Coral Reefs of the Red Sea with Special Reference to the Sudanese Coastal Area

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Abstract

Several features have favored the development of coral reefs in the Red Sea including the semi-enclosed nature, situation in an arid area with no permanent rivers or significant upwelling, its warm sea water and a reduced tidal range with moderate winds. The fact that the Red Sea coral reefs are the best developed in the western Indian Ocean is not surprising; more than 60 different genera of reef forming corals are found in the Red Sea alone with an exceedingly large recorded number of species. However, reef development varies from north to south in the Red Sea. North of 20°N reefs are well developed, occurring as narrow fringing reefs with steep slopes that drop into very deep water, particularly in the Gulf of Aqaba. South of 20°N the continental shelf widens and therefore reefs are less well developed vertically and often occur in more turbid water. Nevertheless, reef health is generally good throughout the Red Sea, with 30–50 % live coral cover at most locations and more than 50 % total cover on average. General threats to coral reefs and coral communities of the Red Sea include land filling and dredging for coastal expansion, destructive fishing methods, shipping and maritime activities, sewage and other pollution discharges, damage from the recreational scuba industry, global climate change, and insufficient implementation of legal instruments that affect reef conservation such as Marine Protected Areas (MPAs). The Sudanese reefs consist of three primary coral habitats along the Sudanese coastline: barrier reefs, fringing reefs and the Sanganeb atoll. They are considered to be in moderate to good health, with good fish fauna health. Raised fossil reefs that form coastal cliffs are characteristics of some sites such as Suakin and Dungonab Bay, while Sanganeb Marine National Park and Dungonab Bay–Mukawwar Island are the only MPAs in Sudan. Many of the present problems with coral reef conservation in Sudan are attributed to a lack of law enforcement, a lack of awareness, a weak legal framework, and the absence of surveillance. The crown-of-thorns starfish (COTS) *Acanthaster planci* was not recorded in plague numbers at any of the Sudan reefs. However, in 1999, bleached corals were estimated to cover 14 % of the substrate. In addition to the Jeddah Consolidated Convention, the Red Sea countries have become signatories to a number of international, regional, bilateral or multilateral agreements, and other legal instruments. Each country also possesses a relatively complete set of national laws and regulations. However, the implementation of these remains generally poor, and in some cases, there is no implementation or enforcement. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA) has made significant efforts to assist its member states, including the Sudan, to conserve their coastal and marine ecosystems and key species. Nevertheless, there is a need for further continued research on coral reefs and an information dissemination programme to enhance community participation and awareness.

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Introduction

The unique setting of the Red Sea has attracted the attention of scientists and divers from all over the world. It is situated in an arid area and has been described in literature as being one of the world's most diverse and varied tropical marine habitats and communities (Chiffings 1995; PERSGA/GEF 1998, 2001). It is a semi-enclosed sea nearly isolated from the Indian Ocean with great biogeographic complexity and high levels of endemism (Chiffings 1995; PERSGA/GEF 2001), especially among reef fishes and invertebrates, the latter including a number of dinoflagellates and euphausiids (Roberts et al. 1992; Getahun 1998).

Extensive surveys on coral reefs have been carried out in the Red Sea as one of the most attractive ecosystems. They have been among the most photographed and most studied of any in the world (Head 1987). Yet, signs of deterioration have appeared as a result of human influences (PERSGA 2006) as well as the recent phenomenon of global warming. Accordingly, several conservation initiatives have been carried out on regional and national levels under the guidance of the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA).

The Red Sea Coral Reefs

On a global scale, coral reefs are regarded as the most spectacular and diverse marine ecosystems on the planet, hosting hundreds of thousands of species, many of which are currently undescribed by science (Hoegh-Guldberg 1999). They are renowned for their extraordinary natural beauty, biological diversity, and high productivity. They represent crucial sources of income and resources through their role in tourism, fishing, building materials, coastal protection, and the discovery of new drugs and biochemicals (Carte 1996).

The coral reefs of the Red Sea are the best-developed reefs in the western Indian Ocean (PERSGA/GEF 2004a). Several factors are responsible for the development of such beautiful coral reefs in the Red Sea, for instance the absence of permanent rivers flowing into it bringing land sediments with their waters, and the absence of significant upwelling that brings the cold nutrient-rich bottom waters to the surface layers. Consequently, the amount of sediment is kept to a minimum and the Red Sea is regarded as one of the youngest and the deepest seas in the world despite its narrow shape (Vine 1985) (Fig. 1). The lower level of suspended sediments allows the penetration of sunlight further than in many other tropical seas (Vine 1985).

There is a clear north–south trend in the occurrence of the different community types and it appears that latitude, bathymetry, and coastal morphology are the underlying factors responsible for this pattern (Sheppard et al. 1992).

Fig. 1 Map of the Red Sea showing its *narrow shape* and surrounding countries (modified from Google Earth)

Additionally, the Red Sea is characterized by warm sea water, and a reduced tidal range with moderate winds indirectly related to the Monsoon. All these features have greatly favoured the development of coral reefs, particularly in the mid-portion of the Red Sea (Vine 1985). High evaporation and low precipitation also maintain the Red Sea as one of the most saline water masses of the world oceans. Due to the high evaporation and low precipitation, surface water salinities range from about 36.5 near Bab-al-Mandab to about 40-41 ‰ at the northern end of the main Red Sea basin (Alraddadi 2013). However, the salinity at the entrance of Bab-al-Mandab is 38 ‰ (Morcos 1970), the salinity at Port Sudan is 39 ‰ and at Dongonab Bay (180 km north of Port Sudan) it is 42 ‰ (records of the Institute of Marine Science of the Red Sea University, Port Sudan), and it reaches 42.5 ‰ at the Gulf of Aqaba. Therefore, the mean salinity of the Red Sea may be about 40.4 ‰.

The above description does not apply to the whole Red Sea; the Gulf of Suez, for instance, is shallow and sedimented and is not part of the main, deep Red Sea rift system (Sheppard et al. 1992). Reef development varies from north to south in the Red Sea. North of 20°N reefs are well developed, occurring as narrow fringing reefs with steep

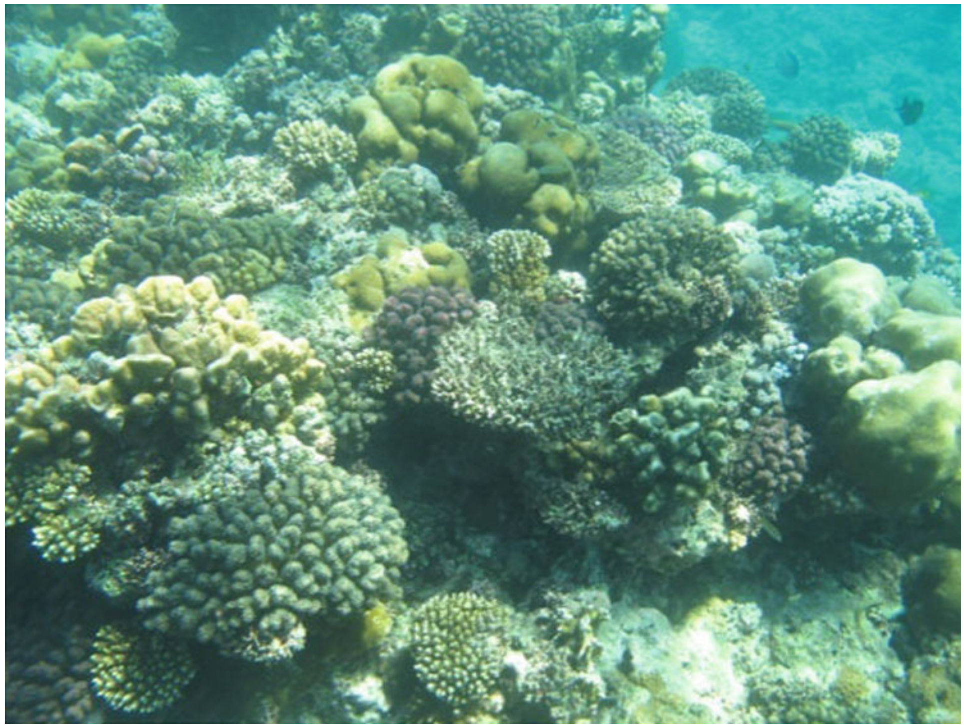

Fig. 2 Narrow fringing reef north of Jeddah allowing sediments to be washed to the deep waters (photograph by M. Qurban)

slopes that drop into very deep water, particularly in the Gulf of Aqaba. In Egypt, however, the distribution and development of reef-building corals is mainly restricted by water temperature, sediment load, salinity and light intensity. These factors combined make the Gulf of Aqaba a more suitable reef habitat than the Gulf of Suez (PERSGA 2006). The fringing reefs in the central and northern Red Sea are mostly narrow allowing sediments to be washed away to the deep waters (Fig. 2), while in some areas, especially further south, reefs extend commonly 1 km to seaward with well-developed beaches (Sheppard et al. 1992).

In contrast, the coastal shelf is much wider in the southern Red Sea, so sediments are less readily lost to deeper water. The shallow bathymetry created by these sediment deposits in the southern Red Sea combined with their fine nature results in substrate instability and associated turbidity in exposed conditions which limits the opportunity for the development of coral reefs (MEPA/IUCN 1987). Even if conditions are suitable for the growth of corals, the continuous deposition of sediments would cover the growing corals leading to their smothering and death. With more deposition of sediments, the newly formed soft bottom creates a suitable condition for seagrass and algal growth. Thus, seasonal coverings of macroalgae are a feature of shallow coral reefs in the southern Red Sea (Fig. 3), and they often form the major coverage of hard substrates in areas too turbid for coral growth (Gladstone 2000; PERSGA/GEF 2001). An account of the increase in algal cover with the fall in coral cover in the southern Red Sea is given by Sheppard et al. (1992). However, reef diversity in the southern Red Sea is greatest offshore and includes platform and patch reefs, barrier reefs, coral cays, and extensive fringing reefs around island systems, especially the Farasan and Dahlak (Eritrea) groups of islands (PERSGA 2006).

The richness of hermatypic corals in the Red Sea was believed to include 180–200 species (Vine 1986; Sheppard and Sheppard 1991; Sheppard et al. 1992). However, a recent extensive study of the central-northern Red Sea coastline of Saudi Arabia extended this to probably 260 species, based on recently described species and range extensions (DeVantier et al. 2000a). Descriptions of the composition and status of corals, coral reefs, and coral communities of the Red Sea and Gulf of Aden are given by Sheppard and Sheppard (1991), Sheppard et al. (1992), DeVantier et al. (2000a, 2004), Kemp (1998) and Kemp and Benzoni (2000).

Status of Coral Reefs in the Red Sea

The status of corals and coral reefs in the Red Sea and Gulf of Aden has been described by several workers, for example Sheppard and Sheppard (1991), Sheppard et al. (1992), DeVantier et al. (2000a), Kemp (1998) and Kemp and Benzoni (2000). Some of these works have been compiled by PERSGA (2006), based primarily on PERSGA/GEF (2003a, b).

Fig. 3 Macroalgae forming the major coverage of hard substratum north of Jazan (photograph by M. Qurban)

Reef health is generally good throughout the Red Sea and Gulf of Aden, with 30–50 % live coral cover at most locations and more than 50 % total cover on average (PERSGA 2006). These values are within the range of other reefs surveyed globally as part of the Reef Check programme. Coral diversity and reef-associated fauna were considered among the highest in the Indian Ocean region (PERSGA 2006). Between 1998 and 1999, in the central-northern Red Sea living coral cover ranged from less than 10 % to more than 75 % and averaged 35 % (PERSGA 2006). Most of these reefs were in good condition (DeVantier et al. 2000a) with little evidence of human impact apart from on reefs near urban areas.

The greatest development of corals in the Egyptian coast occurs at the tip of the Sinai Peninsula at Ras Mohammed and between Hurghada and Safaga (PERSGA 2006). However, live coral cover varies from 55 % in exposed areas to 85 % in sheltered areas (PERSGA/GEF 2003b). The diversity of reef-building corals, however, is distributed in the following pattern: Gulf of Aqaba (47 genera, 120 species), Gulf of Suez (25 genera, 47 species), northern Red Sea (45 genera, 128 species), central portion of the Egyptian Red Sea (49 genera, 143 species) and southern Egyptian Red Sea (31 genera, 74 species) (PERSGA/GEF 2003b). Fifty-three species of reef-building corals were found at reefs off Hurghada (Ammar and Amin 2000). The fringing reefs of the Jordanian coast border up to 50 % of the Jordanian coastline supporting a high diversity of coral and associated fauna. They contain at least 158 coral species from 51 genera (PERSGA/GEF 2003b).

Compared to other PERSGA countries, a lot of information is available with regard to the species composition and assemblage diversity of Saudi Arabian Red Sea coral reefs. Saudi Arabian reefs comprise of at least 260 species of scleractinian corals from 68 genera and 16 families, in addition to at least 30 taxa of soft corals, fire corals, zoanthids and gorgonians (PERSGA 2006). Coral reefs fringe much of the Saudi Arabian Red Sea coastline and offshore islands. The best-developed barrier reef system in the region occurs along the seaward margin of the Al-Wajh Bank. South of Jeddah reefs become less well developed along the coast (PERSGA 2006). Generally, the coral reefs of the Saudi Arabian Red Sea are in good condition, with the exception of those near Jeddah and Yanbu (PERSGA/GEF 2003b).

With regard to Yemen's Red Sea only about 25 % of the coastline supports coral reefs. The most highly developed reefs occur offshore, in the vicinity of the many islands that characterize the southern Red Sea (PERSGA/GEF 2003b). A total of 176 species of stony corals have been recorded from the Red Sea coast of Yemen, with richness at individual sites ranging from 1 to 76 species. At least 19 new records have been identified for the southern Red Sea. Reefs in the northern Yemeni Red Sea showed low live coral cover (average 17 %), high dead coral (DC) cover (average 34 %) and a high percentage cover of macroalgae (20 %). The northern and central Yemeni coast and near shore islands had very low live coral cover (3 %) and high DC cover (average 34 %) (PERSGA/GEF 2003b).

In Djibouti, most coral reefs are in average to good condition (PERSGA/ALECSO 2003) in relation to the mean abundance of fish and invertebrate indicator species and average of impact levels and substrate cover. Living hard coral cover across reefs averaged 39 % with a maximum of 80 % (PERSGA 2006). One hundred and sixty-seven species of corals have been recorded from Djibouti, including three species of black coral (PERSGA 2006). The highest diversity of corals was recorded from Arta Plage, Gulf of Tadjoura (93 species) followed by Iles des Sept Frères (84 species) and Trois Plages, Gulf of Tadjoura (75 species) (PERSGA/GEF 2003b). The corals of Djibouti are a unique assemblage of species due to the confluence of several biogeographic zones including the tropical warm water biota of the Indian Ocean and Red Sea and species common to cold water upwelling habitats of the Somali and Arabian Sea regions (PERSGA 2006). The southern coast, however, has poorly developed reefs due to cold water upwelling from the Indian Ocean.

Status of Coral Reefs in Sudan

The coastline of the Sudanese Red Sea is characterized by a large number of inlets, *mersas* and bays. In addition to others, it encompasses three primary coral habitats: barrier reefs, fringing reefs and the Sanganeb atoll (Fig. 4). The Sudanese coral reefs (Fig. 5) have attracted the attention of many national and international scientists. For instance, species lists for Sanganeb (Schroeder and Scheer 1981) and Wingate (Scheer and Pillai 1983) are available, and the reefs in the vicinity of Port Sudan have been extensively described (Schroeder and Nasr 1983). The Wingate and Towartit reef complex has been studied extensively by Vine and Vine (1980). Comparative ecological analysis of biota and habitats in littoral and shallow sub-littoral waters has been carried out in the Sudanese Red Sea with an emphasis on the Sanganeb Atoll (Krupp et al. 1994b).

Most of the coast is bordered by fringing reefs 1–3 km wide that are separated by deep channels from a barrier reef 1–14 km offshore. The outer barrier drops steeply to several hundred metres depth. Previous studies along these reefs suggested they are among the most diverse and spectacular in the Red Sea (Head 1980; IUCN/UNEP 1985; Krupp et al. 1994b; Ormond and Edwards 1987; Schroeder 1981; Schroeder et al. 1980; Vine and Vine 1980; Vine 1985, 1986). One of the most unique reef structures in the Sudanese Red Sea is the Sanganeb atoll (Krupp 1990), whose steep slopes rise from a sea floor more than 800 m deep (Fig. 6).

Some of these authors referred to these reefs, in the past, as being among the most diverse in the Red Sea (UNEP/IUCN 1988). However, the reality is more complex due to the interplay of many physical and environmental factors (Vine and Vine 1980). Others considered these reefs to be in moderate to good condition (depending on the abundance of fish and invertebrate indicator species, the average of impact levels and substrate cover), despite recent reports of extensive coverage of algae over a high proportion of the fringing reefs. The condition of Sudan's coral reefs was assessed in 1997 (PERSGA/

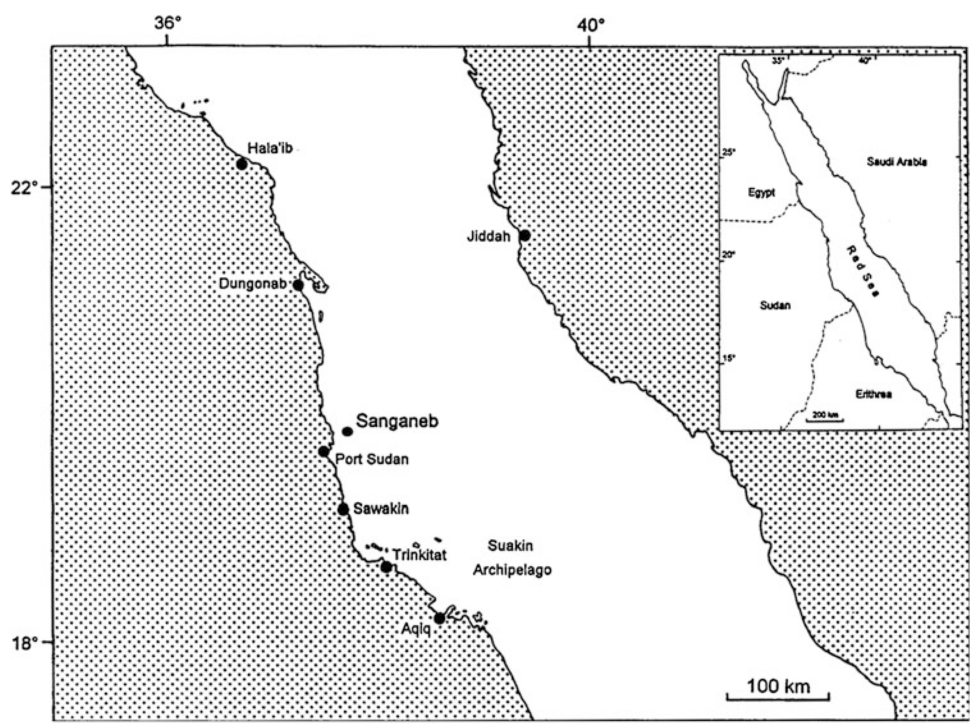

Fig. 4 The Sudanese coast with sites mentioned in the text (after Pilcher and Nasr 2000)

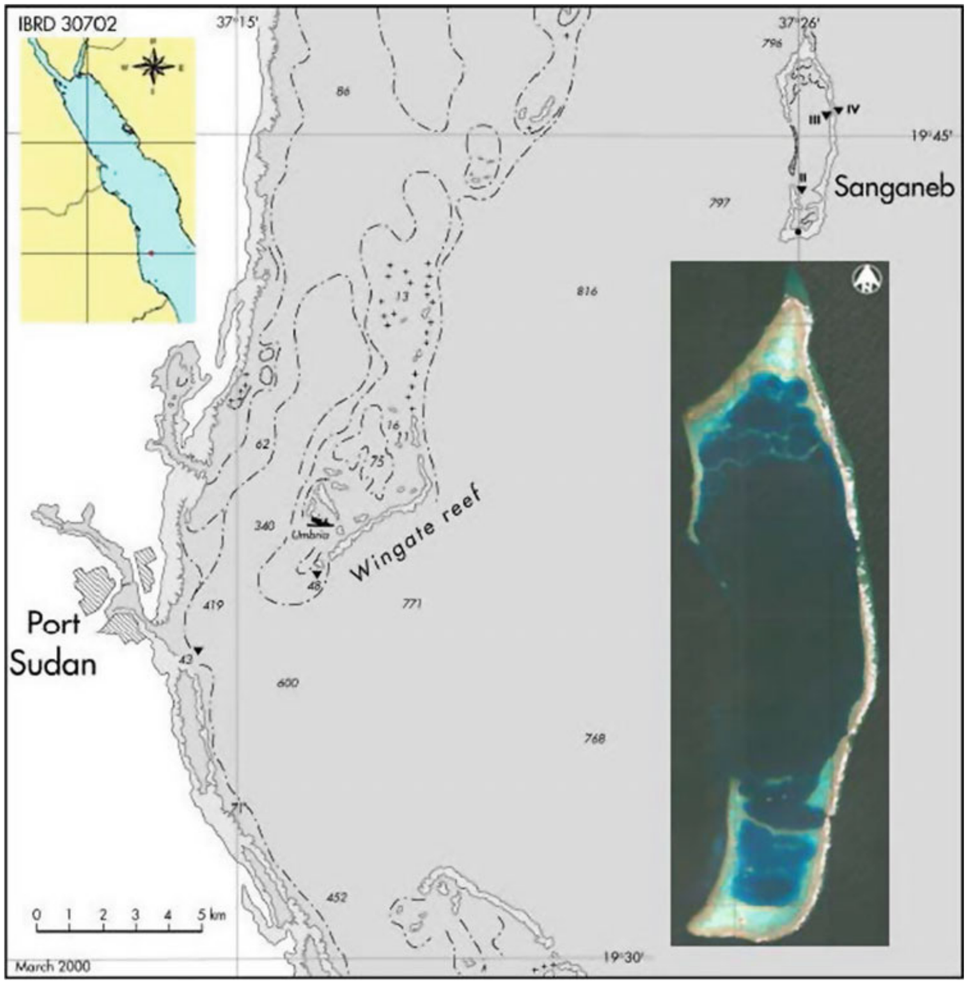

Fig. 5 Reefs in the vicinity of Port Sudan (modified from PERSGA/GEF 2001)

Fig. 6 Sanganeb atoll, a marine national park (photograph by Hans and Nasr)

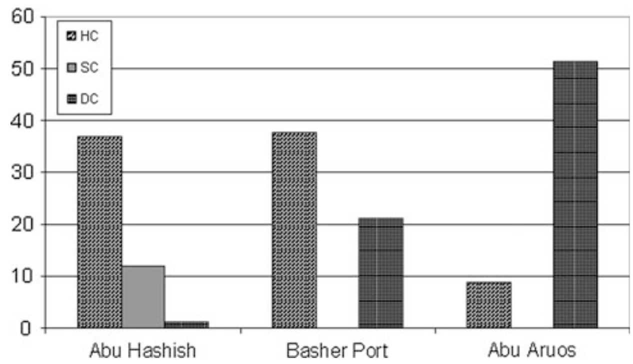

Fig. 7 Average percentage of coral cover in the three selected sites on the Sudanese Red Sea coast (after Nasr and Al-Sheikh 2000)

ALECSO 2007), 1999 (Nasr and Al-Sheikh 2000, PERSGA/GEF 2003b) and in 2008 (PERSGA 2010). Surveys by Nasr and Al-Sheikh (2000) at Abu Hashish Jetty (at Port Sudan) found that the percentage of hard live coral (HC) ranged from 23.5 % at 10 m depth and 50 % at 5 m, while DC ranged from 2.5 % at 10 m depth and 0 % at 5 m depth suggesting that the area was comparatively healthy (Fig. 7). However, key indicator species were abundant and diversity appeared high relative to other Red Sea sites (PERSGA/GEF 2003b).

The offshore reefs of Suakin have also been described as being of high diversity offshore with decreasing diversity as one proceeds towards the coastal fringing reef (Head 1980). Recent observations during June 2012 by the author showed that the reefs at the Sanganeb atoll, Shaab Rumi and the wreck of the Umbria, in the vicinity of Port Sudan city, are still in good condition (Fig. 8a–c). The wreck of the Umbria has been completely covered by various colonies of soft and hard corals, with cabins of the wreck providing perfect shelter and nursery grounds for various coral fish and other marine organisms.

The famous Conshelf 2 underwater living experiment conducted at Shaab Rumi reef by the Cousteau team of divers in 1964 has provided a unique opportunity to study growth rates of various corals and to investigate the factors affecting their settlement and development on what has turned out to be an almost perfectly designed artificial reef (Fig. 9, Vine 1985).

The coastline of some parts of both Dungonab Bay and Suakin harbour is characterized by raised fossil reefs forming coastal cliffs (Fig. 10). A combination of sea-level change and tectonic movements that have elevated certain sections of previously flourishing reefs above the present day sea level have resulted in such fossilized coral reefs (Vine 1985). In both areas, these fossils form coastal cliffs that are under continual erosion from the effects of waves, rainfall, wind and sun (Vine 1985). Although fragments of molluscs and branching corals cover the surfaces of these cliffs, massive corals such as *Porites* or the brain coral *Platygyra* are quite distinguishable as they effectively resist breakdown and remain as evidence of once flourishing prehistoric coral reefs (Vine 1985).

Threats Facing Coral Reefs

Coral reefs are being endangered by a diverse range of human-related threats (Hoegh-Guldberg 1999). The continued deterioration of coral reefs as a result of human influences has been observed by several writers (Bruno et al. 2007; Hughes et al. 2003). Such influences include eutrophication, increased sedimentation, over-exploitation of marine species and physical destruction by reef users (Sebens 1994), in addition to overfishing and land development causing widespread changes in reef ecosystems over the past two centuries (Hughes 1994). Such threats are compounded by the more recent, superimposed impacts of global climate change (Hughes et al. 2003). Many reef ecologists suspect that anomalously high ocean temperatures contribute to the increased incidence and severity of disease outbreaks (Bruno et al. 2007) causing global decline of reef-building corals; an estimated 30 % are already severely damaged, and close to 60 % may be lost by 2030 (Wilkinson 2002).

Moreover, increasing atmospheric carbon dioxide is expected to alter the alkalinity of the world's oceans over the next century, creating challenging conditions for growth and survival of corals and other carbonate secreting organisms (PERSGA/GEF 2003b). Coral bleaching and disease have already increased greatly in frequency and magnitude over the past 30 years (Hoegh-Guldberg 1999, Hughes et al. 2003). Present predictions are that calcification rates may slow by as much as two-third over the next 50 years, with the potential for catastrophic effects on reef growth and marine biodiversity in general (Kleypas et al. 1999).

Although large parts of the Red Sea are still in a pristine state (PERSGA 2006), coral reefs of the region are exposed to a variety of threats including land filling and dredging for coastal expansion, destructive fishing methods, shipping and maritime activities, sewage and other pollutants discharges, damage from the recreational scuba diving industry, lack of public awareness and insufficient implementation of legal instruments that affect reef conservation (PERSGA/GEF 2003b). The depth distribution of coral damage suggested that most of the damage in shallow sections of reefs was caused by anchors (PERSGA 2006). These rapidly increasing environmental threats require immediate action to protect the region's coastal and marine environment.

The Report on the State of Marine Environment in the Red Sea and Gulf of Aden (PERSGA 2006) has focused on the particular threats that affect coral reefs in coastal areas of PERSGA member states. These include pollution, port activities, intense coastal development (Jordan), high levels

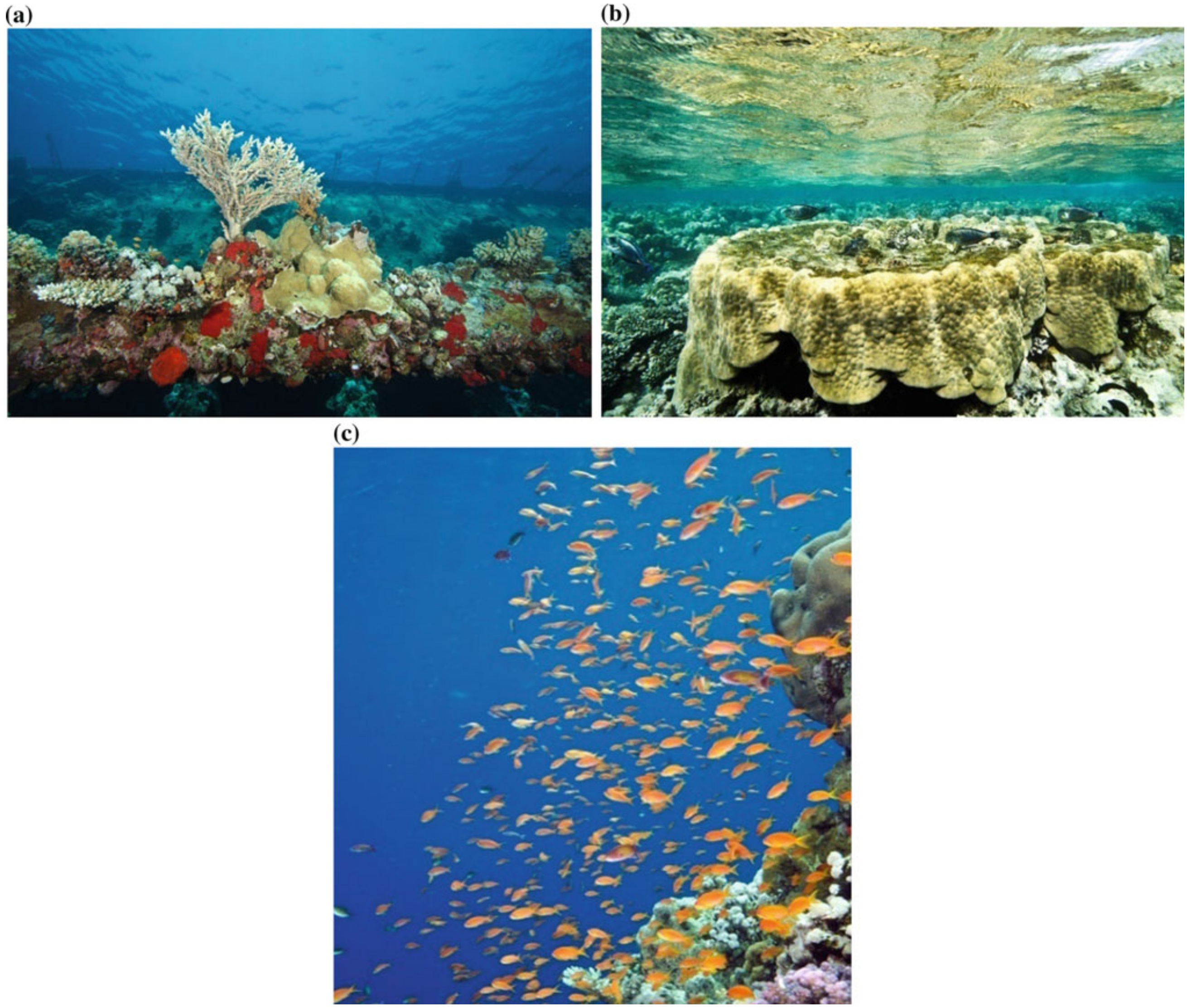

Fig. 8 **a** The wreck of the Umbria completely covered by various colonies of soft and hard corals (photograph by Hans and Nasr). **b** A "Micro-atoll" formed by *Porites* at Shaab Rumi (photograph by Hans and Nasr). **c** The steep reef slope at Sanganeb Marine National Park showing healthy corals and coral community (photograph by Hans and Nasr)

of coral usage, bleaching, crown-of-thorns starfish (COTS), or sedimentation on approximately 10 % of reefs (Egypt), fishing practices that damage coral reefs and the discharge of high temperature brine from power stations (Yemen) in addition to tourism and sewage discharges (Djibouti). Threats to Saudi Arabia's coral reefs originate primarily through industrial development and maritime transport, including oil spills, land filling, pollutant discharges and effluents from desalination activities (PERSGA 2006). The most acute damage to reefs is localized around major urban areas. With regard to Sudanese coastal areas, due to the limited industrial development along the Sudanese coastline threats are localized at the few urban centres, such as dredging and land filling for the extension of the main Port and the port at Suakin, as well as land-based pollution from the petroleum industry, although the tourism sector contributes to damage of the reefs by anchors and flipper damage.

Coral Die-off

Anthropogenic pressures on the Sudanese reefs are low, with those most affected being the fringing reefs along the coast in the vicinity of Port Sudan and Suakin (Pilcher and Nasr 2000). However, over 80 % of the shallow coastal fringing coral reef sites surveyed in 1997 had a high percentage of thin algal film cover, averaging 28.8 %. Such algal film

Fig. 9 The "garage" of Cousteau's Conshelf 2 underwater living experiment conducted at Shaab Rumi reef by the Cousteau team of divers in 1964 (photograph by Hans and Nasr)

Fig. 10 Raised fossil reefs forming coastal cliffs characterize parts of the coasts of Dungonab Bay and old Suakin, with close-up in inset image (photographs by Hans and Nasr)

cover was not found to affect those in depths greater than 10 m where reefs contain healthy colonies of framework corals (Pilcher and Nasr 2000). Similar observations were recorded by Vine and Vine (1980) who extensively studied the Towartit reef complex and reported poor hard coral growth and high algal covering on the fringing reef south of Port Sudan. The origin of the high algal film cover was attributed to a thermal event, possibly through runoff of high temperature waters from the lagoon (PERSGA/ALECSO 2007). The die-off event is consistent with reports of similar events in Saudi Arabia and Eritrea at the same time (PERSGA/GEF 1998). The algal cover did not affect larger colonies of *Porites* and *Acropora*, and it was suggested that the reef may recover from this within a span of decades, rather than centuries. The coral die-off has been observed even at the Sanganeb reefs which are far from the impacts of coastal activities (about 35 km NE of Port Sudan city), and also at Shaab Rumi situated north of Sanganeb atoll (Fig. 11). This observation suggests that anthropogenic coastal activities are not the only cause of coral die-off and that it is a natural phenomenon that requires further investigations.

Fig. 11 Coral die-off seen at various parts of the Sudanese reefs (photograph by Hans and Nasr)

Although coral diseases have never been investigated in the Sudanese waters, it is probable that competition between coral communities for light and space has resulted in weakening neighbouring colonies making them susceptible to diseases. Corals compete directly by damaging the tissue of neighbouring colonies with tentacles and digestive filaments (Lang and Chornesky 1990). These encounters usually cause lesions and local tissue necrosis (Lang and Chornesky 1990) that could facilitate pathogen transmission and colony infection (Bruno et al. 2007). The results of investigations in the Great Barrier Reef (GBR) showed that major outbreaks of the coral disease white syndrome only occurred on reefs with high coral cover after especially warm years (Bruno et al. 2007). Competitive interactions among corals on the GBR are relatively rare when cover is below 50 % (Connell et al. 2004). However, little progress has been made in identifying the causative agents for marine diseases or in applying standard epidemiological methods to assess impact or mode of transmission (Harvell et al. 1999).

Coral Bleaching

Coral bleaching is the disruption of symbiosis between coral hosts and photosynthetic microalgal endosymbionts, referred to as zooxanthellae (Brown 1997). The bleaching process is the loss of the zooxanthellae and/or their photosynthetic pigments causing the coral to lose colour (Rosenberg and Ben-Haim 2002). Bleaching may occur at local scales (Egana and DiSalvo 1982; Goreau 1964) or as a mass bleaching (Hoegh-Guldberg and Salvat 1995; Brown 1997). Six major episodes of coral bleaching have occurred since 1979 with massive mortalities of coral affecting reefs in every part of the world (Hoegh-Guldberg 1999).

The coral bleaching of 1998 was the most geographically extensive and severe in recorded history (Wilkinson et al. 1999), causing significant mortality worldwide (Baird and Marshall 1998). An estimated 16 % of the world's reef-building corals died (Wilkinson 2000). The impact of thermal stress on reefs can be dramatic, with the almost total removal of corals in some instances (Hoegh-Guldberg 1999; Brown 1997; Mumby 2001). This is why it is considered by most reef scientists to be a serious challenge to the health of the world's coral reefs (Hoegh-Guldberg 1999). In studies on coral diseases, some scientists describe coral bleaching as a disease—a process resulting in tissue damage or alteration of function, producing visible physiological or microscopic colour symptoms (Rosenberg and Ben-Haim 2002). On the other hand, coral biologists do not agree with this statement (Peters 1984; Hayes and Goreau 1998; Richardson 1998). However, the subject is debatable and no definite conclusions have been reached.

In the Red Sea and Gulf of Aden region, coral bleaching caused extensive coral mortality, including near total mortality on several reefs in 1998 (Pilcher and Alsuhaibany 2000; Spalding et al. 2001), with the exception of Jordan, possibly as a result of Jordan's more northerly latitude (PERSGA/GEF 2003b). Bleaching caused mass coral mortality in the central-northern Saudi Arabian Red Sea in August–September 1998 when sea-surface temperatures exceeded 31 °C, which was more than 2 °C above the mean monthly average (DeVantier et al. 2000b). Bleaching was patchily distributed and highly variable in intensity. The most intense bleaching occurred near Rabigh, where more than 65 % of total coral cover was bleached or had died

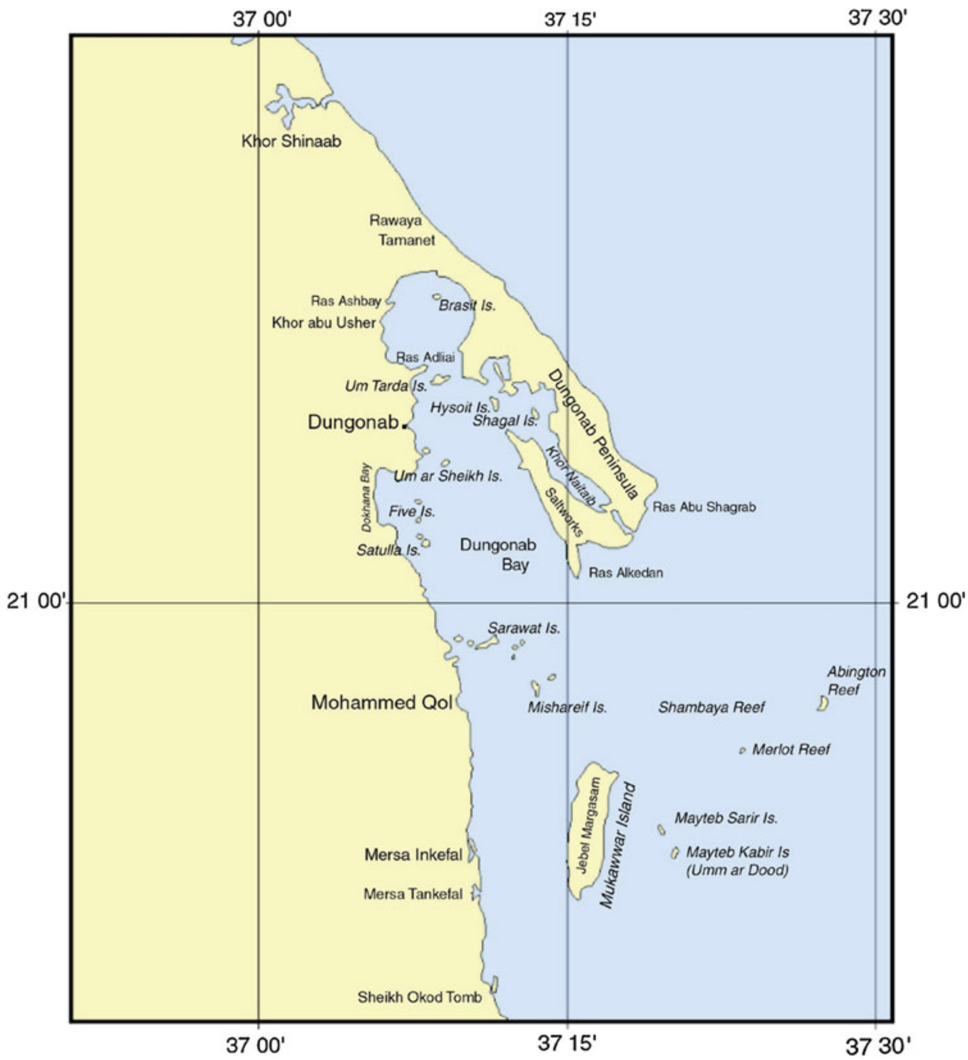

Fig. 12 Dungonab Bay/Mukawar Island MPA (after PERSGA/GEF 2004b)

recently (PERSGA 2006). Significant levels of coral mortality were observed along the southern Red Sea, where at some sites (e.g., Abalat Islands) live coral cover declined from 80 % in 1993 to about 10 % in 1999 (PERSGA 2006).

Coral reefs in the Dungonab Bay–Mukawwar Island MPA that lies at 180 km north of Port Sudan (Fig. 12) were assessed in 2002 (PERSGA/GEF 2004b). Major differences in the health of coral communities were present between parts of the MPA. The coverage of living coral was generally greatest within Dungonab Bay. The greater coverage of DC outside Dungonab Bay was attributed to the effects of the 1998 coral bleaching event. Corals within Dungonab Bay may be pre-adapted to greater ranges in sea-surface temperature because of the semi-enclosed nature of the bay. Additionally, it is possible that Dungonab Bay may not have experienced the elevated sea-surface temperatures because it is somewhat isolated from the main body of the Red Sea, unlike coastal areas of the MPA (PERSGA/GEF 2004b). Thus, Dungonab Bay may be regarded as a refuge for corals from future bleaching events.

The Crown-of-thorns Starfish (COTS)

The COTS (*Acanthaster planci*) feeds on coral tissue also resulting in coral bleaching. This starfish has been observed in low densities in several areas in the Sudanese waters without causing any problem to coral reefs. However, densities of COTS greater than 30 mature individuals per hectare consume living coral tissue at a rate greater than the rate of replenishment and the coverage of DC increases (PERSGA 2006). Outbreaks have been reported since the 1970s from Australia, Japan, Palau and Fiji (PERSGA 2006). Such outbreaks have been reported for many years in the Red Sea and some authors believe these to be associated with the removal of predators (by fishing) such as puffer fish and triggerfish (Ormond and Campbell 1971, 1974; Moore 1990) while others (Vine 1970, 1973) attribute such fluctuations to natural causes. Natural causes responsible for the outbreak of the COTS are described in some papers (e.g., Birkeland 1982), such as rain water run-off bringing nutrients and enriching plankton fauna thereby supplying food for the COTS larvae.

The outbreaks of the COTS varied in different locations in the Red Sea. In Egypt, for instance, there was an increase in the outbreaks of the COTS from a localized outbreak of 200 individuals at Ras Mohammed in 1994, causing 20–30 % loss of total live coral cover (Wilkinson 2000), to outbreaks of 250–300 small individuals at Ras Mohammed and 10,000 starfish around Gordon Reef near Tiran Island in 1998 (PERSGA 2006). Coral damage at Ras Mohammad was estimated to be 60 % (Abou Zaid and Kotb 2000). Between 1998 and 1999 over 60,000 starfish were removed from reefs (PERSGA/GEF 2003b). The COTS were present on patch reefs at a density of about 100 ha^{-1} in Saudi Arabia. Some sites had suffered substantial reductions in coral cover with associated shifts in relative abundance and community structure (DeVantier et al. 2000b). Coral reefs in Sudan were extensively damaged by COTS in the 1970s and 1980s. However, in 2002 and 2003, there was no evidence of outbreaks and the numbers of starfish were generally low (Kotb et al. 2004; PERSGA/GEF 2004b). Outbreaks are believed to have occurred in Yemen in 1994 and 1996 (Turak and Brodie 1999). In Djibouti, only 96 COTS were seen in 34 reef surveys and no aggregations were observed (PERSGA/ALECSO 2003).

Maritime Transport and Pollution

Having a semi-enclosed nature, the water mass of the Red Sea has limited opportunity for renewal, a process that takes 200 years for the entire water body, and 6 years for the surface layer (Sheppard et al. 1992). Hence, the Red Sea is vulnerable to all sorts of pollution especially by oil and other pollutants from land-based activities. The Red Sea is regarded as one of the busiest shipping routes in the world where about 25,000–30,000 ship transits occur annually, mostly involving the transport of petrochemical products (Gladstone et al. 1999), including more than 100 million tonnes of oil (UNEP 2002). Hence, the potential for major oil spills and disasters at sea is high (PERSGA/GEF 1998). The coral reef systems also pose several problems to navigation taking into account insufficient tanker safety specifications and poor navigation aids (Pilcher and Nasr 2000). The absence of adequate reception facilities at most ports in the Red Sea presents another risk of pollution by ballast water and bunker oil discharge. Chronic oil pollution has already been observed in the immediate vicinity of some major Red Sea ports as a result of operations at oil terminals or discharges from power plants (Gerges 2002).

The coastal and marine biodiversity on the Sudanese coast is in moderate to good condition; the mean percentage of living substrate cover is 32.66 for hard corals and 13.52 for soft corals (PERSGA 2010). Nevertheless, it has witnessed a recent rapid growth of maritime transport activities and industrial development, particularly in the coastal stretch between Port Sudan and Suakin (Nasr and Eltayeb 2012). In the past, Port Sudan used to handle approximately 1.5 million tonnes of petroleum products annually and accidents involving tankers together with discharges from unloading operations constitute a serious pollution risk (Pilcher and Nasr 2000). Recently, three oil exporting terminals have been established immediately south of Port Sudan increasing the risk of oil spills, but decreasing oil contamination in Port Sudan harbour.

Sewage

Sewage is a major source of coastal contamination throughout the Red Sea (UNEP/PERSGA 1997). It is discharged into the sea with poor treatment or sometimes untreated, especially in areas with rapid population growth and inadequate treatment facilities (PERSGA/GEF 1998). The input of nutrient-rich sewage water also results in eutrophication of the coastal waters around some population centres, major ports and tourist facilities (Gerges 2002). Vessel sewage and ship discharges of solid waste pose additional threats. Without waste reception facilities at the ports, ships dispose their waste directly into the sea.

Pollution from solid waste is a major problem, although it is limited to small areas around urban centres, coastal villages, large tourist developments and major shipping lanes (PERSGA/GEF 1998; Gladstone et al. 1999). Chemical pollution is limited to the vicinity of industrial zones and facilities (PERSGA/GEF 1998), which usually discharge their effluents directly into the sea. These industries include phosphate mines, desalination plants, chemical industrial installations and oil production and transportation facilities.

Coastal Development

Growing human populations, coastal urbanisation and tourist development as well as increasing oil and gas exploitation and transport in the region are expected to place increasing pressures on the health of the Red Sea (PERSGA/GEF 1998; Gladstone et al. 1999). Most of the environmental threats and impacts can be prevented by proper environmental planning and management, use of environmental assessments and through the enforcement of appropriate regulations, most of which are already in place.

Habitat destruction as a result of coastal development is localized. The extension of Port Sudan and the port of Suakin, which involved dredging and land filling, resulted in severe sedimentation pressure on coral reefs. In Suakin, parts of the coastal fringing reef have been removed for the extension of the port. A new port has been constructed at O'Seif and a fourth one is planned at Agig, and further reef damage is expected at these locations (Pilcher and Nasr 2000). The establishment of a proposed Economic Free Zone (EFZ), which will cover 600 km^2 between Port Sudan and Suakin, may also impact diverse coral reefs at Towartit, which are located immediately in front of the planned EFZ. Heavy industries, petrochemical industries, fish processing factories, slaughter houses with a capacity of 3,000 head per day, tanneries, and warehouses will be established in the area (Pilcher and Nasr 2000).

Coral Reefs Conservation Initiatives

For coral reef conservation to improve and to be effective in the region, there is a need for increased public awareness, increased implementation and enforcement of national and international legal instruments, and the execution of coastal management plans that integrate coastal development, pollution control and tourism with the maintenance of environmental quality in marine habitats (Pilcher and Nasr 2000). The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA) has played a key role in most initiatives formulated to conserve the marine resources of the Red Sea and Gulf of Aden including coral reefs. Concentrating on its long-term objective to safeguard the coastal and marine environments and ensure sustainable use of its resources, PERSGA has been active in promoting regional cooperation and providing support to national environmental plans through meetings, surveys, environmental assessments, legal developments and training workshops.

Legal Aspects

One of the most significant achievements of PERSGA was the development of international laws protecting the environment of the region. The Regional Convention for the Conservation of the Environment of the Red Sea and Gulf of Aden (the 1982 Jeddah Convention), the Protocol Concerning Regional Cooperation in Combating Pollution by Oil and other Harmful Substances in Cases of Emergency (1982), and the Action Plan for the Conservation of the Environment of the Red Sea and Gulf of Aden were signed and ratified by PERSGA member states; they provide the legal framework for cooperation in marine environmental issues, focusing on the prevention, reduction and fight against pollution. Major functions of PERSGA include the implementation of the Jeddah Convention, the Action Plan and the Protocol (PERSGA 2005).

New Legal Instruments were developed by PERSGA following a regional review of all marine environment-related legislation. In this context, three additional important protocols have been developed and signed by member states, namely the Protocol on Biodiversity and the Establishment of Regional Network of MPAs (2005), the Protocol on the Protection of the Marine Environment from Land-Based Sources (2005) and the Regional Protocol Concerning Technical Cooperation to borrow and transfer Experts, Technicians, Equipment and Materials in Cases of Emergency (2009).

The Red Sea countries have become signatories to a number of international, regional, bilateral or multilateral agreements and other legal instruments. Each country also possesses a relatively complete set of national laws and regulations. However, the implementation of these remains generally poor, and in some cases there is no implementation or enforcement (PERSGA/GEF 2003b).

Action and Contingency Plans

PERSGA has succeeded in the preparation of several action plans on regional and national levels in cooperation and coordination with member states and relevant international organizations. The objectives of these action plans were the conservation and sustainable use of key habitats and species in the Red Sea and Gulf of Aden region. These action plans were preceded by the preparation of a set of standard survey methods for key species and habitats (PERSGA/GEF 2004a) and collection of critical baseline data on key habitats and species through surveys and a series of training workshops.

The action plans relevant to coral reefs included the Regional Action Plan for the Conservation of Coral Reefs in the Red Sea and Gulf of Aden (PERSGA/GEF 2003a) and the Regional Programme of Action for the Protection of the Marine Environment from Land-based Activities (UNEP/PERSGA 1997). As an implementation of this regional programme of action, PERSGA supported the preparation of national programmes of action for the protection of the marine environment from land-based activities in member states. The countries of the region also prepared their national oil spill contingency plans and ICZM plans. For Sudan, PERSGA prepared the National Oil Spill Contingency Plan (PERSGA/GEF 2003a), a national ICZM plan, as well as surveys of habitats and plans for their protection in Sudan (PERSGA/ALECSO 2007).

Marine Protected Areas (MPAs)

MPAs are currently the best management tool for conserving coral reefs and many other marine systems. MPAs range from ineffective "paper parks", to multiple-use areas with varying degrees of protection, to marine reserves or no-take areas (Hughes et al. 2003). The Red Sea contains a number of MPAs (PERSGA 2006), and the formation of a regional network of MPAs has been proposed by PERSGA (PERSGA/GEF 2001).

During the implementation of the GEF supported project "Strategic Action Programme (SAP) for the Red Sea and Gulf of Aden", PERSGA succeeded in the establishment of a network of MPAs in the region, and the development of a Regional Master Plan which formed a regionally agreed framework for the planning and management of each MPA in the network (PERSGA/GEF 2002). With GEF support and PERSGA execution, existing MPAs have been enhanced, and new ones established, accelerated through a range of ecological and socioeconomic workshops, training and surveys. Further, PERSGA prepared a set of site-specific master plans with management guidelines for each of the new proposed MPAs based on the results of the field surveys.

Given Sudan's relatively small coastline, two important protected areas exist, with Sanganeb being a world-renowned marine protectorate. Sanganeb has yielded a wealth of information on Sudan's marine habitat and is the centre of much of the country's research into coral reef ecosystems (Pilcher and Nasr 2000). Dungonab Bay and Mukkawar Island National Park include within their boundaries, a highly diverse complex of coral reefs, mangroves, seagrass beds, beaches, and intertidal areas.

Sanganeb and Dungonab Bay/Mukawwar Island MPAs were declared by the Government of Sudan in 1990 and 2004, respectively. Both MPAs are not designated as no-take areas (NTAs) although NTAs provide the most effective protection of corals and coral communities from destructive activities such as uncontrolled coastal development; they also serve as a spatial refuge for a portion of the stock from which larvae and adults can disperse to neighbouring deteriorated areas. Dungonab Bay/Mukawwar Island MPA, at present, is regarded as a multiple-use area being used mostly by local fishermen, while Sanganeb MPA, with varying degrees of protection, is mostly visited by tourists.

Monitoring and Management Capacity to Conserve Coral Reefs

Capacity building. Regional capacity in the marine sciences has been improved through numerous workshops and training courses provided by PERSGA through an Annual Training Programme aiming at improving the performance of all stakeholders in the region in managing the marine and coastal environments as laid down in the Jeddah Convention (1982) and its attached subsequent Regional Action Plans and Regional Protocols. Such courses included, for instance, sewage management, fish stock assessment, environmental inspection, ballast water management, monitoring of invasive species, persistent organic pollutants, contingency planning in case of pollution, and economic valuation of marine resources. These training courses have been organized in collaboration with various international and regional organizations. However, routine follow-up monitoring from selected training should be performed immediately following the training programme to examine how the skills learned are being used within Sudan.

The on-the-ground projects. Under the framework of on-the-ground projects in the Member States, PERSGA implemented a number of projects at national levels which focused, for instance, on education for sustainable development (Jordan), eco-tourism (Egypt), coral reef conservation in Farasan Islands (Saudi Arabia), environmental awareness (Djibouti), and the development of national systems for contingency planning and marine pollution control (Sudan, Yemen).

The Regional Environmental Monitoring Programme (REMP). The Regional Environmental Monitoring Programme aims to provide information on the status of sea water to be delivered to the PERSGA's Information Centre in order to discuss patterns of changes in reporting the current status of the marine environment in the region and take the necessary decisions accordingly at the national and regional levels. The programme continuously and periodically follows physical and chemical changes of sea water in the Red Sea and Gulf of Aden region, where reports of monitoring data are collected from Member States as well as supporting countries to raise their technical and human resources to carry out collecting operations and sample analyses.

PERSGA's strategy to cope with the impacts of climate change. The Strategy is a regional initiative that aims to develop integrated programmes implemented through national strategies and includes a package of measures and procedures for the coastal and marine environments; these measures have been included within the main PERSGA programme components to facilitate the application process. These actions, when implemented as proposed, are regarded as an integrated plan by which to assess the viability and impact of climate change on environments, natural resources and economic development in coastal areas, in addition to enhanced capacities required for the implementation of plans to cope with these changes.

Main Conclusions

1. The Red Sea is renowned for its extraordinary natural beauty, biological diversity and high productivity especially with regard to coral reef ecosystems.

2. Reef health is generally good throughout the Red Sea with coral diversity and reef-associated fauna being considered among the highest in the Indian Ocean region.
3. General threats to coral reefs of the Red Sea include land filling and dredging for coastal expansion, shipping and maritime activities, sewage and other pollutants discharges, lack of public awareness and insufficient implementation of legal instruments.
4. Coral bleaching in the Red Sea caused extensive coral mortality, including near total mortality on several reefs in 1998.
5. PERSGA has played a key role in most initiatives formulated to conserve the marine resources of the Red Sea and Gulf of Aden including coral reefs.
6. Although the Red Sea countries have become signatories to a number of international, regional, bilateral or multilateral agreements, the implementation of these remains generally poor, and in some cases, there is no implementation or enforcement (PERSGA/GEF 2003b).
7. Much of the infrastructure needed for regular monitoring and effective management of coral reef resources in the Red Sea countries is available. Nevertheless, many of the present problems can be attributed to a widespread lack of law enforcement, a lack of awareness among law enforcement authorities and the absence of surveillance.
8. Although climate change is by definition a global issue, coral bleaching, die-off, diseases and resilience need further investigations in the Red Sea. A major problem in conservation of reef resources in most countries of the Red Sea is funding for research and management efforts.
9. In spite of PERSGA's efforts in training, authorities responsible for the management of MPAs in the Red Sea still lack experience in doing so in most countries.
10. The International Convention for the Prevention of Pollution from Ships (MARPOL) has not yet been ratified by all countries, because of a lack of port reception facilities. Member countries should assist PERSGA in its efforts to declare the Red Sea Special Area by ratifying MARPOL in addition to joining other related international conventions such as the International Convention on Oil Pollution Preparedness, Response and Co-operation (1990), the International Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties (1969), the Civil Liability Convention (1969), the International Oil Pollution Compensation Fund, and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention).
11. An environmental awareness and education programme for various target groups are urgently needed to enhance public participation in environmental initiatives.

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