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Coastal adaptation to Sea Level Rise: An overview of Egypt's efforts

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ABSTRACT

Coastal zones are recognized as priority areas for climate change adaptation. Without robust and effective adaptation, numerous coastal zones will be drastically affected. There is an ongoing need for coastal adaptation particularly, for the low-lying deltas, which are highly vulnerable to the coastal hazards-based Sea Level Rise (SLR). Worldwide, the national coastal strategies mainly focusing on the three coastal adaptation approaches issued by the International Panel of Climate Change (retreat, accommodation, and protection). The developed and developing countries are being made serious efforts to adapt to the SLR. This paper investigates the Egyptian efforts, best practices, and experiences in dealing with coastal erosion, flooding, and inundation-based SLR. The Egyptian national strategy for coastal adaptation mainly adopted the protection approach. Along the Nile Delta coast of Egypt, various national projects contain coastal adaptation measures were detected, such as seawalls, revetments, sand dunes, nourishment, and artificial sand dunes based on a geotextile sand-tube core using natural reed mats for sand trapping. In addition, different actions such as constructing modern fish farming, regular dredging for coastal lakes and lagoons, and enforcing the coastal road were observed. All provide defense systems. Most of these promising adaptation technologies, efforts, and actions show favorable responses to guarantee adequate protection against SLR hazards.

1. Introduction

Coastal regions represent an interface space between water and land areas. Typically, coastal regions are densely populated and have a highly dynamic natural environment (Linham and Nicholls, 2012). Among the climate change impacts, Sea Level Rise (SLR), storm surges, and high waves were categorized as worldwide issues threatening coastal cities and communities, particularly the low-lying deltas (Pachauri and Rajendra, 2007; Fatorić and Chelleri, 2012). The typical physical impacts of SLR in the coastal zones include coastal erosion, inundation, coastal flooding, saltwater intrusion and rising of groundwater tables, and biological effects that could pose potential threats to the countries respecting the socio-economic aspects (Fatorić and Chelleri, 2012; Pachauri et al., 2014). Due to SLR, many coastal areas could be inundated, and the shorelines could be eroded and retreated. Also, the land subsidence could accelerate and exacerbate that matter. Additionally, the coastal squeeze is one of the widely observed consequences of shoreline retreats based on SLR (Zhu et al., 2010).

Coastal zones are identified as priority areas for climate change adaptation. Without robust and effective adaptation, numerous coastal zones will be drastically affected. Mitigation measures refer to the implemented efforts to minimize greenhouse gas emissions, considered the primary driven source of climate change. In contrast, adaptation measures refer to the applied actions, skills, techniques, plans, and technologies that could limit the impacts of climate change and relevant coastal hazards (Pielke, 1998; Baills et al., 2020). Subsequently, the developed and developing countries seek to formulate coastal adaptation plans and strategies which could diminish losses caused by SLR (Gibbs, 2015). Coastal adaptation to SLR should be integrated with contemporary and future development plans for the coastal areas. Hence, the Integrated Coastal Zone Management (ICZM) is extensively categorized as the most appropriate iterative process to deal with coastal issues and promote sustainable coastal management (El-Raey et al., 1999; Nicholls et al., 2007). For instance, ICZM covers coastal-environment data collection, planning, analyzing, issuing policies, and tools for coastal adaptation to SLR (Eldeberky, 2016).

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The Intergovernmental Panel on Climate Change (IPCC) had classified the coastal adaptation strategies into three classes, retreat, accommodation, and protection (Stocker et al., 2014). Retreat strategy allows shoreline and coastal-land areas to migrate inland in a managed manner due to the natural coastal system effects. Accommodation strategy depends on keeping the coastal areas vulnerable to SLR threats and the natural impacts, synchronously improving preparedness, proper resistance, and adjustment against different hazards should be considered. Protection strategy refers to the enforcement of the coastal areas via a defensive approach using coastal adaptation structures to shelter the coastal regions from beach retreat, inundation, flooding, storms, etc. (Linham and Nicholls, 2012; Pachauri et al., 2014; Eldeberky, 2016).

Regarding social considerations, many residents opt to stay and adapt rather than emigrate (Buchori et al., 2018; Esteban et al., 2020; Gibbs, 2020). Others believe that many implemented coastal adaptation strategies remain ineffective and inadequate to deal with the SLR issues (Odafivwotu, 2018). Coastal adaptation technologies in terms of rigid structures were the most widespread and globally applied technology. The developed countries emphasized the coastal adaptation technologies based on the gained experiences. They modified them to combine hard and soft engineering solutions taking into account the concept of working with nature and interacting with the natural processes to mitigate the coastal hazards (Iskander, 2010; Linham and Nicholls, 2012; Carmo, 2018). Coastal adaptations strategies/technologies to SLR could reduce the vulnerability to coastal threats and provide satisfied benefits (Koraim et al., 2011). However, selecting the proper technique for a specific coastal zone depends mainly on geophysical, climatical, and socio-economic circumstances considering local governmental policies (Eldeberky, 2011; Onat et al., 2018).

Worldwide, many researchers reviewed the climate change hazards and impacts on the coastal zones. They presented different learned lessons, expertise, and best-gained practices in their coastal cities based on various executed coastal adaptation measures, actions, and strategies (e.g., Fatoric and Chelleri, 2012; Stronkhorst et al., 2018; Esteban et al., 2019; Esteban et al., 2020; Baills et al., 2020; Busayo and Kalumba, 2021; Donoghue et al., 2021). Furthermore, universities and research institutions play an important role in partnering with coastal managers and stakeholders to provide various data, information, skill training, and experiences to decision-makers and leadership to develop novel adaptation methods (Doust et al., 2021).

This paper highlights the Egyptian efforts in dealing with coastal erosion-based SLR along the Nile Delta coastal area. The vulnerable coastal regions along the Nile Delta were investigated, showing the expected erosion rates considering different SLR scenarios. The implemented coastal adaptation structures were presented. The proposed contemporary adaptation technologies and plans based on the Egyptian strategy were also presented and discussed.

2. Study area

Numerous detailed articles discussed the Egyptian Nile Delta's properties and features, covering agriculture, economic, social, and environmental aspects. The following section presents the highlighted and remarkable information that serves this research. Furthermore, the SLR impacts and projected coastal erosion, a beach retreat, and beach loss were investigated.

2.1. Nile Delta coastal zone of Egypt

The Nile Delta coastal area, as shown in Fig. 1 (about a 250 km strip along the northern coast of Egypt), consists mainly of sandy and deltaic beaches. It has two promontories (namely Rosetta and Damietta), three main lagoons (namely Idku, El-Burullus, and El-Manzala), three main commercial ports (Alexandria, Damietta, and Port Said), and five fishing harbors (namely Abo-Qir, Elmaadiya, El-Burullus, Ezbt Al-Borg, and Port Said) (Negm et al., 2016; Sharaan et al., 2017). Furthermore, the investigated coastal area has many social, industrial, environmental, and economic features, including coasts' vital role in providing recreational coastal regions for tourism purposes (Koraim et al., 2011). Like most global deltas, the Egyptian Nile Delta was formed by ongoing carried and transported sediments from large rivers into the sea and by the association of the coastal processes such as tides, waves, and currents (Zhu et al., 2010). A low-lying coastal area features the Nile Delta coast, approximately 1-m elevation above the Mediterranean mean sea level. Also, the coastal slope along the Nile Delta is varied from a gentle slope (2.2%, from Port Said to Abo Qir) to a moderate coastal slope (5.5%, mostly detected at Alexandria coast) (Hereher, 2015). In addition, local land subsidence is spatially varied along the coast of the Nile Delta from 1 to 4 mm/yr (Frihy and El-Sayed, 2013).

The tide pattern along the Nile Delta coast is semi-diurnal, with a typical average range of 40 cm (Eldeberky, 2016). While the wave action is seasonal, NW and NE winds are the dominant direction responsible for the propagation of waves across the Nile Delta coast (Frihy et al., 2010; Iskander, 2013). The Nile Delta coast of Egypt is subjected to erosion based on the wave actions, currents, and relevant coastal processes. This erosion was exacerbated since the construction of the Aswan high dam, where the Nile River's sediments source and discharge were obstructed (El-Raey et al., 1999). Hence, coastal protection structures (such as groins, seawalls, detached and submerged breakwater, jetties, etc.) were constructed to reduce the coastal erosion issues. Further details and descriptions about the implemented protection structures were presented and discussed in many articles (Fanos et al., 1995; El-Raey et al., 1999; Frihy et al., 2003; Masria et al., 2015; Abd-Elhamid et al., 2016).

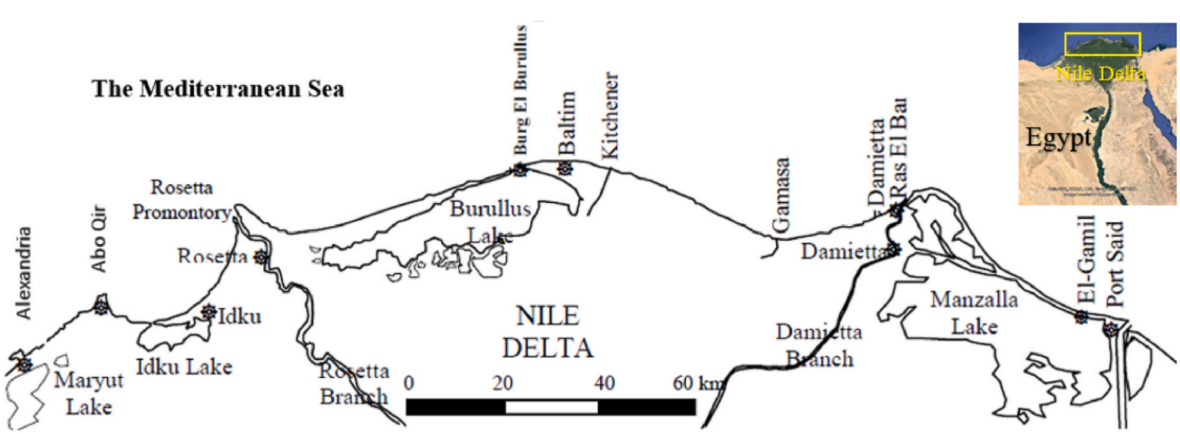

Fig. 1. Egyptian coast of the Nile Delta.

2.2. Vulnerable coastal areas to SLR

The Egyptian Nile Delta coast is a highly sensitive environment. It is directly affected by ongoing human activities and natural climatic factors, which significantly alter the coastline behaviors. The Egyptian Nile Delta coast is projected to suffer from coastal erosion, consequently to climate hazards, SLR, low-lying elevation, and land subsidence. It was classified as the most vulnerable coastal area along the Mediterranean Sea coast due to climate change (Eldeberky, 2011; Koraim and Negm, 2016; Jimenez and Sanchez-Arcilla, 2019; Sharaan and Udo, 2020a). The Fifth Assessment Report of the IPCC (issued 2013) showed that global sea levels would rise at higher rates than in the past four decades (Stocker et al., 2014). And the recent IPCC assessment report (AR6) indicates that the global mean sea level will continue to rise throughout the 21st century (IPCC, 2021).

Different studies were conducted to investigate and project the vulnerable coastal areas to inundation due to SLR and erosion rates along the Egyptian Nile Delta, considering hypothetical SLR scenarios. For instance, Frihy and El-Sayed (2013) reported that the Egyptian Nile Delta's beaches are highly vulnerable to SLR impacts; the highly vulnerable Nile Delta's coasts are El-Manzala Lagoon, Rosetta City, and El-Gamil (Port Said). Similarly, Hassaan and Abdrabo (2013) investigated the susceptible coastal areas to inundation and SLR-based GIS approach. The inundated coastal area by 2100 ranged from 22.49% to 49.22% of the total coastal areas under different scenarios of SLR. Hereher (2015) used the coastal vulnerability index to investigate the most vulnerable coastal areas to SLR threats along the northern Egyptian coastline. The results refer that the Nile Delta coastal zone is the most susceptible area along Egypt's north coast. Refaat and Eldeberky (2016) revealed that 7% of the Nile Delta coastal area would be inundated if subjected to a 1m SLR by 2100. Most researchers argue that the Nile Delta is the most vulnerable coastal area along the Mediterranean Sea.

Sharaan and Udo (2020a) applied the Bruun rule to estimate the projected beach retreat and loss along the northern coast of Egypt in 2100, including the Nile Delta coastline. The major results are

a) The Nile Delta's coastal area is subjected to severe erosion amongst the northern coast of Egypt.
b) The highest projected coasts retreated along the Nile Delta coast are detected from Abo Qir to Damietta Promontory, Alexandria, and El-Manzala to Port Said coasts, respectively.
c) The Nile Delta's gentle coastal slope increased from the vulnerability to SLR. Consequently, the projected erosion rate crosses the Nile Delta's coasts were higher than other Egyptian coasts.

Table 1 represents the markable results for the projected shoreline retreat by meter, equivalent shoreline erosion m/yr, and the beach loss (%) for the different SLR scenarios.

Fig. 2 shows a reference map for the shoreline retreat (m) left panel, and beach loss (%) right panel, which are extracted from the results issued by Sharaan and Udo (2020a). Furthermore, the results refer that some of the coastal areas along the Nile Delta have a narrow beach, and it would be entirely eroded by 2100, respecting the lowest SLR scenario.

Table 1
The effect of the SLR on the Nile Delta coast considering different SLR scenarios, according to Sharaan and Udo (2020a).

SLR Impact	lowest scenario, RCP2.6 SLR	Moderate scenario, RCP4.5 SLR	Highest scenario, RCP8.5 SLR
Shoreline retreat (m)	23.4 to 29.0	28.2 to 35.0	39.6 to 49.1
Annual erosion rate (m/yr)	0.24 to 0.30	0.29 to 0.37	0.41 to 0.51
Eroded beach area (Km^2)	7.78	9.49	13.31
Beach loss (%)	25.57%	30.84	43.25

Consequently, it would be submerged before 2100 if the highest scenario occurred. Without robust and effective adaptation plans/strategies, SLR threats to the Nile Delta could be worse than expected, including the existing coastal infrastructures, facilities, and activities.

3. Coastal adaptation to SLR

Egyptian coasts, particularly the Nile Delta coasts (low-lying delta), are exposed to SLR threats. If no action is taken, inundation, flooding, storm surges, and SLR threats would negatively impact the coastal environment, including physical impacts, damaging beaches, overtopping issues, deterioration of the tourist facilities, and existing infrastructures, if any (EL-Shinnawy, 2011; Abutaleb et al., 2018; Torresan et al., 2020; EL-Geziry, 2020). Vulnerability and adaptation are intertwined and mutually reinforcing (Odafivwotu, 2018). If the coastal area has a robust adaptive system to SLR, the susceptibility to SLR impacts and threats would be intangible, where the adaptation technologies decrease the vulnerability.

On the contrary, the vulnerability to SLR hazards would be undesirable if the coastal area has an inadequate or improper adaptive technique (Odafivwotu, 2018). This section briefly reviews the coastal adaptation technologies considering the three adaptation approaches commonly functional worldwide to cope with SLR risks and reduce the coastal erosion-based SLR. Hereafter, the Egyptian status and efforts, focusing on the protection approach, were presented in subsection 3.2.

3.1. Coastal adaptation approaches and technologies

Adaptation is defined as "the undertaking of actions to minimize threats or maximize opportunities resulting from climate change and its effects.". Adaptation approaches express the promising efforts, skills, techniques, plans, and technologies that might reduce the impacts of climate change and relevant coastal hazards. Coastal adaptation approaches are classified into retreat, accommodation, and protection approaches (CZMS, 1990; Nicholls et al., 2007). Each approach/technology has its benefits and constraints, and it requires specific knowledge and skills for implementation and monitoring.

Retreat strategy refers to the migration process for shoreline and coastal-land areas, inland planned relocation, and resettle inhabitants away from the vulnerable coasts to coastal hazards based on SLR and climate change impacts. Also, it could refer to prohibiting any developed projects along with the highly vulnerable coastal areas. Retreat approaches are mainly applied via two technologies, managed realignment and coastal setbacks (CZMS, 1990). Both technologies could satisfy potential benefits such as avoidance of impacts of inundation, storm surges, coastal flooding. Furthermore, it could provide a specific coastal area confined between the old and new planned defense lines (creation of intertidal habitat) (US Army, 1989; Zhu et al., 2010). Frequently, the retreat approach is relatively less expensive than the accommodation and protection approaches, where the costs of maintenance and protective measures could be avoided. Although, it occasionally requires a specific budget if a relocation option is selected (Eldeberky, 2011, 2016; Koraim et al., 2011). In some cases, political and social resistance could be a significant obstacle to selecting this approach (IPCC, 2014).

Accommodation strategy depends on keeping the coastal areas vulnerable to SLR threats and natural climatic effects while improving preparedness, society's ability, proper resistance, and adjustment against different hazards are considered simultaneously (CZMS, 1990; Nicholls et al., 2007). The accommodation approach follows the working with nature concept and sustaining human activities (IPCC, 2014). Additional coastal land areas or space coast areas are not essential for execution, unlike some applied adaptation technologies of retreat and protection approaches. Furthermore, the associated costs of the accommodation approach are affordable. Conversely, this approach needs highly specialized knowledge and skills for efficient implementation. Also, it has some social limitations, particularly on highly dense coasts.

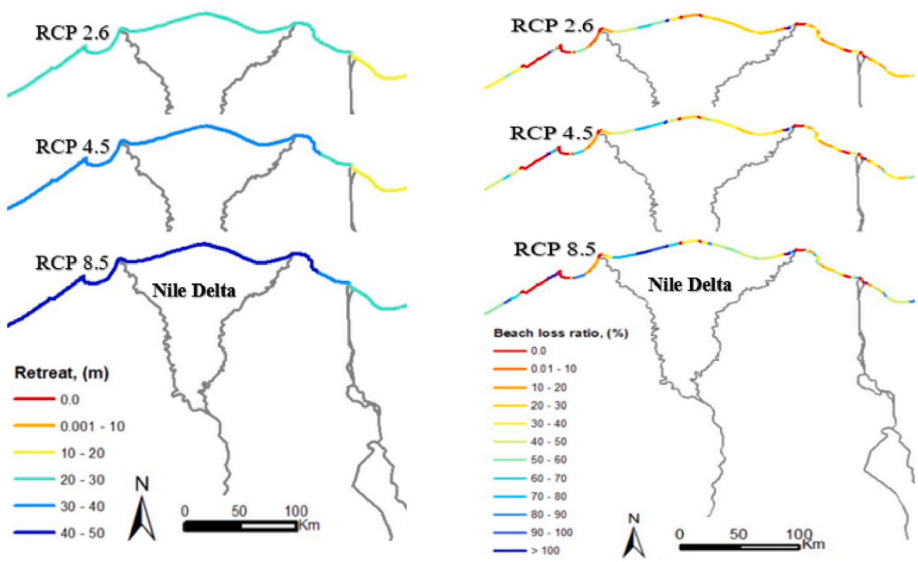

Fig. 2. Shoreline retreat (m) and beach loss ratio (%) along the Egyptian Nile Delta for the lowest, moderate, and worst RCP SLR scenarios by the year 2100 (Sharaan and Udo, 2020a).

Also, some coastal residents cannot adapt and live facing the expected coastal threats (Zhu et al., 2010).

Protection strategy refers to the enforcement of the coastal areas via a defensive measure using coastal adaptation structures to shelter the coastal regions from beach retreat, inundation, flooding, storms, etc. (CZMS, 1990; Nicholls et al., 2007). This approach is commonly a worldwide approach-based society's desire and economic benefits, leisure activities, and the society's attitude to be adjacent to the coast (Koraim and Negm, 2016; Carmo, 2018). The protection adaptation measures could be categorized under soft and hard protection measures (CZMS, 1990; Zhu et al., 2010). Hard defense structures are trusted protection measure which provides physical protection against wave energy and tides. Due to its rigid barrier, it prevents erosion in front of the rigid structure and, unfortunately, causes environmental impacts on the adjacent coasts due to the continuous dynamic process of the wave climate (French, 2001; Nicholls et al., 2007).

Furthermore, in some cases, rigid structures could be an obstacle regarding recreational activities, mainly in the vulnerable coasts to coastal hazards. Also, the implementation and maintenance costs are relatively high (US Army, 2002; Zhu et al., 2010). In contrast, soft adaptation measures promote ecosystem services and better aesthetics. Furthermore, it could be a friendly environmental alternative for coastal adaptation. The associated environmental impacts of using soft technologies are insubstantial if compared with hard structures. Also, working with the natural and dynamic coastal process is beneficial for using soft adaptation measures (Dean, 2002; Hanson et al., 2002; Iskander, 2010).

3.2. *Egyptian efforts towards an adaptive Nile Delta coast to SLR*

The Egyptian government seriously considered the coastal hazards. The official Egyptian authorities for planning and managing the coastal zones are the Egyptian General Authority for Shores Protection (SPA) and the Egyptian Environmental Affairs Agency (EEAA). SPA is represented by the Ministry of Water Resources and Irrigation-national water research center (https://www.nwrc.gov.eg/default.php) (National Water Research Center, 2021). Since its construction in 1981, SPA has had the central role and responsibility towards the following tasks: preparing an integrated study for shore protection, coastal conservation, developing proper plans and management strategies for existing and upcoming coastal projects, regular monitoring for the beach morphology, coastal structures maintenance, etc. EEAA is part of the Ministry of Environment and is responsible for protecting the environment and preparing the strategy for integrated environmental management for coastal zones (Abutaleb et al., 2018).

The Adaptation to SLR in the Nile Delta considering the Integrated Coastal Zone Management (ICZM) approach promotes successful planning and Egyptian coast resilience. It reduces vulnerability to SLR (Ibrahim and Shaw, 2012). ICZM was familiarized in Egypt since 1996, respecting four national strategies: shoreline protection, coastal land use, marine water quality, and marine resource preservation (Anon, 1996; Eldeberky, 2016). Different adaptation measures were executed to deal with future risks of inundation and SLR hazards on the Egyptian coastal areas. Such as beach nourishment, seawalls, issuing legal regulations (particularly land use and development on beaches), enforcing environmental laws, and activating environmental monitoring (IDSC, 2011).

For this purpose, an integrated monitoring network using tide gauges has been installed, the wind, waves, and currents measurements have been analyzed, marine surveying measurements have been conducted along the Egyptian coasts. All the collected data were subjected to integrated investigation for estimating the actual trends of the SLR, detecting the vulnerable coastal areas, and the appropriate adaptation technologies were reported. Also, the existing coastal structures which could protect SLR were subjected to further investigation to check its consistency to potential hazards induced by SLR. Similarly, the appropriate actions for rehabilitation were reported (https://www.nwrc.gov.eg/CoRI.php.) and (https://www.nwrc.gov.eg/img/brochure/NWRC%20Brochure.pdf). The Egyptian research authorities and individuals are still acting to increase monitoring efforts, update and modify the current database and potential scenarios, and prepare a set of countermeasures and adaptation technologies for a sustainable coast.

Coastal adaptation structures against SLR in terms of protection technologies include but are not limited to seawalls, beach nourishment, artificial sand dunes, dune rehabilitation, storm surge barriers, and land claim. Also, it could be categorized into hard and soft technologies.

Seawalls and revetments were classified as rigid structures used for coastal adaptation and protection. It is the most globally implemented protection technology to prevent shoreline erosion and beach retreat. It provides high protection against SLR threats and mitigates inundation and flood hazards. In addition to the offered security to coastal hinterlands, seawalls may promote coastal development and investment activities, including tourism and recreational purposes (Nicholls et al., 2007). Also, the revetments could effectively dissipate the wave energy.

Unfortunately, seawalls are aesthetically displeasing, threaten beach tourism and provide undesirable feelings to the tourists and coast's residents (Zhu et al., 2010). Although seawalls could obstruct the shoreline erosion, the adjacent unprotected beach remains under threats of progressive deterioration due to mutual natural processes and human encroachment (French, 2001). Additionally, failure of seawalls could be a typical result of the regular occurred scour at the vertical seawall's foot, which requires high maintenance costs (Zhu et al., 2010). Typically, seawalls are an expensive adaptation option, need an efficient design that includes overtopping scenarios, which requires a specific and reasonable height to the coastal stakeholders (Abutaleb et al., 2018).

Egypt has significant experience in constructing and implementing hard structures such as seawalls, revetments, breakwaters (detached or submerged), groins, etc. The availability of experienced laborers, materials, and specialized machinery for the construction procedures of seawalls promotes the Egyptian abilities for coastal protection. Many coastal projects implemented seawalls or revetments for coastal protection purposes in the Nile Delta. The most popular seawall in Egypt is the Mohamed Ali seawall (see Fig. 3), located at the coast of Abo Qir bay mainly for protecting the low backward land (1.5–2.5m below SLR) (Iskander, 2010). Other examples are located on the coast of Burg El Burullus and west of Damietta. Also, revetment protection technology was implemented at different beaches along the Nile Delta, such as on the Rosetta promontory, east of Burg El-Burullus

Recently, the Egyptian plans and strategies for promoting the coastal environment considered the climate change impacts. The constructed seawalls and revetments are subjected to regular rehabilitation and maintenance. Some implemented projects were reinforced by additional armor units (such as dolomite stones and tetrapod blocks). Also, some of the coastal structures were raised to consider the potential wave forces, storms, and overtopping scenarios in the future. Also, in some coastal areas, protected beach with seawalls is nourished by sand or provided by sandbags for further beach enforcement and increasing its stability and durability.

Beach nourishment is classified as a soft adaptation technology to protect sandy beaches from erosion and flood hazards. Specific amounts of borrowed sands from an external source, which have the same characteristics and quality as the beach sediments, are usually involved (Zhu et al., 2010). Beach nourishment enhances the natural landscape of the coast, promotes an aesthetically pleasing particularly to the coastal vacationers, and provides a vast space for recreational and tourism activities. Although the dissipation of wave energy features beach nourishment, it does not prevent coastal erosion, the beach is eroded naturally, and regular re-nourishment is required. The eroded materials redistributed and transferred via the natural process (longshore drift) induced waves and tides. Beach nourishment projects should be carefully implemented considering the associated environmental impacts such as water turbidity and reformed sediment configurations which could affect the existing marine environment (Dean, 2002).

Many projects used sand nourishment techniques to mitigate erosion issues and provide a wide beach for recreational activities (particularly at Alexandria, Damietta, and Ras El-bar coasts). These projects are under regular monitoring, investigation, and assessment for detecting the critical beach volume that needs re-nourishment. Furthermore, the evaluation of these projects shows that it looks acting well today and provide a proper defense system against flooding during storms (El-Raey et al., 1999; Koraim et al., 2011; Eldeberky, 2011; El-Sharnouby, 2011).

Sone nourishment projects are executed at Alexandria city using the borrowed sand from Cairo's west deserts, categorized as a valuable and compatible source compared with the original beaches' materials (El-Raey et al., 1999; Abd-Elhamid et al., 2016). While, dredged sediments from the navigation channel of Damietta port were used as a nourishment source for the nearby coasts (east Damietta port, new Damietta beach, and Ras El-bar beach) (https://archimarine.com/project-show/?id=632). This process is conducted under the supervision of Coastal Research Institute and SPA, based on the Egyptian national strategy. Sharaan and Udo (2020b) estimated the required volume of sand nourishment along the Nile Delta coast, mainly for adaptation to SLR and land subsidence, considering different SLR scenarios. The needed sand fill ranges from 191.7 to 278.7 million cubic meters in 2100 to maintain the current beach width of the Nile Delta coast without retreat for the lowest and worst SLR scenarios (RCP2.6 and RCP8.5, respectively).

Artificial sand dunes are soft adaptation technology implemented mainly at the undeveloped sandy coasts to mimic the functioning of natural dunes. Both have tangible features in reducing coastal erosion and flooding hazards in adjacent coastal lowlands (Zhu et al., 2010). While, **dune rehabilitation** technology indicates the maintenance and renewal procedures of the dunes to restore its functional protection and adaptation amenities against coastal flooding, erosion, and inundation induced by SLR. The dune capacity fluctuates based on the winds, waves, and SLR conditions. Sand dunes could supply and compensate the beaches by the required sediments (sediment source) during erosion periods, and contrary, dunes could store the sand sediments when needed (French, 2001). The dune is the most recommended soft adaptation option in the Ebro Delta (Spain). Also, it is the most harmonic option with nature (Fatorić and Chelleri, 2012).

Furthermore, sand dunce has many environmental and economic features. For instance, it could provide an appropriate coastal habitat, an onshore-wide beach for tourism and recreational activities, and aesthetically attractive. The construction and maintenance costs are relatively low compared with other adaptive techniques (French, 2001). On the other hand, forming a new artificial sand dune is a great challenge. It needs a wide land area which could increase the coastal squeeze. Also, it requires a large amount of sand, specialized labor, and knowledge. Hight of the sand dune (considering the proper sea view) should be satisfied to different stakeholders and the coastal residents (EL-Shinnawy, 2011).

Fortunately, the Egyptian Nile Delta has natural sand dunes at separate locations along the coastal Nile Delta, particularly between Borg El-Burullus and Baltim (El-Bady, 2016). Fig. 4 shows a small

Fig. 3. Examples for the implemented hard structures as a protection adaptation option to SLR (Iskander, 2010); Left panel: Mohamed Ali Seawall implemented at Abo Qir bay; Right panel: Revetment located at Rosetta city, Nile Delta, Egypt.

Fig. 4. Sand dunes at the east of Burg El Burullus city, Nile Delta, Egypt.

longitudinal natural dune located adjacent to the shoreline. Through many years, the existing natural sand dunes protected the nearby coastal areas from flood hazards, erosion, landwards migration, provided sediment sources for nearby eroded beaches, and featured as an aesthetical and recreational area. Recently, the Egyptian government gave more attention to rehabilitate the existing natural sand dune systems as one of the effective adaptation strategies due to its essential role in protecting the Nile Delta. Rehabilitation procedures include reshaping, reinforcing, and adjusting the proper elevation height. Generally, sand dunes could be strengthened using a vegetation planting approach, increasing sand dune stability and durability. Also, it promotes further sand traps and accumulations based on wind-blown sand sources (US Army, 2002; Zhu et al., 2010).

The projected threats of SLR and associated environmental impacts of hard structures forced SPA to consider new soft technologies to protect the low-lying coastal region in the middle of the Nile Delta (from west of El-Burullus fishing harbor to Rosetta promontory). The new proposed technologies are targeted to protect the beach from inundation due to SLR, flooding hazards during storms, preserve residential fishers and fisheries and promote the coastal investment along this region.

Consequently, two experimental technologies were proposed, designated, and constructed to formally work as an artificial dune under the supervision of the Coastal Research Institute (CORI) and SPA. The project is subjected to regular monitoring, investigation, and testing to check its performance. Fig. 5 shows a cross-section for the first experimental artificial dune. It is a predominantly earth structure consisting of a silty clay core and a waterproof outer protection layer.

Fig. 6 shows real field photos for the implemented project via ARCHIMARINE contracting company (https://archimarine.com/project-show/?id=712). Firstly, the land was dredged to the level (−0.50) m, and a geotextile layer was provided below a clay layer representing the core of the dune (Fig. 6a). Then, a clay embankment was provided. The clay source was the output of El-Burullus lake's dredged sediments overlay by a 1.0 m sand layer. Sand bumpers (3.0 m* 3.0 m) were installed using natural reed mats (each 3.0 m length, 1.0 m height, about 2.54 cm thickness, and submerged by 60 cm into dune surface) for fence construction (Fig. 6b and Fig. 6c), and trap sands induced winds (Fig. 6d). The last two figures (Fig. 6e and Fig. 6f) refer to the actual exposed threats and impacts on the mats, such as inundation and climatic weather.

Regarding the second experimental adaptation technology, real field photos for the implemented project via ARCHIMARINE contracting company (https://archimarine.com/project-show/?id=627) were presented in Fig. 7. The experimental project involves the construction of a sand embankment. The central core is Geo-tube 4.0 m diameter filled with sand (Fig. 7a) and covered by dolomite stones which weigh (50–150) kgs as an armor layer (Fig. 7b).

In recent years, geotextile technology has been globally used in shore protection projects and coastal defense structures. Its growth and development could be attributed to economic, social, and political environmental factors respecting project purpose and site conditions. Worldwide experiences show that using sand-filled geosystems (such as geotextile containers, tubes, and bags) as hidden components have demonstrated an effective and positive response in protecting sandy coasts from storm attacks and maintaining the equilibrium conditions of the coastal dynamic. Generally, geotextile as a permeable material

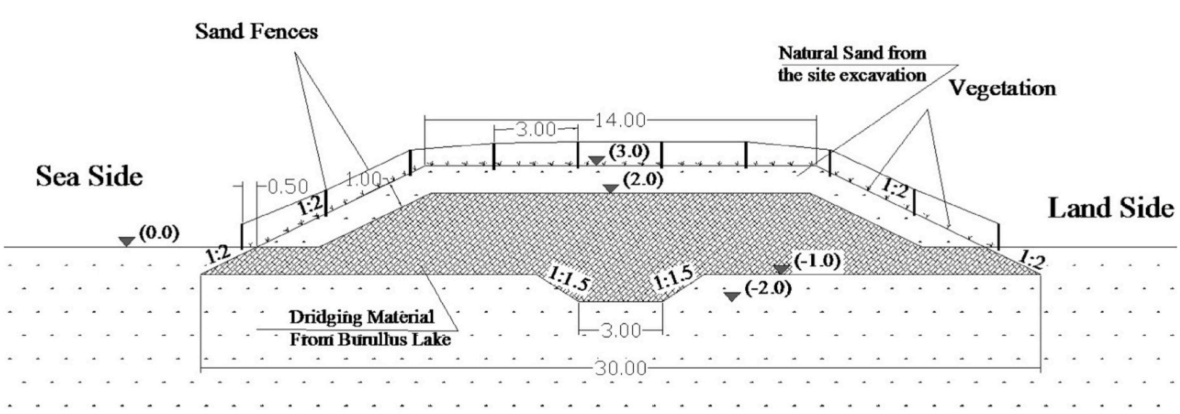

Fig. 5. Typical artificial sand dune cross-section of the first experimental technology.

Fig. 6. Construction phases of the artificial sand dune (31°29′49.93″N, 30°41′15.74″E); a) Geotextile layer and the clay layer (the core of dune); b) and c) Sand bumpers installation and the sides and top dune; d) trapped sands induced wind; e) and f) Observed impacts due to inundation and rough weather.

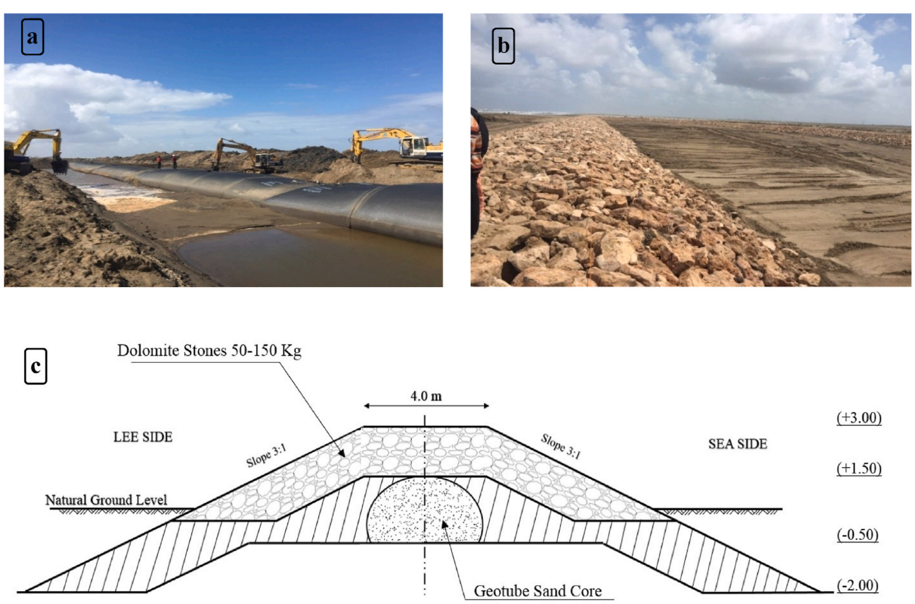

Fig. 7. Construction phases of the artificial sand dune of the second experimental technology (31°29′58.42″N, 30°41′44.07″E); a) Geo-tube (4.0 m diameter) installation; b) Armor layer of dolomite stones; c) Typical artificial sand dune cross-section of the second experimental technology.

allows water to flow while retaining the soil. It could be used as a core of groins, revetments, breakwaters, seawalls, and artificial sand dunes. The core layer of the second experimental technology is considered as geotextile tube sand core (sand-tight geotextile). It is installed in situ with a specific inlet/outlet for filling purposes. Generally, the tube diameters range from about 1.6 to 5 m; when filled with sand materials, it acquires a pillow form. Experiences show that geotextile tube sand core could enhance reinforcement for dune stabilization and provide further effectiveness of an artificial dune for coastal protection purposes against during winter storm periods.

In addition to the aforementioned coastal adaptation measures and respect for the Egyptian strategy 2030, the following actions were also included through the integrated strategies and plans by SPA and EEAA.

a) Considering the international coastal road as a secondary defense adaptation technique, as the United Nations Development Program recommended in 1992, the coastal highway and nearby coastal infrastructures were reinforced considering a proper elevation.
b) Setting and enforcing the issues regulations regarding SLR adaptations by prohibiting further investment or development, particularly at the highly vulnerable coastal areas to SLR, before the agreement and consulting SPA and EEAA.
c) Increasing the efficiency of coastal lakes and lagoons, maintaining appropriate water depth through regular dredging, and raising the bank's elevation to 2.0 m at least above the mean sea water level.
d) Increasing the public awareness towards benefits of the adaptation and mitigation to the SLR phenomenon.
e) Developing wetlands and constructing national coastal projects such as fish farming, recently two large fish farming projects applied east of Rosetta promontory and east of Port Said.

4. Discussions

The Egyptian northern coastal strip, particularly the Nile Delta, has significant economic, environmental, social, recreational, and industrial aspects. Accordingly, many investments plans and development projects were executed, and others are under construction. Hence, the Egyptian Nile Delta has been categorized as highly vulnerable to SLR, particularly the low-lying coasts. From the social perspective, the northern coastal zone of Egypt is expected to suffer different impacts due to climate hazards such as saltwater intrusion, groundwater contamination, and soil salinity, affecting food productivity and security. Vulnerable coastal areas along the Nile Delta amongst the northern coast of Egypt are a direct threat and risk due to SLR. The coastal area of the Nile Delta shows distinctive though diverse socio-economic characteristics and resources, including recreation and tourism, agriculture, industry, and ports and fisheries. Some low-lying coastal areas are subjected to inundation and flooding during storms that reach the coastal road, threatening agricultural lands and residential fishing communities. On the other hand, creating job opportunities in safe areas is essential for successfully absorbing migrant populations.

Worldwide three alternatives are identified for coastal adaption to SLR and flooding hazards, retreat, accommodate, and protect IPCC (1990). Regarding the retreat approach, the entire vulnerable coastal areas are subjected to abandonment, no protection efforts or costs are considered. In contrast, it could be an impractical solution in highly populated or economically valued coasts. Otherwise, the accommodation approach refers to coexistence with the natural and mutual responses. i.e., reducing the vulnerability and ongoing threats of SLR and promoting preparedness using appropriate adaptation measures. The protection approach means providing the vulnerable coastal areas with the proper defensive measures to stop SLR threats and climate change impacts. This approach is the most applied in developed and developing countries. The protection approach involves both hard and soft structures or combined technologies.

IPCC was reporting the continuity of the rising global sea level. In this concern, the Egyptian government readily works to secure the Nile Deltas coasts from different climatic threats. The Egyptian prepared national plan/strategy for coastal adaptation to SLR includes further rational steps for understanding the problem, analyzing, and preparing proper solutions. In Egypt, hard protection measures were commonly applied to prevent coastal retreats in the past century. Regarding SLR, the Egyptian government is making significant efforts to overcome relevant coastal issues, many of the protected coasts showing efficient response to deal with the natural process. Also, a favorable reaction to SLR and climatic hazards is expected. Several protection adaptation structures were implemented (Seawalls, revetments, beach nourishment) and others under construction and consideration (rehabilitation of dunes, experimental dunes, enforcing coastal road, and combined technologies).

Although hard protection measures could provide a robust and effective defense against coastal hazards, the associated environmental impacts to the protected beaches by hard structures such as altering erosion and sedimentation patterns forced the coastal stakeholders to contemplate environmentally soft protection measures. Soft environmental technologies (beach nourishment and rehabilitation of dunes) are expected to be highly applied along the sandy coasts. It is attractive to coastal managers, seems naturally appealing, is more effective considering long-term, provides buffer zones for recreational aspects and is relatively less expensive. It requires a tremendous amount of qualified sand sediments considering the affordable cost. Offshore or navigational channels dredging provides a valuable source of suitable sand material.

In some cases, dunes and dykes could obstruct sea sight and direct beach access. At a particular time, dunes were partially removed for development or investments (using high qualified sand material in different industries). Therefore, reconstructing artificial dunes or rehabilitation of natural dunes are somewhat facing obstruction from the coastal residents.

Recently, the combination of adaptation approaches (retreat, accommodate, and protection) has been thoughtfully considered worldwide. Seawalls could be executed with managed realignment (retreat approach) or beach nourishment through an integrated plan. Sometimes, beach nourishment is combined with groins as a mixed solution. It can accumulate transported sediments due to longshore drift. Recently, geotextile materials were included in some adaptation technologies construction along the Nile Delta coast. It is categorized as friendly environmental material. Geotextile containers or tubes could improve the performance of the coastal adaptation structures.

SPA and EEAA have a significant role in achieving a sustainable coastal environment. SPA has implemented many coastal protection and adaptation projects during the past two decades, which approximately costs 63 million USD (1 billion Egyptian pounds). For the Nile Delta, experience indicated that the costs of the protection measures are about 10 thousand USD per meter length (Arab Republic of Egypt, 2010). Recent official reports refer that the current project (artificial sand dune) implemented along 30 km of the low-lying coastal area between El-Burullus and Rosetta promontory costs about 9 Million USD (140 million Egyptian pounds). Initial assessment of these projects refers to the remarkable progress towards adaptive Nile Delta coast, and promising results were observed during few recent years, mainly at the current experimental projects (artificial sand dunes) and protected the coastal areas from flooding hazards during storms. However, increasing the public awareness towards the SLR phenomenon, climatic risks, and the role of adaptation and mitigation measures could positively sound and support the local authorities' efforts. In addition, activating the integrated management concepts increases the success of the implemented coastal adaptation projects considering community participation.

Environmental, long-term outcomes, effectiveness, and socio-economic assessment should be carefully investigated for each alternative/approach for detecting the prioritization of actions before selection and implementation. The choice of the reasonable adaptation technology is roughly site-dependent. Also, it depends on social, topographical, climatic, and environmental conditions. Once the adaptation technology is selected, and the project is initiated, regular observation, monitoring, and review are ongoing operational actions to readily modify or adjust any unexpected adaptation behavior or response. Regular reports for each phase of planning, construction, rehabilitation are recorded and published to the stakeholders.

In Egypt, cooperation between different national research centers and universities has been highly observed in recent years. They could provide an integrated knowledge bank about the coastal sector. Understanding various social and economic constraints to each approach facilitate detecting the most appropriate options and actions. The provision of a climatic, topographic database also enables more effective adaptation planning. Financial conditions are considered one of the main obstacles to the adaptation technology selection. Regarding the retreat approach, losing land property (coastal area) and relocation is deemed impractical due to the coastal squeeze and current investments along the Nile Delta coasts.

Furthermore, rebuilding the coastal infrastructure would face significant opposition in addition to the expected huge required costs. Therefore, this option is not directly allowed. While the accommodation approach option in some coastal areas could be undertaken, modifying or adding some change to the property values, living with temporary natural hazards, and relevant costs could be accepted. The commonly applied technique in Egypt and worldwide, the protection approach is a highly valued adaption option. The adaptation costs could be reliably high, but the social and long-term benefits of having a robust defense system towards adaptive coast and achieving sustainability increase from this option. Another alternative strategy that could be considered is no action is taken, i.e., do nothing. Inundation, flooding, storm surges, and SLR threats can act naturally. This strategy could contribute to the physical impacts such as damaging beach and tourist facilities and existing infrastructures and activities. No costs or efforts are required, no economic burden is detected on the national communities, in contrast to the execution of protection or accommodation technologies which are relatively costly. Some researchers argue that if the life cycle cost of maintenance, relocation, and protection is higher than the investment's value, the nothing strategy could be the proper action.

5. Egypt's vision 2030

In 2015, Egypt presented its strategy/vision for a better future by establishing the Sustainable Development Strategy (SDS), "Egypt's Vision 2030", Considering three central dimensions of sustainable development (economic, social, and environmental dimensions). Each dimension is subdivided into pillars, followed by key performance indicators for measuring progress (www.sdsegypt2030.com). The Egyptian vision is consistent with the Sustainable Development Goals (SDGs) issued by the United Nations (UN).

Focusing on the coastal adaptation to SLR and climatic hazards. The Egyptian strategy applied different technical and managerial actions and planned to address the climatic risks and targets to enhance the efficiency of protecting coastal and marine areas. It should be mentioned that UN Development Program (UNDP) supports integrated solutions that strengthen coastal communities' resilience to SLR threats. UNDP supports the national strategy for adaptation to climate change and disaster risk reduction. Strengthening the regulatory framework and building institutional capacity to improve the resilience of coastal settlements and development infrastructure; implementing innovative and environmentally adaptation measures that facilitate and promote adaptation in the Nile Delta; establishing a monitoring and assessment framework and knowledge management systems on adaptation were all part of this strategy.

Some of these actions were already implemented; others are under process or construction. Furthermore, it is targeting to implement programs for developing the technical and administrative capabilities of coastal management stakeholders. Also, develop a specific program to adapt to the SLR hazards in the vulnerable coastal areas by conducting scientific research to produce accurate studies on the expected risks and the best scientific methods to address them, all while considering sustainability.

Most importantly, the Egyptian government realized the necessity to broaden the application of innovative coastal protection works used along the Nile Delta (two experimental dune projects) to the Egyptian coast. In addition, a national observation system for monitoring the oceanic parameters along the Nile Delta coast is planned. It would enhance monitoring tools for reviewing the climatic variations, collecting and analyzing sea level and wave data. Also, pieces of training on coastal modeling and construction techniques of the coastal environmental structures have been targeted (www.un.org/sustainabledevelopment/development-agenda/).

6. Conclusion

The northern Egyptian coast, particularly the Nile Delta coast (low-lying coastal area), is subjected to severe impacts due to climate change and SLR. The expected losses in shoreline erosion, a beach retreat, deterioration of coastal tourism facilities and infrastructures, industrial activities, and undoubtedly the agricultural activities are varied based on climatic-weather variation, SLR scenarios, and spatial land subsidence. These hazards require an appropriate adaption measure to avoid further deterioration in the coastal environment. This article highlights Egyptian efforts towards an adaptive coast and provides fruitful information and knowledge to coastal managers and stakeholders worldwide.

The most appropriate adaptation approach/technology to SLR is mostly coastal site-dependent. Relevant coastal databases should be available and analyzed before final selection considering socio-economic, environmental, long-term assessments. Amongst the three adaptation approaches (retreat, accommodate, and protect), the protection approach seems the most appropriate and effective coastal adaptation approach in Egypt, based on the Egyptian great historical experience, skills, and best practices.

A variety of protection adaptation structures were implemented (seawalls, revetments, and their rehabilitation considering elevation of coastal structures, and beach nourishment), others actions being considered (restoration of sand dune systems, experimental artificial sand dune using geotextile sandbag core, enforcing coastal road, and combined technologies), and enforcing different managing regulations. Furthermore, constructing two national projects for fish farming support the coastal areas considering accommodate approach. Generally, traditional adaption and other unique technologies were employed under the Egyptian strategy and future vision for coastal adaptation to SLR. Also, the transition to environmentally friendly adaptation protection technologies that work with natural processes is increasingly used globally. A similar shift is observed in Egypt, which appears positive response in front of inundation, flooding during storms, and SLR. Recent experimental projects to protect the Nile Delta using sandy dunes with inner geotextile sand tube and natural mats which traps the sand show a positive response. Simultaneously, it conserves the hinterland agriculture's areas from further deterioration and encourages beach development and investments, promoting economic values and benefits. However, Egyptian experience shows serious actions to deal with SLR and conserve the Nile Delta coast. Mutual participation between coastal managers, researchers, policy, and decision-makers could provide an integrated framework promoting coastal sustainability and dealing with future coastal challenges.

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Declaration of competing interest

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