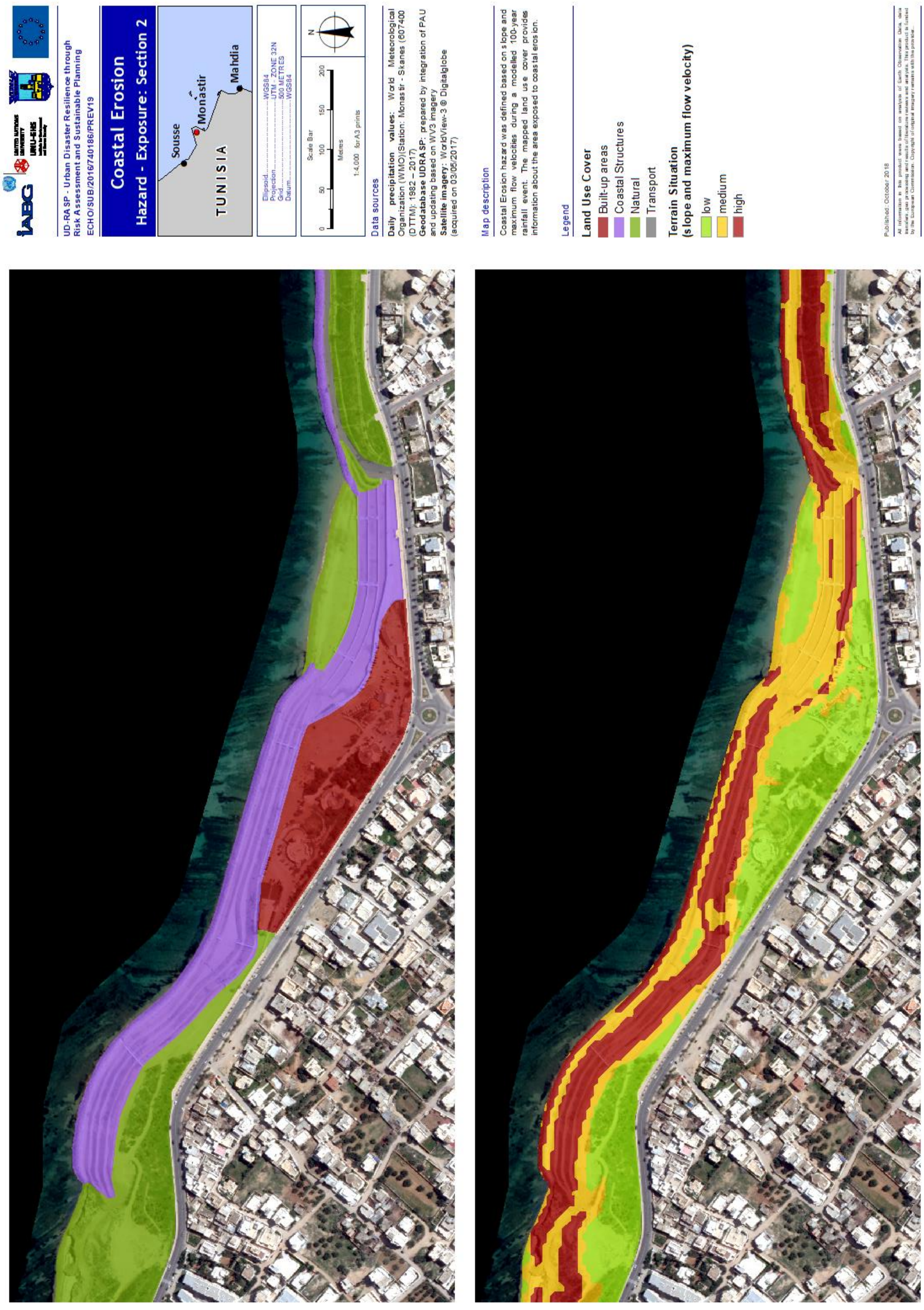
Annex – Maps "Coastal Erosion"

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Hazard - Exposure: Section 2
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Monastir
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Data sources
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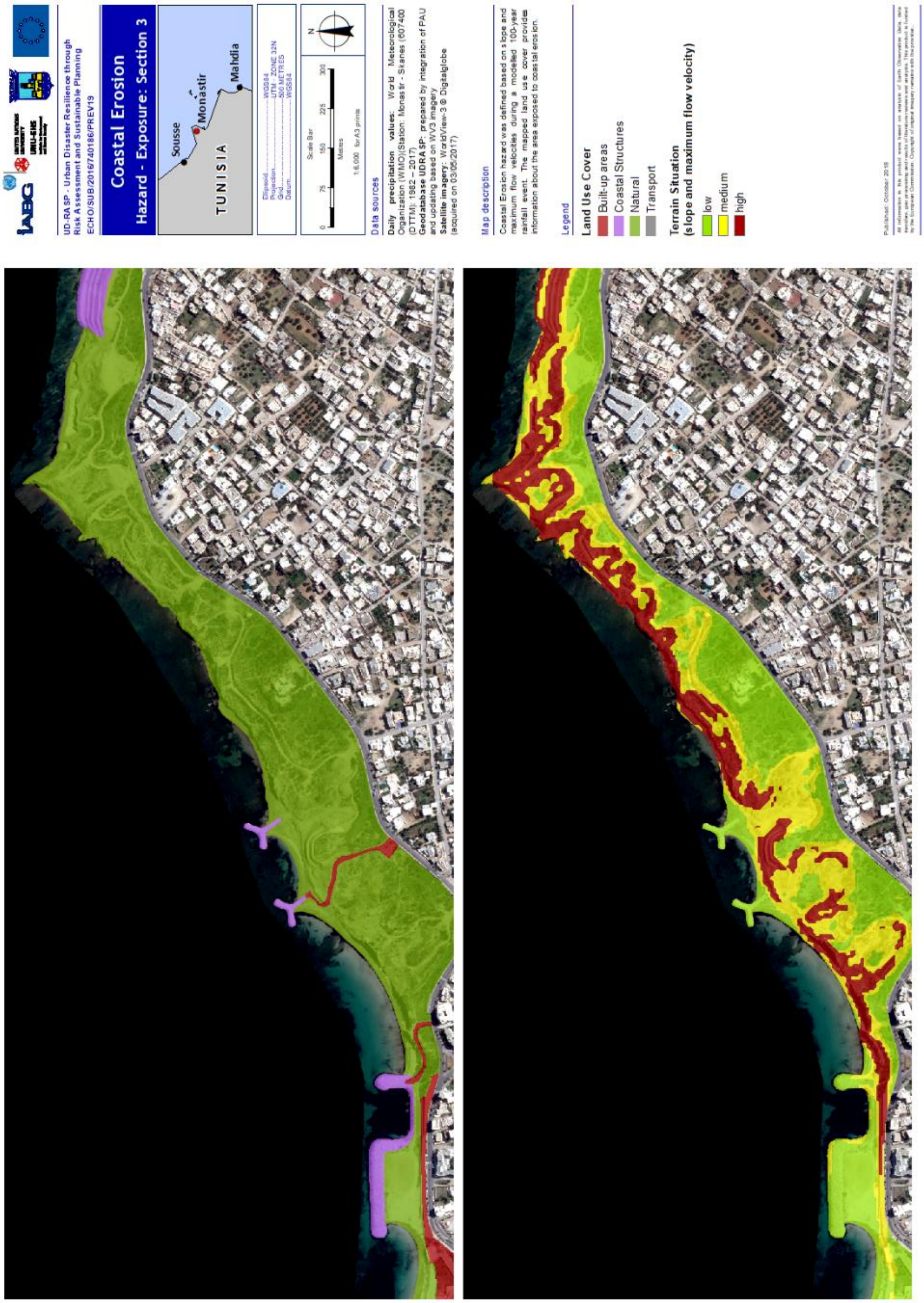
Geodatabase UDRASP: prepared by integration of PAU and updating based on WV3 imagery
Satellite imagery: WorldView-3 © Digitalglobe (acquired on 03/05/2017)
Map description
Coastal Erosion hazard was defined based on slope and maximum flow velocities during a modelled 100-year rainfall event. The mapped land use cover provides information about the area exposed to coastal erosion.
Legend
Land Use Cover
Built-up areas
Coastal Structures
Natural
Transport
Terrain Situation
(slope and maximum flow velocity)
low
medium
high
Published: October 2018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UD-RA SP - Urban Disaster Resilience through Risk Assessment and Sustainable Planning
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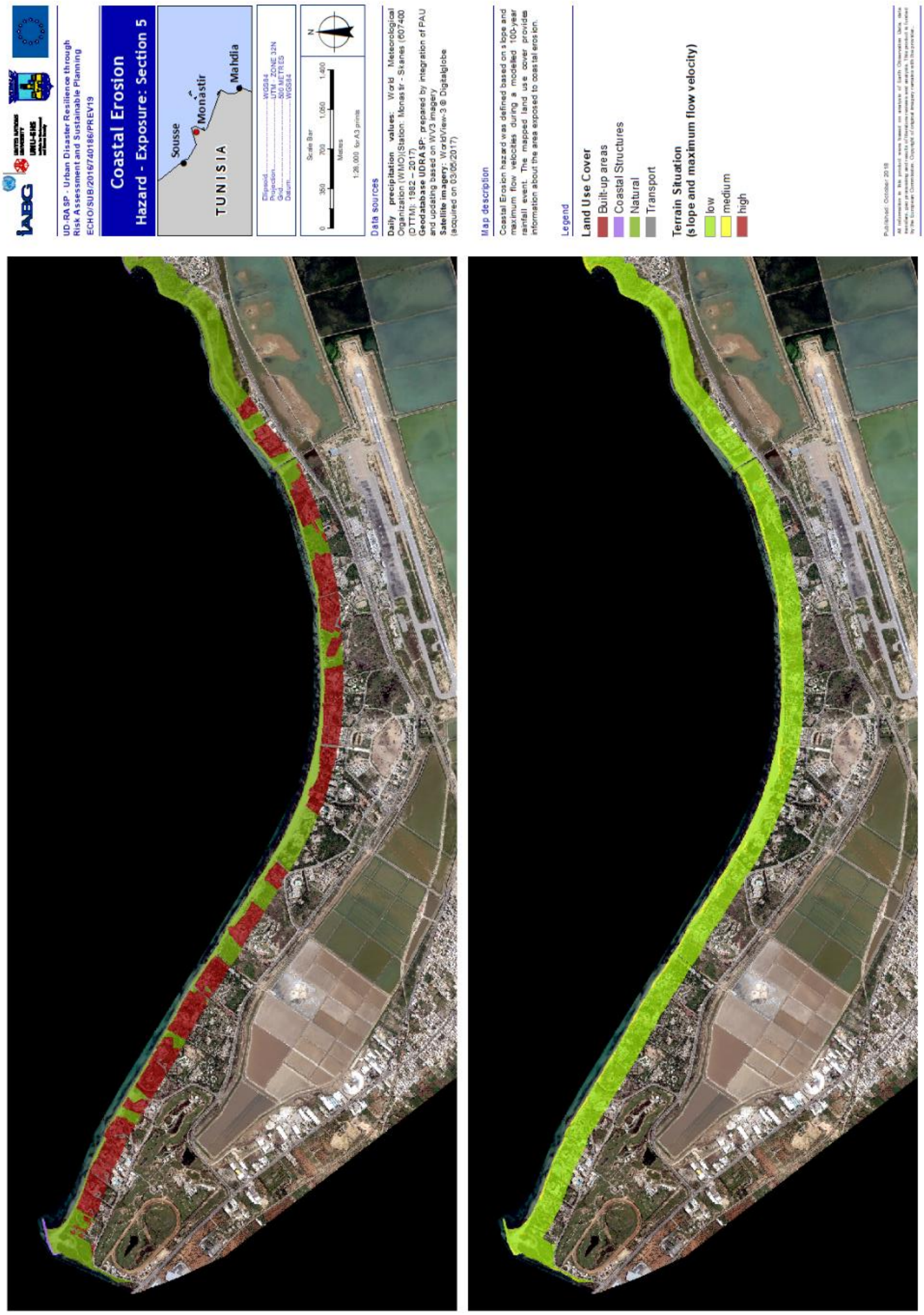
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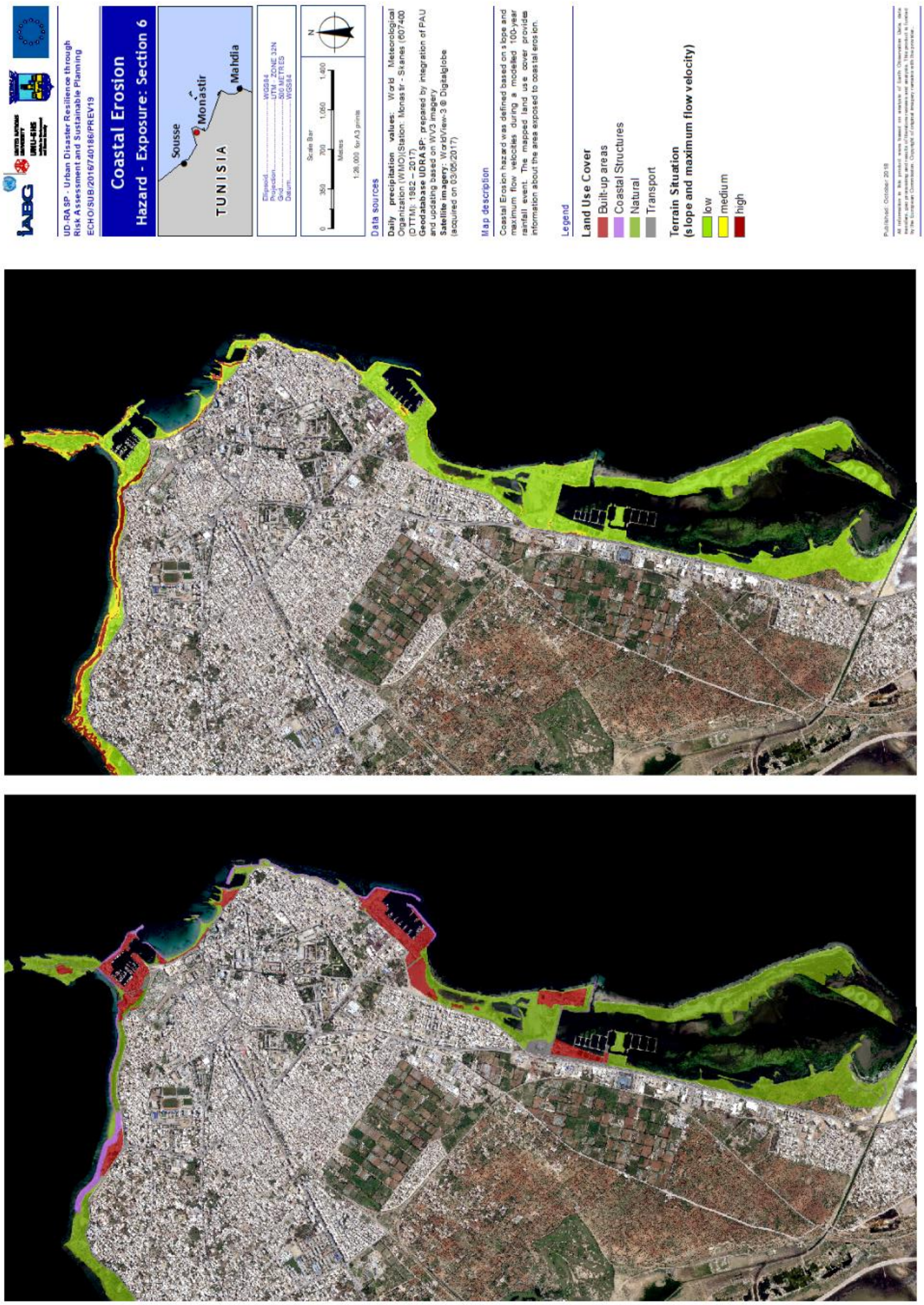
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