ECOSYSTEMS AND BIODIVERSITY OF THE ARABIAN GULF

SAUDI ARABIAN WATERS

Fifty Years of Scientific Research

A Publication by Saudi Aramco and King Fahd University of Petroleum & Minerals

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جامعة الملك فهد للبترول والمعادن
King Fahd University of Petroleum & Minerals

أرامكو السعودية
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Preface

For nearly five decades, the King Fahd University of Petroleum and Minerals (KFUPM) has partnered with Saudi Aramco to document and explore the wondrous ecosystem that exists in the Arabian Gulf. The book before you offers a comprehensive and up to date guide on the fruits of that work and its findings.

Through its pages, marine scientists, decision makers, students and indeed anyone with an interest in marine environmental protection, will have access to a wealth of scientific information.

The Arabian Gulf is environmentally challenged because of the natural stressors of salinity and temperature fluctuations. Rapid population growth and associated developmental activities along its coasts, particularly those related to the urban and industrial development, are adding additional stress on the Arabian Gulf's fragile environment.

The partnership between KFUPM and Saudi Aramco, has resulted in a greater understanding of the Arabian Gulf's natural ecosystems, ensuring greater protection of biodiversity and natural resources. The backbone of this partnership has been the Marine Environmental Sustaining Research Program, which has produced fundamental knowledge on the Arabian Gulf's marine environment. In addition, detailed and in-depth environmental impact assessments have been systematically conducted for proposed development projects as well as environmental monitoring during construction and commencement of operations, all contributing to our knowledge of the ecosystems. This information has contributed to the protection of the ecosystems and the development of a fisheries management framework in the Arabian Gulf.

We are grateful for the collaboration and efforts of the interdisciplinary teams of the Environmental Protection Department of Saudi Aramco and the Marine Studies Section of KFUPM in preparation of this book. A deep and sincere appreciation is extended to each and every person who, for nearly five decades, has played a part in this partnership in marine environment protection. This book is a testament to your hard work and our collective desire to preserve the beautiful ecosystem that flourishes in the Arabian Gulf.

Amin H. Nasser
Saudi Aramco President & CEO

Foreword

The Arabian Gulf has always been a special component of the Kingdom's economy and culture. Aside from its rich oil and gas resources, it is also an important source of food and water, and is a major transportation point. But not to be undermined or forgotten is the fact that it also supports vital and thriving ecosystems. In its waters are seagrass, coral reefs, salt marshes, and mangroves, as well as intertidal and subtidal sediments and deeper water areas. These interacting habitats provide the essential components for a vibrant and productive marine ecosystem. However impressive this may sound, the Arabian Gulf is also facing natural and human-induced stress, such as elevated seawater temperature and salinity; coupled with coastal urbanization and rapid industrialization. These stresses, if not managed, can impact the long-term ecosystem services currently provided by the Arabian Gulf.

Scientific research on its marine environment is the result of collaboration between industry and academia. It was in 1982 that the Environmental Protection Department of Saudi Aramco and the Marine Studies Section of the King Fahd University of Petroleum and Minerals began joint research into the Arabian Gulf's ecosystem. This partnership involved the development of research programs to study the Arabian Gulf's ecosystem values, interactions, and reduce the impact of stress. Currently, the sixth phase of this sustaining research program is focusing on the biodiversity status across the Arabian Gulf's ecosystems. This book gathers the results and the major scientific findings of this long-term collaborative program and provides a detailed, updated review on the state of the marine ecosystems and biodiversity of the Western Arabian Gulf. For anyone who has an interest in the topic, it serves as the current definitive work, and is a reminder of the importance of marine ecosystems.

Prof. Sahel N. Abduljauwad
Rector of King Fahd University
of Petroleum & Minerals

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Benthic Ecosystems (Soft and Hard Substrata)

Thadickal V. Joydas[1] and Angel Borja[2]

Introduction

The benthic ecosystem is a complex of living organisms, their physical environment and all their interrelationships in the bottom of a body of water. The marine benthic environment extends from intertidal regions down to the deepest parts of the sea. The organisms living in the seabed ecosystem are called benthos and include a wide range of plants, animals, and microbes. The benthic communities form an important component of all kinds of aquatic food webs. The term "phytobenthos" is used when referring to the plant members (i.e., various algae and aquatic plants), whereas "zoobenthos" is applied in reference to all consumers (i.e., benthic protozoans and metazoans). "Benthic microflora" (bacteria, fungi, and many protozoans) constitute the decomposer community. The zoobenthos is divided into three functional groups, infauna, epifauna, and hyper-benthos (i.e., those organisms living within the substratum, on the surface of the substratum and just above it, respectively) (Pohle and Thomas, 2001). According to size, benthic animals are divided into three groups such as: (i) macrobenthos (organisms which are retained in the sieve having a mesh size between 0.5 mm and 1 mm), (ii) meiobenthos (between 63 μ and 0.5 mm or 1 mm), and (iii) microbenthos, (those organisms that are not retained in the finest sieve used for meiobenthos separation and include bacteria and most protozoans) (Mare, 1942).

Marine benthic communities are generally dependent on primary production in the overlying water column for their energy. Consequently, the distribution and abundance of benthic organisms depend on water column processes, which affect the transfer of organic material between benthic and pelagic systems (Davis and Payne, 1984; Fowler and Knauer, 1986; Townsend and Cammen, 1988). The contribution of energy through benthic algal production is restricted to the euphotic zones.

The benthic ecosystem plays a significant role in the functioning of the marine ecosystem. Many ecosystem processes such as carbon cycling and burial are mediated by infaunal invertebrates through their mechanistic processes such as bioturbation (Solan, et al., 2008), which stimulates the release of nutrients from the sediment (Ieno, et al., 2006). The feeding, burrowing, and tube construction of infaunal benthos tend to influence particle transport, while irrigation of burrow structures influences water and solute exchange (Solan, et al., 2008).

The phytoplankton biomass, phytoplankton production, and system metabolism are enhanced in the shallow coastal areas with increased nutrient loading from the sediment (Boynton, et al., 1982; Cloern,

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2001). Megafauna also directly contribute to organic matter recycling by stripping organic matter in the debris from the sediment (Smallwood, et al., 1999; Jeffreys, et al., 2009). The megafauna also have indirect effects upon ecosystem processes through predation and disturbance of meio- and macrofaunal taxa (Ambrose, 1993; Hudson and Wigham, 2003). In marine sediments, microbes mineralize organic material by transferring electrons from organic molecules (electron donors) to other chemical species (electron acceptors). In undisturbed sediments, organic mineralization by microbes occurs in a vertically stratified manner that follows the sequence of energy yields from available electron acceptors. As a result, specific biogeochemical reactions are characteristic of specific sediment layers.

The sediment water interface is one of the most important transition zones for solute exchange; it is characterized by steep gradients and extensive spatial and temporal heterogeneity (Fenchel, 1969). As diagenetic reactions in surface sediments are dramatically affected by biogenic activity, decomposition of sedimentary organic matter and nutrient remineralization can be rapidly accelerated within the biogenic mixing zone (Forster and Graf, 1995; Aller, et al., 2001), resulting in a vertical color transition from brown at the sediment surface to olive black at depth (Fenchel, 1969).

Benthic communities are considered to be good indicators of ecosystem health because of their sedentary nature and longevity, which provides long-term exposure to toxic substances, and the presence of diverse taxa, which can respond to multiple types of stress (Jewett, et al., 1999). Because they are relatively sessile, the status and well-being of marine benthic communities can be used to determine the response to several kinds of environmental conditions, e.g., eutrophication, or effects of man-made perturbations (Pearson and Rosenberg, 1978; Guidetti, et al., 2000; Hampel, et al., 2009).

As such, in the western Arabian Gulf, more than the pelagic zone, the seabed presents the greatest diversity and productivity (Sheppard and Borowitzka, 2011). This coast supports a variety of benthic habitats, which are distributed in intertidal and subtidal habitats. Both soft and hard substrata are seen in these habitats. Intertidal habitats include mangroves, sandy beaches, patchy rock shorelines, protected tidal flats associated with coastal embayments and lagoons. Subtidal habitats include sandy, muddy, seagrass beds, coral reefs, and rocky habitats.

The benthic ecosystem of the western Arabian Gulf incurred severe damage from the 1991 Gulf oil spill (Jones, et al., 1998). The spill devastated the intertidal and nearshore subtidal habitats from Kuwait to Abu Ali Island in the south, Figure 3.71. Although, recovery was reported from a majority of the open water benthic habitats within five years (Price, 1998), accumulated oil in the sheltered bays slowed the recovery until it was incorporated into deeper sediment layers. Since the 1991 event, no major oil spill has occurred in this area; however, currently, other human activities, such as oil-related development activities, wastewater discharges, dredging and land reclamation, are causing stress to the benthic ecosystems of the Gulf (Zainal, et al., 2012). For example, large-scale coastal habitat modification by dredging, construction of causeways and artificial islands and converting shallow, productive marine areas into land for homes, recreation, and industrial facilities are major threats to the Gulf's ecosystem sustainability (Munawar, et al., 2002; Khan, 2007; Jones, et al., 2007; Sheppard, et al., 2010).

This chapter reviews what is known about the various benthic habitats of the western Arabian Gulf with a special reference to the communities living in each habitat.

Methods of Obtaining Data

The majority of the data used for this chapter are based on several field studies conducted by King Fahd University of Petroleum and Minerals (KFUPM) and Saudi Aramco over the past 30 years in the Saudi waters of the Arabian Gulf. Where the KFUPM/Saudi Aramco data are not available, available literature was used as the data source.

Visual and quadrat surveys were employed by the KFUPM/Saudi Aramco field teams in the intertidal rocky shores. Grabs (normally van Veen grab of 0.1 m^2 bite area) were used to obtain macrobenthic samples from the subtidal soft bottom. During the 1970s and 1980s, diver operated scoops (0.1 m^2) were used for collecting nearshore sediment samples. Divers used to push this device through the sediment so that the upper 10 cm of the sediment would be brought into the scoop.

Several methods have been used for biotope surveys also. This includes the conventional visual observation and photographic documentation by SCUBA divers and snorkelers, as well as the modern methods such as a submersible camera and remotely operated vehicles. In the past, grab methods were used to collect the sediment samples and to observe the seabed features in the deeper regions.

Distribution of Ecosystems

The major benthic habitats of the Saudi coast of the Arabian Gulf include intertidal area and subtidal areas, Figure 3.71. Generally, the intertidal area in the open coast is sandy and is protected from strong wave action by the subtidal shallows that usually occur in front of them. The sheltered bays of Manifa, Musallamiyah, Khursaniyah, Abu Ali, Tarut Bay and the Gulf of Salwa contain large areas of tidal flats, which appear as mud flats, sand flats and rock flats (see Chapters 3.3 and 3.4). The tidal flats occupy 30% to 40% of the various bays in the western Gulf (Basson, et al., 1977). Mangroves are confined to only four regions, including Tarut Bay-Dammam, Gurmah Island, Abu Ali Island and Khafji area (KFUPM/RI, 1994; Saenger, 2011) (see Chapter 3.6). Rocky intertidal regions are of limited occurrence and are mostly fragmented, and often intermixed with sand. Intertidal rock flats occur extensively in the Gulf of Salwa.

In the subtidal region, the largest proportion of seabed by far in terms of area comprises of soft sandy or muddy substrata. Sand is normally seen from the immediate subtidal levels to a depth of 7 m to 10 m; below the sandy zone, mud gradually increases and predominates. Tidal deltas occur in most of the bay systems along the Saudi Arabian Gulf coast and are extensive in Tarut Bay. Erosional forces produce these deltas, which are modified by the presence of seagrass beds. There are offshore sand deposits at depths down to at least 30 m. These offshore deposits occur around coral reefs and islands where the structures break the tidal water movements and retain sand. The coral breakdown products also add to the surrounding sand bottom. A rocky bottom is a common feature of the immediate subtidal region of the open coast, which is seen as patches, bands and boulders. Both the rough and smooth rocky bottoms are seen in the western Gulf (Basson, et al., 1977).

Seagrass beds occupy large areas of sandy and silty sand substrata in the shallow depths (see Chapter 3.7). The depth range of seagrass is generally limited by light penetration in the Gulf and it is normally to

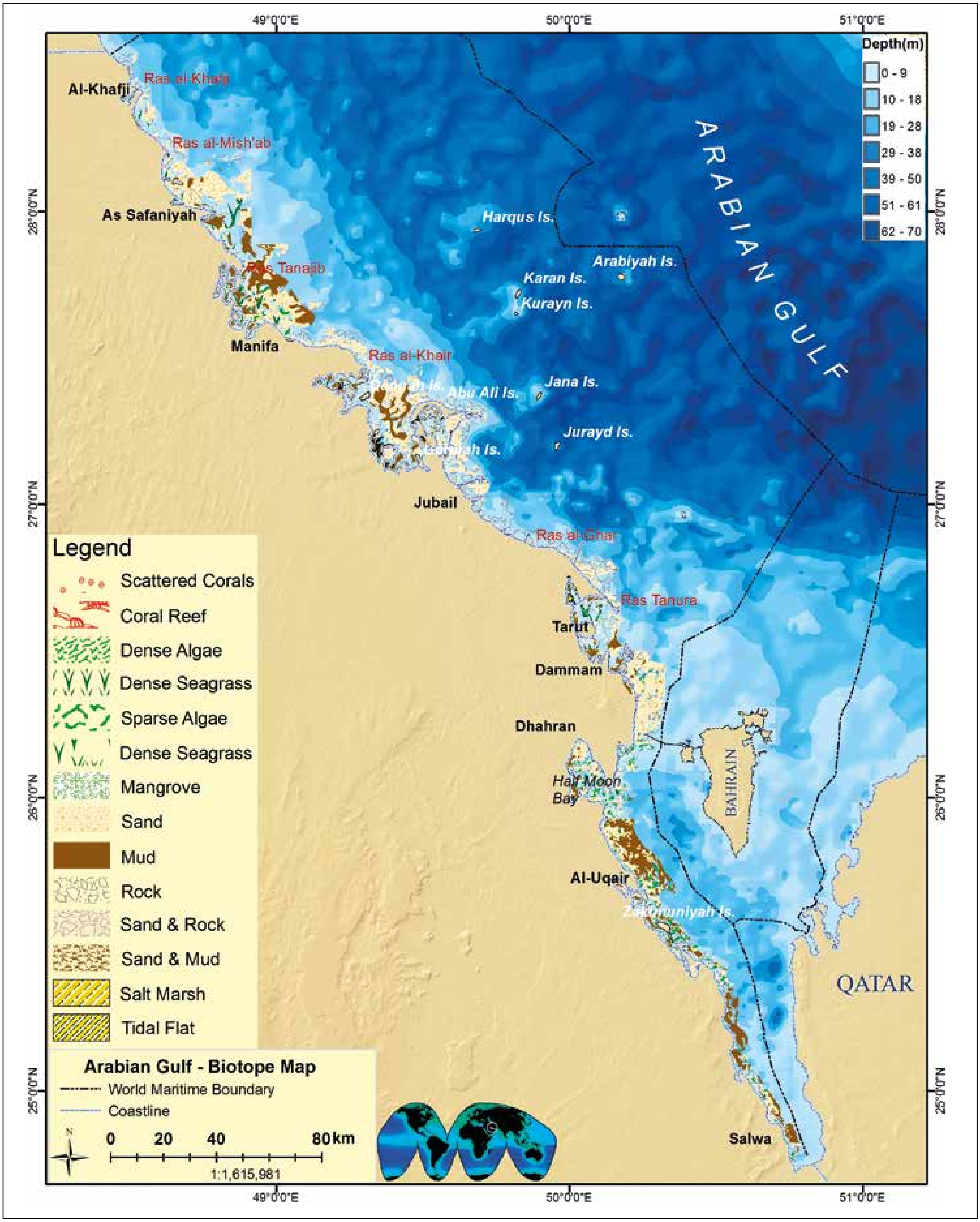

FIGURE 3.71. *Biotope map of the Saudi coast of the Arabian Gulf (KFUPM/RI, 2014a).*

a depth of 10 m to 12 m. Seagrass occurs as sparse to dense patches from Safaniyah to Salwa in the Saudi coast. Seagrass beds are quite common in sheltered bays.

Coral reefs have a scattered distribution in the western Arabian Gulf and the distribution is salinity dependent (see Chapter 3.10). Because salinity increases southward, the number of coral reefs decreases gradually from Abu Ali south to Ras Tanura and decline dramatically further south (Basson, et al., 1977; IUCN, 1988; Coles and McCain, 1990; KFUPM/RI, 2014a). Although species diversity is lower, coral reefs flourish around the offshore islands of Jana, Jurayd, Karan, Kurayn, Harqus, and Al Arabiyah, Figure 3.71.

In the Arabian Gulf, artificial reefs, which include planned artificial reefs (reef structure built for attracting fishes) and non-planned artificial habitats (such as oil and gas infrastructure, sunken vessels, waste materials and coastal development) provide habitats for a variety of organisms (KFUPM/RI, 1994; Feary, et al., 2011). The offshore oil platforms in the Arabian Gulf , ranging from single well or flare tripods to large gas-oil separation plants (GOSPs), offer an unusual combination of vertical and hard bottom environments for settlement and colonization by assemblages of fishes and invertebrates derived from different habitats (KFUPM/RI, 2013a, 2014b).

Abiotic Characteristics

The distribution of benthic communities is controlled by bottom water and seabed characteristics. The seawater characteristics of the Arabian Gulf are determined by the shallow depths, extreme air temperatures, high evaporation rates, and restricted oceanographic connection of the Gulf with the Arabian Sea, through the Straits of Hormuz (Hunter, 1982). The resulting seawater condition is harsh, with a range of temperature and salinity extremes exceeding most other marine areas in the world. Bottom water temperatures are generally in the range of 16 °C to 36 °C in the nearshore and 17 °C to 34 °C in the offshore areas (KFUPM/RI, 2013a, 2013b, 2014a). Extreme water temperature variations are unique features of the sheltered water bodies such as the Manifa-Tanajib Bay System (MTBS) (18 °C to 36 °C) and the Gulf of Salwa (17 °C to 40 °C), (Coles and McCain, 1990; Coles and Fadlallah, 1991; Jones, et al., 1998; KFUPM/RI, 2014a). Salinity shows a spatial variation with a range of 38 to 42 in the region north of al-Khobar, but increases dramatically southward. Open water salinities in the Gulf of Salwa range from 52 in the north to 63 in the south, with no indications of vertical salinity stratification (KFUPM/RI, 2014a).

Because the water related parameters are explained in Chapter 2, this section focuses only on the characteristics of the substrata and the major contaminants in the sediment.

Sediment Texture

Sediment texture is one of the most important factors controlling the distribution of benthic invertebrates. Several studies have correlated the distribution of infaunal invertebrates with sediment texture, leading to the generalization of distinct association between animals and specific sediment types (Peterson, 1913; Ford, 1923; Davis, 1925; Jones, 1950; Sanders, 1958; Jansson, 1967; Johnson, 1977). A predominant generalization proposed by Sanders (1958) was that suspension feeders were more abundant in sandy environments and deposit feeders were more abundant in muddy environments.

In the Arabian Gulf, sediments and their characteristics generally follow distributions that align with the northwest-southwest axis of the Gulf. Sediment types include coarse to fine sands, muddy sands, and fine mud particles. Wagner and van der Togt (1973) classified 14 major sediment types in the Arabian Gulf, 12 of which were essentially carbonated. In the shallow region (≤10 m depth), sand mixed with lamellibranch, gastropod, and foraminiferan remains is the predominant sediment type. Coral and algal fragments make up some of the coarse and fine sands in this region. In the depth below 10 m, mud fractions predominates (10% to 98%). These offshore sediments have a grade from skeletal, oolitic, and pelletoidal sands through an irregular zone of compound grain sands, to widespread skeletal muddy sands, and finally in-basin center muds with a high content of noncalcareous material.

Studies have shown a significant positive correlation ($r=0.63$; $P<0.001$) between depth and mean grain size (MGS Φ) indicating a decrease in mean size with depth (KFUPM/RI, 2006a; Joydas, et al., 2012). These studies showed the occurrence of three types of sediments along the depth gradient, Figure 3.72. At ≤10 m depth (shallow depth zone) sediments were of large grain size (sand) with MGS 1.62 ± 0.71 Φ and moderately sorted or moderately well sorted sediment. At 11 m to 28 m depth (intermediate depth zone) sediments were of small grain size (mixed sand and mud) with MGS 4.87 ± 2.16 Φ and poorly sorted or

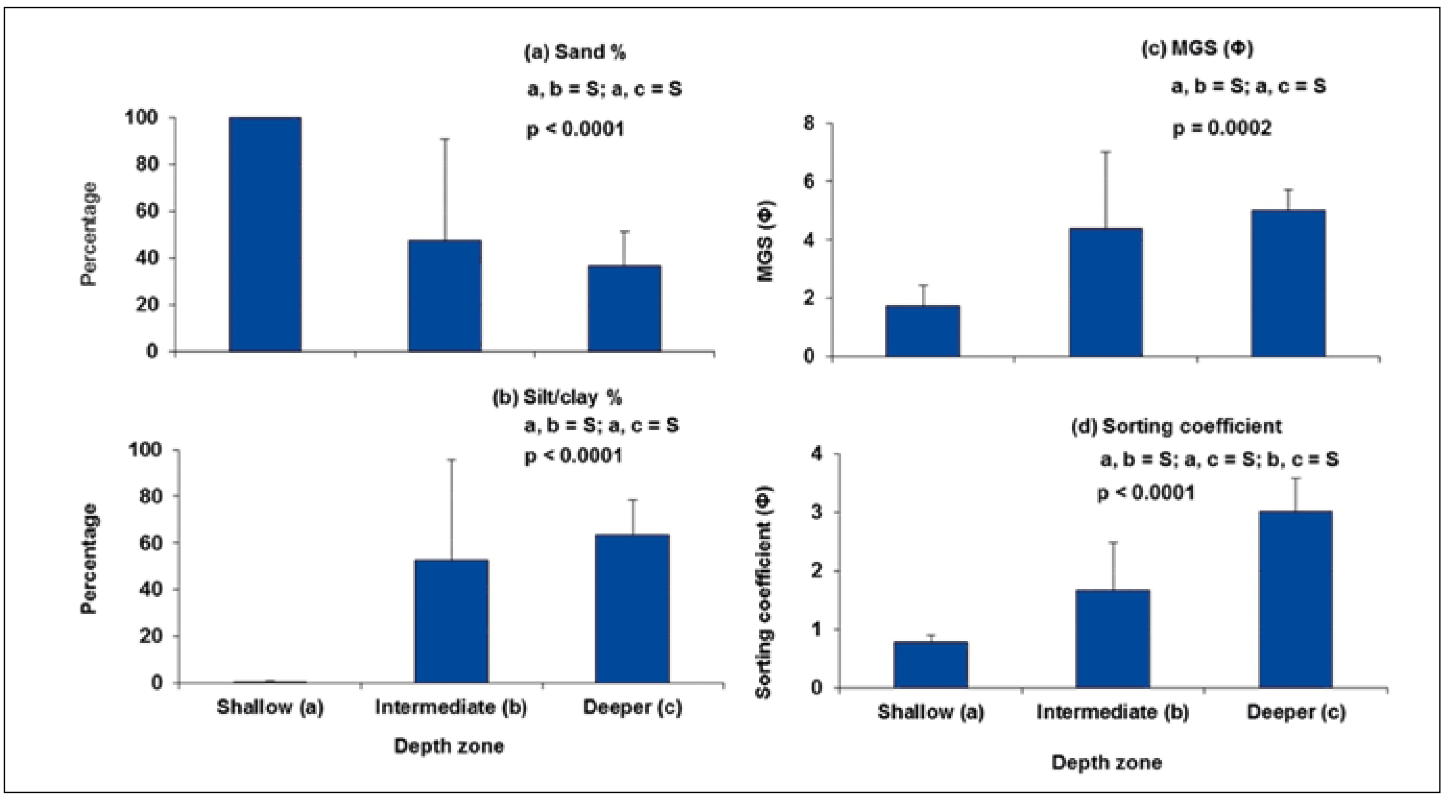

FIGURE 3.72. *Distribution of (a) sand%, (b) silt/clay%, (c) mean grain size, and (d) sorting coefficient in the three different depth zones of the Arabian Gulf study area. The results of one-way ANOVA are shown by p value. "S" denotes a significant variation between the pairs as shown by post-hoc Tukey/Kramer tests (KFUPM/RI, 2006a; Joydas, et al., 2012).*

very poorly sorted sediment, plotted on the right lower side. At ≥29 m (deeper depth zone), sediments were of small grain size (mud) with MGS 4.98 ± 0.75 Φ and very poorly sorted sediment. According to Wagner and van der Togt (1973), the decreasing sediment grain size with increasing depth, the result of increasing protection from wave action in the center of the basin, cause the transport of only fine materials to the center of the Gulf basin.

The sheltered inner bays, for example, MTBS, are sandy at their openings, but the sediment grain size tends to decrease inwards, Figure 3.71. The primary sediment supply to the relatively calm interior of the inner bays is the finer, suspended sediments carried by tidal flows.

The major single source of Gulf sediments is the calcareous shells and skeletons of marine organisms, which account for 47% of the sediments in the entire Gulf (Emery, 1956). Wind-driven dust is a major source of fine sediments in the coastal areas of the western Gulf, especially during *shamal* (northwesterly wind) conditions. Particle sizes are primarily in the silt size fraction with virtually all of the remainder being clay size particles. Analysis of dust collected on shipboard from the Gulf (Emery, 1956) showed it to be more than 80% calcareous calcite, with most of the remaining terrigenous material to be feldspar. Minor sources include direct chemical precipitation and sediments from the Tigris-Euphrates River system and evaporites that are deposited during the evaporation of seawater.

Total Organic Carbon in the Sediment

The nutritional quality of sediment measured as organic carbon is one of the major factors determining the standing stock and composition of the benthic communities. The level of total organic carbon (TOC) in a marine ecosystem plays a significant role in the accumulation and release of different micropollutants, and it also acts as an indicator of organic pollution (Khalaf, et al., 1981; Al-Ghadban, et al., 1994). The TOC content in the Arabian Gulf is mainly contributed by organic matter from biological productivity as well as petroleum origin. The Arabian Gulf has received fairly high amounts of organic material from the 1991 Gulf oil spill, which accounted for 0.5% to 1.5% TOC compared to the 0.5% natural background level (Al-Ghadban, et al., 1994).

A recent study on TOC in the Saudi coast of Arabian Gulf showed values ranging from 0.3% to 3.40%, Figure 3.73 (KFUPM/RI, 2014b). Although statistically not significant, an increase in the percentage of TOC with an increase in water depth was observed. Generally, the TOC showed an affinity toward finer grain size ($r=0.362$; $P<0.01$). The association between organic matter and grain size is considered to be due to the adsorption capacity of organic matter onto clays and the similarity in the settling velocity of organic particles and clay (Kemp, 1971).

Contaminants in the Sediment

The Arabian Gulf is considered to be one of the most human impacted regions in the world and a recent evaluation designates the Gulf as a young sea in decline (Sheppard, et al., 2010). One of the reasons for this deterioration is the oil-related activities and the discharge of pollutants such as hydrocarbons and metals. Annually, around 2 million barrels of oil are spilled from routine discharges of ballast, tanker slops

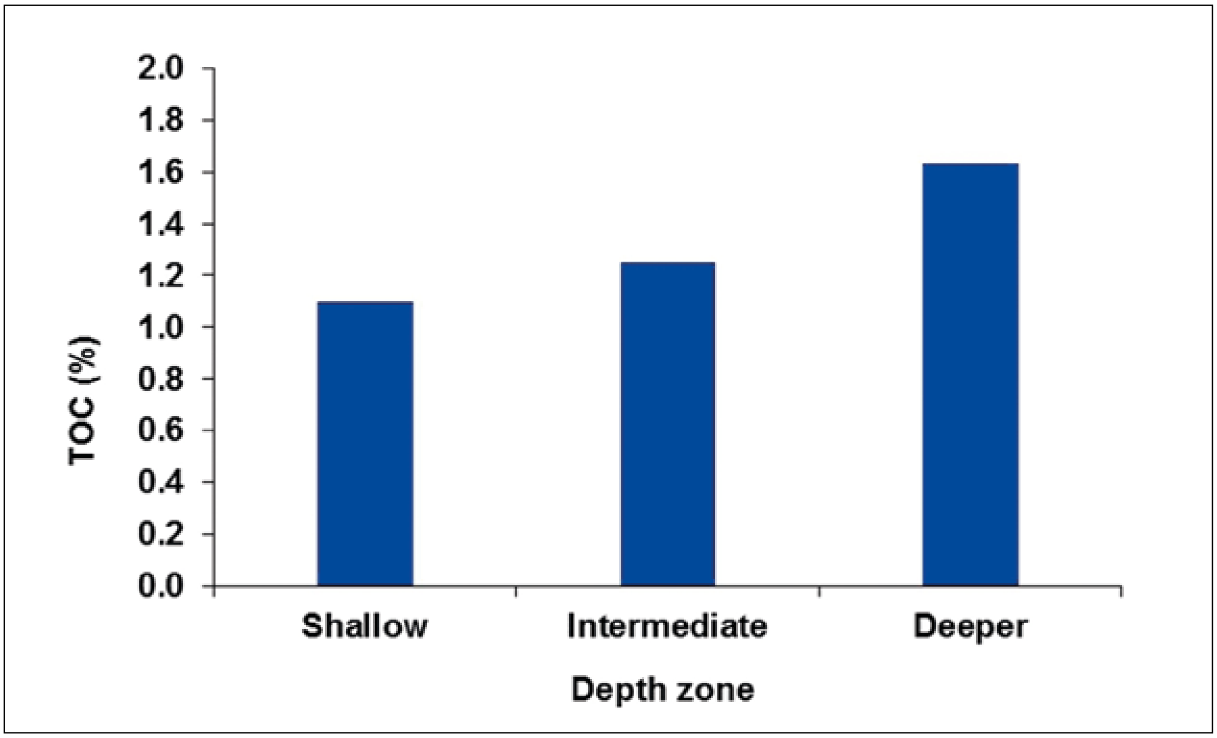

FIGURE 3.73. *Distribution pattern of sediment TOC (in percentage mean+SE) in the western Arabian Gulf (KFUPM/RI, 2014b).*

and from 800 oil and gas platforms (Butayban, 2005). Nonetheless, no single incident other than the 1991 Gulf oil spill has caused extensive damage to the western Gulf coast. The spill, which was the largest oil spill in history, with an estimated release of 6 to 8 million barrels of Kuwait crude oil, heavily affected the coastal areas located between Ras Al-Khafji in the north and Ras Abu Ali in the south of the Saudi Arabian coast (Readman, et al., 1992, 1996; Literathy, 1993; Tawfiq and Olsen, 1993; Michel, et al., 1993; Sadiq and McCain, 1993; Price, 1998). Metals are the next most serious pollutant in the Arabian Gulf and are introduced to the water through industrial effluents, brine discharges, coastal modifications and oil pollution (Naser, 2013).

The concentrations of hydrocarbons in the Arabian Gulf reported for sediment and tissues varied in samples taken before and after the 1991 spill, Table 3.26. Prior to the 1991 Gulf oil spill, total petroleum hydrocarbon (TPH) concentrations in the sediment ranged from non detectable to nearly 300 mg kg^{-1}, with high concentrations occurring sporadically. Following the 1991 Gulf oil spill, the intertidal regions and sheltered bays were severely affected by the spill (Readman, et al., 1992, 1996; Fowler, et al., 1993; Hayes, et al., 1993; Al-Lihaibi and Al-Omran, 1996; Massoud, et al., 1996, 1998; Al-Lihaibi and Ghazi, 1997; Banat, et al., 1998). About one year after the spill, the TPH concentrations up to 47,000 mg kg^{-1} were reported from the sheltered habitats like tidal flats, marshes and mangroves of Saudi Arabia (Sauer, et al., 1993). Eleven years after the oil spill, TPH concentration in subtidal sediments of the Saudi offshore region were within the range of non-detectable levels to 500 mg kg^{-1} dry weight while, sheltered bays such as Abu Ali and Manifa Bay showed high levels of TPH (ND to 89,000 mg kg^{-1}) (KFUPM/RI 2003). Fourteen years after the spill incident, de Mora, et al. (2010) reported TPH concentrations ranging from 6 to 238 mg kg^{-1} from the surface sediments of the coastal region of Saudi Arabia with the highest from the Abu Ali region.

Table 3.26. *Hydrocarbon concentrations reported for sediment and tissues in the western Arabian Gulf. Note: TPH: total petroleum hydrocarbon; TPAH: total Polycyclic Aromatic Hydrocarbons; ND: non detectable; wt: weight, KSA: Kingdom of Saudi Arabia.*

Location	TPH		TPAHs		Source
	Sediments (mg kg⁻¹)	**Tissue** (mg kg⁻¹ dry wt)	**Sediments** (ng g⁻¹)	**Tissue** (ng g⁻¹ dry wt)	
Bahrain (W. Coast)	0.5–8.6	13.1–18.5[a]	–	–	Fowler (1985)
Bahrain (E. Coast)	43.2	41.8–84.3[b]	–	–	Fowler (1985)
Kuwait	1.0–291	–	–	–	Zarba, et al. (1985)
Kuwait (subtidal)	–	2.3–5.3[f]	32-1,670	145-1,320[f]	De Mora, et al. (2010)
KSA (intertidal)	ND–148	–	–	–	KFUPM/RI (1988c)
KSA (subtidal)	0.07–5.4	3.3–287[c]	–	–	KFUPM/RI (1987)
KSA (offshore)	ND–6.8	–	–	–	KFUPM/RI (1988c)
KSA (Abu Ali Bay)	1.0–2,500	–	3-59,300	–	Michel, et al. (1993)
KSA (Abu Ali Bay)	0.2–47,000	–	–	–	Sauer, et al. (1993)
KSA (Manifa Bay)	13,000–19,000	–	–	–	Sauer, et al. (1993)
KSA (Sheltered bays)		16–480[c,d,e]	5000-175,000	89,000-240,0000[c,d]	Fowler, et al. (1993)
KSA (offshore)	ND.–500	–	ND-5,681	–	KFUPM/RI (2003)
KSA (Manifa Bay)	ND–89,000	–	–	–	KFUPM/RI (2003)
KSA (offshore)	–	–	10-29	–	KFUPM/RI (2013a)
KSA (subtidal)	6–238	26–28[c]	12.6-125	112-153[c]	De Mora, et al. (2010)

[a] Concentrations in rock scallops (*Spondylus* sp.).
[b] Concentrations in pearl oyster (*Pinctata margaritifera*).
[c] Concentrations in mud clam (*Meretrix meretrix*).
[d] Concentration in clam (*Tapes sulcarius*).
[e] Concentration in cockle (*Trachycardium lacunosum*).
[f] Concentration in venus clam (*Circentia callipyga*).

One year after the 1991 Gulf oil spill, the levels of total polycyclic aromatic hydrocarbons (TPAHs) up to 175,000 ng g^{-1} (dry weight) were reported by Fowler, et al. (1993) from the sheltered muddy basins along the Saudi Arabian coast. Eleven years after the spill, TPAH concentrations in the offshore sediment were found to vary from ND to 5,681 ng g^{-1} dry weight with the highest value recorded off Abu Ali (KFUPM/RI, 2003). Fourteen years after the spill, a high PAH concentration of 1,670 ng g^{-1} was reported from Kuwait, while comparatively lower (up to 125 ng g^{-1}) concentrations were recorded from the Saudi region (de Mora, et al., 2010). Recent studies showed that the total PAHs in the Saudi region are within the range of 9.5 ng g^{-1} to 29.4 ng g^{-1} (KFUPM/RI, 2013a).

Prior to the oil spill, the levels of TPH in bivalve tissues ranged from 3.3 mg kg^{-1} to 287 mg kg^{-1} in various parts of the western Arabian Gulf, Table 3.26. Fowler, et al. (1993) reported concentrations as high as 480 mg kg^{-1} about one year after the spill. Recent studies (de Mora, et al., 2010) showed that the tissue levels of TPH in bivalves were generally below 6 mg kg^{-1} in the western Arabian Gulf. The levels of PAHs in bivalves recorded one year after the spill ranged from 27,000 ng g^{-1} to 240,000 ng g^{-1} in the Saudi coast (Fowler, et al., 1993). The highest concentration was observed in the clam *Tapes sulcarius*. The more recent studies in Asiatic clam *Meretrix meretrix* showed total PAHs in the range of 112 ng g^{-1} to 153 ng g^{-1} dry weight in Saudi waters (de Mora, et al., 2010).

Various studies reported from the Saudi coast of the Arabian Gulf (Table 3.27) and a recent review (Naser, 2013) indicated that generally the levels of metals in this region are within the natural background levels found in other offshore areas and the elevated levels in most cases are associated with land-based anthropogenic activities such as oil refineries and desalination plants. The concentrations of Cd and Ni had occasionally exceeded from the guideline values prior to the 1991 Gulf oil spill (KFUPM/RI, 1983; Sadiq and Zaidi, 1985; Linden, et al., 1990). Following the spill, elevated levels of V, Ni, Cr and Pb were noted by Fowler, et al. (1993) at the heavily contaminated areas such as Ras Al-Mishab, Ras Al-Tanajib and Ras al-Khair. KFUPM/RI (2003) estimated the metal concentrations in sediment in the Saudi territorial region and found that the concentration of Cr, Cu, Ni, Pb, V and Zn were comparable to the baseline values of 1983 and 1985 (KFUPM/RI, 1983; Sadiq and Zaidi, 1985; Linden, et al., 1990) from the Saudi Arabian coast, and are less than the values reported for the period between 1992 and 1994, immediately after the 1991 Gulf oil spill.

Studies have shown that in the western Arabian Gulf, the highest concentrations of metals are present offshore rather than in nearshore areas (KFUPM/RI, 2003, 2013a). This results from the affinity of the metals to the finer sediment particles (Thorne and Nickless, 1981; Basaham and Lihaibi, 1993), and in the western Arabian Gulf, generally, sediment is silt/clay below 10 m depth. Naser (2013) reported a trend of decreasing metal concentrations from north to south in the Arabian Gulf, which was correlated to the increasing particle size from the north to the south.

TABLE 3.27. *Metal concentrations (mg kg^{-1} dry weight) in sediment recorded from the Saudi Arabian coast of Arabian Gulf.*

Metals/References	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn	Hg	Se	As
Guideline value NOAA ERL*	1.2	81	34		21	47			0.15		8.2
Guideline value ISQG ERL**	0.7	52.3	18.7			30.2		124	0.13	2	7.24
KFUPM/RI (1983)	3.22-4.9	7.32-40.5	—	—	23.7-50.4	0.7-3.0	—	—	0.004-0.03	—	—
Sadiq and Zaidi (1985)	2.5-5	3.4-53	5.6-16.6	—	20.5-64.6	0.6-4.2	3.4-29.3	4.2-22.6	—	—	—
Linden, et al. (1990)	0.02-5	—	1.3-16.6	—	0.4-65	0.6-15.1	0.1-56.4	1-51	—	—	—
Al-Arfaj and Alam (1993)	<1-6.9	4.7-24.2	2.5-7.9	—	3.2-39.1	8.4-35.8	4.5-31.1	2.4-20.1	—	—	—
Basaham and Al-Lihaibi (1993)	—	4-63	3-16	553-9,925	6-54	—	3-26	13-65	—	—	—
Fowler, et al. (1993)	0.089-0.21	24.6-99.2	3.1-5.5	3,374-11,003	7.86-27.8	1.7-4.4	10.2-26.2	3.41-10.2	—	—	4.61-22.7
Alam, et al. (1998)	1.9-15.2	2.4-56.1	0.7-17.4	344-15,598	5.6-84.2	14.3-50.1	6.8-31.1	2.3-43.4	—	—	—
KFUPM/RI (2003)	ND-1.8	0.29-48	ND-18	51-12,000	0.4-60	ND-6.2	0.19-25	ND-24	ND-0.07	ND-3.9	ND-11
KFUPM/RI (2013a)	0.2-0.7	4.8-59.6	2.6-20.7	588-19,377	5.2-74.1	4-52.5	4.1-46.7	1.7-934	ND-0.03	—	—

* The Marine Sediment Quality Guideline (MSQG) values suggested by NOAA, which designate an Effects Range Low (ERL).
** Canadian Interim Marine Sediment Quality Guideline (ISQG); ND. Not detected.

Prior to the 1991 Gulf oil spill, the reported concentrations of metals from the tissue of marine organisms were generally low, except some higher values (up to 139 mg kg^{-1}) noted for copper in mud clam *Meretrix meretrix* from Tarut Bay and Manifa Bay (KFUPM/RI, 1987). The 1991 Gulf oil spill caused the increase in Cu, Pb and Zn in the tissue of pearl oysters *Pinctada radiata* and the gastropod *Lunella coronatus* in Kuwait during 1994 (Buo-Olayan and Subrahmanyam, 1997). KFUPM/RI (2003) reported that the concentrations of Hg, Pb, Cd, Ni and Cr in tissue samples of demersal fishes were within the World Health Organization (WHO) permissible concentrations. However, the concentration of non-oil related metals As and Hg exceeded the WHO permissible level of 17 mg kg^{-1} and 2.2 mg kg^{-1} dry weight, respectively, in demersal fish groups such as sharks, rays, catfishes and lobsters (KFUPM/RI, 2003). Naser (2013), in a recent review, noted the high concentrations reported by De Mora, et al. (2004) for Zn (4,290 µg g^{-1} dry weight), V (7.3 µg g^{-1} dry weight) and Pb (3.9 µg g^{-1} dry weight) in pearl oysters near the oil refinery in Bahrain and by Al-Yahya, et al. (2011) for Pb (2.49 µg g^{-1} dry weight) in *M. meretrix* exceeded the maximum permissible level (1.5 µg g^{-1} dry weight) recommended by European Union standards along the Saudi coast.

Flora

Microalgae

Microalgae are mainly seen as algal mats, which are distributed in the intertidal and subtidal environments of the western Arabian Gulf. The growth and distribution of the microalgae depend on light and nutrient availability. Cyanobacteria form the major component of the algal mat. The dominant species reported from the mud flats of the western Arabian Gulf are *Microcoleus chthonoplastes, Oscillatoria nigro-viridis*, and *Lyngbya aestuarii*, *Chrococcus* sp., *Schizothriz* sp. and *Phormidium* sp, (Al-Thukair and Al-Hinai, 1993; Al-Mohanna, et al., 2007). A detailed description of microalgae is provided in Chapter 3.5.

Macroalgae

Macroalgae (seaweeds) are seen in the nearshore region usually attached to hard substratum, though they can even be found on sand where wave or current disturbances is low and where dead shells or dead fragments of corals provide attachment points (Sheppard and Borowitzka, 2011). Some of the most common taxa include *Caulerpa taxifolia* (Green algae), *Sargassum latifolium*, *Hormophysa triquetra*, *Padina* sp., and *Colpomenia sinuosa* (brown algae), *Laurencia* sp. (red algae). A remarkable feature of the macroalgae in the western Arabian Gulf is its seasonality, where brown algae such as *Colpomenia sinuosa, Hormophysa triquetra* and *Sargassum latifolium* completely cover corals and reef surfaces on inshore reefs during winter months, and disappear during spring warming (KFUPM/RI, 1988a, 1994; Coles, 1988). Despite being virtually covered by algal growth and restricted from light for at least a month during the winter, reef corals, mostly *Porites compressa*, are apparently undamaged and maintain high live coverage throughout the year. On offshore reefs where a greater number of coral species occur, the seasonal pattern of algal vs. coral dominance is less pronounced, probably resulting from the less extreme seasonal temperatures offshore. Subsequently, in deeper water at some offshore reefs, an opposite annual cycle of summer blooms of the algae *Dictyota* sp. and *Lobophora variegata* alternating with winter reductions of the coverage of these algae is found (KFUPM/RI, 1988a; Coles and Tarr, 1990). Chapter 3.5 provides a detailed description of macroalgae.

Seagrasses

Only three seagrass species viz. *Halodule uninervis, Halophila stipulacea* and *Halophila ovalis* have been reported from the western Arabian Gulf (Basson, et al., 1977; SATTL, 1982; KFUPM/RI, 1986, 1988b). A detailed description of the seagrass is presented in Chapter 3.7. Seagrass beds support diverse and productive benthic fauna. The benthic communities associated with the seagrass beds are discussed in the Seagrass section of this book.

Fauna

Meiofauna

Meiofaunal studies have been rather neglected in the western Arabian Gulf due to the lack of expertise in this field. Meiofauna have been the subject of intense quantitative study elsewhere, however, due to the important role they play in the marine food chains (McIntyre, 1969; Gerlach, 1971; Coull and Bell, 1979). Despite their small size, the mieobenthos can exhibit high turnover of biomass and are taxonomically diverse. In this section, meiofaunal samples collected from the offshore regions of the Saudi waters of the Arabian Gulf are discussed.

The identification of the specimens was carried out only to the major group level; however, as many as 19 taxa were recorded from the samples collected from the western Arabian Gulf where depth ranged from 13 m to 69 m, Table 3.28. Nematodes (47%) dominated the samples followed by polychaetes (29%) and copepods (14%). At a given station, the number of taxa ranged from 6 to 13. The density was within a range of 22 ind.10 cm^{-2} to 82 ind.10 cm^{-2} with a mean ± SD of 170 ± 231 ind.10 cm^{-2}. In general, a decrease in number of taxa and density of nematodes and total meiobenthos with increases in depth ($p<0.05$) was noticed in the study area. This can be a result of the preference of meiobenthic taxa to sandy substratum, which is prevalent in the shallower nearshore region.

TABLE 3.28. *Composition and density details (ind.10 cm^{-2}) of various meiofaunal taxa.*

Taxa	Density	Taxa	Density
Nematodes	80.6 ± 128.7(3.4-437.9)	Cumaceans	0.1 ± 0.3(0-0.7)
Polychaetes	48.7 ± 37.2(10.9-132.6)	Brachyurans	0.1 ± 0.4(0-1.4)
Turbellarians	0.1 ± 0.3(0-0.7)	Gastropods	2.8 ± 3.5(0-11.6)
Gammarids	1.5 ± 1.5(0-5.4)	Pelecypods	5.3 ± 9.8(0-34)
Caprellids	0.1 ± 0.2(0-0.7)	Polyplacophorans	0.1 ± 0.4(0-1.4)
Copepods	24.1 ± 56.2(0-189)	Ophiuroids	0.1 ± 0.2(0-0.7)
Tanaids	0.1 ± 0.2(0-0.7)	Rhynchocoels	0.9 ± 1.8(0-6.1)
Isopods	0.2 ± 0.4(0-1.4)	Sipunculids	1.4 ± 1.8(0-4.8)
Myodocops	0.5 ± 1(0-2.7)	Unidentified taxa	0.1 ± 0.2(0-0.7)
Podocops	3.6 ± 3.8(0-12.9)		

Data presented as mean ± SD (range)

Macrofauna

Intertidal

Generally, the intertidal communities in the western Arabian Gulf are impoverished (Basson, et al., 1977; Al-Bakri, et al., 1997a, 1997b). The rocky shore, which is normally more diverse and productive than the soft substrata in many parts of the world, is also less productive in this region. This is the result of the intense heating and desiccation by the sun at low tides, especially in summer, which limits the growth of algae (Basson, et al., 1977). Therefore, fauna includes animals, which inhabit crevices, rock pools, holes, and the underside of boulders, or else are mobile forms capable of retreating to suitable shelter when the tide is low.

Rocky shore fauna in the Saudi region includes both sessile and vagile animals (Basson, et al., 1977). Sessile animals comprise bivalve molluscs, serpulid polychaetes, barnacles, tunicates, and sponges. A majority of these animals are plankton feeders and obtain their nourishment while covered with water at high tide. The common bivalves include oysters (*Crassostrea)*, jingle-shells (*Anomia)* and jewel boxes (*Chama)*, Ark-shells (*Arca, Barbatia),* mussels (*Mytilus)* as well as pearl oysters (*Pinctada)*, hammer oysters (*Malleus, Isognomon)*, date mussels (*Botula, Lithophag),* and piddocks (*Gastrochaena)*. The serpulid polychaete, *Pomatoleios kraussii,* is usually seen in crevices and on the underside of rocks. Other tube dwelling polychaete worms and barnacles (e.g., *Euraphia sp*., *Balanus amphitrite*) are also found in dense clusters covering large parts of the rock where conditions are favorable. The most important vagile animals are gastropods or snails, which are herbivorous and graze on algae. On the Saudi Arabian rocky shores their food supply consists mainly of cyanobacteria, which are noted for their resistance to adverse environmental conditions. The dark color of the intertidal rocks along the Saudi Arabian shore is largely due to the growth of various species of cyanobacteria, which forms a mat on the surface of the rock (Basson, et al., 1977). The species commonly seen in this region are *Lyngbya aestuarii*, *L. majuscule*, Oscillatoria *princeps*, and *Phormidium* sp. Important grazing gastropods are the top shell (*Trochus erythraeus)*, turbans (*Turbo coronatus)*, the limpet like pulmonate (*Siphonaria rosea)*, slug like *Onchidium peronei,* and several others, including *Nodolittorina subnodosa, Planaxis sulcatus, Cerithium scabridum, Mitrella blanda*. A few common snails (e.g., *Thais* spp. and *Drupa margariticola*) are carnivorous, feeding on sessile animals such as barnacles. Crabs are an important group among the more active types of animals at rocky shores. Crabs include the herbivrous *Metopograpsus messor*, *Grapsus tenuicrustatus* and spider crabs, of which the former is the most common. Predatory crabs, including portunid and xanthid crabs, feed on other crustaceans or on snails. The examples of predatory crabs include *Portunus* spp., *Thalamita admete, T. crenata, Pilumnus longicornis, Xantho exaratus* and *Eripbia sebana*. Other crustaceans that inhabit the rocky shore are mantis shrimp (*Gonodactylus dermanii)* and pistol shrimp (*Alpheus* spp.).

An estimate of the number of taxa of rocky shore fauna is not available from the Saudi region. Al-Bakri, et al. (1997a, 1997b) reported the existence of as many as 110 taxa from Kuwait rocky shores. The number of taxa in each station in the Kuwait rocky shore ranged from 11 to 34 and with a density range of 71 to 3,695 individuals m^{-2}. Rocks in the upper intertidal area generally had lower numbers of organisms compared to the lower and middle zones. Generally, communities in this group were dominated by the polychaete (*P. kraussi)*, gastropods (*Cerithium bifasciatum*, *C. caeruleum*, *Umbonium vestiarium*, *Cronia margariticola)*, barnacle (*Balanus amphitrite),* hermit crab (*Pagurus* spp.), and bivalve (*Lithophaga malaccana)*.

Prominent macrofauna associated with sandy beaches include ghost crabs (*Ocypode saratan*), mole crabs (*Hippa* sp.), and mud crabs (*Macrophthalmus depressus*) (SATTL, 1982; KFUPM/RI, 1988c). McCain (1984a) reported the dominance of polychaetes (50 species), followed by nematodes (41 species), oligochaetes (26 species), and mollusks (18 species) among the infaunal samples collected from the intertidal sandy beaches of the Saudi waters of the Arabian Gulf.

In contrast to rocky shores, sandy beach communities include an interstitial fauna living on and between sand grains (macro, micro, and meiofauna) in addition to larger macrofauna. Macrophytes are rare (except as drift material) and are replaced by diatoms; grazers and carnivores are generally absent, while detrital feeders predominate. Drift algae and seagrasses are an important, transitory food source.

Subtidal

Soft Bottom

In the western Arabian Gulf, subtidal soft bottom macrobenthos are the most studied group among the seabed fauna. The parameters that influence the distribution of benthos in the natural environment include salinity, temperature and sediment texture (Basson, et al., 1977; McCain, 1984b; Coles and McCain, 1990; KFUPM/RI, 2006a; Joydas, et al., 2012). The effect of temperature and salinity are particularly noted in the sheltered inner bays and Gulf of Salwa (Coles and McCain, 1990; KFUPM/RI, 2006b; Joydas, et al., 2011; KFUPM/RI, 2014a). The mean grain size and natural sediment sorting, which are functions of the hydrodynamic regime, also play a role in the distribution of macrobenthic communities in the western Arabian Gulf. The sediment in shallow, high energy environments is more sorted (similar sediment size classes) with coarser sediment particles. The sediment sorting decreases and finer particle abundance increases with depth, resulting in three macrobenthic communities along depth and sediment gradients in the northwestern Arabian Gulf (KFUPM/RI, 2006a; Joydas, et al., 2012), Figure 3.74. They are sandy (shallow bottom), mixed sand and mud (intermediate depth zone) and muddy (deeper) depth zone communities. Apart from this, seagrass, which is prevalent in the shallow soft bottom, also provides a habitat for the benthic communities.

Although the Gulf is not deep enough to illustrate depth variations compared to other seas, as mentioned earlier, the change in sediment pattern with increasing depth causes a depth variation in fauna in the soft bottom. A general decrease in density of total benthos ($r=-0.34$, $P<0.05$), polychaetes ($r=-0.34$, $P<0.05$), molluscs ($r=-0.33$, $P<0.05$) and biomass were observed with an increase in depth (KFUPM/RI, 2003). Joydas, et al. (2012) noticed an increase in species diversity of polychaetes with depth ($r=0.72$; $P<0.001$), MGS ($r=0.48$; $P<0.05$) and sorting coefficient ($r=0.74$; $P<0.001$) in the northwestern Gulf. They correlated the diversity with the occurrence of rare species. They found fewer 16 species of rare polychaetes in the shallow sandy bottom compared to deeper muddy bottom areas species 45.

Coles and McCain (1990) recorded as many as 835 macrobenthic species from Ras Tanajib to the Gulf of Salwa during 1985-1986. Although a number of taxa were excluded from species identification, KFUPM/RI (1986) recorded 624 species from Bandar Mishab to Manifa during 1981-1982. In the later years, only targeted taxa such as polychaetes and major crustaceans were counted, nevertheless, the recorded number of species for a given taxon was comparable to the data of previous studies, Table 3.29. In general, polychaetes

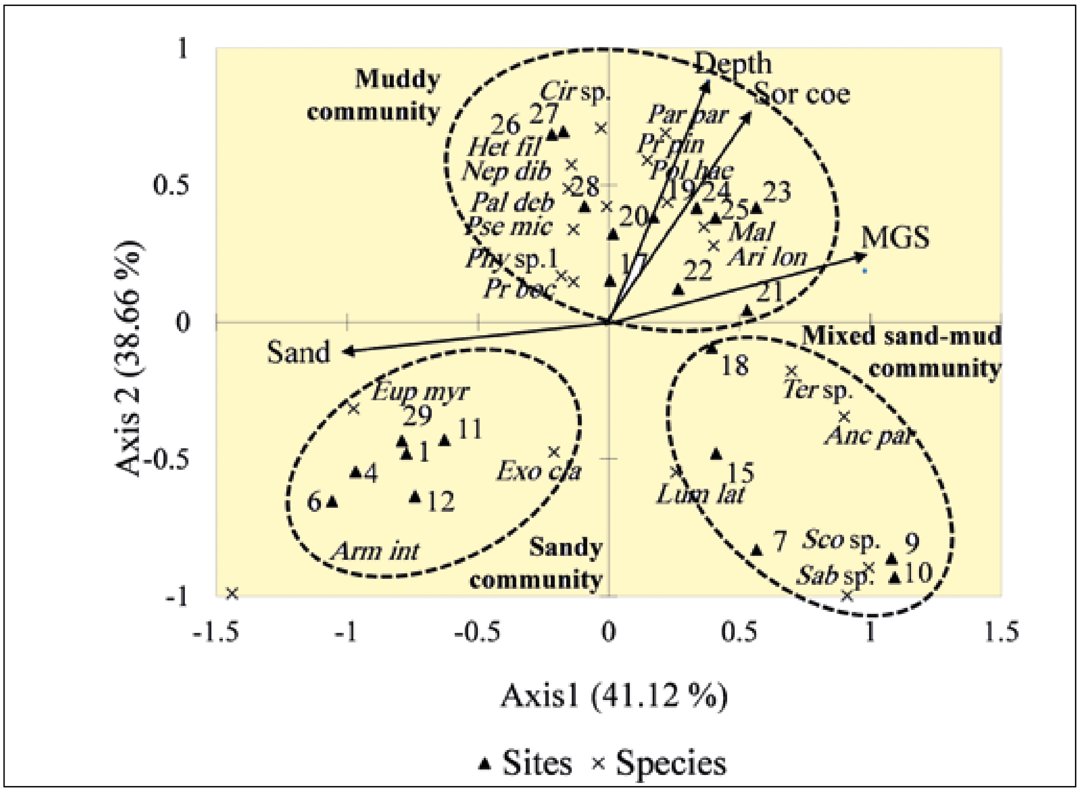

FIGURE 3.74. *Canonical Correspondence Analyses triplot showing scores of sites, the 20 most abundant polychaete species and explanatory variables showing distinct communities according to the depth and sediment variation in the northwestern Arabian Gulf. [MGS: mean grain size; Sor Coe: Sorting Coefficient. Species used area Exo cla (Exogone clavator), Bha goo (Euphrosine myrtosa), Lum lat (Lumbrineris latreilli), Pse mic (Pseudeurythoe microcephala - Linopherus sp.), Pal deb (Paleanotus debilis), Anc par (Ancistrosyllis parva), Par par (Paralacydonia paradoxa), Nep dib (Nephtys dibranchis), Phy sp.1 (Phyllodoce sp.1), Arm int (Armandia intermedia), Pr boc (Prionospio bocki), Sab sp. (Sabellides sp.1), Sco sp. (Scoloplos sp.), Het sp. (Heteromastus sp.), Ter sp. (Terebellides sp.), Cir sp. (Cirriformia sp.), Pr pin (Prionospio pinnata), Mal (Maldanidae indet.), Ari lon (Aricidea longobranchiata), Pol hae (Polycirrus cf. haematodes) (Modified from Joydas, et al., 2012)].*

TABLE 3.29. *Comparison of number of species recorded in various studies in the Saudi waters of the Arabian Gulf.*

Study Area	Period of study	Mesh Size (mm)	Poly-chaetes	Amphi-pods	Ostra-cods	Cuma-ceans	Mysids	Study
Safaniyah–Manifa	1981-82	1	228	67	36	32	—	KFUPM/RI (1986)
Safaniyah–Salwa	1985-86	1	271	57	48	30	2	Coles and McCain (1990)
Khafji–Ras Tanurah	2002	0.5	216	60	14	37	3	KFUPM/RI (2003)
Khafji	2005	0.5	218	—	—	—	—	Joydas, et al. (2012); KFUPM/RI (2006a)
Manifa & Tanajib Bay System	2006	0.5	118	—	—	—	—	Joydas, et al. (2011); KFUPM/RI (2006b)
Gulf of Salwa	2009	0.5	113	—	—	—	—	KFUPM/RI (2014a)

(40% to 90%) are by far the most dominant taxa in terms of individual abundance and species contribution in the soft bottom. Crustaceans (3% to 71%) or molluscs (1% to 49%) are the second or third dominant taxa.

Sand bottom communities: Generally, sand bottom conditions prevail in the shallow region above a 10 m depth. The fauna of sand bottoms is exposed to natural stresses like hyper salinity and high temperature variation, and various anthropogenic stresses. Coles and McCain (1990) studied the sand bottom communities of the western Gulf and reported that salinity was the most important factor influencing the distribution of benthic organisms in the western Gulf. They observed a decrease in abundance of species and individuals with increasing salinity toward the south, while biomass showed a trend opposite to that. The effect of depth and grain size was earlier noted by McCain (1984) in the northwestern Gulf, where, as depth increased, the diversity decreased and as mean grain size increased, diversity increased.

The main structural parameters of macrobenthos observed during 2002–2013 are presented in Table 3.30. Overall, macrobenthic communities in the sand bottom are polychaete dominated (24% to 84%). KFUPM/RI (2003) recorded 49% of polychaetes, 29% crustaceans, 10% molluscs and the remaining 12% constituted by 22 taxa from the sandy bottom of the Saudi coast of the Arabian Gulf. The typical species of sandy bottom communities included polychaetes *Nereis* sp. 1, *Prionospio* sp. 1, *Syllis* sp. 1, *Cumella forficula, Eunice* sp., *Phyllodoce* sp. 1, *Magelona cincta, Euphrosine* sp. and *Lumbrineris* sp. and crustaceans *Cypridina* sp., *Euphilomedes* sp., *Parasterope* sp. (ostracods), *Gammaropsis* sp., *Natarajphotis manieni* (amphipods). In the northwestern Arabian Gulf, polychaete species *Exogone clavator*, *Armandia intermedia* and *Euphrosine myrtosa* were found to prefer sandy sediment, Figure 3.74 (KFUPM/RI, 2006a; Joydas, et al., 2012). This study also showed the overall dominance of carnivorous polychaetes in the sand bottom. A rich assortment of molluscs (*Bullaria ampulla, Cerithium scabridum, Cerithidea cingulata, Meretrix meretrix, Calista florida, Circe* sp., and *Aneilla castanea*), echinoderms (*Clypeaster humilis, Echinodiscus auritus, Astropecten nonocanthus*) and sipunculids have been reported in sandy bottom areas by KFUPM/RI (1994).

Basson, et al. (1977) observed three communities in the subtidal sand bottoms, which are described below:

1. *Sand bottom community adjacent to exposed sandy beach*: This community is composed of larger polychaetes, decapod crustaceans such as ghost shrimp (*Callianassa* sp.) and the crab (*Matuta planipes*) and numerous snails, which includes the predominant *Strombus decorus persicus* and less abundant *Oliva*

Table 3.30. *Structural parameter values of macrobenthos from various nonvegetated subtidal habitats.*

Structural parameters	Sand Bottom	Mixed Sand and Mud	Mud Bottom	Seagrass Bed	Sheltered Bay (MTBS)	Gulf of Salwa
Density (ind. m^{-2})	1,173–8,683	2,163–8,365	1,667–4,230	2,580–12,153	290–3,750	70–18,770
Species diversity	2.6–4.7	4.2–4.9	4.3–5.6	3.8–4.6*	1.0–4.3	0.7–4.6
Species richness* (per m^2)	07–61	28–83	39–80	15–84**	2–32	3–43
Biomass (g. m^{-2})	0.2–5.6*	–	0.57–2.7*	0.6–4.7*	–	–

* For polychaetes and crustaceans.
** For all species.
Remaining values of species diversity and species richness are only for polychaetes.

sp., *Cypraea turdus* and *Natica* sp. Sea urchins such as sand dollars and heart urchins are also important components of this community, where organic material makes up part of the sandy substratum. Sand dollars (*Clypeaster humilis* and *Echinodiscus auritus)* and the heart urchin, (*Metalia townsendi)* are the common sea urchins. Generally, the members of this community are predatory. Because this habitat is in the well-lighted zone, diatoms and other microalgae are commonly seen on the sand grains.

2. *Sand bottom community in the high energy tidal deltas*: The benthic communities found in the high energy tidal deltas are much less diverse because of the rapid transport of sediment. A small clam, *Ervilia scaliola*, is found in dense numbers, and is able to move about in the sand surface very rapidly.

3. *Sand bottom community surrounding coral reef islands*:This community occurs in the deeper sand bottoms (15 m to 30 m depth) on the sand slopes of coral reefs at Jana island. The community is composed of colorful starfish (*Pentaceraster mammillatus)*, burrowing protochordate (*Branchiostoma* sp.), sea urchin (*Temnotrema siamense)* and sipunculid worms (*Aspidosiphon* sp.).

Seagrass benthic communities: Extensive seagrass biotopes occur up to a depth of about 10 m along the western Arabian Gulf coast (KFUPM/RI, 2014a). Seagrass beds stabilize bottom sediments and provide a substratum for a variety of benthic organisms. Rich beds of seagrasses in the Gulf have shown high productivity and support diverse biota (John and George, 2006). Numbers of species and individuals of benthos are greater in seagrass than in sand silt substrata, indicating that the finer grained sediments of the seagrass areas support more diverse and abundant benthic communities, Table 3.30. An estimate shows that about 9% of the Gulf's faunal taxa occur in the seagrass meadows, about half of which are molluscs (Sheppard, et al., 2010). Of commercial significance in the Gulf is the pearl oyster (*Pinctada radiata*), which spends considerable time during its juvenile stage in seagrass. Many important shrimps (*Penaeus semisulcatus*) in early post-larval stages also occur in association with seagrass (Sheppard, et al., 2010). Studies have shown that seagrass beds in the western Arabian Gulf are acting as a nursery grounds for penaeid shrimps (Basson, et al., 1977; KFUPM/RI, 2006b; Al-Maslamani, et al., 2007). The vulnerable young of commercial shrimp (*Penaeus semisulcatus)* get shelter in the leaves of seagrass. The common larger benthic fauna associated with seagrass beds include pearl oysters, black sea cucumbers (*Holothuria* (*Halodeima*) *atra),* clams *(Pinna bicolor)*, bubble shells (*Bulla ampulla)*, snails (*Murex kusterianus)* and crabs (*Portunus pelagicus)* (Basson, et al., 1977; KFUPM/RI, 1994). Further details of the seagrass associated communities are given in Chapter 3.7.

Seagrass beds in this region are vulnerable to various natural as well as human-induced disturbances such as warming events, fishing activities, coastal development, dredging, and oil related activities (Sheppard, et al., 2010). These disturbances are expected to affect not only the seagrasses but also the abundance and diversity of the associated macrofauna (Whanpetch, et al., 2010). At the same time, the presence or absence of seagrass vegetation may modify the degree of impact on animal communities caused by the physical disturbance. This is because the vegetation acts as a buffer, reducing water current velocity and sediment erosion (Fonseca and Fisher, 1986; Koch and Gust, 1999; Madsen, et al., 2001).

Mixed sand/mud bottom communities: These communities occur in the intermediate depth (11 m to 28 m) zone and represent the transition between the sand and mud bottom communities. KFUPM/RI (2006a) and Joydas, et al. (2012) reported that these communities were distinct from the sand and mud bottom communities because of the difference in sediment sorting and depth. Species richness and species diversity values were found to lie between that of sand and mud bottom communities, Table 3.30. The polychaete species were composed of both carnivores and deposit feeders without any indication of the dominance of either group. The co-existence of carnivores and deposit feeders in the intermediate depth zone indicates that organisms inhabiting this zone are capable of utilizing different food resources in a particular niche. The most typical polychaete species were *Terebellides* sp., *Ancistrosyllis parva, Scoloplos* sp., *Sabellides* sp. 1 and *Lumbrineris latreilli*. The major non-polychaetes noted were bivalves, ophiuroids, nemertines, gammarids and cumaceans.

Mud bottom communities: Although mud gradually predominates below a 10 m depth, the continuous mud bottom appears down to a 30 m water depth. In the mud bottom, the amount of fine sand was found to positively correlate with the species richness while coarse sand was found to favor the species dominance (KFUPM/RI, 2003). The depth, mean grain size and sediment sorting coefficient were found to be important parameters controlling the distribution of mud bottom benthos in the northwestern Arabian Gulf (KFUPM/RI, 2006a; Joydas, et al., 2012). Generally, the diversity was higher in the muddy bottom than in the sandy and mixed sand/mud bottom, Table 3.30.

KFUPM/RI (2003) recorded 57% of polychaetes, 23% crustaceans, 4% molluscs and the remaining 16% constituted by 30 taxa from the mud bottom of the Saudi coast of the Arabian Gulf. This study noticed a dominance of polychaetes in the mud bottom, and the typical polychaetes included *Prionospio* sp. 1*, Paralcydonia paradoxa, Syllis* sp. 1*, Heteromastus filiformis, Nephtyis sphaerocirrata*, *Phyllodoce* sp. 1, Glycera sp. 1, *Magelona cincta*, and *Cossura coasta*. Ostracods *Cypridina* sp., *Euphilomedes* (ostracods), and *Parasterope* sp. were the important crustaceans. Apart from that, clams, nematods, rhynchocoels, ophiuroids, and gastropods were also common in mud bottom habitats. In the northwestern Arabian Gulf, a number of polychaete species, which were mostly deposit feeders, were found to associate with mud bottom, Figure 3.74 (KFUPM/RI, 2006a; Joydas, et al., 2012).

Basson, et al. (1977) noticed two distinct communities in the subtidal mud bottom of the Saudi coast of the Arabian Gulf at a depth of 6 m to 15 m and at locations between Tarut Bay and Safaniyah. They are:

1. *Murex/Cardium community*: The dominant species in this community are the cockle *Cardium papyraceum*, snail *Murex kusterianus*, sea urchin *Temnopleurus toreumaticus*, the burrowing crab *Dorippe dorsipes*, pen shells *Pinna* sp., shrimps *Penaeus semisulcatus*, *Metapenaeopsis* spp. and *Trachypenaeus curvirostris* and demersal fishes *Platycephalus indicus*, *Upeneus tragula, Lutjanus fulviflamma* and *Epinephelus tauvina*. Predominant smaller fauna includes polychaetes and amphipods. Such a bottom area is considered to be good shrimp trawling ground because this type of bottom is occupied by commercial shrimp *P. semisulcatus*. This is a reasonably high diversity community.
2. *Brissopsis/Amphioplus community*: This is an extremely low diversity assemblage dominated by two species, the heart urchin (*Brissopsis persica)* and the brittle star (*Amphioplus seminudus)*. Other fauna rarely occur in this community with the exception of a few polychaetes, molluscs and ostracods. Generally the biomass is high due to the abundance of the numbers of two dominant species.

Hard Bottom

Rocky bottom communities: According to the nature of rocks, the characteristic biological communities also vary slightly in the western Arabian Gulf (Basson, et al., 1977). The shallow subtidal rocks that have rough surfaces provide a habitat for mantis shrimp (*Gonodactylus demanii)*, crabs of the family Xanthidae and Porcellionidae, as well as many species of polychaete worms. Gastropods, chitons, and limpets graze on the dense algal mats. A wide variety of bivalves (oysters) are represented, including rock oyster (*Spondylus* sp.), pearl oysters (*Pinctada* spp.), hammor oysters (*Malleus* sp.) and *Isognomon* sp. These bivalves are preyed upon by the carnivorous gastropod *Thais pseudohippocastaneum*. The date mussel (*Lithophaga* sp.) and the paddock (*Gastrochaena* sp.) bore holes in to the rock and are connected with the outside by a narrow opening. KFUPM/RI (1988a) recorded orange sponges, sea urchins (*Echinometra mathaei, E. auritus),* crab (*Eriphia smithii),* tunicate *(Phallusia nigra),* and muricids from the shallow water rock bottoms of Abu Ali Bay.

The shallow flat rock bottoms are also colonized by the same type of organisms that inhabit the rough rocks at corresponding depths; nevertheless, the differing physical nature of the substrata greatly affects the success of such colonization (Basson, et al., 1977; KFUPM/RI, 1988a). Algal species such as *Sargassum* spp. or attached bivalves occur on the flat surfaces, where there is a certain amount of water mixing. More cryptic organisms live in the fissures and cracks. Boring bivalves and some species of polychaetes do not occur in or on this substratum. In shallow bays where large expanses of flat rock bottom are found, the species diversity is low due to extreme fluctuations in salinity and temperature. Even in this ecosystem, the rock surface is often covered by microscopic blue-green algae (Basson, et al., 1977).

Generally, in the deeper rock bottoms, rocks are flat, sometimes with a thin layer of sand or silt. Because of insufficient light penetration, large brown algae (e.g., *Sargassum* spp.) is replaced by red algae and by corals in such habitats. Up to a 6 m depth, pearl oysters and tunicates are commonly seen attached directly to the flat rock surface; however, in this depth, the majority of the animals (xanthid crabs, sea anemones, gobies, snapping shrimp (*Synalpheus* sp.), snails, etc.) are found in the crevices or joints between adjacent rock plates (Basson, et al., 1977). At this depth range, in some areas, isolated colonies of corals (*Favia* spp.) can also be seen. At a 10 m to 15 m depth, swimming crabs (*Portunus pelagicus*, *Charybdis natator)*, mole lobsters (*Thenus orientalis)* and fish hamour (*Ephinephelus tauvina*) are common, and at a further depth (below 20 m), Basson, et al. (1977) noticed pearl oysters (*Pinctada radiate),* seafans, brittle stars and snails (*Primovula rhodia)*.

Coral reef communities: Coral reefs provide habitats for a number of benthic organisms. Basson, et al. (1977) reported the occurrence of about 540 species of reef animals in the western Arabian Gulf. Some organisms inhabit the corals by boring or by hiding among the crevices. Several species such as rock-boring bivalves, polychaetes, and barnacles tunnel their way into species of *Porites* and find refuge in the coral. These animals extend structures outside of the coral to obtain food and oxygen. Other animals, such as caridean shrimp, galatheids, alpheids, palaemonids, and xanthid crabs (*Trapezia cymodoce*, *Tetralia glaberrima*) hide among the branches of corals, while sessile animals like sponges, hydroids, alcyonarians, bivalves, bryozoans, and tunicates take residence on the surfaces of corals (Basson, et al., 1977; KFUPM/RI, 2014a).

KFUPM/RI (2007) studied the reef associated macroinvertebrates in various reefs of the Saudi waters of the Arabian Gulf, being sea urchin (*E. mathaei),* bivalves (*Chama pacifica*, *Chlamys ruschenbergerii*, *Malleus regula*, *Pinctada radiata*, *Barbatia* sp., *Spondylus* sp.) and gastropods (*Vermetus* sp. and *Drupella* sp.) as the most common species. Abundance of *E. mathaei* (up to about 5,000 individuals per 50 m^2 as from the reef flat and slope of the Manifa reef) and bivalves (up to about 1,700 individuals per 50 m^2 from the Safaniyah reef) were recorded from the northern reefs, while such higher abundance of any taxa were not noticed from the reefs of the southern region such as Abu Ali and Ras Tanura reefs. Further details of the coral associated organisms are presented in Chapters 3.10 and 4.2.

Artificial reef communities: The Arabian Gulf has numerous oil platforms, which act as artificial reefs that facilitate fouling and associated organisms. In this region, most offshore platforms are placed on soft sediment bottoms, and as a result, they offer the only suitable permanent habitat for settlers that require hard substratum. Algal spores and invertebrate larvae rapidly colonize submerged portions of platform structures, establishing a fouling assemblage, which provides food and shelter for associated fauna (Wolfson, et al., 1979). Basson, et al. (1977) reported that the marine growth on the platform legs was arranged in a series of concentric layers around the steel piling. The inner layer was composed of permanently sessile and hard-shelled organisms, including barnacles (*Balanus amphitrite*, *B. tintinnabulum*) and oysters (*Spondylus exilis, Hyotissa byotis, Pinctada radiate, P. margaritifera*) while the outer layer comprised of softer organisms, like sponges, various algae (*Ectocarpus irregularis, Sargassum latifolium, Dasya ocellata*) and gorgonians.

KFUPM/RI (1994) studied the vertical distribution and quantification of fouling communities of platforms 184/189 and GOSP-3 of Safaniyah. The former was used as a control platform and the latter was selected to study the effect of contaminants as a suite of discharges such as sewage, chlorinated firewater, and oily wastewater were released from this platform. Safaniyah GOSP-3 supported a luxuriant fouling community, even more luxuriant than that found on the legs of platforms 184/189, Figure 3.75. This may be a result of the discharge of sewage from Safaniyah GOSP-3, which provides nutrients to the generally nutrient poor waters of the Gulf. This nutrient enrichment was supposed to stimulate the growth of algae and other food chain organisms. The density and wet weight of fouling organisms were found to decrease with increase in depth, Figure 3.75. In both the offshore structures and in the three depths, the dominant fouling fauna were bivalves, barnacles, gammarids, tanaids, isopods and polychaetes. The wet weight values were essentially those of the barnacles since the combined weight of most other organisms was negligible.

Occurrence of several species of faviid corals at the platforms and its associated pipeline in the Manifa region (e.g., Manifa Platform P-2) was observed by KFUPM/RI scientists during various oceanographic studies (KFUPM/RI, 1994; KFUPM/RI, 2014a). The presence of a substantial population of corals on Platform P-2 and its associated pipelines is strongly linked to its proximity to several patch reefs in the shallow (7 m) area where the platform is located. Corals have not been observed on the platforms located in deeper waters in the Saudi region of the Arabian Gulf, e.g., Abu Safah (20 m) and Zuluf (35 m) (KFUPM/RI, 1994).

In a review, Feary, et al. (2011) reported the increased use of artificial reefs in the Arabian Gulf as a means to mitigate environmental impacts from the oil-related or developmental activities, with growing numbers of artificial reefs being deployed (Abdel-Moati, 2006; Al-Saffar and Al-Tamimi, 2006; Al-Haimi, 2007; Richer, 2008; Maghsoudlou, et al., 2008). Artificial reefs can hold higher diversity (Reed, et al., 2006) and higher percent cover of corals (Burt, et al., 2009a) than natural reefs, but the community structure associated with an artificial reef may be distinct from adjacent natural reef habitats, as a result of differences in the relative abundance of dominant species (Pizzolon, et al., 2008; Burt, et al., 2009b).

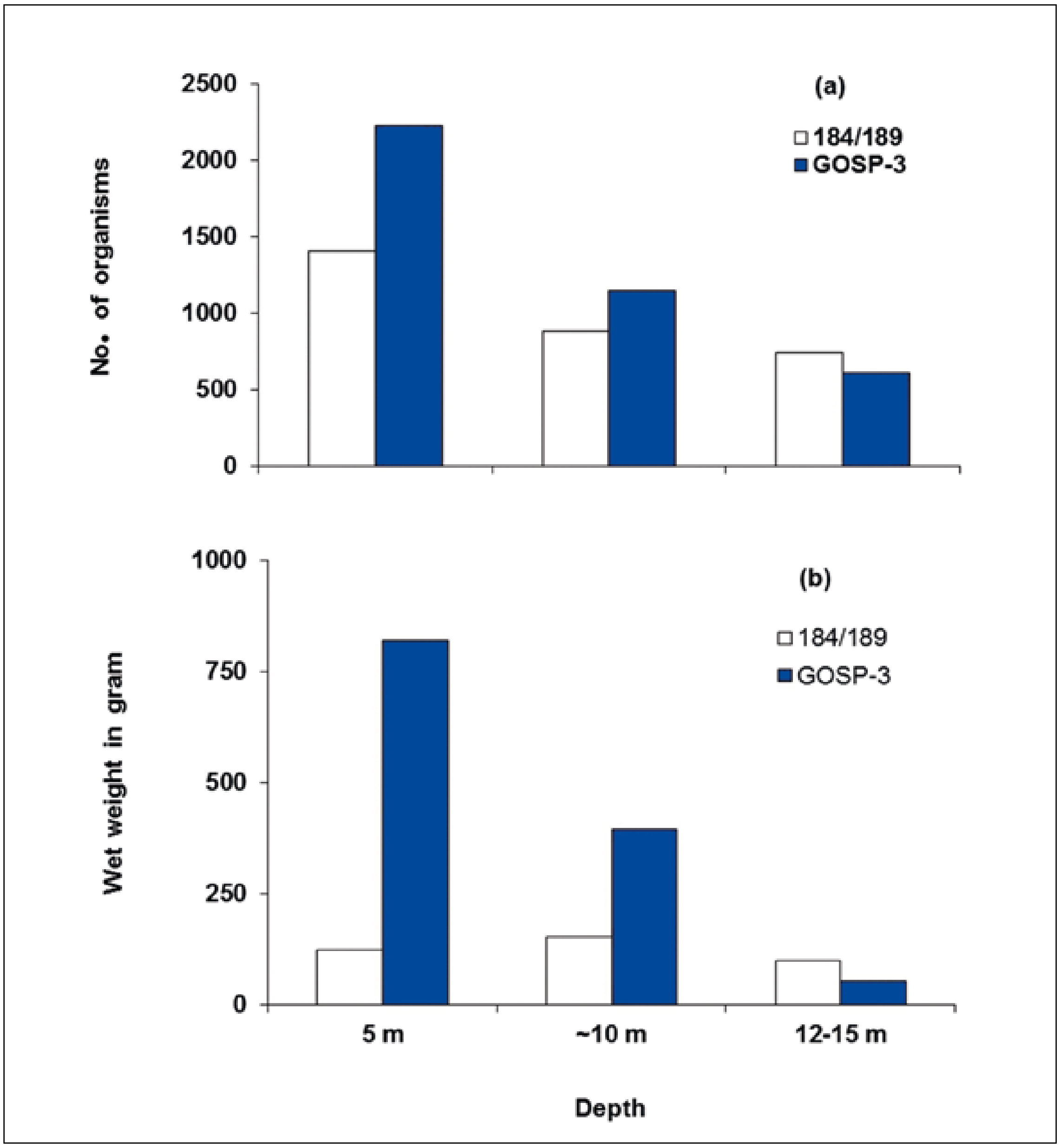

FIGURE 3.75. *Vertical distribution of fouling organisms (mean values per 0.0625 m² quadrats) on the legs of offshore platforms 184/189 and GOSP-3 in Safaniyah: (a) abundance, and (b) wet weight (Based on data from KFUPM/RI, 1994).*

Response of Benthic Communities to Natural and Human Pressures

Benthic Communities in the Naturally Stressed Ecosystem

Benthic communities in the Gulf of Salwa and sheltered bays, e.g., MTBS, are good examples of the responses of communities to natural stress. As mentioned earlier, these areas share common features of having hyper salinity and wide temperature variations.

The Gulf of Salwa is a unique marine ecosystem, which is nearly cut off from the main water body of the Arabian Gulf by the Island of Bahrain and shallow water flats. These shallow flats form a tidal barrier to water movements, which reduce the tidal amplitude within the Gulf of Salwa. This results in the extreme oceanographic conditions with salinities ranging up to 60 psu in open water and above 70 psu in embayment (Purser and Siebold, 1973; Basson, et al., 1977) and annual temperature variations (17 °C to 40 °C). There is a southward increase in the salinity and temperature due to the increase in stagnancy toward the south. There are sheltered inner bays in the northern part of the Gulf of Salwa, where hyper salinity also occurs.

Recent studies (KFUPM/RI, 2014a; Joydas, et al., 2015) conducted during the winter and summer seasons of 2009 showed a southward decrease in species richness and diversity, and an increase in species dominance of polychaetes in the Gulf of Salwa. A total of 147 taxa (113 polychaete species and 34 non-polychaete taxa) were recorded from the macrobenthic samples collected during the two seasons. Polychaetes predominated during both seasons (49% and 58% of the total macrobenthos during winter and summer, respectively), while molluscs and crustaceans, the next important major groups, showed seasonal variations. During winter, molluscs (28% of the total macrobenthos) were the second important taxa followed by crustaceans (20% of the total macrobenthos), whereas during summer, crustaceans (29%) were the second dominant taxa followed by molluscs (10%). Of the four regions of the Gulf of Salwa, such as a deeper region (10 m to 17 m depth), shallow north (1.5 m to 9 m depth), inner bay in the north (1 m to 1.5 m) and southern region (1 m), benthic fauna was found to be severely affected in the southern region. Fewer number of polychaete species (average five and four during winter and summer, respectively) and lower species diversity (1.8 and 1.3 during winter and summer, respectively) were observed in the southern region compared to the other regions, while comparatively lower density was recorded in both southern (1,575 and 1,406 during winter and summer, respectively) and deeper regions (1,109 and 878 during winter and summer, respectively), Figure 3.76. Three polychaete species such as *Platynereis isolita, Heteromastus filiformis,* and *Fabricia bansie* were considered to be opportunistic species as they were found to withstand the extreme conditions in the southern stations. Dominance of *F. bansie* was observed in the sheltered inner bay region; nevertheless, richness and diversity were higher in this region than the southern region. Reduction of benthic organisms with the increasing salinity has been observed at salinities above 45 in the Gulf of Salwa (Clarke and Keij, 1973; Coles and McCain, 1990) and the Abu Dhabi barrier island complex (Evans, et al., 1973). Echinoids, phoronids, penaeids, carideans, and halacarideans were totally absent from stations where salinity exceeded 45% and 50% and more reduction in species of hydroids, gastropods, pelecypods, copepods, gammarideans, mysids, ostracods, stomatopods, decapods and holothurians from these stations were reported from the Gulf of Salwa (Coles and McCain, 1990).

The MTBS includes eight sheltered "inner bays," which are characterized by extreme temperature variations (18 °C to 33 °C) and elevated levels of salinity up to 54 units than the remaining part of the bay system (outer bay). This trend in salinity clearly indicates the effects of limited tidal flushing, which constrains water renewal, in the inner bays. Several polychaete species and crustacean taxa were not encountered in the inner bays, although they were recorded from the outer bay, which indicates the prominent effect of hyper salinity. Higher average density of taxa and species evenness and species diversity of polychaetes were recorded from the outer bay while species dominance was higher in the inner bays. A total of 118 polychaete species were recorded from the MTBS during 2006, of which only 54 species were recorded from the inner bays while the outer bay showed the presence of 105 species (KFUPM/RI, 2006b; Joydas, et al., 2011). The existence of distinct polychaete communities was evident at the inner bays and the outer bay of MTBS as a result of the heterogeneity in depth, salinity and temperature, Figure

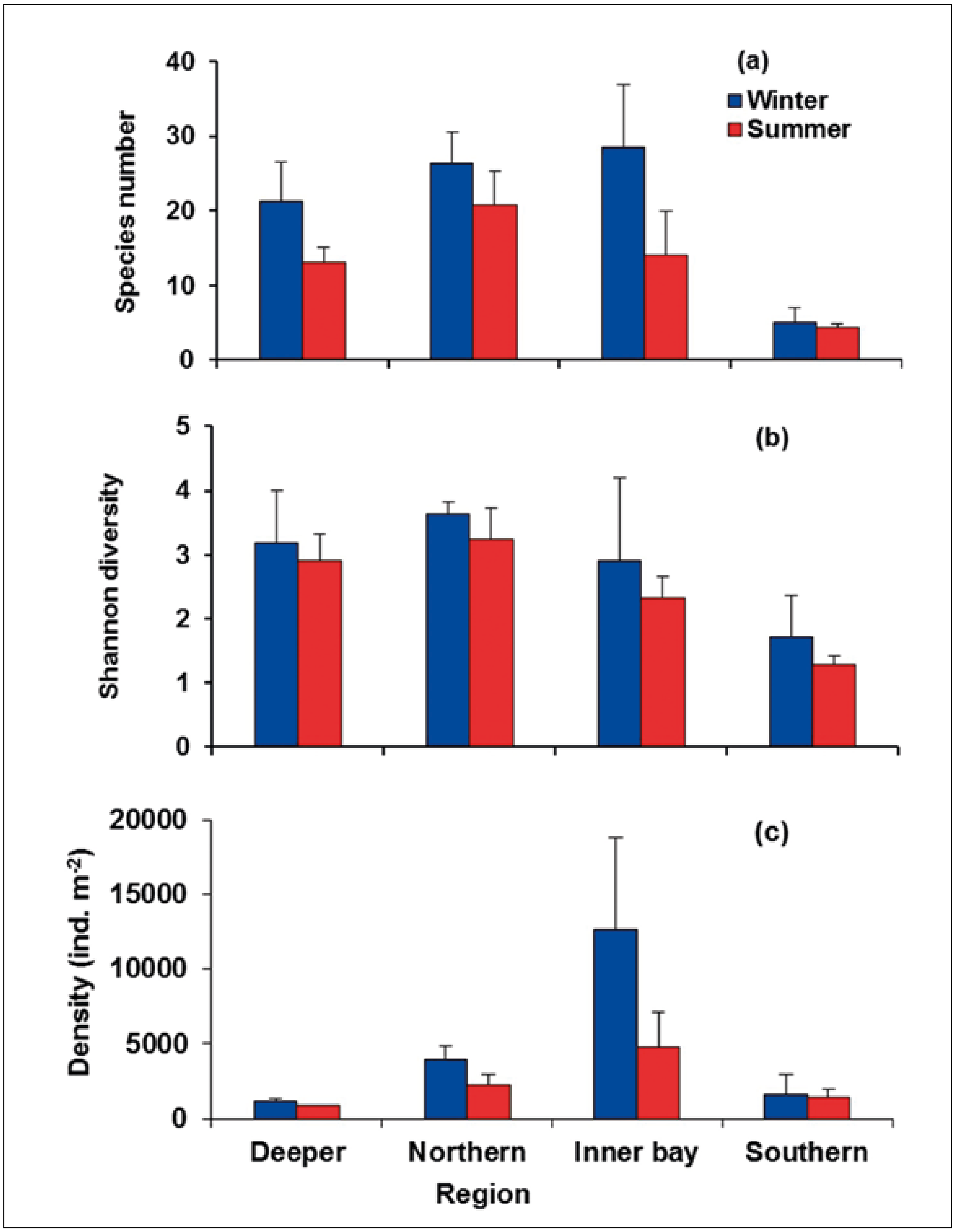

FIGURE 3.76. *Benthic characteristics of various parts of the Gulf of Salwa: (a) species number of polychaetes, (b) species diversity of polychaetes, and (c) macrobenthic density.*

3.77. Polychaete assemblages in the inner bays were dominated by *Platynereis isolita, Dasybranchus sp.,* and *Armandia intermedia*. Of these, *Platynereis isolita* was the most dominant species in the inner bays, and is considered to be an opportunistic species, which can withstand the hyper saline conditions in the inner bays. Of the dominant species of the outer bay*, Euphrosine myrtosa, Ancistrosyllis parva, Nephtys dibranchis, Nephtyssphaerocirrata, Eunice* sp. 1, *Lumbrineris latrielli, Prionospio* sp. 1, *Magelona cincta*, *Orbinea* sp., *Scoloplos*

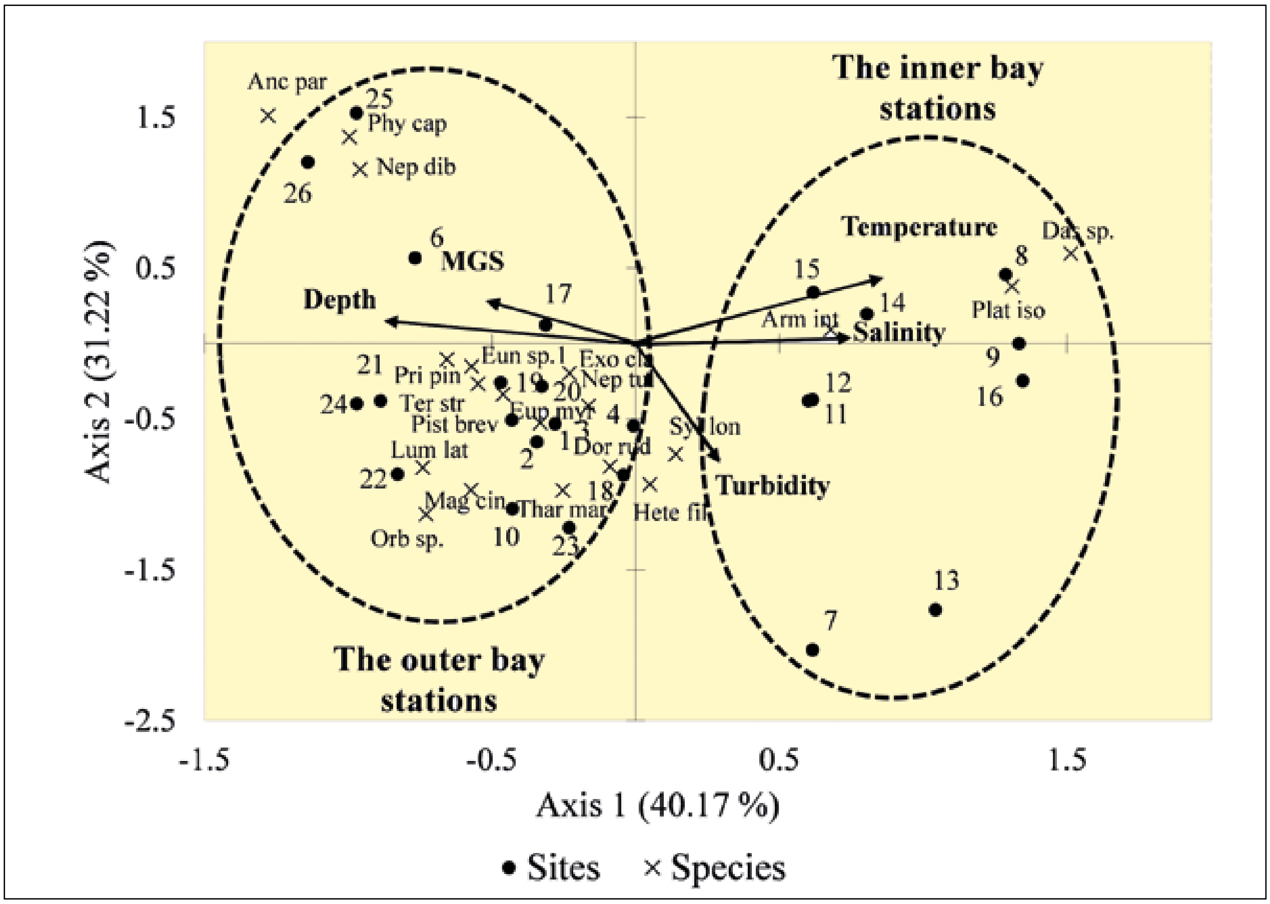

FIGURE 3.77. *Canonical Correspondence Analyses triplot of the Manifa-Tanajib Bay System benthos showing scores of sites, the 20 most abundant polychaete species and explanatory variables. MGS: mean grain size (Joydas, et al., 2011).*

sp., and *Terebellides stroemi* were not recorded from the inner bays. Certain taxa, which were abundant in the outer bay, were either totally absent in the inner bays (ostracods, sponges, hydroids, polyplacophorans, copepods, mysids, penaieds, brachyurans and caprellids) or feebly represented (sipunculids, cumaceans, and ophiuroids).

In conclusion, the benthic organisms living in the Gulf of Salwa, particularly its southern part, and inner bays of MTBS are in the upper tolerance levels of temperature and salinity. According to Coles and McCain (1990), hyper salinity is the critical parameter affecting the spatial distribution of benthos and its effects clearly mask any other effects such as pollution stress or seasonal variations in the benthos. The extreme water temperature variations and high salinity, sometimes coupled with low oxygen are important environmental stressors (Sheppard, et al., 2010) and studies indicated that warming enhances effects of pollution (Schiedek, et al., 2007).

Impacts of Large-Scale Oil-Related Activities in the MTBS

During 2008–2010, a causeway was constructed across the mouth of the MTBS to provide the transporting facility and access to offshore drill sites. The causeway consists of a main route with lateral branches connecting

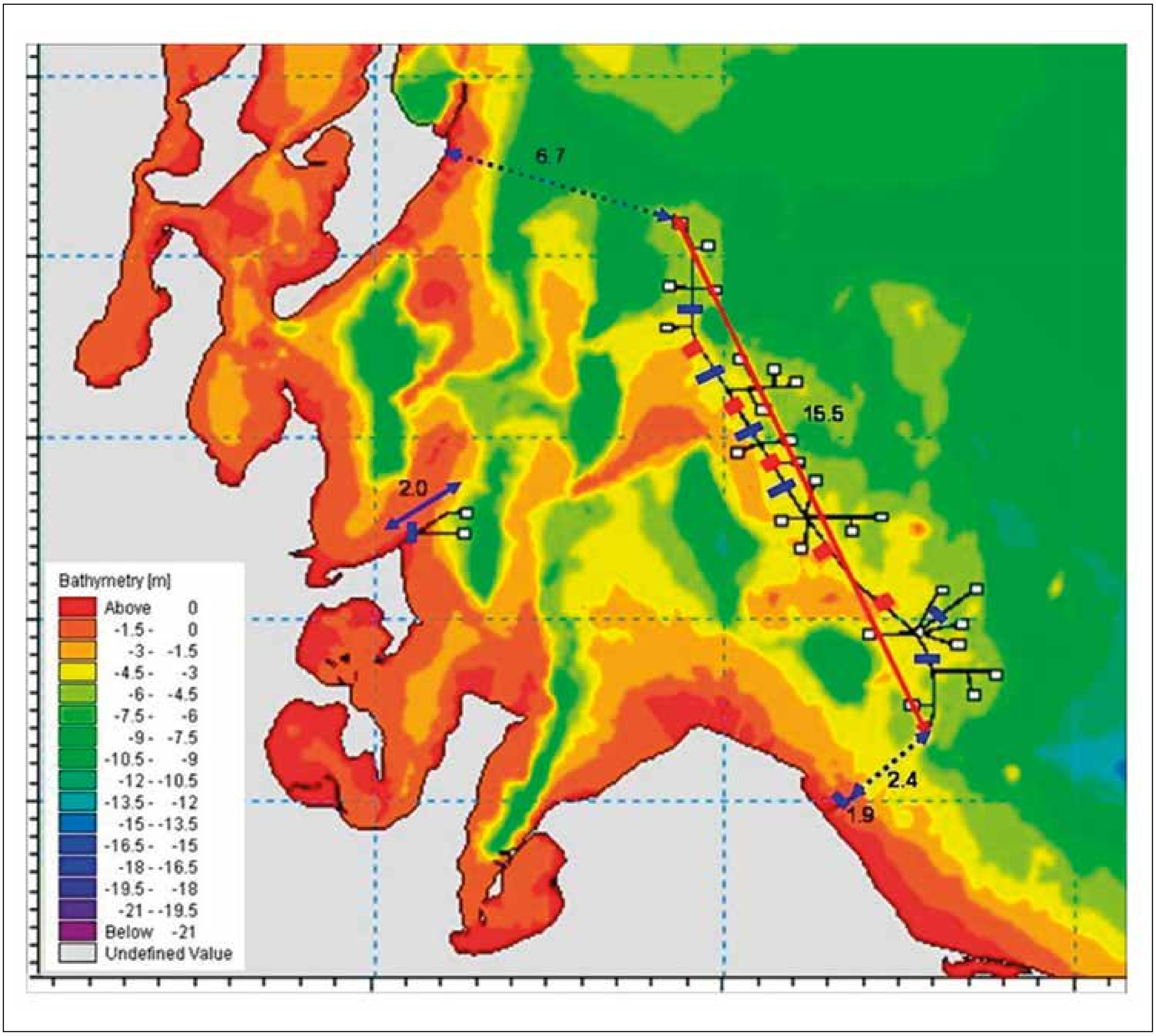

FIGURE 3.78. *Schematic diagram of the causeway design. Short blue and red segments indicate the location of culverts and short bridges, respectively. Blue broken lines indicate the location of the southern bridge and the northern channel. Numbers indicate the axial length for the derivation of effective flow opening in kilometers.*

to 25 offshore drill site islands, Figure 3.78. The main causeway is about 20 km long, which is equivalent to a two-lane black top highway that allows for passage of traffic in both directions and connects the drill site islands through subsidiary routes. The total length of the lateral causeways and coastal offshoot is about 23 km. The causeway and drill site islands were constructed by means of dredging sand from adjacent borrow areas using cutter suction dredgers and pumping it into the reclamation works. One of the important mitigation measures recommended by the EIA (KFUPM/RI, 2006b) was providing openings along the main causeway in the form of 14 long and short bridges as per the hydrodynamic modeling. EIA also recommended deployment of silt screens during reclamation and excavation to minimize the dispersion of sediment. Apart from the many bridge openings, 8 km of the bay mouth was also left opened after the construction. The causeway resulted in the intensification of the current in the mouth of the bay. The surface current in the northern part was 12.4 cm s^{-1} in 2006 before the construction. After the construction of the causeway, the surface current in the mouth ranged from 17.7 cm s^{-1} (August 2013) to 32.5 cm s^{-1} (February 2013) (KFUPM/RI, 2015). The causeway also caused the formation of a new current flow pattern inside the MTBS with northwest and southeast current flowing in and out, parallel to the axis of the causeway. Bridges allowed water movements between both sides of the causeway. All these benefited the water exchange efficiency in Manifa Bay. Sedimentation rates above 10 mg cm^{-2} day^{-1} were observed at the vicinity of the causeway during the construction period.

The monitoring study (KFUPM/RI, 2010a, 2015) showed that the region located in the vicinity of the causeway was impacted. There were reductions in the total macrobenthic density and polychaete species richness in the vicinity of the causeway in 2008, probably as an immediate effect of the causeway construction and the causeway structure, Figure 3.79. Following 2008, density increased regularly, whereas richness showed fluctuations until 2010. Subsequently, the post-construction monitoring conducted during 2013 revealed a recovery with density matching with that of the pre-construction period and species richness of polychaetes much higher than that of the pre-construction period. Density and richness of macrobenthos recorded from the construction period up to 2010 were still within the broad ranges known for the pristine locations along the Saudi coast of the Arabian Gulf. The main reason for the minor impacts during the construction period can be attributed to the strict obedience with the mitigation measures.

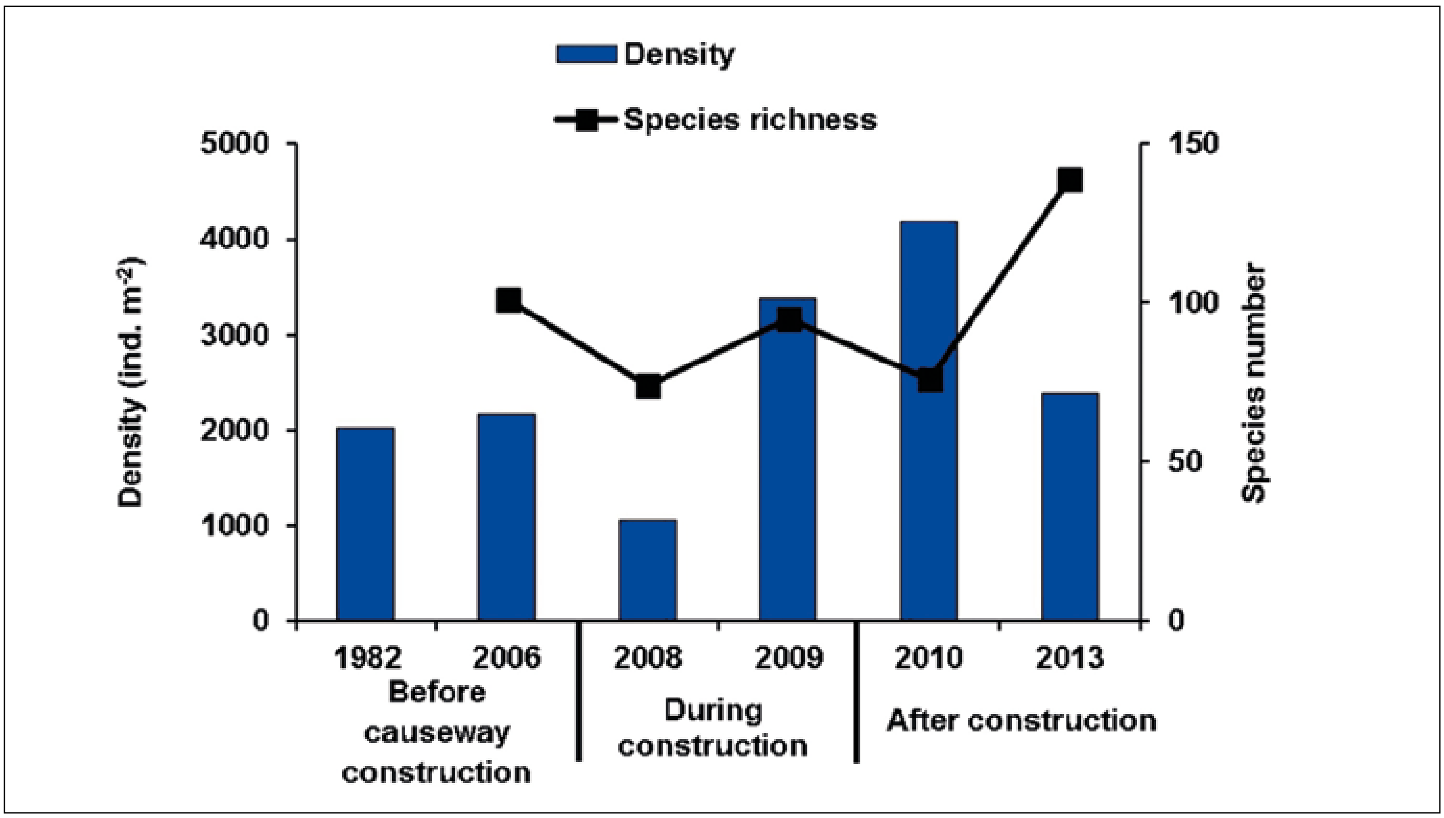

FIGURE 3.79. *Temporal variation in total macrobenthic density and species richness of polychaetes in the vicinity of causeway construction in the Manifa-Tanajib Bay System.*

Long-Term Impact of the 1991 Gulf Oil Spill on the Benthic Communities

The oil spill affected the coastal areas located between Ras al-Khafji in the north and Ras Abu Ali in the south of the Saudi Arabian coast (Tawfiq and Olsen, 1993; Michel, et al., 1993; Sadiq and McCain, 1993; Readman, et al., 1996; Price, 1998). The intertidal regions and sheltered bays were severely affected. The 1991 Gulf oil spill, not only due to the largest oil spill in the history but also due to the Gulf's perturbed nature and short-term dynamics, required a longer recovery time. Progressive recovery of faunal diversity in the shoreline regions of the Gulf was reported by various researchers (Michel, et al., 1993; Hoffmann, 1994; Jones, et al., 1994; Richmond, 1994). Price (1998) evaluated the status of the Gulf coastal environment five years after the 1991 Gulf oil spill based on a number of studies (McGlade and Price, 1993; Sadiq and McCain, 1993; Price, et al., 1994; Jones, et al., 1998) and reported the ecological recovery of most of the spill affected coastal environments within five years. This time period also matched results from the assessment of the recovery period made by Sell, et al. (1995). According to Jones, et al. (1998) the heavily affected rocky shores in Saudi Arabia showed signs of recovery during 1993 with 80% diversity compared to the unimpacted sites, although some key species such as gastropods (*Nodolittorina subnodosa, Planaxis sulcatus)* were found alive only during 1995. They also noticed 83% recovery in 1995 species in the spill affected sandy shores.

Eleven years after the oil spill incident, an extensive study was conducted by KFUPM/RI (2003) under the *Oceanographic Survey in Support of the Marine and Coastal Damage Assessment* project (funded by the United Nations Compensation Committee) intended to assess the long-term impact of the 1991 Gulf oil spill on marine resources and environment of the Kingdom of Saudi Arabia. This study, conducted during 2002, showed recovery of macrobenthos in the open waters, while the sheltered inner bays were found to have impacts on benthic communities from residual oil. In the open waters, species diversity of macrobenthos was higher than three in 97% of the stations (range 2.2 to 5.0), which are comparable to the values reported by pre-spill studies in the Gulf, e.g., 0.5–5.5 (McCain, 1984). In the open waters, there were 89 locally rare species of polychaetes and crustaceans to maintain the high diversity and low dominance throughout the area. The situation was different in the sheltered bays, where benthic communities had not recovered during 2002. Based on the TPH levels, benthic communities were studied in the impacted and non-impacted (control) sites of five inner bays of the Saudi waters of the Arabian Gulf. The species diversity (Shannon-Wiener Diversity Index) values were considerably lower in the impacted sites as compared to the control sites, Figure 3.80.

Recent studies reported the residual effect of the 1991 Gulf oil spill at certain locations in the northern Arabian Gulf about 14 years after the spill incident (de Mora, et al., 2010). TPH concentration of 72 $\mu g\ g^{-1}$ was reported off Khafji (northwestern Gulf) and 78 $\mu g\ g^{-1}$ from MTBS (de Mora, et al., 2010). During the period of the study of de Mora, et al. (2010), a benthic study was conducted in the Khafji waters (KFUPM/RI, 2006a; Joydas, et al., 2012). Regardless of the oil pollution, an overall healthy status of resident macrobenthic communities was noticed. The high species richness and Shannon-Wiener diversity, the higher number of rare species, abundance of amphipods and abundance-biomass curve (ABC) plots indicated a healthy status with few anthropogenic stressors in the Khafji waters.

The study conducted in the sheltered MTBS (KFUPM/RI, 2006b; Joydas, et al., 2011) was slightly different from that of the open waters of the oil spill's affected area. This study revealed the residual

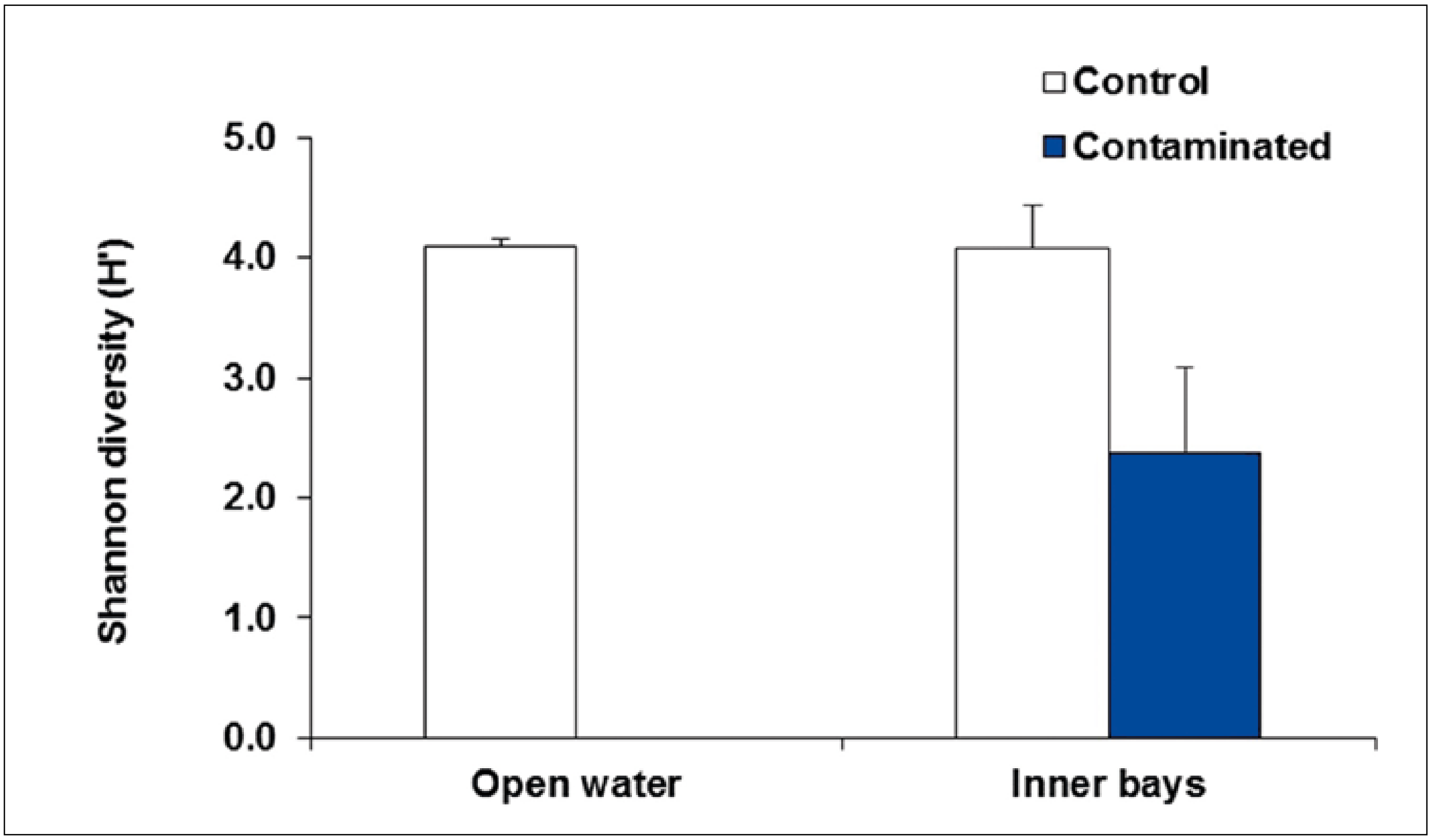

FIGURE 3.80. *Species diversity of macrobenthos in the open water region and sheltered inner bays 11 years after the 1991 Gulf oil spill. Bars indicate standard error (Modified from KFUPM/RI, 2003).*

oil effect in 20% of the studied locations, where amphipod recolonization had not taken place even 15 years after the oil spill. As far as oil pollution is concerned, amphipods are an important taxon, which disappear immediately after an oil spill, and their recolonization is an indication of the overall recovery of the benthic communities (Gesteira and Dauvin, 2000). Generally, such sheltered bay environments and intertidal habitats had severe oil contamination but reports indicate a slow natural recovery is occurring (Michel, et al., 1993; Fowler, et al., 1993; de Mora, et al., 2010; Bejarano and Michel, 2010).

Temporal Variations on Benthic Communities

The temporal variations in the density and diversity of soft bottom macrobenthos in two locations in the Saudi waters of the Arabian Gulf show that no drastic changes have happened in the communities from 1980s to the present time, Figure 3.81. Tarut Bay is an area in which large mangrove stands were landfilled and where sewage effluents and refinery discharges are acting as the main stressors. The average diversity did not go down to three. Similarly, in Khursaniyah, where recently several oil-related activities such as dredging/trenching and laying of pipelines and cables were made, did not show significant change in diversity and density over time.

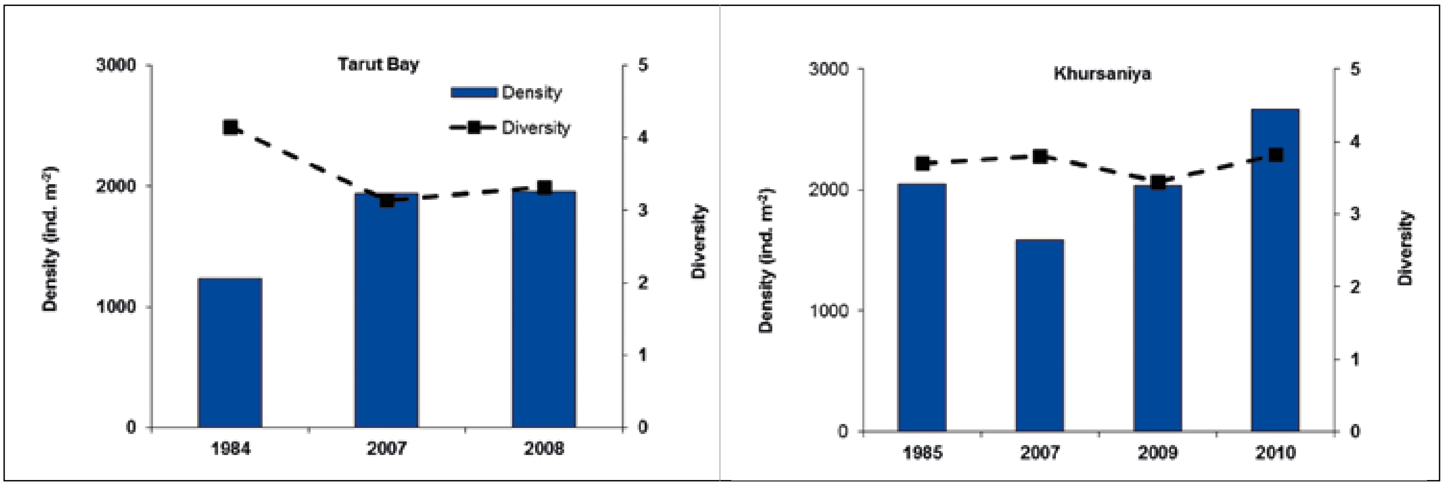

FIGURE 3.81. *Temporal variations in density and diversity of the macrobenthos in Tarut Bay and Khursaniyah.*

Discussion

Role of Benthic Compartment in the Western Arabian Gulf Marine Ecosystem

The benthic system in the western Arabian Gulf is very complex, with the existence of muddy, sandy and rocky habitats in the intertidal and subtidal regions, and the seagrass beds and coral reefs in the subtidal region. Because of this heterogeneity, the interactions between the biotic components and the environment are complex, and therefore, the benthic compartment plays a major role in the overall functioning of the Gulf's marine ecosystem. Invertebrate assemblages are heavily involved in the regulation of ecosystem processes (Snelgrove, 1998). Ecological functioning of benthic assemblages is central to the maintenance of ecosystem processes and the links between benthic and pelagic systems. Carbon, oxygen and nutrient cycling and decomposition of dead matter or waste materials are the important processes driven by the benthic assemblages (Snelgrove, et al., 1997; Austen, et al., 2002). There is a transfer of organic matter from the benthic ecosystem to the pelagic ecosystem. The low energy intertidal mud habitats in the western Arabian Gulf are very productive and accumulate an excess of organic matter. Degradation of organic matter by bacteria provides an energy source for organisms living in the sediment and a major share of it is transferred to the water column by the tidal action. This is considered to be very important because about 190 km coastline of the Saudi coast of the Arabian Gulf has mud flats with a typical width of ca. 200 m to 300 m. Consequently, because of the absence of concerted studies in this field, an estimate of the transfer is not known.

Being a shallow sea, ample light energy reaches much of the bottom area, and so benthic plants contribute a reasonable portion of total photosynthetic primary production. Of the plants, the widespread seagrass beds play manifold roles in the marine ecosystem of the western Arabian Gulf. The seagrass provides an indirect food source and a habitat for the resident fauna and temporary visitors, among other important ecosystem services (Cullen-Unsworth and Unsworth, 2013). Generally, only very few animals such as dugongs, Green Turtles, some sea urchins, and fishes directly use seagrass vegetation as a source of food (Price, et al., 1993). A great majority of the residents in this habitat consume seagrass indirectly after it has been broken down by mechanical and microbial action to become available through detrital food chains.

Seagrass beds play a vital role as the nursery or critical habitat for commercially important species, including shrimp (*Penaeus semisulcatus)*, in its early post-larval stages, and pearl oyster (*Pinctada radiata)* in its juvenile stage. The beds provide shelter for diverse organisms, which interact in different ways with the rest of the regional biota. Dugongs, which are prevalent in the region south of Ras Tanura, maintain their population (the Arabian Gulf has the second largest population after Australia) because of the seagrass and the preferred environmental conditions (Preen, 2004). Seagrass in the Arabian Gulf is also an important foraging area for the endangered Green Turtle (*Chelonia mydas)*, which exhibits a continuous decline in population worldwide.

Coral reefs occur sporadically in the western Arabian Gulf from Kuwait to the south along the Saudi coast up to Ras Tanura (Sheppard, et al., 1992). Coral reefs play a major role in maintaining the high biodiversity in the benthic ecosystem, and supporting many ecosystem services (Laurans, et al., 2013). Coral reefs support a diverse fauna of macroinvertebrates and fishes, by using a great variety of available ecological niches of the coral reef ecosystem. The associated fauna uses coral reefs as feeding grounds, nursery areas, living space, and places to hide from predators. The fishing industry depends on coral reefs because many fish spawn there and juvenile fish spend time there before making their way to the open sea. Coral reefs are the source of nitrogen and other essential nutrients for marine food chains. They assist in carbon and nitrogen fixing and help with nutrient recycling. Although only limited studies have been conducted to estimate the species' richness of the reef associated fauna, it is expected to be more than 1,000 species (KFUPM/RI, 2014a).

Mud flats in the western Arabian Gulf provide both the necessary foraging (= fat loading) and roosting (= energy sparing) stopover for thousands of migrant birds coming from Northern Hemisphere breeding grounds to Southern Hemisphere wintering grounds and returning to breeding sites (Medio, 2006). The mud flats are rich and abundant with polychaetes and amphipods that form the preferred food of migratory shorebirds (KFUPM/RI, 1988, 1994). Al-Sayed, et al. (2008) noticed a lower abundance of polychaetes compared to molluscs in Duwhat Arad Bay, a mud flat in Bahrain, as a result of intensive feeding of birds on polychaetes. This is because, in this mud flat, dominant birds such as Black-headed Gull and Ringed Plover prefer poychaetes as their main food (Moreira, 1995; Perez-Hurtado, et al., 1997).

So far, no studies have been conducted on the benthic ecosystem of the Gulf that focus on the functions of the benthic ecosystem or how various assemblages or species function. Previous studies indicated that diversity of functional types is more important than the species diversity (Bengtsson, 1998; Bolam, et al., 2002; Biles, et al., 2003; Raffaelli, et al., 2003; Bremner, 2003). This is because several different species perform similar roles within an ecosystem, and reductions in the frequency of a species performing a particular role may be compensated by increases in other similar species (Frost, et al., 1995). These studies focus on maintaining the levels of particular functional groups or types within assemblages and not preserving each individual species because functioning would be conserved as long as each functional type was represented (Borja, et al., 2000). Similar benthic studies in the Arabian Gulf will help guide effective ecosystem management and evaluation of the impacts because this region is exposed to large-scale oil-related and other types of developmental activities. This effective management will be reinforced by undertaking studies on the valuation of the ecosystem services provided by the benthic compartment of the Arabian Gulf.

Current Status of the Benthic Ecosystem in the Western Arabian Gulf

The Arabian Gulf is a naturally stressed water body because of the general hyper salinity and elevated temperature during summer. This nature causes the majority of the existing organisms to live in their upper tolerance levels. In such environments, any human pressure including that of climate change will enhance the stress many times over that which happens in a normal water body. In this region, the major human pressures are in the form of oil-related activities, oil spills, and urbanization. Unlike water column organisms, the benthic communities are sedentary or have only limited mobility, and therefore, any disturbance on the marine environment, particularly on the seabed, will impact the benthic fauna substantially.

Since the 1950s, the Arabian Gulf has been exploited for oil and gas production. The marine environment is being impacted from oil-related activities such as trenching/dredging, platforms, drilling, production, transportation, and refining. Subsequently, studies conducted by KFUPM/RI indicate that even the large-scale causeway construction had only a nearby impact because the impact was within about 3 km either side of the causeway. The studies also show that the laying of pipelines had only minimal impacts, when it was simply laid on the seabed. Consequently, when the burying of the pipeline was required, a proliferation of opportunistic species was noticed in the dredged site following the dredging (KFUPM/RI, 2010b). In the latter case, recovery of the benthic fauna occurred within 6 months, indicating that there was only a short-term impact. In all the above cases, the density and diversity of benthos were still contained within the broad ranges known for the pristine locations along the Saudi coast and other parts of the Arabian Gulf. There was no total or near-total decimation of the fauna as a result of the developmental activities, and this leads to a conclusion that the impacts so far noticed in the Saudi coasts are minor to moderate in nature and much localized.

Although, oil spills have an immediate and large impact on the marine environment. The intentional 1991 Gulf oil spill severely impacted the Saudi coast. Currently, the nearshore region is the only location, where residual oil effects of the 1991 spill can be found. It appears that there was no long-term impact in the open water regions, while in the sheltered bays it might have taken more than 15 years for a complete recovery. The recovery of benthic communities following major oil spills sometimes required several years, because of the direct effects of spilled oil and indirect and chronic effects (Peterson, 2001). Generally, sensitive taxa such as crustaceans in general and amphipods in particular, required longer recovery periods. For example, after the Amoco Cadiz oil spill, amphipod recolonization took 15 years in the Bay of Morlaix (Dauvin, 1998; Gesteira and Dauvin, 2000). Considering the severity of the 1991 Gulf oil spill and the nature of the habitats in the Gulf, the requirement of more than 15 years for the complete recovery is not surprising. The sunken oil in the sediment in the sheltered bays is a continuing threat because of the chances of re-introduction to the water column by activities such as dredging. Nevertheless, since the 1991 Gulf oil spill, no incidence of intentional or accidental major spill has happened in this region and currently, oil pollution is not the most harmful ecological disturbance in this region (Sheppard, et al., 2010).

Recently, marine reclaimed areas for urbanization are considered to be a major threat (Al-Ghadban and Price, 2002; Bishop, 2002; Khan, et al., 2002; Jones, et al., 2007; Munawar, et al., 2002; Zainal, 2009; Loughland, et al., 2012). Many productive mangroves and other intertidal habitats of the western Arabian Gulf, which were important nursery grounds for fishes and shrimps, have been reclaimed for coastal infrastructure development (Loughland, et al., 2012). Generally, the human stress, if any, in the benthic ecosystem in the western Arabian Gulf is mainly experienced in the intertidal and the subtidal regions near the lowest low tide level. These activities produce an important loss of ecosystem services, as demonstrated in the Kingdom of Bahrain (Zainal, et al., 2012).

Recent studies (KFUPM/RI, 2006b; KFUPM/RI, 2010b; Joydas, et al., 2011, 2012) indicate that in the Saudi waters of the Arabian Gulf, benthic fauna in the open waters maintain high diversities. Examples are diversity values (*H'*) of 2.61 to 5.57 recorded from the northern part (KFUPM/RI, 2006a; Joydas, et al., 2012), *H'* 2.3 to 4.0 from the central part (KFUPM/RI, 2010b) and *H'* 2.23 to 4.95 from a large area, Khafji to Ras Tanura (KFUPM/RI, 2003) of the Saudi waters of the Arabian Gulf. In all the above studies, 70% to 90% of *H'* recorded was >3 and if the suggestions of Molvaer, et al. (1997), Vincent, et al. (2002), and Borja, et al. (2004) for the Ecological Quality (EcoQ) status (suggested by the Water Framework Directive (WFD) for European waters) based on *H'* are adopted, the EcoQ can be qualified as *"high"* (uncontaminated) and *"good"* (slightly contaminated) (*"High"* if *H'* >4; *"good"* if *H'* 3 to 4; *"moderate"* if *H'* 2 to 3; *"poor"* if *H'* 1 to 2 and *"bad"* if *H'* <1). Subsequently, compared to the diversity values reported from the Saudi coast, considerably lower values were reported from the other parts of the Arabian Gulf recently. For example, macrobenthic species diversity of 1.9 to 3.1 reported from Qatari nearshore waters (Al-Khayat, 2005), less than 1.5 from Kuwait Bay (Bu-Olayan and Thomas, 2005) and <2 from the Dubai creek (Saunders, et al., 2007). The goal of these studies are to understand the pollution effects on benthos, therefore, sampling was restricted within the polluted areas, which might have resulted in recording low species' number and diversity. On the other hand, a more recent study conducted in the Kuwait waters reported a high species diversity of 2.8 to 5.3 (Al-Yamani, et al., 2009). This shows that poor benthic fauna in various parts of the Arabian Gulf may be the result of localized anthropogenic effects, and therefore, a generalization is not possible. The major part of the Arabian Gulf still may have high diversity; however, in the near future, investigations on the benthic ecological status of the Arabian Gulf should be undertaken using more accurate assessment methods, such as those used for the WFD in Europe (Borja, et al., 2009). This will allow getting a better view of the current status of benthos, following the above ongoing human impacts.

Conclusions

The benthic ecosystem in the western Arabian Gulf experiences both natural and human stressors. The hyper saline and elevated temperature conditions cause the majority of the existing organisms to live in their upper tolerance levels. The oil-related activities and urbanization are the main human pressures on the benthic ecosystem. The fishing practices, such as bottom trawling, may also be one of the important human pressures, yet, not many studies have been conducted on this aspect in this region. Consequently, the presence of seagrass beds, coral reefs, sandy, muddy and rocky habitats provide heterogeneity within the benthic ecosystem. This helps in maintaining a high diversity and a general robustness in the benthic assemblages. Currently, oil pollution is not a major threat to the benthic ecosystem, although the effect of residual oil from the 1991 Gulf oil spill may be observed in certain areas of the sheltered back bays. Generally, the human stress, if any, in the benthic ecosystem in the western Arabian Gulf is mainly experienced in the intertidal and the subtidal regions near the lowest low tide level. For the coming years, studies on the valuation of ecosystem services provided by benthos, assessment of the benthic ecological status (in response to human pressures), and the influence of climate change on the benthic composition and shifts, should be undertaken.

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APPENDIX I

Environmental Studies of the Sustaining Research Project Conducted by Research Institute of King Fahd University of Petroleum and Minerals (KFUPM/RI) and Funded by Saudi Arabian Oil Company (Saudi Aramco).

Project	Project Title	Project Start	Project End
GST E-4009	Meteorological and Oceanographic Data Report	01-Sep-77	01-Mar-79
CEW0000	Preliminary Benthic Biology Survey	01-Jan-80	01-Jan-12
24004	Simulation of an Oil Spill in the Arabian Gulf	01-Jul-80	31-Dec-80
TC-4030	Pollutant Pathways Characterization in Shallow Bay Systems	01-Jul-81	01-Jul-83
24010	Ambient Air Suspended Particulate Sampling and Characterization	01-Oct-81	30-Nov-82
TSI 57-111	An Analysis of the Impact of the Ghazlan Generating Station on Benthic Marine Communities	01-Dec-81	01-Jan-82
RP878-1	Methodology for Evaluation of Multiple Cooling System Effects	01-Jan-82	01-Jan-83
24011	Trace Metals in Marine Sediments and Water Columns	20-Feb-82	30-Nov-82
AER-5229	A Survey of Infaunal Communities of the Western Arabian Gulf	01-Jun-82	01-Jun-83
TC-3598	Marjan Offshore Gas/Oil/Pipeline Current Data Analysis and Numerical Simulation	01-Oct-82	01-Oct-83
24028	Estimating Oil Spill Size by Visual Observation	13-Nov-82	15-May-83
24038	Ballast Discharge Evaluation at Yanbu' Natural Gas Liquids Facility	01-Nov-83	13-Jul-85
24058	Mixing Heights for Three Cities in the Eastern Province	01-Jan-84	30-Jun-85
24059	Marine Environmental Investigation in the Arabian Gulf with Emphasis on the Northern Area of Saudi Arabia	01-Feb-84	30-Sep-86
24065	Solid Waste Planning Guide	01-Mar-84	31-Dec-84
24079	Saudi Aramco Sustaining Research Project Marine Environmental Studies I	01-Oct-84	30-Oct-90
GST E-4032	Sampling and Monitoring Report	10-Nov-84	11-Nov-84
24108	Marine Environmental Effect of the Abu Ali-Berri Causeway Extension	01-Aug-87	28-Feb-88
24114	Groundwater Resources Evaluation in the Eastern Province of Saudi Arabia	31-Dec-87	31-Mar-88
24120	Wave Climate Study in the Arabian Gulf	15-Aug-89	15-Aug-91
24129	Marine Environmental Study at the Safaniyah GOSP-4 Offshore Facility	11-Dec-89	30-Sep-90

Project	Project Title	Project Start	Project End
24131	Sustaining Research Project Marine Environmental Studies	18-Aug-90	30-Sep-94
24137	Gulf Atmospheric Pollution 1991	01-Feb-91	30-Sep-92
24138	Arabian Gulf Oil Spill Research Program 1991 (also called Gulf Atmospheric Pollution 1991)	01-Feb-91	30-Sep-92
24142	Ras Tanura Refinery/Terminal Upgrade: Environmental Impact Assessment	15-Aug-92	15-Apr-93
21132	Solubility of Calcium Carbonate in Synthetic and Natural Oil Field Brines	01-Apr-94	31-Mar-96
24150	Contaminant Transport Model for the Ras Tanura Groundwater Investigation	22-Aug-94	15-Dec-95
24154	Sustaining Research Project Marine Environmental Studies Phase III	01-Jul-95	31-Mar-01
24162	Investigation of Ambient Concentrations of Automotive Emissions in Three Major Cities	01-May-97	30-Apr-98
24164	Development of Red Sea Biotope Maps Using Remote Sensing Imagery	01-Jul-97	30-Jun-99
CEW2217	Marine Biological and Oceanographic Database Development	15-Nov-00	15-Nov-02
CEW2236	Environmental Impact Assessment for Abu Safah Offshore AM Producing Facilities	01-Jun-01	31-Jul-01
CEW2233	Saudi Aramco/KFUPM-RI Sustaining Research Project Marine Environmental Studies Phase IV	01-Oct-01	30-Sep-06
CEW2242	Conceptual Estimate of Environmental Impacts of Existing and New Arabia-Bahrain Pipeline Routings	28-Oct-01	24-Apr-02
CEW2259	Duba Marine Terminal Permanent Berth (BI-8232) Environmental Impact Assessment for the Construction and Removal of Temporary Roads	15-Jan-03	31-Oct-06
CEW2269	Offshore MP Facilities Berri-119 Pipeline (BI-8294) Environmental Impact Assessment Study	01-Apr-03	31-Oct-03
CEW2278	Offshore MP Facilities 15 kV Cable (BI-8294) Environmental Impact Assessment	15-Sep-03	31-Dec-03
CEW2285	Environmental Impact Assessment North Safaniyah Artificial Lift (BI-10-0047)	12-Jul-04	09-Feb-05
CEW2287	Offshore MP Facilities Qatif QV Cable (BI-8294) Environmental Impact Assessment	26-Jul-04	29-Sep-04
CEW2310	Environmental Impact Assessment of the New Khursaniyah 30" Dia. Pipeline (BI-10-08022)	04-Jun-05	30-Nov-05
CEW2311	Environmental Impact Assessment Upgrade Northern Area Oil Operations Offshore Platforms Wastewater (BI-01-00197).	13-Jun-05	31-Oct-05
CEW2303	Environmental Impact Assessment for the Berri Causeway and Associated Drill Site Landfilling	24-Dec-05	12-Apr-06
CEW2325	Operational Marine Modeling System (OMMS)	01-Jan-06	31-Dec-08
CEW2328	Environmental Impact Assessment for Manifa Field Development (NAFD/L-001-06): Causeway Construction	11-Mar-06	30-Sep-06
CEW2329	Environmental Impact Assessment for Abu Ali Flanks Scraped Water Handling (BI-10-00220)	01-Apr-06	31-Jul-06
CEW2338	Environmental Impact Assessment for Manifa Field Development Program: Platforms, Pipelines and Submarine Cables (BI-01-00452 and BI-01-00453)	11-Nov-06	30-Jun-07
CEW2336	Marine Environmental Monitoring of the New Khursaniyah 30" Dia. Pipeline (BI-10-08022) Project	01-Jan-07	31-Dec-09
CEW2345	Environmental Impact Assessment for the King Abdullah University of Science & Technology Development Project	02-Jun-07	30-Jul-08
CEW2342	Marine Environmental Monitoring of the Manifa Causeway	12-Jun-07	30-Jun-10
CEW2343	Assessment of Ras Tanura Marine Environment and Bioaccumulation Monitoring along the Saudi Coastal Waters of the Arabian Gulf	21-Jul-07	30-Dec-10
CEW2350	Environmental Impact Assessment for Tanajib Channel and Basin Dredging	31-Jul-07	31-Oct-07

Project	Project Title	Project Start	Project End
CEW2344	Saudi Aramco/KFUPM-RI Sustaining Research Project, Marine Environmental Studies Phase V	15-Aug-07	16-Aug-12
CEW2353	Biodiversity of the Offshore Saudi Islands of the Arabian Gulf	21-Oct-07	31-Jul-11
CEW2354	The Western Arabian Gulf Ecosystem: A Reference for Researchers, Planners and Environmental Managers	21-Oct-07	31-Jul-11
CEW2355	Marine Atlas of the Western Arabian Gulf Phase I: Coastal and Marine Surveys and Photo Documentation	21-Oct-07	31-Jul-11
CEW2352	Environmental Impact Assessment for a Seawater Reverse Osmosis Water Treatment Plant at King Abdullah University of Science and Technology	03-Nov-07	31-Mar-08
CEW2343-01	Assessment of Ras Tanura Marine Environment and Bioaccumulation Monitoring along the Saudi Coastal Waters of the Arabian Gulf Additional Scope	01-Jan-08	30-Nov-08
CEW2357	Environmental Impact Assessment for Karan Platforms, Power (BI-10-00579) and Pipelines (BI-10-00580) Construction	01-Jan-08	31-Aug-08
CEW2359	Environmental Impact Assessment for Drill Cutting Disposal at Manifa	01-Jun-08	31-Dec-08
CEW2360	Environmental Impact Study for Channel Dredging at Safaniyah	07-Jun-08	31-Dec-08
CEW2370	Environmental Impact Assessment for Land Filling and Reclamation at Ras Tanura Refinery	15-Nov-08	31-Dec-09
CEW2373	Environmental Impact Assessment for the Upgrade of Crude Gathering and Power Supply Facilities Phase I: Safaniyah Field	27-Jun-09	31-Mar-10
CEW2380	Conduct LC-50 Drilling Fluid Sampling and Toxicity Testing	11-Nov-09	31-Dec-11
CEW2379	Environmental Impact Assessment for Installing Instrument Scraping Facilities at Zuluf and Marjan Oil Fields (BI-10-00187)	20-Feb-10	20-Apr-10
CEW2381	Environmental Impact Assessment for Upgrade of the Fire Protection System, Ju'aymah Offshore Platform (BI-10-00185)	24-Apr-10	31-Aug-10
CEW2382	Environmental Impact Assessment for Arabiyah-Hasbah Platforms, Power (BI-10-00916) and Subsea Pipelines (BI010-00917)	19-Jun-10	19-Dec-10
CEW2374	Fisheries Program: Population Dynamics and Stock Assessment of the Major Fisheries Resources in Saudi Arabian Waters	01-Jan-11	30-Nov-13
CEW2375	Fisheries Program Assessment and Management of Essential Fish Habitats in Saudi Arabian Waters	01-Jan-11	30-Nov-13
CEW2376	Fisheries Program Environmental Impacts of Fishing Methods in Saudi Arabia: Toward Mitigation and Management	01-Jan-11	30-Nov-13
CEW2377	Fisheries Program Development of a Strategic Framework for Fisheries Management in Saudi Arabia	01-Jan-11	30-Nov-13
CEW2385	GMARS Development of GIS Compatible Marine Database and Analysis System (GMARS)	01-Feb-11	31-Jul-12
CEW2389	Red Sea Environmental Impact Assessment for Drilling Exploration in the Shallow Waters of the Northern Red Sea	11-Jun-11	03-Jun-12
CEW2390	Tarut Bay Environmental Assessment Report for Tarut Bay Pipelines & Structural Support System	02-Jul-11	31-Dec-11
CEW2392	Safaniyah Pier Environmental Assessment for the Safaniyah Pier Trestle Replacement	23-Jul-11	31-Mar-12
CEW2399	Environmental Impact Assessment for Dredging (Category III) for Upgrade of Electrical Power Supply to Abu Ali Plants	15-Feb-12	15-Aug-12

APPENDIX II

Checklist of marine invertebrates

*Checklist of marine invertebrates occurring in the area of the Arabian Gulf. Bold Arabic numbers (**1** to **34**) indicate the references of record of the species. Note that the list represented in this appendix has been modified from those published in the references used. Some non-identified species or only identified to the order/family level were excluded from the present list. Taxa identified to only genus level (noted as Genus sp.) were kept but they may refer to one or many species (belonging to the same genus) recorded in one or various references; more details about this can be obtained from the original references of record. The species belonging to each class are listed in alphabetic order.* **1** Price (1991), **2** KFUPM/RI (1987), **3** Al-Yamani et al. (2012), **4** Hasam (1994), **5** Al-Naser et al. (2010), **6** Nithianandan (2012), **7** Smythe (1972), **8** Al-Khayat and Al-Ansi (2008), **9** Tehranifard and Dastan (2011), **10** Al-Khayat (2008), **11** Roper et al. (1984), **12** Sheppard and Borowitzka (2012), **13** Al-Yamani et al. (2011), **14** Carpenter et al. (1997), **15** KFUPM/RI (2003), **16** Apel and Türkay (1999), **17** Hogart and Tigar (2002), **18** Al-Sayed and Zainal (2005), **19** Al-Khayat and Al-Maslamani (2001), **20** KFUPM/RI (1990), **21** Grabe et al. (2004), **22** Murano (1998), **23** Razzaq (1991), **24** Abdulqader (1999), **25** Price and Jones (1975), **26** Enomoto (1971), **27** Hosny (2007), **28** Badawi (1975), **29** Chen et al. (2013), **30** Monniot and Monniot (1997), **31** KFUPM/RI (2006a), **32** KFUPM/RI (2013), **33** KFUPM/RI (2006b), **34** Njinkoué et al. (2006).

PHYLUM PORIFERA
Class Demospongiae
Adocia sp. **2**
Aplysina sp. **2**
Axinella sp. **2**
Biemna sp. **2**
Cacospongia sp. **2**
Gelliodes cf. *incrustans* **34**
Callyspongia cf. *siphonella* **34**
Callyspongia sp. **2, 34**
Choristida sp. **2**
Cinachyra sp. **2**
Ciocalypta sp. **2**
Cliona schmidti **2**
Cliona sp. **2**
Cliona vastifica **2**
Coelosphaera sp. **2**
Dysidea sp. **2**
Europon sp. **2**
Fasciospongia sp. **2**
Gelliodes cf. *incrustans* **34**
Gelliodes sp. **2**
Halichondria sp. **2**
Haliclona sp. **2**
Haliclona sp. **2**
Mycale sp. **2**
Niphates sp. **34**
Spongia sp. **2**
Tedania sp. **2**
Tethya aurantium **2**
Tethya sp. **2**
Tetilla sp. **2**

PHYLUM CNIDARIA
Class Anthozoa
Acanthastrea echinata **12**
Acropora clathrata **12**
Acropora downing **12**
Acropora horrida **12**
Acropora pharaonis **12**
Acropora valenciennesi **12**
Actiniaria sp. **2**
Anemonactis sp. **2**
Anomastrea irregularis **12**
Blastomussa merleti **12**
Coscinaraea monile **12**
Culicia rubeola **12**
Cyphastrea micropthalma **12**
Cyphastrea serialia **12**
Echinophyllia aspera **12**
Favia favus **12**
Favia pallida **12**
Favia speciosa **12**
Favites chinensis **12**
Favites pentagona **12**
Heterocyathus aequicostatus **12**
Hydnophora exesa **12**
Leptostrea inaequalis **12**
Leptostrea purpurea **12**
Leptostrea transversa **12**
Madracis kirbyi **12**
Montipora circumvallata **12**
Montipora spumosa **12**
Paracyathus sp.12
Pavona cactus **12**
Pavona diffluens **12**
Pavona explanulata **12**
Pavona varians **12**
Platygyra daedalea **12**
Platygyra sinensis **12**
Plesiastrea versipora **12**
Pocillopora damicornis **12**
Porites compressa **12**
Porites harrisoni **12**
Porites lutea **12**
Porites murrayensis **12**
Porites nodifera **12**
Psammocora contigua **12**
Psammocora haimeana **12**
Psammoseris sp. **12**
Pseudosiderastrea tayamai **12**
Siderastrea savignyana **12**
Stylophora pistillata **12**
Tubastraea aurea **12**
Turbinaria mesenterina **12**
Turbinaria peltata **12**
Class Hydrozoa
Aequorea pensilis **13**
Aglaura hemistoma **13**
Amphinema rugosum **13**
Campanularia crenata **2**
Clytia cf. *gravieri* **2**
Clytia discoida **13**
Clytia gravieri **2**
Clytia latitheca **2**
Corynactis sp. **2**
Cunina octonaria **13**
Cytaeis nassa **2**
Diphyes chamissonis **13**
Dynamena cornicina **2**
Dynamena crisioides **2**
Dynamena quadridentata **2**
Eirene viridula **13**
Eudendrium capillare **2**
Eudendrium sp. **2**
Eutima gegenbauri **13**
Gonionemus murbachi **2**
Halocordyle disticha **2**
Hydractinia cf. *diogenes* **2**
Liriope tetraphyla **13**
Obelia bispinosa **2**
Obelia cf. *dichotoma* **2**
Obelia sp. **13**
Octophialucium funerarium **13**
Plumularia cf. *setacea* **2**
Plumularia sp. **2**
Podocoryne sp. **13**
Rhizorhagium robustum **2**
Sanderia malayensis **13**
Sertularia distans **2**
Sertularia longa **2**
Solmundella bitentaculata **13**
Staurocladia vallentini **2**
Thyroscyphus fruticosus **2**

PHYLUM ANNELIDA
Class Polychaeta
Aglaophamus sp. **2**
Amaeana sp. **2**
Ampharete acutifrons **31**
Ampharete sp. **15**
Amphicteis gunneri **15**
Amphicteis sp. **2**
Amphiglena mediterranea **15**
Amphiglina sp. **2**
Amphinome sp. **15**
Amphisamytha sp. **2**
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Ceratocephale sp. **2**
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Eumida sp. 2
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Eunice australis 15
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Euphrosine myrtosa 15
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Eurythoe sp. 15
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Exogone normalis 15
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Glycera rouxi 2
Glycera sp. 2
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Glycera tesselata 31
Glycinde sp. 2
Glyphanostomum abyssale 31
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Neanthes unifasciata 2
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Nephtyis sphaerocirrata 15
Nephtys dibranchis 15
Nephtys hombergi 15
Nephtys polybranchia 15
Nephtys tulearensis 2
Nereimyra sp. 2
Nereis coutierei 2
Nereis persica 2
Nereis sp. 15
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Ninoe sp. 2
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Paraonis gracilis oculata 15
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Pectinaria capensis 31
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Pionosyllis sp. 2
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Polydora ciliata 15
Polydora kempi 31
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Polyodontes sp. 2
Polyophthaimus sp. 2
Polyphysia crassa 15
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Potamila linguicollaris 31
Potamila reniformis 31
Potamilla sp. 15
Potamilla tanelli 15
Praxillella sp. 2
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Prionospio cirrifera 31
Prionospio cirrobranchiata 15
Prionospio ehlersi 15
Prionospio pinnata 15
Prionospio sexoculata 15
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Pseudomalacoceros sp. 2
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Pseudopolydora antennata 2
Pseudopolydora sp. 2
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Sabellaria sp. 31
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Sabellides octocirrata 31
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Sphaerosyllis brenicirrus 2
Sphaerosyllis capensis 2
Sphaerosyllis semiverucossa 15
Sphaerosyllis sp. 2
Sphaerosyllis sublaevis 15
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Spio sp. 15
Spiochaetopterus sp. 2
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Sternaspis scutata 15
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Syllidia armata 15
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Typosyllia sp. 2
Typosyllis armillaris 2
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Vermiliopsis pygidialis 15
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Bathydrilus sp. 2
Duridrilus tectus 2

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Heterodrilus sp. **2**
Inanidrilus sp. **2**
Limnodriloides appendiculatus **2**
Limnodriloides bipapillatus **2**
Limnodriloides tenuiductus **2**
Limnodriloides sp. **2**
Olavius manifae **2**
Olavius verga **2**
Paranais litoralis **2**
Phallodrilus sp. **2**
Tectidrilus arabicus **2**
Tubificoides sp. **2**
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Apionsoma trichocephalus **2**
Aspidosiphon sp. **2**
Phascolapsis sp. **2**
Phascolion convestitum **2**
Phascolion valdiviae var. sumatrense **2**
Phascolion sp. **2**
Phascolosoma sp. **2**
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Aeginella sp. **15**
Aeginellopsis arabica **15**
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Alpheus sp. **13**
Ampelisca brevicornis **2, 15**
Ampelisca hemigera **15**
Ampelisca insignis **2, 15**
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Ampelisca sp. **2, 3**
Ampelisca tulearensis **2, 15**
Amphiascopsis subdebilis **20**
Amphiascus minutus **20**
Amphiascus sp. **2**
Amphilochus neapolitanus **2**
Amphilochus sp. **2**
Ampilochus hemigera **15**
Ampilochus neopolitanus **15**
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Apanthura sandalensis **3**
Apseudopsis sp. **2, 3**
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Balanus sp. **3**
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Bodotria parva **15**
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Cirolana sp. **2**
Cirolana sulcata **2**
Cleistostoma sp. **3**
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Colomastix pusselia **2**
Corophinum sp. **3**
Cumella forficula **2, 15, 20**
Cumella nispida **15, 20**
Cumella sp. **2, 3, 15**
Cumopsis sp. **3**
Cyclaspis cingulate **20**
Cyclaspis hornelli **2, 15, 20**
Cyclaspis picta **2, 15, 20**
Cyclaspis sp. **3, 15**
Cyclopoid sp. **2**
Cyelaspis cingulate **2**
Cylindroleberis sp. **2**
Cymadusa filosa **2, 15**
Cymadusa sp. **3**
Cymodoce sp. **2**
Cypridina sp. **2**
Cypridinodes minuta **2**
Cyproidea sp. **3**
Cyproidea tecticauda **2, 15**
Cytherella sp. **2, 15**
Cytherelloidea sp. **2**
Dactylopodia sp. **2**
Darcythompsonia sp. **2**
Dardanus sp. **13**
Diogenes sp. **13**
Diosaccid sp. **2**
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Dotilla sulcata **16**
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Ebalia sp. **13**
Ectinosoma sp. **2**
Elasmopus pectinicrus **15**
Elasmopus rapax **15**
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Eocuma rosae **3**
Eocuma sarsi **2, 3, 20**
Eocuma sp. **3, 15**
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Euphilomedes sp. **2**
Euraphia withersi **3**
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Euryte pseudorobusta **20**
Euterpina acutifrons **20**
Eviopisa sp. **3**
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Gitanopsis sp. **15**
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Haliophasma sp. **2**
Haplostylus bengalensis **21**
Haplostylus parerythraeus **22**
Harpacticoid copepodites **20**
Harpacticus nicaeensis **20**
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Hersiliodes latericia **20**
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Idunella similis **2**
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Ilyoplax sp. **3**
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Iphinoe crassipes **15**
Iphinoe ischnura **20**
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Kainomatomysis foxi **21**
Kalliapseudopsis mauritanicus **2**
Keijella darwini **2**
Lankacxthere coralloides **2**
Lanocira gardineri **2**
Lanocira glabra **2**
Laomedia sp. **13**
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Laophonte inornata **20**
Laophonte sp. **2**
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Lembos sp. **2**
Lembos teleforus **2**
Leptochela aculeocaudata **2**
Leptochela sydniensis **2, 15**
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Leptochelia minuta **2**
Leptochelia savignli **2**
Leptochelia sp. **2**
Leptochryseus kuwaitense **16**
Leucosia sp. **13**
Leucothoe lesson **2**
Leucothoe sp. **2, 15**
Leucothoe spinicarpa **2**
Leucothoella bannwarthi **2, 15**
Leucothoella sp. **15**
Leucothoides sp. **15**
Leucothrals sp. **2**
Liljeborgia sp. **2**
Limbos leptocheirus **2**
Longipedia sp. **2**
Lourinia armata **2**
Loxoconcha amygdalanux **2**
Loxoconcha gurneyi **2**
Loxoconcha indica **23**
Loxoconcha multiornata **23**
Loxoconcha ornatovalvae **2**
Lucifer hanseni **13**
Lucifer typus **13**
Lycomysis platycauda **21**
Lysianassa cinghalensis **2, 15**
Lysianassa coelochir **2**
Lysmata sp. **13**
Lyssianassa sp. **2**
Macrophthalmus (Macrophthalmus) laevis **16**
Macrophthalmus (Macrophthalmus) sulcatus **16**
Macrophthalmus (Mareotis) depressus **16**
Macrophthalmus (Venitus) dentipes **3, 16**
Maera hemigera **15**
Maera pacifica **2, 15**
Maera quadrimana **2, 15**
Maera sp. **2, 15**
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Malacanthura mombasa **2, 20**
Manningia sp. **2**
Manningis arabicum **16**
Maua sp. **2**
Medaeops granulosus **3**
Megabalanus sp. **3**
Megabalanus tintinnbulum **3**
Melita sp. **2, 3**
Metamphiascopsis hirsutus **20**
Metapenaeopsis mogiensis **24**
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Microlysias denoceras **2**
Microlysias sp. **2**
Microphotis blachei **3**
Microsetella norvegiga **20**
Mycrolysias xenoceras **2**
Mysidopsis kempi **21**
Nannastacus gibbosus **15**
Nannastacus gurneyi **15, 20**
Nannastacus inflatus **2, 15, 20**
Nannastacus lepturus **2, 15, 20**
Nannastacus lepturus **20**
Nannastacus sp. **2, 15**
Nannastacus stebbingi **2, 15, 20**
Nannastacus zimmeri **15**
Nannastacuss gurneyi **2**
Nanosesarma minatum **3**
Nasima ditilliformis **16**
Natarajphotis manieni **15**
Natatolana neglecta **2, 20**
Nebalia marerubri **2**
Nebalia sp. **2**
Neomonoceratina sp. **23**
Neonesidea schulzi **2**
Nitocrella sp. **2**
Nitrocra sp. **2**
Ocyode rotundata **16**
Oediceroides cinderella **2**
Orchomene sp. **3**
Pachcheles sp. **13**
Paguristes sp. **13**
Pagurus sp. **13**
Palaemon sp. **13**
Panulirus versicolor **14**
Paracytheridea sp. **2**
Paradexamine sp. **2**
Paradiastylis brachyura **2, 15, 20**
Paradiastylis culicoides **2**
Paradiastylis sp. **2, 15**
Paralaophonte congenera **20**
Paralaophonte mediterranea **20**
Paralaophonte sp. **2**
Paranamixis sp. **2**
Parapenaeopsis stylifera **13, 26**
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Parathalestris sp. **2**
Paratymolus sp. **2**
Parhyale sp. **15**
Paromoera capensis **15**
Parthenope sp. **13**
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Perioculodes longimanus **2**
Perioculodes pallidus **2**
Perioculodes sp. **3**
Philyra platychira **2**
Philyra sp. **3**
Photis digitata **15**
Photis dolicammota **2**
Photis longimanus **2, 15**
Photis sp. **2**
Pilumnopeus sp. **2**
Pilumnus vespertilis **3**
Pinnixa sp. **2**
Platyisohnopus herdmani **3**
Podocerus brasiliensis **2**
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Amphipholis squamata 1
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Amphiura (Amphiura) fasciata 1
Amphiura (Amphiura) sp 1
Amphiura (Amphiura) sp. nov. 1
Asterina burtoni 1
Asteropsis carinifera 1
Astropecten indicus 1
Astropecten monacanthus 1
Astropecten polyacanthus phragmorus 1
Astropecten polyacanthus polyacanthus 1
Astropecten pugnax 1
Decametra mollis 1
Euretaster cribrosus 1
Leiaster leachi 1
Linckia multifora 1
Luidia hardwicki 1
Luidia maculata 1
Macrophiothrix elongata 1
Macrophiothrix sp. aff. Hirsuta cheneyi 1
Macrophiotrix sp. 1
Ophiactis savignyi 1
Ophionereis dubia 1
Ophiothela danae 1
Ophiothela venusta 1
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Ophiura kinbergi 1
Paracrocnida persica 1
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Amphioplus personatus 2
Amphioplus seminudus 2
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Amphiura crispa 2
Amphiura fasciata 2
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Ophiocentrus asper 2
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PHYLUM BRYOZOA

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Microporella orientalis 2
Nellia quadrilatera 2
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Parasmittina gnata 2
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Parasmittina unispinosa 2
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Celleporaria labelligera 2

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Styela canopus 30
Symplegma bahraini 30
Symplegma brakenhielmi 30

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