Chapter 1

The Gulf [*]: A young sea in decline

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Abstract

This review examines the substantial changes that have taken place in marine habitats and resources of the Gulf over the past decade. The habitats are especially interesting because of the naturally high levels of temperature and salinity stress they experience, which is important in a changing world climate. However, the extent of all natural habitats is changing and their condition deteriorating because of the rapid development of the region and, in some cases from severe, episodic warming episodes. Major impacts come from numerous industrial, infrastructure-based, and residential and tourism development activities, which together combine, synergistically in some cases, to cause the observed deterioration in most benthic habitats. Substantial sea bottom dredging for material and its deposition in shallow water to extend land or to form a basis for huge developments, directly removes large areas of shallow, productive habitat, though in some cases the most important effect is the accompanying sedimentation or changes to water flows and conditions. The large scale of the activities compared to the relatively shallow and small size of the water body is a particularly important issue. Important from the perspective of controlling damaging effects is the limited cross-border collaboration and even intra-country collaboration among government agencies and large projects. Along with the accumulative nature of impacts that occur, even where each project receives environmental assessment or attention, each is treated more or less alone, rarely in combination. However, their combination in such a small, biologically interacting sea exacerbates the overall deterioration. Very few similar areas exist which face such a high concentration of disturbance, and the prognosis for the Gulf continuing to provide abundant natural resources is poor.

Keywords: Arabian Gulf, Persian Gulf, Coral reefs, Mangroves, Sea grass, Climate stresses, Temperature rise, Sedimentation, Fisheries, Development, Gulf War, Oil pollution, Pollution

[*] 'Persian or Arabian Gulf'. The name of this water body remains contentious. 'Persian Gulf' (or variants of it) is a name that dates back more than 1000 years. However, the name used by Arab states on the Arabian peninsular side is 'Arabian Gulf'. Fourteen historical variants of the name are known. On a regional level, the name 'Inner Gulf' of the ROPME Sea has been accepted by the ROPME Council. All riparian states have accepted this name. Here 'Gulf' is used (as is the case in several preceding scientific texts) hoping that the omission of geographic descriptors will be less offensive to some parties than use of the 'wrong' one would be.

1. Introduction

The Gulf is located in a subtropical, hyper-arid region (Fig. 1). It is shallow, and bordered by several wealthy states undergoing rapid economic growth involving substantial construction along shores and offshore regions, underpinned by its massive oil and gas industry, and by wealth derived from financial centres.

The Gulf's marine environment is changing rapidly, as is documented by numerous reports, referenced here. Some are derived from consultancy reports connected with major developments in the coastal zone. Changes are so rapid in this region, however, that many accounts are soon overtaken by developments which include construction, substantial coastline alterations, habitat loss, creation of beds of shifting or suspended sediments, and temperature and salinity changes in restricted water flows along the coast, as well as by climate warming.

This review does not repeat the fairly well understood marine ecology of the region. It focuses on the problems that cumulative changes are causing to the region's benthic and coastal ecosystems. It begins with a brief summary of biological information published since earlier reviews (Sheppard et al. 1992; Price 1993; Subba Rao and Al-Yamani 1998, 2000; Subba Rao et al. 1999; Khan et al. 2002; Abuzinada et al. 2008), underlining the naturally stressed environmental conditions. It shows that cumulative impacts and exploitation are all contributing to a general but marked decline in the Gulf's health.

1.1. The Gulf's 'shifting baseline'

A problem from which the Gulf suffers is the shifting baseline syndrome (Pauly 1995; Sheppard 1995). Even without the enormous construction projects, the accumulation of many smaller projects adds up to major changes. Most projects include 'baseline' surveys using a range of tools such as environmental impact assessments (EIA), in which, typically, the existing habitat is examined and a judgement made on the extent of potential impacts, and proposals on how to reduce these and monitor them. Sometimes expensive and lengthy modelling is undertaken as part of engineering studies. But commonly, the science has the ability to advise only slight changes to a project, and what is often missed also is that the 'baseline' chosen is little more than an already severely degraded marine ecosystem. Today it is difficult to find any meaningful baselines, not only because of ongoing, intensive constructions, but also because of several recent episodes of marine mortality from seawater warming.

The authors have been involved in numerous biological studies in this Gulf, but far too many studies remain confidential for alleged commercial or security reasons, and there is too little sharing of environmental information in this sea area. This is, perhaps, one reason why Gulf marine ecosystems are so poorly contextualised, why synergies are poorly understood, and why cumulative and trans-boundary impacts are rarely considered. Because of this, some studies preceding developments today may provide deceptively little useful information on how much more stress a benthic habitat might tolerate, and confusion in terminology adds to ambiguity (Foden et al. 2008). Some planned constructions near or on Gulf coral reefs provide a good example, because their present condition is now so distorted that the study can provide no meaningful, scientific reference value. This article attempts to add context to such developments.

An overarching problem in assessing development impacts is the difficulty of adopting a

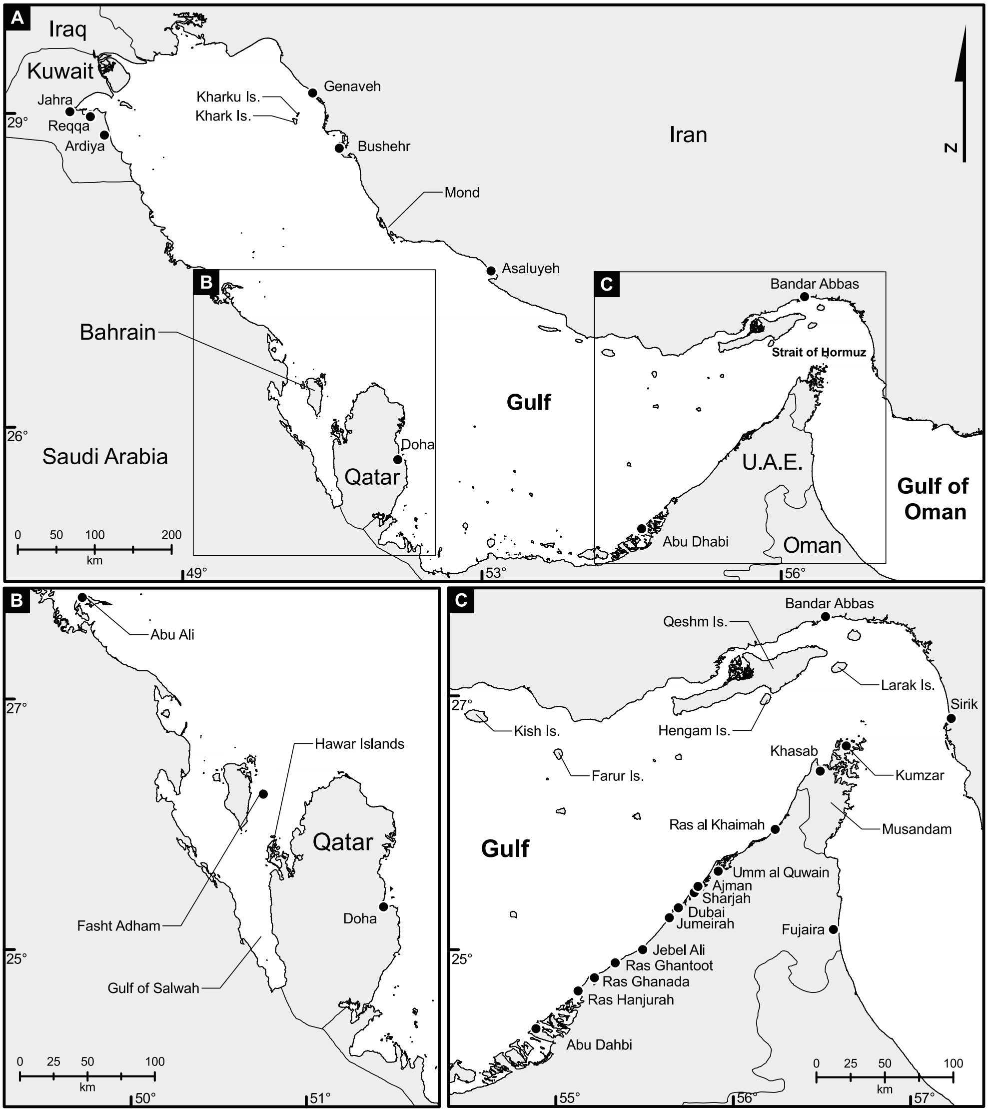

Fig. 1. Map of the Gulf showing place names and political boundaries.

synergistic or strategic approach. Of all the world's multi-national bodies of water, the Gulf is both of a uniquely small scale and is almost enclosed. Despite efforts of the Regional Organization for Protection of the Marine Environment (ROPME), there is limited exchange of information among government agencies, projects or neighbouring countries. There remains a general resistance towards a holistic approach that looks not only at immediate impacts but also synergies with other projects close by, despite calls for greater integration such as advocated by Krupp et al. (2006), Krupp (2002, 2008) for 'Transboundary Diagnostic Analyses', and a start made towards this essential aim.

Many new developments have very robust and well designed mitigation measures with, in

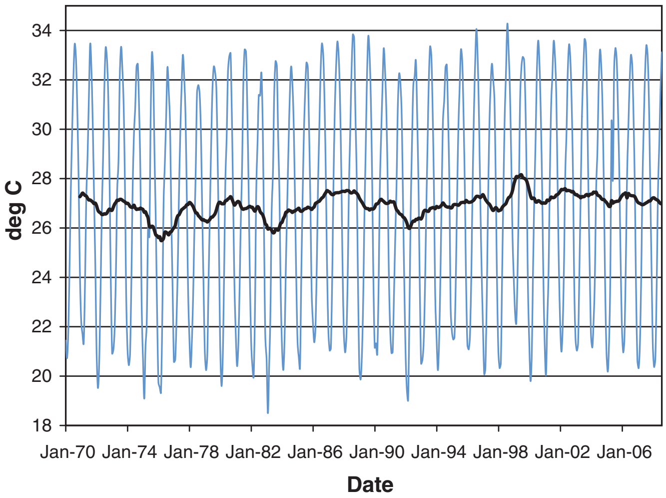

Fig. 2. Sea surface temperature from central Gulf (Hadisst1 data). 1 × 1° lat/long block whose top left corner is 57 N, 52 E. Central line is 12 month running mean.

Table 1. Temperature extremes recorded from Arabian coral reefs or from limestone platforms supporting coral communities.

Location	Latitude (N)	Min (°C)	Max (°C)	Range	Source
Saudi Arabia	27	11.4	36.2	24.8	Coles and Fadlallah (1991)
Qatar	24	14.1	36	21.9	Shinn (1976)
Abu Dhabi	25	16.0	36.0	20.0	Kinsman (1964)
Kuwait	29	13.2	31.5	18.3	Downing (1985)

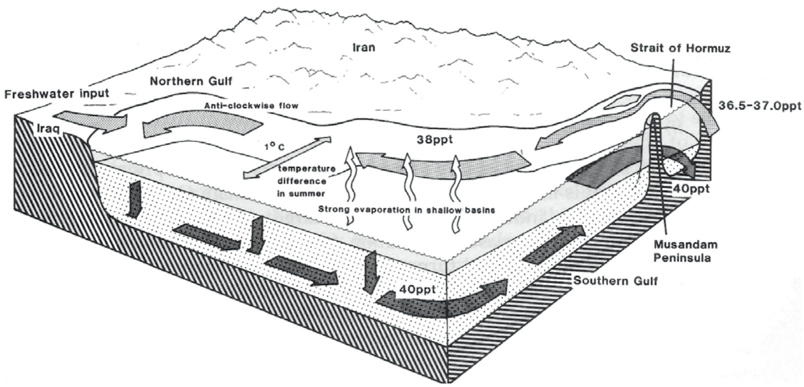

Fig. 3. Major current flows in the Gulf (from Sheppard et al. (1992)). Mechanisms causing the density gradient in the Gulf and the flow through the Straits of Hormuz. Light arrows are incoming surface water from the Gulf of Oman. Dark arrows are a denser, deeper water flow. Light shading in Gulf shows "wedge" of water of increasing density.

Table 2. Estimates of the water, dust and sediment budgets for the Gulf. All aquatic discharge values are in km3 y1. From Wright (1974), Saad (1985a,b), Reynolds (1993), Akmansoy (1996), ROPME (1999), Johns et al. (2003), Hashim and Hajjaj (2005), AlYamani (2008). [a] This waste water is mostly not new input, but is recycled from intakes. Note that although this overall value of 2 cm appears relatively small, it is not evenly spread but is concentrated in nearshore, shallow localities.

	Volumes	Depth equivalent
Water flows: Total volume	~8,600 km^{-3}	
River discharge	35–133 $km^3 y^{-1}$	0.2 my^{-1} depth
Surface inflow at Hormuz	7250 $km^3 y^{-1}$	
Deep outflow	6620 $km^3 y^{-1}$	
Net evaporation	350–800 $km^3 y^{-1}$	1.67 ± 0.39 m y^{-1}
Industrial discharges cooling water etc[a]	>7.3 $km^3 y^{-1}$	0.02 my^{-1}
Sediments: Dust storms input	60–200 × 10^6 tons y^{-1}	
River sediment input	62.4 ×10^6 tons y^{-1}	

some cases, state of the art monitoring programmes, but these might achieve little in terms of ecological sustainability because they are not encouraged or allowed to look at coastal development in a holistic or cumulative manner. This is recognised by Zainal (2009) who has considered accumulated impacts over the last 40 years in Bahrain, and by Al-Yamani et al. (2001, 2004) who similarly assessed past, current and future integrated impacts on Kuwait's marine environment. Some projects may eventually fail economically precisely because of their ecological shortcomings.

1.2. Topography and oceanography limitations

The Gulf has a maximum depth little more than 60 m; less than half that over most of its depth. Its photic zone mostly extends to only 6–15 m. Only the Iranian shore has steeply sloping sections. The Arabian shore is mostly sedimentary (Siebold 1973), with a very gradual slope. Limestone domes and some reefs give relief to the otherwise flat, sedimentary sea bed, supporting seagrasses, coral reefs, non-accreting coral communities, and algal beds, most of which intergrade with each other in many places.

High temperature and salinity of Gulf waters, combined with vigorous aeration of sediments by long-shore currents, causes much unconsolidated sediment to become cemented to hardgrounds by fibrous aragonite growth. Cementation may be rapid, requiring only months to a few years to develop. The resulting solid limestone provides habitat for hard substratum species, though sometimes the constant shifting of unconsolidated sand sheets can make new settlement difficult.

1.3. Natural stresses: temperatures and salinity

The water temperature regime and elevated salinity are important environmental stressors, and warming enhances effects of pollution (Schiedek et al. 2007). Air and water temperature track each other strongly (Sheppard and Loughland 2002). The Gulf's subtropical location means that it is warm enough to harbour a wealth of tropical biota both subtidally and intertidally, but its high-latitude location results in significant seasonal insolation fluctuations (Kleypas et al. 1999). Combined with atmospheric dynamics driven by cold winds (the Shamal) from the nearby Anatolian and Iranian highlands, these result in a marked amplitude of summer/winter temperature differences (Fig. 2 and Table 1).

High temperatures in summer and dry winds in winter create 1–2 m equivalent of evaporation per year, added to which is the general lack of precipitation. Salinity of >39 psu occurs in most Gulf waters. Much of the evaporation takes place along the shallow Arabian shorelines, causing increasing salinity and density currents which sink towards the northeast, eventually exiting the Strait of Hormuz in its deepest part (Hunter 1986). Replacement water flows in through the Strait of Hormuz in surface levels, passing inwards along the Iranian coast before reaching the Arabian coasts in a broadly anti-clockwise flow (Fig. 3). The mass water balance is given in Table 2. Several complications to this pattern are caused by, for example, the projection of Qatar into the central part, but the general pattern appears to be clear. Low flushing rates in major embayments such as the Gulf of Salwah south of Bahrain lead to salinities of over 70 psu. It has been supposed that propagules of corals, fishes etc. from outside the Gulf reach the Iranian shoreline first, and then circulate towards the Arabian States (Sheppard et al. 1992).

1.4. Historical ecological constraints

At the start of the Holocene, the basin was almost completely dry, so its marine history is only 15,000 years or so. Seabed presently at depths of 4–6 m has only been submerged for 3000– 4000 years, so modern benthic habitat development is comparatively young. The most extensive high-diversity marine environments in the Gulf are coral reefs and coral dominated substrata of hardgrounds, seagrass meadows and algal beds. At species level, the Gulf, on many counts, is biologically impoverished, partly because of its young age, but mostly, because of harsh environmental conditions. Low species richness was reported in early studies (Basson et al. 1977), and was confirmed by most later research, for most major benthic groups such as corals and echinoderms (Sheppard et al. 1992; Price 1982). Recent assessments of fish have raised earlier estimates to 542 species (Krupp et al. 2000) though the total number may be well over 600 (Price et al. 2002), while groups such as ocypodid crabs may be surprisingly species rich (Al-Khayat and Jones 1996). For reef-building corals, the Gulf is an impoverished subset of the Indian Ocean (Sheppard, 1998), ranking 24th out of 26 Indian Ocean sites in terms of species richness. In contrast, population densities of several groups are comparable to those of other tropical areas.

2. The main benthic habitats, ecosystems and species groups

2.1. Muddy habitats

The most widespread habitats are muddy substrata, which extend from inter-tidal saltmarshes and flats to the maximum depths of the Gulf. Because the photic zone is commonly <10 m depth, much of the benthos lacks significant plant life, but the large extent of this habitat, together with its high secondary productivity, make it extremely important, though commonly neglected.

Muddy tidal flats such as some in Kuwait Bay support dense algal mats where numerous small- and medium-sized diatoms, mainly *Amphora* and *Nitzschia*, and filamentous blue-green algae, play important roles in grazing food chains (Al-Zaidan et al. 2006), in CO_2 assimilation and also in adding mechanical stability to the mud (Al-Yamani and Saburova in press). Extensive muddy areas also provide feeding grounds for sea bird colonies too

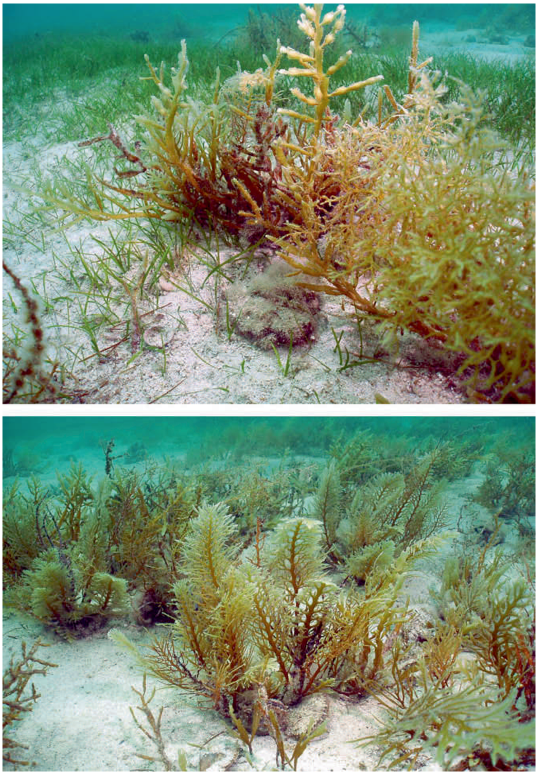

Fig. 4. Typical algal beds of the Gulf (Fasht Jaradah, between Qatar and Bahrain) 3– 5 m depth. Top: The phaeophytes *Sargassum* sp. and *Hormophysa*. Note intermixed seagrasses. Bottom *Hormophysa cuneiformis* on hard substratum concealed by a thin layer of sand. Photos Charles Sheppard.

(Al-Zaidan et al. 2006; Al-Yamani and Saburova in press).

Brief assessments in the Emirates of Ras Al-Khaimah and Umm Al-Quwain have revealed that their extensive submerged and tidal muddy habitats are extremely rich in invertebrates (>800 individuals m^{-2} for the hermit crab *Diogenes avarus* plus other crab species in lower densities), sting rays (as much as 1 Dasyatis spp. in each 5 linear metre), high densities of juvenile fish (>5 families) and 37 species of birds (Medio 2006).

These Emirates, Ras Al-Khaimah, and that at Ras Al-Beidah (Umm Al-Quwain) in particular, are crucial for birds, and provide large, important coastal wetlands which act as the last refuelling stop-over for thousands of migrants coming from Northern Hemisphere breeding grounds to Southern Hemisphere wintering grounds before crossing the Arabian Desert. They also provide a stop-over for these migrants before reaching breeding sites on their return. The tidal flats provide both the necessary foraging (= fat loading) and roosting (= energy sparing) sites for migrants before they continue their long journey (Medio 2006). In addition, many of these sites are crucial for turtle feeding and nesting.

2.2. Macroalgae

Macroalgal meadows (Fig. 4) are a major sublittoral habitat on limestone mounds and diagenetic hardgrounds. These usually have patches of sand which commonly support seagrasses in intermixed assemblages (Fig. 4 top). Where seagrasses are sparse, macroalgal beds are the primary habitat for all organisms requiring plants for shelter. Algae meadows also co-occur with seagrasses and corals, and all these habitats are not mutually exclusive in the Gulf (Fig. 4 bottom). Large *Sargassum* beds commonly dominate off- shore domes of limestone which otherwise appear relatively depauperate, developing to a maximum extent in winter (John and George 2001). Dense *Hormophysa* beds occur around the Qatar peninsula and western Abu Dhabi, along with the coral *Siderastrea savignyana*. These large phaeophytes are rarely consumed directly by herbivorous animals, but their substantial volume and subsequent decay provides considerable input into the microbial loop. During winter and spring, especially after a storm, *Enteromorpha* and *Ulva* are washed upon sandy and muddy shores in many areas such as Kuwait Bay (Fig. 5), giving rise to further input to the detrital food chain in both supralittoral and sublittoral zones.

2.3. Seagrasses and mangroves

Seagrass and mangrove ecosystems are poor in species. Three seagrasses (*Halodule univervis*, *Halophila ovalis*, *Halophila stipulacea*) and only one mangrove (*Avicennia marina*) occur naturally.

Rich beds of the seagrasses have high productivity and support diverse biota (John and George, 2006). In very shallow embayments, seagrasses are intermixed with algal beds. About 9% of the Gulf's faunal taxa have been estimated to occur in its seagrass meadows, about half of which are molluscs. Of commercially significant species, the pearl oyster (*Pinctada radiata*) can occur in association with seagrass especially as juveniles, and many important fisheries species such as shrimp (*Penaeus semisulcatus*) depend on these meadows in early postlarval stages, having migrated there from dense algae thickets in close proximity. Seagrasses also sustain the world's second largest population of the vulnerable Dugong (*Dugong dugon*) and are important breeding and foraging areas for the endangered Green Turtle (*Chelonia mydas*), which exhibit continuous decline in populations worldwide.

Fig. 5. *Enteromorpha* on Kuwait Bay shore, April 2008. During winter and spring time, seaweeds cover the shallows and sandy and mud shores after storms in Kuwait Bay, giving rise to detrital food chain at supralittoral and sublittoral zones. Photo Igor Polikarpov.

Mangrove forests today consist of just one species, *Avicennia marina*, but possibly one or two more species occurred in past centuries in some locations. Today they occur mostly as reduced remnants of once much greater expanses. Mangrove forests in Iran still cover more than 15,000 ha, distributed from the Gulf of Oman to the Mond protected area in the western part of the Gulf (Fig. 6) (Safiari 2002; Mehrabian et al. 2009). In Iran a second species, *Rhizophora mucronata*, is found at Sirik in the Strait of Hormuz where it occupies about 20 ha. One of the largest mangrove stands is located at Qeshm Island in the Strait of Hormuz, with an extent of about 9,000 ha and a density of 859 trees ha1 (Danehkar and Jalali 2005).

Mangrove habitat has suffered one of the more striking reductions in extent due to recent developments. Intra-specific genetic diversity may remain high within this species, possibly due to high degree of isolation between increasingly restricted stands (Dodd et al. 1999). The genetic variation of *A. marina* shows inbreeding in Bushehr province (Valipour Kahrood et al. 2008), but overall genetic diversity in the Gulf has received little attention.

Several efforts have been made to restore mangroves. In 1991 the Kuwait Institute for Scientific Research initiated studies to naturalize mangroves under Kuwait's coastal environmental conditions. Three experimental plantations established in 1993 and five more established during 1999–2000 suggested that various ecotypes had good potential (Bhat et al. 2004). The *Avicennia marina* used were procured from the United Arab Emirates, and marine fauna

Fig. 6. Mangrove vegetation of *Avicennia marina*, Mele Gonze, Bushehr province. Photo: A. Mobaraki.

flourished in these plantations. Large amounts of leaf debris accumulated in the inter-tidal zones and crab burrows increased (Al-Nafisi et al. 2009). In Dubai Creek also, extensive mangroves were planted in the early 1990s, using seedlings with different genetic origin, into mudflats where mangroves did not naturally occur, so that intertidal birds in those mudflats disappeared. They do now have important resident and migratory bird populations, though not of 'natural' origins. In Qatar, on the other hand, some replanted mangroves (as well as existing mangrove areas) have subsequently been eradicated on a large scale after planting, for various construction reasons, including the desires of nearby residents who dislike them (Gillespie 2009).

2.4. Corals, coral reefs and diagenetic hardgrounds

Many of the 'coral reefs' described for the Gulf are areas of hard substratum which are not actively accreting but are modern veneers of living coral on much older limestone domes or recently formed diagenetic hardgrounds, many of which are visually indistinguishable from true reefs (Shinn 1969) (Fig. 7 and 8). These together with the relatively few true reefs provide the most diverse habitats, though not necessarily the most productive. They have been subject to the most research (Table 3). Most of the 55–60 coral species are found widely in the Indo-west Pacific, but the closest faunistic proximity to other coral areas unsurprisingly is the Arabian Sea and Red Sea (Sheppard and Sheppard 1991; Wallace 1999; Veron 2000) due to a shared paleoceanographic history of restriction during the last sea level low stand and simultaneous flooding during the Holocene transgression (Sheppard et al. 1992). There are few or no endemic corals in the Gulf; some previously thought to be endemic also occur in the Gulf of Oman (Claereboudt 2006), a situation which also probably applies to fish (Krupp pers. comm.).

The total reef extent and coral diversity may be highest along the Iranian shore, but throughout, many corals have been killed by warming episodes, which are predicted to increase in severity and frequency (Sheppard 2003). Scleractinian corals off Kish and Larak Islands have been used for investigating the predominance of clade D (heat tolerant) *Symbiodinium* and its possible relation to high or extreme temperatures (Ghavam Mostafavi et al. 2007). Some Iranian coral communities are unique: Samimi-Namin et al. (2009) describe one at Larak Island which is partly inter-tidal with a particularly high tolerance to exposure. In the last 15 years there has been a general sharp decrease in living coral cover over most of this region (Rezai et al. 2004), with an accompanying modification of coral species distribution.

Along the Arabian Peninsula, coral assemblages show best development offshore, but there are important fringing systems too (in particular Abu Dhabi, Qatar, Saudi Arabia). Reef development is patchy, but is of ecological interest given the stresses they encounter, and

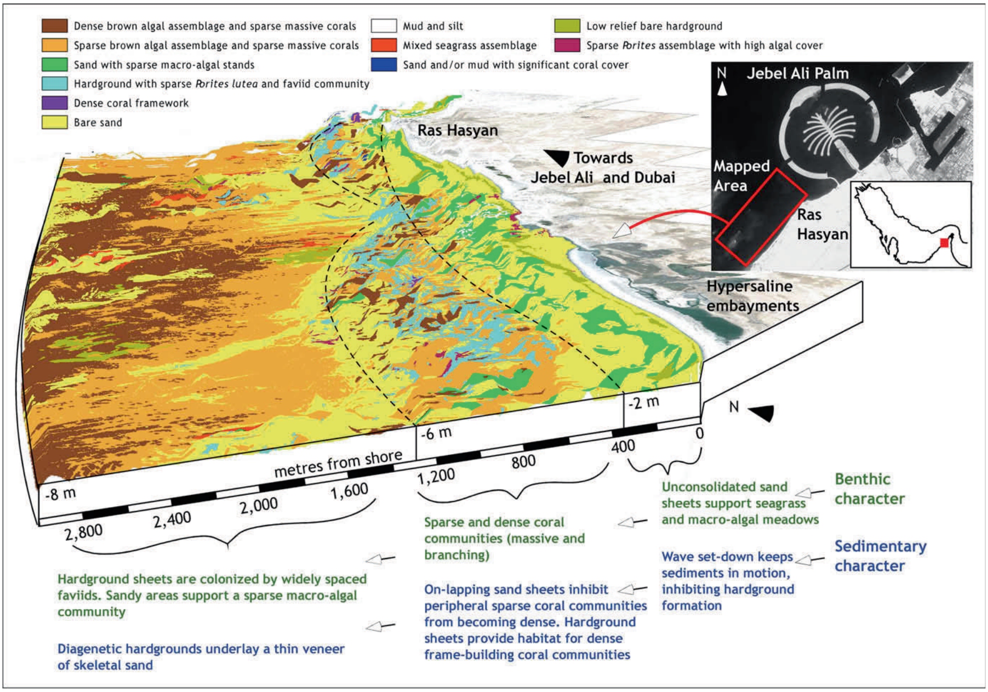

Fig. 7. 3D map of Dubai reef. Image by S. Purkis.

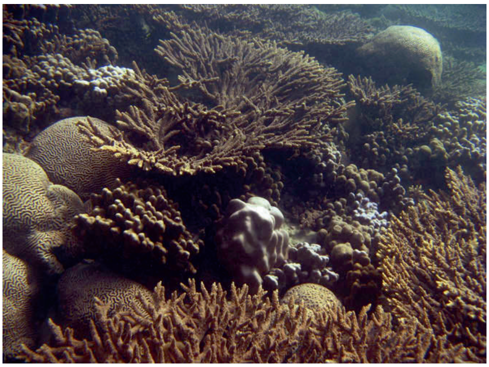

Fig. 8. Healthy fringing coral assemblages, east side of Kharku Island, near the most western boundary of developed coral communities in the northern part of the Gulf. 7–9 m depth. Photo: Samimi-Namin.

because of competition from other benthic groups. At Umm Al-Quwain for example, coral patches are limited (less than 10 species and 0.01% cover) and hardgrounds are mainly occupied by very extensive algal reefs, mangrove and seagrass habitats surrounded by a 30 km long sand spit. Similarly most sites visited in the Emirate of Ras Al-Khaimah have shown only occasional (<10 species and <0.01% cover) corals, being dominated instead by tidal lagoons, with high cover by muddy and sandy substrata with mangrove and seagrass habitats.

Many older 'reef' descriptions, however, are increasingly invalid following recent mortalities from massive developments and from warming water during the past 15 years. Mass mortality events, especially in 1996 and 1998, affected species differentially (Shinn 1976; George and John 1999, 2006; Riegl 1999, 2003; Purkis and Riegl 2005; Riegl et al. 2009; Wilkinson 2008). Detailed studies in Dubai showed six species of *Acropora* temporarily disappeared after the 1996 temperature anomaly, but these regained a foothold ten years later. The two main warming events in 1996 and 1998 (Fig. 2) removed mainly the shallow *Acropora* species, but while they have shown some recovery, especially in offshore locations,

Table 3. Some recent atlases, sketches and descriptions of Gulf reefs, and publications with lists of species. Includes some older but key works.

Location	Reports of reef distributions and component corals
General	Sheppard and Wells (1988), Sheppard and Sheppard (1991), Sheppard et al. (1992), Pilcher et al. (2000), Spalding et al. (2001), Wilkinson (2008), Fadlallah et al. (1993), Carpenter et al. (1997a), Sheppard et al. (2000), Fatemi and Shokri (2001), Wilson et al. (2002), Coles (2003), Rezai et al. (2004); Reefbase http://www.reefbase.org
Iran	Harrington (1976), Harger (1984), Rezai (1995), Shokri et al. (2000), Samimi-Namin et al. (2009), Samimi-Namin and van Ofwegen (2009a,b)
Kuwait	Coles and Tarr (1990), Downing (1985, 1992), Fadlallah et al. (1993, 1995), Hodgson and Carpenter (1995), Carpenter et al. (1997b)
Saudi Arabia	MEPA/IUCN (1987), Krupp et al. (1996), Basson et al. (1977), Vogt (1996), Fadlallah et al. (1993, 1995), Loughland and Abdulkader (in press-a,b)
Bahrain	Alkuzai et al. (2009), Fadlallah et al. (1993,1995), Loughland and Zainal (2009)
Qatar	Fadlallah et al. (1993), Shinn (1976), SCENR (2007), Qatar Ministry of Environment (in press)
Abu Dhabi	George and John (1999), John et al. (2006), Hellyer and Aspinall (2006) (incl. several chapters by D. George and D. John), Loughland et al. (2004)
Dubai	Riegl (1999), Riegl et al. (2001), Purkis and Riegl (2005), Purkis et al. (2005)

faviid corals and Porites are now achieving spatial dominance in perhaps most mid depth areas (Figs. 9 and 10), changing the nature and overall rugosity of the reef.

Qatar has seen striking coral decline, a condition typical of the Gulf generally (Figs. 11 and 12). Recent (2007–2008) surveys found only 20 species of hermatypic coral, and only five species (three genera) at the offshore island of Halul (SCENR, 2007; Qatar Ministry of Environment, in press). Twenty five years ago, *Acropora* was "very common" in the west and north coasts of Qatar (Emara et al. 1985), and it was even recorded in the Gulf of Salwah (Sheppard, 1988). In 2007 and 2008, however, extensive surveys found living *Acropora* only at Halul Island, and the previous presence of staghorn corals along the mainland coast could only be inferred by dead colony fragments in the rubble. Genera like *Montipora* and *Pavona*, once abundant around Qatar (Emara et al. 1985), no longer appear to exist. Further south on the east coast of Qatar hard corals are now largely absent from inshore areas; surveys in 2005 and 2007 recorded much long-dead *Porites* with *Acropora* rubble, and only occasional *Siderastrea* and faviids. In deeper water (10– 12 m) on flat hardgrounds in non-reef settings, reef dwelling genera (*Anomastraea*, *Turbinaria*) are found in several areas.

Most shallow coral reefs around Qatar are now covered in thick algal turf. The remnants of the previous high coral cover are found as rubble or lie beneath a thick layer of crustose coralline algae (CCA). These secondary carbonate producers (Perry et al., 2008), dominate over corals.

At the extreme eastern entrance to the Gulf, in Musandam, coral communities survive in much better condition. Around Khasab and Kumzar, they are still dominated either by high cover of Acroporids including *Acropora pharaonis*, *A. valida* and *A. arabensis*, interspersed by assorted faviids or, where rock shelves are narrow and shaded, by extensive overlapping *Platygyra daedalea* interspersed with occasional *Stylophora*, *Porites* and small branching *Acropora*. In many instances coral cover can exceed 50–80% over small areas, providing a basis for relatively diverse fish and invertebrate assemblages.

Once thought to be largely absent, octocorallia are now being discovered in greater abundance than previously expected, and so far 35 species of octocorals in 24 genera have been identified from the Gulf (Samimi-Namin and van Ofwegen 2009a). While several authors reported occasional soft coral species, most provide little information (Thomson and Simpson 1909; Stiasny 1940; Burchard 1979; Rezai 1995), though George (2006) is a useful exception. The striking *Dendronephtha* occurs in the east, as does the precious black coral *Antipathes* in Mussandam (Sheppard et al. 1992). Several species occur around Iranian islands (Rezai 1995, 2004; Samimi-Namin and van Ofwegen 2009a,b) including alcyonaceans *Sinularia* and *Sarcophyton*, sometimes in high abundance. Their distribution is mainly limited to the east, and they have not reached further west than Farur Island on the Iranian side, suggesting an ecological barrier to their distribution. They may be the dominant components in some coral communities, and some live in the low inter-tidal zone (Samimi-Namin et al. 2009). Being zooxanthellate species, they are found only shallower than 10 m depth where there is sufficient light. Azooxanthellate pennatulacea and gorgonians can be found in deeper waters (>10 m depth) where suitable substrata exist. No reef-building hydrozoa are known to occur but the gorgonid *Menella* is fairly conspicuous at least to the mid-Gulf deeper reefs.

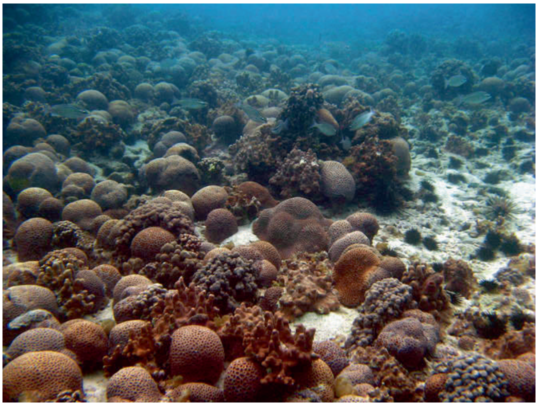

Fig. 9. Juvenile faviids showing healthy recruitment. Healthy fringing coral assemblages, faviidae dominant, western side of Kharku Island, the most western boundary of developed coral communities in the northern part of the Gulf, 9 m depth. Photo: Samimi-Namin.

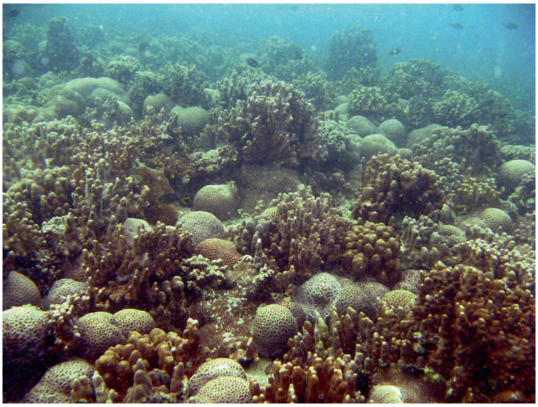

Fig. 10. Healthy fringing coral assemblages, faviidae and Porites equally dominant, western side of Kharku Island, the most western boundary of developed coral communities in the northern part of the Gulf. 9 m depth. Photo: Samimi-Namin.

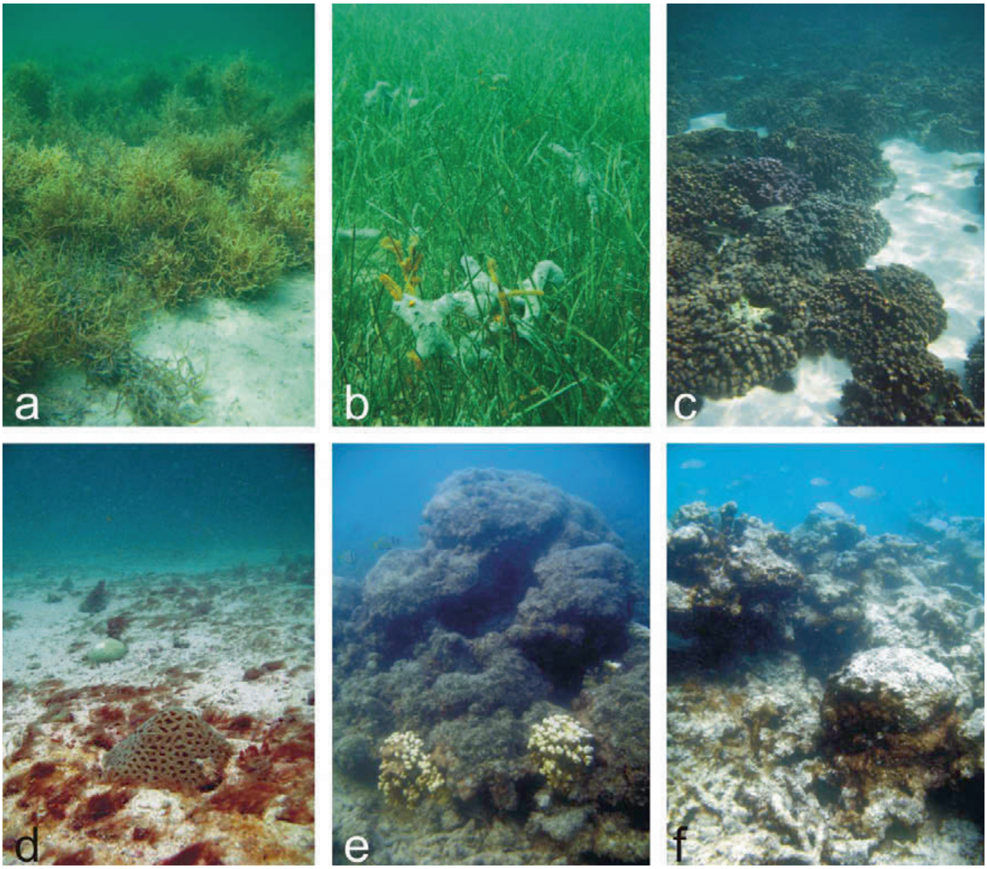

Fig. 11. The main sub-tidal benthic assemblages found in Qatar: (**a**) bed of brown alga *Hormophysa* in the northern Gulf of Salwah (4 m), (**b**) seagrass (*Halodule*) with sponges (light blue) and colonial tunicates (orange) growing on the leaves of the marine plants (6 m), (**c**) high cover monospecific patch of *Porites* cf. *harrisoni* in Halul Island (2 m), (**d**) scattered coral colonies growing on flat hardgrounds off the northern tip of the Qatari peninsula (12 m), (**e**) two living and partially bleached *Porites harrisoni* colonies growing on a dead coral community covered in algal turf (4 m), and (**f**) dead massive and branching corals covered in sediment and algal turf devoid of any living coral colonies for tens of square metres (2 m). Photo: Francesca Benzoni.

2.5. Special regions of very low and very high salinity systems

2.5.1. The Shatt Al-Arab estuary

By far the largest, and regionally the only important, estuarine system is the Shatt Al-Arab where the Tigris and Euphrates enter the northern Gulf. The freshwater appreciably dilutes the high salinity of the water in the north-western Gulf, and the estuary is a strong connection between the marshes and northern Gulf from the point of view of species and nutrients (Al-Yamani et al. 2002, 2007a, 2008a). This area has been subjected to substantial alterations in recent times, some connected with military activities. The estuarine marshes contain vast areas of *Phragmites* reeds, on huge rafts on which communities of people used to live. Over the last decade some restoration has been undertaken of damaged and drained areas, but overall there is a decrease in river water discharge due to upstream use (later sections).

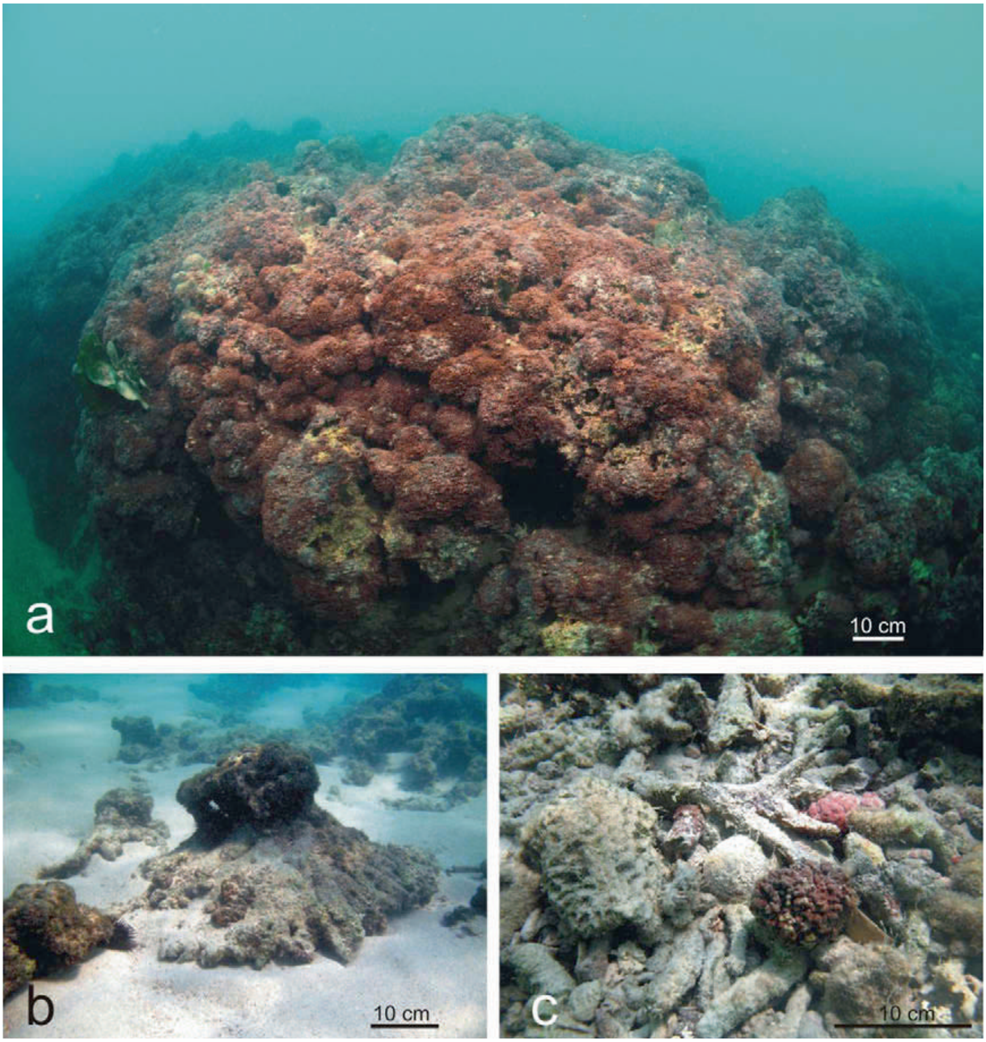

Fig. 12. Shift from coral to crustose coralline algae dominated benthic assemblages: (**a**) a crustose coralline algae dominated reef south of Fasht al Dibal (5 m), (**b**) dead and toppled *Acropora* colony in a shallow lagoon off the north coast of Qatar (2 m), and (**c**) living crustose coralline algae rhodoliths (pink) and dead coral rubble and, a large *Platygyra* fragment is recognisable on the left hand side, and a large branching *Acropora* fragment in the top-centre of the image. Photo: Francesca Benzoni. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An additional concern is effects on nutrient uptake by the reed beds from discharging water, with consequent effects on waters and plankton of the northern Gulf (Al-Yamani and Khan 2002; Polikarpov et al. in press). This is the major source of fresh water entering the Gulf, and in summer, the northwest Gulf is rich in total chlorophyll (Fig. 13). Chlorophyll concentrations in the Gulf waters range widely, and commonly vary between 0.01 and 10 mg/m^3 (Al-Yamani et al. 2007b), but shallow waters influenced by the Shatt Al-Arab River discharge are more productive than open Gulf waters (Nezlin et al. 2007).

2.5.2. Very high salinity habitats

Exceptionally high salinity embayments are common, good examples of which occur in many locations along the southern shores, particularly south of Bahrain in the Gulf of Salwah and in many others of Saudi Arabia (e.g. Jones et al. 1978), Qatar and the UAE. Fig. 7 shows some on the Dubai coastline. The relative richness and productivity of these areas is poorly understood; south of Bahrain salinity rises to between 55 and 65psu around the Hawar archipelago, yet benthic diversity remains moderately high (Loughland and Zainal 2009), but where salinity rises to over 60–90 psu, algae ultimately grade to cyanophyte dominated zones, with diminishing diversity. In extremes of these gradients, fauna become very limited though a very few species may remain abundant. The ultimate extent is seen where salt crystals appear in inter-tidal regions (salinity >300 psu; Basson et al. 1977), though even here nematodes clearly visible to the naked eye may thrive.

3. Pressures on fisheries

Fishing makes an important contribution to food security in Gulf countries and has historical and traditional significance as well as being a source of recreation. Commercial vessels tend to target shrimps and pelagics, while artisanal fishers tend to focus upon predatory demersal species (groupers, emperors) using gillnets, traps ('gargoor'), staked nets (hadra) and handlines (De Young 2006).

Saenger (1993) and Bishop (2002) have shown a link between the permanent loss of inter-tidal and shallow sub-tidal nursery grounds with declining fish and shellfish catches. Data from two areas clearly show very substantial declines in commercial fish over the past 10–20 years, following growth of this industry in the period 1970s to 1990s.

Kuwait's total fisheries landings initially fluctuated to about the mid 1990s during its expansion phase, but have steadily declined thereafter, such that landings in 2007 were less than half their peak 1995 level (Fig. 14). The large fluctuations in 1990 and 1991 were affected by the Iraqi destruction of many fishing vessels. Since 1979, finfish have accounted for 49–87% of the total landings, with the remainder being primarily penaeid shrimp (CSO 1979– 2007).

Probable reasons include overfishing, nursery ground destruction, and reduced discharge of the Shatt Al-Arab (discussed later). Particularly hard hit are species directly affected by the Shatt AlArab discharge, such as the anadromous *Tenualosa ilisha* and estuarine-dependent *Pampus argenteus* (Fig. 15a and b). From 1995 to 2007, landings of the former decreased 93% from 1197 t to just 78, while the latter decreased 91%, from 1128 t to 101. These two species accounted for 32% of Kuwait's total finfish landings in 1995, but in 2007, they accounted for 6%. Other important species in decline are *Epinephelus coioides* and *Lutjanus malabaricus*, whose landings decreased 68% and 92%, respectively (Fig. 15c and d).

Circumstantial evidence shows a relationship between the decreased landings of these species and the decreased river discharge, although overfishing is undoubtedly important. The changed salinity conditions have been favourable for other species: sport fishermen report catching *Lethrinus nebulosus* in Kuwait Bay, a species formerly confined to Kuwait's southern waters. Commercial landings of this species from 1994 to 2007 increased from 17 to 92 t, an increase of 441% (Fig. 15e). Another species whose landings have increased since the mid 1990s include *Nemipterus japonicas* (Fig. 15f). However, these total amounts are low and do not offset losses of the others, including some of Kuwait's most esteemed fishes.

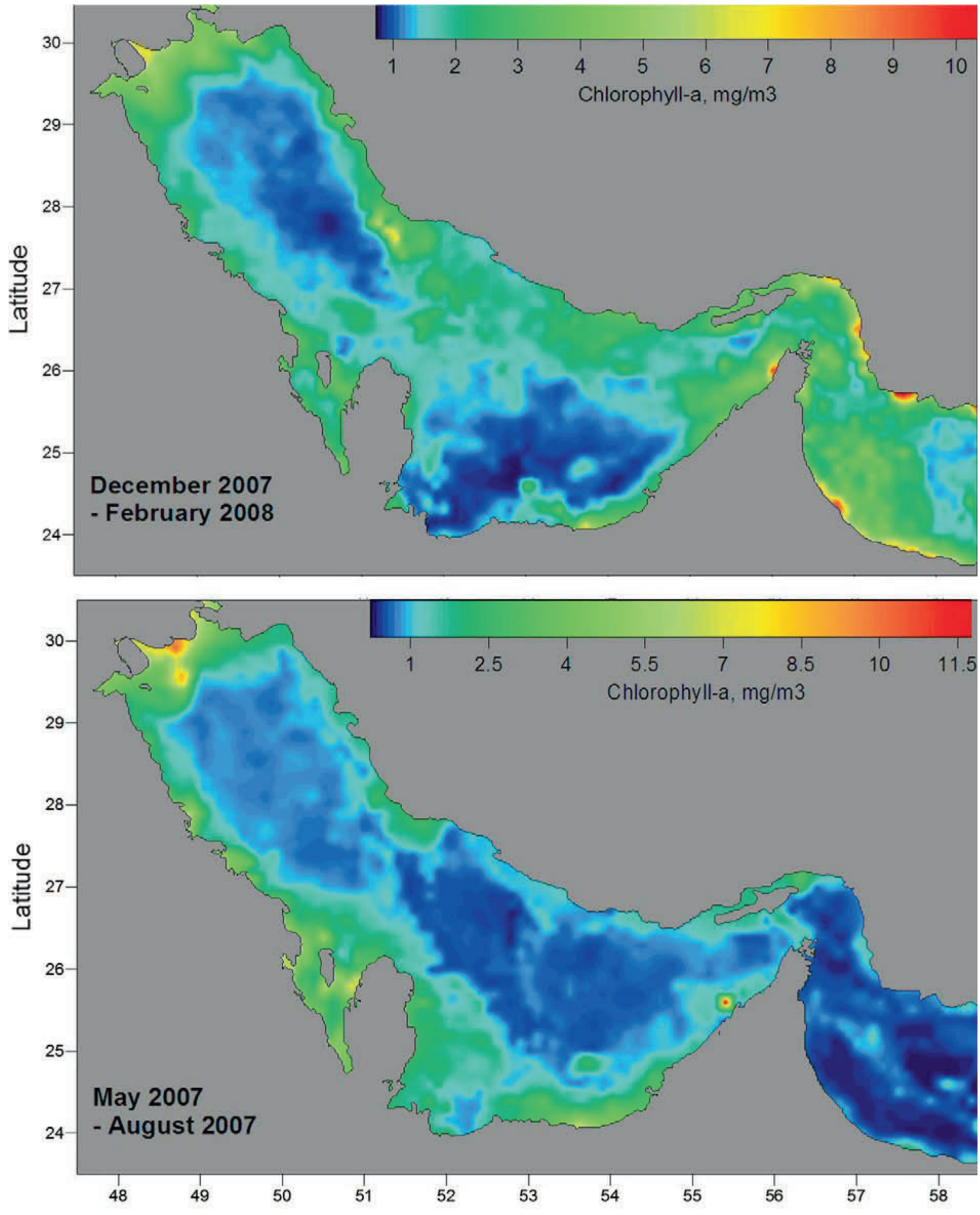

Fig. 13. Winter and summer surface chlorophyll distribution in the Gulf, based on MODIS-aqua satellite derived data, acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

In the UAE, fish stock assessment surveys conducted in 2002–3 showed significant differences relative to comparable surveys conducted in 1978. In this location there are no estuarine effects to complicate the patterns seen. Table 4 compares biomass data for several groups in 1978 and 2002 (Shallard and Associates 2003a,b; EAD 2008), in which data are broken down into at least eight genera or Family groups. In summary, using the total measured commercial and non commercial species, biomass in 2002 was only 18.8% of that in 1978 (range 17–20%).

In both areas, overfishing because of increased demand, as well as changes to essential habitats including, in the Kuwait case, reduced river water input, appear to be the causes of the large declines.

4. Pressures on and changes to marine mammals

Many coastal cetaceans have distinct 'home ranges' restricting their ability to simply move to alternative habitats nearby (Baldwin et al. 1999; Baldwin 2003) and alternatives are, in any case, often greatly altered themselves. A range of insidious threats such as pollution and noise occur in the Gulf, some of which are difficult to quantify either alone or in synergy with others (Reynolds and Rommel 1999).

Few cetaceans have been studied in the Gulf in any detail (Baldwin 2003), some exceptions being the 'very rare' finless porpoise (*Neophocaena phocaenoides*) (Reeves et al. 1997; Jefferson and Hung, 2004), the status of the Indo-Pacific humpback dolphin (*Sousa chinensis*) is unknown (Baldwin et al. 2004) except for records at Kuwait's Boubyan Island (Bishop and Alsaffar 2008).

A single published set of cetacean abundance measurements in UAE waters, however, provides evidence for a marked decline in dolphins. During an aerial census focussing on dugongs in 1986 and repeated in 1999, Preen (2004) detected a statistically significant decline of over 70% in dolphin abundance. Over the same period, the dugong population remained unchanged despite documented chronic impacts from fisheries activities, such as bycatch (Baldwin and Cockcroft 1997). Major oil spills coincident with the study period (e.g. those in 1986 and 1991 associated with regional conflicts) were not found to be a cause of high dolphin mortality. Instead, mass die-off events in 1983, 1986 and 1991, involving a documented 33, 520 and 78 cetaceans, respectively, were speculated to have been caused by disease or toxins

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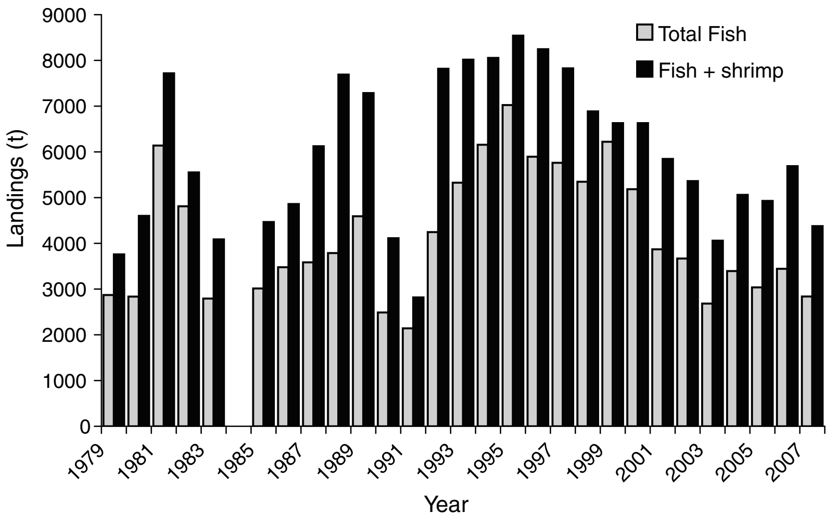

Fig. 14. Kuwait's landings of fish, and of fish and shrimp (total) from 1979 through 2007 (data from CSO, (1979–2007)).

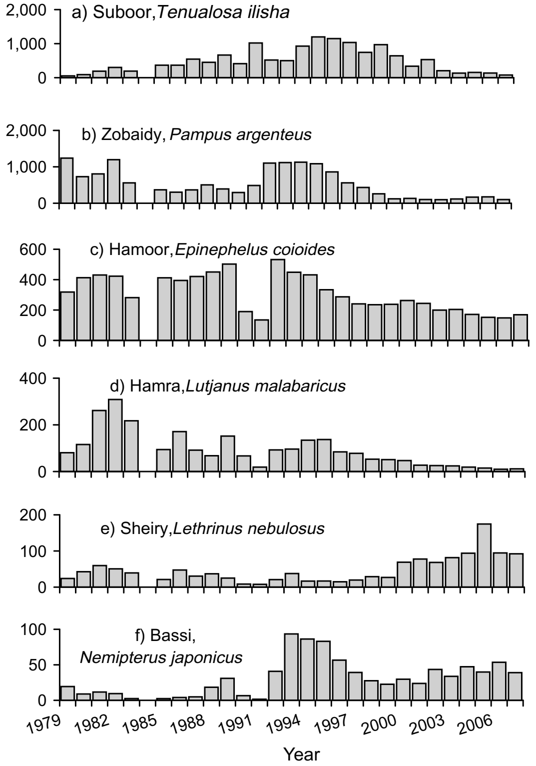

Fig. 15. Kuwait's landings of selected species from 1979 through 2006 (data from CSO (1979–2007)).

from red-tide events, and these also involved mass mortality of dugongs.

Dugong numbers, in contrast, appear to be steady. There appears to be much similarity between threats to dolphins and dugongs in the Gulf so a possible explanation for a steady dugong population but decline in dolphins is needed; this may be a reduction in prey species of the latter and changes associated with anthropogenic alteration of habitats.

5 Consequences of climate change

5.1 Reef associated invertebrates

The effects of the warm water spikes that occurred in 1996 and 1998 especially (see Fig. 2) and the massive coral mortality that arose from them, is increasingly well documented (Riegl 1999, 2002; George and John 1999; Sheppard and Loughland 2002; Purkis and Riegl 2005; Riegl and Purkis 2009). These events affected all species groups associated with corals; several of the authors have reported extensive searches for previously thriving *Acropora* reefs at <4 m depth without finding many, or even any, associated live sponge or other large invertebrates remaining, and in several cases also, almost no reef fish at all over many hectares.

Deeper than about 4 m, many reef areas still supported numerous small coral patches and colonies unaffected by bleaching. Importantly, a few years later some areas remained unchanged while others showed significant recovery of coral cover (>50% at times). But significantly, many recovered shallow reefs became dominated by faviids and poritids instead of the previous *Acropora* (see Figs. 9 and 10; Riegl 2002, 2003). This does not apply to all locations, however; in locations from Musandam to Kuwait, *Acropora* sp. and Pocilloporidae now thrive in many locations (Benzoni et al. 2006), and in several offshore areas *Acropora* have also recovered their former abundance. Marine life mortality from these warm episodes thus showed clear evidence of stratification, with effects extending to approximately 5 m depth, as well as some regional differences, all probably related to patches of persistent cooler water.

5.2 Harmful algal blooms (HABs), degraded water quality, and marine mortality

Where conditions of high surface water temperatures, low wind speeds, light and nutrient levels combine, harmful algal blooms can result (e.g. Al-Aarajy 2001; Heil et al. 2001; Glibert

Table 4. Biomass density estimates (tons km^{-2}) of demersal species (based on trawl surveys) from the current survey and the demersal fisheries survey of 1978 (FAO, 1981). Taken from Shallard and Associates (2003a,b).

Fish group	1978 biomass (tons km^{-2})	2002 biomass (tons km^{-2})
Non-commercial	2.0–3.0	0.44–0.53
Commercial	2.0–3.0	0.26–0.65
Total fish	4.0–6.0	0.70–1.18
	% of 1978 biomass present in 2002	
Non-commercial fish	350–800 km^3 y^{-1}	1.67 ± 0.39 m y^{-1}
Commercial fish	>7.3 km^3 y^{-1}	0.02 m y^{-1}
Total fish	60–200 10^6 tons y^{-1}	

et al. 2002). On their decay, these reduce dissolved oxygen, resulting in significant fish kills (Al-Ansi et al. 2002). Toxins produced by the algae may also lead to fish kills, and can accumulate in shellfish (e.g. paralytic shellfish toxins; Glibert et al. 2002) with the potential to poison consumers. Warming water temperatures may lead to increases in the frequency and severity of fish kills associated with plankton blooms.

The frequency of HABs is increasing in the Gulf, with examples being reported from almost all areas. A rise in nutrient levels around fish cages (mariculture) may contribute to this: in Kuwait Bay mariculture led to a HAB incident (*Karenia selliformis* and *Prorocentrum rathymum*) that affected the caged, as well as the wild fish, causing a massive fish kill in 1999 (Al-Yamani et al. 2000). Moreover, the discharge of approximately 30,000 m3 of untreated sewage water into Kuwait Bay, combined with an abnormally hot and humid summer with very low wind speed and low mixing activity for the water column, led to a massive fish kill in 2001. The probable cause of the mortality was attributed to deteriorating water quality, affecting the immune system of the marine biota, which were in turn affected by the pathogenic bacterium *Streptococcus agalactiae* (Jafar et al. 2009). Elsewhere in the Gulf, HAB incidences accompanied by massive fish kills have been reported from Abu Dhabi, Dubai, Ajman, Fujaira, the waters of Iran and Oman during August 2008–May 2009. The main HAB species causing the marine mortality has been identified as *Cochlodinium polykrikoides*.

5.3 Potential impacts of climate change on fisheries

As noted above, many fishery species are in severe decline. Projected temperature increases as well as habitat changes can affect distributions, migrations and abundance of fish stocks, and coastal and inland fisheries (Allison et al. 2009). For exploited species, the impacts of climate change include effects on individuals (Wood and McDonald 1997), populations (Cushing 1982; Edwards and Richardson, 2004), and ecosystems (Feeley et al. 2004; Harvell et al. 2002). These effects are likely to coincide with more general warming-related changes in habitat quality and productivity which are likely to affect fished species and fisheries, e.g. in the event of coral reef loss (Hoegh-Gulberg 2005; Graham et al. 2006). Gulf fish species are notably hardy, but tend to show high fidelity to specific sets of environmental conditions.

In the Gulf, average projected air temperature rises by the end of the century are around 2–4 °C (Meehl et al. 2007). Precipitation is expected to increase slightly overall (Meehl et al. 2007), but outputs from rivers entering from the Shatt Al-Arab are expected to decrease (Milly et al. 2005, and see later). Mud flats, many of which are being 'reclaimed' are important nursery ground for some species (e.g. Wright 1988; Bishop and Khan 1991; Al-Yamani et al. 2008a), and their biology and recruitment is affected by the level of discharge from the Shatt Al-Arab estuary in the north of the Gulf (Wright 1988; Morgan 1989; Ye and Almatar 2003).

The impacts of climate change on primary production will also affect fish and fisheries production (e.g. Cushing 1982; Jennings et al. 2008). Primary production is likely to decrease in some regions (Sarmiento et al. 2004; Behrenfeld et al. 2006), and its timing also can be critical to fish recruitment success. Peak fish spawning events may be coincident with periods of high zooplankton abundance (Houde et al. 1986), while recruitment success may also be related to temperature and salinity conditions at the time of spawning (Wright 1988). Changes in timing of annual recurring life cycle events such as spawning could lead to a decoupling or mismatch between predatory fish and their prey resource, affecting population dynamics and abundance.

Because fishing increases the sensitivity of fish populations to climate change (Rindorf and Lewy 2006), reduction of current overfishing will improve resilience, at least in the short term. However, the reduction in the diversity and abundance of smaller reef fishes (Graham et al. 2006, 2007) and the increase in human population which causes an increasing demand for fish, further increases the unsustainability of coral reef fisheries including those of the Gulf.

6. Diversity and robustness in the Gulf

The extent to which different measures of biodiversity are related to resilience or robustness of the system, or indeed to other indicators of ecosystem functioning, is unclear and requires urgent research attention given the rates of change and levels of stress being encountered in the Gulf (Pimm et al. 2001; Price 2002). Conceptually, high β-diversity areas might be envisaged as having several distinctive 'compartments', each containing a particular and perhaps semi-autonomous suite of species or assemblages; this might be either taxonomic, or have a functional standpoint (e.g. variety of feeding types or ability to absorb shock). Systems characterized thus, particularly with limited connectedness between compartments, have high modularity: this is one hallmark of resilient or robust systems (Walker and Salt 2006).

Diversity in the Gulf is naturally influenced by spatial scale which will inevitably be reduced in smaller areas compared to that in oceanic basins (Warwick and Clarke 1995). This can create difficulties when comparing the Gulf's diversity with other areas. For example, echinoderms, a group that has been comprehensively studied (Price and Izsak 2005), show a species richness which is lower than that in the Red Sea at four different spatial scales, though species richness correlated positively with spatial scale in both regions (Table 5). Further, when size of water body was compensated for in a recent study of 2894 species of marine algae from 66 sites in the Indian Ocean region, the Gulf overall ranked 62nd out of 66 (Price et al., 2006). Thus it is relatively species poor for this group too. However, the diversity of macrozoobenthos (270 species) is relatively high while the level of dominance is low (Al-Yamani et al. in press).

β-diversity, or change in species composition along a spatial gradient may, in contrast to other measures, may be relatively high in the Gulf (Table 6). In this respect, the Gulf shares certain ecological features with other 'stressful' environments which are characterized by harsh conditions and low species richness, yet which tend to have high levels of β-diversity (Price 2002).

On the basis of species richness alone, which is the measure favoured by global conservation programmes and most ecologists, the Gulf has sometimes been perceived as unimportant. Yet with an expanded view of biodiversity, incorporating for example β-diversity and taxonomic distinctness (a relatedness measure), the Gulf's status improves. Like rarity, taxonomic distinctness is relatively uninfluenced by spatial scale and sampling thoroughness (Izsak and Price 2001). Values of taxonomic distinctness in echinoderms are very similar for the Gulf and the Red Sea over all spatial scales (see Table 5), for example. Similarly, taxonomic distinctness of algae is exceptionally high, at least for certain sub-regions of the Gulf (Saudi Arabia, Bahrain and Kuwait), in contrast to patterns of species richness.

Whether marine environments exhibiting high β-diversity, like the Gulf, are more resistant to specific or multiple disturbances are considered to be a priority research objective.

7. Stresses from developments and discharges

Most scientists working in the Gulf agree that the most significant and important threats to the sustainability of the Gulf ecosystems come from the massive extent of coastal habitat modification by dredging and converting shallow, productive marine areas into land for homes, recreation and industrial facilities (Bishop 2002; Khan et al. 2002; Khan 2007; Jones et al. 2007; Munawar et al. 2002; Zainal 2009). By the early 1990s, over 40% of the coast of most Gulf States had been subjected to modification resulting in significant loss of biodiversity and productivity (Al-Ghadban and Price 2002). This loss of habitat is now expanding even more rapidly with increasingly ambitious projects including causeways and artificial islands (Erdelen 2007). Many projects involve massive deposition of material into shallow waters, resulting in replacement of several square km of productive tidal flat by inert fill material. Creation of offshore islands and structures has involved destructive dredging of seagrass and algal beds whose 'reclaimed' material, taken from 'borrow pits' then further destroys other areas onto which it is dumped. Areas with constricted water flow, such as Dubai Creek, have become polluted, with grossly changed fauna (Saunders et al. 2007). In addition, there is some unpublished evidence that some of these developments (e.g. the Palm developments in Dubai Emirate) may have caused significant increases in coastal erosion in neighbouring Sharjah as well as localised changes to sea surface temperatures as a result of significant discharges of hot water associated with their infrastructure. Solid fill causeways and barriers greatly interrupt long-shore water and sediment movements, leading in many cases to further armouring to counter undesirable and sometimes unexpected consequences of earlier work. Furthermore, there is reason to believe that a system of causeways currently planned in parts of the Gulf may potentially lead to habitat fragmentation of very sensitive and endangered species such as the Dugong. Al-Jamali et al. (2005) cite other examples of poor construction design leading to coastal habitat degradation. Probably no other sea area of this size in the world is affected by such a high intensity of coastal manipulations. Numerous authors have remarked on the damage being caused, and most also caution that coastal resources must be accorded much more recognition and attention if their remaining areas are to survive and provide beneficial goods and services.

Diversity and productivity of fisheries also are particularly threatened by these activities. Saenger (1993) and Bishop (2002) suggested that permanent loss of inter-tidal and shallow sub-tidal nursery grounds due to converting shallow sea to land contributes to declining fish and shellfish catches. Using stable isotope signatures, this link has been confirmed between inter-tidal mudflats, which have a high microbial mat productivity, with most of the important inshore fish and shrimp species (Al-Zaidan et al. 2006). More recently, Al-Maslamani et al. (2007) demonstrated the importance of inshore seagrass beds as nursery grounds for penaeid shrimp in Qatar. They observe that this habitat is rapidly disappearing due to dredging and sea conversion to land. Primary productivity in inter-tidal and unimpacted shallow sub-tidal habitats is six times higher than that in offshore waters (Jones et al. 2002). For most Gulf States, coastal habitats are less than 20% of the total sea area, yet their ecological value, especially seagrass and tidal flats, is 40–75 times greater than open ocean (Costanza et al. 1997; Balmford et al. 2002). There is little ecological value to saline desert or urban development, yet developers prefer the coast and shallow seas rather than sites further inland because of the increased value of water-front property.

7.1. Coastal developments

Particularly since the advent of the oil and gas industry, high profile and large-scale developments have occurred all along the Arabian coastline. From having low and largely rural populations fifty years ago, high indigenous birth rates and a shift to urban areas have greatly increased total and localised populations, added to which is immigration of labour which in some countries has increased populations several-fold. Sometimes developments have been spectacular and dramatic, such as in Dubai, but ports, airports and coastal industry (e.g. Khalifa Port in Abu Dhabi and New Doha Airport in Qatar) may have consequences to coastal and offshore ecology equally important.

Table 5. Comparison of biodiversity of echinoderms in the Gulf and Red Sea according to one or more values of species richness (SR), endemism and taxonomic distinctness (D*) at different spatial scales (P, point; S, sample; L, large area; B, biogeographical province) (from Price and Izsak (2005)). [a] Range of values from separate (qualitative) sampling units from eight intertidal sites in Tarut Bay, Gulf coast of Saudi Arabia, during 1945–47 and 1977 (computed from Price (1981)). [b] Values for two transects 500 m, one in the Gulf of Suez and the other in the northern Red Sea (data from James and Pearse (1969)). [c] Values for pooled (qualitative) sampling units from eight sites in Tarut Bay during 1945–47 and 1977 (see Izsak et al., 2002). [d] Values for pooled triplicate 0.1 m coastal benthic samples using box scoops at eight sub-tidal sand/seagrass stations in Safaniya/Manifa area of Gulf coast of Saudi Arabia (from McCain (1984)). [e] Values from collections in Sharm Obhur creek, Red Sea coast of Saudi Arabia (from Tortonese (1979)). [f] Values for Gulf coast of Saudi Arabia (Price, 1981). [g] Value for the Gulf coast of Iran (from Heding (1940), Mortensen (1940), Price and Rezai (1996)). [h] Assuming the Amphiura ?sp. nov. reported from Manifa on the Gulf coast of Saudi Arabia was actually a new species (Price, 1981). [i] Values for the Red Sea, Gulf of Aqaba and Gulf of Suez respectively (from Price (1982)). [j] Value for whole Gulf (from Price and Rezai (1996)). [k] Value for whole Gulf (from Izsak et al. (2002)). [l] Values for whole Red Sea (including Gulfs of Aqaba and Suez; from or computed from Price (1982)).

Scale	Gulf			Red Sea		
	SR	Endemism (%)	Δ^*	SR	Endemism (%)	Δ^*
P	2–10[a]	0	3.83–4.90[a]	17[b]	0	4.610[b]
	1–8[a]	0	3.00–5.00[b]	26[b]	0	4.400[b]
S	16[c]	0	4.508[c]	53[e]	<1	4.546[e]
	16[c]	0	4.475[c]			
	22[d]	?	4.546[d]			
L	55[f]	2[h]	4.546[f]	176[i]	5.3	4.529[i]
	c. 66[g]	7.5		139[i]	5.1	4.588[i]
				114[i]	7.3	4.450[i]
B	101[j]	12	4.572[k]	235[l]	10.4	4.528[l]

In Dubai, much of the coastline was originally fringed by relatively dense coral growth. In the 1990s, dense coral existed between Ras Ghantoot and Jebel Ali, off the Deira corniche, and wide rubble fields today indicate previously dense coral off the Dubai aluminium smelter. In Jebel Ali these were verified to be in good health in 2004 (Purkis and Riegl 2005; Purkis et al. 2005) but likely met their demise sometime shortly prior to 2007 when construction gathered pace. During the 1980s and early 1990s, heavy industry, shipping and increasing effluents from desalination and electricity generation exerted a smaller toll on the coral reefs than natural temperature variability. In the late 1990s, construction was begun on the Jumeirah Palm, in an area that harboured dense pearl-oyster beds, some seagrass and algae, but no coral reefs. In 2004, work began on the Jebel Ali

Table 6. Biodiversity in the Gulf and other stressful marine environments, showing various measures of biodiversity on ordinal scale (+: low, ++: moderate, +++: high; –: insufficiently known). SR: species richness at small and large spatial scales up to biogeographical province for the Gulf, and at smaller scales (sample species richness) for estuaries and hydrothermal vents. D*: taxonomic distinctness (from Price 2002).

Scale	Element of biodiversity			
	SR	Endemism	D*	D-diversity
Gulf	+	++	-	+++
Estuaries	+	+	-	+++
Hydrothermal vents	+	+++	+++	+++

Palm which is now situated over what was previously the Gulf's second most biodiverse and documented ecosystem. Although the extent of the coral reefs was known from 1995 onward, adjustments in construction layout were only introduced at a late stage, causing severe losses in the core coral reef area.

From detailed previous research in Dubai during the 1990s and early 2000s (Riegl 1999, 2003; Riegl et al. 2001; Purkis and Riegl 2005), it is known that 34 hard coral species occurred between Jebel Ali and Ras Ghantoot (Fig. 7). The largest impacts on coral diversity, until the construction of the Jebel Ali Palm, came from sea surface temperature anomalies of 1996 and 1998. Selective mortality removed all *Acropora* from the system for several years. Subsequent strong regeneration has led to re-establishment of much of the fauna along this substantial stretch of coast, including outside the footprint of the Jebel Ali Palm. This suggests that the coral communities here are very robust, with a resilience that evolved in step with repeated heat stress events.

A further major dredge and fill project, the Deira Palm, will cover a coral area that was, until the late 1980s, the location of some good *Acropora* growth, but which was already impacted by construction of the Deira corniche. With the enormous expansion of Dubai, development has moved into Sharjah, Umm Al-Quwain and Ras Al-Khaimah, where major coastal developments are planned or are in early phases of construction.

The Emirates of Umm Al-Quwain and Ras Al-Khaimah have limited coral growth. However, they do have several examples remaining of unique, pristine and highly complex systems of inter-tidal, sub-tidal and terrestrial habitats: two of their main sites (Khor Qurm and Ras Al-Beidah) are undergoing or have been proposed for large-scale coastal developments. Important ecological features include a wide range of marine and inter-tidal assemblages; extensive mangroves; high numbers of marine turtles and birds; and widespread sea grasses with a good water quality and rich and varied benthic life. As a result the Umm Al-Quwain site in particular is considered one of the most important bird areas of the Middle East and was classified as a Globally Important Bird Area by Evans (1994) and an Important Bird Area of Middle Eastern importance.

These Emirates presently contain extremely rich and unusually unimpacted marine and nearshore environments which, aside from presenting a high level of biodiversity, clearly play a crucial role in many marine processes within their borders and beyond. This should be borne in mind when considering developments beyond their borders as well as within, given the extent of coastal modifications already undertaken and planned. This kind of holistic approach has largely been lacking.

One of the largest and hitherto least impacted high-diversity habitats in the UAE is situated at Ras Ghanada. Around this headland, mangrove-lined creeks, dense seagrass beds and an extensive coral area are found, and the area is important for foraging green and hawksbill turtles and coastal and marine birds. It is the only area in the southwest Gulf that has as many high-diversity habitats in such close proximity. This area is threatened by a major port development between Ras Ghanada and Ras Hanjurah.

Nowhere has coastal alteration been more marked than in Bahrain. The Kingdom itself has expanded its land area into shallow water by 91 km^2 from 668 km^2 in 1963 to 759 km^2 in 2007, an increase of 11% (Table 7) (Zainal 2009). Further, the area dredged for material has severely damaged or destroyed an additional several hundred square km in the sea to the north of the Kingdom. From ten of the projects where data exists, 153 km^2 shallow marine habitat has been lost from the dredging and fill combined (Zainal 2009). In both excavation and filled areas, sediment plumes of unmeasured size have covered equally significant additional areas for extended durations.

The dredging, from areas sometimes euphemistically named 'borrow pits', and its deposition on shallow habitat to form land, doubtless combined with temperature stress, has also caused the complete demise of the largest single reef in the area, and possibly once the largest in the Gulf. Fasht Adham with other smaller detached sections (with different names) extended from eastern Bahrain into Qatari waters. In the 1980s it was a rich reef with high coral cover of 50–75% in most measured locations (Alkuzai et al. 2009), while today it supports almost no living coral at all (Fig. 16). The limestone substratum is composed of dead coral skeletons covered with sediment and fine filamentous algae. Its demise was attributed to a combination of the warm water events of 1996 and 1998, together with coastal engineering works which added significant levels of stress through sedimentation.

To seal the demise of this once rich reef, the Qatar-Bahrain Causeway is in its final stages of design. The 40 km long mixed road and rail causeway-bridge will link Bahrain to western Qatar using Fasht Adham. About half of this length will be solid fill, leaving only the remainder as bridge (Zainal 2009). This causeway east of Bahrain would be the second linking Bahrain to a neighbouring state, the other being the existing one on its western side connecting it to Saudi Arabia.

Many key issues are being investigated regarding the causeway, including potential modifications to currents, sediment transport and effects on seagrass beds, algal reef habitats and dugong populations. But while these issues are being investigated by the developer, regulators and other relevant government departments in both Bahrain and Qatar, what is missing in this and other major developments may be the ability to deflect such high-prestige developments completely if or when it is found that their environmental costs are too high. For the total Gulf system, cumulative effects may be greater than the effects of any one development alone.

It is self evident that Gulf coral and seagrass species have a relatively higher thermal tolerance compared to other Indo-Pacific species (Hughes et al. 2003): only the 'toughest' few have ever occurred in the Gulf in any case. Coral species killed in 1998 in the central Indian Ocean, for example, include about 20–30 species found in the Gulf which survive temperatures 2–3 °C higher every year without being killed. However, the combined stresses of increasing temperatures and anthropogenic impacts mean that even these 'toughest' of habitats are proving to be decreasingly less productive and resilient. The resulting declining trajectory is already clear and well advanced. Despite their relative thermal resilience, predictions of climate change suggest that the maximum thermal tolerance thresholds for these species will be chronically exceeded in future (Hoegh-Gulburg 1999). Additionally, climate change-induced ocean acidification is likely to reduce the calcification rates of all calcifying organisms too (Caldeira and Wickett 2003; Hughes et al. 2003; Veron et al. 2009) and in the Gulf these include several important algal species as well as corals.

In many instances, if there had been better site selection (i.e. if ecologically poor sites which abound were selected rather than rich ones), and if there was better, long-term synergy/strategy in development, the Gulf could probably achieve the desired development without so many local examples of important loss.

7.2. Oil pollution

The Gulf has about 800 offshore oil and gas platforms and 25 major oil terminals. About 25,000 tanker movements sail in and out of the Strait of Hormuz annually and transport about 60% of all the oil carried by ships. These resources are so valuable to consumer countries as well as producers that, in a recent series of reports analysing the full social cost of car use in USA, Delucci and Murphy (2008) showed that the economic cost to the United States of defending the Gulf's oil reserves and supply infrastructure is US$3–30 billion per year.

Activities associated with oil traffic include shores heavily contaminated with oil residues, tar balls and trace metals. About 2 million barrels of oil are spilled annually from the routine discharge of dirty ballast waters and tank washing, partly due to the lack of shore reception facilities. Toxicity and physical damage from clean-up operations, remains a problem, though responsible and appropriate use of dispersants and sorbents can result in substantial benefits (Kirby and Law 2008). An additional source of oil pollution is the estimated 6–8 million barrels spilled into the Gulf during the Iran/Iraq war (Price and Robinson 1993), some habitats of Kuwait and the northern half of Saudi Arabia were extensively affected.

Oil pollution accounts for 0.5–1.51% total organic carbon (TOC) compared to the 0.5 natural background level. Data by Al-Ghadban et al. (1994) showed an increase in TOC to 2.8%, which results in shifts in planktonic populations from diatoms to flagellates, dinoflagellates and benthic algae. Besides increasing primary production, benthic algae may out-compete corals and other reefbuilding organisms (Pastorok and Bilyard 1985). Spilled deposits may persist for many decades (Owens et al. 2008).

The enormous volume of ballast water from tankers may have introduced exotic biota; for example there has been an increase in recorded dinoflagellate species from <40 in 1931 to 200 species in 1996 (Subba Rao and Al-Yamani 2000). A programme is underway to investigate this subject in more detail (Clarke et al. 2003).

7.3. Discharges from desalination and other industry

Desalination has an environmental cost (Purnama et al. 2005). The combined seawater desalination capacity in the Gulf countries exceeds 11 million m^3 per day which is 45% of the total world capacity (Lattemann and Höpner 2008), equivalent to 15% of the former flow of the Euphrates. Saudi Arabia, Kuwait and the UAE have the largest installed desalination capacity in the Gulf with a production of about 1.8 $km^3\ y^{-1}$ (Hashim and Hajjaj 2005). This industry returns to the Gulf over 7 $km^3\ y^{-1}$, using 2005 figures (Table 3). This water may be brine (from desalination plants), is commonly hot, and often also contains pollutants including bioocides introduced to prevent pipe and conduit biofouling. Extreme aridity and unfavourable geology result in these countries not having suitable alternative sources of potable water for domestic and industrial use. For example 90% of Kuwait's potable water is derived from desalinating seawater (Darwish et al. 2008), and this level of dependence is seen throughout the region.

Sewage is discharged to such an extent in the north of the Gulf to have been implicated in the shift in the dominant forms of plankton. For example about 23 × 109 m^{-3} d^{-1} wastewater and 0.003 × 106 km^3 d^{-1} sanitary wastewater are dumped into the Gulf (Al-Muzaini and Hamoda 1998). Three Kuwait coastal suburbs Ardiya, Jahra and Reqqa discharge 0.282 × 106 m^{-3} d^{-1}(AlMuzaini et al. 1991). The organic content of the sewage dumped into Kuwaiti waters was also relatively high.

Table 7. Original size of Bahrain and its expansion since 1963 (from Zainal (2009)).

Period	Area (km^2)
Original land mass (1963)	668
Additions:	
1963–1977	13
1977–1982	1.5
1982–1989	20
1989–1997	9
1977–2004	16
2004–2006	10
2006–2008	22

Discharges of heated water into the Gulf are massive, from discharges from >55 desalination plants as well as power stations and heavy industrial facilities. In Kuwait alone 33.6 × 106 m^3 d^{-1} chlorinated cooling water and 17 metric tonnes of residual oxidants are discharged (Al-Mutaz 1991). These can cause elevations of 5 °C and 3 psu above ambient into waters which are already warm and highly saline (Linden et al. 1988). These values can be compared with the volumes naturally exchanged, input and evaporated in the Gulf (Table 3). Their effects are sometimes assessed in a local sense, but not on a Gulf-wide basis.

8. Developments designed for reduced environmental impacts

The now very popular concept of Gulf desert water-front cities and recreational facilities constructed on low lying saline desert or sabkha areas was initiated in the 1980s. Developments linked to the sea via artificial waterways raise issues of the amount of dredging and landfill that would be needed, and the possibility of poor flushing in the desired canals and inlets, leading to overheating and eutrophication. Key to their success would be provision and maintenance of high quality seawater through natural circulation (Ealey et al. 1989). Design should also take account of climate induced sea level rises, make use of land that will be potentially flooded and provide marsh areas to remediate future inundation by the sea.

Two residential and commercial examples that addressed these questions are the West Bay Lagoon site in Qatar with 6 km^2 of marine waterways and the much larger Pearl City at Al-Khiran, Kuwait, which currently has 8.75 km^2 of waterways (Fig. 17). Doubts were expressed as to the viability of such projects, due to potential for stagnation and high salinity (Kana 2002). Both projects were therefore subjected to rigorous simulations to optimize tidal and wind flushing as well as stability of internal beaches (Al-Handasah 1994; Ealey et al. 2001).

The site at Al-Khiran is projected to be over 40 km^2 centred on two hyper-saline khors (inlets or estuaries) which contained 126 macro species (Al-Zamel et al. 1997). Studies have been undertaken to examine the potential of the waterways to create new areas of marine

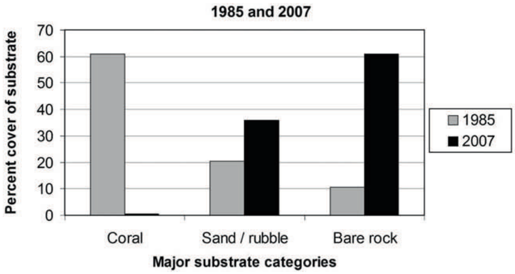

Fig. 16. Top: Fasht Adham in 2006. Coral cover was almost zero; figure shows remnants of rapidly eroding massive corals and barely recognizable *Acropora* colonies. Bottom: Change in Fasht Adham 1985–2006. Cover by coral, sand and bare, sedimented rock.

productivity. The project contains new tidal beaches, saltmarsh and mangrove areas, islands, and a greatly expanded sub-tidal benthos. Rock revetments and areas of cobbles introduce a new marine habitat. The Costanza et al. (1997) ecological value of these new habitats in just their earlier phase doubles the original value of the hyper-saline khors (Jones et al. 2007).

In the latter, water quality measurements so far have remained within guideline limits with a single exception when ammonia and nitrate levels were elevated, coincident with a *Noctiluca scintillans* bloom which originated in open sea. This rapidly dispersed and there was no impact upon waterway biota.

The site at Doha, Qatar, was originally a saltmarsh, whose connection to the sea had been lost by construction of a coastal road leaving a hyper-saline shallow pool with *Dunaliella salina* and *Phragmites* as the only living biota. The completed project now contains 11km^2 of housing, each dwelling with its own beach, surrounding over one million square metres of lagoon water 2–3 m deep opened to the sea in the late 1990s. Channel dimensions created a through flow, at the same time ensuring that currents would not be too high for recreational water sports. Seawater temperatures, salinity and oxygen levels in the lagoon were similar to those in the open sea during the study period (Al-Jamali et al. 2005), indicating good flushing.

8.1. Colonisation by marine biota

Inter-tidal and sub-tidal surveys (PERSGA 2004; Al-Jamali et al. 2005; Al-Jamali 2006a,b) monitored recolonisation. Grab sampling at 1.0 m depth within the lagoon showed 11–18 species compared to 12–21 species per station in the open sea. Dredge sampling produced 3–16 species within the lagoon compared to 5–35 species per station in the open sea. Seagrass and macroalgae were absent within the lagoon. Abundances of invertebrates averaged 1824 m^{-2} at 1.0 m and 3648 m^{-2} at 2.5 m depth within the lagoon compared to 6,074 m2 in the open sea. There was a high similarity among stations, although following Coles and McCain's (1988) findings, Al-Jamali et al. (2005) concluded that the absence of seagrass in the waterways caused lower diversity and invertebrate abundance. Therefore seagrass *Halodule uninervis* was transplanted into the lagoon (Jones et al. 2007), and by April 2003 more species were found in seagrass beds than in bare sand, with significant increases in diversity and abundances. Transplanted seagrass grew well and doubled in area within a year leading to rapid faunal colonisation (Al-Jamali 2006a, b).

For the Kuwait example (Jones et al. 2007), inter-tidal mean macrobiota diversity and abundance is shown in Fig. 18. Species diversity on artificial habitats reached levels similar to those on natural open sea beaches within two years, and by 2007 exceeded the mean diversity on open shores. Mean macrobiota abundances exceeded or approximated mean values for natural beaches. Most key species (Jones et al. 2002) now occur in the artificial shores, although the high shore isopod *Tylos* has yet to colonise. Over 20 bird species have been observed feeding in the new habitats including terns, flamingos and plovers.

Colonisation of sub-tidal benthos within the new waterways shows the waterways resembled or exceeded open sea stations by 2007, although they mostly still lacked seagrasses. Waterways opened to the sea in March 2006, contained abundances of some species as high as 2928 m^{-2} (Jones et al. 2007). Subtidally, four months after flooding, nine species were found with abundances of 6000 m^{-2}. In summary, total macro species diversity (Fig. 19) shows the original khors contained 126 species of macrofauna, which dropped to 25 during construction, but which rose rapidly to 556 species in 2007, including three species of corals. This includes 77 species of fish, with over 50 commercial species, together with *Portunus pelagicus*, *Penaeus semisulcatus*, *Metapenaeus affinis* and *M. stebbingi*. Most species occur in the zooplankton as juveniles and as adults, indicating that the waterways are acting as both feeding and nursery grounds.

A key to success in large shoreline developments is a multidisciplinary approach to design and modelling prior to construction to ensure good circulation is achieved using only tidal and wind forces (Al-Jamali et al. 2005; Jones et al. 2007). On land also, saltmarsh halophytes (*Halocnemum, Arthrocnemum*) were removed before construction and transplanted successfully onto the artificial islands at Al-Khiran. Genetically suitable mangrove seeds (Maguire et al., 2000) have also been transplanted. These newly created salt marshes furnished with micro channels were recolonised by the crabs *Nasima* and the endemic *Manningus* in 2007, and diversity exceeded that of natural salt marsh in 2008.

It is calculated (Jones et al. 2007) that when this project is completed, the new marine productivity created will both compensate for coastal habitat lost elsewhere in Kuwait (Bishop 2002), but will also contribute significantly to conservation of biodiversity and fish and shellfish stocks.

8.2. Other examples and limitations

There are several more examples, though with so far little published information. Recolonisation of hard corals onto breakwaters has occurred at some of the Dubai Palms, where rocky reef ecosystems are developing with sometimes good cover but with a lower diversity than is found on natural reefs nearby (Burt et al. 2009a,b). In Qatar, translocation of coral colonies from sites near the New Doha International Airport to existing reef habitats offshore in Qatar has apparently been successful, which has led to increased interest in coral transplantation.

There remains the dilemma of whether new habitats can equal those destroyed by developments in terms of size, diversity, resilience and 3D complexity, or whether they simply aim to meet certain simplistic criteria recommended by present, non-holistic (i.e. project by project) EIA processes. In the case of coral colonies removed from the new Doha airport site and transplanted offshore, the venture is apparently a success. In the case of more complex and extensive reef habitats such as Taweelah (Abu Dhabi) and other well studied reef areas mentioned above, there is no possibility that whole integrated reef systems could be moved *in toto* to offset developments. In many cases, artificial substitutes are vastly smaller than the damaged areas they are supposed to replace. The approach in some cases has been to negotiate the best possible location for the proposed development and to develop and implement robust, science based monitoring programmes, but the drawback to the latter is that monitoring can do nothing useful if the results are not acted upon, as has too often been the case once a project has started.

As noted earlier, better site selection, coupled with appropriate design, can achieve both economic and ecological goals. While some developments have demonstrated that it is possible to create new marine productivity in desert areas of low ecological value, the question must also be asked if these man-made habitats are more or less resilient to environmental stress than those they have replaced.

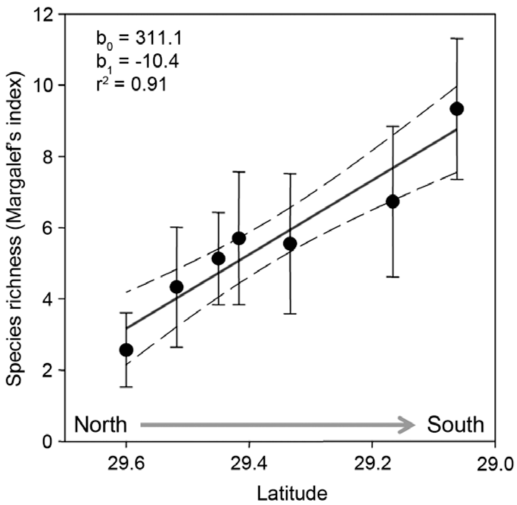

Fig. 20. Margalef's index for phytoplankton community in Kuwait's waters (β-diversity) showing an increase in diversity from waters nearest to Shatt Al-Arab northern area towards the south.

9. Ongoing and proposed 'mega projects'

Two major projects or proposals are in one case well underway and, in another case, speculative and futuristic, but with much about it already written. Both could result in enormous increases to Gulf salinity, above the already high existing level.

9.1. Damming of the Tigris and Euphrates: Turkey's Southeastern Anatolia Project (GAP)

The Tigris and Euphrates join in southern Iraq and, along with the Karun River, drain through the Shatt Al-Arab into the Gulf. This, together with other smaller rivers, adds the equivalent of 0.2 m y^{-1} into the Gulf (Table 2). However, the Gulf's evaporation equivalent of 1–2 m y^{-1} greatly exceeds both precipitation and the input of river water (Ahmad and Sultan 1991) Table 8 shows details of the river inputs and their sediment loads. Peak flow from melting snow is usually during April–May.

In 1970 the Southeastern Anatolia Project (GAP: Turkish acronym) was planned to utilize the rivers (Tomanbay 2000). This project will comprise 56 dams (Lawler 2005) which, once completed, will generate annually 27,300 GWh and irrigate 1.7 $\times 10^6$ hectares (Yüksel 2006). It aims to increase production of agricultural crops and, by 1999, it was 40% completed at a cost of $32 billion. Its completion requires $900 million by 2010 and financial problems have extended its deadline until 2047 (Cumhuriyet 1999).

Many groups campaigned against the Ilisu Dam on the Tigris as it would dislodge 50,000 people and would destroy Hasankeyf, renowned for its first settlement built in 10,000–8000 B.C. This has survived nine civilizations to date, but it may not survive the tenth, because in

Fig. 17. Photo of Pearl City water channels under development. Photo: La Ala Al Kuwait Real Estate Co. K.S.C., Kuwait.

2007 a consortium of companies, Turkey's Water Management Authority as well as financiers signed a loan agreement for $1.63 billion to build the Ilisu Dam. Some fear it could be Turkey's white elephant (Braun 1994).

9.1.1. Concerns about the dams

The effects on Kuwait's fisheries are already described. There are also concerns over water sharing in the riparian down stream nations (Çarkoglu and Eder 2001) as GAP will greatly diminish and degrade their water supply in future (Gruen 2000). Once GAP is completed, the flow of the Euphrates will decrease from the 30 billion cubic meters (BCM) at the Syrian border to 16 BCM, and to 5–9 BCM at the Iraqi boarder (FAO 1997). Water regulation, fragmentation, sediment imbalance, partial or complete drying, salinisation, chemical contamination, acidification, eutrophication and microbial contamination are some of the syndromes commonly associated with damming rivers (Maybeck 1990), and in the GAP area itself there have been greatly increased insect transmitted diseases (Gratz 1999) as the hydroclimate changed.

The marshlands themselves need to be flushed with fresh water for removal of salt and hydrogen sulphide. Reduced flushing decreased the Mesopotamian marshland from 8500 km2 in 1984 to 745 km2 in 2002. Flooding the marshlands with river waters after the 2003 war partially restored them to 4000 km^2 (Jones et al. 2006; Richardson et al. 2005).

Iraq completed a "Third River" with 565 km outfall drainage. This river was designed to remedy the chronic salinity problem in the farmland between the rivers; it collects wastewater and drainage from 1.5 × 106 km^2 salt-encrusted fields and discharges into the Gulf via Khor Al-Zubair and Khor Al-Sabbiya. An extensive study was conducted on the impact of the man-made Third River on the northern Gulf's salinity, water quality and biota (Al-Yamani et al. 2008; Al-Yamani 2008).

Undammed, these rivers supply over 11% of the water which replaces that lost by evaporation. Effects of river damming on final Gulf salinity appear not to have been computed, and nor have there been studies on the effects on Gulf biota, with the exception of the fisheries impacts already described. As GAP dams are completed, river discharges will greatly diminish. Fluvial outflow is rich in nutrients (Talling 1980) and contains 1.82–7.07 μmol l^{-1} PO_4–P, and 365.9–733.8 μmol l^{-1} NO_3–N. High levels of nutrients exist in Shatt Al-Arab waters: 1.55–6.01 μmol l^{-1} PO_4–P, 135.6– 306.9 l^{-1} SiO_2–Si and 21.5–52.7 μmol l^{-1} NO_3–N (Saad, 1985), which can be attributed to the river run-off. These nutrients, silicates in particular, sustain a qualitatively and quantitatively rich diatom crop (116 species ~94 μg chl *a* l^{-1}in the northern Gulf waters (Subba Rao and Al-Yamani 1998, 2000).

An increase in planktonic diversity with distance from the river mouth (Fig. 20) may be caused by the decrease in river discharges and depletion of silicates; a replacement of diatoms by dinoflagellates that do not require silica has been observed in other areas such as the Baltic (Suikkanen et al. 2007; Wasmund and Uhlig 2003) and in a Swedish fjord (Filipsson et al. 2005). Diversion of water increased pollution, and negatively impacted the biota in the Azov Sea Basin also, reducing catches of commercially important fish (Volovik 1994), as was the case also with the Nile's Aswan dam in 1965 which reduced freshwater flow by 90%, resulting in a collapse of the fishery in the next 15 years (Nixon 2003). Changes in nutrient load caused by damming the Danube River similarly affected the food web in Black Sea surface waters (Humborg et al. 1997). It is possible that in the Gulf, trophodynamics of sardines and larvae of fish and shrimps, which are pelagic feeders, may be also affected due to shifts in pelagic biota.

The socio-economic impact of reducing the flow of fresh water to the northern Gulf may also be significant. Rising salinity will increase the costs associated with desalination and may result in ambient seawater salinities exceeding design specifications of facilities. This has potentially serious implications for the security of water supplies in Gulf States as desalination remains the only realistic supply source.

While the GAP will benefit Turkey, it leaves a trail of environmental impacts on the riparian areas, marshlands and the Gulf.

There is great merit in the suggestion (Freeman and Angin 1999) of applying organizational theory and practical experience with management of this large-scale common property resources problem. Downstream (literally in this case) problems for the Gulf as a whole have not been addressed to anything like the necessary degree.

9.2. Hormuz Strait dam futuristic macroproject

Imaginative plans have been provisionally developed to create a dam across the Strait of Hormuz, leading to evaporative loss of water in the Gulf, creating a water level difference of about 20 m which would then be used to generate hydro-electric power (Schuiling et al. 2005). It would replace hydrocarbons as a source of revenue and energy, when hydrocarbons run out.

The principle is straightforward enough, and has been proposed for the Red Sea also (Schuiling et al. 2007). From the total water volume of about 8600 km^3, about 326 km^3 yr^{-1} of water evaporates from the Gulf. Replacement is mostly from the Indian Ocean, with about 37–133 km^3 yr^{-1} entering from rivers. The sill in the Strait is about 100 m deep. If there were a dam, evaporation would drop the level of water in the Gulf by 1–2 m yr^{-1}.

Construction could be by cement, the volume needed being about 30% of one year's global cement production. But, ingeniously, much of the substrata in the Strait is limestone, and injection of sulphuric acid into this (sulphur being a waste product of the present oil industry) converts limestone to gypsum. Gypsum has double the molar volume of limestone, and the expansion thus caused can only be accommodated by upward lift of the sea bed. Less concrete would then be needed.

The authors acknowledge that this would cause difficulties. Developments along the coast, such as the Dubai Palm and World islands, would no longer be island settlements, for example, but would become, if this proposal is realised, mounds in a salty dust bowl. Nevertheless, the energy gained from the hydro-electric generation might be considered to be worth it.

The claim has been made that this development could accommodate both wildlife and

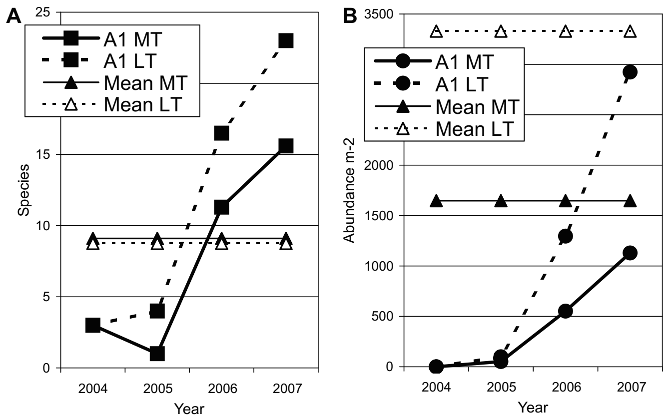

Fig. 18. Colonisation by inter-tidal macrobiota, diversity (**A**) and abundance (**B**) of artificial beaches (n = 6) in Phase A1 Al-Khiran Pearl City Waterways since flooding in 2004. Midtide (MT), and lowtide (LT) levels sampled on beaches. Mean diversity (A) and abundance (B) for midtide (Mean MT •) and lowtide (Mean LT o) for natural open coast beaches in Kuwait (n = 20) (2001–2005).

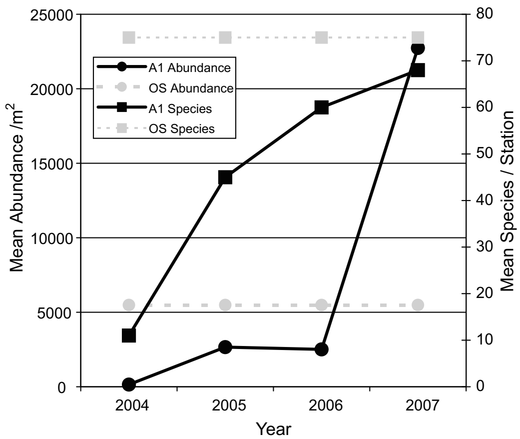

Fig. 19. Colonisation by sub-tidal macrobiota, diversity and abundance (A1) of benthic habitats (n = 3) in Phase A1 Al-Khiran Pearl City Waterways since flooding in 2004. Mean diversity and abundance for open sea (OS) benthos in Kuwait (n = 22) (2001–2005).

humans simultaneously. At present it is difficult to see how. Salinities would not only be raised to levels well beyond that seen in present constricted embayments (like the southern Gulf of Salwah) but would continually rise for the duration of the dam as seawater continued to evaporate. After several years the Gulf would simply become a salt basin. This could, however, be partly avoided by outlet pipes which would permit highly saline water to exit into the Arabian Sea; suitable depths for the discharge are over 200 m which would require pipes to extend for about 100 km.

The proponents point out that the electricity produced would save 23.8 megatons of CO_2 annually if produced by coal, an increasingly important point. But the terrain left by the receding water in the Gulf as evaporation takes place would be highly in-conducive to life, with no biota larger than nematodes able to survive in the highly saline soils, a point which appears to be overlooked in those parts of the proposals which talk of using the newly exposed land for agriculture (though the authors point that genetic engineering might help species, even crops, to survive). If the Turkish damming of the major rivers proceeds according to plan too, then the reduced fresh water input would accelerate sea level fall so that the efficiency of the generating system would increase proportionally. It would also remove the only reliable and plentiful source of water on which the region depends for desalination.

Whether or not this is science-fiction (many present developments here would have seemed equally futuristic a century or two ago), ecological aspects are treated with the same cavalier lack of attention that ecology often receives (although in this case this obviously is a preliminary and outline sketch, focussing on engineering aspects only). The documents of Schuling et al. (2005, 2007) are clearly interesting, and the carbonate-to-gypsum technique has already been proven on limited scale. If it happens, then any other environmental impact in the Gulf would be relatively insignificant.

10. Problems from recent Gulf Wars

The deliberate 1991 oil spill occurred in an environment that was both far from pristine and highly naturally stressed already (Price 1993, 1998). Published figures put the spill at around 6–8 million barrels, although some estimates (e.g. Tawfiq and Olsen 1993; Linden and Husain 2002) consider the volume was higher. In addition to the oil spill, extensive pollution, a drop in temperature and reduction in photosynthetically active radiation (PAR) came about from the conflagration of more than 700 oil wells, which burned for several months (Literathy 1993; Munawar et al. 2002).

The 1990–91 Gulf conflict, one of several in the region in recent decades (Literathy et al. 2002), generated much research. Books (Sadiq and McCain 1993; Krupp et al. 1996; Otsuki et al. 1998), special issues of journals (e.g. Price and Robinson, 1993; Al-Muzaini et al., 1998) and numerous research papers (e.g. Readman et al. 1992, 1996a,b; Fayad and Overton 1995; Jones et al. 1998) and reviews as noted earlier, have been devoted to both immediate and wider environmental consequences. These studies and ongoing assessments, including those linked to environmental damage claims, have helped to make this part of the Gulf well studied.

Despite numerous assessments, issues surrounding environmental damage have not been fully resolved, although damage to inter-tidal regions, including their cyanobacterial mats, was severe (Al-Thukair et al. 2007). This partly reflects the challenges in characterizing 'damage' and 'recovery'. Overall impact was greatly influenced by geographical location; the Abu Ali island half way down the Saudi Arabian coast acted as an oil trap. Sub-tidal damage was relatively limited, and inter-tidal systems that were impacted showed considerable variability. Inter-tidal recovery in many oiled areas was well underway by the mid- to late-1990s (Jones et al. 1998). These authors tentatively suggested a period of 3–5 years for return to normal diversity (species richness), and a period of 3–6 years for restored abundances on rocky shores and inter-tidal soft substrata. Later assessments for environmental damage compensation by claimant countries, believed recovery times to be substantially longer than half a decade, particularly for marsh areas and low-energy tidal flats.

In many areas, large-scale clean-up operations increased damage (Linden and Husain 2002). Studies in 1991, for example, revealed that in areas cleaned, particularly using high

Table 8. Distribution of Euphrates and Tigris River waters.

River	Total	Turkey	Syria	Iraq	Iran
Length (km), and % of river in each country					
Euphrates	3000 km	41	24	35	0
Tigris	1862 km	22	2	76	0
Euphrates–Tigris basin area (km^2) and% of distribution in each country					
Euphrates	444,000 km^2	28	17	40	0
Tigris	387,000 km^2	12	0.2	54	34
Total	765,000 km^2	22	10	51	17

pressure flushing and where the upper layers of sediment were removed, faunal recovery took significantly longer than if the oil had been left to degrade naturally or had been only partly removed (Watt et al. 1993). This highlights the importance of ensuring that clean-up technologies result in net environmental benefit.

During the early and mid 2000s, environmental assessment of the 1991 Gulf War was re-invigorated as part of damage compensation claims under the aegis of the UN Compensation Commission (UNCC). Remediation and restoration work is ongoing. In total, the UNCC received and has resolved over 2.7 million claims amounting to $352 billion (Kazazi 2007). Of these, 170 claims amounting to $85 billion were for environmental loss and depletion of natural resources. Successful claimants have received a total of $5.3 billion through the UNCC, as follows: $243 million for monitoring and environmental studies; $864 million for loss of natural resources and damage to public health; and, by far the biggest suite of environmental claims, $4.2 billion for cost of future environmental restoration (Kazazi 2007). Remediation of coastal areas impacted by oil is included in the latter claims, although most of the funding is for remediation of aquifers contaminated by petroleum, gas residues and seawater, the latter pumped to desert areas to help extinguish the burning oil wells. Although desalination has been the principal source of freshwater for several decades, aquifers are considered a critical resource that, like oil, is not renewable.

Habitat Equivalency Analysis (HEA) was widely used in the assessment of environmental damage and settlement of compensation for impacts arising from the 1990–1 Gulf conflict. This increasingly used method estimates appropriate levels of compensation for interim losses resulting from such spills or releases of other toxic substances (Dunford et al. 2002). "Specifically, it calculates the natural resource service losses in discounted terms and then determines the scale of restoration projects needed to provide equal natural resource service gains in the future in discounted terms, thereby fully compensating the public for the natural resource injuries" (Dunford et al. 2002). Using HEA, there is flexibility in how damage is translated into a compensatory project. As a hypothetical illustration, damage amounting to 20 km^2 over a 10-y period (200 km^2 y^{-1}) could result in a project encompassing this area and operate for this duration. Alternatively, the compensatory project could be the equivalent overall magnitude of, for example, 200 km^2 for a period of one year, or 10 km^2 over 20 years.

Substantial data have accumulated from the monitoring, assessment and other studies linked to resolution of the UNCC environmental claims; much more is also likely to follow over the coming 5–10 years as restoration projects progress. However, much information is confined to consultancy and government reports which, for reasons for perceived sensitivity and

Table 9. Major environmental disturbances in the Gulf arising from human uses and activities within the region (from Price (1993)), added to which are the major impacts from climate change.

Coastal and marine use	Actual or potential environmental pressures
Shipping and transport shipping ports	Oil spills; anchor damage Coastal 'reclamation' and habitat loss; dredging, sedimentation; oil and other pollution
Residential and commercial	Coastal 'reclamation' and habitat loss; dredging, sedimentation; sewage, fertilizer and other effluents; eutrophication; solid waste disposal
Industrial development oil & petrochemical industry	Oil, refinery and other effluents containing heavy metals; drilling muds and tailings; air pollution
Desaliniation & seawater treatment plants	Effluents with elevated temperatures, salinities and sometimes heavy metals and other chemicals
Power plants	Various effluents; air pollution, increasing greenhouse gases and global warming; acid deposition
Fishing and collecting	Population decline of target and non-target species and changed species composition of fish, shrimp and other biota; habitat degradation (including anchor damage)
Recreation	Some reef degradation from anchor damage and collecting
Agriculture	Local eutrophication (e.g. from fertilizers), only low levels of insecticides such as DDT, aldrin, dieldrin & lindane recorded in marine sediments and biota, saline intrusion and possible effects on coastal ecosystems

confidentiality, may never be published nor enter the public domain.

11. Prognosis for the Gulf

To avoid further degradation of marine habitats, any single project should consider existing, planned and ongoing projects together. Reefs and mangroves in particular are more threatened here than in any other sea. According to a recent compilation by Wilkinson (2008) only 3% of all reef habitats in the Gulf have low threat levels, which compares very poorly with most other warm sea areas. A summary of the main pressures facing the Gulf is given in Table 9. But although the region contains the world's largest oil fields and second largest gas reserves, and despite the deliberate input of at least 8–10 million barrels in 1991, oil is not the most harmful ecological disturbance. Coastal dredging, infilling and conversion of shallow waters into land currently represent a much more serious threat (Al-Ghadban and Price 2002). A once-productive tidal flat or shallow nursery area, replaced by say a corniche road, buildings or other invasive coastal infrastructures, is unlikely ever to become biologically productive again. Insufficient attention is being given to the costs of loosing habitats (Costanza et al. 1997; Beaumont et al. 2008).

Lost or degraded coastal systems can be offset to some degree by the creation of artificial marine waters in saline sabkha and hyper-saline khors of low ecological value, as has been shown above. But while engineering solutions such as this might help offset some damage, it is not, by itself, sufficient to reverse the last 15 years of unsustainable and damaging coastal development that is now so prevalent throughout much of the Gulf. Moreover, the prevailing approach envisaging the translocation of existing habitats or the creation of new artificial ones cannot remain unchecked forever as, in principle, suitable areas may soon be exhausted.

Besides pressures originating within the Gulf, its environment is subject to severe outside disturbances. Particularly significant is episodic seawater warming and consequent coral mortality, sea level rise, and the diversion of rivers entering the Shatt Al-Arab. Changes in salinity, nitrate, chlorophyll-a in Kuwaiti Gulf waters, for example, have already come about and permanent removal of seasonal flooding will also impact the northern Gulf's marine environment, with serious implications for fisheries.

Despite the many marine studies undertaken in the Gulf, collateral environmental damage from coastal development continues at an unprecedented and alarming scale. Effects of scores of individual environment impacts are clearly by far the greatest threat to the region. Extensive research, environmental assessments and alleged 'baseline surveys' have brought no guarantee of natural resource or coastal protection. Short-term and often ill-conceived investments continue to be big drivers of coastal use and allocation of beach frontage in the region.

Critical over the coming decade will be the degree to which the Gulf can absorb additional shocks and disturbances, yet continue to provide valuable ecosystem and economic services. Resource damage is progressing on such a scale that it possibly will overwhelm the resilience of the system. Resilience or robustness is a useful framework for understanding and assessing this (Jen 2005; Wagner 2005; Walker and Salt 2006) but, with few exceptions (e.g. Izsak et al. 2002), empirical and synergistic studies incorporating long-term or historical data have not been done in the Gulf.

Increasing the Gulf's network of coastal protected areas (Krupp et al. 1996) may be one practical means of retaining or re-instilling functionality and robustness. These will help against the many uncertainties now facing the Gulf's productive habitats. To that end a number of proposals are being considered in many countries, and some marine protected areas have in fact been declared in the past two decades. But to be effective, given the small scale of the Gulf and the obvious cumulative and trans-boundary impacts, only a large network of closely monitored and protected sites could effectively offset many of the ongoing and planned threats. In other words, stronger environmental considerations, greater interaction amongst projects, increased information sharing between government departments, a longer-term viewpoint and agreed Gulf-wide strategic approaches are required to ensure both the ecological and economic sustainability of the Gulf.

The alternative is that one of the world's youngest seas will become one with the least value and greatest problems. If current trends continue, we will also lose a unique marine environment whose coral reefs could crucially function as a living laboratory to explore how reefs may adapt elsewhere on the planet, given the forecast rise in sea surface temperatures.

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