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Towards a combined human-natural system approach in the Northern Red Sea Region: Ecological challenges, sustainable development, and community engagement

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ABSTRACT

The northern Red Sea coastal ecosystem is one of the most diverse coastal ecosystems in the world. Fortunately, it has shown extraordinary resilience against climate change and is predicted to survive global warming during the coming decades. However, with warming waters, increased sediment and pollutants, and other human impacts, the ecosystem and consequently thriving reef tourism which forms a pillar of the ongoing economic diversification policies of the northern Red Sea region are under threat. A variety of evidence indicates significant damage has already been done to terrestrial and ocean ecosystems on both sides of the northern Red Sea. Expenditures on ecosystem protection and research lag behind Egypt's billions in USD revenue from tourism. Unfortunately, the economic drive to generate profit has resulted in sprawling touristic, industrial, and mixed development without careful planning or assessment of the fragility and sustainability of the natural ecosystem. As a result, the future of coastal urban growth is murky. Given its natural, social, and touristic value, the northern Red Sea system requires a special ecological security system with detailed analysis, inclusive development, and proactive governance across coastal cities and their adjacent inland secondary cities. This study identifies the geological research gaps, human-ecological interactions, inclusive urban development challenges, and related literature pertaining to the northern Red Sea. We propose immediate, targeted, multidisciplinary research

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trajectories and provide policy recommendations to ensure that the region's existing and future developmental pursuits are undertaken in an environmentally sustainable and inclusive approach.

1. Introduction

The Red Sea has had a significant role in human history and continues to shape society in the region to this day. Throughout history, the Red Sea as a narrow body of water separating the Arab Peninsula and Northeast Africa has played an important role as a water trade route [1]. Five trading ships were built by Hatshepsut, the fifth pharaoh of the eighteenth dynasty of ancient Egypt, for her incredible expedition over the Red Sea to Punt 3500 years ago [2]. Despite the lack of topographic features conducive to natural harbors [3], the Red Sea was home to many ancient harbors. At the head of Wadi Gawasis lies the Harbor of Mersa/Wadi Gawasis, the oldest long-distance seafaring archaeological site in the world [4]. Previously, the Egyptian Nile River was connected to the Red Sea through an artificial canal, which was originally attempted long before during the time of the Saitic Pharaoh Necho II (610–595 BC) [5]. Curiously, even the religious narratives of the Red Sea are intensively discussed, not only in the usual historical studies but also through physical and numerical modeling. Drews and Han [6] performed a set of hydrodynamic modeling experiments to test possible explanations of Moses crossing the Red Sea [7], as mentioned in Exodus 14.

The Western interest in the Red Sea started with the Napoleonic invasion of Egypt in 1798 as shown in the book, the *Description of Egypt* [8] that was produced by the accompanying scientists. The discovery of minerals such as phosphate resulted in several colonial industrial complexes scattered along the coast at the turn of the century. The new mining enterprises constituted Red Sea development representing a significant turn for the ecosystem. Although Egyptian and Arab leaders tended to consider the Red Sea as an "Arab Lake" [9], the geopolitics of the Red Sea and the extractive impetus of its natural resources transcended its immediate locality. Furthermore, digging the Suez Canal, an artificial waterway linking the Red Sea and the Mediterranean, shortened international trade routes significantly. Currently, around 10% of the global seaborne oil, and 15% of international maritime trade passes through the Red Sea [10]. As a result of the energy projects, flourishing infrastructure, and tourism development along the Red Sea coast, serious threats to the environment have been identified and documented [11] including urbanization and coastal development (i.e., dredging and filling operations), desalination plants, coastal mining, quarrying activities, oil bunkering, offshore drilling, overfishing [12,13], and oil spills [14]. Unsustainable fishing practices, weak management, and increasing demand for seafood have led to overfishing and the depletion of fish stocks [15].

Significant advancements in environmental legislation have occurred in the past three decades among the Red Sea countries. For instance, Egypt witnessed its first environmental law in 1982, which was subsequently updated in 1994, 2009, and 2015 and expanded to include the protection and development of lakes and fisheries [16–19]. Moreover, administrative changes led to the elevation of the General Authority for Fish Resources Development (GAFRD) to an entity under the Cabinet of Ministers, departing from its prior affiliation as a department within the Egyptian Ministry of Agriculture. On the regional level, the Regional Organization for the Conservation of the Environment of the Red Sea, and Gulf of Aden (PERSGA), an intergovernmental organization uniting seven Red Sea coastal nations and focusing on environmental policymaking, was founded. PERSGA's mandate is to implement Strategic Action Programs and regional protocols aimed at conservation and sustainable practices. It also emphasizes the development of specialized plans, guidelines, and initiatives, such as establishing Marine Protected Areas (MPAs) and pollution management strategies [20]. Since 2005, the Red Sea and Gulf of Aden (RSGA) region has had a Regional Network of MPAs, with a recent 21.67% increase in MPA coverage. Five regional protocols are being developed, with three already ratified (pertaining to oil and hazardous noxious substances, biodiversity and marine protected areas, and land-based activities), while two are currently underway (relating to the exchange of equipment and personnel during emergencies, and the management of fisheries and aquaculture). Remarkably, PERSGA's proposal suggests a regional project to address overfishing through committees led by PERSGA representatives within each country, promoting cooperation to overcome institutional conflicts and gaps in overfishing management.

Sofia [21] identified the Red Sea as a region with high levels of overfishing and unsustainable fishing practices, particularly in Egypt and Saudi Arabia. The report noted that the most used fishing methods in the region are bottom trawling and gillnetting, which are known to cause habitat destruction and high levels of bycatch. Unfortunately, the southern parts which are considered politically unstable are threatened by a potential environmental catastrophe from the abandonment of the *Safer* oil tanker containing more than 1.1 million barrels of oil in 2015 [14]. Fortunately, the United Nations recently announced an initiative to remove the oil from the tanker [22]. Enhancing environmental cooperation between countries bordering the Red Sea necessitates crucial action to sustain valuable marine resources for future generations [23]. Despite the fact that legislation and management plans are in place all across the Red Sea, enforcement is low due to several reasons; for instance, the war in Yemen has dramatically impacted fisheries management [24], while in the central Red Sea, the recent expansion in commercial fishing and targeting of top predators still needs to be controlled [25]. Similarly, in the northern Red Sea, Egypt is struggling with the limited resources and capacities of the responsible authorities, and a lack of political will [26,27].

The Red Sea has previously been considered as a natural laboratory for wind and wave modeling [28] but we can also consider it as a large natural laboratory for a very resilient biome [29-32] currently enduring global stressors such as ocean warming and acidification. This paper will discuss key areas of northern Red Sea (NRS) research, namely geological research gaps; NRS ecological challenges along with overfishing; rapid coastal development; and challenges to inclusive development presenting an Egyptian coastal city named El-Quseir. The paper will begin with an analysis of past research in the Red Sea and will end with recommendations for crucial actions to take.

2. Red Sea environmental status and knowledge gaps

2.1. Bibliometric analysis

Bibliometric analyses are an established method to evaluate research literature, particularly in scientific fields benefiting from computational data treatment and witnessing increased scholarly output [33]. To highlight the trends of studies conducted over the NRS in the last eighteen years (2005–2022), we performed a bibliometric analysis using the VOSviewer software (VOS stands for visualization of similarities – see www.vosviewer.com). VOSviewer is a software that generates clear graphical representation of bibliometric maps, especially for extensive datasets [34]. We analyzed 4018 research papers (3218 articles, 228 proceeding papers, 166 review articles, 94 book chapters, and others) from the online database Web of Science (WOS). WOS comprises a vast collection of significant research papers and offers integrated analysis tools for creating informative visual representations. VOSviewer was employed to analyze each keyword, calculating links, total link strengths, and co-occurrences with other keywords. This gives a holistic overview of the past research based on keywords' co-occurrences

(Fig. 1). The analysis reveals a discernible prominence reflecting three principal domains of investigation, namely geological research, biological research (with a strong focus on coral reefs), and climate and oceanic studies (including atmospheric circulation, dust storms, and oceanography). There have been more studies in the Gulf of Aqaba than in the Gulf of Suez, with a gradual shift from dominant geological studies to fisheries and biological studies. Oil companies like Saudi Aramco and ExxonMobil mostly funded geological exploration in the Red Sea, and the recent shift towards studying the Red Sea environment more likely relates to the growing awareness of marine ecosystem services [35,36]. In addition, recent papers have become increasingly interested in quantifying human impacts and conservation studies in the western and eastern coastal zones. Finally, they have recently addressed the resilience and adaptive capacity of ecosystems. Interestingly, land-sea interaction (i.e., the effects of flash floods on marine ecosystem) is extremely under-studied (only a few papers exist) [37,38].

Gaps still exist in our understanding of land-sea interactions in this arid region despite efforts to improve our knowledge of Red Sea marine ecosystems. Flash floods extensively disrupt coastal cities on the Red Sea and Gulf of Aqaba leading to casualties, deaths, and infrastructure damage as reported in newspapers and mass media [39]. For example, few studies [40] have tracked the impacts of frequent flash floods on the rich coral reef areas. Even though global warming is intensifying, and many small dams are being built to mitigate the impact of flash floods, hydrological-biological studies on marine ecosystems have not yet been conducted. The groundwater intrusion in coastal areas, particularly in developed neighborhoods (e.g., Elgouna, and Hurghada), also needs further investigation. However, an analysis of the recent flash floods over the Sinai Peninsula showed decreasing precipitation trends with time [41]. This is aligned with the scenarios reported by the Intergovernmental Panel on Climate Change - IPCC's Sixth Assessment Report [42]. These findings suggest that the marine ecosystem could be impacted by the disturbance of the sedimentation processes and nutrients originating from the flash floods. Both the cases of increasing flash flood frequency (i.e., increasing nutrients/sediments entering the sea), and decreasing flash flood frequency (i.e., loss of a crucial source of nutrients in the oligotrophic Red Sea) should be further investigated. Similarly, researchers started to highlight the regional impact of dust and its role in the heat budget and circulation in the Red Sea [43,44] which could be addressed in future physical-biogeochemical studies. Ultimately, the unusual climate of the Red sea and its rich sedimentary archive of past climate makes it an excellent field laboratory to study how an enclosed sea responds to climate.

2.2. Geological research and gaps

The Red Sea is a unique geological setting. Beneath its waters lies a complex geology that has intrigued geoscientists for decades. This section delves into the intricate world of the Red Sea's geological and geophysical aspects, shedding light on the ongoing investigations, challenges, and discoveries that contribute to our understanding of the Earth's dynamic processes. The Red Sea (Fig. 2) is a rift basin formed by the separation of Arabia from Nubia, which started some time before ~24 million years ago (mya) [45,46]. Evaporites (sediments formed by precipitation from water) were deposited within the Red Sea during the Miocene period (up until 5.3 mya) and reach kilometers in thickness [47-49]. These thick evaporites obscure the underlying geology making it largely inaccessible so most research on it has relied on geophysical methods [50-52,48]. As the following illustrates, some studies of the Red Sea are not only important to the region but are important more generally and hence there has been a strong international element to geoscientific research.

The Red Sea is valuable for Earth science because it is a rare example of a rifted continental shield transitioning to oceanic seafloor spreading. Properly characterizing the types of crust under the Red Sea could potentially constrain, for example, models for how Earth's lithosphere deforms during extension and how the underlying hot mantle melts as it experiences reducing pressure as it rises (e.g., [54,55]). One set of

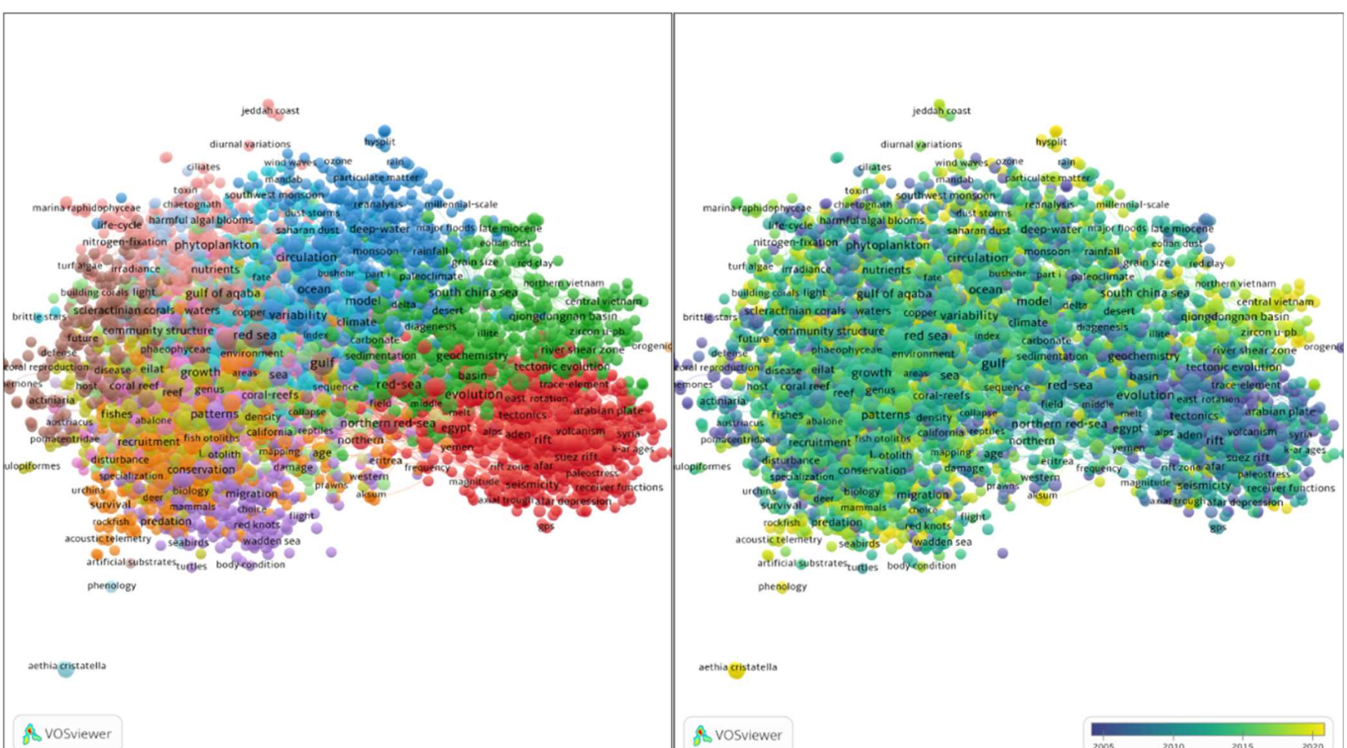

Fig. 1. Bibliometric analysis of research on the northern Red Sea (NRS): Left Panel: Visualization of the papers network confirming the main themes of research. Right Panel: Evolution of research trends between 2005 and 2022. The colors in the left panel indicate the themes of research that the papers (N.B. unfiltered) are discussing (e.g., geology, climate and modeling, biological research.etc.) while in the right panel the colors indicate the year of publication.

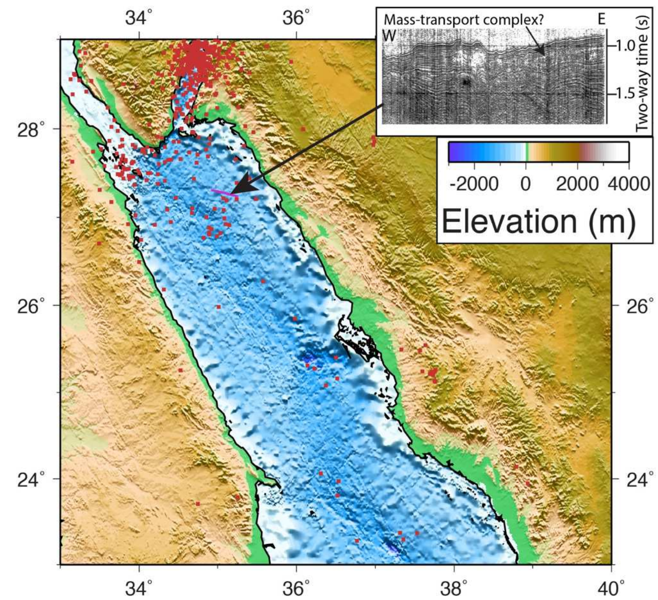

Fig. 2. Locations of earthquakes (red circles) in the NRS obtained from the International Seismological Centre for the period 1964–2016 (only earthquakes of magnitude $M>4.0$ are shown). Background hill-shaded topography is from Becker et al., [53]. Inset top-right shows high-resolution seismic reflection data collected with a watergun source by Jim Cochran and other scientists on RV *Conrad* in 1984. The data were collected where shown by the purple line on the map.

observations and arguments suggests that the NRS is almost all underlain by highly stretched continental crust, with the products of only modest magmatism [56,52,57,58]. For example, seismic velocities of the crust determined from seismic experiments [59] are lower than normal oceanic crust [60]. If the crust were oceanic, magnetic field anomalies would be expected to be organized into parallel stripes that are symmetric about a central axis of spreading [61], but this is not generally the case except at Mabahiss Deep [56,62]. However, other evidence points to the crust being oceanic [48]. For example, crustal thicknesses obtained from seismic experiments [59,63,64] are similar to that of oceanic crust, the match of lithological structures along the two coasts does not leave much scope for stretched continental crust [65-67], cross-rift trends in gravity anomalies are similar to those elsewhere in the Red Sea where we know the crust is oceanic [68] and basalts dredged from the deeps have mid-ocean ridge basalt compositions [69]. The lack of oceanic-like magnetic anomalies may be explained by the ultra-slow spreading rate and emplacement of magma under the thick evaporites [70]. In practice, the evidence of the crustal type is ambiguous and more geophysical experiments will be needed to address this and other questions of the structure beneath the northern Red Sea.

Earthquakes of magnitude $M>4.0$ (Fig. 2) are common in the Gulf of Suez and Gulf of Aqaba but are rare in the rest of the NRS [71-75]. Seismic coupling (the proportion of the Nubia-Arabia plate-tectonic movement recorded in the earthquake catalogues) for the northern Red Sea is an order of magnitude smaller than it is in the southern half of the Red Sea [74]. There is also no evidence for large earthquakes beneath the sea in historical records [76,77]. However, without a convincing explanation for this lack of seismicity, it is unclear if it instead represents a "seismic gap", i.e., merely a long period of quiescence between otherwise damaging major earthquakes. If so, it represents a significant hazard to communities around the coasts. Mitchell et al. [78] interpreted a cluster of landslides from high-resolution seismic data from the central Red Sea and speculated that they were triggered by earthquake ruptures on underlying normal faults. A small section of seismic data shown in the inset to Fig. 2 reveals an interval of chaotic reflections within otherwise simple parallel stratigraphy. This may be a mass-transport complex, i.e., a deposit produced by a giant landslide as could be triggered by a major earthquake. Further high-resolution geophysical studies are needed within the Red Sea to determine if such features are indeed caused by landslides and attempts should be made to date them to assess their frequency. The occurrence of ancient tsunamis (giant waves created by earthquakes and submarine landslides) can in principle be assessed from the sedimentary deposits they produce, which typically contain marine fauna that has been moved onto land and is clearly anomalous [79,80]. A systematic search for tsunami deposits (tsunamites) has yet to be carried out around the Red Sea, though such a search would provide a valuable constraint on tsunami hazards.

Sediments recovered from the Red Sea have revealed changes in the regional climate, with most detailed information from shallow sediment cores extending to ~500 thousand years (ka) in age [81-91]. The oxygen isotope ratio $^{18}O/^{16}O$ in Red Sea waters reflects the balance of evaporation (which preferentially removes ^{16}O) and replacement of water with normal oceanic ratios from the Indian Ocean. During the Last Glacial Maximum and other glacial maxima, the narrow and shallow entrance to the Red Sea from the Gulf of Aden at Hanish Sill restricted the replenishment and led to the waters becoming more enriched in ^{18}O than the global oceans. This is recorded in the isotopic composition of carbonates [92]. A model for the exchange of water over Hanish Sill coupled with evaporation effect on $^{18}O/^{16}O$ has been used to develop a relationship between sedimentary $^{18}O/^{16}O$ and relative sea-level at the sill [93,94]. Sea-level variations predicted with the relationship extend to ~500 thousand years ago (kya) and are compatible with global sea-level estimates, providing independent corroboration of them [95, 96]. The Red Sea sediments are therefore also important for research beyond the region. At present, only samples from rotary drilling [97] or from marginal sites and wells [98–100] are available that are older than 500 kya. Collecting a continuous sample of sediments to much older than 500 kya should now be a priority, particularly if that could include the Pliocene, which is widely considered an analogue for Earth's near warmer future given on-going global warming [101-103].

2.3. Red Sea ecology challenges

By examining the geological foundations of the Red Sea, we lay the groundwork to comprehend the ecological dynamics and concerns that have arisen in this extraordinary aquatic biome. In the following sections, we transition from the geological aspects to the ecological challenges that the Red Sea faces today. The Red Sea derives its value from a diverse range of productive habitats including coral reefs, mangroves, and seagrass meadows, which support the region's flourising tourism and fisheries.

2.3.1. Seagrasses of the Red Sea

The seagrasses are marine flowering flora (angiosperms) that are adapted to live entirely submerged. They grow in soft-bottom areas of the shallow seabed from the intertidal zone down to 70 m in areas with sufficient light which is critical for photosynthesis [104-109]. There are 12 major species extending along the Red Sea belonging to two families Cymodoceaceae (*Cymodocea rotundata; Cymodocea serrulate; Halodule pinifolia; Halodule uninervis; Syringodium isoetifolium; Thalassodendron ciliatum*) and Hydrocharitaceae (*Enhalus acoroides; Halophila decipiens; Halophila ovalis; Halophila ovata; Halophila stipulacea; Thalassia hemprichii*) [110,111]. Notably, the highest seagrass diversity is located between 18° and 25° N along the central Red Sea [107].

Light availability primarily determines the distribution and abundance of seagrasses, followed by depth, temperature, sediment characteristics, and salinity [112]. Sites with high abundance were observed located at ends of wadis (i.e., bed or valley of a stream) running into coastal areas, enriching the seagrass with organic matter, essential minerals, and good sediment characteristics for seagrass beds. On the other hand, the seagrass abundance and distribution can be restricted by the deposition of finer sediments and wave action [113,114]. Seagrass meadows are considered to be coastal primary producers that support a dense assemblage of marine organisms, especially commercially important shrimps and fishes, and function as nursery and feeding areas for sea turtles and dugong [115]. They can also sequester nutrients, and combat ocean acidification in the local area (by sequestering carbon) [116]. Furthermore, seagrasses can be used as important ecological indicators: the ratio of C/N can be measured to provide valuable information on the health and productivity of coastal ecosystems [117,118].

Unfortunately, Red Sea seagrass ecosystems are subject to direct and indirect stressors that can reduce productivity and cause major habitat degradation and loss. Seagrass growth and survival can be affected by rising sea temperatures, ocean acidification, and changing weather patterns as a result of global warming [106]. In addition, other anthropogenic factors such as coastal development and pollution from urban and industrial sources, as well as increased runoff of nutrients and toxins negatively impact seagrass growth. Overfishing of herbivorous species increases algal growth, which competes with seagrass for light and nutrients [106,119]. To prevent the long-term degradation of seagrass ecosystems in the Red Sea, it is imperative that these effects are addressed as part of rapid management strategies.

2.3.2. Red Sea corals

Red Sea reef ecosystems offer one of the most diverse and rich marine environments in the world [120]. With a limited connection to the ocean and minimal freshwater input, the Red Sea is extremely warm and getting warmer with an annual increase of 0.74 °C [121-124]. Furthermore, Red Sea coral reefs are ecologically and economically significant, and are also a popular diving and recreational destination [23]. In recent years, global marine heatwaves have caused mass bleaching events and deterioration of vast areas of coral reef communities all around the world, especially around the Great Barrier Reef [125,126]. In contrast to other biogeographic regions that are susceptible to heatwaves and suffer severe bleaching and mortality due to extreme warming events, coral communities of the NRS are known to tolerate extreme warming events [31]. Krueger et al. [127] showed a lack of bleaching signs in the Gulf of Aqaba despite exposure to accumulative heat stress equal to eleven Degree Heating Weeks (DHWs). However, a study [128] indicated that the regional Red Sea average Sea Surface Temperature (SST) was 27.88 ± 2.14 °C, with a trend of + 0.029 °C yr^{-1}, while Alawad et al. [129] identified that the warming in the NRS is around 0.04 °C $year^{-1}$ which is four times the global trend. Interestingly, Eladawy et al. [29] suggested that the NRS corals might resist the potential increase in water temperature beyond 2100 while a nested model reveals the moderating role of the northern island on the local thermal regimes [130].

The worst-case global emissions scenario would permanently impair the coral reef ecosystems of nearly all coral reefs worldwide (approximately 99% [131]). In spite of the fact that the Red Sea was historically considered a low-pressure environment, increased economic development has led to increased human pressure [132,133]. Usually, Egyptian Protected Areas rangers' reports found no bleaching stress, except for localized short-term bleached patches that were observed to recover quickly. This could be attributed to several factors such as temporary loss of zooxanthellae, predation, or competition over space by other neighboring colonies. Colony-specific bleaching could be due to diseases, lower salinity, high temperature, or temporarily increased light exposure that when combined for long durations cause stress on the coral tissue that can eventually lead to mortality [134]. Recently a study [135] covered rich spots of Egyptian corals in 2020; they concluded that bleaching mostly occurred in shallower reefs (0–5 m) with no correlation to the shore distance and was mostly concentrated in the southern Egyptian coasts, which should raise concerns about their climate change vulnerability. In part, this variance can be explained by the fact that corals along the Red Sea have the same thermal threshold (not location-specific) due to the fact that they were thermally selected for after the Last Glacial Minimum when they had to recolonize [30]. Another explanation of the bleaching-free Egyptian corals [31,136] could be related to the cooling mechanisms in the northern parts through the Northern Gulfs as well as upwelling in the western parts as discussed in our past analysis [137,130,138]. Remarkably, Osman et al. [139] suggested that NRS corals have novel associated microbiome communities (zooxanthellae and bacterial) that likely have the potential to tolerate thermal stress. Despite these hypotheses, the NRS coral regions are in great necessity of integrated physical and biological studies to shed light on local oceanic and biological features rather than relying on data-limited explanations.

2.3.3. Red Sea mangroves

Moving to mangroves, about 135 km^2 of the Red Sea coast is covered with mangroves (see Fig. 3) and their area is slowly expanding [140]. The absence of rivers lead to mangroves with dwarf height (~2–3 m) which grow taller moving to the south [141]. Major threats identified on the west coast (i.e., Egyptian coast) are coastal development (i.e., urbanization in El Gouna), destructive unregulated fishing (i.e., northern island region), and animal grazing as in Wadi El Gemal [142,143]. Moreover, continuous development on both sides of the Red Sea increased the heavy metals contamination hazard as confirmed by Alharbi et al. [144] and Mosa et al. [145] and was relatively higher in Yanbu than Jeddah and Al-Shuaiba, due to the adjacent petrochemical industries [146]. Previously, surveyed mangrove forests in the eastern part of the Red Sea proved to act as efficient traps for marine litter mostly linked to maritime traffic routes rather than land-sea activities [147]. The litter abundance was higher in the denser mangrove areas such as Yanbu which was confirmed to be one of the highest carbon sink spots in the Red Sea [148]. Although climate change mitigation can be significantly enhanced by mangrove reforestation rather than afforestation [149], approximately 410 km^2 of the Red Sea, mostly in Saudi Arabia, could be afforested with mangroves [150]. Although damaged mangrove areas due to coastal development were compensated for through afforestation projects leading to an overall slight increase in mangrove stands [140], there have been very few studies on the potential impacts of climate change (i.e., shifting wet season lengths and rainfall intensities [151]) on mangroves of the region [152]. Additionally, with the absence of permanent rivers in the Red Sea, the impacts of increasing freshwater (i.e., flash floods) damming along with excessive groundwater pumping [153] on mangroves have not yet been adequately analyzed through validated land-sea interaction models.

2.3.4. Red Sea fisheries challenges

Exploring the challenges that these marine ecosystems encounter sheds light on the intricate interplay between human activities and the natural world. In the subsequent section, we delve into the realm of fisheries and confront the pressing issue of unsustainability that looms over the Red Sea's delicate aquatic life. The NRS is a popular destination for tourists, and seafood is a key component of the local cuisine. The increasing demand for seafood regionally and internationally has put pressure on fish stocks [154]. For instance, Egypt's total catch has exhibited a marked elevation in contrast to other nations bordering the Red Sea (see Fine et al. [132]). Evidently, populations of some commercially important species such as groupers and snappers have declined by more than 80% in recent decades due to overfishing [15, 155]. The main destructive fishing method is bottom trawling, which can damage seafloor habitats and result in the unintentional capture of non-target species. Additionally, the lack of effective regulation and enforcement of fishing laws has allowed for overfishing and illegal, unreported, and unregulated (IUU) fishing practices to persist. IUU fishing includes activities such as fishing without a permit, using banned gear or methods, and fishing in protected areas, and is driven by the demand for high-value commercial fish species such as groupers, snappers, and emperors, which are often targeted by fishermen. The high demand for these species has led to their overexploitation and depletion, further exacerbating the problem of overfishing in the region [156,157].

Fig. 3. Top: Mangrove protectorate south of Qusier, and Bottom: Wadi Hammamat (i.e., dry river between Qena and El-Quseir), Credits: Nabil Elhady.

The aforementioned practices can further deplete fish stocks and undermine efforts to manage and conserve the region's marine resources.

Furthermore, Kitto and Regunathan [158] discovered a 12-year reduction in the catch per unit effort (CPUE) of commercial fish species in the Saudi Arabian Red Sea. The CPUE of the emperor fish species fell from 15 kg/hour in 2000 to 5 kg/hour in 2012, while the CPUE of the blue swimming crab fell from 7 kg/hour in 2000 to 1.5 kg/hour in 2012. According to Gabr et al. [159], the rabbit fish (*Siganus rivulatus*) population in Jeddah was overexploited based on growth rates and mortality coefficients. Overfishing of sharks in the Red Sea is a significant concern. The shark fishery experienced the highest annual decline rate, 10.3%, with several species facing the risk of extinction [160]. Similarly, the Red Sea Torpedo (*Torpedo suessi*) was assessed as critically endangered due to overexploitation [161]. Moreover, Egypt's overall catch in the early 1950s was roughly 6000 tons per year; this figure quickly climbed in 1960 and remained high, with the exception of a significant reduction in 1973 caused by the Israel-Arab war [162]. The catch peaked at roughly 50,000 tons in 1993 and had declined to around 25,000 tons per year by the end of the 2000s

Translocation of fishermen from outside the Red Sea to the region is widely considered to lead to overfishing and environmental degradation. Kaddah [163] reported that fishermen from the Fayoum region use illegal fishing methods such as dynamite fishing and poison fishing, which are highly destructive to the marine environment. This has led to declines in fish stocks and damage to coral reefs and other important marine habitats. Efforts to address these issues include the enforcement of regulations to prevent illegal fishing practices and the promotion of sustainable fishing practices. The General Authority for Fish Resources Development (GAFRD) has established a system of permits and licenses for fishing activities in the Red Sea, and has implemented measures to enforce fishing regulations [164]. However, Samy-Kamal [27,165] reported that despite the presence of regulations and management plans, there is limited enforcement, leading to continued unsustainable fishing practices. In addition, there have been efforts to promote capacity building programs for fishermen as well as alternative livelihoods revenues, such as ecotourism and aquaculture, which can help to reduce pressure on fish stocks and provide economic opportunities for local communities [166,167].

3. Red Sea development

Having delved into the geological history and ecological dynamics of the Red Sea, we now consider the bustling coastal zones that have become focal points of human activity and development. The shores of the NRS have witnessed remarkable transformations in recent years as burgeoning growth and urbanization shape the coastal landscapes on both sides of this iconic body of water. This section explores the dynamic coastal developments that are reshaping the socio-economic and environmental facets of the Red Sea region and explores strategies for ensuring an environmentally sound and socially just future.

3.1. Red Sea rapid coastal development

At roughly $7 billion/year, the NRS reefs were considered to be the reefs with the highest economic value worldwide [168]. Their strengths, weaknesses, opportunities, and the threats to their sustainability have previously been detailed [132]. Spalding et al. [169] reported that the annual on-reef tourism value was $4.51 billion out of a total tourism value of $5.46 billion, highlighting the impact of geopolitics and regional instability. However, it was projected that Egypt may experience 94.0% less tourism value by 2100 under the RCP 8.5 scenario as a result of reef loss [168]. However, these values have been contested after recent studies confirming the resilience of northern Red Sea corals [30,31]. Land-based activities, such as landfilling and the construction of inland coastal lagoons [170,171], place the most significant pressure on the Red Sea's marine environment. Severe interference with the shoreline, flash flood dams, wastewater treatment, desalination plants, and the destruction of coral reefs and mangroves significantly damage marine life. Unregulated tourism development has already caused severe damage to inshore reefs, created sediment transport imbalances, and disturbed the natural hydrodynamic system of the northern Red Sea during the past thirty years, especially in the western Egyptian side. As a result of the poor materials used in landfilling processes, 6.21 km^2 of the fringing reef between Safaga and Hurghada has been destroyed since 1984 [172-174].

With the establishment of a luxury Tawila Island Resort, Egypt's booming tourism industry recently expanded into the previously non-habitable NRS islands protectorate area [175,176]. Moreover, along the Ain Sokhna and Zaafarana coast, seasonal private resorts continue to grow with new state-sponsored cities such as Al-Galala City, which is built on a 700-meter mount plateau (spanning over 69 km^2) with a waterfront, is estimated to house more than one-million residents, and is planned to include two university campuses, hotels, an international marina, and an industrial zone of seven factories for marble, granite, phosphate and a desalination complex [177]. Furthermore, there is a new mineral-rich area development project in southern Egypt, known as the Golden Triangle Project, between the Red Sea cities of Safaga and El-Quseir, and Qena westward, on the banks of the Nile [178]. All these projects came with frequent accidents of oil spills from the Gulf of Suez (i.e., 60% of Egyptian crude oil production) and other anthropogenic activities near harbors [179-181]. Although environmental impact studies of the Egyptian Red Sea coastal zone started decades ago [182, 183], the area lacks comprehensive guidelines for different forms of coastal development leading to repeated disputes between developers and authorities [184]. Finally, quantifying the ecological services of impacted and healthy Red Sea corals could support the national and regional conservation efforts [185].

On the western side, three out of four mega-construction projects in Saudi Arabia are directly linked to the Red Sea marine ecosystem [186] and have potential environmental impacts [187]. Saudi Arabia intends to build NEOM (a new city spanning 468 kilometers along the coast with beaches and coral reefs) by 2025 at a cost of $500 billion [188]. Moreover, as a sustainable luxury tourism destination on Saudi Arabia's west coast, "The Red Sea Project" (TRSP) stretches over 28,000 km^2 including 92 islands with sensitive habitats [189]. In a similar manner, the AMAALA project (also called the Riviera of the Middle East) has already awarded over 100 contracts worth over $1 billion, covering nearly 4000 km^2 of Saudi Arabian Red Sea coast with 2500 hotels [190]. Notably, some studies assessed the anthropogenic impacts on the Saudi coastal zone with more focus on the southern parts. For example: human activities impacts on Jeddah [191]; Jazan development impacts [192]; shoreline changes in Al Lith [193]; and mass backfilling in Yanbu [194]. It is important to measure and model the impact these projects may have on the environment locally rather than simply relying on the claims that they will be minimally invasive or even enhance the biota and biodiversity [195]. Moreover, in the field of seawater desalination, Saudi Arabia is the world's leading country [196] and by 2050, 61 million people will rely on desalinated water from the Red Sea [197]. Consequently, local impact assessment studies should cover not only the brine outflow impacts on the adjacent marine environment but also the potential impacts disposal of desalination brines have on groundwater [198]. Noteworthily, while most of the Egyptian development projects are located within regions that are legally protected areas and their implementation and management are unknown, most of the Saudi Arabian development projects (i.e., NEOM, AMAALA, and "The Red Sea Project" (TRSP)) are located within regions that are not recognized by any legal means (see Fig. 1 in Gajdzik et al. [199]).

3.2. El-Quseir as a showcase for Red Sea development challenges

Inland cities with interdependent relationships to the Red Sea coast emerged over time. Understanding their historical development is another important aspect when investigating the region. El-Quseir city and Qift city are a case in point. The Eastern desert acted as a vital connection that joined the Nile to the Red Sea [200]. This arid terrain was rich in precious minerals that were highly sought after, prompting ancient Egyptian monarchs to dispatch expeditions that left visible marks along the Qift to El-Quseir route. Queen Hatshepsut even sent her own expedition from the anchorage at Marsa Gawasis, situated approximately 50 km north of El-Quseir, to trade wheat for valuable wood and other goods from African territories bordering the Red Sea. The city of El-Quseir, as with any other coastal city, depended on fish as a prime source of food in addition to small amounts of livestock feeding on desert vegetation. Some cereal, vegetables and other food subsidies were imported from nearby areas to supplement the diet of the limited number of city dwellers.

Surviving thousands of years, El-Quseir is an indication of the significant trade ecosystem between cities taking advantage of its geographic location, infrastructural corridors, and the resources existing in and around the city. Because of the thriving industrial activities, residents moved from nearby Upper Egypt cities such as Qift and Qena as well as other parts of Egypt. Its golden age, however, came to an end with the lack of fresh water needed for the growing number of migrant residents; nearby water wells and even water carried from the Nile by camels could no longer satisfy the booming city and water desalination became a necessity.

During the late 1980s the Red Sea coast was discovered by tourism. Resorts spread along the coast of the sea to make use of the magical corals and the aquatic life they support. The demand for fresh water increased and the government responded in El-Quseir by providing a water pipeline stretching from Safaga city 80 km away to bring the Nile water to supplement the water network existing in the city. In conversations during our field research in El-Quseir, locals indicated water as the number one problem of the city. All sorts of food are being imported from a 600 km away El-Obour wholesale market. Some vegetables and fruits are also being imported from the 180 km away Qift area. Fish as a food still exists but the percentage of fish sold every day that we observed is very low. From around fifteen small fishing boats at the port area, we witnessed only four functional ones operating daily. Fig. 4 shows a timeline of the evolution of El-Quseir.

Recent efforts by the Egyptian government to address challenges and opportunities of the Red Sea coastal region were addressed in Egypt vision 2052, where Safaga, El-Quseir and Qena were identified as the Golden Triangle area. This area is seen as rich with valuable minerals including limestone, phosphate rocks, sand glass, shale rocks, and gold among others. Moreover, sustainable tourism is envisioned to be the future of the area. The Golden Triangle [201] is planned to be a Special Economic Zone (SEZ) and one of the main drivers attracting foreign direct investment for boosting the Egyptian economy. Limited data is available regarding that ambitious project, let alone being publicly discussed and/or debated. The Golden Triangle proposal developed by D.Appolonia consultancy will include the four main categories: mining, urban planning, tourism, and transportation [202]. The proposed strategy focused on east-west linkages between the Red Sea and the Nile valley. Two new cities, New Safaga and New El-Quseir, are planned with an expected population of 250,000 citizens each. The total population target for the Golden Triangle is 800,000 inhabitants, a number that is more than fivefold of the existing population. The future vision of the Golden Triangle will significantly impact the Red Sea coast at the western Egyptian side. The adjacent areas of Hurghada, Safaga, El-Quseir, and Marsa Alam known as the Eastern Gate, will likely experience rapid subsequent growth, and is expected to increase by 6

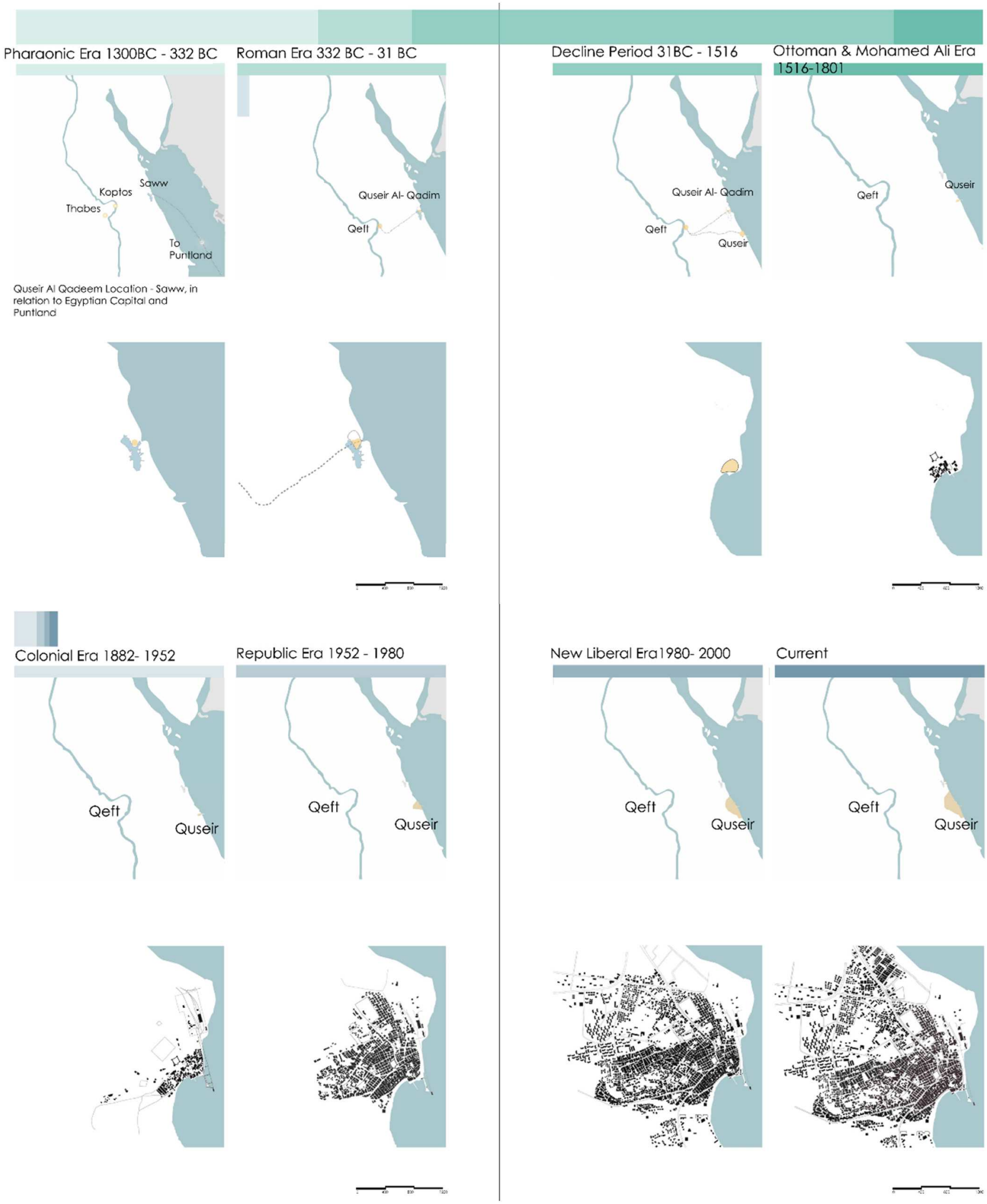

Fig. 4. Timeline of El-Quseir from 1300 BC till present.

million inhabitants by 2052.

Funding resources and feasibility studies are major concerns in long-term planning visions. In principle, strategic development towards massive growth attain their outcomes after many decades, and often risk high stakes; past experiences of new cities in Egypt are quite alarming, holding many lessons [203,204]. Environmental impacts are another major concern, especially with the colossal extraction of minerals and their accompanying industrial processes. The production of energy, water, and food to support the expected enormous activities represent an eminent threat to the environment, particularly with Egypt's commitment to the Paris accord of COP21. An intricate calculation of carbon emissions, with inclusive development of such a megaproject, is crucially vital on the local, regional, and global levels. The speculative masterplan is an updated version of an earlier one drawn back in 1998 with a targeted population of 110,000 inhabitants by 2017 through the generation of 14,000 jobs mainly in the tourism sector. Unfortunately, these numbers did not materialize by 2017 leaving only about 50,000 people inhabiting the area, according to CAPMAS (Central Agency for Population, Mobilization and Statistics, https://www.capmas.gov.eg/HomePage.aspx, 2015, 2017). The current masterplan for the city, prepared in 2019 and developed by GOPP (General Organization for Physical Planning – a central state-led agency), targets 82,000 inhabitants by 2032. Knowing that the main activity within the city is tourism, achieving its goals remains to be seen, yet aligning the city with climate change and biodiversity objectives seems to be the main way to proceed and so that is what we are investigating.

In contrast to megaprojects such as the Golden Triangle and the speculative masterplans, it is important to pose critical questions related to everyday realities. First, how to propose an urban development process [205] that is sensitive to historical areas, where sensitivity does not only include monuments but also situates people and nature equally at the center. Secondly, how the scale of intervention(s) of such development processes deals with significant challenges, especially those brought to attention by climate change assessment reports [206]. Here, the risks and inherent problematic outcomes of large-scale interventions stand against the potential low-risk outcomes of small-scale and surgical interventions. Thirdly, how to conduct projects in a context where the government is not effectively in control (Sims, 2010) and where local municipalities are not adequately elected and do not represent local communities, and where the non-governmental organizations (NGOs) are tightly controlled by the government [207]. Specifically, within Egypt, unelected local councils, mayors, and municipalities rely on central government funding, which remains notably modest at 11% of the state budget. This figure represents less than half of the municipal budgets observed in the majority of emerging economies [208,209]. Unfortunately, unsustainable approaches of bilateral donors underscore the deficiency in Egypt's environmental capabilities, hindering the effective allocation of environmental aid to domestic contracting firms [210] and local research centers. What is the kind of developmental process and action that can take place?

3.3. Challenges to inclusive development

Megaprojects proceed in the Red Sea region in ways that disavow sustainable and inclusive development. Questions of citizenship, local communities, legal rights, land tenure, recognition, representation, and distributive justice face social, environmental, political, and economic dilemmas of inclusion [211,212]. The ongoing development of mixed land use, zoning and foreign interventions require state policies and political will to address the environmental and social loss and damage. Reducing the problems of ecosystem disruptions to simple gatherings of so-called "community participation" upon which people's voices may or may not be included makes inclusion a performative act [213,214].

On the Saudi side of the Red Sea, Chalastani et al. [189] previously documented the challenges towards engaging stakeholders in the eastern coast of the Red Sea due to the lack of unions or even limitations of the national legal system. There is insufficient ethnographic research to assess realities on the ground. In fact, there is an overall lack of anthropological reports observing the downturns faced by local communities surviving at the edge of megaprojects, which is itself indicative of the risk accompanying conducting such research and speaks to the problem of safe and inclusive participation and freedom of speech. Indeed, unions cannot fully exist without some degrees of protection, and the presence of local representative governance and elected municipalities.

Similarly on the Egyptian side, Mr. Ali Yousef from SEAS (BEHAR in Arabic) for Environment and Training highlighted the challenges faced by permanent residents in the southern Red Sea coasts in Egypt; megaprojects often dismiss the everyday realities of indigenous Bedouin communities including challenges such as finding job opportunities, and inadequate public amenities and infrastructure (Mr. Ali Yosef statement). According to Yousef, communities in the area between the south of El-Quseir city until 100 km south of Marsa Allam city such as Abu Ghosoun village, Tondoba, Hamata village and Baranec village suffer from a lack of sustainable means of transportation, poor quality of education, a severe lack of medical services, and inadequate drinking water. Unfortunately, local inhabitants and natural reserves are deployed as backdrops for promoting tourism with slogans of biodiversity and exotic desert life, while the lifestyle of tourist resorts are exclusively luxurious and consumptive. Incentivizing the private sector to embrace sustainable means of inhabitation, micro-mobility, and respecting the culture of place is indispensable, and can be achieved through "urban acupuncture" and "tactical urbanism" with small-scale interventions [215]. Embracing such an approach of retrofitting existing masterplans of the private-sector towards inclusive development entails sharing amenities and facilities for health, education, fresh-water, and mobility that are on-site yet vacant and underutilized by resorts' tourists and are only partially operating seasonally. Opening up such infrastructure within enclosed private-sector projects to the local community can be effectively beneficial for diversifying users and engaging the various stakeholders in the area.

Moreover, economic justice is key to inclusive development. Due to the nature and characteristics of the type of tourism development in the Red Sea region, there has been a clearly documented leakage of tourism revenues; the revenue generated through tourism is lost to other institutions, countries or economies [216]. Local communities feel a sense of risk, with regional development robbing their workplaces, especially their heritage, and fishing and hiking often being rebranded as "ecotourism" to serve the private sector and international supply chains [217-219].

4. What is needed: crucial actions!

There has been a limited amount of multidisciplinary coastal research studying the assemblage of expansive urban growth, human-centered habitats, nature-based development, and small-scale tactical interventions in the Red Sea region. Our literature review reveals the relatively specialized way in which Red Sea research is conducted, which often lacks multi-disciplinary analysis in working towards environmentally sustainable and inclusive development. Research covering the topics of ecology, oceanography, development, and impact assessments remains modest in relation to the value of ecosystem services provided by the NRS. The National Fish and Wildlife Foundation (NFWF) and U.S. National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Conservation Program (CRCP) suggest implementing priority projects for Priority Reef Sites (PRS). In addition to coral restoration, their suggested projects cover establishing water quality targets, reducing land based pollution, increasing fish stocks of key species and responding to episodic threats [220]. Indeed, a holistic understanding driving focused and effective intervention efforts to restore the damage recurring to the environment is a top priority rather than large-scale megaprojects with unfocused objectives.

4.1. Immediate action: five crucial actions

The northern Red Sea is not alone in the world in dealing with coastal issues, and lessons can be learned from successes globally. Community and national efforts from the Middle East to the Americas can be used to inform science, engineering, and decision-making, through regular and repeated stakeholder engagement. Below, five critical actions or steps are proposed to help get the NRS on a path towards sustainability.

- **Development of a Red Sea spatial plan that prioritizes stakeholder inputs, reduces conflict and showcases sustainable growth**

  Research and successful implementations have proven that major endeavors involving use of coastal and marine areas require careful collective considerations with comprehensive stakeholder engagement. Marine spatial planning has been recognized as an invaluable approach that led to the management strategy and careful use plan for the Great Barrier Reef Marine Park [221], involving a spectrum of multi-use zones [222]. Key to the process of successful marine spatial planning is immediate and lasting stakeholder engagement with open, transparent process [223,224]. For example, valuable lessons may be learned from the planning process for offshore wind expansion in the United States, specifically in Rhode Island where the first offshore turbines were constructed in America [225]. Here a combination of science and stakeholder discussions enabled the identification of potential areas for offshore wind, and this allowed relatively rapid installation while other states have struggled. Challenges remain as expansion is planned, but for sustainability, stakeholder engagement should be coupled with science to guide decision-making. Organization cooperation and continued engagement has shown to be invaluable in a variety of cases [224], and the enabling and disabling conditions along with inclusivity and integration with government are critical to consider for the acceptance and expansion of the planning [226]. Additionally, opportunities for synergistic joint use of coast and ocean, also known as "multi-use", should be explored. Collaboration between different sectors, such as tourism and fisheries and/or conservation (e.g., creation of marine protected areas) can offer mutual benefits and reduce conflicts [227]. Guiding materials for stakeholder engagement and an assessment approach is available at: https://www.submariner-network.eu/multi-frame.

- **Integrated coastal ecosystem measurements and modeling to reveal the combined impacts of climate change and development**

  Tourism-related coastal development is growing exponentially in both Egypt and Saudi Arabia [189]. Generally, land-sea interactions have not been well studied in the NRS. For example, how the construction of small dams for flash floods will affect sediment and solute inputs and transport regimes along with the nutrient cycle is unknown. Furthermore, the impact of landscape and runoff changes (e.g., the reworking of the topography and introduction of vast vegetated areas and watering) on the coral ecosystem has not been considered. Moreover, it is unknown how land reclamation and/or the creation of inland lagoons will impact the important and sensitive balance of marine ecosystems. These combined stressors should be accurately addressed to inform and support sustainable small growth and mega-development, especially in Egypt and Saudi Arabia. An integrated study using a combination of measurements (e.g., of water quality properties, and coastal changes), sophisticated modeling, and analysis of geological history as a future climate analogue should be used to guide management planning for growth. The northern Red Sea is ideal to serve as a natural laboratory for testing local and global stressors on the resilient ecosystem.

  In the Red Sea, many physicochemical factors and stresses interact complexly, making an integrated coastal modeling approach necessary. The Red Sea, as a semi closed basin, is a research laboratory where one can not only discover one of the largest thermal refugia for corals [29-31], but even assess the coral response to unusual cold events [228]. Additionally, the limited land-sea interactions in the region, coupled with rapid tourism development, necessitate localized models (Fig. 5). In addition, the carbon cycle in the region has not been fully assessed, and some interventions, such as dam

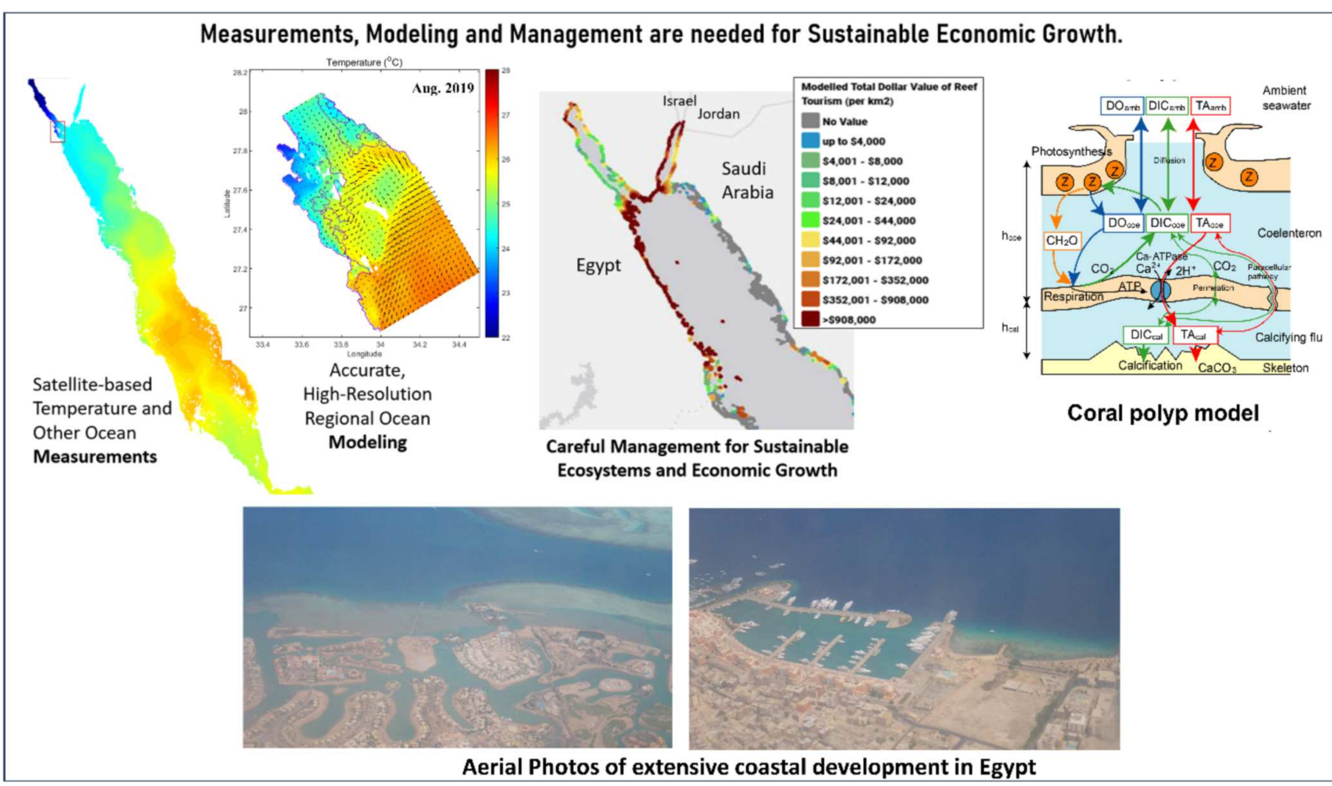

Fig. 5. Top Left: Nested Model for the Northern Islands region based on the developed regional modeling system for the Red Sea [130]. Top Middle: Coral reef value (US$) for tourism in the Red Sea, (Nature Conservancy, ocean wealth mapping http://maps.oceanwealth.org/). Top Right: A coral polyp model of photosynthesis, respiration and calcification [231]. Photos credits (Kazuo Nadaoka).

construction, should be studied through simulation. The suggested approach combines a three-dimensional ocean circulation model with a coral ecology model and a coral coverage model to simulate fluctuations in water temperature, carbon cycling, and nutrient concentrations around the coral reefs. A similar model can be applied to the Red Sea to assess the effects of coral calcification on photosynthesis and the impact of global ocean acidification. Finally, more connectivity studies [199] based on extensive modeling and monitoring can enhance the collaboration between Red Sea countries.

- **Determine and showcase sustainable growth practices and plans**

  As a proxy for the ongoing impacts of mega-developments on the marine environment, past development practices in Egypt and elsewhere should be examined and, where better, should be showcased. A good example might include how the coast, including coral ecosystems, has reacted to interventions in Hurghada. A multidisciplinary field-data collection approach should be combined with an integrated modeling approach to accomplish this. Additionally, the ways in which climate change (e.g., increasing thermal stresses, and significant changes in precipitation regimes) could limit the capacity of the NRS's ecological resilience should be further considered. Knowledge gaps in the region's earthquake and tsunami risk should also be addressed, and if necessary be taken into consideration in the design of disaster resilient human developments. Along with new research, insights from past projects, and sustainable growth insights, key data from around the globe should be collated, reviewed, rated, and shared publicly to inform wise development. Major multidisciplinary studies should be undertaken to assess how the ongoing, proposed, and future projects, such as the Golden Triangle in Egypt and the Red Sea Project in Saudi Arabia may impact the sensitive balance of the Red Sea biome.

- **Promoting cooperative sustainable fishing practices**

  Overfishing in the Red Sea has become a serious concern, and solutions are needed to ensure the sustainability of the region's fish stocks. It is important to note that solutions to overfishing in the Red Sea require a collaborative effort from governments, local communities, and the fishing industry. By working together, we can develop sustainable management strategies that ensure the long-term health of the region's marine environment and the livelihoods of those who depend on it. One of the most basic solutions to overfishing is to set a fishing quota for each country depending on several factors such as their population, growth rate, etc. In addition, a unified bylaw could be written for all of the Red Sea countries, to be implemented and enforced strictly with the collaboration of legal and executive entities in each country and under the supervision of regional organizations such as (PERSGA) with the help of local NGOs and scientific institutions in each country. Moreover, the role of education is critical to raise public awareness, starting in coastal cities, to promote sustainable fishing practices and communicate the impacts of overfishing on the local community's livelihoods. The imperative to raise fishermen's awareness and engagement should extend beyond conventional awareness campaigns and educational initiatives, encompassing additional incentives, notably subsidies to facilitate the transition to sustainable fishing gear. Furthermore, it is imperative to proffer alternative income sources, particularly targeting the poor fishermen in Egypt. Attaining this objective may be realized through a precise evaluation of the ecosystem services imperiled by these unsustainable practices. The engagements with fishermen should be characterized by a judicious balance of pragmatism and equitability. Finally, special support should be given towards filling research gaps related to overfishing and illegal fishing such as regular assessment of fish stocks for both key species and bycatch, including any consequent ecological interactions or potential threats. Similarly, investigation of the impact of climate change on fisheries, addressing the socioeconomic impacts of overfishing and future planning, and mapping of the scale of illegal fishing around the Red Sea should be prioritized.

- **Enact an ecological security system for monitoring selected sites and safeguarding the land and sea.**

  The construction of a novel ecological security system [229] would be an innovative approach to monitoring the marine ecosystem of the NRS. This system would ensure that critical aspects are tracked and that the negative impact of development will be minimized. Ecological security would be assessed by collecting and synthesizing multiple sources of data (e.g., turbidity, temperature, pollution), developing models, and integrating insights with ecological protection [230]. Community-based practices and input at key sites would be used to generate a localized assessment and integrated ecological security map for risk reduction and climate change adaptation. Through this system, urban growth areas, economic activities, and the nature of sustainable development activities would be identified. Engagement with the specific communities would occur through collective workshops, roundtables, and assembly discussions to exchange information and knowledge between private, public, and government stakeholders, indigenous communities, academics, researchers, and university students.

The NRS region encompasses four nations, with Egypt and Saudi Arabia possessing the preponderance of coastline within this geographic expanse. Several pivotal initiatives are feasible across all these nations, with a pronounced imperative for concerted endeavors, particularly in the realm of "Integrated Coastal Ecosystem Measurement and Modeling". Concurrently, Egypt is advised to accord primacy to the promotion of sustainable fishing practices, commensurate with its proportionate stake in the fisheries sector. Moreover, Egypt and Saudi Arabia are encouraged to establish effective channels of communication to reassess prior interventions within the Egyptian coastal zone and investigate potential congruent impacts of analogous projects executed in the Saudi Arabian ongoing projects.

5. Conclusions

The authors contend that there is a pressing necessity for the expeditious embrace of the five recommended pivotal measures within each nation, with collaborative endeavors fostered through external support. The future of the unique and diverse marine ecosystems of the NRS – as well as the striking desert landscapes surrounding it – will in great measure be determined by the magnitude and manner of land-based activities, most notably, the rapid development supporting the burgeoning tourist economy. This region faces a paradoxical situation in which a once sparsely populated beautiful natural environment attracts a rapidly growing number of visitors, who through their aggregate impacts jeopardize this very attraction. Further research is required to adequately understand the interplay between the natural world and current and future human developments. Ocean warming and acidification associated with global climate change threatens the health of coastal ecosystems, particularly coral reefs [232]. Coastal development, land use change, and pollution from a variety of anthropogenic sources, when not outright destroying them, may upset the balance of coastal ecosystems in unforeseen ways. Overfishing and bad or exploitative fishing practices are already impacting fisheries, which not only has negative implications for the coastal and oceanic ecosystems, but also has poorly characterized socioeconomic and cultural consequences for local communities. Important dimensions of this larger research undertaking will be to model and better understand the dynamic environment and the challenges it confronts, and to analyze the specific ecological and hydrological impacts of current development practices. This will help guide the adoption of ecologically responsive design and planning approaches such that future developments achieve new positive watershed development (NPWD).

Sedimentation associated with normal development site preparation and amendment practices, harmful concentrations of brine resulting from growing reliance on desalination technologies for water supply, and nutrient loading associated with current forms of wastewater treatment, combine to markedly alter the conditions of coral reef habitats. With the aim of minimizing further environmental degradation associated with the high concentrations of contaminants and pollutants, a sustainable approach to future seaside development should incorporate consideration of these specific water-related challenges at the outset of the design process. Such an approach should identify low cost means of rerouting contaminants away from threatened habitats and convert these to resources for use in other contexts. It brings to the fore cost-effective, ecologically responsive construction/development practices and water and wastewater technologies attuned to the hydrological and ecological particularities of the Red Sea. This systems-based design approach guides better, more sensitive site, landscape, and project planning, giving those developers embracing these practices market leverage in providing genuinely eco-touristic resort facilities and experiences.

Reciprocally, the condition and health of the natural world also impacts the course of human development. The ways in which and the degree to which local communities and economic activities rely on the Red Sea coastal ecosystems, the impact of changing climatological and ecological conditions, and unknown disaster risks such as earthquakes and tsunamis should be further studied to guide development in a resilient and sustainable manner. Regional tourism is driven in large part by the alure of coral reefs, so their degradation could have widespread and devastating socioeconomic consequences. Traditional approaches to megaproject and luxury resort development tend to alienate local communities and exacerbate existing socioeconomic injustices. Going forward, many lessons can be learned by collating and assessing past successes and failures. Inclusive approaches to development should balance the needs of local communities with the objectives of the tourism industry, state-sponsored urbanization, and outside economic drivers, and with the health of the coastal ecosystems. The engagement of stakeholders at all levels and across all social and economic classes, combined with a comprehensive and scientifically grounded understanding of the complex interplay of ecosystem utilization, ecosystem services, and biogeochemical and physical ocean systems, is critical for the planning and execution of environmentally sound, commercially successful, socially just, and forward-facing development. This will safeguard the unique ecological and cultural heritage of the Red Sea region, while adapting to changes and embracing future progress.

CRediT authorship contribution statement

Ahmed Eladawy: Conceptualization, Methodology, Writing – original draft. **Neil Mitchell**: Writing – review & editing. **Takashi Nakamura**: Writing – review & editing. **Yuta Takagi**: Writing – review & editing. **Momen El-Husseiny**: Writing – review & editing. **Nabil Elhady**: Writing – review & editing. **Brook Muller:** Writing – review & editing. **Sara Abdel-Hamid:** Writing – review & editing. **Asmaa Mohammed:** Writing – review & editing. **Kazuo Nadaoka:** Writing – review & editing. **J.P. Walsh:** Writing – review & editing.

Data Availability

Data will be made available on request.

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