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IMPACTS OF ACCELERATED SEA LEVEL RISE ON THE COASTAL ZONES OF EGYPT

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Abstract

The coastal zones of Egypt are expected to be particularly vulnerable to the rise of the sea level in the Eastern Mediterranean. Depending on the scenario of sea level rise, a considerable share of the precious agricultural land in Egypt is threatened, likely to cause not only economic losses but also risks to the livelihoods of millions of inhabitants of the coastal zones and subsequently even possible dangers to the stability of the entire society. In this paper, we look at the risks imposed by sea level rise on the Egyptian coastal zones and assess the adaptive capacity of the affected society to address these issues adequately. This analysis is conducted in the context of an analytical framework that links climate change and its implications to societal stability and conflict via interactions with aspects of resource availability and individual wellbeing.

1 Introduction: Sea level rise and its extent in the 21st century

In addition to rising temperatures, changing precipitation patterns, and increasing frequencies of severe weather events, the rise of the global mean sea level is considered to be one of the most dangerous consequences of climate change. This aspect of climate change is of particular interest as already more than one tenth of the world’s population lives within 10 m elevation of the current sea level (McGranahan et al. 2007), which is potentially at risk of needing relocation as the sea level continues to rise. Furthermore, the tremendous rate at which coastal zones are developed also increases the vulnerability of these areas. To preserve the livelihoods of the inhabitants of the coastal areas and to protect the assets in these regions, it is necessary to have a profound understanding of the processes leading to sea level rise. This is important to effectively plan and manage adaptation options to deal with an increasing sea level.

The extent of sea level rise is influenced considerably by several factors. First of all, there is steric sea level rise, i.e. the thermal expansion of the oceans as a consequence of global warming. Another component is eustatic sea level rise due to the melting of glaciers and ice sheets in Greenland and the Antarctic which store vast amounts of fresh water (Jacob et al. 2012). Furthermore, there are other terrestrial sources of water such as high mountain glaciers and rivers. All these contributions taken together affect the relative sea level rise. In order to obtain estimates of the absolute sea level rise, the dynamics of ocean currents as well as the tectonic movement of the land arising from e.g. subsidence or uplift also have to be taken into consideration (Nicholls et al. 2011, Rahmstorf 2012). The latter contribution is referred to as isostatic sea level rise.

Simulations based on the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) have led to estimates of an increase in global mean sea level (Fig. 1) between 18 and 59 cm by the end of the 21^{st} century (Solomon et al. 2007). Considerable uncertainties arise because the extent of the contribution of the melting of the Antarctic and Greenland ice sheets is unclear. This factor may increase substantially in importance beyond a certain tipping point in global temperature increase (Church et al. 2010). Recent assessments of the development of the sea level indicate that the actual increase in sea level is likely to be much closer to the upper bound of the projections than to the lower bound (Rahmstorf et al. 2007, Schaeffer et al. 2012). Consequently, sea level rise is expected to become an increasingly urgent issue among the consequences of climate change.

However, there is substantial regional differentiation when it comes to the amount of sea level rise. It is the global average change of the sea level with regional variations due to the ocean dynamics (Stammer 2008) in combination with local land motion that actually determines whether a particular coastal zone is at risk. One of the regions that can be considered to be exceptionally vulnerable to the impacts of sea level rise is the Egyptian coast along the Eastern Mediterranean. This is because of an unfavorable combination of sea level rise and land movement in this region.

In this paper, we have a closer look at the impacts of sea level rise on this particular coastal region, which encompass ecological changes and land losses as well as the resulting economic and social implications. All of these interact in a complex way and consequently have to be considered jointly (c.f. figure in Scheffran et al. 2012a). In this context, we will also address the strategies and measures that already have been taken or need to be taken to counter the adverse impacts of sea level rise on Egypt.

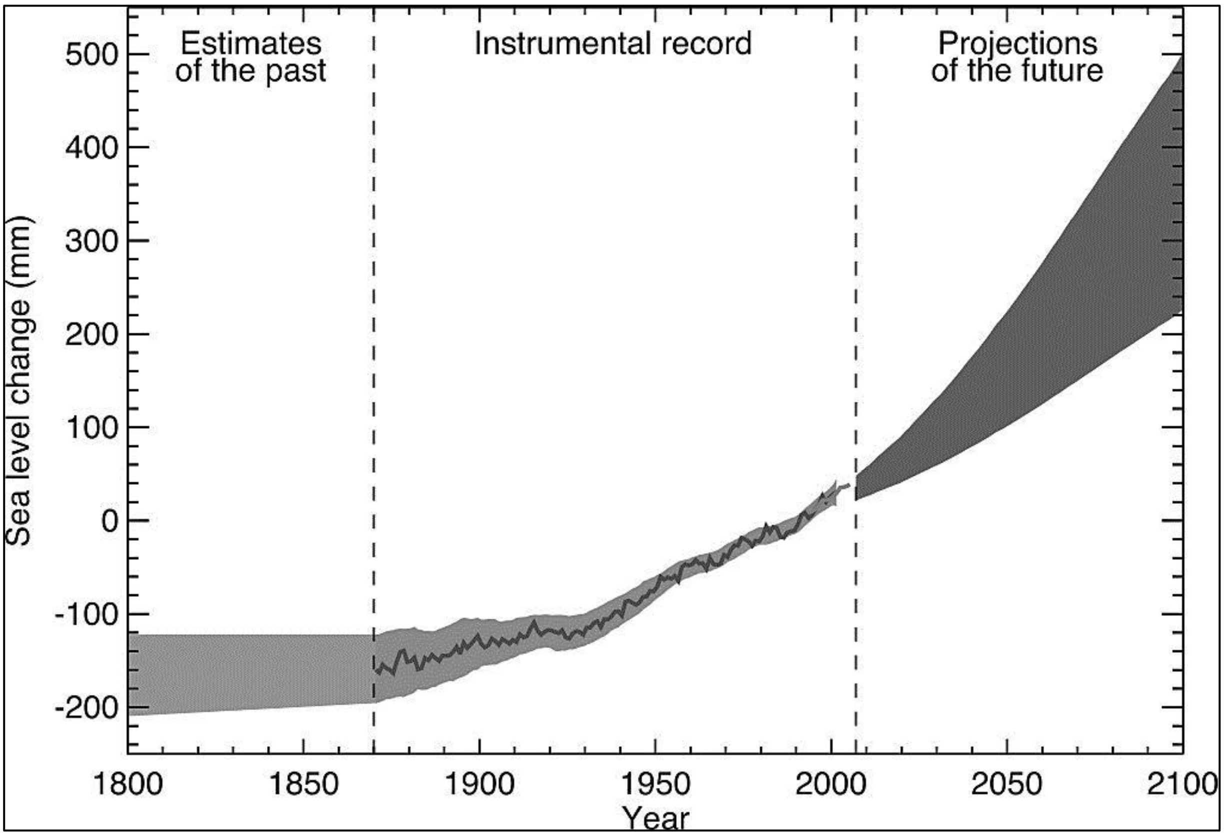

Fig. 1: Projections of global mean sea level change. The grey areas indicate the uncertainty in the long term estimates of the rate of sea level change. The line is a reconstruction based on measurements using tide gauges (Solomon et al. 2007).

2 The coastal areas of Egypt

The coasts of Egypt extend over more than 3500 km along the Eastern Mediterranean and the Red Sea. The Mediterranean coast of Egypt can be divided into four main subregions (Frihy and El-Sayed 2012): The northwest coastal sector extends from Sallum to Alexandria. It can be characterized as being particularly suitable for recreational activities and tourism. The Alexandria coastal sector extends further eastward from Hammam to Abu Qir. Then, the Nile Delta coastal sector extends all the way to Port Said in the East. The easternmost sector of the Mediterranean coast of Egypt is the North Sinai coastal sector, which extends from Port Said to Rafah. This sector consists of large dunes that reach considerable heights, thus naturally protecting the coastal area.

More than 40% of the Egyptian people live along the coastlines of the country, mostly in the Nile River Delta between Alexandria and Port Said (Elsharkawy et al. 2009). The shoreline of the Nile Delta itself is 275 km long and consists of several promontories that are separated by saddles and bays (Frihy 2003). There are three large lagoons that are separated from the sea.

Initially, seven branches of the Nile River formed the delta. By now, these have silted up and Nile water passes through two remaining branches, the Rosetta branch in the West and the Damietta branch in the East (ibid.).

The Egyptian coast along the Mediterranean is intensively used by the Egyptian people. There is considerable tourism infrastructure as the coastal zones of Egypt are the most popular tourism destinations in the country. Revenues from tourism amount to more than 11% of the Egyptian GDP (El Raey 2011). Furthermore, there is substantial agricultural use of the flat land in the Nile Delta for food production and of the lakes and lagoons for fisheries, the latter providing more than 60% of the total catch of Egyptian fishermen (ibid.).

Even though the area of the Nile Delta amounts to only four per cent of the entire land area of Egypt, this region contributes more than one third of Egypt's agricultural production and almost two thirds of the country's fisheries' output (Frihy 2003). To add to the value of this costal land, the Nile Delta is one of the few regions of Egypt in which large scale agricultural production is possible at all.

In the recent past, the Nile Delta has experienced considerable changes in environmental conditions. Some of them have been of natural, some of anthropogenic origin (Becker and Sultan 2009, Syvitski et al. 2009). For instance, there is erosion along the delta coast (El Banna and Frihy 2009, Frihy et al. 2008) and the drying up of wetlands (El-Asmar and Hereher 2011), which occurs by expansions of agricultural production areas. Furthermore, there are considerable human-induced changes to the coastal geomorphology in the region of the Nile Delta. Land reclamation projects have added several hundreds of square kilometers of agricultural land (El Banna and Frihy 2009), and previously unproductive land has been converted into fish farms, considerably increasing the economic output in this part of the country. These changes increase the vulnerability of the coastal zone with regard to sea level rise because natural protection is removed and the likelihood of subsidence of the land is thus increased. Therefore, protective measures become more and more important in order to avoid loss of land due to inundation even at moderate rates of sea level rise.

In this context, it has to be noted that the regional implications of sea level rise for the Egyptian coast vary depending on the geographic location. Assessments of historic records indicate that there is a continuous relative increase in sea level irrespective of changing climatic conditions that fluctuates between 1.8 and 4.9 mm/a (Frihy et al. 2010). The highest rates generally occur near the Rosetta promontory while there is less sea level rise near the harbor of

Alexandria. These differences can be attributed to the local tectonic settings. Recent measurements at the tide gauge station in Alexandria using global positioning systems (GPS) yield a relative sea level rise of 1.7 mm/a (Shaker et al. 2011). Taking into account tectonic settling of the area at the rate of -0.47 mm/a, the measurement-based estimate of absolute sea level rise at the northwest Mediterranean coast of Egypt is almost 2.2 mm/a (ibid.). This corresponds well with tidal gauge measurements at different sites that indicate an increase in water level in the past decades between 1.0 mm/a in Burullus and 2.3 mm/a in Port Said (Frihy 2003).

Nonetheless, these current rates of eustatic sea level rise that have been measured do not yet pose a threat to the Nile Delta (Hereher 2010). There are coastal sand dunes, ridges and elevated strips along the coast that serve as initial barriers. Furthermore, there are already active coastal protection measures such as seawalls and the elevated design of the international coastal highway that protect the delta against the sea. On the other hand, there are processes that lead to the submergence of parts of the delta. These include the removal of coastal dunes and subsidence from water pumping from fossil aquifers, which can reach up to 5 mm/a (Stanley 1998) and occur because of tectonics and sediment compaction.

Such land subsidence, which shows the highest rates in the area of Alexandria, is an important issue. In addition to coseismic subsidence, which mainly occurs in non-continuous fashion after e.g. earthquakes, the influence of aseismic land subsidence, which occurs as a consequence of soil compaction and water withdrawal from aquifers, plays a considerable role in this region. Subsidence of the coastal regions of Egypt has been accounted for in the past. Subsidence after major tectonic activity has already been confirmed in the fourth century A.D. (Frihy 2003). In combination with the low elevations and flat character of large parts of the coastal areas along the Mediterranean coast of Egypt, subsidence can pose considerable problems should the sea level continue to rise. Assessments with digital elevation models indicate that almost 20% of the Nile River Delta already lies below the mean sea level (Hereher 2010) and that another 25% lies below an elevation of 2 m. These include drained lagoons that are now agriculturally used. All of these areas are prone to flooding if the sea level rose as projected.

Because of the diverse use of the coastal zones of Egypt, it is already necessary to protect the coast against the current moderate increase in sea level. However, there would be widespread consequences if the sea level rose at a considerably higher rate in the Eastern Mediterranean as this would pose an additional burden on the protective measures that may overstretch the adaptive capacity of the Egyptian society. Such impacts are not only confined to land losses through inundation and erosion but also affect the population of this area in many direct and indirect ways.

3 Ecological and economic consequences of accelerated sea level rise in Egypt

When looking at the implications of sea level rise for the Egyptian coastal zones, it is important to note that it is a combination of several factors that contribute to the vulnerability of the regions. Of course, one key factor is the extent of increase in the sea level due to changing climatic conditions (Frihy 2003). But additionally, the tectonic setting of the individual parts of the coastline also has to be addressed: does the land subside or does it currently emerge? And how do human activities influence the local development of the coastal zones as large scale removal of water from ground water aquifers contributes significantly to land subsidence? Furthermore, short term meteorological events such as storm surges also have an impact on the coastal zones that should not be disregarded.

Assessments of the vulnerability of the Mediterranean coastline of Egypt that take into account a combination of the factors mentioned above indicate that approximately 30% are considered to be vulnerable to sea level rise (Frihy, 2003). These areas mainly consist of narrow natural sand barriers, the low and flat coastal plain and some low-lying beaches consisting of very fine sand. In contrast, about 55% of the coast is naturally protected and thus fairly safe from sea level rise. The remaining part of the coast (15%) is artificially protected and continuously needs to be protected this way to maintain the integrity of the Egyptian Mediterranean coast (ibid.).

A vulnerability ranking of the different geographic sectors of the Egyptian Mediterranean coast indicates that in the northwestern coastal sector, the low-lying beaches are particularly vulnerable to sea level rise (Tab. 1, Frihy and El-Sayed 2012). The same holds for the region of Alexandria. In the Nile Delta region, also the coastal lagoon barriers are extremely vulnerable. All these are subject to subsidence or high rates of coastal erosion. The moderately vulnerable zones are naturally protected, whereas the artificially protected areas can be considered to now have a low vulnerability to the current rate of sea level rise.

When the sea level rises, increased storm surges become a more prominent threat to the coastal areas. An assessment of the impacts of these climate change impacts indicates that the area of the coastal zones in Egypt affected by storm surges would almost double as a consequence of higher storm surge intensity (Dasgupta et al. 2009b). More than 2.6 million people would then be additionally affected by increased inundation, with an emphasis on the region around Port Said, the urban area that is considered to be the most adversely affected city in the Mediterranean North African region with respect to the consequences of sea level rise (Elsharkawy et al. 2009).

Tab. 1: Vulnerabilities of the Egyptian Mediterranean coasts with regard to sea level rise (adapted from Frihy and El-Sayed 2012)

sector	**vulnerability**
Northwest coast: coastal plain	vulnerable only in extreme events or safe
Northwest coast: low-lying beaches	highly vulnerable
Alexandria: coastal plain	vulnerable only in extreme events or safe
Alexandria: low land	vulnerable only in extreme events
Alexandria: low-lying beaches	highly vulnerable
Nile Delta: around Rosetta extension	moderately or hardly vulnerable
Nile Delta: west of Damietta port	moderately or hardly vulnerable
Nile Delta: coastal lagoon barrier	highly or moderately vulnerable
Nile Delta: sand dunes	safe
Nile Delta: accretional beaches	safe
Nile Delta: low-lying beaches	highly vulnerable
North Sinai: coastal plain	vulnerable only in extreme events or safe
North Sinai: Bardawil Lagoon	hardly vulnerable
North Sinai: flash flood drains	vulnerable only in extreme events
North Sinai: low-lying beaches	highly vulnerable

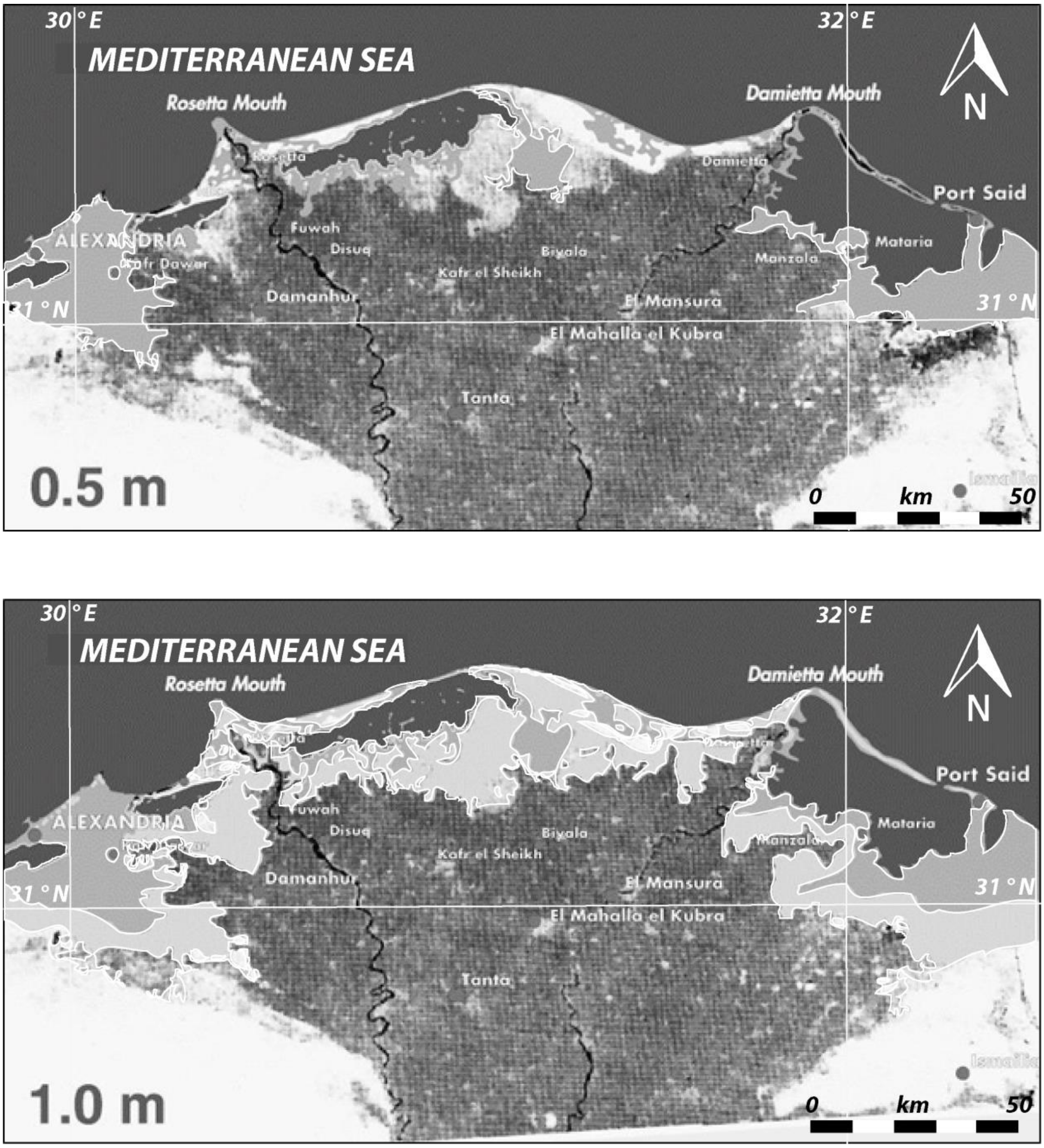

Fig. 2: The land areas in the Nile Delta that would be flooded if the sea level rose by 0.5 m and by 1.0 m (FitzGerald et al., 2008): The Mediterranean is shown in dark grey, the areas affected by an increase in sea level of 0.5 m are shown in medium grey, and the areas affected by a sea level rise of 1.0 m are shown in light grey.

In addition to the impacts of more extensive extreme events, inundation of the flat and low-lying coastal land is the prime danger arising from sea level rise. Simulation results indicate that the Nile River Delta is one of the regions that would be most affected worldwide by a rise in sea level of one meter (Dasgupta et al. 2011). Vast areas of the directly exposed parts of the coastal zone would be flooded. If the sea level only rose by 0.5 m, more than 1800 km^2 of agricultural land would be lost (Fig. 2), affecting approximately 3.8 million people

(FitzGerald et al., 2008). If the sea level rose by 1 m, the number of people that would need to leave their land would increase to more than 6 million (Dasgupta et al. 2009a), as approximately 4500 km^2 of land become uninhabitable. But because of the heterogeneous terrain in the Nile Delta, not the entire plain is affected by sea level rise in the same way. However, continued sea level rise also increases the risk of coastal erosion and saltwater intrusion, which are the other key impacts in addition to direct land losses (Frihy et al. 2010).

Salt water intrusion into ground water aquifers is a severe problem particularly in those areas of the coastal zones, which have an elevation that is only slightly above the current sea level. Model simulations suggest that an increase in sea level by 0.5 m leads to an intrusion of salt water into the Nile Delta aquifers, which could reach up to nine kilometers inland (Sherif and Singh 1999). Recent studies have confirmed this order of magnitude (Werner and Simmons 2009). Degeneration of fresh water sources over such a large area is likely to have a substantial negative impact on agricultural production in this area. Additionally, this implies a considerable challenge to provide the large number of Egyptians that live in the coastal zones with adequate amounts of clean potable water. Should it become impossible to sustain the population currently living near the Egyptian coasts, large numbers of coastal inhabitants would need to migrate into other parts of the country.

However, the most direct economic impacts of sea level rise on Egypt arise from losses of agricultural land due to inundation. Depending on the extent of losses of agricultural land in the Nile Delta, the economic consequences can vary considerably. If only the northernmost coastal areas in the Nile Delta are affected, the economic impact may remain limited (Frihy and El-Sayed 2012). But for a more pronounced sea level rise, the effects may become particularly devastating to the Egyptian economy since the Nile Delta is one of the few parts of the country that can be used for large scale agricultural production. Although coastal lagoons are expected to be able to adjust to salinity changes in environmental boundary conditions (Frihy 2003), declines in fish catches in the lakes and lagoons in northern Egypt are likely, which in turn leads to the abandonment of the fisheries by many fishermen and the subsequent decline in Egyptian GDP (Elsharkawy et al. 2009).

Assessments of the economic consequences of sea level rise highlight the necessity of artificial coastal protection in Egypt on a large scale because even the economic losses incurred by an increase in sea level by only 0.5 m without any adaptation measures would be considerable. More than 1.5 million people only in the vicinity of the city of Alexandria would have to be relocated (El

Raey 1997). The damage to land and infrastructure, e.g. due to the abandonment of the harbor of Alexandria would amount to more than 30 billion US-Dollars (ibid.).

But even with considerable artificial protection, the Egyptian economy would be seriously affected by an extensive rise in sea level (Dasgupta et al. 2011). If the sea level rose by one meter, the gross domestic product would decline by almost 6.5% with the agricultural sector being hit disproportionally strong with a decline by 12.5% (ibid.). Such a development is a direct threat to food security for the rapidly growing population, as the needs for fundamental food crops could be fulfilled to a far lesser degree than at present.

However, agriculture and fisheries are not the only economic sectors that would be adversely affected by sea level rise. Particularly the western part of the Mediterranean coast of Egypt has experienced a considerable development of tourism infrastructure and recreational activities. Assessments indicate that sea level rise is likely to cause local erosion and inundation of sandy beaches, which would have negative implications for the affected resorts and tourist destinations (Frihy and El-Sayed 2012). These impacts can be expected to be very serious although no assessments quantifying these consequences have been carried out yet. Similarly, there are possible impacts of sea level rise on oil and gas exploration in the Nile Delta, on road infrastructure (e.g. the coastal road from Rafah to Matruh), and on coastal ecosystems and wetlands. As with the impacts on tourism, impacts on all the latter sectors have, until now, only been assessed qualitatively.

4 Impacts on societal stability

Sea level is just one of several environmental factors that may be altered considerably by climate change. In combination with other factors of climate change, it may have strong long-term impacts on the most downstream country of the Nile. A reduction in the amount of agricultural land available for food production and a decline in fresh water availability can force large numbers of people living in the coastal areas of Egypt to migrate to other parts of the country. Such a development may increase the conflict potential within the Egyptian population and thus contribute to a destabilization of the society as a whole.

But due to their different environmental characteristics, there needs to be a differentiation of the risks among the different coastal zones of Egypt. A qualitative assessment of the risks with regard to the consequences of sea level rise indicates that there are definite geographical differences (Tab. 2). The Nile

Delta region faces the highest risks, and in all coastal sectors the economic risks from sea level rise are more prominent than the ecological risks or the direct risks for the population. Despite the relatively low effectiveness of coastal protection, it appears to be adequate for the current sea level (Frihy and El-Sayed 2012). However, protective structures have to be maintained and even improved if the sea level rise accelerates. This requires substantial financial investments that may no longer be available if the country is affected by the combination of several climate change impacts such as increasing temperatures, less precipitation in conjunction with a higher sea level and a possible increase in the frequency of storms.

Tab. 2: Risks with regard to sea level rise for different sectors of the Egyptian Mediterranean coasts (adapted from Frihy and El-Sayed 2012)

	population	**economy**	**environment**	**effectiveness of protection**
Northwest coast	low risk	moderate risk	low risk	low
Alexandria	moderate risk	high risk	moderate risk	moderate
Nile Delta	moderate risk	high risk	high risk	moderate
North Sinai	low risk	moderate risk	low risk	low

The impacts of climate change affect many parts of the society and cause a multitude of responses. Some of them lead to increased cooperation and some may cause conflicts, possibly even violent conflicts (Link et al. 2012). These responses do not follow a simple pattern that can directly relate the occurrence of conflict to a particular change in environmental conditions. Instead, these responses are the result of the influence of the environment on the individuals living in the coastal zones of Egypt who then act and also interact with each other. These interactions between the various actors in the Nile River Basin and in this case particularly in Egypt are the basis of a model that has been developed at the Research Group Climate Change and Security (*CLISEC*) at the University of Hamburg (Scheffran et al. 2012b). It looks at the consequences of (climate change induced) environmental change for societal stability and considers the complex interactions between climate change, environmental impacts, resource availability, individual human wellbeing and societal stability (see Fig. 3).

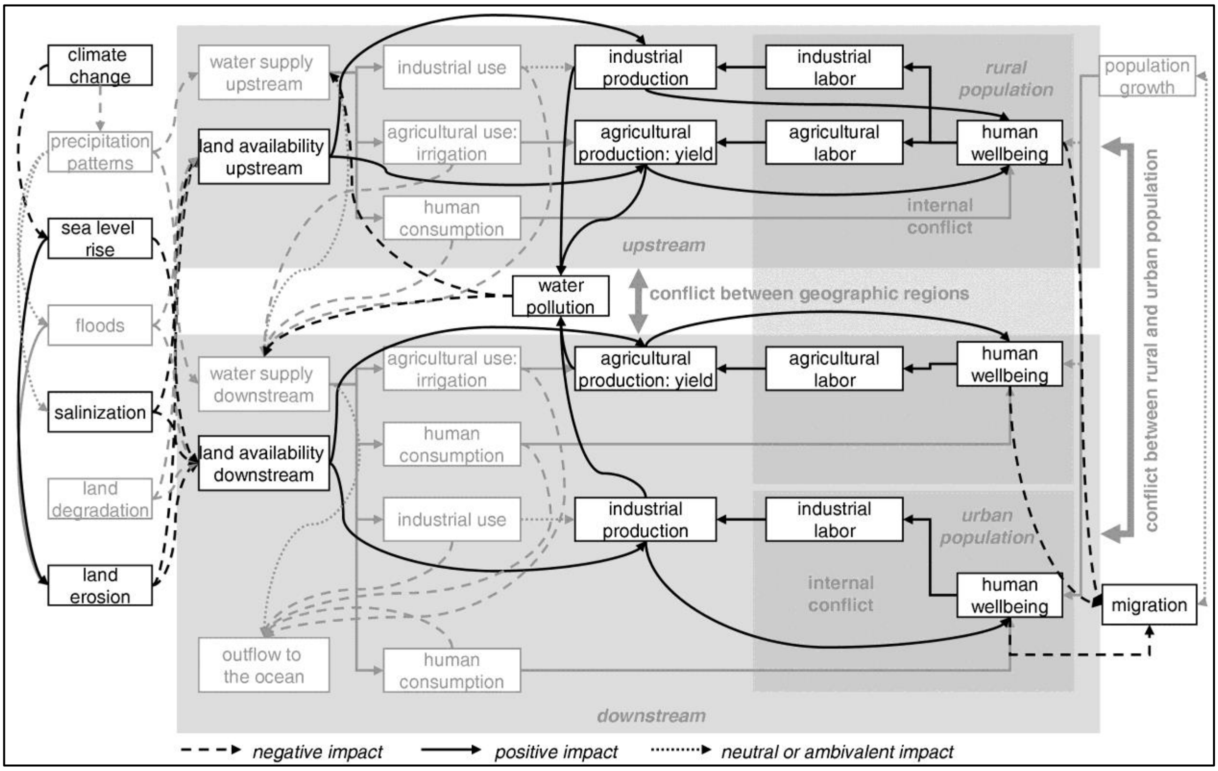

Fig. 3: Schematic representation of the interactions between actors and issues in the Nile River Basin in times of climate change with a particular focus on the impacts of sea level rise (adapted from Scheffran et al. 2012b).

Sea level rise is one of the factors directly influenced by climate change that has to be considered in this context as it aggravates the already difficult situation to adequately supply the Egyptian population with fundamental resources such as drinking water and fundamental crops. In the model framework, a combination of sea level rise, salinization of water resources, and land erosion affects the coastal zones of Egypt. This affects land availability, mainly in the far downstream part of the Nile in the Nile Delta but also to a lesser extent in the eastern part of Egypt along the Red Sea coast. Land availability has an influence on agricultural and industrial production and also affects value added from tourism. Human wellbeing declines because of reduced economic revenues, which in turn further reduces the number of jobs available. Consequently, there is a self-reinforcing feedback loop back to economic output. Reduced job availability triggers out-migration into the other (presumably less affected) parts of the country, possibly upsetting the stability of the social systems and causing unrest and conflict.

More detailed assessments of the particular implications of sea level rise on the coastal zones of Egypt and their societal consequences are subject of future research to support this qualitative framework with results of quantitative model simulations. But the already existing results of initial assessments of the impacts of sea level rise on the Egyptian coastal zones indicate that large scale coastal protection is mandatory if the worst impacts, particularly due to inundation of the sea, are to be avoided.

5 Strategies to deal with sea level rise

There are already a number of measures taken to protect the Egyptian coast against the consequences of sea level rise. Already, more than US$ 300 million have been spent to install sea walls along the most severely threatened parts of the coast (Elsharkawy et al. 2009). In some parts of the coast it is possible to rely on natural features with an elevation that is high enough to serve as protection (Frihy and El-Sayed 2012). These include extensive sand dunes and ridges that run parallel to the shoreline. They are complemented by artificial structures such as seawalls or breakwaters. In particular, the outer parts of the promontories where the Nile River meets the sea are protected by seawalls. In these areas, erosion has declined considerably near the seawalls or has in some instances even changed to sand accumulation (Frihy et al. 2003). However, in the areas adjacent to these protective structures erosion has intensified in the downstream direction of the seawalls.

Prior to the Arab Spring in 2011, the Egyptian government had also started protecting the areas at risk by establishing new environmental regulations (Elsharkawy et al. 2009). First efforts to reduce the adverse impacts of sea level rise on water resources by implementing a National Improvement Plan are supposed to reach their targets by 2017. However, these plans have been criticized for mainly protecting tourism infrastructure. A more comprehensive protection plan would need to include stronger monitoring efforts and better enforcement of the measures. This includes the establishment of an Integrated Coastal Zone Management Committee and the improvement of community awareness of the risks of climate change to the coastal zones.

6 Conclusion

The current political situation in Egypt could prove to be a real problem when it comes to coastal protection. Assessments of the adaptive measures that have already been implemented indicate that these are currently insufficient to adequately prepare the Egyptian coastal zones for a future increase in sea level rise (Dasgupta et al. 2009a). But in times of political turmoil and power changing hands, environmental protection often takes a back seat in comparison to individual rights and economic considerations of many. It is not clear how the importance of coastal protection will rank among the priorities of the many problems that need to be addressed by the new Egyptian administration in the coming years. Furthermore, it is not easy to implement plans for coastal protection as they require joint actions by all administrative levels in the country and a substantial increase in awareness of the expected problems that will arise in conjunction with sea level rise.

So, despite the efforts to protect the Egyptian coasts against the impacts of sea level rise, particularly the coast along the Nile Delta is only protected in a very fragmented manner (Malm 2012). This is mainly due to the limited resources available in Egypt to invest into adaptation measures to climate change and the fact that some tourism developments directly on the edge of the sea need particular protection. The protective measures for this infrastructure consume the majority of the available resources as considerable economic assets would be lost if these tourism resorts were abandoned. However, it is unlikely that coastal protection in Egypt can be successful if the prioritization in protection projects remains unaltered. If Egypt aims at successfully adapting to the consequences of sea level rise, it needs to abandon the business-as-usual protection strategies of the coasts and to implement a “revolutionary sea wall” (Malm, 2012: 23) that includes the raising of public awareness and public participation which includes the whole society.

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