DOCTOR OF PHILOSOPHY

Bahrain marine habitats and some environmental effects on seagrass beds : a study of the marine habitats of Bahrain with particular reference to the effects of water temperature, depth and salinity on seagrass biomass and distribution.

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BAHRAIN MARINE HABITATS AND SOME ENVIRONMENTAL EFFECTS ON SEAGRASS BEDS.

A Study of the Marine Habitats of Bahrain with Particular Reference to the Effects of Water Temperature, Depth and Salinity on Seagrass Biomass and Distribution.

A thesis submitted to the University of Wales (BANGOR)

by

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DEDICATED ....

To my parents who never ceased to support me.

To my good friend and mentor, David Jones, for his advice and encouragement.

Most of all to my wife, Caroline, for her patience and understanding.

'I must go down to the seas again, to the lonely sea and the sky,

And all I ask is a tall ship and a star to steer her by,

And the wheel's kick and the wind's song and the white sails shaking,

And a grey mist on the sea's face and a grey dawn breaking.'

'Sea Fever', John Masefield.

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N.B. All tables and figures are located at the end of the chapter in which they are cited.

ABSTRACT

This thesis presents a study of the marine habitats of Bahrain together with details of some of the physical factors which may effect the distribution of those habitat types. Satellite remote sensing techniques were employed together with aerial photography and in-field 'ground-truthing' to locate 8 distinct habitat type. A comparison between the satellite-predicted habitat types and the actual habitats present reveals an accuracy of greater than 87%. Over 250 intertidal and subtidal study sites were surveyed for community type, key species, water quality measurements and seasonal variation. A final map of 12 habitat types was produced by expanding on the satellite characterisation using results from the detailed field surveys and the aerial reconnaissance. A set of sensitivity maps was drawn up to identify areas of commercial and scientific importance and to allocate areas in need of conservation, protection and management. The importance of each habitat type and its role in the overall ecosystem is discussed. The findings of this survey constitute the foundations for an effective national marine conservation strategy.

Seagrass beds are identified as one of the most important habitat types around Bahrain and the effects of temperature, depth and salinity on the distribution and biomass of the three native species of seagrass are investigated. These three factors are identified as being the most variable physical factors likely to constrain seagrass growth and distribution. 14 sites were surveyed at different seasonal periods to collect data on the biomass, leaf length and leaf number of the different species of seagrass along with temperature, depth and salinity data. The leaf measurements and biomass data from the 3 species of seagrass show a clear relationship to physical factors. Temperature effects the growth of all 3 species to a varying extent. Water depth influences the distribution and growth patterns of Halodule uninervis and Halophila stipulacea. Salinity has no apparent effect on biomass or distribution. The possibility that salinity influences growth pattern and leaf morphology, particularly in Halophila ovalis, is inconclusive and would require further investigation.

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I apologise to any persons who should have been included in these acknowledgements but were inadvertently forgotten. I thank all the above for their invaluable assistance and absolve them from any errors in this thesis for which I take full responsibility.

CHAPTER ONE

INTRODUCTION

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INTRODUCTION

The State of Bahrain lies in the Arabian Gulf in an elbow formed between the Kingdom of Saudi Arabia and the State of Qatar (see figure 1.1). This partially-enclosed sea is often referred to as the Gulf of Bahrain with its southern extension being the Gulf of Salwah (Dawhat Salwah). The main island of Bahrain is located at approximately latitude 26°.00' N, longitude 50°.30' E.

The Arabian Gulf is an extensive, shallow epicontinental sea occupying a tectonic basin of late pliocene-pleistocene age and is linked to the Indian Ocean in the east by the narrow Strait of Hormuz. Water depths of over 100 m are recorded in the central Gulf, however, the waters around the islands which constitute Bahrain are extremely shallow and average water depths rarely exceed 8 m with the maximum depth recorded in the study area being 32 m off the south-west coast of the main island of Bahrain.

The territories of Bahrain constitute some 33 natural islands as well as numerous drying banks and reefs. The main island is 48 km long , 14 km wide and is oriented in a north-south direction parallel to the adjacent coastline of Saudi Arabia which lies 25 km to the west. The highest point on the island is Jebel Ad Dukhan reaching 122 m. The Hawar islands lie nearly 30 km to the south-east of the main island and represent the next largest landmass in the Bahrain island group. The Hawar islands lie very close to the mainland of Qatar and water depths around these islands are extremely shallow averaging around 1 m. A more detailed discussion of the geography and geology of the area is included in chapter 2.

The study area (figure 1.1) includes all the islands of Bahrain and their territorial sea area defined by the following Universal Transverse Mercator grid bearings based on the UTM zone 39 at Ain al Abd, Qatar.

Easting 420030 : Northing 2930009
To
Easting 500000 : Northing 2820000

Previous Work

Early scientific studies within the Arabian Gulf focused mainly on marine geology. Emery (1956) presents results from a 2 week cruise through the Gulf by several research vessels which collected a large quantity of information on the sediments and water characteristics of Gulf. Sarnthein (1972) looked at the distribution of sediments within the Gulf and their indication of previous climatic and sea level regimes. Doornkamp et al (1980) gives by far the most comprehensive and significant review of the geological history and geomorphology of this area with specific reference to Bahrain.

An extensive ecological survey of the neighbouring coastline of Saudi Arabia was carried out between 1970-1976 by Basson et al (1977).They identified the presence, distribution and environmental requirements of many plant and animal species which are now known to occur in Bahrain. Their work also identifies many of the physical conditions prevailing in the Arabian Gulf and explains how the stresses imposed on the biological environment by physical extremes tend to maintain a generally low biodiversity, especially among the more sensitive biota such as the corals. The work of Basson et al (1977) also identifies salinity as being one of the principal constraints to biodiversity, but acknowledges that temperature might be equally important with upper and lower temperature records being close to or, in some cases exceeding, the tolerance levels of local species.

Jones et al (1978) investigated the flora and fauna of the hypersaline lagoons which are common along the Saudi Arabian coast adjacent to Bahrain. They found that biodiversity was low, but that numbers of certain individuals were often high at specific periods of the year when primary productivity was at its peak. Secondary productivity was generally low. Temperatures were not found to vary significantly between the lagoons and the open coastline. In his field guide to the seashores of Kuwait and the Arabian Gulf, Jones (1986a) provides a valuable identification guide to the flora and fauna of the Arabian Gulf and also includes a good synopsis of the oceanographic and geographic characteristics of the region.

Various other studies around Bahrain have provided some additional information on salinity, temperature measurements, nutrient levels and pollutants, but these have all been of too localised a nature or too general to give a holistic picture of the environment in the waters around Bahrain. These additional studies include the United Nations Environment Programme State of the Environment report (1980), Mattson and Notini (1981), Linden (1982) and Johnson (1983).

Hill and Webb (1983) provide an introductory discussion of the wildlife found on the islands of Bahrain with particular reference to birds, but discussion is lacking on the more obvious marine biota. In addition, a number of more specific studies on taxonomic groups have been conducted. Newton (1955) gives a brief introduction to some of the marine algae of Bahrain, while Gallagher (1971) provides an excellent review of the reptiles and amphibians found on the islands around Bahrain. Gallagher and Rogers (1978) discuss the breeding colonies of birds which are associated with Bahrain and Jennings (1981) gives a good short discourse on the birds of Bahrain with colour plates and descriptions.

The first detailed study of the marine environment around Bahrain was that undertaken by Price and Vousden in 1983 and published as Price et al (1984). This study surveyed 6 offshore and 6 intertidal sites on a seasonal basis 3 times during the course of one year. The data collected, results and recommendations from that study had a direct effect upon the initial decision to undertake a Marine Habitat Survey which led to this present study and thesis.

Another important survey was that undertaken by W.S. Atkins and Partners (Atkins, 1985) who were acting as consultants to the Ministry of Housing in Bahrain. This survey was undertaken in 1984 at the request of and under the management of the Environmental Protection Committee of the State of Bahrain through its implementation agency, the Environmental Protection Technical Secretariat. The study consisted of an environmental impact assessment of the potential effects of a large-scale reclamation of the Fasht al Adhm reef complex (see figure 1.1). This constituted a rapid but nonetheless very useful survey of the ecology and oceanography of the reef structure and surrounding habitats. The environmental studies and the resultant recommendations from the study supported the need for a full-scale mapping exercise of Bahrain's marine habitats to identify their scientific and economic value as well as to highlight their vulnerability.

Much of the historical background to the present study and the marine history of the Environmental Protection Technical Secretariat of Bahrain is contained in Vousden (1985b).

Aims and Objectives:

The need for a more detailed survey of the marine habitats around Bahrain and some understanding of their distribution and environmental limitations has been recognised by several previous studies (see above). Vousden (1985b) and Vousden and Price (1985) recommended that to protect the marine biodiversity a better knowledge of the marine habitats around Bahrain was required and this would allow the creation of a conservation and management strategy and the designation of marine management and protected areas .

Routine monitoring by the Environmental Protection Technical Secretariat together with the studies discussed above revealed the following information on Bahrain's marine environment prior to the initiation of the present study:

1. Large seasonal differences in water temperature occur ranging from 14-35° C at coastal sites and 13-31° C at offshore sites.

2. Coastal and offshore salinities range from 42 ppt (parts per thousand) in the north-east to 60 ppt in the south-west and as high as 70 ppt in some of the shallow coastal lagoons throughout the year.

3. Sea temperatures and salinities are considered to be closely related to climate and to the shallow and partially land-locked nature of the waters. Sea temperatures parallel air temperatures as a result of the small thermal capacity of the shallow waters. Intense summer temperatures induce high rates of evaporation and, coupled with the relatively small net flow of water around the southern end of the island, cause the high salinity levels recorded. Seasonal extremes in temperature coupled with high salinities produce a naturally stressful marine environment around Bahrain

4. Three critical marine habitat types are present around Bahrain. These are coral reefs, mangroves and seagrass beds. Of these the seagrass beds constitute by far the largest area and support a major fishery and provide an important food-source for certain endangered or threatened species such as dugong and sea turtles.

Based on this information Price et al (1984), Vousden and Price (1985) and Vousden (1985b) made the following recommendations :

A. Monitoring of the coastline and offshore waters with particular reference to temperature and salinity regimes should be continued and extended

B. Selected areas identified as being of economic or scientific importance to the State of Bahrain should be given government-approved protection.

C. Detailed mapping of the habitats within Bahrain's territorial waters should be conducted to assess their present status and vulnerability and to allow the development of a management programme. The possibilities for using satellite imagery to cover the large territorial waters around Bahrain was suggested by a number of authors including Price et al. (1984) and Vousden (1985b).

Hence the present study was initiated to confirm and expand the available information on the marine environment of Bahrain and to fulfill as many of the above recommendations as possible.

The main objectives of this study were:

1. To map the distribution of the marine habitats around Bahrain and to evaluate the potential of remote sensing, and particularly satellite imagery, as a rapid and accurate means to survey this large area.

2. To identify the 'critical marine habitats' defined by IUCN (1976) and Ray (1976) as identifiable areas which are vital to the survival of a species at some phase of its life-cycle, or to the survival of a community because of the ecological processes which occur within it.

3. To understand and define the principal physical characteristics of the waters around Bahrain which control critical habitat and associated species distribution.

4. To arrive at a set of recommendations for the protection and management of critical habitats and commercially and/or scientifically important species.

In order to achieve these objectives the study was broken down into the following components:

A. A survey of the physical environment of the waters around Bahrain with emphasis on temperature, salinity and any other factors closely related to these two or which can be seen to be having a major effect on habitat or species distribution.

B. An intertidal survey of the coastline of Bahrain to identify and map habitat and species distribution and to provide preliminary management recommendations.

C. A subtidal survey of the waters of Bahrain to identify and map habitat and species distribution and to provide preliminary management recommendations.

D. An investigation into the potential value of remote sensing as a marine habitat surveying technique.

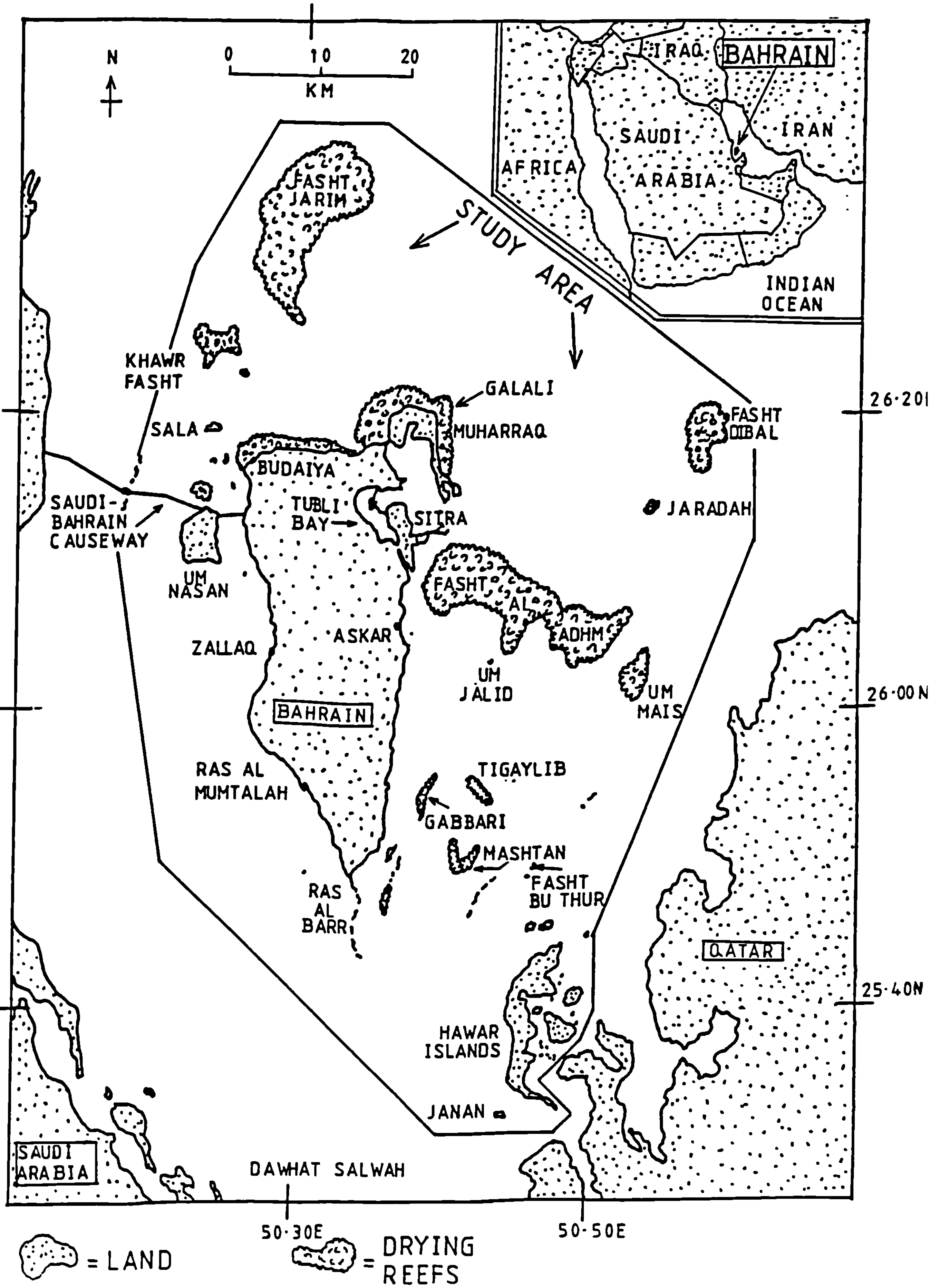
E. A more detailed study of the principal critical habitat 'seagrass beds' found around Bahrain in view of their commercial and scientific importance.

Each of these components represents a chapter in this thesis.

The reader is asked to note that it was not possible to reduce the satellite imagery and habitat maps to fit into Volume 1 without losing important detail. The imagery and maps have therefore been included as a separate volume (Volume 2). Reference is made to this second volume in the main text wherever discussion of the maps or imagery arises.

FIGURE 1.1 MAP OF BAHRAIN SHOWING MAIN ISLANDS, REEFS AND STUDY AREA

(INSET: POSITION OF BAHRAIN IN MIDDLE EAST)



CHAPTER TWO

THE PHYSICAL MARINE ENVIRONMENT

CHAPTER TWO - THE PHYSICAL MARINE ENVIRONMENT

INTRODUCTION

The Arabian Gulf was probably formed some 4 to 5 million years ago when the area presently known as Arabia separated from the continent of Africa. This split resulted in the Red Sea to the west and, where the Arabian plate was forced up against the land mass of Asia, the Zagros mountain range in the east. As a direct consequence of the formation of the Zagros mountains, a downward depression appeared along the eastern part of the Arabian plate forming what is now the sea floor of the Arabian Gulf. In the present day this represents a very shallow sea with an average depth of only 35 m and a maximum depth of 100 m (Basson et al., 1977). The only connection to the open ocean is through the Strait of Hormuz, a narrow passage between Oman and Iran, which opens into the Arabian Sea and thence to the Indian Ocean. The physical constriction at the mouth of the Gulf results in very little exchange of water between the inner Gulf and the Indian Ocean. The Gulf may have a water retention time of hundreds of years (Hunter, 1982).

Sea levels have risen and fallen with respect to the present day chart datum a number of times throughout geological history. As a result, the fossilised remains of marine organisms such as coral, seagrasses and associated flora and fauna can be found in the rocky outcrops (jebels) on the islands. Doornkamp et al (1980) provides a detailed description of sea level changes and their impact on the marine environment and biota. The principal physical effects associated with sea level changes were alterations in the movement and type of substrate (soil or sediment) around the main land mass of Bahrain.

The area south of the Saudi-Bahrain Causeway and Fasht Adhm in particular has experienced periods of inundation and dessication due to the presence of a ridge of rock which forms the base of the Fasht and upon which the Causeway is built. This is the Bahrain ridge, an anticline running from Dhahran across the northern end of the main island to Qatar. This ridge is a north-west to south-east oriented structure which is a result of the Zagros mountain-building period, and has continued to rise until recently. This forms a natural barrier to rising sea levels. Since the last inundation of the area to the south-west and south-east of the main island there has been a reduction in the flow of subaerial, quartz sediment with wind-blown, sedimentary material being reduced to silt components alone.

Since then the island of Bahrain has experienced a net loss of land-based sediments in a south-easterly and easterly direction where they have been stored and reworked offshore. The southern end of the island is now accreting and prograding due to the effects of the northerly winds and wind-induced surface currents.

Bahrain' s territorial waters are generally shallow and average water depths rarely exceed 8 m . The maximum depth recorded in territorial waters during this study was 32 m off the southwest coast of the main island of Bahrain. Depths in the main channel which runs north-south off the east coast of Muharraq reach 30m. Admiralty charts 1501, 1502, 2501,5001, 5002 and 6001 were available at the time of the study. Figure 2.1 provides a coarse representation of the bathymetry within the study area.

In the present day environment high temperatures and salinities have created a carbonate and evaporite sedimentary component with considerable sediment transportation by currents. Many areas of young, shallow marine sediments now exist with progradation due to intertidal deposition over sand banks and shoals which are becoming sites of mineral deposits (gypsum, anhydrite, dolomite etc.). The marine environment is becoming dominated by marine (carbonate) rather than subaerial (quartzose) sedimentation, but with some interaction due to winds. Most of the carbonate sands and muds consist of foraminiferal, algal, coralline, bivalve, gastropod and oolitic deposits in various proportions. Many exist as loose sediments deposited from currents, others are bound by black mangrove (Avicennia marina) or seagrass or are burrowed by crabs. Some are represented by stromatolitic formations (carbonate sediments compacted by the binding action of algae).

Approaching the coastline, the effects of high temperatures and salinities reduce the biogenic component of the sediments and increase the inorganic component. Surface waters can become saturated with calcium carbonate encouraging the precipitation of aragonite which eventually converts to calcite. This is probably the origin of much of the local beach-rock or 'Faroush' which is a common component of the intertidal and parts of the subtidal (Doornkamp et al, 1980).

Salinity in the Arabian Gulf is generally high as a result of high temperatures and consequent evaporation. In Kuwait, mean monthly salinities rarely rise above 38 ppt due to the effects of freshwater flowing out of the Shatt al-Arab (Jones, 1986a). High salinity levels can be found in sheltered areas away from the open sea with 60 ppt recorded for the western end of Kuwait Bay (Jones, 1986b).

Surface salinities throughout the Gulf are generally between 37-43 ppt but vary in the actual location of the salinity fronts from summer to winter (Reynolds, 1993). The Bay of Bahrain and Dawhat Salwah stand out with regard to their extreme salinity as a result of their enclosed nature and the sill running across the northern edge of these embayments.

Sea temperatures and salinities in Bahrain waters are closely related as a direct result of the climate and the shallow and partially land-locked nature of this region (Vousden and Price, 1985). In this area of the Arabian Gulf there is very little inflow of fresh water due to the arid nature of the surrounding land masses. This lack of fresh water coupled with high temperatures and consequent evaporation of water content results in a sea that is very saline in comparison to the rest of the world's seas and oceans. The net current circulation pattern, in conjunction with reduced water exchange in the Bay of Bahrain and natural evaporation due to high (summer) temperatures, creates a considerably higher salinity to the south of Bahrain and into Dawhat Salwah than is found elsewhere in the Arabian Gulf (Basson et al., 1977; Price et al., 1984). Where shallow lagoons or long stretches of shallow waters are found, temperatures and salinities can reach as high as 40-45^{0} C and 60-70 ppt respectively.

Price et al (1984) report mean salinities of 43-45 parts per thousand (ppt) on the east coast of Bahrain and 50-57 ppt on the west coast. They conclude that surface salinities do not follow an obvious seasonal pattern but show appreciable spatial variation. Vousden (1985b) proposes that salinity fluctuations are directly related to tidal currents and presents figures showing that the difference in salinity values between the ebb and flow tide increases from the north east to the south and west of the island.

While salinity in the open sea appears to exert little influence on the distribution of marine organisms, its variability in coastal waters may be of great significance (Kinne, 1971). The restricting effects of salinity on biota in the Gulf has been discussed by Basson et al (1977) and Price (1982).

Winter surface temperatures (late February) throughout the Gulf increase from 15^{0} C off Kuwait moving southeast down the Gulf past Saudi Arabia (16-17^{0} C) along the coast of Qatar and the United Arab Emirates (18-20^{0} C) to reach 21^{0} C at the Strait of Hormuz (Reynolds, 1993). Early Summer temperatures (early June) show a similar gradient down the Gulf but with higher temperatures starting at 24-25^{0} C off Kuwait and northern Saudi Arabia and rising to 29-30^{0} C at the Strait of Hormuz.

Jones (1986a) identifies air temperature extremes on the shores of Kuwait from below 0^{0} C to above 50^{0} C while mean monthly sea temperatures vary from 14^{0} C in January to 30^{0} C between June and September. Basson et al (1977) note that high air temperatures and insolation levels are characteristic features of the Gulf.

Although thermal ranges are less in the island climate of Bahrain than on the mainland of Saudi Arabia, maximum air temperatures regularly exceed 37° C in summer and minimum values fall to below 16° C. Price et al (1984) recorded large seasonal variations in water temperature around Bahrain (13° C in January to 35.5° C in September).

Extremes in temperature (high and low) and their effects on species survival have been recorded in other parts of the Gulf (Enomoto, 1971; Price, 1979).

Within the Gulf, tidal regimes are complex, consisting of both diurnal and semi-diurnal components (Sugden, 1963; Hunter, 1982). Tidal ranges in Kuwait vary from 4 m in the north to less than 2m in the south and both diurnal and semi-diurnal tides occur along Kuwait's coastline (Jones, 1986a). Bahrain is located close to the amphidromic point of the diurnal tides so that, unlike the northern and southern end of the Gulf, Bahrain experiences semi-diurnal tides. Jones and Clayton (1983) have noted that in Kuwait the lowest spring tides of the year always occur at night in the summer and during the day in winter. The net circulation around Bahrain is documented as being clockwise (Sugden, 1963). This is a result of shallower water depths in the strait between Bahrain and Qatar as well as phase differences within the tides in the Gulf.

Water moving from the Gulf into the Bay of Bahrain and Dawhat Salwah encounters an obstruction in the form of a sill running almost continuously from the east coast of Saudi Arabia to the west coast of Qatar. This sill passes across the northern end of Bahrain and is generally less than 5 m deep. The net effect of the presence of the sill is to cause a heavy damping of tidal movement resulting in a considerably reduced tidal range to the south (Price et al, 1984; Vousden, pers. obs.). The Saudi-Bahrain Causeway was completed in 1988 and runs along the sill, crossing the Bay of Bahrain from the west coast of Bahrain to the east coast of Saudi Arabia, a distance of some 25 kilometres. Over some of this distance the structure is solid embankment and the central feature of the Causeway is an artificial island. However, water flow in and out of the Bay of Bahrain and Dawhat Salwah remains unimpeded as a substantial section of the structure on either side of the central island is made up of bridge sections.

On the west coast, the situation is complicated by the presence of deep water (32 m +) south of the restricting sill. This acts as an `energy' sink and consequently the higher water velocities (approximately 3-4 knots) experienced within the immediate vicinity of the Saudi-Bahrain Causeway are considerably reduced (< 0.5 knots) when they encounter this deeper water 5-6 kms further south (Price et al., 1984: Vousden, water quality data collected for State of Bahrain, 1983-1989). This effects both the salinity regime and habitat distribution of this coastline.

This pattern is yet further complicated by the effects of local weather conditions. Local low pressure atmospheric conditions during the summer months maintain water levels approximately 20 cm above those in the winter. Also there is some evidence that south-west monsoons over the Indian Ocean increase water levels in the Gulf by as much as 50 cm (State of Bahrain Meteorological Office and Hydrographic Survey Section, pers. comm.).

Local wind conditions may have a significant effect on tides. A northerly wind of 18 knots blowing over a 24 h period can increase the high water level north of the sill by 50-70 cm and to the south by as much as 100-160 cm due to water accumulation in the bay (State of Bahrain, Hydrographic Survey Department, pers. comm.). This increase in high water level is enhanced to the south due to the funnelling effect of the Dawhat Salwah embayment.

Water column nutrient levels are low around Bahrain favouring the development of corals (W.S. Atkins and Partners., 1985). Chlorophyll levels in the water column are also low especially offshore and primary productivity is mostly benthic rather than phytoplanktonic (Price et al., 1984; Vousden and Price, 1985; Vousden, 1985b). Very high levels of chlorophyll have been recorded from the surface of intertidal muds (Price et al., 1984) due to the presence of cyanobacteria and diatomaceous algae.

Suspended sediment levels vary with position, tide and particularly wind regime, but are generally considered to be high with respect to their influence on the biological environment (Price et al., 1984).

Winds are predominantly northerly and north-westerly for most of the year although there is a south-easterly component (Bahrain Meteorological Department). This domination by winds from the north influences the marine environment by virtue of the wave action created. Wind-induced waves from the open Gulf will break on or disturb shallow coastal areas facing north, northwest or northeast (e.g. Fasht Jarim, Fasht Jaradah, Muharraq, northern Hawar - see figure 1.1) creating a relatively high-energy environment. High sediment loads result further offshore and clean, scoured beaches occur on the coast. These winds are also important for their role in creating the existing coastline (Doornkamp et al, 1980).

Anthropogenic Influences on the Physical Environment

The main concentration of industry and hence the principal sources of industrial impact to the marine environment around Bahrain is mainly located in the Sitra area on the east coast. The principal industries discharging into the marine environment are BALEXCO (Bahrain Aluminium Extrusion Company), the petrochemical refinery of BAPCO (Bahrain Petroleum Company) and GPIC (Gulf Petrochemical Industries). BAPCO is a major source of hydrocarbon discharge on the east coast of Bahrain.

Oil wastes from garages and machine shops on the island are collected by road tankers and find their way into the sea. Despite laws to the contrary, these road tankers are forced to discharge their loads on the beaches as the sewage reception facilities provided by the Water Pollution Control Centre (WPCC) at Sitra cannot handle impurities such as oil and other chemicals which are commonly mixed into the tanker load. The main areas for dumping are once again in the Sitra region and immediately south where much of the harmful liquid ends up in the intertidal zone. Large-scale oil-spills within the Gulf region are an inevitable hazard in an oil-producing area. On a large scale these can have disastrous effects on the marine environment (Gerlach, 1976; Ferguson Wood and Johannes, 1975; Clark, 1982, Price and Robinson, 1993) and require detailed planning on the part of oil-spill response teams to alleviate the worst effects on the environment. Other sources of oil discharge into the marine environment include tanker ballast and small-scale spills from loading and off-loading facilities. A $1.2 million scheme for improving the handling of tanker ballast and washings at Bahrain terminals has already been approved but is awaiting the necessary finance. This will consist of proper shore-based reception facilities rather than using the now-antiquated floating slops tanker based near the ship repair yard.

In 1991, large quantities of oil found its way into the marine environment of the Gulf as a result of the Gulf War. Much has been done to monitor the effects of what is the world's biggest oil spill (see Price and Robinson, 1993). One of the principal drawbacks to such monitoring was the lack of pre-war baseline data. Around Bahrain hydrocarbons and trace metals in sediments and bivalve tissues had been monitored for several years prior to 1991. Fowler et al (1993) compared pre- and post-war data for Askar off the east coast of Bahrain and found that petroleum concentrations in both sediments and bivalve tissue were lower post-war than had been recorded in previous years. They relate this to reduced chronic inputs from tanker traffic and de-ballasting between late 1990 and 1991. Bahrain's Environmental Protection Technical Secretariat (EPTS) monitors industrial discharges on a quarterly basis to detect any obvious signs of environment degradation such as high BOD's or low dissolved oxygen levels.

On the positive side, the discharge of untreated liquid wastes into the sea has fallen considerably over the last few years due to expansion and modernisation of the sewage system, the commissioning of the Tubli Bay Water Pollution Control Centre and improvements in the operation of the refinery. There are plans presently under consideration for the up-grading of the refinery to handle increased consumption of crude oil and to expand the production of petroleum derivatives for marketing. These plans include the potential for improving the effluent processing system to reduce the outfall. This would not mean a reduction in the amount of hydrocarbons or other contaminants discharged, but it would make it feasible to introduce biological treatment ponds prior to discharge to the sea, a situation which is not practical at present due to the large volumes of effluent being discharged.

The effects of coastal development represent another significant problem to the marine environment of Bahrain. Water turbidity related to suspended sediment levels is naturally high due to wave action and the shallow nature of the coastal waters. The increasing incidence of reclamation and dredging around the island is creating an additional stress on the marine biota. The most immediate impact other than the direct destruction of the coastline and seabed is the outslip of fine sediments both at the cutter-head of the dredger and at the outfall end of the delivery pipe. Thick plumes of sediment are noticeable at the site of any dredging activity around Bahrain, often stretching several kms down current. At the reclamation site the material pumped ashore from the dredger is in the form of slurry with more water by volume than solids. This water drains off the reclamation site and returns to the sea carrying with it much of the finer sediment still in suspension. As a consequence, the shallow intertidal becomes smothered in anoxic silt. Offshore benthic communities become choked by the fine, clogging silts and primary productivity is reduced drastically by the high sediment loads and water turbidities. There is a continuous loss of highly productive intertidal flats around the coast of Bahrain due to these reclamation projects. A number of local dredging projects have been monitored over the past few years (Vousden, 1985b) to assess and advise on reduction of their impact on the environment.

The dumping of solid waste materials also constitutes a large problem in Bahrain especially in areas where people are working on or from the beach or using it for recreation. Both individuals and companies use the shoreline for dumping solid waste. This waste is both unsightly and is a health hazard. Much of the rubbish contains broken glass, nails, sharp wire and toxic paints or other chemicals which are harmful to marine life and to humans who use the beach for pleasure or work. Such waste matter attracts vermin such as rats and cockroaches. The rubbish can also create an obstacle during clean-up operations following an oil-spill by clogging and jamming beach-cleaning machines.

Various desalination plants operate in the area including the reverse osmosis plants at Ras Abu Jarjur and Sitra, the latter being linked to the power station. Both of these discharge water with temperatures and salinities above ambient levels.

Much work has already been done on identifying the principal sources of pollution and the effects of coastal development in Bahrain. The geology of the area is well-known and understood. Water quality is typical for a shallow, sub-tropical coastal area and the wind regime and its effects on the coastline are also well-documented. It is evident, however, that the extreme seasonal fluctuations in water temperature and significant spatial variations in salinity are two of the most important physical factors effecting the distribution of intertidal and subtidal habitat types and biological communities around Bahrain. Previous work has recorded large seasonal fluctuations in water temperature. Spatial variations in salinity have been noted but are not yet properly understood. Although they do not seem to follow a seasonal pattern it is possible that they may be related to tidal fluxes. There is limited data on tidal current movements around the islands and the relationship of these currents to salinity fluxes.

The aim of the work presented in this chapter is to collect and analyse data in order to define the seasonal variations in temperature and to understand the cause of the spatial variations in salinity. Water temperature data is necessary throughout an annual cycle. Salinity measurements are needed from geographically different sites around Bahrain and at different stages of the tide. In order to seek a clear relationship between tidal cycle and salinity flux, data on tidal velocity and direction along with salinity measurements is necessary over several tidal cycles and from at least two geographically distinct sites.

Because of equipment limitations only surface salinities were collected in the earlier stages of the study. After March 1988 it was possible to collect subsurface data with an electronic probe. Salinity profiles have been collected in 1988-89 at a number of selected sites (see methods).

This chapter contains data from investigations made by the author during the period 1983 to 1989 in conjunction with a review of relevant available literature and information provided by the Hydrographic Section of the Survey Directorate, Ministry of Housing, State of Bahrain. Also included are the records taken during the Marine Habitat Survey.

METHODS

Temperature and salinity data was recorded between July 1985 and April 1989 and is presented in appendix 2.1 along with site positions. UTM coordinates can be identified on the map included as Volume 2, figure 1. Data was collected either by means of a Hydrolab Surveyor (which also records depth) or by mercury thermometer (taking the mean from two separate thermometers) and a temperature-compensated refractometer (American Optical Corporation). Temperatures were recorded to 0.5^0 C and salinities to 0.5 ppt (parts per thousand). In view of limited boat time and constraints on the amount of field work which could be scheduled, temperature and salinity data was collected on all field trips to the coast or offshore. In collecting this data, consideration was always given to the need for good, all-round coverage of the coastal waters on a seasonal basis and with respect to tidal state. Priority was also given to areas where there were few or no previous records (e.g. Hawar, Khawr Fasht, south of Askar, the offshore islands and the western and southern offshore waters). Information on winds was provided by the Meteorological Section of the Civil Aviation Directorate.

Vertical salinity profile data was collected to assist in the interpretation of the spatial salinity fluctuations. Sites were chosen to provide a representative example of the different salinity regimes noted around the coast and particularly in relation to the geographical sectors allocated to the surface salinity values from the initial data (see Results).

Tidal data has been taken from tide tables provided by the Hydrographic Section of the Survey Directorate. Current meter data was collected using Aanderaa RCM4 current meters which record time, temperature, pressure, current direction, current velocity and salinity. Recording intervals were set at 30 min. Experience with hand-held current meters in this area (Price et al, 1984) confirmed this interval as providing sufficient data on changes in the measured parameters without producing an excessive and unnecessary number of data points. The sites for locating the current meters (see figure 2.2) were chosen to display a gradual increase in salinity gradient through a tidal cycle moving north to south along the coast of Bahrain. Originally four current meters were deployed. Regrettably one off Fasht Dibal was never relocated and the second fell into disputed waters outside the jurisdiction of the State of Bahrain due to a disagreement with a neighbouring country over territorial waters.

Air temperature data is missing for June and surface water temperature information in June is limited to 1 data point as the author was out of the field area every year during that month.

Sublittoral fringe water temperatures and salinity values are absent for March, May, July and December. The collection of this data had not originally been planned so a schedule for annual data collection was not designed for this site. The data has been included as incidental but nonetheless useful material.

RESULTS

Salinity

Surface (< 1.0 m below surface) salinity values taken around Bahrain between 1985 -1989 are presented in appendix 2.1. Table 2.1 lists average salinity values (calculated from the records in appendix 2.1) together with maxima, minima and range of values for 8 sectors around Bahrain. These sectors (figure 2.3) have been assigned on the basis of natural physical divisions such as the sill which runs from Saudi Arabia through Bahrain to Qatar and the restrictions caused by island groups and deeper waters. Figure 2.3 shows the mean, maximum and minimum salinity recorded in each sector.

Between 1985 and 1989, average surface salinities are between 43.7 ppt and 57.3 ppt with minimum and maximum values of 41.5 ppt and 65 ppt respectively. The range of salinity values recorded in any one sector varies geographically around the study area. The smallest range (4.0 ppt) is found in the northeast of the study area toward the open Gulf (sector 1 in figure 2.3). The greatest range (17 ppt) is found in sector 6 in the shallow area between Mashtan, Ras al Barr and Hawar.

Table 2.2 gives salinity values recorded at Galali Beach (Northwest of Muharraq - see figure 1.1) in the sublittoral fringe (>0.5 metres water depth) at low water. Salinity values between January and April do not rise above 46 ppt. By late August salinity values are reaching 50 ppt and remain above 49.5 ppt through to late November when maximum values reach 53 ppt. There is no data recorded for December, March, May or June.

In areas of restricted water flow such as tidal pools, bays or lagoons, higher salinity values are often recorded. 80 ppt was noted at high tide over sabkha flats in the Hawar Archipelago and 70 ppt within the lagoon at Ras Al Mumtallah (figure 1.1).

Appendix 2.2 gives the results of the vertical salinity profiles taken throughout the study area and these are summarised as table 2.3. The data is arranged by sector (see figure 2.3). There is a close relationship between salinity gradient and tidal state with the smallest gradients tending to occur at low or high tide and the largest gradients at mid tide when the tide is ebbing or flooding. The largest salinity gradient of 6.6 ppt is recorded at Middle Shoal in sector 6 (see figures 1.1 and 2.3). Small gradients are recorded at a number of sites and some of these are reversed where salinity is higher at the surface than it is near the seabed (e.g. West al Hul, 880803 = -0.3 ppt). Some sites show multiple stratification rises and falls several times throughout a vertical profile but never by more than 0.5 ppt.

Temperature

Appendix 2.1 lists surface (< 1 m below surface) temperature data for Bahrain waters collected between 1985 and 1989. Table 2.4 gives average monthly surface seawater temperatures around Bahrain as calculated from appendix 2.1. Data for Saudi Arabia (McCain et al, 1993) collected at 1.5 m below surface and for Kuwait collected in the top 50 cm (Jones, 1986b) are included for comparison. Figure 2.4 gives a plot of mean monthly surface sea temperatures for Bahrain compared to Saudi Arabia and Kuwait. Data from McCain et al (1993) was used to compare Bahrain mean monthly sea temperatures with values for Saudi Arabia. Although McCain et al only provide mean monthly sea temperatures for June through to December they provide a plot of mean daily sea temperatures from which mean monthly sea temperatures can be estimated quite accurately. Minimum surface temperature values for Bahrain are recorded in January (16.4^0 C) and February (13.3^0 C) with maximum values found in August (39^0 C) and September (37^0 C). Mean surface temperatures are generally low between December and April (between 19.9^0 - 21.2^0 C) and peak in August and September (34.1^0 - 36^0 C). Mean temperature data for June and September are unreliable (N=1; N=2) but would seem to conform to the annual pattern.

Mean surface temperatures for Saudi show a peak in July (31.9^0 C) and August (32.4 C) and fall to a minimum in January (15^0 C). Kuwait mean surface water temperatures are at their lowest in December (16^0 C) and January (14^0 C) and reach a maximum (30^0 C) between June and September.

Mean monthly sea temperatures in the sublittoral fringe (>0.5 m water depth) at the Galali site (calculated from table 2.2) are shown in figure 2.5. Peak temperatures are recorded between August and October and are greater than 30^0 C with a maximum value of 43^0 C in late August. Mean values for January and February are less than 22^0 C. There is no data recorded for December, March, May June or July.

Table 2.5 presents some average monthly air temperature values and ranges for Bahrain. Although limited data was collected for air temperature, this data shows that sea temperatures closely reflect air temperatures.

Tides and Currents

Table 2.6 presents various tidal levels for sites (see figure 2.2 for locations) around Bahrain. This shows that sites on the north-east coast of Bahrain (e.g. Mina Sulman, Mina Manama, Port of Sitra) have a greater tidal range than those sites situated south of Fasht al Adhm and on the west coast of the main island(Um Jalid, Zallaq, Hawar). This confirms previous observations by Price et al (1984). A 2 m spring tide in the Gulf is reduced to less than 0.3 m in Dawhat Salwah (State of Bahrain Hydrographic Survey Section, pers. comm. and Government Tide Tables).

A study of the Government Tide Tables reveals that the lowest spring tides occur during the night in the hot summer months and during the day in the cold winter months. Furthermore, daily tidal ranges are smaller in the summer (1.5 m maximum in the north).

Tidal current data were collected from two sites (see figure 2.2), south west of Mashtan at 25.46.10N : 50.38.51E (see appendix 2.3) and West al Hul at 25.42.51N : 50.33.45E (see appendix 2.4) during the period of 8 - 13 March 1989. The area south west of Mashtan was selected for its large salinity gradient and the area west of al Hul for its high salinity values and position at the south west end of the island where current velocities are lower (Vousden, pers. obs.).

Figures 2.6 - 2.10 show current meter data plotted against tidal cycle for South West Mashtan from 0010 h to 2340 h on 9th March, 1989 collected at 30 minute intervals. Current velocity rises rapidly in the first 2.5 h (see figure 2.6) and reaches a maximum (48 cm sec^{-1}) at 0140 h. Velocity then falls until it reaches slack water between 0540 and 0610 h. During this period, current direction remains north northeasterly between 16^0 and 30^0 magnetic (see figure 2.7). After slack water there is another rise and fall in current velocity between 0640 h and 1110 h, peaking at 47 cm sec^{-1} and reaching slack water at 1210 h. During this second period current direction remains south southwesterly between 193^0 and 213^0 magnetic. Over the next 11 h the cycle repeats itself with two more bursts of current activity running in opposite directions. These four discrete cells of current movement constitute two full tidal cycles throughout a 24 h period. North northeasterly flows constitute an ebb tide when water is moving from of the enclosed Bay of Bahrain and Dahwat Salwah out into the open Gulf. South southwesterly flows represent the returning water on the flood tide. These periods of ebb and flood tide separated by slack water have been marked on figures 2.6 and 2.7.

Figure 2.8 represents salinity fluctuations for 9th March, 1989. Salinity rises rapidly with the ebbing tide reaching maximum values (53.9 ppt) just before low water slack. As the tide floods, salinity starts to fall rapidly and reaches a minimum (48.5 ppt) at high water slack. This cycle repeats itself over the next 11 h.

Figure 2.9 represents temperature fluctuations with time (and therefore tidal movement) for 9th March, 1989. Temperature falls rapidly with the ebbing tide with minimum temperature (16.9^0 C) recorded just before low water slack. Temperature starts to rise with the flooding tide and reaches a maximum (19.8^0 C) at high water slack.

Temperature is plotted against salinity in figure 2.10. An inverse relationship is clear with temperature falling as salinity rises.

Figures 2.11 - 2.15 show current data plotted against tidal cycle for West al Hul from 0010 h to 2340 h on 9th March, 1989 collected at 30 min intervals. Tidal velocities at this position (see figure 2.11) are lower than at south west Mashtan (figure 2.6) and the pattern of events is not so clearly defined. Current direction varies constantly in a clockwise rotation with tidal cycle (figure 2.12). Salinity is fluctuating with time, falling over the periods defined as A and C (see figure 2.13) and rising during the period defined as B. The same labels have been applied to the same time periods in figures 2.11 - 2.14.

During period A, where salinity is falling, current velocity doubles but is still minimal (from 4.2 cm sec^{-1} to 8.4 cm sec^{-1}). Current direction is between 83^0 and 159^0 magnetic (east to south southeast). During period B, salinity rises sharply with current velocity and current direction is now between 330^0 and 19^0 magnetic (north northwest to north northeast). Period C shows a sharp fall in salinity again which corresponds to an increase in current velocity with current direction lying between 73^0 and 103^0 magnetic (ENE toESE).

Water temperature (figure 2.14) is rising on periods A and C when current velocities are increasing and current direction is principally to the east and southeast. Temperature is falling during period B when velocity is increasing with current running to the north. Once again, the values for temperature suggest an inverse relationship to salinity which is confirmed in figure 2.15 where temperature is plotted against salinity for the 9th March, 1989 at West al Hul.

Figures 2.16 and 2.17 show the overall rise and fall in salinity values throughout the study area with the ebb and flow of the tide. These have been calculated from the maximum and minimum salinity values presented in figure 2.3 along with data from the Tidal stream Atlas provided by the Hydrographic Section of the Ministry of Housing's Survey Directorate and the knowledge of the relationship between tidal flux and salinity fluctuations provided by the current meter data and vertical salinity profiles.

Main Sources of Industrial Pollution

Table 2.7 lists types of discharges and some of the outfall rates for the principal industries located in the Sitra area. BALEXCO discharges approximately 170 tonnes of aluminium oxide sludge into the sea per annum, while BAPCO pumps some 5-600 tonnes per annum of various by-products of the refinery process out to sea carried in a cooling water discharge of over 600,000 cubic metres per day. The International Atomic Energy Authority has studied this discharge and its effect on the local marine environment (IAEA, 1985). Their report shows that the outfall from BAPCO is effecting the benthic environment with heavy metals and hydrocarbons reported in high concentrations several kilometres south of the discharge. Tar-ball counts for the beaches around Bahrain were found to be higher than any other part of the Gulf. Analysis of seawater, bivalves and surface sediments all indicated the presence of hydrocarbon contamination localised mainly around the outfall and downstream from BAPCO.

DISCUSSION

The aim of this section of the study was to (i) identify the extremes in water temperature noticed by previous workers and to relate these extremes to the changing seasons through the year, (ii) identify the spatial variations in salinity also observed by previous workers and to attempt to relate this to fluctuations in water movement, specifically tidal cycle. The results of the analysis of the data reveal that tidal cycle plays a major role in salinity fluctuations and, to a lesser extent, in temperature variations throughout the study area. In the case of temperature, the tidal variations are overshadowed by the much larger seasonal variations.

Fluctuations in salinity generally increase in magnitude southward down the coast towards Dawhat Salwah. However, sector seven shows a reduced range (7ppt) in comparison to sector five (11.1 ppt) and sector eight (11 ppt) to the north and south respectively. The fact that these fluctuations are often temporal at the same site and even on the same day suggests the presence of a tidal relationship.

An analysis of the vertical salinity profiles against tidal state further supports this hypothesis. The greatest vertical gradients in salinity occur on full flood or full ebb tide when there would be little opportunity for mixing. At reduced tidal velocities, approaching and during high and low water, there is more opportunity for mixing, especially in such shallow waters.

The production of haloclines on a flood tide is to be expected in an area which shows such large spatial variations in salinity. However, it is unusual that there should be such clear gradients on an ebb tide. On a flood tide, incoming water from the open Gulf would be less saline and would rise over the denser, more saline water forming a halocline and hence a salinity gradient. On an ebb tide, higher salinity water from Dawhat Salwah would flow out into the open Gulf. This high salinity water will attempt to flow over the low salinity water because of frictional effects between the lower end of the water column and the seabed. As the higher salinity water is more dense it collapses through the low salinity water and mixing occurs. This system is the reverse of the situation found at the mouth of fresh water estuaries where low salinity water flowing out on an ebb tide forms a salt wedge in the mouth of the estuary but is not reversed and sustained on a rising tide. The situation around Bahrain is more complicated and needs regular and repeated profiling at selected sites over 24 h periods to progress any further with a detailed explanation.

The high salinity records for the sublittoral fringe at Galali Beach with fluctuations of between 41 and 55 ppt

The high salinity records for the sublittoral fringe at Galali Beach with fluctuations of between 41 and 55 ppt are unlikely to be linked to tidal flux in such shallow waters, considering the proximity to the open Gulf. These salinity fluctuations are more likely to be a result of the shallow nature of the water and high insolation rates producing evaporation. Data given in 2.4 shows that shallow water sublittoral fringe salinities are seasonal. Records of high salinity values (50 ppt) begin in August and correspond to high temperature measurements (43^0 C). Salinity values remain high through to late November, two weeks after coastal water temperatures have started to fall.

Tables 2.4 and 2.5 show that there is insufficient data collected on offshore sea temperature in June and no data for air temperatures for the months of January and June. Although this does not interfere with the identification of an overall trend in seasonal temperature fluctuations it does represent a limitation to the data analyses and prevents an accurate prediction of mean temperatures for certain times of the year.

Rapid air temperature changes occur within the region on a daily and seasonal basis. The seasonal air temperature changes are reflected within the shallow seas (figure 2.17). The lack of deep water means that there is very little damping effect on these changes and the water column is generally well-mixed by the frequent strong winds for which the region is renowned. Water temperature closely parallels air temperature so that water temperature fluctuations are extreme and place considerable stress on marine organisms.

In the winter months, sea temperatures around Bahrain drop as low as 13.3^0 C while summer temperatures can rise above 39^0 C offshore and as high as 43^0 C in the shallow coastal waters (table 2.2). These extremes in temperature present tolerance limitations for many organisms, especially in the intertidal zone. These may be ameliorated by the damping effects of the tidal regimes.

Two seasons of summer and winter are identifiable from the temperature data and approximate to the periods May to October and November to April respectively. In between these two seasons is a very brief transition period of a week or two occurring in April and early November. Summer is a period of stable, hot, humid weather broken by a 'Shamal' or strong northerly wind in June-July. Winter is a period of lower temperatures which are more changeable and less stable. The seasonal 'Shamal' winds from the north also affect sea temperatures, especially in the nearshore areas, with values as low as 0^0 C having been recorded around Qatar in 1964 (Shin, 1976). Shallow water temperatures in the sublittoral fringe follow the same seasonal trends (within the limitations of the data). Temperatures rise from 27.5^0 C (April) to 43^0 C (August) and remain high until mid November when they drop to 23^0 C.

The results from the two current meters confirm the suspected relationship between tidal cycle and salinity fluctuations. This relationship is clearly stronger on the south-east coast where tidal current velocities are stronger and current direction is definitive (south west Mashtan). The data for West al Hul was not so conclusive, almost certainly reflecting the low current velocities, the very small tidal ranges found to the south west of the main island and the constantly changing current direction.

It is regrettable that the data from the two northerly sites was lost with the meters as this would have hopefully confirmed that smaller salinity fluxes relative to tidal cycle are experienced nearer the open Gulf where lower salinity water is having a more prolonged effect. However, despite the loss of data from the two northerly current meters, salinity records from the north and east of the island (see table 2.1 and figure 2.3) along with the results from the vertical salinity profiles confirm that there is a smaller gradient between minimum and maximum salinities with tidal period at the north and northeastern edge of the study area reflecting its proximity to open Gulf Waters.

relationship between salinity and temperature. For the SW Mashtan meter this may be explained by the shallow nature of the water north of the meter and the deeper water to the south. Water moving past the meter on a flood tide will have been heated up in the shallows thereby raising the temperature. The water flowing past the meter on an ebb tide will have come from the deeper water mass to the south and may well have stratified so that colder water is passing by the temperature sensor. This may also be true for the meter at West al Hul as water depths to the west, north and east were shallow compared to those to the immediate south (see figure 2.1). Lower temperatures for this meter were only recorded on northerly currents.

Figures 2.16 and 2.17 shows the salinity fluctuations with tidal flow around Bahrain. On a flood tide, a southerly flow carries less saline water in from the open Gulf reducing salinities. On an ebb tide the reverse occurs and more saline water is carried out of Dawhat Salwah into the waters around Bahrain. On the east coast this produces a salinity fluctuation of 4 ppt to the north of Fasht al Adhm rising to 11 ppt to the west of Bahrain and reaching an extreme of 17 ppt difference between Ras Al Bar and Hawar. Salinities therefore fluctuate quite considerably over a tidal cycle on the east coast ranging from 45 ppt to 62 ppt in one tidal period between Ras al Barr and Hawar. On the west coast, salinity fluctuations around Khawr Fasht in the north and to the south west of the main island are in the order of 11 ppt (see figure 2.3). Due west of the main island between the Causeway and down beyond Zallaq salinity fluctuations are only 7 ppt.

Tides within the Gulf are complex and vary dramatically between the centre of the Gulf and the northern and southern ends. In the shallow waters around Bahrain, tidal height and periodicity can be effected quite significantly by barometric pressure and by winds. The maximum annual tidal range is around 2 m in the north with a significantly reduced range as one moves south (< 30 cm at Ras al Barr). The lowest spring tides occur during the night in the summer and during the day in the winter. This is the same pattern as has been found in Kuwait by Jones and Clayton (1983). Daily tidal ranges around Bahrain are smaller in the summer which reduces the area of intertidal which will be exposed to summer insolation. It is probable that tidal regime is directly effecting the distribution of marine habitats around Bahrain.

Price et al (1984) noted spatial differences in salinity values but did not relate these differences to tidal cycle and the restrictive nature of specific geographical features. Salinities are generally higher to the south and west of Bahrain as a result of the combination of low tidal velocities, shallow waters and evaporation. Furthermore, there are relatively large fluctuations in salinity over a full tidal cycle to the south and west of Bahrain. Salinities to the north and particularly the northeast of the study area are generally lower reflecting their proximity to the open Gulf and do not alter so dramatically with tidal cycle. This confirms earlier observations by Vousden (1985b).

Tables 2.1 and 2.2 along with figure 2.3 show that salinities in this area of the Gulf and especially to the south of Bahrain are some of the highest open water salinities in the world. Edwards (1987) comments that 'The waters of the Red Sea are the saltiest of all the worlds oceans exceeding even the waters of the Arabian Gulf'. However, he later states that 'Over the coastal flats of the Arabian Gulf, in water less than 10 m deep, salinities of up to 60 ppt have been measured' and quotes salinities for the Red Sea in the order of 38-40 ppt (parts per thousand) with a maximum of 42.5 ppt in the Gulf of Suez. These salinities are substantially lower than those recorded for the Gulf during the course of the present study which compares well with previous records (Jones et al, 1978; Price et al, 1984; Atkins and Partners., 1985; Jones, 1985; Vousden, 1985b and Vousden and Price, 1985).

Air temperatures are more extreme in Kuwait than in Bahrain. Jones, (1986a) notes that intertidal organisms on the coast of Kuwait may have to withstand frost in January and air temperatures of up to 55^0 C in July-September. Figure 2.4 shows that the highest mean monthly sea temperatures in Kuwait (30^0 C) do not reach the values found around the coast of Bahrain (36^0 C). However, mean winter sea temperatures for Kuwait are the values found around the coast of Bahrain (36^0 C). However, mean winter sea temperatures for Kuwait are more extreme dropping to 14^0 C as opposed to around 20^0 C for Bahrain. However, individual records for Bahrain frequently show January and February sea temperatures below 18^0 C with a minimum recorded value of 13.3^0 C (table 2.4).

Mean sea temperature records for Saudi Arabia (McCain et al, 1993) are very similar to Bahrain, but again *do not quite reach the summer extremes* (32.4^0 C for Saudi Arabia) recorded for Bahrain and fall lower (15^0 C) in the winter months. Basson et al (1977) recorded coastal water temperatures for Saudi Arabia ranging from 10^0 C in winter to 35^0 C in summer which is more typical of records for Bahrain.

Average salinity values in Kuwaiti waters are much lower than for Bahrain because of the seasonal input of fresh water from the Shatt al-Arab. As a result of this freshwater discharge mean monthly salinities for Kuwait Bay vary seasonally from 33.5 ppt in January to just over 40 ppt in September (Jones, 1986a).

Salinities along the open coast of Saudi Arabia range from 38.5 ppt to 41 ppt but are much higher in the Gulf of Salwah immediately south of Bahrain where they range from 55 ppt adjacent to Bahrain to > 70 ppt in the southern extremity of the Bay (Basson et al, 1977).

High water temperatures and salinities pose a physiological problem to marine life and have a dramatic effect on the distribution and diversity of marine biota throughout the region. Less salinity-tolerant species are likely to disappear as salinity levels increase. This has been noted previously in Bahrain waters (Price et al., 1984). Jones (1986a) points out that extreme temperatures and salinities found in the Arabian Gulf are partly responsible for the somewhat impoverished intertidal fauna and flora of the region. The large seasonal fluctuations in temperature coupled with the often massive tidal fluctuations in salinity must place enormous stress on both the intertidal and subtidal biota.

Dicks (1987) looked at the origins of oil pollution in the Gulf compared to the rest of the world (See table 2.8). Oil production and transportation still account for most of the pollution from the oil industry within the Gulf but refining and urban sources have increased in significance since 1977. Figures for the discharge rate and oil load from BAPCO (Table 2.7) show that some 1.5 tonnes of oil are being discharged onto the eastern coastline of Bahrain every day. The effects of the BAPCO discharge are clearly noticeable in the immediate vicinity of the outfall. The discharge pipe empties into a shallow embayment several hundred metres wide. The entire seabed throughout the embayment is covered in a bacterial mat and the sediments are completely anoxic.

The discharges into the marine environment from the various desalination plants in Bahrain may not represent a problem with regard to temperatures as they do not significantly raise the ambient water temperature above local summer values. Mixing in the water column is probably sufficient to negate any deleterious effects. The increased salinity from the brine content of the discharges requires further study. Although this may prove to be equally well compensated for by mixing, unusually high levels have been recorded particularly south of Ras Abu Jarjur (W.S.Atkins and Partners., 1985). The discharge from the new desalination plant at Ad Dur should be carefully monitored. The outfall from Gulf Petrochemical Industries which introduces water to the environment at 45^0 C has a localised restrictive effect on the flora and fauna (pers. obs.).

From table 2.7 and figure 2.2 it is clear that most of the principal industrial discharges to the marine environment are on the northwest coast of Bahrain between Muharraq and Askar. This area is close to the Fasht al Adhm reef and the effects of the discharges on the coral communities could be deleterious.

The Water Pollution Control Centre at Tubli discharges brackish water (< 10 ppt) into an almost enclosed embayment (Tubli Bay). There are localised effects such as high algal levels and a number of algal blooms have occurred in the bay with algal cell counts reaching 6 million cells litre^{-1} (pers. obs.). The presence of

potentially harmful biota such as nematodes (Ministry of Health, pers comm.) is of concern to human welfare. much of the island's raw sewage is still discharged into the sea by outfall pipes or taken from septic tanks by road tankers and deposited on the shoreline.

The effects that these various discharges may be having on the marine environment give cause for concern. The extreme temperatures and salinity values experienced by the local marine biota already place many of the organisms under stress and any further man-made stress could be critical to their survival. Monitoring of the marine environment is essential in order to guard against long-term damage to marine habitats and the species which they support. The EPTS (Environmental Protection Technical Secretariat) already have an industrial monitoring programme in place, but this has limitations due to staff shortages and equipment requirements.

Monitoring cannot be effective without background knowledge of the status of Bahrain's marine habitats and the species which they support. Some useful work has already been carried out which can be built on, but this alone does not provide sufficient information. One of the key recommendations from the IUCN ecological study of sites on the coast of Bahrain (Price et al, 1984) was to undertake a detailed study of the coastal and offshore habitats in Bahrain's waters. A full intertidal and subtidal study of the marine habitats is essential in order to provide baseline data with which to compare any future changes. The possession of a detailed knowledge of local habitats and species enables assessment of the impact of future development and the effects of existing pollutants. It will also allow avoidance of ad hoc misjudgements due to ignorance on the part of consultants or government staff faced with the task of preparing an environmental impact statement for a new industry or development.

AVERAGE SALINITY VALUES AND RANGES - BAHRAIN, 1985 - 1989

SECTOR	SALINITY MEAN	SALINITY STD	SALINITY N	SALINITY MINIMUM	SALINITY MAXIMUM	SALINITY RANGE
1	43.7	1.4	19	42.0	46.0	4.0
2	43.9	1.2	23	42.0	47.0	5.0
3	44.3	1.3	96	41.5	49.0	7.5
4	46.3	2.1	19	43.0	50.0	7.0
5	50.2	4.0	9	44.9	56.0	11.1
6	50.5	3.4	37	45.0	62.0	17.0
7	56.3	2.0	33	53.0	60.0	7.0
8	57.3	3.3	10	54.0	65.0	11.0

Calculated from data in appendix 2.1. All values measured in top 1 metre of water column
See figure 2.3 for sector locations

TABLE 2.1

TEMPERATURE AND SALINITY DATA RECORDED IN THE SUBTIDAL FRINGE (GALALI BEACH) BAHRAIN 1988-1989

MONTH	DATE	SAMPLE TIME	TIDAL STATE	LOW TIDE	HIGH TIDE	WATER TEMPERATURE Degrees Centigrade	SALINITY Parts per Thousand
August	880830	1230	Falling	1320	0632	43.0	50.0
September	880912	1200	Falling	1320	0632	35.0	49.5
October	881026	1115	Low	1146	0522	35.0	49.5
October	881031	1030	Falling	1519	0850	27.0	51.0
November	881110	1200	Low	1144	1745	30.5	50.0
November	881112	1200	Falling	1241	0623	30.0	50.0
November	881116	1200	Falling	1548	0921	23.0	53.0
November	881123	1100	Low	1046	1647	20.0	51
January	890123	1230	Low	1231	0553	18.7	44.0
February	890208	1300	Low	1251	1853	17.2	45.0
February	890222	1315	Low	1235	1836	21.8	44.0
April	890407	1200	Low	1202	0535	27.5	43.0

All records taken in 0.2 metres of water in the subtidal fringe

TABLE 2.2

VERTICAL SALINITY GRADIENTS AND TIDAL CONDITIONS - BAHRAIN 1988-1989

(from raw data in Appendix 2.2)

SECTOR *	DATE	SITE NAME	LOW TIDE	HIGH TIDE	SAMPLE TIME	TIDAL STATE	SALINITY GRADIENT (in ppt)	WATER DEPTH (in metres)
1	880330	Vidal Buoy	1035	1625	1611	High	0.6	13.1
2	890403	N of Half Tanker	0909	1519	1450	High	0.5 *	5
3	880329	Big Red 1	1224	0340	0845	Mid Ebb	3.3	5.3
3	880329	Sitra Gate	1301	0406	0835	Mid Ebb	2.6	5.4
3	881206	SE of Big Red Two	1051	0503	1030	Low	0.8	12
3	890320	Big Red 2	1338	0555	0950	Mid Ebb	1.1	5.9
3	890320	Big Red 1	1339	0500	1210	Low	2.1	6
3	890320	Big Red 1	1433	0622	0930	Mid Ebb	3.1	8.1
3	890402	Sitra Gate	1030	0215	1000	Low	0.1	2
4	880329	Gabbari Rock	1232	1725	1530	Mid Flood	3.7	7
4	880803	Gabbari Rock	1730	1040	1615	Low	0.1	7
4	881004	Gabbari Rock	0646	1237	1135	High	1.4	6.5
4	881206	S of Big Red Two	1051	0503	1017	Low	0.1	5.2
4	881206	NE of Tighaylib S. Pole	1041	1700	1115	Low	0	5.4
4	881207	Gabbari Rock	1207	0501	1140	Low	0.3	4
4	890320	Gabbari Rock	1337	0618	1130	Low	3.4	8.7
4	890402	Gabbari Rock	1041	1630	1245	Mid Flood	3	7.8
5	880330	Khawr Fasht	1035	1625	1300	Mid Flood	1.8 *	7.6
5	890403	Khawr Fasht	0923	0220	0840	Low	0.5	5
6	880329	Middle Shoal	1152	1756	1545	Mid Flood	1.5	7.7
6	880803	Middle Shoal	1756	1130	1415	Mid Ebb	6.6	4
6	881206	S.E. Of Mashtan	1051	1733	1500	Mid Flood	2.6	3.5
6	881206	East Al Hul	1215	1835	1230	Low	0.9	2.7
6	881206	S.E. Of Mashtan	1051	1733	1625	High	0.5	2.9
6	881206	W.N.W. Of Mashtan	1051	1733	1130	Low	0.2	4.7
6	881207	Mashtan South	1207	0501	0745	Mid Ebb	1.6	2.5
6	890320	Mashtan South	1338	0555	1100	Mid Flood	1.3	4.7
6	890402	Middle Shoal	1041	1630	1515	Mid Flood	1	5
7	880330	Zallaq	1345	0633	0940	Mid Ebb	0.2 *	7
7	890313	Zallaq Tower	1152	1603	1330	Low	0.3	4.5
7	890403	Zallaq	0041	0630	0600	High	-0.1	2
8	880329	West Al Hul	1230	1813	1745	High	0.4 *	12.5
8	880803	West Al Hul	1850	1130	1200	High	-0.3	10
8	890217	West Al Hul	1258	0520	1230	Low	-0.1	10
8	890402	West Al Hul	1045	1700	1545	High	0.2 *	8.2

Tidal state calculated by dividing tidal period into thirds. * = Multiple stratification
See Figure 2.3 for sector distributions around Bahrain

TABLE 2.3

AVERAGE MONTHLY SURFACE SEAWATER TEMPERATURES IN DEGREES CELSIUS FOR BAHRAIN (1985-1989), SAUDI ARABIA (1986-1990) AND KUWAIT (1982).

MONTH	MEAN TEMP	STD	N	MINIMUM	MAXIMUM	RANGE	SAUDI MEAN *	KUWAIT MEAN **
January	20.8	3.5	44	16.4	30.0	13.6	15	14
February	20.2	2.7	36	13.3	27.0	13.7	17	16
March	21.2	1.7	24	18.7	26.5	7.8	20	19
April	19.9	0.3	7	19.6	20.4	0.8	25	22
May	26.5	0.9	3	25.5	27.7	2.2	29	26
June	31.0	0.0	1	31.0	31.0	0.0	29.8	30
July	32.7	1.2	18	30.5	35.5	5.0	31.9	30
August	34.1	1.4	74	30.1	39.0	8.9	32.4	30
September	36.0	1.0	2	35.0	37.0	2.0	30.80	30
October	28.8	1.7	6	27.0	31.5	4.5	27.20	28
November	27.8	0.3	7	27.0	28.0	1.0	21.50	22
December	21.1	0.4	4	20.6	21.7	1.1	18.40	16

Saudi Arabian data collected around Dammam, Arabian Gulf coast.
Kuwait data collected around Kuwait City on Arabian Gulf
All values measured in top 1 metre of water column. * = McCain et al, 1993. ** = Jones, 1986

TABLE 2.4

AVERAGE MONTHLY AIR TEMPERATURES (IN DEGREES CENTIGRADE) AND RANGES BAHRAIN 1985-1989

MONTH	MEAN TEMP	STD	N	MINIMUM	MAXIMUM	RANGE
January	No Data					
February	15.5	0.3	2	15.2	15.8	0.6
March	23.1	3.1	16	19.1	28.6	9.5
April	19.8	1.1	14	17.8	21	3.2
May	30.6	1.9	2	28.7	32.5	3.8
June	No Data					
July	37.0	2.9	10	34.5	45	10.5
August	37.7	3.0	17	32	43	11
September	30.5	-	1	30.5	30.5	-
October	32.3	-	1	32.3	32.3	-
November	23.4	1.7	5	22	26	4
December	25.0	-	2	25	25	0

Measurements for Bahrain recorded at various study sites

TABLE 2.5

TIDAL LEVELS - BAHRAIN - PREDICTED LOCATIONS

Heights in metres reduced to Chart Datum which is approximately the level of the lowest astronomical tide.

Table reproduced from 1989 Tide Tables. Published by Survey Directorate, State of Bahrain.

LOCATION	LAT	MLWS	MLWN	MSL	MHWN	MHWS	HAT	YEAR
1. Mina Salman	0.0	0.6	1.0	1.5	1.9	2.4	2.7	1976
2. Port of Sitra	0.1	0.6	1.0	1.4	1.9	2.3	2.8	1976
3. Mina Manama	0.0	0.8	1.1	1.6	1.9	2.4	2.7	1985
4. Fasht al Jarim	0.1	0.6	1.1	1.4	1.8	2.3	2.7	1988
5. Khawr Fasht	0.1	0.6	1.0	1.4	1.8	2.2	2.6	1987
6. Budaiya	0.1	0.5	0.7	1.0	1.2	1.5	1.8	1987
7. Causeway	0.0	0.3	0.5	0.6	0.8	1.1	1.2	1987
8. Zallaq	0.0	0.0	0.1	0.2	0.2	0.2	-	1986
9. Bahrain Yacht Club	0.0	0.2	0.4	0.5	0.6	0.7	0.8	1985
10. Um Jalid	0.0	0.2	0.4	0.5	0.6	0.7	0.8	1985
11. Hawar NE Jetty	0.0	0.2	0.2	0.3	0.4	0.6	0.7	1986

MLWS = Mean Low Water on Spring Tide. MLWN = Mean Low Water on Neap Tide
MHWS = Mean High Water on Spring Tide. MHWN = Mean High Water on Neap Tide
LAT = Lowest Astronomic Tide. HAT = Highest Astronomic Tide

See figure 2.2 for locations of tide gauge sites

TABLE 2.6

MAIN SOURCES OF POLLUTION INTO BAHRAIN'S COASTAL WATERS

SOURCE	TYPE	DISCHARGE	OUTFALL RATES	DISCHARGE	TOTAL BOD TO LOCAL WATERS
BALEXCO	Aluminium production	Aluminium oxide sludge	316 cu.m day (sludge load = 1477mg litre)	170 tonnes per annum	No Data
BAPCO	Petrochemical refinery	Oil hydrocarbons, ammonia, phenols, metals, sulphates	625,000 cu.m day (oil load = 2.4 mg litre)	547.5 tonnes per annum	19%
GPIC	Petrochemical products	Ammonia, Hot water (>45 C)	No Data	No Data	No Data
RAS ABU JARJUR	Desalination	Hot water, brine	No Data	No Data	No Data
SITRA	Desalination, Power station	Hot water, brine	No Data	No Data	No Data
WPCC	Sewage Treatment	Brackish water (<8ppt)	No Data	No Data	No Data
AGRICULTURE	Vegetables, Animal feeds	Organic material, (Fertilisers)	No Data	No Data	50%
DOMESTIC EFFLUENTS	Domestic waste,	Kitchen/laundry water, Sewage, Food waste	No Data	No Data	25%

TABLE 2.7
(After Zainal, 1985)

ORIGINS OF OIL POLLUTION IN THE ARABIAN GULF V WORLD

DISCHARGE SOURCE	ARABIAN GULF 1977	ARABIAN GULF 1980	WORLD 1978
Tanker and Ship Traffic (spills and routine discharges)	86%		23%
Offshore Production and Natural Seepage	14%	22%	14%
Refining, Industrial and Urban	<0.12%	20%	63%

Figures represent the percentage of all oil pollution entering the marine environment

TABLE 2.8
(After Dicks, 1987)

FIGURE 2.1 BATHYMETRY WITHIN STUDY AREA

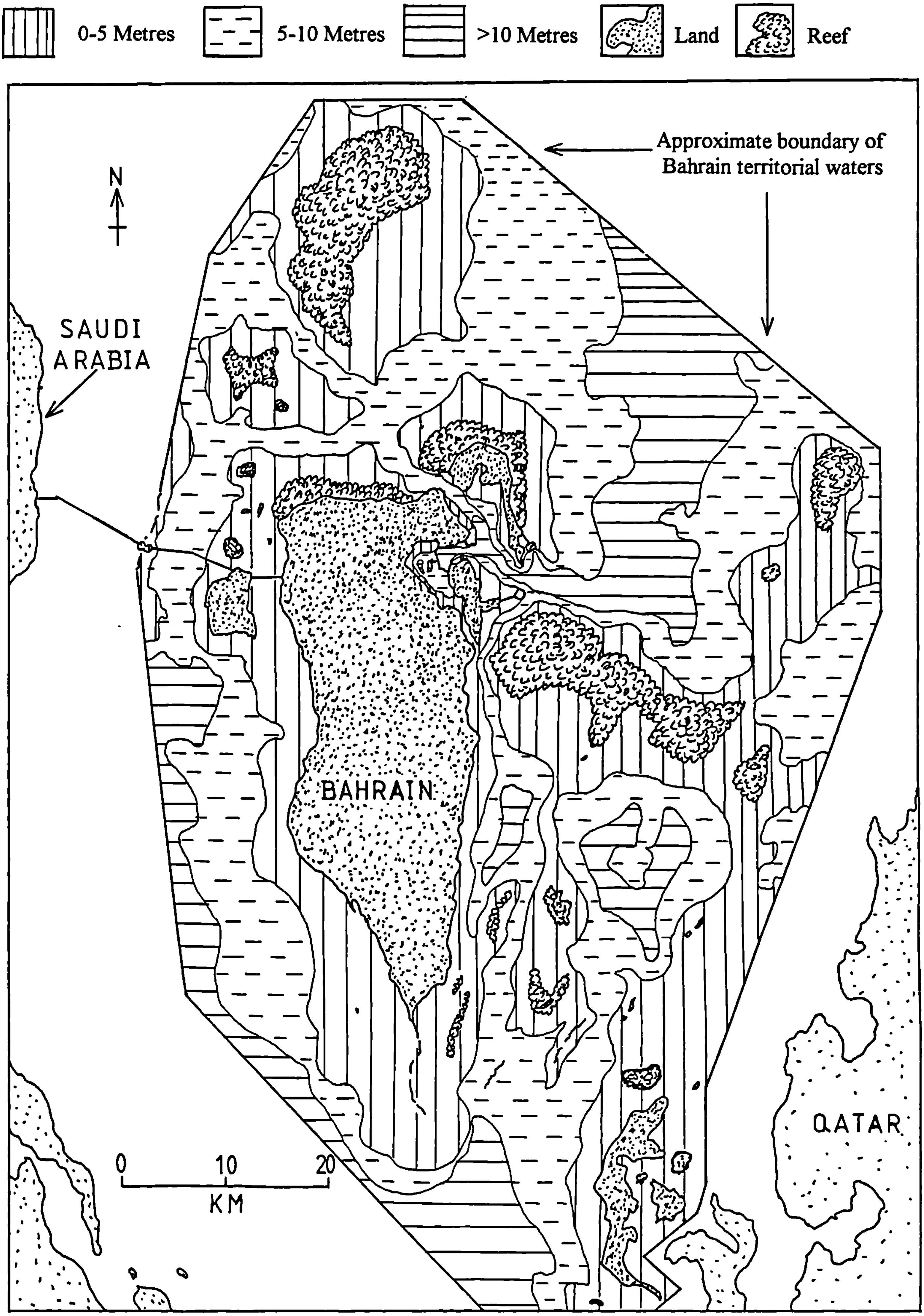


FIGURE 2.2 POSITION OF TIDE GAUGES, SOURCES OF POLLUTION AND SITES OF CURRENT METER DEPLOYMENT

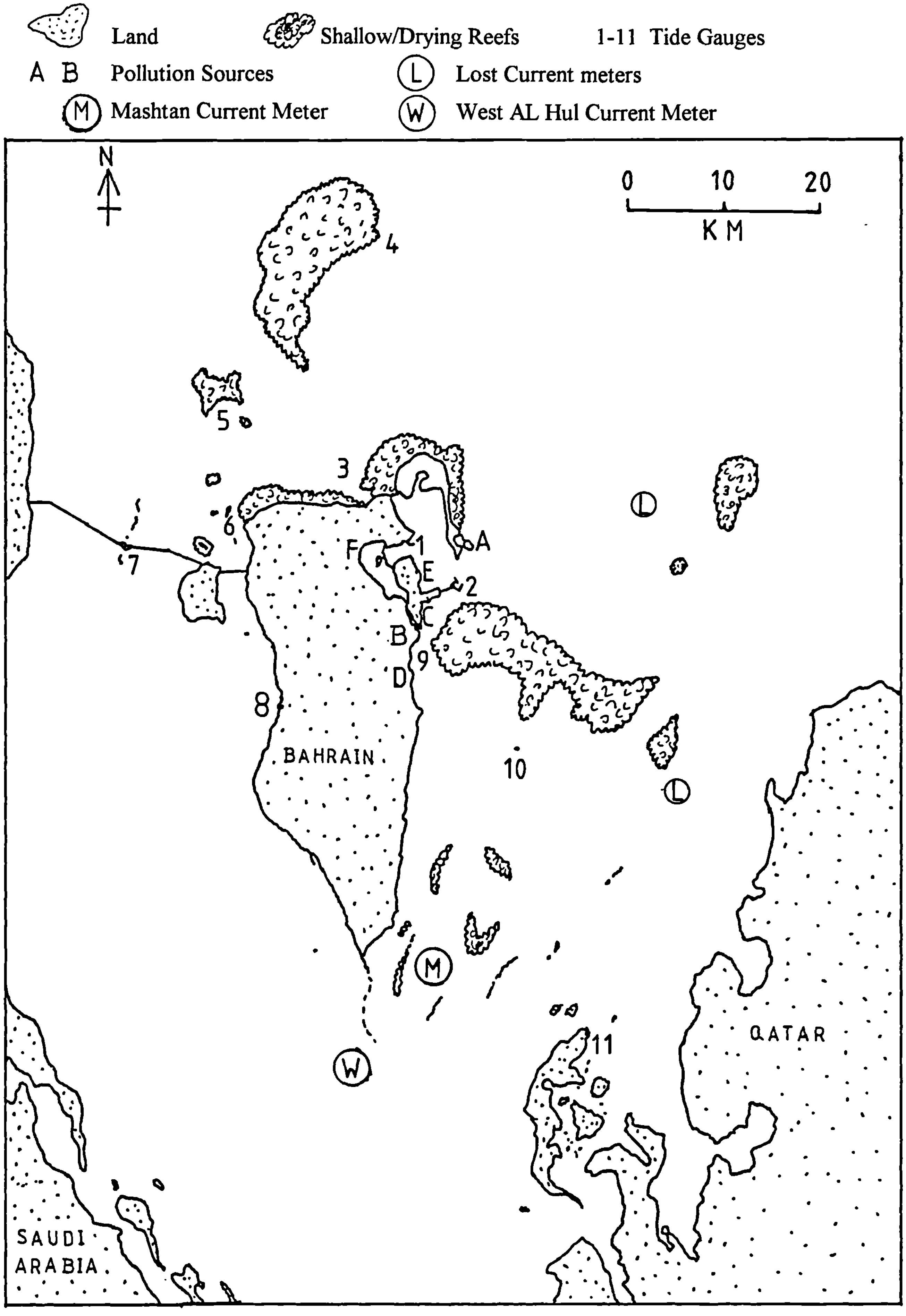
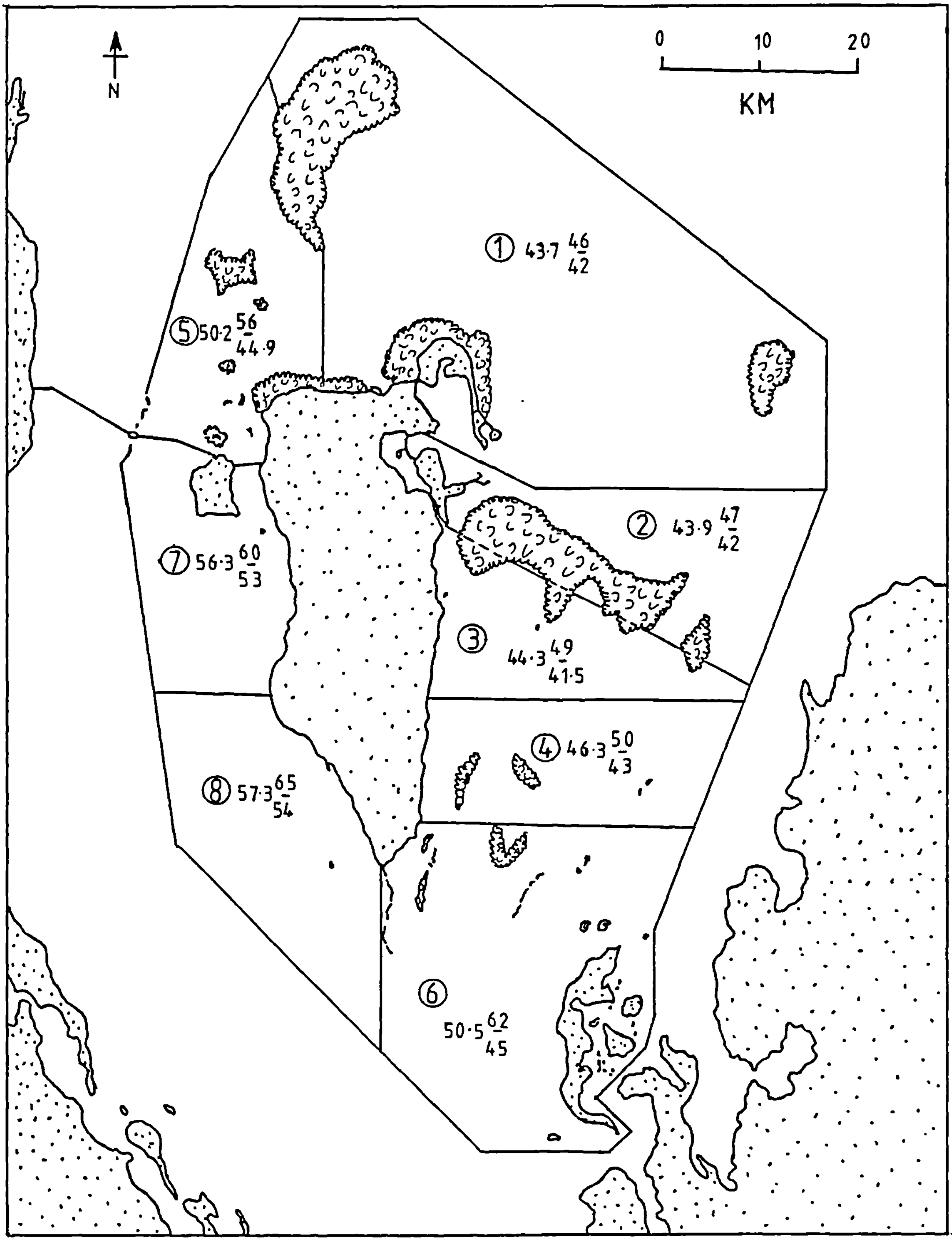


FIGURE 2.3 MAP OF STUDY AREA SHOWING DIVISIONS INTO SECTORS REPRESENTING AREAS WITH SIMILAR SALINITIES

(Salinities in parts per thousand)

(5) Sector $49\ \frac{56}{45}$ Mean $\frac{\text{Maximum}}{\text{Minimum}}$



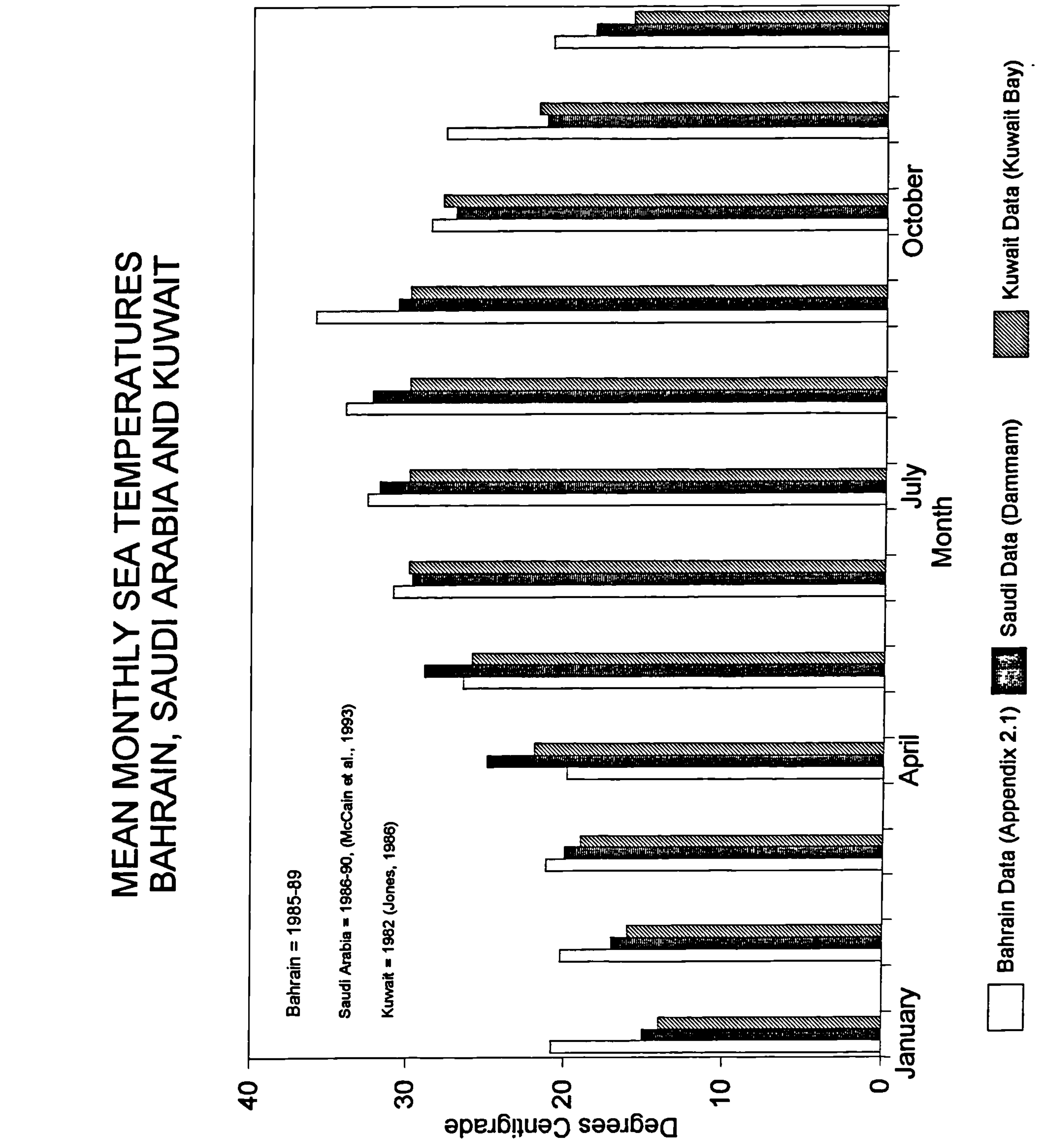

MEAN MONTHLY SEA TEMPERATURES
BAHRAIN, SAUDI ARABIA AND KUWAIT
Bahrain = 1985-89
Saudi Arabia = 1986-90, (McCain et al., 1993)
Kuwait = 1982 (Jones, 1986)
Degrees Centigrade
0
10
20
30
40
January
April
July
October
Month
Bahrain Data (Appendix 2.1)
Saudi Data (Dammam)
Kuwait Data (Kuwait Bay)

FIGURE 2.4

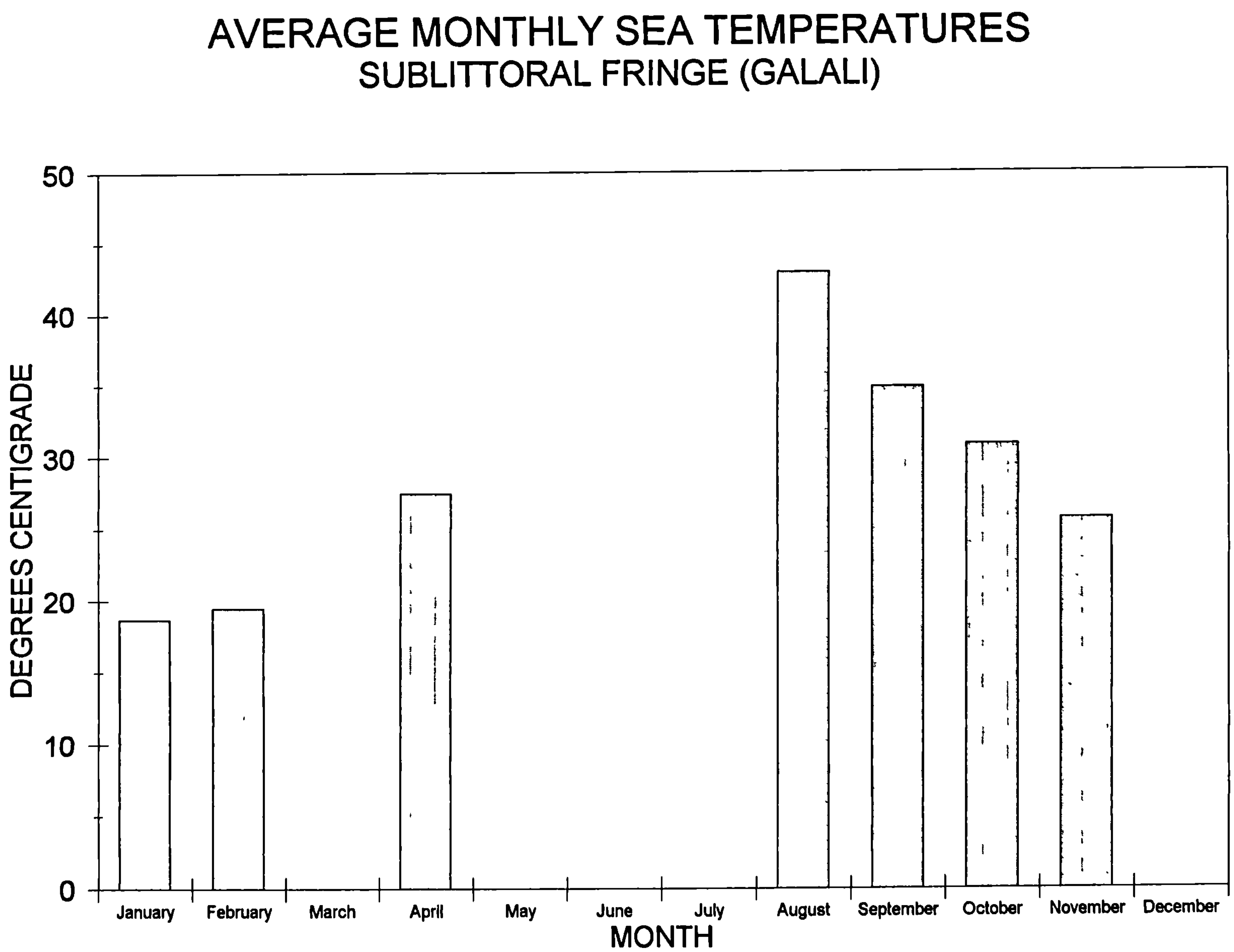

AVERAGE MONTHLY SEA TEMPERATURES
SUBLITTORAL FRINGE (GALALI)
DEGREES CENTIGRADE
50
40
30
20
10
0
January
February
March
April
May
June
July
August
September
October
November
December
MONTH

FIGURE 2.5

MASHTAN SW CURRENT METER 9 MARCH 1989
TIME V CURRENT VELOCITY OVER 24H

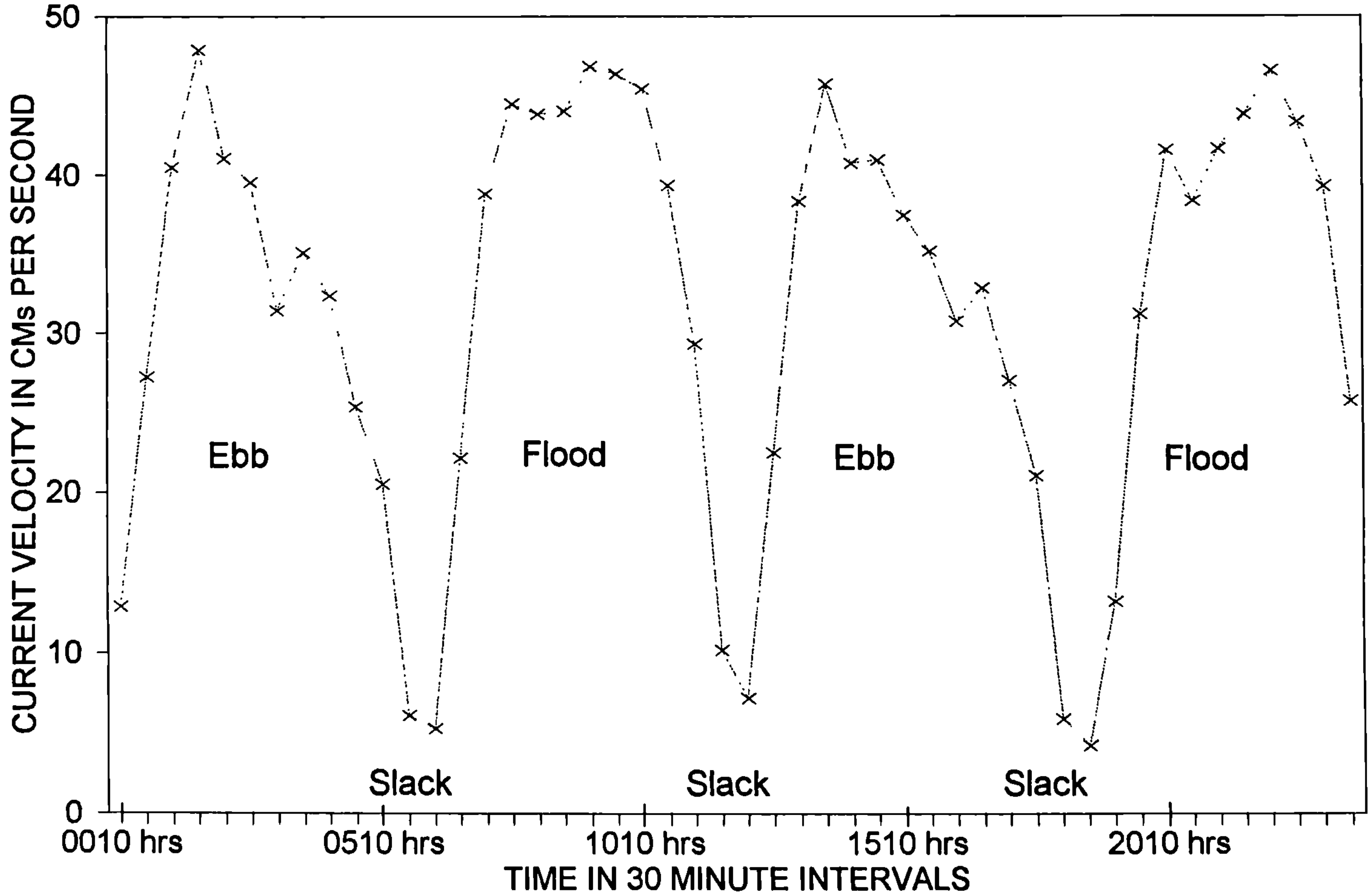


FIGURE 2.6

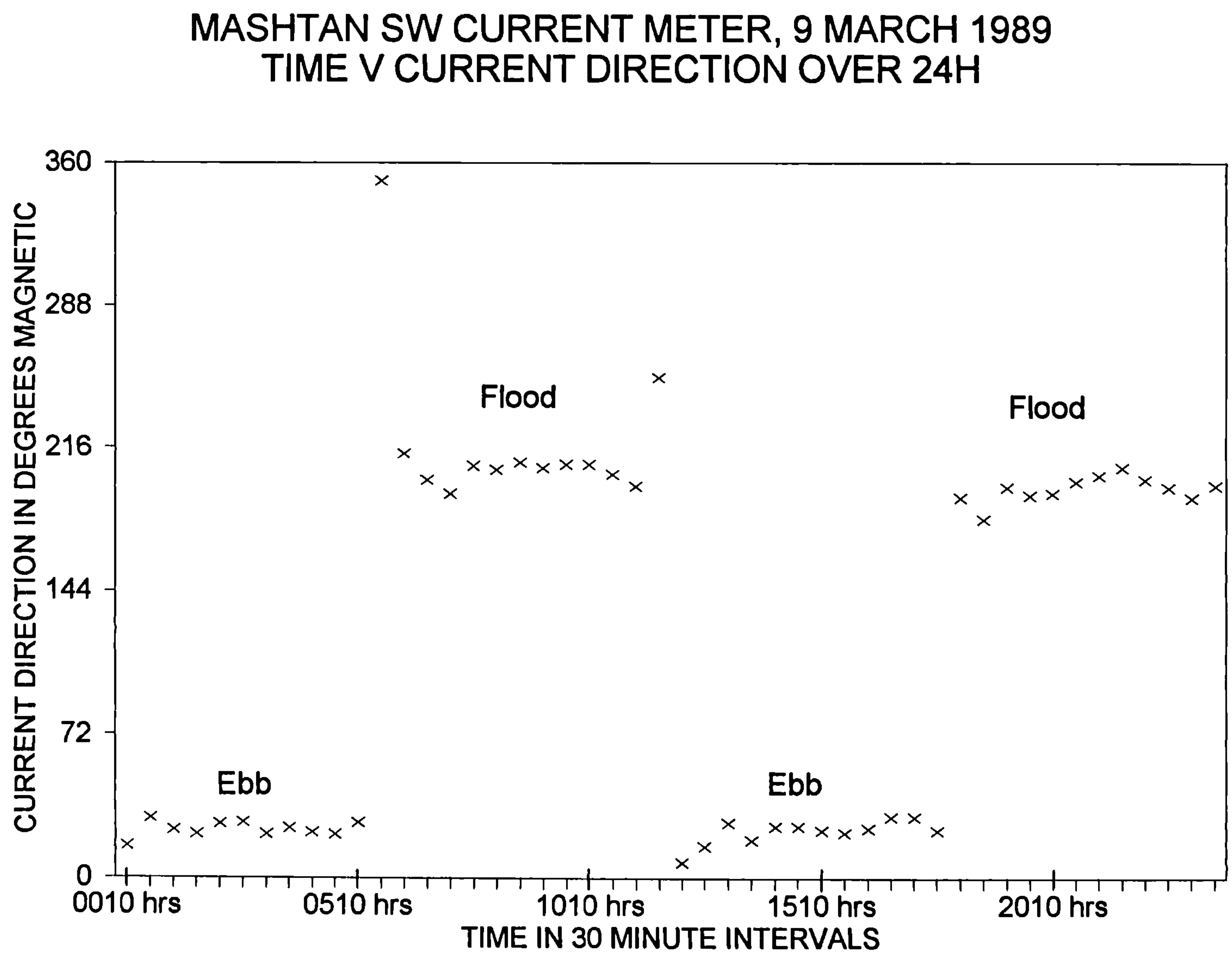

MASHTAN SW CURRENT METER, 9 MARCH 1989
TIME V CURRENT DIRECTION OVER 24H
CURRENT DIRECTION IN DEGREES MAGNETIC
360
288
216
144
72
0
Flood
Flood
Ebb
Ebb
0010 hrs
0510 hrs
1010 hrs
1510 hrs
2010 hrs
TIME IN 30 MINUTE INTERVALS

FIGURE 2.7

MASHTAN SW CURRENT METER 9 MARCH 1989
TIME V SALINITY OVER 24H

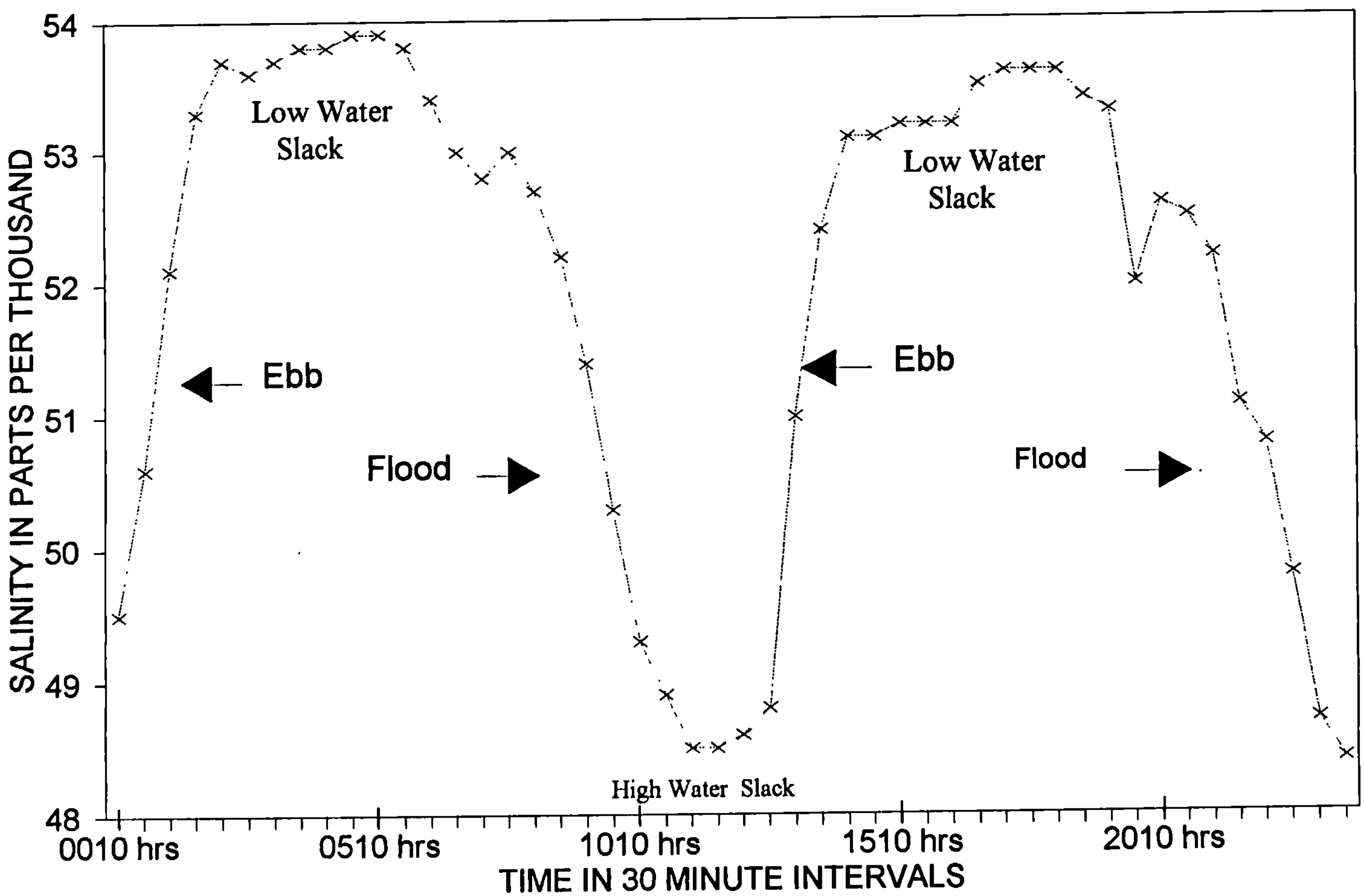


FIGURE 2.8

MASHTAN SW CURRENT METER 9 MARCH 1989
TIME VERSUS SEA TEMPERATURE OVER 24H

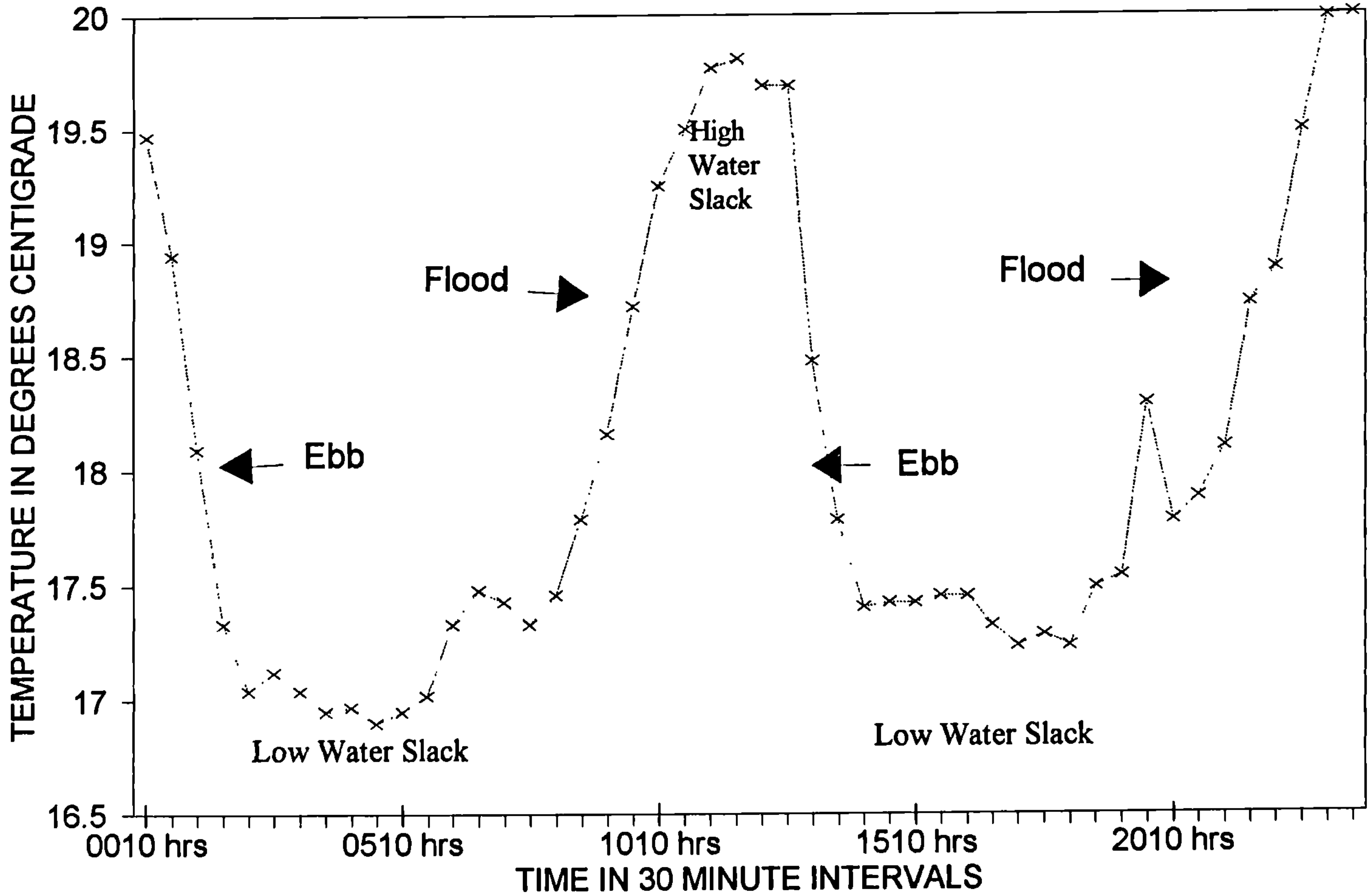
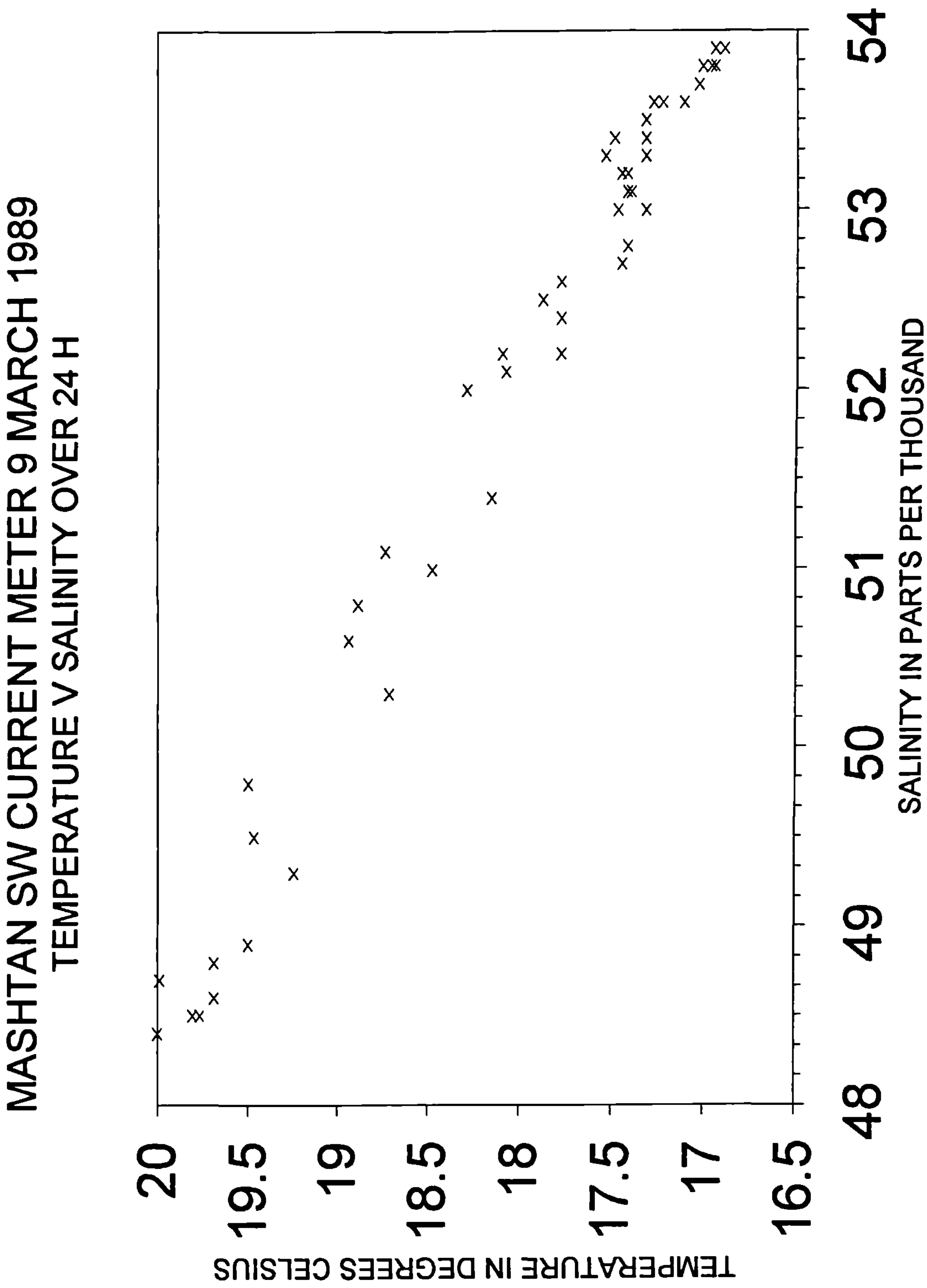


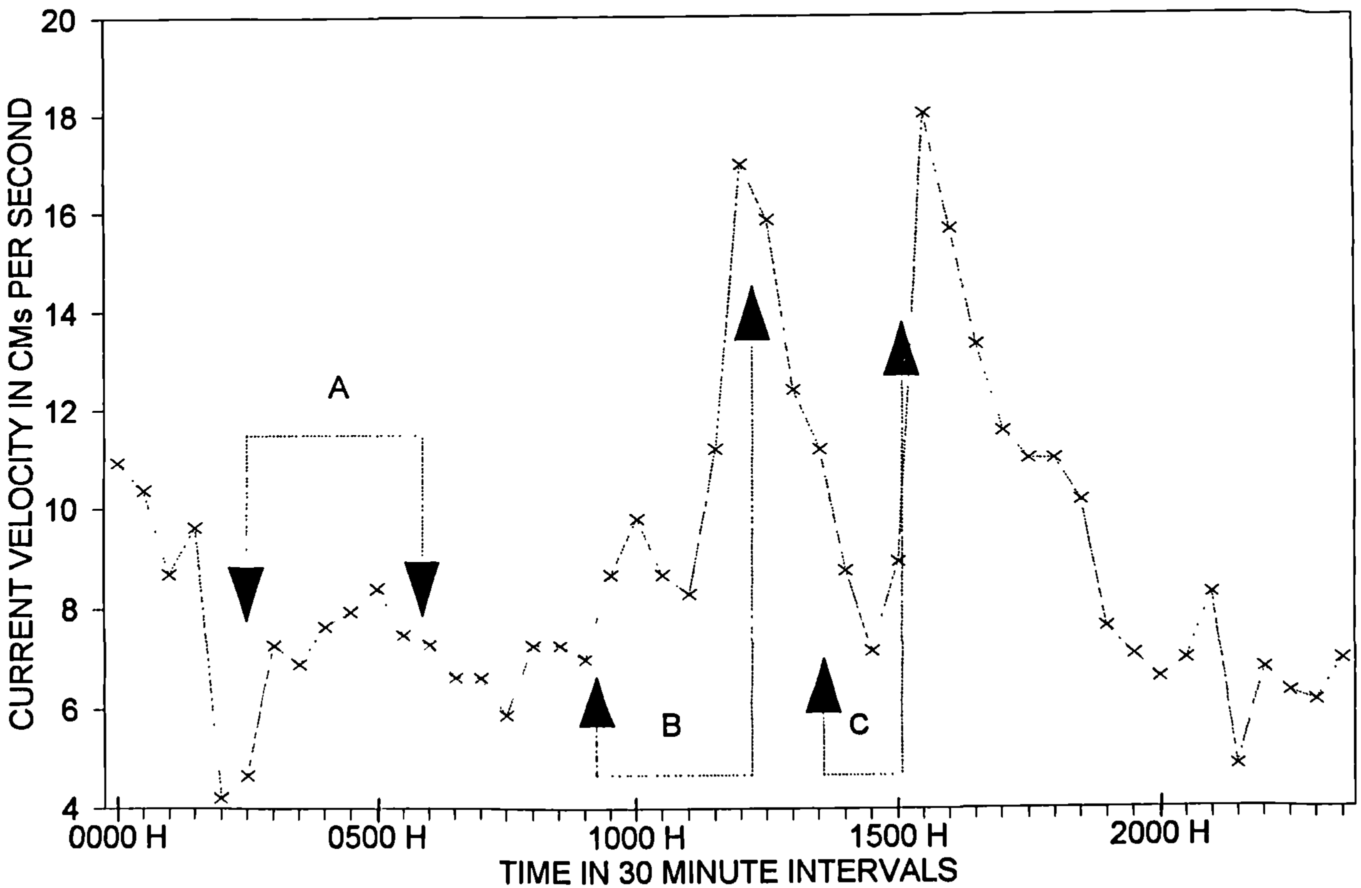
FIGURE 2.9



MASHTAN SW CURRENT METER 9 MARCH 1989
TEMPERATURE V SALINITY OVER 24 H
TEMPERATURE IN DEGREES CELSIUS
20
19.5
19
18.5
18
17.5
17
16.5
48
49
50
51
52
53
54
SALINITY IN PARTS PER THOUSAND

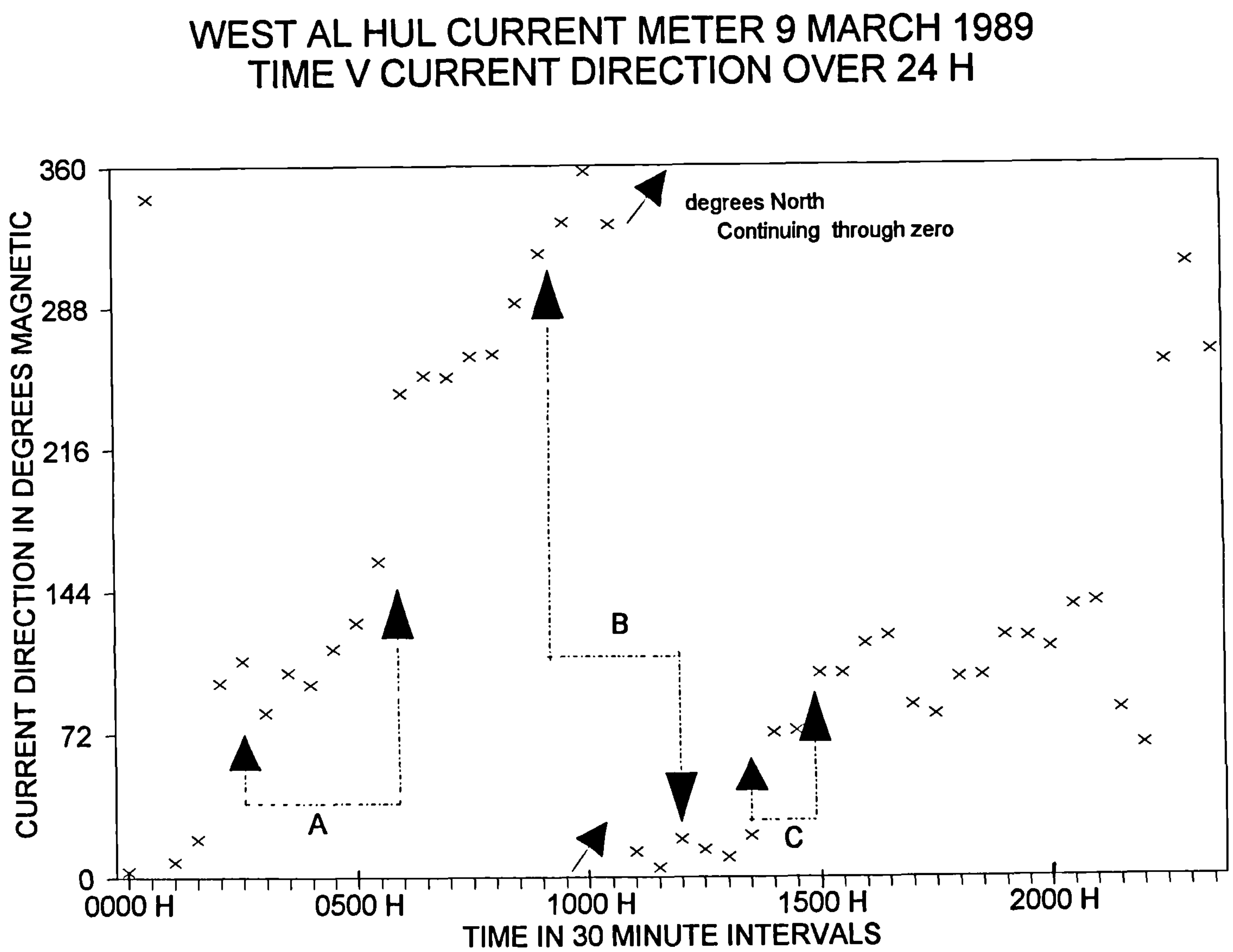
FIGURE 2.10

WEST AL HUL CURRENT METER 9 MARCH 1989
TIME V CURRENT VELOCITY OVER 24 H



See text for explanation of A, B and C

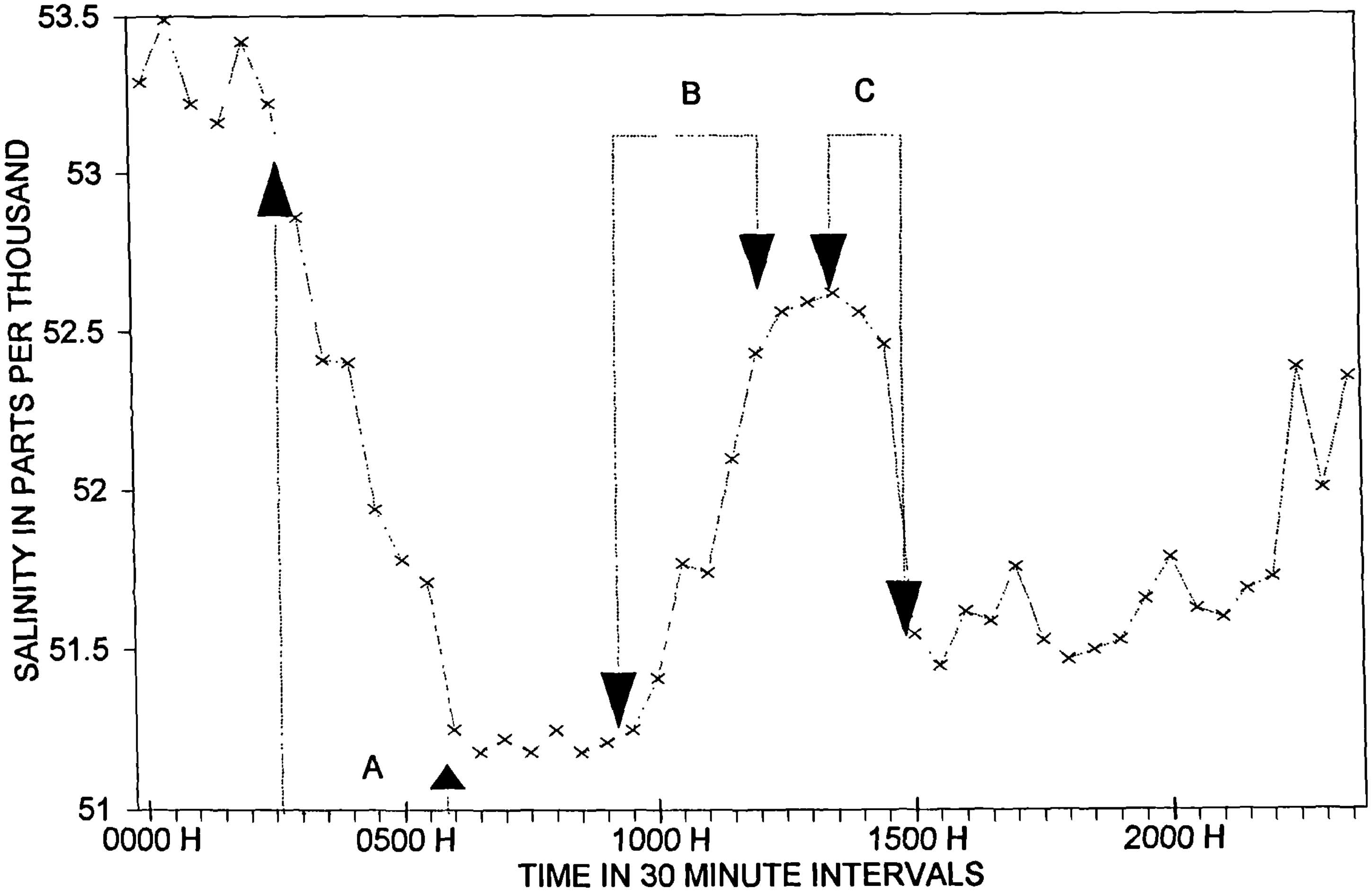
FIGURE 2.11



See text for explanation of A, B and C

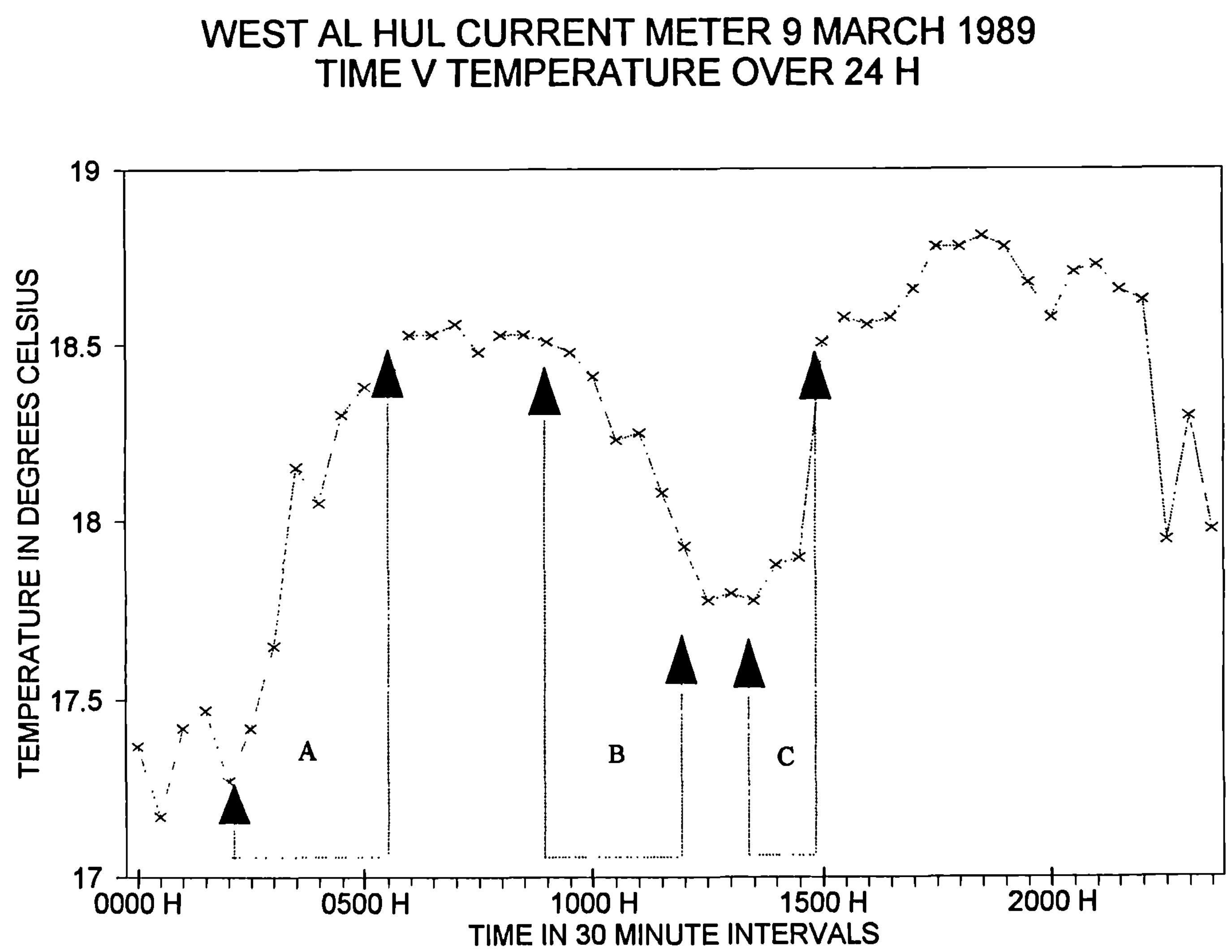
FIGURE 2.12

WEST AL HUL CURRENT METER 9 MARCH 1989
TIME V SALINITY OVER 24H



See text for explanation of A, B and C

FIGURE 2.13



See text for explanation of A, B and C

FIGURE 2.14

WEST AL HUL CURRENT METER 9 MARCH 1989
TEMPERATURE V SALINITY OVER 24 H

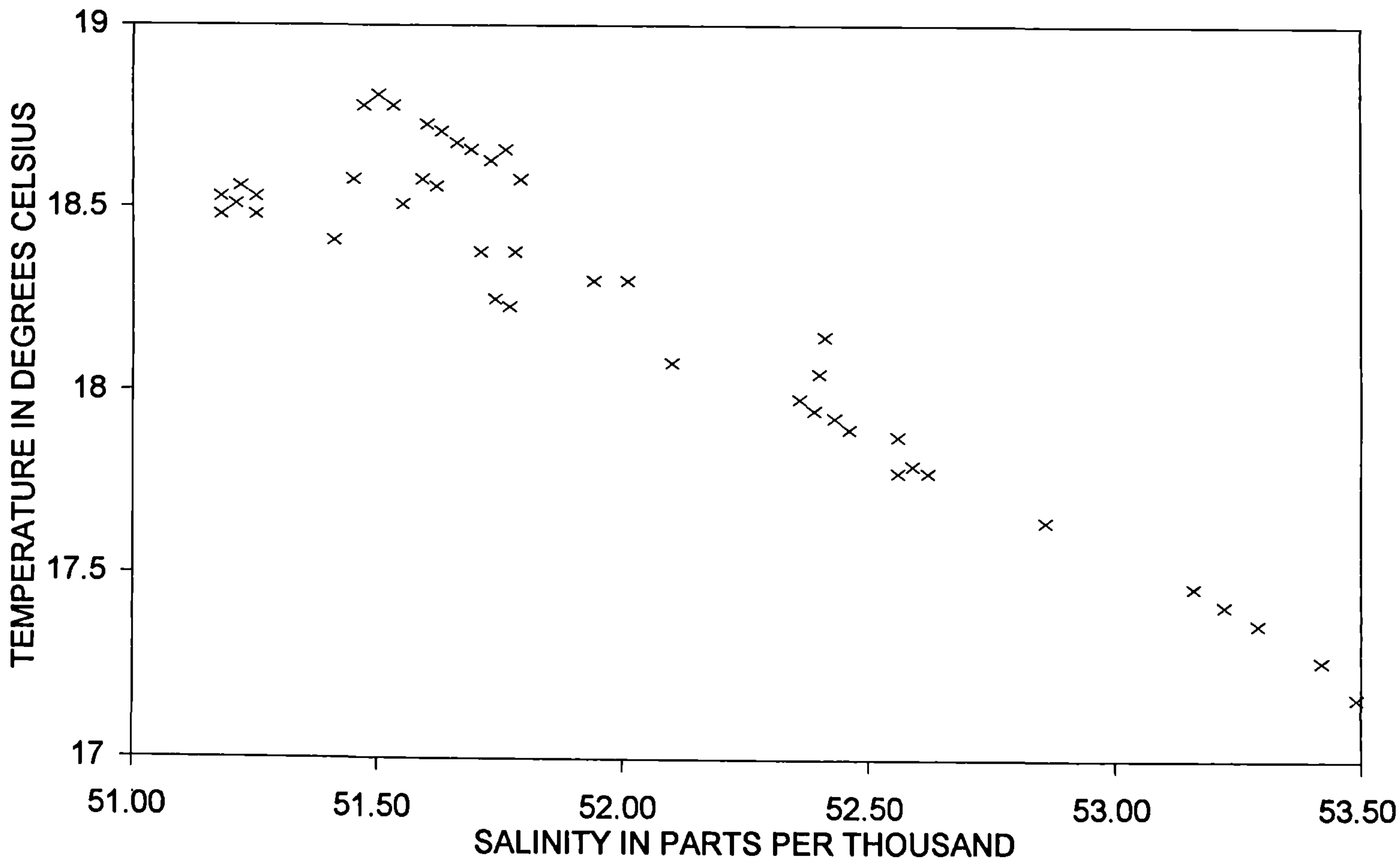


FIGURE 2.15

FIGURE 2.16 MEAN SALINITY LEVELS APPROACHING SLACK WATER ON A RISING TIDE

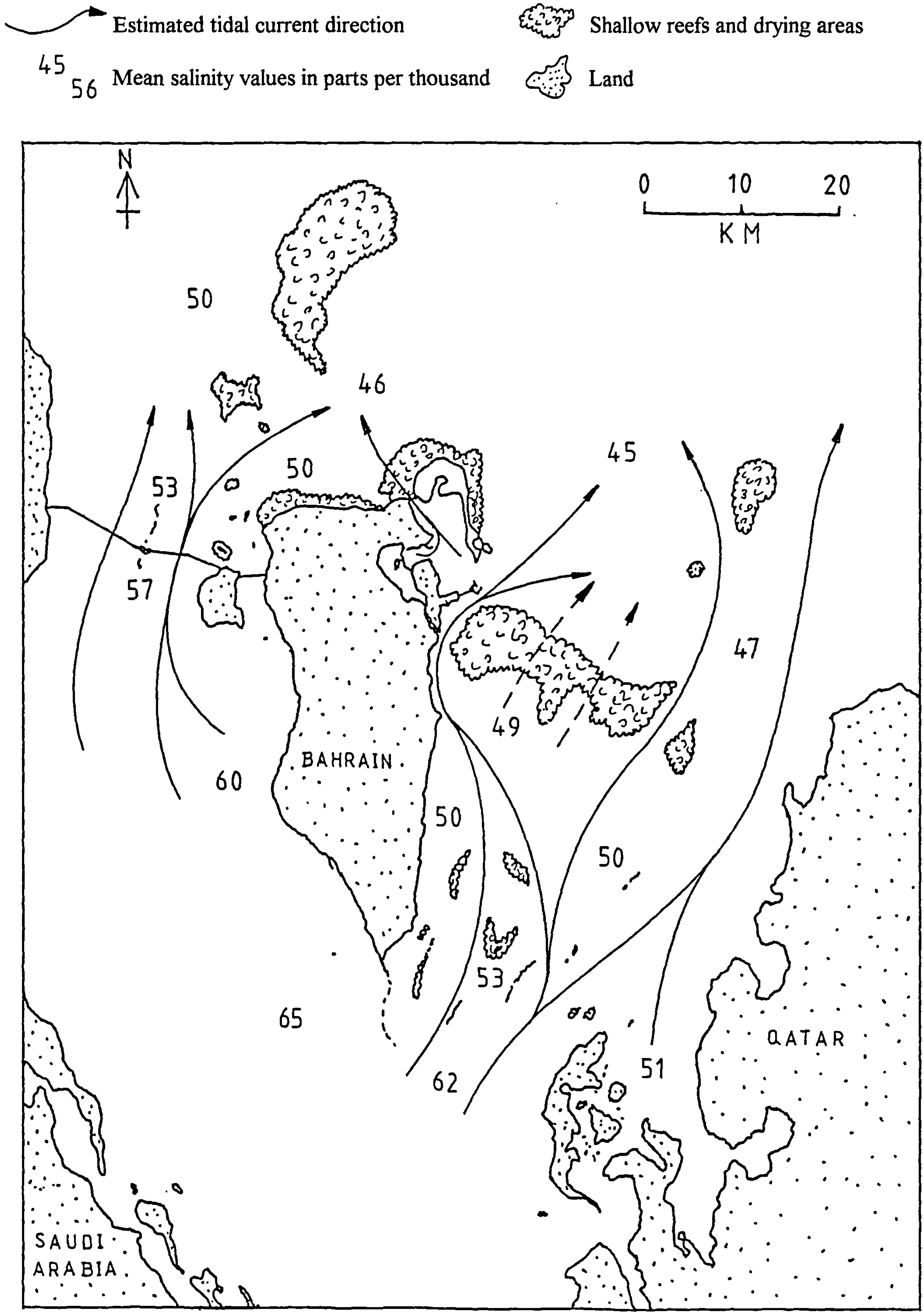
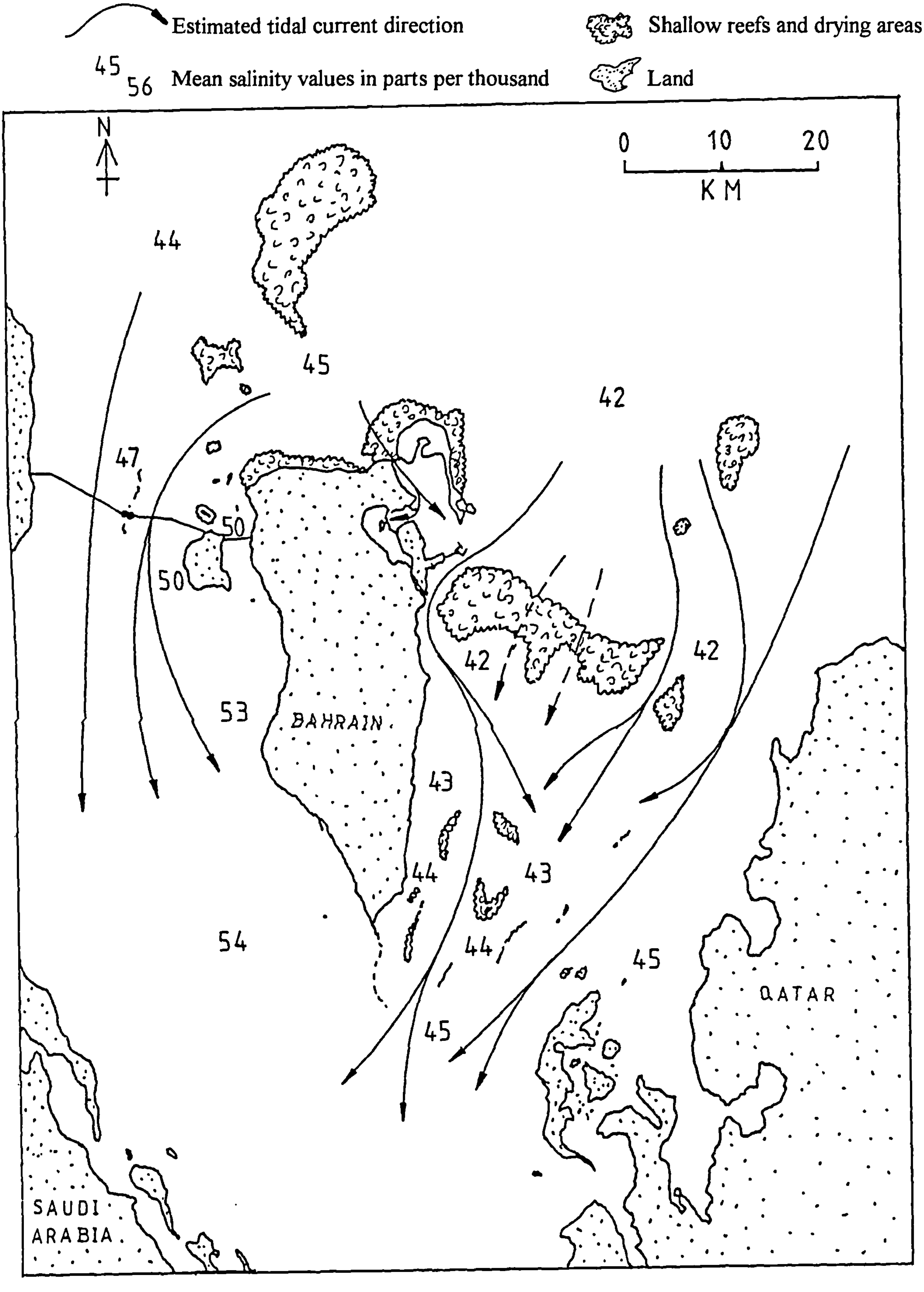
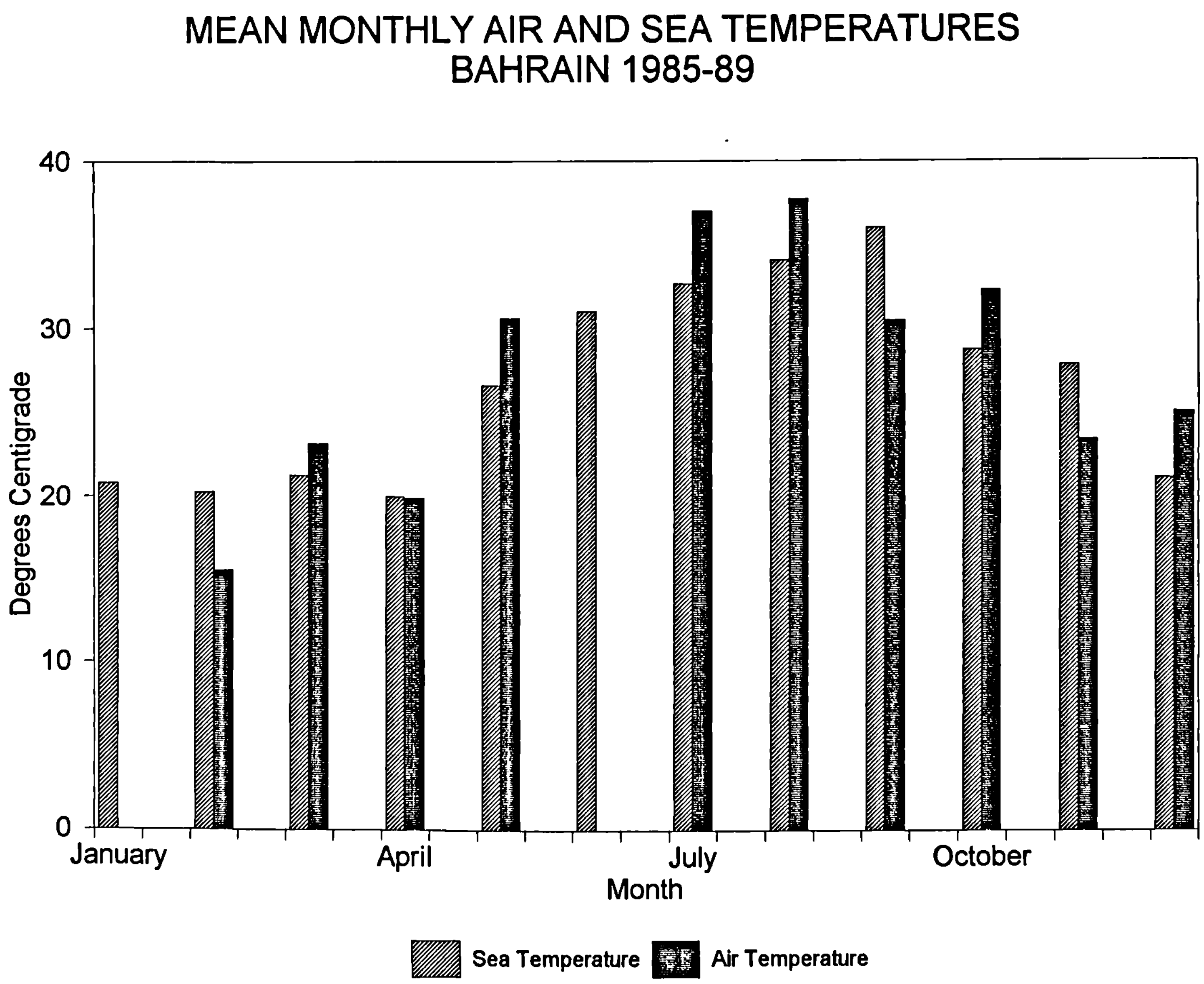


FIGURE 2.17 MEAN SALINITY LEVELS APPROACHING SLACK WATER ON A RISING TIDE





MEAN MONTHLY AIR AND SEA TEMPERATURES
BAHRAIN 1985-89
40
30
20
10
0
Degrees Centigrade
January
April
July
October
Month
Sea Temperature
Air Temperature

FIGURE 2.18

CHAPTER THREE

BIOLOGICAL CHARACTERISTICS AND DISTRIBUTION OF INTERTIDAL HABITATS

CHAPTER THREE

BIOLOGICAL CHARACTERISTICS AND DISTRIBUTION OF INTERTIDAL HABITATS

INTRODUCTION

The shoreline of the Arabian Gulf includes a variety of mixed, intertidal habitat types ranging from rocky coastlines through sands to fine muds, saltmarshes and mangroves (Basson et al, 1977; Jones et al, 1978; Jones, 1985; Jones, 1986a). Bahrain has representatives of all these intertidal types along with various mixed combinations displaying elements of several different habitat types (Vousden, 1985b). The distribution of the various habitat types is a result of a combination of factors of which the most important must be exposure to wave action. A significant influence is also imposed at the community level by salinity and temperature and especially the seasonal effects of the latter.

Intertidal biota on the shorelines of Bahrain are subject to harsh physical conditions including extremes of temperature and rapidly changing salinities. These extremes are related to tidal or seasonal fluctuations (See Chapter 2). Intertidal biota must withstand annual temperature extremes as low as 13^0 C and as high as 43^0 C while salinities can fluctuate between 42 ppt and >65 ppt in one tidal cycle. High levels of insolation, winds and the resultant desiccation add to the direct physical stresses mentioned above.

Basson et al (1977) identify alternate exposure and submergence as the dominant environmental factors controlling the occurrence of plants and animals in the intertidal zone of the Arabian Gulf coastline of Saudi Arabia. One of the outstanding features of the coastline on the western side of the Arabian Gulf is it's extremely low relief with an extensive intertidal and gentle, subtidal slopes so that even exposed beaches are generally fronted by a wide belt of subtidal shallows. Much of the coastline is characterised by an extensive and complex system of shallow bays. As a result of the lack of freshwater input in this area of the Gulf, these bays tend to be hypersaline and contain large areas of sheltered, intertidal flats which, despite high salinities and extreme temperatures, are amongst the most productive of Arabian marine biotopes. Basson et al (1977) list the key species characteristic of rocky, sandy and muddy shores. Jones et al (1978) found that the flora and fauna of hypersaline lagoons on the Gulf coast of Saudi Arabia were species-impoverished and that this was attributable to high temperatures and salinities in the lagoons. In particular they found that high salinity values (40-80 ppt) were responsible for the lack of marine angiosperms, macroalgae, and echinoderms and for the reduced numbers of species of molluscs, coelenterates and crustacea. Quantitative data of the species present in the lagoons demonstrated similar levels of high productivity to those recorded by Basson et al (1977).

Jones (1986a) also recognises that the extreme temperatures and salinities associated with the coastline of the Arabian Gulf are partly responsible for the impoverished intertidal flora and fauna. The close proximity of and access to the tropical Indian Ocean, with the richest diversity of marine life in the world, allows the possibility for the immigration of a wide range of marine species. The timing of the tides on the shores of Kuwait along with the influence of lower salinity water from the Shatt al-Arab means that intertidal life is perhaps richer than expected. However, in Kuwait low winter temperatures are most important in influencing the character of intertidal life which is largely warm temperate in nature rather than the subtropical and tropical biota found further south in the Gulf and central Indian Ocean. Northern temperate intertidal species which might well flourish in parts of the Gulf are absent.

This is because colonisation of Gulf shores can only take place via eurythermal species which survive the passage through tropical waters at the mouth of the Gulf. Jones provides further detail on zonation patterns for various intertidal habitat types on the coast of Kuwait.

Detailed studies specific to the shoreline of Bahrain include an ecological study of sites on the coast by Price et al (1984) and the Fasht al Adhm Environmental Study undertaken by W.S. Atkins and Partners (1985). Hill and Webb (1983) provide an introduction to the wildlife of the islands of Bahrain with particular reference to seabirds. Gallagher and Rogers (1978) discuss the breeding colonies of birds to be found around the islands while Jennings (1981) presents a small discourse on the birds of Bahrain with descriptions. Newton (1955) gives a brief introduction to the marine algae of Bahrain.

Price et al (1984) noted a rich surface fauna supported by high benthic primary productivity on the tidal flats at Askar on the east coast and north of the Causeway. The role of phytoplankton as a source of productivity was considered to be only secondary, an opinion shared by Basson et al (1977). Fish counts from the flooded intertidal showed that a major portion of the dominant species feeding in this zone are either herbivores or detritivores with very few planktivorous fish present. Price et al (1984) noted the presence of seagrass in the intertidal which is unusual for the Arabian Gulf (Basson et al, 1977). The paucity of invertebrate species types collected from the Bahrain intertidal in comparison to those found by Basson et al (1977) on the nearby Saudi coast is considered to be related to the much higher salinities generally experienced around Bahrain's coastline. In their final recommendations, Price et al (1984) propose detailed mapping of the distribution of coastal and marine habitats (particularly critical habitats) and the occurrence of species of economic or scientific importance as a priority. Among their list of intertidal sites requiring urgent attention were the mangrove stands in Sanad (Tubli Bay) and the very productive intertidal flats in sheltered bays such as Askar, Sitra and Tubli Bay as well as the northern coastline.

The aim of this section of the present study is to identify the distribution and zonation of intertidal and sublittoral fringe organisms in key habitat types, and to compare their ecology to adjacent or similar coastlines. Particular emphasis is placed on areas identified by previous workers as being of critical importance and wherever possible comparative data collection methods are used.

MATERIALS AND METHODS

A total of fifty-four intertidal sites were sampled during the summer (July and August) and during the spring transition period (February and March) of 1986 (figure 3.1). These sites were chosen either because they had previously been used as monitoring stations (Price et al., 1984), or to give a representative example of each habitat type under different environmental constraints. Data collection included measurements of the intertidal profile from extreme high water to low water, collection of sediment samples, air and water temperatures, salinity and tidal range. Replicate collections of macrobiota (those retained by a sieve with a mesh size of 0.5 mm) were taken for identification where this was not possible on-site. The mesh size of 0.5 mm was selected following research into the literature. Some workers have used a mesh size of 1.0 mm which speeds up the process of sieving and washing but which many other workers have shown results in the loss of a number of organisms. Lewis and Stoner (1981) provide a very good account of a comparative study in which this particular method was used. They showed that the use of the larger mesh size resulted in the under-sampling of the species retained by a 0.5 mm mesh by as much as 50% and that many of the species lost were of both numerical and ecological importance. Wherever possible quantitative estimates of the dominant intertidal biota were made using 0.25 m^2 quadrats or 1178 cm^3 core-samplers. This volume for the core sampler represents a coring tube of 10 cm diameter taking out a core 15 cm deep. The quadrat and core measurements were selected following experimentation with several core sampling tubes and various quadrat sizes in a previous study undertaken in Bahrain (See Price et al., 1984).Lewis and Stoner (1981) have shown a slightly smaller core size used more frequently to be more effective. However, certain macrofauna were encountered during the previous study (Price et al, 1984) which were beyond the size limitations of a smaller coring tube. The depth of the core sample was also based on the results of this previous study with respect to the maximum depth for the seagrass rhizome/root system. The methodology employed was dependent on the substrate-type encountered. In addition, snorkel surveys were made to characterise the shallow sublittoral, descriptively identifying this adjacent habitat type and the species it supported. Habitat photographs were taken at all sites. Sediment samples taken at all major sites were frozen until processed. Each sample was then washed in fresh water to remove the salt content and oven-dried at 100 C for 24 h before sieving through a standard sieve series and weighing the sieved fractions. (Buchanan, 1984).

All identifications were made principally from Newton (1955), den Hartog (1970), Basson et al (1977), Jennings (1981), Jones (1986a) or from other authorities used by the taxonomic experts working on the study (see Acknowledgements) and cited in the Bibliography. Species authorities are those listed in these references.

Detailed descriptive notes were kept on the intertidal habitats visited. These notes along with other intertidal data collected by the author between 1983-89, photographic records (from land and low level aerial surveillance) and grain size analysis assisted in the preparation of a set of intertidal habitat maps. The base layout of the maps was taken from a False Colour Image of Bahrain developed from a Landsat Five image recorded on the 16th February, 1985. Percentage cover of intertidal and sublittoral fringe habitat types were estimated from the original hand-drawn habitat maps of the main and offshore islands along with the low level aerial reconnaissance photographs.

RESULTS

Appendix 3.1 lists all the intertidal sites studied in Summer, 1985 and Spring, 1986. Table 3.1 gives substrate descriptions for each intertidal site along with mean sediment particle sizes where relevant. Temperature and salinity data can be found in appendix 2.1.

1. Rocky or Mixed Rock and Sand Shores

Table 3.2 presents the main faunal and floral components to zonation on the rocky shores studied around Bahrain in summer (July, 1985). Although the rocky shores studied varied widely with regard to slope and therefore the area exposed at different levels of the tide, there are obvious similarities in the organisms inhabiting these shores. Distinct bands or zones of both flora and fauna are present on all shores. Because of the mixed sand and rock nature of many of Bahrain's shores and their flat profile, it is often difficult to distinguish these zones clearly and key biotic elements may be absent or masked. It is possible that these mixed habitats may support their own distinctive communities and that these could be significantly different to those `pure' communities supported by the individual component habitats.

1.a Littoral Fringe

Nodolittorina subnodosa and a black zone of Cyanobacteria are characteristic indicators for this zone. In sheltered positions, (e.g. Hawar Islands) Planaxis sulcatus may replace N. subnodosa, otherwise the former occurs below N. subnodosa. Ligia will also be found under stones or in crevices. Chthamalus malayensis may occur at the lower levels of this zone and often extends into the eulittoral.

1.b Upper Eulittoral Zone

This zone is marked at the highest level by the occurrence of a second chthamalid barnacle, Euraphia sp. nov. On the higher shore it is often found under stones, appearing exposed further down the shore. Below Euraphia it is usual in the Gulf to find a Crassostrea cf. margaritacea zone (Jones, 1985). However, this is poorly developed in Bahrain and although evident at Causeway North (850729) this zone was absent at most sites and replaced by the hammer oyster, Isognomon dentifera, in the Hawar islands (850821, 850811). The mussel, Brachydontes variabilis, is often associated with the hammer oyster and extends right down the shore. Below the oyster zone it is usual to find Balanus amphitrite, although, again, it is rare to find a sharp zonation represented by a clear band of barnacles. The BDF jetty (850810) south of Ras al Qurayn on the south-east coast and other vertical (usually man-made) surfaces provide exceptions.

The flora of the upper eulittoral is very poorly represented during the summer study. Few green algae are present and those that are recorded such as Enteromorpha, Ulva, Chaetomorpha and Cladophora spp. never dominate the shore. Acetabularia calyculus forms a characteristic species where a thin sand layer is present, but is often seen to be in the process of dying back. Mobile elements of the fauna of this zone include the crabs Petrolisthes rufescens and Metopograpsus messor as well as the gastropods Lunella coronatus and Euchelus asper. Many of the common, mobile species are less obvious in the summer, especially from the mid-shore upwards, but are more apparent during the winter/spring period.

1.c Lower Eulittoral Zone

During the summer, much of this zone remains inundated and supports a much richer biota. It is marked in Bahrain by the growth of algae wherever rock surfaces appear above the sand. Common species include Chondria sp. and Dictyosphaeria cavernosa together with Laurencia sp. These species appear to cope best with sand. In cleaner regions such as Budaiya and Hawar Cystoseira myrica dominates. Towards the lower end of this zone, Hypnea, Spyridea and Hormophysa dominate, although the latter in particular was dying back in July. Amongst the sheltered islands behind Jazirat Hawar, this zone displayed almost complete algal cover and an algal turf of various red and brown algae extended down into the sublittoral zone.

Elsewhere, the lower eulittoral is marked by the presence of Pomatoleios colonies, often under stones at the highest levels. Although always present, these do not form an obvious zone in Bahrain and are often mixed with tunicates (Styella canopus, Phallusia nigra) and the bivalve mollusc, Malleus regulus which may be more obvious.

The lower edge of this zone is denoted by the occurrence of Serpulorbis sulcatus, Chama aspera and an increasing diversity of sponges (Halichondria, Haliclona, Gellius etc.). The mobile fauna is dominated by cerithids (Cerithium scabridum) and the herbivorous gastropod, Priotrochus obscura. On shores in higher salinity areas (South Hawar, 850813; North Hawar, 850811) a black colonial tunicate often dominates the lower eulittoral at densities of up to 20 m^{-2}.

1.d Sublittoral Fringe

This zone is marked botanically by the appearance of Hormophysa triquetra reaching lengths of 1-2 m. Also associated with this zone are Avrainvillea amadelpha and a variety of red algae. Coralline algae is recorded on bare rock and Sargassum sp. are apparent on the south eastern coast near Ras al Barr, and in small patches off Budaiya as well as off the shallow west coast of Hawar. Coralline algae has been recorded in the Arabian Gulf as Lithothamnion sp. (Basson et al, 1977; Jones, 1986a) while Walker (1987) lists Porolithon and Melobesia for the Red Sea. Faunistically the sublittoral fringe is marked by the large hydroids Dynamena cristoides and Thyroscyphus fruticosus (Ras al Barr, 850801; Budaiya, 850723). Sponges occur in profusion together with spat and juvenile Pinctada radiata. Balanus tintinnabulum clearly marks the sublittoral on vertical surfaces such as the BDF jetty at Ras al Barr. Typical mobile species include the crabs, Dardanus tinctor, Portunus pelagicus and Thalamita poissoni. The goby/alphaeid shrimp association (Cryptocentrus cryptocentrus/Alpheus djeddensis) is a common feature of the shallow sublittoral wherever sediment is present in sufficient depth.

The most exposed shores are to be found to the north of Bahrain, but although these possess a rich biota from the mid-tide downwards, all show severe impact from oil-spill and/or infill at higher levels. The only rocky shores showing no signs of contamination by oil are those in the shelter of Jazirat Hawar. In the absence of continuous or heavy wave action and due to their steep profile, these probably represent the best examples of undisturbed rocky shore communities in Bahrain.

During this study some new records for Bahrain have arisen including a new excirolanid isopod, an animal usually associated with soft habitats, found for the first time in a rocky shore habitat (e.g. Zallaq, 850727).

2 Sandy Shores

Table 3.3 presents the main macrobiotic components to zonation on sandy beaches studied around Bahrain in summer (July, 1985). Although sand is an almost universal feature of the littoral fringe of Bahrain, in many cases it is either too shallow, too coarse or too patchy to support a sand beach fauna. Pure sandy beaches are rare around Bahrain and only three were studied in any detail at Ras Hayyan, Galali and the southern shore of the island of Mashtan.

Examination of sediment particle sizes from table 3.1 together with data in table 3.3 shows that it is difficult to define sand beach biota in terms of particle size range. Generally, typical species occur in beaches with particle sizes ranging from 280-800 um m.p.s. (median particle size). However, many exceptions are found (e.g. Ras Hayyan), probably reflecting the mixed nature of rock and sand together with the poor sorting of sediments in the absence of wave action and large tides. This is especially so to the east and south-east of Bahrain in the sheltered waters where most of the sandy beaches are to be found. None of the sites studied displayed a typical sand beach biota across the entire intertidal zone. Ras al Barr, Ras al Mumtallah and Ras al Qurayn display typical upper shore sand biota but rocky shore biota on the lower shore. Galali has a mixed rock-sand upper shore biota, but typical lower sand shore fauna and flora. The island beaches of Mashtan and Um Jalid approximate most closely to typical sand beaches, although once again many elements are absent on the mid-shore where sand depth is minimal.

Despite the absence of typical sandy beaches it is possible to observe all of the sand beach biota at one site or another and thus classify the biotic zones for the intertidal sand habitats of Bahrain.

2.a Littoral Fringe

Characterised by Ocypode rotundata occurring in densities of up to 3 burrows m^{-2} on offshore islands usually above the height of the last tide. Orchestia platensis is common under weed or debris on the high tide line. Tylos maindroni is found on semi-exposed shores but is absent on sandy mud flats. Oligochaetes are present in high densities at this tidal level.

2.b Eulittoral Zone

The upper edge of this zone is sharply delimited by Eurydice peraticus on semi-exposed shores (Ras al Mumtallah, Ras al Barr, Mashtan) and by Excirolana orientalis on exposed shores (Um Jalid). On more sheltered shores Scopimera crabricauda dominates the high shore in the absence of Ocypode and cirolanids. Several polychaetes are characteristic of the upper eulittoral and often occur in high densities (120 m^{-2}, Ras al Qurayn). Gastropods typical of the mid-beach area are Mitrella blanda, Umbonium vestiarium and Nassarius plicatus. Where the sand is shallow Cerithium scabridium appears feeding on attached algae, and where sediments become muddier, Cerithium cingulata dominates. In areas of higher salinity Pirinella conica replaces C. cingulata. Burrowing bivalves found in sheltered sand beaches include Circe calypyga, Meretrix meretrix, Dosina sp. and Ancilla castanea. At Ras al Qurayn and Galali Macrophthalmus spp. are present. These are predominantly M. depressus at Ras al Qurayn but at Galali M. grandidieri and M. telescopicus are also noted at different times of the year on different areas of the beach. M. telescopicus is found on the lower shore in summer and M. depressus and M. telescopicus occur on the top shore in winter, the latter in tidal pools.

Surprisingly on sheltered beaches such as Galali and Ras al Qurayn the pioneer seagrass, Halodule uninervis, occurs in the lower eulittoral where standing pools are present or sand remains sufficiently moist between tides. This has been recorded previously in Bahrain at the Askar North site (Price et al., 1984). If the sediment is muddy this species may be accompanied by Halophila stipulacea.

2.c Sublittoral Fringe

Where soft sediment predominates seagrasses are almost always present, the exception being where a substrate is too mobile (e.g. Qit al Jaradah). The distribution of the three species (Halodule uninervis, Halophila stipulacea and Halophila ovalis) appears to be related to depth and substrate type.

The infauna is dominated by polychaetes and the scaphopod, Dentalium octangulatum as well as bivalves (mostly juvenile). Portunid crabs and penaeid shrimp (Metapenaeus stebbingi) are common mobile elements. The goby/alpheid shrimp association often dominates extensive areas of soft substrate in the shallow sublittoral.

Where soft sediments continue into the sublittoral zone they are characterised by productive seagrass beds and a rich infauna of bivalves and polychaetes. Where the sediments merge into rocky substrata the lower shore is characterised by a rich algal flora dominated by Cystoseira and Hormophysa which in turn support a predominately molluscan fauna (e.g. Pinctada sp. and Malleus regulus) as well as sponges, hydroids and epiphytic algae.

3 Muddy Shores, Mangrove and Saltmarsh

Table 3.4 presents the main macrobiotic components to zonation on muddy shores studied around *Bahrain in summer (July, 1985).*

Muddy shores are the least common intertidal habitat in Bahrain. Nearly all examples are found within Tubli Bay with exceptions at Askar and in the Hawar islands. Of all the sites visited, only three contained small stands of the mangrove, Avicennia marina. At Ras Sanad and Al Ak infill is already encroaching upon the mangrove and smothered plants are noticeable. At both sites the untouched mangrove is healthy and showing evidence of colonising fresh mud and drainage channels. The third site by the outfall at Khawr Mugli is also healthy with flowering and seeding bushes.

3.a Landward Fringe

This is characterised by saltmarsh at most sites with a strong growth of Salicornia herbacea and Arthrocnemon macrostachyum. In areas where these are absent (Al Ak due to infill) mats of *Cyanobacteria may be present. Where low salinity run-off occurs* (Jurdab) Juncus rigidus or Phragmites communis are found. Characteristic fauna included Metopograpsus messor (which digs burrows in this habitat), Eurycarcinus orientalis, and in softer muds Nasima dotilliformis. All of these species occur above the Avicennia zone, but are not found on mud flats in the Hawar Islands.

3.b Avicennia Zone

This extends from high tide to just below mean sea level and was best developed at Ras Sanad with 100% cover and bushes reaching 1.5-1.7 m in height. The three crabs Nasima dotilliformis, Metopograpsus messor and Eurycarcinus orientalis extend throughout the zone. N. dotilliformis reaches highest densities (85 m^{-2})on the landward fringe and disappears on the seaward side of the mangal. M. messor and E. orientalis are more numerous at mean sea level with concentrations of 35 m^{-2} and 5 m^{-2} respectively. M. depressus burrows into the soft mud below the mangal and extends down to the low tide. Planaxis sulcatus is common on the leaves and trunk of Avicennia marina replacing the specialised Littorina sp. found elsewhere in the Indian Ocean region (Macnae, 1968). A freshwater gastropod Melania tuberculata is also found on Avicennia plants at Ras Sanad. The mud snail Cerithidea cingulata reaches highest densities for juveniles on the landward side and for adults on the seaward fringe of the Avicennia. Further studies of this area in February revealed the presence of Ilyoplax frater between mid-tide and low water with Metaplax indicus merging in as a relatively rare species toward low water. It is now apparent that the mangal habitat supports all of the species of crab found associated with other various mud habitats elsewhere in Bahrain.

A similar pattern of zonation is present at Khawr Mugla and Al Ak although the outfall and landward disturbance produces minor modifications. At Al Ak where the Avicennia are more diffuse the tiny crab Ilyoplax frater extends down beyond the seaward fringe. It is also notable that on the open shore and at Al Muwayligah, where Avicennia is absent, the same crab species occur with a similar zonation. However, all of these species were absent from the high salinity mud flats in the Hawar islands.

3.c Lower Shore

At Ras Sanad the open mudflat beneath the Avicennia is colonised predominantly by Macrophthalmus depressus and adult Cerithium cingulata. Where sandy areas occur at a similar level on other shores Macrophthalmus sp. or Scopimera crabricauda are present and in softer, water-logged areas Metaplax indicus and Alpheus lobidens burrow (M. indicus was present in the mangrove zone but only in small numbers nearer low water). Where the mud is sandy, extensive mats of cyanobacteria extend down towards low tide. These are a common feature of mud flats in the Hawar islands and under these high salinity conditions appear to be associated with extensive populations of Pirinella conica.

At low tide the flow through the creeks at Ras Sanad produces a coarse, sandy sediment, while elsewhere muddy shores merge into seagrass beds dominated by Halophila stipulacea in the summer and a reduced cover of Halodule uninervis and very sparse H. stipulacea in the winter. In all cases infaunal populations of polychaetes, bivalves, amphipods and interstitial fauna are high, providing rich feeding grounds for birds, penaeid shrimp and juvenile fish.

Seasonal Changes

Some animals and plants, especially the less mobile organisms, have a seasonal life-cycle. Many of the algal species recorded for the intertidal zone in Bahrain have restricted growth periods often associated with the transition between winter and summer. This has also been noted by Basson (pers. comm). Other faunal components of the intertidal zone such as the Swimming Crab (Portunus pelagicus) and the Upside-Down Jellyfish (Cassiopeia andromeda) tend to be found in the intertidal zone only during the cooler, winter months. P. pelagicus moves off into the subtidal during the summer (Price et al., 1984). The seagrass, Halodule uninervis, is found in the intertidal zone during the summer months. At Galali, all three species of seagrass can be found in the lower shore intertidal zone while H. uninervis is found in the eulittoral zone wherever the sand remains moist between tides.

The red algae such as Chondria dasyphylla, Ceramium spp, Laurencia spp. and Polysiphonia spp. are found on more exposed shores in the winter and the early transition period while the green algae are virtually absent. Some brown algae persist but are stunted, sparse and often covered with red algal epiphytes. In the summer the red algae are noticeably absent from the eulittoral being restricted to the sublittoral and sublittoral fringes. On less exposed shores Enteromorpha spp. and Ulva spp. can totally dominate the shoreline with 100% cover during the transition from winter to summer but are completely absent during the summer season itself. Conversely the stunted Hormophysa triquetra and Dictyosphaeria spp. found in February and March are seen to be fully grown and much more dominant on the shoreline by late August. Other algae such as Caulerpa sertularioides and Acetabularia sp. seem to be more capable of withstanding the summer extremes but are absent in the intertidal during the winter and early transition period.

Most of the fauna adapts by sheltering, although it is noted that Rhinoclavis sordidula is present in significant numbers (30 m^{-2}) at Budaiya and Zallaq in February but is rare or absent at the same sites in July. This could be due to the reduction in the primary food supply in summer as this species feeds on algae and plant detritus. Animal species that are recorded out in the open during the winter are mostly to be found under rocks or stones in the summer.

On sandy beaches, mobile organisms escape the direct effects of desiccation or extreme temperature by burrowing. The fauna on all sandy beaches are reduced in numbers of individuals (generally by up to 50%) during the summer months with the exception of Macrophthalmus depressus at Ras Hayyan where numbers are higher in the summer (16 m^{-2}) than in the winter and early transition period (3 m^{-2}). Also noticeable at Ras Hayyan were the large numbers of Pirinella conica (1600 m^{-2}) in and around pools on the upper shore. These were undoubtedly associated with the extensive mats of cyanobacteria found in this area during the summer. Certain species are not found in the winter but are recorded from February/March onwards. These included Ilyoplax frater, Umbonium vestibularium, Diopatra sp. and Zoobotryon verticillatum. During the winter and early transition period there is a lowering of activity among the more mobile fauna such as the crabs.

Macroalgae on a sandy beach are restricted to areas providing a suitable substrate for attachment. Green algae dominate during February but are restricted to the low-tide zone and intertidal fringe where rock substrate occurs. These algae are rare or absent in the summer season and no reds are recorded at any of the sites. Seagrasses showed a marked seasonal variation in distribution. On sandy beaches in July, Halodule uninervis extends into the eulittoral with up to 50% cover recorded and in the intertidal fringe the grass beds are dense. During the winter months this surface growth dies back to about 5% cover with dead leaves and only the vestiges of stalks. Even the rhizomes are reduced in extent and large areas of the beach are washed-out due to the loss of the binding and stabilising effect of the root system. Chaetomorpha sp. is found around low-tide at Galali in February with a 30% coverage.

The Ghost crab, Ocypode rotundata, also displays seasonal behaviour. The towers built by this species along the high-tide mark in summer are absent in winter. On the island of Mashtan the crabs migrate over to the south eastern side of the island. The remnants of burrows were seen although no towers were found.

The crustacea constitute the principal macrofauna on muddy shores along with cerithid gastropods in some areas, particularly in the mangal ecosystem. Crab numbers are noticeably higher (Ilyoplax frater = 200 m^{-2} in July and 120 m^{-2} in February at Al Muwayligah) and crab species are seen to be active at all sites in summer, but are restricted to their burrows in the winter. Interestingly, Metaplax indica is recorded in July but there is no evidence even of its burrows in February. Cyanobacteria dominate the top shore flora in July with the lower shore consisting of exposed, bare mud. In February, the top shore is dominated by green algae that had been washed up on the tide with the lower shore covered (100%) with a thick blanket of unattached, drifting green algae.

Within the mangal ecosystem, Avicennia marina flowers and produces fruits in July. By February the products of this fruiting are seen on the mid-shore and on the seaward edge of the mangal as young seedling mangrove plants a few centimetres high. Cladophora koiei is found on the seaward edge of the mangal in February with 30% cover but is replaced by Ulva sp. in summer. These algae, along with Chaetomorpha sp. and a number of other species, form carpets around the aerial root system of the mangrove plants. Water in the channel between the mangrove stands supports a rich algal bloom in February. Mysids are seen in large numbers in February in the channels and pools and appear to feed on the algal bloom. The cerithids which are normally present within the mangal community are significantly more abundant as adults in summer (> 400 m^{-2}) than in winter (< 10 m^{-2}) probably because of the increased density of cyanobacteria and Ulva sp. on which these molluscs feed during the summer. The adult Cerithidea cingulata are found on the lower shore while the juveniles live up among the mangroves in the high-tide zone.

Intertidal and Sublittoral Fringe Habitat Maps

Volume 2, figures 3 - 9 represent the recorded habitat types for the intertidal and sublittoral fringe from the landward fringe (the edge of terrestrial vegetation) out to a depth of approximately 2 m below mean sea level. The main coastline and islands have been divided up into six sectors (northeast, northwest, east, west, south and Hawar). The habitats are assigned to eight categories as discussed below. Percentages quoted represent the percentage cover of that habitat for that sector of the coastline (see table 3.5).

Algae (A): Macroalgal cover on rocky shores and shallow subtidal (as opposed to bare rock). This was characteristically Hormophysa triquetra which grows in thick stands along the eastern and southeastern sublittoral fringe of the main island of Bahrain and along the western coastline of Hawar. This classification was therefore common on the eastern and southeastern coastline (15% in both cases) and around Hawar (19%) but rare for the northern coastline and almost absent on the west coast.

Seagrass (G): Records the presence of any of the three species of seagrass noted during this study. The greatest percentage of seagrass cover (24%) was found in the eastern and southern sublittoral fringe of the main island and the islands off the east coast. There was very little seagrass (2%) recorded for the west coast sublittoral fringe.

Mangrove and Saltmarsh (T): A rare habitat category for Bahrain denoting the presence of Avicennia marina along with associated halophytes. This category was only recorded in the northeastern sector at Tubli Bay and even in this sector it only represented 6% of habitat cover.

Muds (M): Also a rare habitat category. The actual habitat type and the fauna and flora it supports are described in the main text. The highest percentage presence of this category (8%) was in the northeastern sector in the shelter of Tubli Bay and other low energy areas. Low percentages were also found in the northwest (1%) and eastern (3%) sectors and in Hawar (2%).

Sand (S): A common category found throughout the whole study area and consisting of coarse to medium grain size. Lowest percentage cover (17%) was recorded for the northeastern sector with highest presence in the west (40%), northwest (33%) and southern (32 %, particularly southwest) sectors. Sand represented 23% of the habitat types recorded for Hawar. This category is described in the main text.

Fine Sand (F): This was not a common category and is also described in the main text. Highest presence was in the north east (6%) and east (7%) with little to no fine sand categories recorded for the more exposed northwest coastline.

Rock (R): This was also a rare category with the greatest percentage of rocky shoreline (10%) recorded on the northeastern coastline. Hawar has some rocky habitats also (3%) but this category was almost absent from the southern sector .This category represents bare rock not supporting macroalgae and is described in the main text.

Mixed (X): Not surprisingly, the most common category of habitat type. The mixed category represents intertidal and sublittoral fringe which shows elements of two or more other categories which are intermixed so as to be inseparable. Characteristic of this habitat type would be rock with a thin covering of sands and occasional algal growth. Mixed habitat coastline was particularly common around the north and west (34-55%) of the island and around Hawar (37%).

DISCUSSION

Tables 3.1 to 3.4 contain detailed descriptions of all the major sites visited during the summer study and it is clear from these that the rocky cliffs in the Hawar Island group (850820, Jazarit, Ajirah and Hawar back island sites) show the most distinct patterns of zonation. On Bahrain main island the clearest examples of zonation are seen at Budaiya (850723), Zallaq (850727) and at the B.D.F. jetty (850810), although upper shore elements are missing from the former two sites.

Table 3.1 gives general habitat descriptions and outlines the intertidal and subtidal habitat types for each site. It also lists those habitats already modified by human agency ranging from oil or sewage pollution to infill and the modification of natural habitats. Examination of detailed site data shows that such perturbation has been greatest along the north coast of Bahrain, to such an extent that it is not possible to find any example of an unmodified shore. Undisturbed shores were usually found to the south and west of Bahrain and on offshore islands, particularly the Hawar group.

For this reason it is necessary to use caution in defining the effects of the north-south salinity gradient on intertidal biota. The rocky shore algal diversity appears to be highest in the Hawar islands where salinities ranged from 48 ppt to 50 ppt or more. Similar clean rocky habitats were absent in the north of Bahrain where salinities were at their lowest (42 ppt). Certainly on the west coast of Jazirat Hawar eulittoral communities were dominated by a single tunicate species. However, this may simply reflect the admixture of sand and rock at these sites.

Higher salinity ranges are probably responsible for the sparse biota found on soft substrate shores in the Hawar Island group. Pirinella conica is an excellent indicator of salinity stress (Jones et al, 1978) and its appearance in Hawar as a replacement for Cerithidea cingulata may be taken to show that salinity levels are too high for most of the typical sand and mud biota. P. conica also dominates communities in the Al Jasrah area where raised salinities are an important feature. The Killifish, Aphanius dispar is also commonly found in high salinity waters. In Bahrain, A. dispar occurs in both fresh water and very saline water and has been observed transferring from one to the other in a matter of seconds without any obvious signs of stress. These fish also thrive in the hypersaline waters of Lawzi Lakes in central Bahrain where salinity is greater than 180 ppt. High salinity levels may also explain the absence of the mangrove, Avicennia marina, from otherwise suitable sites in the Hawar Islands. Recent planting of Avicennia marina in this region has been unsuccessful, producing only small stunted bushes (pers. comm., University of Qatar) although there is some uncorroborated evidence that very reduced stands of mangrove may have once existed on the bays on the east coast of Hawar, and that a few plants may still be struggling to survive there.

Caution has to be exercised in the interpretation of the data on faunal zonation in relation to sediment gradation and tidal zonation. Wave energy may well have a sorting effect during the accretion of sediments, but the effects of seasonal temperature gradients may be equally important. Jones et al. (1987) note that on sheltered shores where the sediments are graded, Macrophthalmus telescopicus is found in muddy sands and Macrophthalmus depressus in sandy muds. This is related to the organic content of the sediments with sandy mud having a higher organic content. However, the results from this study show that M. depressus was common in the finer muds associated with the mangrove. Reference to tables 3.3 and 3.4 also confirms this with M. telescopicus representing a main faunal component of sandy beaches in Bahrain and M. depressus of muddy shores. Furthermore, various species of Macrophthalmus are to be found inhabiting different zones on the beach at different times of the year.

Despite perturbation the lower shore and shallow sublittoral regions around Bahrain are zones of high productivity with macroalgae, seagrasses and cyanobacteria all contributing to food webs supporting commercial fish and shrimp species. The importance of benthic rather than planktonic primary productivity in the waters around Bahrain has been identified by the author in previous studies (Price et al., 1984; Vousden, 1985b) and is a research area that is certainly in need of further attention. There is growing evidence that the intertidal and shallow sublittoral areas are essential to some stages in the life-cycles of many commercial species (Basson et al., 1977; Jones, 1985). Jones (1985) identifies the fact that primary productivity throughout the Gulf is unlikely to be limited by light, but shows evidence of nutrient limitation, particularly in deeper waters where a summer thermocline exists. Basson et al. (1977) have found that primary productivity is highest in mixed waters and shallow bays. Jacobs et al. (1981) recorded spring and late autumn peaks in chlorophyll within Kuwaiti waters. Chlorophyll-a levels are much higher in the Gulf of Oman and Northern Arabian Sea especially during the monsoon upwelling (Jones, 1985). The inner part of the Arabian Gulf is, by contrast, impoverished in terms of both phytoplankton and zooplankton species when compared with the Gulf of Oman and Arabian Sea. Zooplankton biomass is also higher in the Gulf of Oman than in the inner Gulf (Krey, 1973).

A Rocky or Mixed Rock and Sand Shores

Comparison with data from other Gulf rocky shores is difficult in view of the lack of data both for other areas and seasons. Table 3.6 summarises the available data for typical rocky shore species zonation within the region. The representative biota vary from typically warm temperate in the north of the Gulf (Kuwait and north west Iran) to tropical in the central Gulf and Gulf of Oman returning to warm temperate once more in the upwelling region of southern Oman. This is reflected in the rich and diverse macroalgae present in the warm temperate regions of Kuwait, north west Iran and southern Oman. Zones of Pomatoleios kraussi are typical of these regions along with a noticeable absence of hermatypic corals which only start to appear in the most southerly areas of Kuwait. In contrast to this the shores of the central Gulf are restricted in macroalgal cover and Pomatoleios is only found intermittently in the shade of rocks while the sublittoral of the central Gulf is marked by the presence of reef-building corals. Biotic diversity increases on reaching the rocky shores of Oman and starts to parallel that of the Indian Ocean. Variations in temperature, limited freshwater input and related salinity are mainly responsible for these differences. However, the restriction of low spring tides to night time in the summer as discussed in Chapter 2 encourages the survival of temperate species in Kuwait and Bahrain. .

The Hawar Islands represent an important topographical extension to the flat, mixed sand and rock shores described for the east coast of Saudi Arabia (Basson et al., 1977) and Kuwait (Jones, 1986b). This is supported by the present species lists for this study which exceed those recorded for Saudi Arabia (Basson et al., 1977) even though detailed quantitative data was only collected for one season.

An obvious difference between the rocky shores of Kuwait and Bahrain is the general absence of a zone dominated by Pomatoleios and Balanus amphitrite, both of which are characteristic of Kuwait's rocky shores (Jones, *1986b). Similarly,* Crassostrea *is never obvious in Bahrain* and is often replaced by Isognomon (table 3.2). At lower levels on the shore, Colpomenia is not obvious in Bahrain during the summer period and zoanthids and Sargassum are not common in the shallow sublittoral. Although the solitary coral, Paracyathus is found in Bahrain, it is generally limited to deeper (> 5 m) water or to offshore areas (the outer reef flats near Muharraq). Other corals are common in the shallow sublittoral zone. In Qatar, which has a coastline adjacent to Bahrain, corals dominate this area on the more sheltered rocky shorelines (Jones, pers. comm.).

A *difference in temperature regimes* between the northern Gulf and Bahrain may explain some of the differences in biotic character. The particular seasonal changes in temperature characteristic of the intertidal and shallow subtidal zones of Bahrain may further explain differences in the biota. The contrast in salinity maxima and minima between the two areas must definitely play a part. The low diversity and distribution of coral fauna associated with the sublittoral fringe in the Hawar islands is almost certainly a direct result of this salinity regime with measurements averaging between 48-52 ppt (In Qatar, eastern coastal salinities do not exceed 42 ppt). It is quite possible that turbidity is limiting the growth of some tropical species. Along the north coast salinity and temperature levels are less extreme. However, long wavelength swells from the open Gulf meet the shallow waters around Fasht Jarim and along the north coast lifting sediments and loose substrates into suspension. Once suspended it does not require much wave energy in such shallow water to keep material in suspension, therefore turbidities remain generally high off the north coast throughout the year.
The Hawar Islands have the best examples of undisturbed rocky shoreline and certain areas should be set aside as part of a coastal management and protection strategy. On the other hand, most of the northern coastline of the main island and Muharraq has already suffered from considerable human impact caused by oil pollution and reclamation. There is probably little point therefore in attempting any form of coastal environmental protection or conservation along the north coast and it may be more wise to consider this area as a `sacrificial' zone to balance the need for stronger protection around Hawar.

B. Sandy Shores

Physical factors such as tidal range and topography preclude the development of typical sand beaches in Bahrain. The shallow water and sheltered nature of much of the coastline prevent good sorting of sand material. A wide species diversity is encountered with elements of rocky shores (such as the gastropods Cerithium scabridum and Lunella coronatus) occurring together with sand biota. This is reflected in the widespread distribution of the 'mixed' habitat category in the intertidal habitat maps (Volume 2, figures 3 - 9). Sheltered beaches are best developed to the south of Bahrain on both the east and west coasts. On the top shore the dominant macrofauna is Ocypode rotundata (e.g. Mashtan and Um Jalid, see table 3.3). Offshore islands to the north-east and east of Bahrain provide the best examples of exposed sand beaches characterised by Excirolana orientalis. These beaches quickly merge into extensive seagrass beds in the shallow sublittoral.

Table 3.7 shows the typical sand beach inhabitants recorded from other parts of the Arabian Gulf (after Jones, 1986b). Despite evidence of recent oil pollution most of Bahrain's sandy beaches exhibit a diverse and healthy macrofauna with densities at least as high as have been recorded for other parts of the Gulf, (Basson et al., 1977; Jones, 1985). A higher diversity of biota on sandy beaches in Kuwait when compared to the rest of the region is apparent from table 3.7. Although this may be a partial reflection of the diurnal/seasonal tidal phenomenon explained above, it is also partly an indication of the greater volume of field research carried out in Kuwait. Throughout the region exposed beaches have low diversity compared to sheltered muddy sand beaches.

Certain species characteristic of sand beaches elsewhere in the Gulf were not found in Bahrain. On sheltered shores several crabs such as Paracleistostoma, Dotilla and the fiddler crab Uca lactea annulipes, were absent as they also are from Qatar and Saudi Arabia. As these species coexist with Scopimera in the northern Gulf it would appear reasonable to assume that suitable habitats do exist in Bahrain (Jones, pers. comm.). Comparative studies on the physiological tolerances of these species may identify possible physical factors which might be excluding them from the sandy beaches of Bahrain. Emerita holthuisi and several of the sandy shore echinoderms (Holothuria arenicola, Echinodiscus, Clypeaster) require deep sediments for burrowing which are rare on the lower shore and shallow subtidal.

Sand beach biodiversity is lower than is found in the open Indian Ocean, several species such as Paracleistostoma and Uca sindensis appear to be endemic to the Gulf and although true sandy beaches are rare around Bahrain, good examples such as Mashtan, Jaradah and parts of Hawar should be afforded some level of protection. The sandy coastlines of certain offshore islands and less accessible parts of the mainland provide important nesting areas for birds such as White-Cheeked Terns and these areas should also be given serious consideration in any conservation strategy for the islands.

C. Muddy Shores, Mangrove and Saltmarsh

Naturally occurring muddy shores are rare in Bahrain and are essentially represented in a small area of the open coast in the Askar region and in Tubli Bay. Muddy shores on Hawar are dominated by mats of cyanobacteria and characterised by an extremely restricted fauna of low diversity tolerating high salinities.

In the northern Gulf (Kuwait, Iraq and the northern coast of Iran) salt marshes are common but mangroves are absent. Both may be found to coexist throughout the rest of the region. Table 3.8 compares the main biotic components of muddy shores for the Gulf, Indian Ocean and Red Sea. Within the Gulf the mangal community is based on a single species of mangrove, Avicennia marina and hence diversity is far lower than is characteristic of mangals outside of the Gulf ,although representatives of most of the characteristic faunal zones are present (Jones, 1985). In the absence or paucity of mangroves it is the salt marshes, cyanobacteria mats and diatoms which appear to be the basis of the food web.

The absence of many classic Arabian Gulf muddy shore inhabitants from Bahrain is almost certainly due to the limited extent of this habitat. Four mudskippers exist on the extensive mudflats of Kuwait together with 17 species of ocypodid crab (Jones, 1986a, Jones and Clayton, 1983). One mudskipper, Periophthalmus koelreuteri, certainly extends to Qatar and fiddler crabs are found in Oman (Jones, pers. comm). However, as mangrove is now extremely limited in Qatar and receding in Saudi Arabia, natural recruitment of mangal fauna from outside Bahrain is unlikely.

Despite the small stands remaining in Tubli Bay the mangrove is healthy and possesses a characteristic fauna with densities of macrofauna higher than anywhere else in Bahrain. Evidence of the high productivity of these areas is supported by the presence of flamingos and large numbers of other wading birds together with shoals of juvenile fish and shrimp. The future well-being and continued productivity of the coastal fisheries and the Tubli Bay shrimp fishery, in particular, is almost certainly dependent upon the continued existence of such areas. In addition, the present construction of marinas and other coastal structures can be seen to be providing sheltered areas where fine sediments are deposited. Colonisation of such new mud habitats will only occur rapidly and effectively if existing reservoirs for recruitment remain. It is unfortunate that the sheltered and easily accessible nature of muddy habitats and saltmarshes attracts development. Furthermore, their appearance and characteristic odour tend to classify such habitat types as expendable to those who do not understand their biological importance. Consequently, it is the mudflats and mangrove stands around Bahrain which are most rapidly disappearing under land reclamation schemes and which are most in need of protection.

Seasonal Changes

Most of the shoreline of Bahrain consists of mixed shores of intermittent rock and sand, rock with a thin cover of sand or plates and boulders of rock scattered across sand on gravel. As there are few examples of pure sand or mud coastline there is very little opportunity for burrowing. To avoid the seasonal temperature extremes the more mobile organisms must shelter in the few shaded or protected areas under rocks. The sessile organisms such as the algae have life-cycles that restrict their growing periods to the most suitable times of the year. In consequence, the shoreline blooms during the transition periods, especially between February and April, when rocky and mixed rocky shores are covered in a thick carpet of algae. The most apparent differences on the shoreline can be seen in the seasonal distribution of the plant life. The presence of stages in the life-cycles of animal species which require algae for food, settlement or shelter must also coincide with these periods of algal bloom.

Table 3.9 presents a generalised seasonal zonation pattern for shores around Bahrain showing the principal changes in intertidal biota between summer (July 1985) and winter (February 1986) although seasonal variations in zonation will depend on wave-action, exposure and topography. Changes in the percentage cover of the flora is clearly noticeable. There is a higher percentage of algal cover and a lower percentage of seagrass cover in February. Green algae are much more prolific across the whole intertidal zone in the winter. Red algae is sparse throughout the year but is more noticeable in the summer months on the mid and lower shore. Cyanobacteria are characteristic of the summer months also and are generally absent in February. These algal mats tend to crack and dry during July and August and are transported offshore during winter storms. Colpomenia is found on the lower shore in February reflecting its detachment from the reef during the winter-summer transition period. Large quantities of this plant are found floating on the surface in coastal waters in February-March and inevitably wash up on the lower shore.

Seagrass cover in the lower intertidal falls from 60% cover composed of all three species in the summer to < 1% of only Halodule uninervis in February. Jones et al. (1987) note that patches of H. uninervis may be found exposed on the lowest tides in the Red Sea, although they only flourish in depressions retaining standing water. In Bahrain, H. stipulacea is also found exposed in the summer, but only on the lower beach. H. uninervis can be found further up the beach in shallow pools on the mid-shore. During the winter, however, the above-ground component of H. uninervis dies back leaving only the rhizome complex below the surface.

The principal changes in the faunal component of the top shore is in the presence, absence or cryptic behaviour of certain molluscs. The pulmonate mollusc Onchidium and the gastropod Priotrochus are noticeable on the open topshore in winter, but concealed under rocks in July. Lunella is found in the intertidal in winter but not in the summer while Euchelus displays the opposite behaviour. Cerithid molluscs are common on the shoreline in winter, especially after blooms of green alga or cyanobacteria, but are rare or absent in summer. In the mid to low intertidal Cassiopeia and Stoichactis are found in February, but are absent in July while burrowing anemones such as Cerianthus which are seen in the midshore in summer are not noticeable in winter.

Because of the seasonal variations recorded in the intertidal biota, and in consideration of the obvious seasonal nature of bird migration and nesting, it may be necessary to include a seasonal management strategy into any coastal zone management plan in order to provide realistic protection to certain species.

Intertidal and Sublittoral Fringe Habitat Maps

The habitat maps for the intertidal zone and sublittoral fringe (Volume 2, figures 3 - 9) show a clear gradation in habitat types around the coastline and islands. The northwest and western coastline of the main island and Um Nasan are principally mixed habitat type and coarse to medium sand. This coastline is relatively sheltered with gently wave action south of the Causeway Along the north and northeastern coastline seagrass becomes more frequent in the sublittoral fringe, whereas seagrass is rare on the west coast in shallow water. The lack of seagrass in the west coast sublittoral fringe is probably a result of the thin cover of soft substrate and the mostly mixed nature of the habitat with hard substrate dominating. There is less sand present along the exposed northeastern coastline and the highest frequency of rocky shore is found in this area. The eastern and southern coasts (along with the numerous fashts, sand banks and islands) have a higher percentage of algal- and seagrass-dominated habitats than other areas of Bahrain. Substrates on this mainly sheltered coastline are much more suitable for the development of seagrass and Hormophysa triquetra thrives in the shallows. These eastern and southeastern areas have an almost equal distribution of algae, seagrass and mixed habitat types. Hawar has less seagrass than the rest of the eastern and southern parts of the study area but has the highest frequency of algal habitat. The western coast of Hawar extends out for many hundreds of metres as shallow water (< 2m) where a hard substrate underlies a thin layer of sand. This type of habitat appears to be ideal for the settlement and growth of H. triquetra which is found here in profusion.

Mangrove, mud and fine sand are the rare habitat types with mangrove only found in any viable quantity in and around the highly sheltered Tubli Bay in the northeast sector. Tubli Bay is also the only area with any significant amount of mud habitat, once again as a result of its sheltered nature.

From an estimate of the overall percentage intertidal and sublittoral fringe habitat cover for the study area (table 3.5) it is clear that mangrove and mud habitats are unique to a small area of Bahrain and in vital need of protection. Mangrove represents only 1% of the total intertidal and shallow water habitat cover of Bahrain. Mud, fine sand and rock are also rare at 3-3.5% and should also be given special consideration in any coastal management plan.

This method of mapping the intertidal and shallow sublittoral using a combination of aerial photography and detailed site visits has proved valuable in estimating habitat cover throughout the study area. However, it is manpower intensive and could not be effectively extended to the sublittoral beyond 1-2 metres. Mapping the subtidal part of the study area requires an alternative methodology.

SUBSTRATE DESCRIPTIONS, MEAN SEDIMENT PARTICLE SIZES, TEMPERATURE AND SALINITY FOR INTERTIDAL SITES - BAHRAIN, 1985.

SITE NUMBER	SITE NAME	GENERAL SUBSTRATE DESCRIPTION	INTERTIDAL SUBSTRATE	SUBTIDAL SUBSTRATE	CORE SAMPLE	PARTICLE MEAN SIZE	AIR TEMP (CELSIUS)	SEA TEMP (CELSIUS)	SALINITY (PPT)
27	Askar N (HT)	muddy sand flats; extensive	fine muddy sand	sandy mud	Fine sand	121	45	31	49
36	Qurayn 5km S (MT)	mixed rock/sand, man-modified	medium/coarse sand	fine sand	Medium sand	290	35	34	48 (58 back sabkha)
36	Qurayn 5km S (LT)	mixed rock/sand, man-modified	medium/coarse sand	fine sand	Fine sand	190	35	34	48
7	Budaiya (subtidal)	mixed rock/sand, reclamation	mixed sand/rock	sand + rock	Coarse sand	480	36	35.5	46 (70 interstitial)
21	Ras Sanad (HT)	mud + mangrove classic habitat	sandy mud	mud/shell gravel	Mud	< 70	35	34	47
21	Ras Sanad (MT)	mud + mangrove classic habitat	sandy mud	mud/shell gravel	Fine sand	123	35	—	—
21	Ras Sanad (LT)	mud + mangrove classic habitat	sandy mud	mud/shell gravel	Coarse sand	800	35	—	45
28	Zallaq North	mixed rock/sand undisturbed	sand/rock	sand/rock	—	—	34.5	32	55
34	Zallaq South	mixed rock/sand undisturbed	sand/rocks	sand/rocks					
37	Al Mumtallah (HT)	fine sand; hypersaline lagoon	medium sand beach	fine sand	Medium sand	235	38	31.5	65 (lagoon)
37	Al Mumtallah (MT)	fine sand; hypersaline lagoon	medium sand beach	fine sand	Medium sand	280	—	—	60 (sea)
37	Al Mumtallah (LT)	fine sand; hypersaline lagoon	medium sand beach	fine sand	Medium sand	205	—	—	—
14	Causeway North	mixed rock sand undisturbed	mixed sand/rock	rock, some sand					
6	Ras abu Subh (MT)	mixed rock/sand man-modified	mixed sand/rock	rock, some sand	Medium sand	214	35	33	46
5	Portuguese Fort	mixed rock/sand man-modified	rock infill + mud	sand/rock					
4	Mina al Manama	mixed rock/sand man-modified	rocky beach + sand	sand + rocks					
8	Al Azl 1km S	*sand modified by man*	*infill + medium sand*	*medium sand*	—	—	36	33	45
3	Muharraq Bridge N	mixed rock/sand man-modified	rocks + sand	———					
2	Galali	extensive fine sand beach	medium-fine sand	fine sand					
35	Ad Dur	mixed rock/sand undisturbed	infill, boulders + sand	———					
12	Nabih Salih N	mixed rock/sand man-modified	rock infill + coarse sand	rock/sand	—	—	34.5	32	42
15	Nabih Salih S	mixed rock/sand man-modified	rock infill + muddy sand	muddy sand					
11	Sitra Causeway E	mixed rock/sand undisturbed	rock platform + sand	muddy sand + rocks	—	—	37	32	45
9	*Al Muwaylighah (MT)*	*open mud flat*	*mud flat*	muddy sand	Fine sand	93	37	33	45
10	Khawr Mugla Tubli	mud + mangrove modified	mud flat	muddy sand	—	—	36	32	5 (sewage outfall)
16	Jurdab (LT)	salt marsh	rock/sand flat	muddy sand	Fine sand	184	36	33	46
41	Ras al Barr W (MT)	medium sand;accreting	sand beach + shall gravel	muddy shell gravel	Coarse sand	620	32	35	52
42	Ras al Barr E (MT)	medium sand on subtidal rock	sand beach + rock flat	rock + sand	Coarse sand	480	32	35	52
31	Ras Hayyan N (MT)	open mud flat	muddy shore/sabkha marsh	muddy sand	Medium sand	380	40	30	46
31	Ras Hayyan N (LT)	open mud flat	muddy shore/sabkha marsh	muddy sand	Medium sand	290	—	34 (pools)	52 (pools)
22	Al Ak	*mud and mangrove (modified)*	sandy mud	sandy mud	—	—	36	33	47
39	Mashtan North (MT)	medium sand	sand beach on rock	sand	Coarse sand	725	43	33.5	50
40	Mashtan South	medium sand	sand beach	sand	Medium sand	370	43	33.5	50
17	Jaradah (MT)	exposed sand	coarse sand	sand + coral sand	Coarse sand	690	38	33.5	42
17	Jaradah (LT)	exposed sand	coarse sand	sand + coral sand	Coarse sand	1.000	—	—	—
35	Ad Dur	muddy sand	fine sand/mud on rock	muddy sand	—	—	37	33.5	45
38	Had al Jamal jetty	rock jetty on sand beach	medium-fine sand	fine medium sand	—	—	37	33.5	48
48	*Gharbiyah Transect A (MT)*	fine sand and mud	sabkha/fine sand beach	fine sand	Medium sand	300	39	36	80 (sabkha)
45	Gharbiyah Transect B	mixed rock/sand ,undisturbed	rocky shore and sand	rocks + sand	—	—	39	36	52
54	Bandar Nakiah S (MT)	mixed rock/sand, undisturbed	sand beach and rock flat	rock + sand	Coarse sand	690	36	34	58
33	Um Jalid Transect SE (MT)	exposed sand	sand beach	medium sand	Coarse sand	680	40	34	45
47	Ajirah (MT)	rocky shore, undisturbed	rocky cliff	rocks + sand	Mud	78	38	36	48
52	Jazur bu Sadad	salt marsh	muddy sand flats	fine sand	—	—	38	40 (pool)	62
23	Jasrah S 2km	mixed rock/sand, partly disturbed	mixed rock/sand	mixed rock/sand	—	—	38	34	60
24	Al Hamalah	mixed rock/sand, partly disturbed	mixed rock/sand	mixed rock/sand	—	—	38	34	60
25	Um Nasan SW (MT)	mixed rock/sand, undisturbed	mixed sand/rock	sandy mud	Coarse sand	1.000	39	38	56

See Figure 3.1 for site locations

TABLE 3.1

MAIN BIOTIC COMPONENTS TO ZONATION ON ROCKY SHORES IN BAHRAIN, SUMMER 1985

ZONE	FLORA	FAUNA
LITTORAL FRINGE	Cyanobacteria: *Lyngbia aestuarii,* *L. majuscula* *Oscillatoria princeps* *Phormidium sp.*	*Nodolittorina subnodosa* *Ligia pigmentata* *Planaxis sulcatus*
UPPER EULITTORAL	*Enteromorpha sp.* *Ulva lactuca* *Acetabularia calyculus* *Chaetomorpha sp.* *Cladophora sp.* *Sphacelaria furcigera*	*Chthamalus malayensis* *Euraphia sp.* *Crassostrea cf margaritacea* *Brachydontes variabilis* *Petrolisthes rufescens* *Barbatia sp.* *Lunella coronatus* *Metopograpsus messor* *Isognomon dentifera* *Euchelus aspera* *Balanus amphitrite (Rare)*
LOWER EULITTORAL	*Chondria sp.* *Padina gymnospora* *Cystoseira myrica* *Dictyosphaera cavernosa* *Laurencia paniculata* *Hypnea comuta* *Spyridea filamentosa* *Hormophysa triquetra*	*Pomatoleios kraussi (Rare)* *Priotrochus obscura* *Cerithium scabridum* *Malleus regula* *Styella canopus* *Phallusia nigra* *Serpulorbis sulcatus* *Chama pacifica* *Halichondria cf glabrata* *Haliclona sp.*
SUBLITTORAL FRINGE	*Cystoseira trinodis* *Hormophysa triquetra* *Avrainvillea amadelpha* Coralline algae *Sargassum binderi*	*Dynamena cristoides* *Pinctada radiata* *Thalamita poissoni* *Thyroscyphus fruticosus* *Portunus pelagicus* *Balanus tintinnabulum*

Authorities as listed in Jones (1986a)

TABLE 3.2

MAIN FAUNAL AND FLORAL COMPONENTS OF SAND BEACHES IN BAHRAIN - SUMMER 1985

	SPECIES	RAS AL QURAYN	RAS AL MUMTALAH	AL HIDD	RAS AL BARR EAST	RAS AL BARR WEST	MASHTAN SOUTH	MASHTAN NORTH	QIT AL JARADAH	UM JALID NORTHWEST	UM JALID SOUTHEAST
LITTORAL	*Ocypode rotundata*	1/100m		1/100m			1			3	
	Orchestia platensis					832	16			37	6
	Tylos maindroni				160		34	20			
	Hyale perieri				32					5	2
EULITTORAL	*Eurydice peraticus*		32**		365		322	100			
					185			48			
	Excirolana orientalis				208					4	74
										69	53
										85	16
	Scopimera crabricauda	30	1	40							
	Nassarius plicatus						16				
	Mitrella blanda	20	16		48						
	Umbonium vestiarium	16						16			
	Ampelisca brevicornis	144									
	Leucothoe spinicarpa										
	Elasmopus rapax	32									
	Cymadusa filosa	32				32					
	Dosinia sp.			32							
	Cerithium scabridum	256									
	Polychaetes	120									
	Pirinella conica		240								
	Metacirolana rotundata		16**								
	Cerithidea cingulata			48							
	Halodule uninervis			2% cover							
	Halophila stipulacea			1% cover							
	Circe calypyga			16							
SUBLITTORAL FRINGE	*H. uninervis*	1% cover		20% cover	ROCK	ROCK	10% cover	60% cover		5% cover	1% cover
	H. stipulacea	30% cover		5% cover			5% cover	40% cover		90% cover	90% cover
	Portunus pelagicus	2					1	2			
	Ceradocus rubromaculata	32						16			
	Lysianassa ceratina	32								32	
	C. filosa	128									
	E. rapax	96								32	
	Bivalve juv. 7		32				50	240			
	Bivalve juv. 16		16								
	Dosinia sp.			16							
	Macrophthalmus telescopicus			4							
	Metapenaeus stebbingi			2							

** Shore open to sea

Figures = number of individuals per square metre except where percentage cover quoted
Species authorities as in Jones (1988a)

TABLE 3.3

MAIN FAUNAL AND FLORAL COMPONENTS OF MUDDY SHORES IN BAHRAIN - SUMMER 1985

	RAS SANNAD	AL MUWAYLIGHAH	KHAWR MUGLA	RAS HAYYAN	AL AK	RABAD AL GHARBIYAH	JAZUR BU SADAD	JURDAB
LANDWARD	Salicornia sp.	Salicornia sp.	Salicornia sp.					Juncus
FRINGE	Arthrocnemon sp.	Arthrocnemon sp.						rigidus
	Ligia exotica		Cyanobacteria	M. messor 2			Halocnemon sp.	
			mat (80%)					
	Metopograpsus					Cyanobacteria	Cyanobacteria	M. messor 2-5
High Water	messor 0.5					mat 100%	mat 100%	
Spring Tide	Eurycarcinus sp. 0.5	M. messor 0.5	M. messor 1		Cyanobacteria			
	Nasima		Eurycarcinus		mat 90%			
	dotilliformis 1		sp. 0.5					
to	Avicennia marina 100%		N. dotilliformis 50		M. messor 4			
	N. dotilliformis 85	Ilyoplax	A. marina 1-3	Scopimera	A. marina 2-3			P. sulcatus 10
		frater 400		crabricauda 30				
	Cerithidea		N. dotilliformis 50	N. dotilliformis 10	I. frater 480	S. crabricauda 3	S. crabricauda 30	S. crabricauda 48
High Water	cingulata 900							
Neap Tide	Ceradocus							
	rubromaculatus 16							
	Planaxis sulcatus 40		P. sulcatus 10	Cyanobacteria				Chaetomorpha sp.
to	M. messor 35			mat 90%				
	Eurycarcinus sp. 5				C. cingulata 10			Ulva sp.
	N. dotilliformis 15		Cyanobacteria	Macrophthalmus				Priotrochus
	M.		mat 100%	grandidieri 12				obscura 16
Mean Sea	quadrimana 48	Dosinia		Cyanobacteria		P. conica 400	P. conica 300	Cerithium
Level	Cymadusa filosa 48	celata 15		mat 40%				scabridum 87
	Elasmopus rapax 16	Metaplax		Pirinella				
		indica 20	C. cingulata 20	conica 1600				
to	Melania	Alpheus		M. depressus 16	M. depressus 40	P. conica 100	P. conica 80	
	tuberculata 32	lobidens 10						
	Macrophthalmus				C. cingulata 30			
	depressus 4							
Low Water								
	C. cingulata 400							
						P.conica 2	C. cingulata 20	
SUBLITTORAL								H. stipulacea
FRINGE	Metapenaeus stebbingi	Flamingos	Flamingos	Halophila	H. stipulacea	H. uninervis +	H. uninervis	
				stipulacea		Cladophora sp.		P. pelagicus
	Portunus pelagicus	Birds	Birds	P. pelagicus			P. pelagicus	
				Birds	Birds	P. pelagicus	Flamingos	
						Flamingos	Birds	
						Birds		

Figures = numbers of individuals per square metre except where percentage cover is quoted
Authorites as listed in Jones (1986a)

TABLE 3.4

ESTIMATED PERCENTAGE HABITAT COVER OF INTERTIDAL/SUBLITTORAL FRINGE - BAHRAIN

HABITAT CATEGORY	NORTHWEST	NORTHEAST	WEST	EAST	SOUTH	HAWAR	TOTAL BAHRAIN
ALGAE	2	6	<1	15	15	19	12
SEAGRASS	12	13	2	24	24	13	16
MANGROVE AND SALTMARSH	< 1	6	<1	<1	<1	<1	1
MUD	1	8	<1	3	<1	2	3
SAND	33	17	40	29	32	23	27
FINE SAND	<1	6	1	7	1	3	3.5
ROCK	2	10	2	1	<1	3	3.5
MIXED HABITAT	50	34	55	21	28	37	34

Estimated from Volume 2, figures 3 - 9

TABLE 3.5

ROCKY SHORE ZONATION PATTERNS - ARABIAN GULF, OMAN AND NEIGHBOURING SEAS

	KUWAIT (1)	BAHRAIN (2)	OMAN (3)	OMAN (3)	RED SEA (4)	BOMBAY (5)
SEA TEMPERATURES	12-30 C	19-33 C	25-27 C	16-27 C	18-36 C	25 C
LITTORAL FRINGE	Cyanobacteria *Nodolittorina subnodosa* *Planaxis sulcatus*	Cyanobacteria *Nodolittorina subnodosa*	*Ligia sp.* *Nodolittorina subnodosa*	Grapsid crabs *Planaxis sulcatus* *Nerita textilis* *Nodolittorina sp.* *Nerita anodonta*	Endolithic algae *Tectarius armatus* *Littorina novaezelandae* *Nerita sp.* Grapsid crabs	*Littorina ventricosa* *L. subgranos* *L. intermedia* *Tectarius malacannus* Grapsid crabs
UPPER EULITTORAL	*Chthamalus malayensis* *Euraphia sp.* *Balanus amphitrite* *Crassostrea cf margaritacea*	*Chthamalus malayensis* *Euraphia sp.* *Brachydontes sp.* *Planaxis sulcatus* *Isognomon dentifera*	*Chthamalids* *Saccostrea cucullata* *Tetraclita sp.* *Acanthopleura sp.*	*Chthamalids* *Nerita sp.* *Saccostrea cucullata* *Monodonta canalifera* *Lunella coronatus* *Tetraclita sp.*	*Chthamalus depressus* *Littorina scabra* *Nerita spp.* *Tetraclita sp.*	*Chthamalus withersi* *Balanus amphitrite* *Saccostrea cucullata*
LOWER EULITTORAL	*Pomatoleios kraussi* *Serpulorbis sp.* *Colpomenia sp.* *Gelidium sp.*	*Pomatoleios kraussi* *Serpulorbis sp.* *Hypnea cornuta* *Laurencia sp.* *Cystoseira myrica*	Red encrusting algae	*Crassostrea cucullata* *Acanthopleura sp.* *Monodonta canalifera*	*Saccostrea sp.* Vermetids Trochids *Echinometra sp.*	*Trochus sp.* *Euchelus sp.* *Calliostoma sp.*
SUB-LITTORAL FRINGE	*Colpomenia sp.* Sponges Tunicates Zoanthids *Sargassum spp.*	*Cystoseira trinodis* *Dictyosphaera* Sponges Tunicates *Hormophysa triquetra*	Zoanthids Brown filamentous algae	*Patella sp.* Red encrusting algae *Turbo sp.*	Hydrozoans Echinometra sp. *Sargassum sp.*	*Tetraclita purpurascens* Zoanthids
SHALLOW SUB-LITTORAL	Zoanthids *Sargassum spp.* *Paracyathus sp.*	Corals *Sargassum spp.*	Corals *Mytilus viridis* *Sargassum spp.*	*Cystoseira trinodis* *Sargassopsis zanardinii*	Corals *Sargassum spp.*	Corals *Sargassum spp.*

SOURCES AND AUTHORITIES	1. Jones, 1986a 3. Barratt, 1984 Sheppard, pers. comm.	2. Price et al, 1983 4. Fishelson, 1971 Hughes, 1977	5. Bhatt and Bal, 1969

TABLE 3.6

SAND BEACH ZONATION PATTERNS - ARABIAN GULF, OMAN AND NEIGHBOURING SEAS

	KUWAIT (1)	SAUDI ARABIA/BAHRAIN (2)	NORTH OMAN (3)	SOUTH OMAN (4)	MADAGASCAR/MOZAMBIQUE (5)
LITTORAL FRINGE	*Ocypode rotundata* *Talorchestia martensi* * *Orchestia platensis* *Tylos sp. nov.*	*O. rotundata* *T. martensi* * *O. platensis* *Tylos sp. nov.*	*O. rotundata* *Ocypode sp.?* Talitrids	O. rotundata Talitrids Coenobita scaevola	*O. ceratophthalmus* *O. cordimana* * *Coenobita cavipes* *C. rugosus* *Tylos ocri* * *Talorchestia malayensis* *Talorchestia sp.*
UPPER EULITTORAL	*Uca lactea annulipes* *Scopimera crabricauda* *Paracleistostoma arabicum* *Dotilla blanfordi* *Donax scalpellum* * *Mitrella blanda* * *Umbonium vestiarium*	*Eurydice peraticus* *Excirolana orientalis* * *S. crabricauda* *Donax sp.* * *M. blanda* * *U. vestiarium* *Philyra scabriuscula*	2 species of isopod * *S. crabricauda* *U. vestiarium* *Dotilla sulcata*	? P. scabriuscula Bulla mauritania? Diogenes sp.	*Excirolana natalensis* * *E. orientalis* * *Uca marionis* *Donax faba* * *Nerine cirratulus* * *Dotilla fenestrata*
LOWER EULITTORAL	*Platyischnopus herdmani* * *Urothoe grimaldi* * *Perioculodes longimanus* * *Emerita holthuisi* * *Diplodonta globosa* *Gari roseus* *Solen vagina* *Matuta lunaris* * *Holothuria arenicola*	*Ampelisca brevicornis* * *Leucothoe spinicarpa* *Ancilla castanea* *Meretrix meretrix* *Dosinia alta* *S. vagina* *Matuta planipes* * *Halodule uninervis*	*Lumbriconereis sp.* * Amphipods Mysids Crangonid shrimps Venerid bivalves *Matuta victor* * *Astropecten spp.* Tellenid bivalves	? Bullia sp. Hippa pacificus? M. lunaris?	*Donax elegans** *Donax madagascariensis** *Saccoglossus inhacensis* *H. pacificus* * *Albunea madagascariensis* * *H. uninervis*
SUB-LITTORAL FRINGE	*H. uninervis* *Branchiostoma sp.* * *Pinna bicolor* *Portunus pelagicus* * *Echinodiscus auritus* *Dentalium sp.* * Mysids	*H. uninervis* *P. bicolor* *P. pelagicus* * *E. auritus* *Dentalium octogonum* * *Penaeus semisulcatus*	? Diverse Fauna	?	*Calappa hepatica* * *Portunus emarginatus* * *Portunus gladiatar* * *Portunus granulatus* * *Astropecten granulatus* *Thalassodendron ciliatum* *Cymodocea serrulata*
SOURCES AND AUTHORITIES	1. Jones, 1986a 2. Basson et al, 1977 Price et al, 1983	3. Ansell, 1984 4. Barratt, 1984	5. Macnae and Kalk, 1962 Pichon, 1967 Thomassin, 1974		

Starred (*) species are characteristic of exposed beaches

TABLE 3.7

MUDDY BEACH ZONATION PATTERNS - ARABIAN GULF, OMAN AND NEIGHBOURING SEAS

	KUWAIT (1)	SAUDI ARABIA/BAHRAIN (2)	OMAN (3)	RED SEA (4)	EAST AFRICA (5)
LANDWARD FRINGE	Saltmarsh with zonation of *Zygophyllum-Aeluropus-Juncus Arthrocnemon*	Saltmarsh and *Avicennia marina*	*A. marina* *Cardisoma sp.*	*A. marina* *Rhizophora mucronata* *Dotilla sulcata*	9 Mangrove species 5 Grapsid crab species 2 Uca species
High Water Springs (HWS)	*Sesarma plicatum*	*Planaxis sulcata*	*Uca inversa*	*Ocypode rotundata* *Uca inversa inversa* *Littorina scabra*	*L. scabra* *Cardisoma carnifex*
HWS to High Water Neaps (HWN) HWN to Mean Sea Level (MSL)	*Cleistostoma kuwaitensis* *Uca sindensis* *Ilyograpsus paludicola* *Cleistostoma dotilliforme* *Ilyoplax stevensi* *Ilyoplax frater* *Eurycarcinus orientalis* *Periophthalmus koelreuteri* *Boleophthalmus boddarti* *Tylodiplax indica* *Metaplax indica*	*I. paludicola* *C. dotilliforme* *I. frater* *E. orientalis* *Metopograpsus messor* *M. indica*	No Published Data	*Uca tetragonon* *Uca lactea albimana* *I. paludicola* *Paracleistostoma leachii* *Macrophthalmus depressus* *Macrophthalmus telescopicus* *P. koelreuteri* *M. messor*	3 Grapsid crab species 3 Uca species *Helice leachii* *I. paludicola* 3 Grapsid crab species *M. depressus* 4 Mollusc species *Eurycarcinus natalensis* *Metopograpsus thukuhar*
MSL to Low Water	*Macrophthalmus grandidieri* *M. depressus* *Scartelaos viridis* *Cerithidea cingulata* *Macrophthalmus pectinipes*	*M. depressus* *C. cingulata* *Pirinella conica*	No Published Data	*Pirinella caillaudi* 7 Mollusc species	4 Uca species 2 Grapsid crab species 15 Mollusc species
SUB-LITTORAL FRINGE	*Portunus pelagicus*	*P. pelagicus*		*Scylla serrata*	*Scylla serrata*
SOURCES AND AUTHORITIES	1. Jones, 1986a	2. Basson et al, 1977 Price et al, 1983 3. Ansell, 1984 Barratt, 1984	4. Fishelson, 1971 Por and Dor, 1984 5. Macnae, 1968 Jones, 1984		

TABLE 3.8

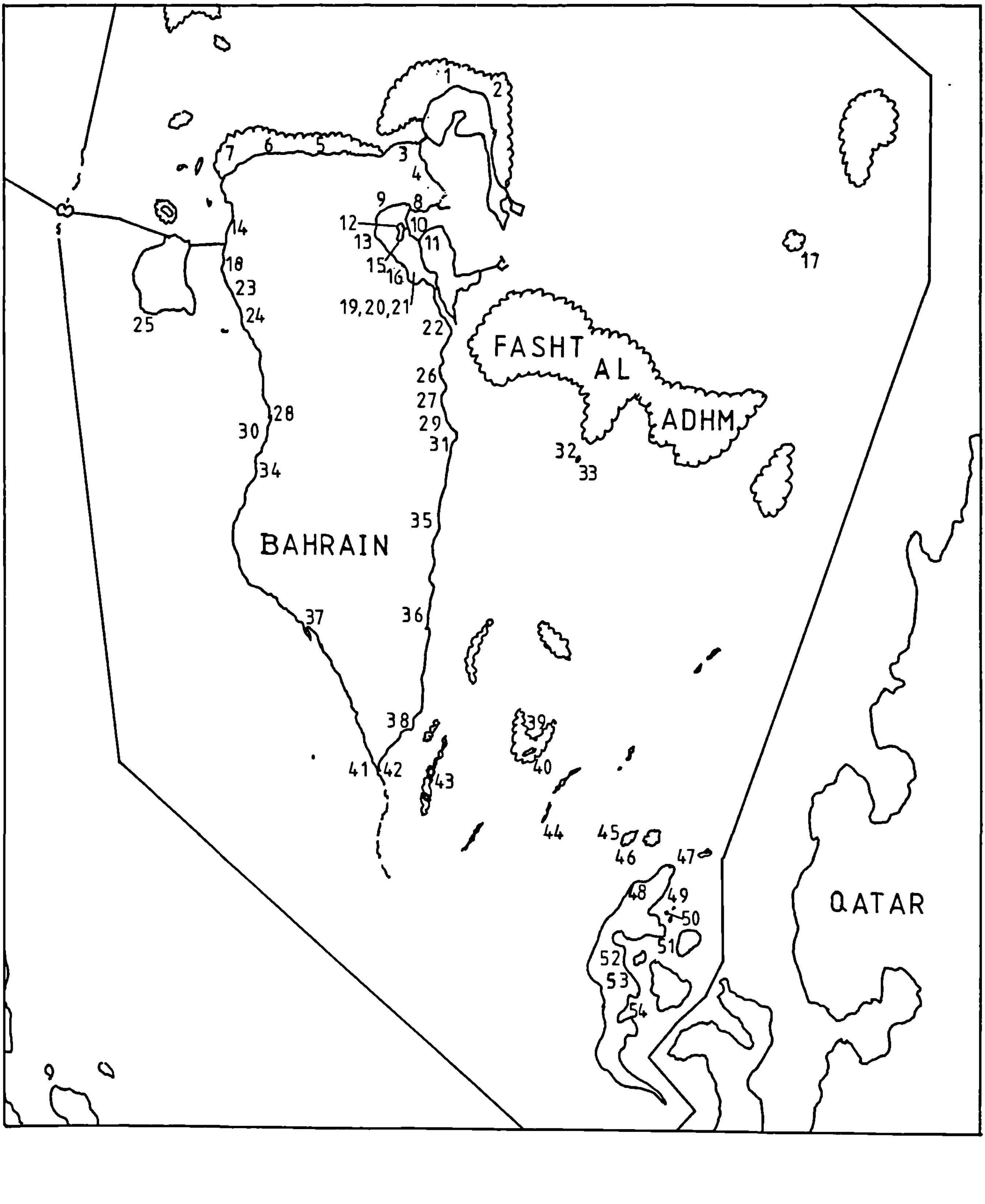
SEASONAL COMPARISON OF BAHRAIN INTERTIDAL BIOTA

ZONE	JULY 1985	FEBRUARY 1986
	FLORA	
TOPSHORE	Cyanobacteria 30% *e.g. Oscillatoria sp.* *Calothrix crustacea* *Schizothrix mexicana*	Green Algae 40-100%
MIDSHORE	Green Algae 10% *e.g. Enteromorpha flexuosa* *Chaetomorpha capillaris* *Caulerpa sp.* Red Algae 10% *e.g. Acanthophora spicifera* *Champia parvula*	Green Algae 40-50% Red Algae 5%
LOWSHORE	5% Algae - mainly Reds *e.g. Sarconema sp.* *Valentia sp.* *Hypnea sp.* *Caulerpa sp.* 15% Cyanobacteria 60% Seagrass - *Halodule uninervis* *Halophila stipulacea* *Halophila ovalis*	Green Algae 50% Brown Algae 10% *e.g. Colpomenia sp.* <1% Seagrass *Halodule uninervis*
	FAUNA	
TOPSHORE	Littorinids Chthamalids *Pomatoleios kraussi* *Onchidium peroni* (under rocks) *Priotrochus obscura* (under rocks) *Euchulus aspera* *Cerithium scabridum* (rare)	Littorinids Chthamalids *Onchidium peroni* (in open) *Priotrochus obscura* (in open) *Cerithium scabridum* (common) *Cerithidea cingulata* *Lunella coronatus*
MIDSHORE	Peachia-type Anemone *Cerianthus sp.*	Peachia-type Anemone *Cassiopiea andromeda (2/sq.m.)*
LOWSHORE		*Stoichactis sp.* *Cassiopiea andromeda (3/sq.m.)*

TABLE 3.9

FIGURE 3.1 POSITION OF ALL INTERTIDAL SAMPLE SITES AROUND BAHRAIN. SUMMER, 1985 AND FEBRUARY-MARCH, 1986.

(See Appendix 3.1 for site names, coordinates and dates)



CHAPTER FOUR

SUBTIDAL HABITATS

CHAPTER FOUR - SUBTIDAL HABITATS

INTRODUCTION

Because of the extremely gradual slope of the seabed in the western Arabian Gulf, much of the subtidal seabed lies within the euphotic zone and is therefore able to support coral reefs and seagrass beds (Basson et al, 1977). Consequently, these two habitat types play an important role in the overall biological economy of the Gulf.

IUCN, (1976) define critical habitats as identifiable areas which are vital to the survival of a species at some phase of its life cycle, or to the survival of a community, because of the ecological processes which occur within it. Such critical marine habitats include feeding, nesting, breeding or nursery areas of marine animals; major sources of food or nutrients for feeding areas elsewhere (e.g. mangroves); and areas that are particularly rich in species (e.g. coral reefs) or highly productive (e.g. seagrass beds). Price et al (1984) identify three critical marine habitats in Bahrain's waters. These are the mangroves of the intertidal and sublittoral fringe and the seagrass beds and coral reefs found in the subtidal zone. The subtidal phase of the field work for the present study concentrated on these latter critical subtidal habitats . However, information was collected for other habitats (e.g. muds, sands and non-coralline hard substrata) for inclusion in the subtidal habitat chart.

Hard subtidal habitat types in the Arabian Gulf include coral, limestone (often derived from dead coral structures) and non- coralline types. Coralline habitats throughout the world are renowned for their biotic diversity (with only the floral diversity being limited) and the Arabian Gulf is no exception. In an area where diversity is generally low in comparison to the neighbouring Indian Ocean, the coral reef habitat represents the most diverse of the marine habitat types available within the Gulf, although this does not mean that it is the most productive.

Light penetration plays a dominant role in determining the type of biota found on hard substrates in the Gulf (Basson et al., 1977). Wherever rocky bottoms occur in well-lit regions there is competition for dominance between the algae and the corals. Reefs do not form in many of the shallow hard substrate areas as coral growth is inhibited by extreme water temperatures and/or sedimentation. Dense algal growth can develop on hard substrates under one set of extreme environmental factors and coral reefs under another with mixed communities occurring in between.

Jones (1985) records the distribution of known reefs or dense concentrations of corals within the Arabian Gulf pointing out that, in general, individual corals occur throughout the region where suitable substrata are present except where winter sea temperatures, fresh water inflow and sedimentation combine to prevent colonisation. Downing (1985) discusses some of the physical parameters affecting the distribution of coral reefs in Kuwait's waters. These are among the most northern reefs recorded in the world. Corals in Kuwait waters are rarely found below 15 m and the most extensive formations are found in waters shallower than 10 m. Salinities are recorded as high as 42.4 ppt with water temperatures ranging from 13.2^0 C to 31.5^0 C. Air temperatures can vary seasonally from 55^0 C in the summer to nearly 0^0 C in the winter months. Low water spring tides can expose the reef flats to temperatures approaching these extremes and turbidity is generally high. The diversity of corals is low with a total of 24 species of Scleractinia in 17 genera having been recorded.

Kinsman (1964) studied reefs off the coast of Abu Dhabi in the United Arab Emirates where they were found between the low water mark and 10-13 m depth. Surface and shallow seawater temperatures ranged seasonally from 16^0 C to over 40^0 C. Below 4-5 m the seasonal temperatures ranged from 20-36^0 C. In late July, August and early September shallow water temperatures in excess of 35^0 C were recorded. So coastal coral reefs in this area endure diurnal temperature ranges of 10^0 C and seasonal ranges of over 20^0 C. Open coastal salinities along the coast of Abu Dhabi were always in excess of 42 ppt and colonies of Acropora sp. were recorded in salinities up to 48 ppt but not beyond. Kinsman further noted that other species of coral could not withstand salinities above 45 ppt. Sheppard (1982) notes that low temperature is one cause of reduced diversity in marginal coral areas and points out that even where corals are surviving at the extreme limit of their temperature tolerance they are often severely limited in their ability to reproduce.

As well as the more obvious physical factors controlling coral and reef distribution (e.g. nutrients, light, temperature and salinity) water movement can also play an important role (Sheppard, 1982). Wave action and strong currents can adversely effect coral settlement and survival. The more severe the water movement the greater is the calcareous algal cover and the smaller the coral component. Sheppard lists direct water movement as the primary control affecting coral growth and distribution. This is probably generally true outside the Gulf in the Indian Ocean, but salinity and temperature must have an important effect on coral and reef distribution in the Arabian Gulf.

Downing and Roberts (1993) looked at the possible effects which the 1991 Gulf War may have had on corals in the Arabian Gulf. They conclude that although some reef areas around Kuwait show signs of mortality it is impossible to link this to reduced temperatures (as a result of reduced insolation caused by the smoke plumes from burning oil wells) or increased toxicity as a result of oil spills and slicks. The mortalities could equally be natural and did not extend south into Saudi Arabian waters. They note that each winter Kuwait's corals survive low water temperature and are smothered by the algae Colpomenia sp. and Giffordia sp.. This has also been recorded in Saudi Arabia and Bahrain (Coles, pers. comm.; Vousden, 1987).

The largest of the Bahrain reefs and the richest in terms of coral cover and diversity is the extensive Fasht al Adhm reef on the east coast stretching almost across to Qatar (see figure 1.2). This reef was described by Barratt and Ormond (1985) and although the physical area of this reef is some 200 sq. km. the actually percentage that supports live coral is considerably smaller, probably less than 10%, most of which is restricted to the north-eastern edge of the reef.

Reef morphology in Bahrain is atypical of reefs generally (Hopley, 1982; Sheppard, 1982 for reviews of reef morphology) because of the gentleness of the gradient found on the reef slopes. This suggests that much of the reef itself is not actively growing even though the corals are themselves. In the waters around Bahrain, coral growth is likely to be severely limited by physical constraints such as high water temperatures and salinities (see Chapter 2) which often exceed the tolerance limits of most, if not all, coral species (Jokiel and Coles, 1977; Kinsman, 1964; Sheppard, 1982).

Many of the soft benthic habitats in the Arabian Gulf are of significant ecological importance from the commercial point of view (fin- and shell- fishery). From the scientific point of view such substrata represent areas of high diversity, high productivity or areas supporting endangered species or habitats (Barnes and Hughes, 1982). Previous authors (Basson et al., 1977; Price et al., 1984; Vousden, 1985b) have commented on the low level of planktonic primary productivity within the Arabian Gulf and the fact that primary productivity is predominantly benthic. The most obvious benthic plant forms within the Gulf are the widespread seagrasses.

Three species of seagrass are commonly recorded for this area of the Gulf. These are Halodule uninervis (Forsk.) Aschers., Halophila stipulacea (Forsk.) Aschers, and Halophila ovalis (R.Br.) Hook. f.. Den Hartog records a fourth species, Syringodium isoetifolium Aschers. in a collection from Bahrain by R. Good kept at the British Museum. This sample was collected adjacent to a coral reef at Jufair in 1950. There are no coral reefs off Jufair today, which is in the centre of the port and industrial area, and it is unlikely that any seagrass remains in the area as that part of the port has been dredged on several occasions, being one of the main shipping lanes. There are no other records for this species in the Gulf. Other authors list 4 species of seagrass for the Gulf on the basis of this one identification from Bahrain (Sheppard et al, 1992: Kenworthy et al, 1993).

The taxonomic criteria (den Hartog, 1970) used to identify the three species under study as well as those used to exclude S. isoetifolium from consideration are as follows:

Halodule uninervis:

Rhizome creeping, with 1-6 roots and a short erect stem at each node. Internodes 0.5-4 cm long. scales ovate or elliptic, up to 6-7 mm long. Leaf-sheath 1-3.5 cm long. Leaf-blade 6-15 cm long and 0.25-3.5 mm wide, narrowed at the base, sometimes falcate; midrib conspicuous, widening and sometimes furcate near the apex; leaf-tip with two linear lateral teeth and an obtuse (but in very narrow-leaved specimens often acute) median tooth in which the midrib ends; median tooth as long as or shorter than the lateral teeth, rarely slightly longer.

Halophila ovalis:

Rhizomes up to 2 mm thick, with 1 or more roots at each node. Internodes 1-5 cm long. Scales transparent, suborbicular or obovate, convex or folded, slightly to distinctly keeled, emarginate at the apex and more or less auriculate at the base, 3-8 mm long. Leaves in pairs on shoots with a little or not developed axis. Leaf-blade oblong-elliptic, spatulate, obovate or ovate, rarely linear, glabrous, 1-4(-7) cm long, 0.5-2 cm wide, rarely narrower; apex rounded; base rounded, obtuse, truncate or cuneate, sometimes gradually merging into the petiole; margin entire; cross-veins in 10-25 pairs, ascending at angles of 45-60^0, often forked, joining the intramarginal nerves; midrib united at the top with the intramarginal nerves; intramarginal nerves sometimes partly marginal. Petiole 1-4.5(-12) cm long. Spathal leaves broadly lanceolate, acute, membranous, sometimes corneous, more or less keeled, 3-5(-10) mm long.

Halophila stipulacea:

Dioecious. Rhizome 0.5-2 mm thick, with one root at each node. Internodes 1-4 cm long. Scales elliptic or obovate, white or transparent, sometimes tinged with purple, 12-17 mm long and 6-10 mm wide, folded, incised along the keel; the 2 apical lobes obtuse. Leaves in pairs on 1-15 mm long shoots. Leaf-blade linear to oblong, elliptic, green, glabrous, papillose or slightly hairy, occasionally bullate, 3-6 cm long, 2.5-8 mm wide; apex obtuse, base cuneate or gradually decurrent into the petiole; margin serrulate, especially in the apical region; cross-veins ascending at angles between 45^0

and 60^0, joining the intramarginal nerves; midrib united at the top with the intramarginal nerves. Petiole 0.5-1.5 cm long, sheathing lopsidedly at its base. Spathe ovate, acute, keeled, hairy, margin at one side glabrous and at the other side ciliate.

Syringodium isoetifolium:

Rhizome slender with 1-3 little branched or unbranched roots and a short erect stem, bearing 2-3 leaves, at each node. Internodes 1.5-3.5 cm. Scales 5 mm long, perishing at an early stage. Leaf-sheath 1.5-4 cm long, often tinged with red. Leaf-blade 7-30 cm long, 1-2 mm wide, narrowed at the base; central vascular bundle surrounded by a circle of 6-8 air channels and a circle of 7-8-10(-15) pericentral vascular bundles, which are considerably narrower than the central one.

Den Hartog (1970) also includes details of the flowers, fruits and seeds. The taxonomy of the seagrasses (like that of other angiosperms) is based mainly on characters of their generative structures. These structures are rarely found in most seagrasses, and in some species they are not recorded at all or only incompletely. Generative structures were never used for identification purposes during the present study and are therefore not included. Den Hartog (1970) points out that as a result of thorough morphological and anatomical studies by a number of workers it is known that all genera and most of the species are well characterised by their vegetative characters. It is the details of those vegetative characters which are listed above.

A review of the listed characters and careful scrutiny of the plant material collected confirmed the presence of Halodule uninervis, Halophila ovalis and Halophila stipulacea and the absence (at least at the sites sampled) of Syringodium isoetifolium (confirmed by Basson, Pers. Obs.). Sheppard et al (1992) state that most seagrass communities in the region are dominated by Halodule uninervis, although mixed stands of seagrass also occur. In the Gulf, seagrasses are often restricted to depths of 8-10 m or less but exceptionally occur at 17 m (Basson et al, 1977).

The importance of seagrass beds lies both in their potential as a food source and in their enhancement of the benthos as a habitat niche. They also serve to stabilise the seabed by reducing the effect of currents on the underlying substrate and encouraging sediment to settle out of the water column (Orth, 1977; Fonseca et al., 1983). Direct grazing is relatively uncommon (Orth and Montfrans, 1984; Wahbeh and Mahasneh, 1985; Sheppard et al, 1992)) which may be a result of the presence of distasteful phenolic compounds (Jones et al., 1987) and the limited ability of most organisms to digest cellulose, the exception being the dugong. However, seagrasses provide an important substrate for the growth of epiphytes which are grazed by a number of invertebrates and may form an important component in the detrital food chain. Recent surveys have identified a herd of over 700 dugong west of Hawar, one of the largest herds ever recorded in the world (Joint Saudi-Bahrain Population Studies). Head (1987) states that dugongs feed exclusively on seagrasses and Frazier et al. (1987) note that dugongs are completely restricted in diet to marine higher plants (seagrasses) mainly of the family Potamogetonacea and Hydrocharitaceae.

Seagrass beds are generally considered to be an important primary producer and a habitat of high species diversity (Odum et al, 1960; Zieman and Wetzel, 1980), but they also play a more specific role in these waters. Seagrass beds in the Gulf play host to the juvenile stages of commercially-important penaeid shrimp, especially Penaeus semisulcatus (Al Attar, 1981) and to a number of adult fish species (e.g. Siganus spp.) which represent a popular local food resource (Basson et al., 1977, Basson, pers. comm., Adams, 1976a and

1976b). Furthermore, they provide a habitat for the settlement of high densities of pearl oyster spat (Pinctada sp.) (Price et al., 1984), once a historically and culturally-important commercial species in Bahrain and one which is being reconsidered for potential commercial development (Vousden, 1985a and 1985b).

Along the west coast of Bahrain, around the Hawar Island group and in other scattered coastal and shallow sublittoral areas, the dominant hard seabed consists of flat, sedimentary sheets of rock or levelled limestone structure usually covered with a thin layer of sediment varying from medium-grain sand to fine silt. These areas are extensive and are the more common form of hard seabed in areas of high salinity. In contrast to those areas supporting coral growth, they usually show a greater degree of uniformity from one area to the next. These non-coralline areas fall into a category between hard and soft substrates and are often characterised by fauna/flora representative of both.

The aim of this section is to identify the distribution of some of the key species commonly found within the two major subtidal critical habitats around Bahrain (i.e. coral habitats and seagrass beds). Furthermore, an attempt will be made to relate this distribution to depth (as a factor controlling light attenuation) and salinity which has already been shown to fluctuate dramatically with tidal cycle and to have considerable geographical variation around Bahrain. Other studies in the Gulf (see above) identify depth (and its effects on light attenuation), salinity and temperature as being the primary controls over coral and seagrass growth and distribution in this enclosed sea, assuming that the correct substrate is present. Chapter 2 already describes the annual temperature extremes experienced in this part of the Gulf and under which both critical habitat types and their component species survive in the long term although short-term fluctuations may occur.

MATERIALS AND METHODS

Site selection was based on the results of survey work undertaken by Price et al. (1984); an aerial survey of the study area by helicopter; initial satellite imagery of the study area and the author's knowledge of the submarine habitats around Bahrain.

The False Colour Image from the initial satellite imagery (see Chapter 5) provided a 1:50,000 scale view of the islands, shoals, sandbanks and reefs. The helicopter survey provided a close-up view of possible sites. During aerial surveillance, two photographers were positioned on either side of the helicopter with a third crew member recording positions from the on-board Loran C position fixing system. The photographers indicated to the recorder whenever they took a photograph of a different habitat type beneath the helicopter and this was noted against the position of the helicopter at the time. During later surveys all three scientific personnel were linked to a tape recorder. The photographers recorded a code letter for their side of the aircraft and a number for the sequence of the photograph. The third crew member then recorded the position, compass bearing, air speed and height on to the tape.

Analysis of the aerial and satellite photography allowed study sites to be selected on the basis of two criteria, 1. To recover useful comparative data from known habitat types under different physico-chemical cónstraints, 2. To identify habitats in areas where they were unknown or uncertain. A full list of subtidal study sites is given in appendix 4.1.

Coral study sites (figure 4.1) were chosen to represent corals existing under different physical regimes (e.g. salinity, depth, turbidity) and to provide information for the subtidal habitat maps. Any topographic discontinuities or features were used to define the boundaries of a study site (e.g. a reef crest or wall or a gully). The majority of reefs in the area are in shallow water and so the reef slope was surveyed at two or more points of the compass around a reef area with each point being counted as one site. Small patch reefs such as Sala and Fasht Bu Thur (see figure 1.1) were treated as a single unit. Where different depths occurred on a reef front (e.g. Fasht al Adhm, near the `half- tanker' site, different depth zones were treated as different sites. In all cases, the site boundaries were designated by physical or geographical parameters and not by the presence of biological zones in an attempt to avoid any bias on the part of the surveyors.

At the coral study sites, the presence and percentage cover values of each coral species were recorded in situ. Recording was carried out over a lateral distance of at least 50 m and up to 100 m. Sites were covered until no more species were recorded for at least 10 minutes. This procedure usually took between 20-30 minutes and sometimes less at low diversity sites. At each study site species were either assigned a percentage cover value estimated by eye or coded as 1 if they could only be accurately recorded as `present'. Other obvious and relevant biotic features were also recorded (e.g. the presence of calcareous red algae, zoanthids and reef-building molluscs). Appendix 4.2. gives site descriptions for the coral study sites. Appendix 4.3 gives a species list of corals found during this study.

Seagrass study areas (figure 4.2) were also chosen to represent the habitat existing under different physical regimes (principally depth and salinity) and to provide information for the subtidal habitat maps (see Chapter 5 and Volume 2). Bottom cover was assessed using repetitive quadrats of either 0.5 m or 0.25 m (Eleftheriou and Holmes, 1984) depending on the concentration of organisms present. Samples were taken from within these quadrats for analysis of leaf length. The percentage cover or number of key biotic components (such as sponges, echinoderms, molluscs, etc) associated with the seagrass were also counted within the quadrat.

116 additional subtidal sites (figure 4.3) were surveyed rapidly for descriptive purposes and for assessing the accuracy of the habitat characterisation maps in chapter 5.

Surface salinity measurements were taken to 0.5 ppt (parts per thousand) using a calibrated, temperature compensated refractometer (American Optical Corporation). Depth was recorded using a weight and measuring tape, by diver's calibrated depth gauge or from the Hydrolab read-out where this instrument was deployed. A Hydrolab Surveyor sampling probe (Hydrolab Inc., Texas, USA) was used to record temperatures and salinities down through the water column at some of the deeper sites. As seawater temperature at depths greater than 1 m did not vary significantly throughout the study period (28th July - 27th August, 1985), temperature statistics are added as a foot-note to the details of the data matrices for coral study sites and seagrass study sites.

All samples were preserved in alcohol, sorted to phyla and either identified to species in Bahrain by the available taxonomic experts or packaged and shipped for identification by internationally-renowned taxonomists (see acknowledgements). All identifications were made from Newton (1955), den Hartog (1970), Basson et al (1977), Burchard (1979), Jennings (1981), Sheppard and Sheppard (1985), Jones et al (1986a) or from other authorities used by the taxonomic experts working on this study (see Acknowledgements) and cited in the Bibliography. Species authorities are those listed in these references. Samples were sorted after identification into two duplicate specimen sets, one for Bahrain's Environmental Protection Technical Secretariat and the other for ROPME (The Regional Organisation for the Protection of the Marine Environment) in Kuwait.

Raw data collected from the coral study sites and from the seagrass study sites is presented as a correlation matrix to identify the stronger correlations between the variables.

Standard univariate statistical analysis was considered to be inappropriate because of the interrelationships between the environmental variables of temperature, depth and salinity. Discussions with staff in the University College of North Wales (UCNW) Department of Statistics, with members of staff in the School of Ocean Sciences and with staff in the Departments of Biology and Terrestrial Ecology analysing similar data confirmed that multivariate statistical analysis was more suitable to the type of data being collected. Using multivariate analysis techniques allowed the data on species numbers and presence to be compared with all of the physical variables at the same time and thus provide information on the significance of each environmental variable. Certain trends are apparent from an initial review of the data matrices, but the true relationships between the environmental variables and their effects on the numerical species data become more obvious using the multivariate techniques.

Principal component factoring and canonical correlation were recommended by the UCNW Department of Statistics and were carried out using methods described by Manly (1986), Causton (1987) and Digby and Kempton (1987). A Unistat IBM PC compatible statistical software package (version 4.5) was used for the data analysis. Results were checked by the UCNW Department of Statistics by running a canonical correlation on selected data using Genstat, a statistical programming language. Correlations proved to be identical.

Summary of multivariate analysis techniques.

Principal component analysis and canonical correlation analysis are ordination techniques. Digby and Kempton (1987) define ordination as "An `ordering' of data in any number of dimensions (but preferably as few as possible) that approximates to some pattern of response of the set of objects". Ordination techniques are commonly applied to biological community analysis with the usual objective of this ordination being to help generate hypotheses concerning the relationship between the species composition at a site and the underlying environmental factors.

Principal component analysis is designed to reduce the number of variables that need to be considered to a small number of indices (called the principal components) that are linear combinations of the original variables (Manly, 1986). It is frequently the case that two or three principal components provide a good summary of all of the original variables. Consideration of the values of the principal components rather than the values of the original variables may then make it much easier to understand the data. Hence, principal component analysis is a means of simplifying the data by reducing the number of variables.

Factor analysis also attempts to account for the variation in a number of original variables using a smaller number of index variables. Each original variable can be expressed as a linear combination of factors plus a residual term which reflects the extent to which the variable is independent of other variables. The number of factors chosen for consideration is up to the analyst but a rough `rule of thumb' is to choose those principal components where the eigenvalues are greater than 1 (Manly, 1986).

Often the first phase of factor analysis will produce factor loadings showing the correlations between all factors and all original variables, making it difficult to assign meaningful attributes to factors. It is possible to improve the interpretation of the factors by rotating the factor matrix. Factor rotation effectively `twists' the axes of the principal components in order to find new factors which are easier to interpret and provide a better explanation of the data. There are a number of different types of rotation using different formulae. Some methods minimize the number of variables which have high loadings, other methods minimize the number of factors needed to explain a variable. The method used on the present data was an 'equimax' rotation which is a combination of both approaches. All of the factoring data has been rotated in this manner to find the strongest relationship between the variables. Causton (1987) provides a detailed but comprehensible explanation of the concepts behind principal component analysis and factor analysis/rotation.

However, principal component analysis and related 'non-grouped' methods of ordination (such as reciprocal averaging and correspondence analysis) make no allowance for any structure in the data matrix. Canonical variate analysis and canonical correlation analysis take into account any grouping of rows or columns of the data matrix. Canonical variate analysis is more useful in taxonomic studies (e.g. observations on a number of individuals for a set of morphometric variables). This technique is not considered to be appropriate for species-by-site abundance matrices (Digby and Kempton, 1987). When a set of variables is divided into two subsets (e.g. Species abundance along with information on environmental factors for a number of sites) then canonical correlation analysis is the preferred method (Gittins, 1979; Digby and Kempton, 1987).

Canonical correlation is a multivariate correlation technique which compares all of the data variance in one group of variables with all of the data variance in another group of variables and effectively explains which of the variables in group 1 are related to which variables in group 2 and with what strength. By placing dependent variables such as species percentage cover in group 1 and independent or functional variables such as depth or total number of species in group 2 it is possible to identify significant correlations between multiple variables. Canonical correlation analysis sets out to find linear combinations of the two sets of variables for the sites such that the linear combinations have maximal correlation. This is repeated to obtain an independent second pair of linear combinations that have maximal correlation, and so on. By this process it is possible to look for combinations of the species abundance that best correlates with combinations of the environmental variables so that the species distribution may be predicted from the environmental information at the sites (Digby and Kempton, 1987). The size of the coefficients required for each variable in order to produce the correlation reflects the importance of the variable in that particular canonical vector (Manly, 1986).

Hierarchical cluster analysis was performed using a euclidian distance measure taking the average distance between groups (Manly, 1986). This was compared to cluster dendrograms derived by taking the average distance within groups. There was no significant difference in the cluster dendrograms derived for either of the two data matrices by using either of these methods. The selection of clusters by the distances at which they merge is always somewhat arbitrary and inevitably requires some knowledge of the expected groupings. However, the two cluster dendrograms derived (for coral communities and for seagrass communities) allowed for a logical selection of clusters. The y axis (labelled 'Distance') on the cluster diagrams (see figures 4.4 and 4.5) represents the euclidian distances between the sites (see Manly, 1986 for details). The x axis represents the sites and displays them in a logical order as they merge to form the clusters. In both cases (coral and seagrasses) the clusters selected to represent the community types are all separated at a distance whereby they are greater than 60% different (no more than 40% similar).

156 subtidal habitats were studied during the summer of 1985. In addition, a purely descriptive and non-quantitative rapid habitat survey was undertaken in March 1986 to identify observable changes in the habitat types.

RESULTS

CORAL HABITATS

Sites studied are listed in Appendix 4.1, a description of each site in Appendix 4.2. and species identified during the study in Appendix 4.3.

The best example of potentially accreting reef structures supporting high coral cover is the large, central section of the north-eastern front of Fasht al Adhm (see figure 1.1). In terms of coral diversity and percentage cover (see 'Statistical analysis of coral habitats' below) as well as extent, this is certainly the richest and most important reef area in Bahrain (table 4.1 and 4.2; appendix 4.2 and 4.3). Other similar areas include some of the deeper parts of the northern Khawr Fasht (table 4.1 and 4.2; appendix 4.2) as well as deeper areas around Fasht Dibal and Qit Al Jaradah , although none of these displayed the same richness of coral diversity and cover as Fasht al Adhm. In the shallower parts of the Fasht al Adhm reef complex, at the eastern and western ends and on the smaller northern reefs, the coral abundance, both by cover and diversity, declines markedly and in shallow reef waters everywhere around Bahrain corals are generally scarce.

Despite its relatively high diversity and cover, Fasht al Adhm lacks the normal steep frontal profile that is common to healthy reef systems elsewhere in the world, e.g. The Red Sea, Indian Ocean and Caribbean.

Several of the smaller reefs to the north and north west of the study area represent coralline structures that are supporting a very limited amount of coral growth representing a cover of only 1-5% (see appendix 4.3) on top of an old reef structure developed earlier in the history of Bahrain. These reefs had a more typical reef topography of steep slopes running down to a soft substrate, but lacked the accreting coral growth and were largely devoid of living coral (table 4.1 and 4.2; appendix 4.2). Examples of such structures include Fasht Jarim to the north, Khawr Fasht and Sala to the north-west and numerous patch reefs around the Muharraq area (see figure 1.1). The reefs in these locations bear evidence of much more prolific growth in the past than is the case in the present day. Dead and eroded coral colonies are commonplace and the reason for such recent decline in the productivity of the reef is of some concern.

East of the central part of the main island of Bahrain were a number of smaller patch reefs near Ad Dur displaying a low diversity with Porites nodifera representing by far the most dominant species (See table 4.1 and 4.2 and appendix 4.2). Although coral cover was high it is unlikely that these are true reefs as defined by Hopley (1982), but rather substantial colonies of this single species growing once again on a much older limestone substrate. This limestone rock extends throughout much of the territory of Bahrain and supports a number of different habitat types and communities dependent on local conditions. However, where currents scour the surface free of sediment and where salinities are favourable it is not uncommon to find coral growth. Examples were seen in several reef structures close inshore along the eastern coastline from Ras Hayyan down to the southern tip of Gabbari reef after which salinities become extreme and probably restrict coral growth (see Volume 2, figure 1 and figure 4.6). Other outcrops were noted to the east across Tighaylib and at Fasht Bu Thur and Qita'at el Erge over on the extreme eastern edge of Bahrain's territorial waters (see Volume 2, figure 1).

Around the north-eastern end of Tighaylib, off the east coast, a series of unusual structures were not discovered until the rapid winter-spring study of 1986. These sites were not part of the detailed study and tables or matrices. These structures take the form of coralline mounds rising out from the seabed at a depth of some 10-12 m to within 1-2 m of the surface. An initial study of these mounds showed them to be limestone structures with scattered small coral colonies mostly of Porites with a low percentage cover of less than 30% (Vousden, pers. obs.). Flanking these mounds and rising to within 3-4 m of the surface were prolific seagrass beds. Most noticeable was the rapid change in faunal characteristics over a short distance. Some of these mounds were less than 10 m across (although some were significantly bigger) but supported a very high density of reef fish (especially Pomacanthus maculosum present in large numbers of both adult and juvenile forms). The coral colonies themselves were covered by large numbers of a bivalve mollusc (Chlamys ruschenbergerii) as well as sponges and ophiuroids.

The most obvious seasonal change associated with the corals is the high percentage cover of algae which appears across certain reef areas in the winter season. Two species are principally involved within the main reef community, Hydroclathrus clathratus and Colpomenia sinuosa. These can be found growing on the actual skeleton of the coral animal itself. The first identification of this phenomenon caused some concern as such a bloom of algae across a coral community would normally suggest that the coral animal itself was dead. Although no specific records have been kept to compare summer and winter coral distribution, it is reasonable to assume that the coral is not significantly affected as the coral is alive and healthy again in the spring when the algal bloom disappears.

STATISTICAL ANALYSIS OF CORAL HABITATS

A total of 33 coral study sites were studied for this investigation of coral habitats and data from these study sites are presented in table 4.1 and 4.2. 30 coral species were observed during the study (Appendix 4.3) with 9 species accounting for the major proportion of coral cover. The other 21 species were present at very few sites and, where present, exhibited very low percentage cover. Three other biotic components were important and frequently observed members of the coral reef community. These components were reef-building molluscs, zoanthids and calcareous red algae.

In the following analysis 15 variables have been analysed. these include the 9 major coral species, reef-building bivalves, zoanthids, calcareous red algae, two derived variables (number of coral species and total percentage coral cover), and depth and salinity. Two Acropora species have been grouped as one variable since they are difficult to separate taxonomically underwater.

In chapter 2 a detailed discussion of physical variability around Bahrain and the study sites has been presented. For the present analysis of the coral study sites, salinity representative of the mean site salinity has been used (see figure 2.3). These salinity data are derived from detailed consideration of both seasonal and tidal salinity variability.

Linear correlation has been conducted as an initial stage in the investigation of interrelationships between the various components of the reef community. The data presented in tables 4.1 and 4.2 was analysed and significant correlations within the data set are summarised and presented in table 4.3.

A number of variables show strong correlations reflecting a common distribution in the reef community. Three coral species exhibit a closely related distribution: Cyphastrea seralia, Favia speciosa and Platygyra daedala. 4 species of coral, Cyphastrea monile, C. seralia, F. speciosa and Porites compressa are significantly related to total coral species while the calcareous red algae show an inverse relationship to coral cover. This data suggests that the presence of these four species of coral is related to high coral cover and that the presence of calcareous red algae will be greater where coral cover is low. All three species of Acropora, a major component of the coral community, and P. compressa are significantly related to the total cover of coral. The three species of Acropora are significantly correlated reflecting their shared distribution and preference for shallow waters. P. compressa is related to depth suggesting that this species is not common in shallow waters. Finally, there is a strong correlation between depth and number of coral species which reflects the light sensitivity of the coral community.

A simple regression analysis of the number of species present at a site against depth and against salinity using data from table 4.1 and 4.2 shows that there is no significant correlation with salinity, but that the number of species is significantly related to depth ($r = 0.39$ at 31 degrees of freedom, $P = < 0.05$). However, certain species of coral disappear as salinity rises (see figure 4.6). Regression analysis of the percentage cover of coral against depth and salinity shows no significant correlation.

As a second stage in the investigation of coral community structure a principal components factor (PCF) analysis was carried out (see 'Methods'). PCF revealed six main factors which, between them, account for nearly 80% of the variance in the original data. Table 4.4 shows the percentage of the original variance accounted for by each component factor, which of the original variables are related to each factor and how much of the variance for each variable has been accounted for by each factor.

Factor 1: This factor reflects the common distribution of the coral species Cyphastrea seralia, Favia speciosa and Platygyra daedalea.

Factor 2: Represents the Acropora species reflecting their common distribution. The close relationship to total cover indicates the importance of these species as major components of the reef community.

Factor 3: Principally relates to the distribution of Cyphastrea monile which shows a strong relationship with total species number.

Factor 4: Represents the absence of zoanthids and calcareous red algae at certain sites.

Factor 5: Reflects the distribution of Porites nodifera and illustrates the high salinity tolerance of this species.

Factor 6: Relates to the absence of reef-building bivalves at certain sites.

This analysis has indicated common groups within the community structure; the three species Cyphastrea seralia, Favia speciosa and Platygyra daedalea; and the Acropora species. It has further shown a relationship between Cyphastrea monile and species diversity, the salinity tolerance of Porites nodifera and reflects the presence or absence of the non-coral biotic components.

As a third stage in the multivariate analysis of the reef community structure canonical correlation (CANCOR) was carried out (see 'Methods'). A series of analyses were carried out using various groupings of the data.

Table 4.5 presents the data subsets used (A-E), the number of significant correlations found, the strength of the significance, the group 1 variables along with their coefficients and the group 2 variables along with their coefficients. Various combinations of coral and non-coral biota have been analysed against various groupings of physical variables, coral diversity and total biotic cover.

Vector A1: This shows a highly significant correlation between the number of coral species present at a site and the depth of water at a site. Both coefficients are positive so coral species number increases with depth.

Vector B1: Reveals the relationship between the 8 coral species and depth. As depth increases there is an increase in the presence of Favia speciosa, Cyphastrea seralia and Porites compressa while the presence of Platygyra daedalea drops significantly. Other species show a weaker relationship to depth.

Vector C1: No significant relationship could be established between the 8 species of coral and salinity.

Vector D1: There are two correlation vectors present for this data set. This first vector represents the effect of overall percentage coral cover on both coral and non-coral biota. Acropora sp1 & 2 is having a strong influence reflecting this component's role in the reef community. The two species of Porites also make a significant contribution to the overall percentage cover of coral as does Platygyra daedelea. There is a small inverse relationship between overall cover and certain species reflecting the absence of those species in situations of high cover. Favia speciosa shows the strongest inverse relationship. None of the non-coral biotic components show strong correlations in this data set. All three have negative coefficients against percentage coral cover indicating an absence of these non-coral species in high-cover communities.

Vector D2: This vector reflects the relationship between different coral species and coral diversity. Favia speciosa and Cyphastrea seralia display the strongest positive coefficients indicating that these two species are commonly found in high diversity coral communities. Platygyra daedalea and Porites nodifera show an inverse relationship and are related to low diversity communities. The calcareous red algae are less likely to be found in high diversity coral communities while the zoanthids and reef-building bivalves can be found there.

Vector E: This data set presents the relationship between the non-coral biota, depth, salinity and coral cover and diversity. This data set reflects the fact that in conditions of high salinity where coral diversity is low calcareous algae are common and reef-building bivalves will be present but not zoanthids.

The above analyses have highlighted some clear relationships in the coral community between commonly-distributed biota and between the biota and physical components of the environment. As total coral cover increases, so does the importance of Acropora spp., Porites spp. and Platygyra daedalea in the coral community. However, a high coral cover does not imply high diversity. As water depth increases, the total number of coral species and therefore coral diversity increases. The principal coral species associated with high (relatively) diversity coral sites are Cyphastrea spp., Favia seralia, Acropora sp.3 and possibly Porites compressa while the main species associated with low diversity coral communities are Platygyra daedalea, Porites nodifera and the calcareous red algae. With increasing salinity, there is a reduction in the total number of coral species. Porites nodifera and the calcareous red algae both display a tolerance for higher salinities. Increasing salinity is related to reduced diversity.

Analysis of temperature data collected at the time of the study (between 28th July and 27th August, 1985) shows an average subtidal temperature of 33.6° C. The maximum temperature measured at a site with recorded live coral is 34.5° C (Sala N Off, 850822).The maximum salinity record for live coral found during this study is also from this site (50.2 ppt) although Porites sp. was recorded at Hawar Ajirah in March of 1986 in a salinity of 50.5 ppt.

Cluster Analysis:

As a final stage in the community analysis of the reefs, cluster analysis was undertaken for all 33 coral study sites using the data on all coral and non-coral biotic components, salinity, depth, coral diversity and total coral cover. Four clusters were identified. Table 4.6 shows the sites nominated for each cluster along with information on the salinity, depth, coral diversity and cover related to each cluster. Figure 4.4 shows a cluster dendrogram giving the distances between the 33 sites.

The first cluster (A) is characteristic of shallow to medium water depths (3.5-7 m) with relatively low (< 44 ppt) salinity levels and a very high percentage cover (> 80%) of coral mainly consisting of Acropora spp. The average number of coral species present (8.7) is the same as the average found for all sites around Bahrain.

Cluster B represents very shallow, relatively high (mean =48.4 ppt) salinity sites with a low number of coral species, but a relatively high (55.5%) overall coral cover. The coral cover is mainly a result of the presence of P. nodifera.

Cluster C includes those sites where the number of species of coral is highest (average of 14.8) and percentage cover is an average of 42% (with a range of 23%-71%). The sites are found at most salinities, but are never in areas of extreme salinity and tend to be in water depths below 6-7 m. Calcareous algae is low in cover or absent at these sites.

The fourth and final cluster (D) represents sites where coral cover is low and the number of coral species present is also relatively limited. These sites can be at any depth or salinity with either Acropora spp. dominating (at shallower sites) or P. compressa (at deeper sites). Zoanthids tend to be more common at these sites.

Coral Community Types

Based on the results of the multivariate and cluster analyses, 4 separate community types can be identified.

Community Type A:

Represents those sites where coral growth conditions are at a maximum. Acropora spp. dominate and flourish and coral cover is high as a result. These sites include the low salinity (< 44 ppt), high wave action and high water movement sites to the north and west of Fasht al Adhm (see figure 1.2 and 2.3). However, the number of coral species is not maximal probably as a result of successful competition by Acropora spp. which thrive in relatively shallow waters with high wave energy.

Community Type B:

These are the highly stressed shallow water coral sites with extreme salinity and where water temperatures can be expected to reach a maximum. It includes those sites at Fasht Bu Thur and Ad Dur which lie in that sector of Bahrain where salinities can fluctuate by as much as 17 ppt over a tidal cycle (see chapter 2). Porites nodifera, which constitutes most of the coral cover at these sites, is a species which has already been noted as being salinity tolerant (see figure 4.6). Calcareous red algae would be associated with this community type as would the presence of reef-building bivalves.

Community Type C:

These are the healthiest coral sites which probably constitute the true reef communities around Bahrain. These are the sites where Cyphastrea spp. and Favia seralia are most likely to be found as well a Porites compressa and Acropora sp.3. This community type is associated with low salinities (mean = 44.6 ppt) and water depths between 2-10 metres. Sites in this cluster include those found on the offshore islands and reefs to the north and northeast of the study area and along the front of Fasht al Adhm in 8-10 m of clear water.

Community Type D:

These are the sites where the percentage cover of corals is low (mean = 7.3) and the number of species is low (mean = 7.2). These are the sites where environmental conditions are marginal for coral growth. Sites in this cluster include nearly all the shallow (<1.5m) sites, the one very deep site and those sites adjacent to sand banks where sediment levels and turbidity have been noted as being high.

SEAGRASS HABITATS

The majority of well-developed seagrass beds were found on the south-east of Bahrain and are commonly associated with silty or muddy sands. Halodule uninervis is the most common species and appears to be more tolerant of a wider range of environmental parameters such as water velocity, substrate types and temperature extremes. For H. uninervis the percentage cover in the summer reached a maximum of 70 %. Assessment of percentage cover by eye in the winter showed cover to have risen as high as 90 %. The data from the summer study showed a correlation between percentage cover and blade length ($p < 0.01$, Pearson's product-moment correlation coefficient).

On the west coast 6 seagrass sites were studied. These sites had an average of 47% cover and a maximum of 80% cover. Halophila stipulacea is the most commonly reported species for the west coast. Salinities tend to be higher and water depth greater on the west coast. This suggests that these two physical factors may be important in controlling the distribution of the three species of seagrass in the study area.

Epiphytic algae or periphyton were found on the blades of all three seagrass species (particularly Halodule uninervis) together with the spat of pearl oysters (Pinctada spp.). Sponges of at least 3 species (blue Haliclona sp., grey sp. and red sp.) along with the epizoic ophiuroid - Ophiothrix savignyi were frequently associated with seagrasses and were often seen to completely encompass the leaves. These sponges were more common in areas of high salinity (greater than 48-50 ppt).

Tunicates were found in among the leaf:rhizome complex including a white/grey epizoic species as well as the black/purple Phallusia nigra, a species also found on hard bottom habitats. Large molluscs such as Pinna bicolor (up to 4 m^{-2} of seabed) and Bulla ampulla were found among the seagrass beds as well as sand dollars particularly Clypeaster humilis (up to 4 m^{-2} of seabed) along with smaller organisms such as Cerithium scabridum. Burrows were a common feature of the seagrass beds. Many of these burrows were associated with the inquilinistic relationship between the shrimp (Alpheus sp.) and the goby (Cryptocentron sp.).

Other inhabitants of the seagrass beds included various coelenterates (e.g. hydroids, cerianthid anemones and penatulids), various small gastropods (e.g. Trochus sp., Phasianella sp., Cerithium scabridum, Rhinoclavis kochi) and bivalves (e.g. Pinctada sp.), several common polychaete species and a number of different crustaceans (e.g. Cymodoce, Squilla). In addition to Clypeaster and Ophiothrix, which were common to the seagrass beds, various other echinoderms (e.g. Asterina burtoni and Amphioplus (Lymanella) species) were encountered. Larger macrofauna included various fish species and the sea-snake (Hydrophis cyanocinctus). The sea-cow (Dugong dugong) and a number of turtle species are commonly found in the seagrass beds and were observed over these areas during the aerial reconnaissance.

The most conspicuous seasonal variation within the subtidal habitats is the change in distribution and cover of the seagrasses. Both in the intertidal and subtidal areas the seagrass cover dropped dramatically over the winter period, often from 90-100% cover down to 30% or less (< 10% in the intertidal areas). This is especially true of Halodule uninervis and, to a lesser extent Halophila stipulacea. The former often undergoes almost complete regression leaving only a few thin, stunted remnants of stalk projecting above the surface. Visual observations during the summer and winter field studies suggest that Halophila ovalis may not undergo this reduction in cover over the winter period. The grass beds visited on the east coast during the winter (which were reduced in cover compared with the summer) were dominated by H. ovalis with H. stipulacea present in lower densities. These same beds consisted primarily of H. uninervis in the summer suggesting that the latter species had died back in the winter whilst H. ovalis remained intact with H. stipulacea probably also remaining at about the same percentage cover.

Where a reasonably healthy cover of H. uninervis remained in the winter (e.g. immediately south of Mashtan) the leaves were thin and fouled with epiphytes. There also appears to be a relationship between the survival of H. uninervis during the winter season and water depth, as the healthier beds of H. uninervis were found in water depths between 2 and 5 m.

Data on the biota associated with these habitat types are given in tables 4.7 and 4.8 and in appendix 4.4. The infauna characteristic of soft or mobile substrates are principally polychaetes, molluscs, some echinoderms, occasional burrowing crustacea and fish. This is inevitably a generalisation and the infauna of these habitat types varies depending upon grain-size and substrate type (see appendix 4.4 - habitat descriptions for subtidal seagrass sites).

STATISTICAL ANALYSIS OF SEAGRASS HABITATS

A total of 21 study sites have been included in this investigation of seagrass habitats and the data from these sites are presented in tables 4.7 and 4.8. All 3 species of seagrass were observed during the study and a further 15 biotic components were important and frequently observed members of the seagrass community. In the following analysis, 25 variables have been analysed. These included the percentage cover and leaf length of the 3 seagrass species, the presence of the 15 non-seagrass biotic components (as percentage cover or as the mean number of individuals m^{-2}), depth, salinity and total percentage cover of all seagrass. As in the analysis of the coral community data, salinity is represented as the mean site salinity (see figure 2.3).

Linear correlation analysis has been carried out as an initial stage in the investigation of interrelationships between the various components of the seagrass community. The data presented in tables 4.7 and 4.8 were used for the analysis (percentage cover of individual seagrass species, presence of non-seagrass biotic components, salinity and depth), but the data for seagrass leaf length, the number of key biota present and total seagrass cover were omitted from this analysis as correlations would be inevitable and would interfere with the identification of other, more relevant relationships. Significant correlations within the data set are presented in table 4.9.

A number of variables show strong correlations reflecting a common distribution within the seagrass community. The relationships between C. scabridum and the tunicate sp. and that between sponge sp. B and the pennatulid sp. are particularly strong. Other significant interrelationships between individual biotic components include shrimp/goby burrows with Linkia multiflora, cyanobacterial mats with burrows (anon.), pennatulid sp. with Pinna muricata, sponge sp. B with Phallusia nigra and hydroid sp. with L. multiflora. Halophila ovalis exhibits a closely-related distribution with Clypeaster humilis. This might suggest that C. humilis is feeding on H. ovalis or a species associated with H. ovalis. It could also suggest that they have very similar environmental requirements or that the presence of one of these species is altering the environment to suit the other. The percentage cover of Halodule uninervis is related to salinity reflecting the salinity tolerance of this seagrass species (McMillan, 1974).

As a second stage in the investigation of seagrass community structure, a principal components factor (PCF) analysis was carried out (see `Methods'). The PCF analysis of the data sets revealed 8 main factors which, between them, account for nearly 85% of the variance in the original data. Table 4.10 shows the percentage of the original variance accounted for by each component factor, which of the original variables are related to each factor and how much of the variance for each variable has been accounted for by each factor.

Factor 1: This factor reflects the common distribution of sponge sp.B and pennatulid sp.

Factor 2: Represents a strong relationship between Cerithium scabridum and tunicate sp.

Factor 3: Reflects the common presence of cyanobacterial mats and burrows (anon.).

Factor 4: Confirms a relationship between the presence of Clypeaster humilis and the seagrass, Halophila ovalis.

Factor 5: Relates to the common distribution of Linkia multiflora and shrimp/goby burrows within the seagrass habitat.

Factor 6: Reveals that salinity is having an effect on the distribution of sponge sp. A and that this sponge is more common at higher salinities.

Factor 7: Represents the absence of the seagrass, Halophila stipulacea from some sites.

Factor 8: Relates to the presence of the pearl oyster, Pinctada radiata at certain sites.

This analysis indicates shared distributions between certain species within the seagrass community revealing multivariate correlations which confirm the linear correlations. In the linear correlation analysis, H. uninervis was related to salinity indicating the salinity tolerance of this species. In the PCF, it is sponge sp.A which is exhibiting a clear salinity tolerance. The only direct relationship established between a non-seagrass biota and a seagrass species is that between C. humilis and H. ovalis.

As a third stage in the multivariate analysis of the seagrass community structure canonical correlation (CANCOR) was carried out (see 'Methods') using various groupings of the data. Table 4.11 presents the data subsets used (A-H), the number of significant correlations found, the strength of the significance, the group 1 variables along with their coefficients and the group 2 variables along with their coefficients. Various combinations of seagrass and non-seagrass biota have been analysed against various groupings of physical variables. In addition, the non-seagrass biotic components have been analysed against both the percentage cover and the leaf length of the three species of seagrass.

Vector A1: This vector represents an increase in percentage cover principally of H. uninervis but also of H. stipulacea as salinity increases and water depth decreases. Rising salinity and reduced depth are having an equal effect on this relationship as can be seen by the similar value for the coefficients for these two physical variables.

Vector B1: Again, this vector represents an approximately equal effect of rising salinity and reduced water depth. The leaf length of H. uninervis is increasing while the leaves of H. ovalis get shorter with increased salinity and reduced depth. H. stipulacea leaf length shows little response to these two physical variables.

Vector C1: A comparison of seagrass species cover against salinity alone reveals the same correlation found for these variables in Vector A1.

Vector D1: A comparison of seagrass species cover against depth also exhibits the same correlation for these variables as was found in Vector A1.

Vector E1: Represents seagrass species leaf length related to salinity and shows the same correlation as in Vector B1.

Vector F1: Demonstrates the relationship between seagrass species leaf length and depth. This vector reflects the same correlation found in vector B1.

Vector G: All non-seagrass biotic components are compared with the percentage cover of the seagrass species. All three species have a substantial effect in this vector. This vector reflects the increase in the presence of tunicate sp. and pennatulid sp. and a decrease in the presence of sponge sp.B and Cerithium scabridum with increasing cover of H. uninervis and decreasing cover of H. stipulacea and H. ovalis.

Vector H: Reflects the relationship between the leaf length of the seagrass species and the presence of the non-seagrass biota. As H. uninervis leaf length increases and as H. stipulacea leaf length decreases, there is a related increase in the presence of sponge sp.B, cerianthid sp., C. scabridum and L. multiflora with a related decrease in the presence of Pinna muricata and tunicate sp. H. ovalis leaf length shows no significant effect in this vector.

The above analyses highlight certain relationships. Where water depth decreases and salinity increases (a logically related sequence of events in view of high insolation levels and evaporation), both Halodule uninervis and Halophila stipulacea thrive with the leaves of H. uninervis reaching maximum length. Sponge sp.A also thrives under these conditions. Halophila ovalis does not survive well in high salinity shallow waters. The presence of associated biota will alter with variations in the balance of the 3 species of seagrass. The balance of the cover of H. uninervis to H. stipulacea is particularly related with tunicate sp., pennatulid sp., sponge sp.B and C. scabridum, while C. humilis is related to the presence of H. ovalis.

Analysis of temperature data collected at the time of the study (between 28th July and 27th August, 1985) shows an average subtidal temperature of 33.6° C. The maximum temperature measurement recorded during this study period at a site with live seagrass is 35° C (Twins S Off, 850810).The maximum salinity measurement recorded during this study period at a site with live seagrass is 60 ppt (Um Nasan West, 860312).

Cluster Analysis:

As a final stage in the community analysis of the seagrass beds, cluster analysis was undertaken for all 21 study sites using the data on all seagrass and non-seagrass biotic components, salinity, depth, number of key biotic components and total seagrass cover. Three clusters were identified. Table 4.12 shows the sites nominated for each cluster along with information on the salinity, depth, number of biotic components and total seagrass cover related to each cluster. Figure 4.5 shows a cluster dendrogram giving the distances between the 21 sites.

The first cluster (A) is found in medium depth waters between 3 and 7.5 m and is dominated by Halodule uninervis with low levels of Halophila ovalis and Halophila stipulacea. The presence of associated seagrass biota is high.

The second cluster (B) represents a shallow water community. Water depth are between 1.7-4 m. Salinities are generally high. H. stipulacea is dominant with H. uninervis frequent and H. ovalis absent. The presence of associated biota is never as high as A but neither is it particularly low.

The third cluster (C) is the deeper water community (on average greater than 9m deep). This cluster is noteworthy for having the highest cover of H. ovalis while both H. uninervis and H. stipulacea cover is low. This cluster includes all of the sites with the lowest numbers of associated biota.

Table 4.13 shows the distribution by species of seagrass at the different sites to identify the relationship between the presence/absence of the different species in monospecific and mixed seagrass beds. This table also shows the frequency of each monospecific and mixed community and the relationships of those communities to salinity and depth ranges.

Monospecific beds of Halophila stipulacea are rare as are dispecific mixed communities of H. stipulacea and Halophila ovalis. Monospecific beds of H. ovalis are only recorded in water depths of greater than 12 m and the only monospecific bed of H. stipulacea was recorded at 15 m. All of the monospecific beds of H. uninervis were recorded in 3 m. Dispecific communities of H. ovalis - H. stipulacea and of H. ovalis - H. uninervis were recorded in 8 and 7 m of water respectively (although the H. ovalis - H. stipulacea mixed community was rare). Mixed communities of H. stipulacea and H. uninervis were the most frequently observed combination of species and were recorded in water depths between 1.7 to 7.5 m. Trispecific communities of all three species were frequent and ranged from depths of 3m to 11m. In these trispecific communities it is noticeable that H. uninervis is by far the most dominant species in depths of 5 m or less while the percentage cover of any of the three species contributing to this community is very low at a depth of 11 m.

The data suggests that monospecific communities of H. uninervis thrive in shallow waters, especially at a depth of 3 m, while monospecific communities of both the Halophila species are only found in deeper waters of greater than 12 m. Dispecific communities of H. stipulacea and H. uninervis show an equal balance of cover between the two species in shallower waters of 3 m or less with H. uninervis becoming the dominant species from 3 m down to 7.5 m after which H. stipulacea regains an equal balance of cover and may exceed the cover of H. uninervis.

Salinity is not having an obvious effect on the contribution of each species to a community and trispecific beds are found throughout the salinity range recorded.

Individual key biota associated with the seagrass are related to both seagrass species and to leaf length. This *requires cautious interpretation as there must inevitably* be a relationship between seagrass species cover and leaf length. However, from the results of the cluster analysis, in conjunction with the principal component factoring and the canonical correlation analysis, it is possible to identify the major seagrass community types around Bahrain and to identify the most likely key biotic components which would be associated with these communities.

Seagrass Community Types

Community Type A:

This is the least stressed seagrass community found in water depths of 3-7 m with salinities across the range. This community is dominated by H. uninervis (36-70% cover) with low levels of H. stipulacea (maximum 22% cover)and H. ovalis (maximum 1.7% cover). It has the greatest number of associated biota present. Key biota associated with this seagrass community are sponge sp. B, pennatulids and hydroids. Shrimp/goby burrows are absent except in areas where the cover of H. uninervis is reduced. Tunicate sp. are be found in this community but only under conditions of low salinity. These communities are mostly found on the east coast between Fasht al Adhm and Hawar.

Community Type B:

A shallow water (1.7-4 m) seagrass community which exists under more stressful conditions. H. stipulacea is dominant reaching 38% cover but H. uninervis is present (up to 30% cover). H. ovalis is absent. Although numbers of key biota may not be as high as in the first community type they are never significantly low. Key associated biota include sponge spp. A and B. Cerithium scabridum is also likely to be present where salinities are high. The Sand Dollar, Clypeaster humilis would be found in this community in areas where the seagrass cover is low. It would be unlikely that tunicate sp. or pennatulids would be present. Shrimp/goby burrows are more likely to be present in this community type than in A. Only two sites fell into this cluster and these are located immediately south of Fasht al Adhm and between the outer (eastern arm) of Fasht al Adhm and the northern tip of Hawar (see figure 1.1).

Community Type C:

Represents a deeper water community (> 7 m) where environmental conditions for the growth of the common seagrass species are becoming marginal. H. uninervis and H. stipulacea cover is very low (maximum of 18.5% and 2% respectively) and the highest cover of H. ovalis is found here although this never gets particularly high reaching a maximum of 23%. Associated species numbers can vary but all of the sites with low species numbers were found in this cluster. Linkia multiflora and cyanobacteria are common and hydroids are probably to be found in this community type. Burrowing biota such as C. humilis, the Shrimp/Goby relationship and other unidentified burrowing organisms will prefer this community type, possibly as a result of the absence of the thick, complex root-rhizome network associated with H. uninervis but not with the Halophila species. Salinities tend to be under 46 ppt. These sites are located where deep water exists off the east coast south of Fasht al Adhm, in the deep waters to the east of Muharraq and the one deep study site located to the north west of the island at Sala (see Volume 2, figure 1).

OTHER SUBTIDAL HABITATS

In addition to the 33 coral study sites and the 21 seagrass study sites included in the statistical analysis above, a further 116 subtidal sites (figure 4.3) were visited for water quality analysis (see appendix 2.1) and a brief descriptive record made. The descriptive data from these sites was used to test the accuracy of the satellite imagery (see chapter 5). The following descriptive results are included for further discussion.

Subtidal Sands:

As was noticed in the intertidal studies, sand as a pure (unmixed) habitat is not common to Bahrain and only 8 of the sites studied could be designated as having pure sand as the principal habitat type. These are Al Mumtallah (sites 197-199), Galali (site 113), Mashtan North (site 203), Mashtan South (site 204), Jaradah (site 131), Um Jalid Trans SE (site 180), Um Jalid Trans NW (site 181) and Zallaq Jetty (site 173 - see figure 4.3). There were few extensive areas that could be described as sand alone as can be seen from the habitat maps discussed in Chapter 5. However, this habitat type tends to occur as a transition band between shallower rock substrate and slightly deeper sandy-mud seagrass habitats. 83 sites were designated as mixed sand with other substrata. Silty or muddy sand is often associated with seagrass beds while coarse-grain sand is frequently mixed with coral or other hard limestone structures from which much of the sand is undoubtedly derived. Fine sand or silt is often found as a thin cover over bedrock (this habitat is common within the shallow subtidal down to 7-8 m on the mainland west coast of Bahrain, as well as on the west coast of Hawar). Even areas bordering the coral reef, which may appear to be a sand habitat from the air, often prove to be a mixture of sand and rubble or sand and cobbles when studied at ground level.

Relatively few surface macro-faunal species were apparent at the subtidal, sandy habitat sites. Echinoderms probably represent the most conspicuous invertebrates present in this habitat. These include 2 asteroids (Astropecten polyacanthus phragmorus and Linkia multiflora) and several echinoids (Echinodiscus auritus, Echinometra mathaei, Diadema setosum, Prionocidaris baculosa and Clypeaster humilis). Of these Astropecten, Echinodiscus and Clypeaster were found on sand. The rest were more commonly associated with coarse rubble than with sand. Molluscs commonly included cerithids (particularly Cerithium scabridum) and other small gastropods (e.g. Calliostoma sp and Mitrella blanda) and bivalves (e.g. Pinctada sp.). Pinctada appears common from the data, but needs a mixed habitat with a hard surface present to provide it with a suitable substrate for settlement. In addition to the cyanobacteria/benthic microflora found coating the sand surface at a number of sites, various macroalgal species were sometimes present. Other organisms sampled from subtidal sandy habitats included hydroids and various crustaceans (e.g. Thalamita poissoni, Cymaduca filosa, Gonodactylus chiragra chiragra.

The most conspicuous seasonal change in the sandy, subtidal habitats is the distribution and concentration of the cyanobacterial mats. This is particularly true of the very shallow, high salinity subtidal where these organisms thrive, especially around Hawar. Cyanobacteria and diatoms bloom during the transition and early summer period often turning the shallow seabed golden-yellow in colour. This provides a highly productive habitat for juvenile fish such as mullet (Bottom-feeders) and silversides (Which feed on harpacticoid copepods).

The main seasonal variations found within the coarser, less mobile substrates such as the gravels and cobbles consist of changes in algal condition and cover (Hormophysa triquetra dying back in the winter and blooming in the summer and Polysiphonia sp. and Dictyota divaricata blooming in the winter and reducing in cover during the summer), and the settlement and development of the oyster spat between late summer and the following winter-summer transition period.

Subtidal Muds:

Very few sites were recorded as pure mud habitats (Askar N (site 171), Al Muwaylighah (site 121) and Ras Hayan N (site 175 - see figure 4.3). However, it is an important component of mixed habitats in deeper waters. Muddy habitats also exist in Tubli Bay and south to south-east of Fasht Al Adhm (Volume 2, figure 1). On the west coast below the 12-14 m mark it is the principal sediment type. The presence of mud is dependent on low water velocities and as such is often associated with deeper water. It is rarely found as a separate habitat in shallow waters less than 10 m in depth and where it does exist in shallow water it is usually stabilised by the presence of seagrass.

The biota of subtidal mud was sampled most thoroughly along a transect between Bahrain and Qatar (sites 97, 98, 99, 102, 103, 194 see figure 4.3). Cyanobacteria (and probably other benthic microorganisms) formed a thin surface film of greater than 80% cover). Dominant fauna included penatulids at a density of around 1-3 m^{-2} and two species of scaphopods (Dentalium longitrorsum and D. octangulatum) with densities of up to 157 m^{-2} . Other invertebrates included various polychaetes, gastropods (Turritella maculata) and small bivalves (e.g. Timoclea sp.). Sponges, sand dollars (Clypeaster humilis) and unidentified burrows were also, observed all at densities of around 1 m^{-2}.

Non - Coralline Hard Substrates:

Many areas in these waters have exposed hard substrates which support little or no coral growth. The most common form of this habitat-type is limestone rock with a thin (usually less than 1 cm) cover of sand or finer sediment. Such areas are common in the north-east and west at 2-8 m deep and good examples exist off Muharraq island (site 109, 111, 114, 118 and 120) and offshore on the west coast between Zallaq and Ras Al Mumtallah (see figure 4.3). On the east coast similar areas exist in water depths of 2-3 m. Just west of Mashtan is an area which rises out of the grass beds and is colonised by tall stands of Sargassum. This shows up clearly on the subtidal habitat maps (Volume 2, figures 10-12) as a pink `v' immediately west of Mashtan and is classified as rock with a thin veneer of sand.

Areas of rocky subtidal are few and where present are nearly always mixed in with a soft substrate. The hard, non-coralline habitat types can be divided into:

1. Exposed rock (Evaporite or sandstone).

2. Rock with sand cover or mixed rock and sand.

3. Dead coral limestone.

Subtidal exposed rock is rare in Bahrain as a result of the high sediment load characteristic of these waters. In nearly all cases, the rock is covered by a layer of sediment or has been colonised by coral. Probably the best examples of exposed, subtidal rock are around the north and north-east of Hawar (sites 212, 214, 215, 220, 221, 222, see figure 4.3). Here the unique rocky, intertidal habitat (see intertidal section) runs into a rocky subtidal zone with small cliffs and overhangs. This subtidal area was only studied during February-March 1986. During the winter period it supported a large cover (50%) of the red algae Laurencia sp. on top of rock with large clumps of Sargassum sp. beneath the overhangs and occasional coralline algae (also beneath the overhangs). An unexpected discovery was areas of coral (Porites sp., <10% cover) which had never been recorded this far south into Dawhat Salwah and must exist on the very limits of salinity tolerance. Salinities at the time were recorded at 45 ppt but are now known to reach at least 50 ppt at low water (see chapter 2).

Another area of exposed rock was recorded at the northern entrance to Tubli Bay (site 124). Here a channel runs in from Khawr Al Qulayah and tidal velocities are considerable on ebb and flood tides. Within the channel beneath the bridge and extending at least several hundred metres either side is an area of scoured rocky sea bed. Within Tubli Bay this supported a 60% cover of algae (Sargassum sp., Hypnea cornuta and Sarconema furcellatum). In the main channel beneath the bridge, algal cover was reduced to 20% or less and the dominant biota were sponges (40-60% cover) with colonial tunicates (Didemnum candidum, Polyclinum constellatum, etc.) and hydroids (Thyroscyphus fruticosus, Ventromma halecoides plus 2 other unidentified species) forming the rest of the biotic cover. Conspicuous macrofauna included Trochus erythraeus, Pilumnus verspertilio, Ophiothrix savignyi and Doriopsilla miniata. Some coral (Porites) was also present at a density of 1 colony per 20 m^{-2}.

Rock with sand cover (or mixed rock and sand) is a common habitat around Bahrain (e.g. west coast Zallaq offshore - site 172, 183, figure 4.3) supporting a mixed flora and fauna taking advantage of the separate components of this habitat. Detritivores exploit the sand/sediment layer over the rock as do errant polychaetes. Cyanobacteria and diatoms grow over the surface of the sediment and interstitially while the occasional exposed rock surfaces support macroalgae such as Sargassum and Hormophysa as well as various hydroids.

On the west coast of Hawar the subtidal slopes gently away from the island and for some hundreds of metres does not exceed 8-10 m in depth. This hard rock substrate with a thin layer of sand supports Sargassum sp. and Hormophysa triqueter with epiphytic sponges, while areas of deeper sediment are colonised by seagrasses. Where the sand is absent, such as west of the island of Rabad Al Gharbiyah (site 176 and 177, figure 4.3) green algae colonise the rock.

Dead coral limestone habitats can be found south of the Fasht al Adhm and occasionally on the west coast. Although they no longer support any coral species, they still maintain the complex labyrinth-like structure of the reef. Despite the absence of live coral the biota normally associated with the coral reef lives in and around such structures. This includes reef fish such as Pomacanthus maculosum, Acanthopagrus bifasciatus, Pseudochromis persicus and the echinoderms, Echinometra mathaei, Prionocidaris baculosum and Diadema setosum.

Off Hawar, west of the island of Janan (site 221), is an area of old, dead coral reef rising to within a few centimetres of the surface. The salinities, often reaching 55-60 ppt are far too high for coral growth, but the structure of the reef is still present supporting green algae and a dense algal turf. The dominant fauna in this area were molluscs and also conspicuous were a number of reef fish.

The major seasonal difference on the non-coralline, hard habitats is the distribution and types of algae. Unfortunately, due to time constraints, these habitats received less attention during the summer study than in the winter. From the amount of algal material found floating in the water column during the late winter-summer transition period and into summer itself it is almost certain that most of the extensive Sargassum beds to the southeast and around Hawar lose part of their benthic cover in the early summer. Some of this may a result of disturbance of the seabed biota by the 40 day Shamal which is common around this time of the year. However, Sargassum does reproduce vegetatively by simple fragmentation of the thallus which can also result in large mats of this alga floating in the water during the growing season. The timing of this phenomenon is coincidental with the survival of the larval and juvenile stages of the shrimp. The larval stages are usually found in the plankton around mid to late March and by late April and early May will be postlarvae. This is when they are particularly vulnerable as they are unable to burrow until they reach the juvenile stage. The large quantities of drifting Sargassum which occur about this time are therefore of particular importance to the juvenile shrimp providing them with shelter from predators (Al Attar, 1981).

Colpomenia sinuosa and Hydroclathrus clathratus are also seen drifting in large mats on the surface in the early summer. Although some of this algal debris will have come off the reef (see previous section on coralline hard substrates), these algae are also found growing in high densities in winter on shallow, non-coralline substrates. These two algae may also provide a protective habitat for the shrimp.

Hormophysa triquetra behaves in a similar fashion in the subtidal as it does in the intertidal, dying back to a few stunted leaves in the winter and blooming again to a large plant tens of cms high in the summer. This was particularly noticeable on the limestone rock seabed running between Ras Al Barr at the southern end of the main island across to Hawar. H. triquetra provides an important substrate upon which the young oyster spat (Pinctada) make their settlement. H. triquetra is also found on the oyster beds to the north of Bahrain which are transitional between a solid, immobile, hard substrate of limestone rock and a mobile substrate of gravels and cobbles.

On the west coast on the shallow subtidal substrates of limestone rock and gravels there is a noticeably vigorous growth of Polysiphonia sp. and Dictyota divaricata during the winter months.

Other Seasonal Biological Variations in the Waters around Bahrain

As well as variations in the actual marine habitats around Bahrain there are also noticeable seasonal differences within the more transient or mobile faunal elements. Certain ichthyofauna show seasonal variations (Smith, G.B., Pers. Comm.; Vousden, Pers. Obs.), examples being particularly obvious among the larger, predatory fish such as Scomberomorus commersoni (the Spanish Mackerel) which is usually seen in large numbers from mid to late summer through to the summer-winter transition in November. This distribution is probably related to an increase in the smaller, schooling fish on which it feeds such as the sardine (Sardinella sp.) and the anchovy (Stolephorus sp.) as well as shoals of other juvenile species, many of them surface plankton-feeders.

The sailfish, Istiophorus platypterus also frequents the waters around Bahrain later in the year feeding on all types of fish in the water column. This species is a very fast-moving, pelagic predator which is prized for its fighting potential when hooked on a rod-and-line and is a favourite among game fishermen.

Turtles are also seen more frequently in the summer months in Bahrain waters, especially the Green turtle (Chelonia mydas), as well as the Hawksbill turtle (Eretmochelys imbricatus bissa). The former is principally a herbivore feeding on the seagrasses while the latter is more omnivorous eating seagrasses, algae, jellyfish, molluscs, crustacea, etc. The Loggerhead turtle (Caretta caretta gigas) is also recorded for the Arabian Gulf, but there are no substantiated records for Bahrain.

The dugong appear to show some seasonal movements, exploiting the more stable deeper waters during the winter, but moving into the shallower waters in the summer. This may reflect a difference in seagrass distribution between the two seasons.

The shrimp, Penaeus semisulcatus is strictly seasonal in its life-cycle with the breeding season starting in late February-early March and the juveniles found in April-May. To avoid over-fishing Bahrain has introduced a closed season on shrimp-trawling from March to early July. This has proved to be effective in maintaining supplies of adult shrimp throughout the year. There is another, smaller recruitment period during the summer-winter transition period

DISCUSSION

There is very little true coral reef in the waters around Bahrain. The reef community is mainly represented by intermediate stages which are poorly developed. Much of the reef structure is actually individual heads and branches supported on a substrate of dead reef which appears to have been relatively prolific at one time but has died at some stage in the past. There is a distinction between coral and reef growth. Coral growth can simply be a few scattered colonies with very little or no interrelationship whereas a reef represents a whole biotope with a characteristic associated flora and fauna and complex interrelationships between the various species which make up the community. This complex reef community requires much more favourable conditions for its development than exist anywhere in Bahrain except possibly in the north-eastern area. Even in these areas the reef does not develop to produce a steep frontal profile.

The natural environmental stresses experienced by corals in the waters around Bahrain represent a severe constraint (see chapter 2). These stresses are principally temperature, salinity and turbidity, with water depth controlling species presence on a localised basis. Corals have specific temperature limitations and low temperature in particular is one cause of reduced diversity in marginal coral areas (Veron, 1974). A rise of 2-4^0 C above optimum growth temperature can cause tissue damage and greater than 5^0 C can result in death (Jokiel and Coles, 1977). The influence of temperature over coral distribution is much more strongly mediated via reproductive rate rather than growth rate (Sheppard, 1982). In salinities higher than 45 ppt, coral diversity and percentage cover falls drastically (Sheppard et al, 1992). Sediment and water movement exert marked biological effects on coral reefs (Stoddard, 1969). These two factors act reciprocally and as water velocity falls and sedimentation increases, coral population declines in richness and depth penetration.

From analysis of the data in table 4.1 and 4.2 it appears that as depth increases the number of coral species increases mainly due to an increase in the percentage cover of Cyphastrea seralia, Favia speciosa, Porites compressa and Acropora sp.3 while Platygyra daedalea and Porites nodifera are associated with low diversity sites. While the first four species mentioned above are displaying a preference for deeper waters, P. daedalea is either a shallow water species or cannot compete under conditions of high coral diversity.

Increased salinity is related to a reduction in coral diversity with the Porites nodifera showing a tolerance for higher salinities. Sheppard et al (1992) record P. nodifera as being a salinity-tolerant species within the Gulf. Certainly it was the only species present as far south as Hawar where salinities are generally higher than in the north (see chapter 2).

Figure 4.6 shows the sequence in which coral species disappear from the coral community as salinity increases at various sites. On Sala Reef off the north-west coast of the mainland, where average salinities are in the order of 50 ppt or more (see chapter 2), only three species of coral remain. These are Porites nodifera, Cyphastrea microphthalma and Siderastrea savignyana. The latter has also been recorded from similarly stressed environments in the Red Sea (Sheppard and Sheppard, 1985). Kinsman (1964) reports healthy corals surviving in natural salinities as high as 48 ppt and these three species of coral appear to be the most saline-resistant species recorded anywhere to date.

Where the percentage cover of coral is greater it is mainly as a result of an increase in cover of Acropora spp. and of Porites compressa. The percentage cover of F. speciosa shows a very slight reduction as the overall percentage cover of coral increases (see table 4.1 and 4.5). According to Veron (1977) F. speciosa is never a common species, but can be found in shallow waters that are not dominated by Acropora spp. F. speciosa is not a particularly successful competitor against other coral species in the Gulf.

Table 4.6 and figure 4.4 show the results of the cluster analysis and reveals 4 groups of sites with different coral communities around Bahrain.

The fact that species diversity in Community Type C is high, but cover is not maximal agrees with Sheppard et al (1992) in that a measure of high coral cover is no guarantee of a healthy reef system. High coral cover is more often associated with the dominance of one species and can often indicate stressful conditions. Percentage cover has often been used erroneously as a measure of the quality of growth and developmental conditions for coral on the reef. In fact, the most diverse coral communities in terms of species have percentage covers of between 35-50%, while many communities supporting a higher cover of fewer species which are particularly tolerant to the prevailing local conditions are usually characterised by high stress factors (Sheppard, pers. comm.).

Price et al (1984) list high salinity values and wide seasonal extremes of temperature as being the main factors limiting coral growth and distribution in the Arabian Gulf. Upper salinity tolerance limits of 40 ppt as well as minimum and maximum temperature limits of 18 and 32^{0} C respectively are quoted for most coral species. Active coral growth in the Pacific may extend as deep as 50 m, but is restricted to 15m in the Arabian Gulf as a result of reduced light attenuation and is often less in turbid coastal waters which are characteristic of Bahrain. This is consistent with present findings where certain hardy species tolerate the shallow water reefs of Bahrain and temperatures often exceed the lower and upper limits cited above. The abbreviated zonation of coral species with depth is a reflection of the generally abbreviated zonation found in the Gulf in comparison to the open oceans. Head (1987) provides examples of abbreviation of the normal Red Sea coral zonation (over a depth range of 30 m or more) to only 6 m in depth within lagoons, condensing the normal association patterns within this depth span. Branching corals were found to be practically absent below 1 m depth and were replaced by the normally deeper water Porites. In only 5 m depth of water the coral assemblages had much of the characteristics of open water reefs at 30-40 m deep. This was attributed to low water clarity and reduced light penetration. This is remarkably similar to the situation found in the turbid waters around Bahrain.

Acropora spp. and P. compressa are the two dominant species of coral in the waters around Bahrain and have the greatest influence on increasing percentage cover, but not necessarily on the number of key coral species. The percentage cover of P. compressa also increases with depth and where the number of coral species is greater although depth and number of species are related. It would seem likely therefore that Acropora spp. is the dominant coral in shallow waters and P. compressa fulfills the same role in deeper waters. When canonical correlation analysis is conducted using these two species against depth and percentage cover there are two significant correlations (see table 4.5). The first shows a direct correlation between an equal balance of Acropora spp. and P. compressa (in group 1) and total percentage cover of coral in group 2, demonstrating that these two species are sharing the dominant effect on percentage cover equally. The second correlation shows group 2 variance dominated by depth with an equal balance of the variance in group 1 between Acropora spp. and P. compressa, but with a noticeable inverse relationship between Acropora spp. and depth while P. compressa and depth display a positive relationship. This serves to confirm that Acropora spp. is the shallow water dominant and P. compressa the deep water dominant. Sheppard (1982) lists Acropora spp. as being shallow water dominants as does Veron (1974). Sheppard et al (1992) also lists P. compressa as the dominant coral species in deeper water Gulf coral communities with Acropora spp. as the dominant species in shallow water.

Head (1987) notes that it is the vulnerable branching corals which are generally the most abundant reef top species. He suggests that Acropora may be an `r-strategist', colonising fast and growing rapidly to reproduce before the next large storm destroys the local population. The branching corals, therefore, tend to dominate the shallow water areas with high wave action, high temperature and potential exposure. In deeper waters the massive corals dominate and the branching corals decline with depth. Head (1987) relates this to the size of polyps and surface area of the corals. Branching corals have small polyps and a large surface area and therefore rely more on the available light energy in the shallower waters. Massive corals have larger polyps which are better adapted to feeding on zooplankton.

The cover of the three key non-coralline biotic components shows a relationship to the number of coral species present with some effect from salinity and, to a lesser extent, depth (Table 4.5). The relationship in group 1 (the three biotic components) is caused by the calcareous red algae which show an increase in percentage cover with a fall in the number of coral species and a rise in salinity. This is also true of the reef-building bivalves. The zoanthids show an inverse relationship preferring higher coral diversity in lower salinity water. There may be some competitive advantage conferred in high salinity waters for the calcareous red algae which would explain the relationship with the low species number of corals. Sheppard (1982) notes that the calcareous red algae flourish where wave energy is most severe. Analysis of the data matrix (tables 4.1 and 4.2) reveals that all of the sites where the calcareous reds are found at greater than 5% cover are very exposed north or northeasterly facing sites, and in the main are in depths of 3 m or less.

In hindsight, a study of the ichthyofauna within the different reef communities would have been a valuable addition to this study. This would have allowed the inclusion in the data matrix of such measurements as fish species, abundance and size and allowed some insight into the relationship between the assemblages of fish and the different coral community types.

Reef growth and development around Bahrain does not compare directly with typical reef growth elsewhere in the world. In many places around Bahrain where the topography of the reef suggests positive reef growth, little or almost no live coral is recorded. In other areas found to support a healthy and relatively extensive coral growth the profile of the reef is gentle and undulating unlike elsewhere (Sheppard, 1982; Sheppard et al, 1992). The extensive underlay of limestone substrate around Bahrain certainly appears to present opportunity for the development of large coral colonies. However, this is very dependent on other limiting physical parameters such as sediment load, salinity, temperature and depth (light attenuation). The fact that present coral cover is generally low, coupled with the evidence of recent quite widespread, coral mortalities is almost certainly due to these physical limits or, more correctly, stress factors which are imposed on this environment. It is quite possible that some of the recent mortalities have been caused by man-made influences such as dredging and reclamation raising these delimiters beyond the tolerance of the coral colonies (Vousden, 1985b). It is also possible that as corals are close to tolerance limits, natural fluxes of salinity, temperature and even sediment load due to climatic factors occasionally stress corals beyond their tolerance. This may have destroyed much of the coral community and currently restricts its fuller development.

Shin (1976) records a widespread mortality of Acropora covered with soft green and brown algae due to an unusually strong and cold Shamal (northerly wind) which persisted throughout January 1964 in Qatar. Water temperatures offshore dropped to 14^0 C and resulted in large numbers of dead fish, seasnakes, cuttlefish and a dugong. The massive head corals, which have been shown to be more temperature-tolerant than the branching forms (Mayor, 1914), survived. By September 1966, new staghorn colonies developed up to 20 cm. in height and Shin postulates that the reefs off the north and north-eastern coast of Bahrain were the most likely source of planktonic coral larvae for reseeding reefs in Qatar, especially in view of the predominantly west to east currents. Similar algal cover of live reefs during low winter temperatures is reported from Kuwait (Downing and Roberts, 1993) and Saudi Arabia (Vogt, 1994).

The measurements for upper temperature and salinity limits for coral around Bahrain (34.5° C and 50.5 ppt respectively) constitute new tolerance records (Sheppard, pers. comm.).

The three species of seagrass found during the course of the Bahrain Marine Habitat Survey are the same as those recorded by Basson et al (1977), Price et al (1984) and Price and Coles (1991). However, Sheppard et al (1992) and Kenworthy et al (1993) record 4 species of seagrass. The case for a fourth species arises from den Hartog (1970). This gives a single record for Syringodium isoetifolium collected from Bahrain by R. Good in 1950. This sample is housed in the British Museum herbarium and was actually identified by Good as Diplanthera uninervis. This species has since been revised and the sample is now included in the Halodule uninervis collection. Personal inspection of the sample shows it to be H. uninervis and not S. isoetifolium.

Either depth or salinity or quite possibly both acting in unison have an effect on seagrass species distribution and standing crop. The multivariate data analysis supports a depth dependent distribution with both H. uninervis and H. stipulacea preferring shallower water and H. ovalis being a deeper water species. The data also reveals a greater salinity tolerance by H. uninervis and H. stipulacea. The precise relationship between H. uninervis, H. stipulacea and depth is not so obvious in the initial stages of the multivariate analysis. The cluster analysis suggests that H. uninervis dominates in water depths between 3.5-7m with H. stipulacea taking a more prominent role in shallower water. The maximum depths for H. uninervis and H. stipulacea are not clear.

Analysis of monospecific seagrass communities and the admixture of di- and trispecific seagrass beds supports the evidence that H. uninervis is a species which dominates in depths between 3 m and 7.5 m. Where H. uninervis contributes to the community in shallower or deeper water it does not dominate and is frequently the secondary seagrass species present in terms of percentage cover. As a monospecific seagrass community, H. uninervis is common at a depth of 3 m while monospecific communities of both H. ovalis and H. stipulacea are only recorded in deeper waters where H. uninervis is rarely found.

The community types listed above (see `Results') compare closely to the findings of other seagrass researchers. Lipkin (1979) recorded H. uninervis from a variety of habitats in the Red Sea from the intertidal down to a depth of several m, but with a narrower ecological distribution than H. stipulacea. Furthermore Lipkin found that H. uninervis grows and often dominates in mixed populations with other seagrass species. Communities are usually composed of nearly all H. uninervis with occasional H. stipulacea or H. ovalis. Lipkin only records H. ovalis between depths of 0.2 to 2 m, although he cites other references which record this species down to 46 m. H. ovalis is rarely found alone but forms communities with both H. stipulacea and H. uninervis. H. ovalis forms one community type where it dominates, but never reaches covers of greater than 30% and is always accompanied by low percentage covers of H. uninervis or H. stipulacea.

Lipkin (1979) also recorded the depth ranges for the same three species of seagrass in the Red Sea and found H. stipulacea between 1 and 45 m, H. ovalis from 1 to 10 m and H. uninervis from 1 to 6 m. Neither H. ovalis or H. uninervis were recorded below 10 m. Data from the present study shows that, in the Arabian Gulf, H. ovalis extends beyond the depth limits recorded for this species in the Red Sea (1979) and data records from the present study show that this species can exist as a monospecific seagrass bed at a depth of 18m.

H. stipulacea is recorded to suffer from photoinhibition at high levels of irradiance (Drew, 1979) which precludes it from very shallow waters. Drew records this species down to depths of 40 m or more. The present study shows that H. stipulacea can attain a percentage cover > 30% in waters as shallow as 1.7 m and has been seen intertidally. The maximum salinity recorded for healthy seagrass during this study was 60 ppt. All of the three species have previously been shown to be capable of tolerating such high salinity (McMillan, 1974). However, the role of salinity tolerance and its effects on the distribution of the three species of seagrass is still unclear, especially when related to depth. All three species of seagrass found around Bahrain have been previously recorded as having survived in temperatures in excess of 39° C (McMillan, 1984). The highest temperature at which seagrass was recorded during this subtidal study was 35° C. Zieman (1975) notes that Thalassia testudinum has a temperature optimum giving maximum values of standing crop, leaf length and blade density. Up to 35° C respiration steadily increases but past 35° C biochemical damage starts to occur and respiration decreases. The temperature optima for maximum growth values for the 3 species of seagrass encountered during the present study is not known.

The presence or absence of a particular key biotic component may be related to the presence or absence of a seagrass species. However, the presence of one is not necessarily a direct result of the presence of the other. It is only possible to speculate on the basis of the existing data as to the control of such relationships. Certain biotic components such as C. humilis, cyanobacteria, L. multiflora and shrimp/goby burrows appear to be related to low densities of seagrass and are never associated with a well-developed seagrass bed of dense H. uninervis. Logic would suggest that C. humilis and L. multiflora may have considerable difficulty in moving through such a grassbed, or perhaps C. humilis feeds by grazing on cyanobacteria which are not found in dense H. uninervis beds. High density of H. uninervis produces a thick complex of root/rhizome in the substrate which may prevent burrowing and may explain the absence of the shrimp/goby burrows, alternatively the shrimp/goby partnership may survive on the basis of predatory and/or potential food detection which would be difficult in dense vegetation. All of these hypotheses could be tested with carefully-designed experimental techniques.

Photosynthesis requirements may explain the depth exclusion threshold of seagrasses, but the shallower limit is more obscure. A number of possibilities could explain this 2 m upper threshold. Wave action is more pronounced in shallower waters producing a coarser loose substrate which may be less favourable to seagrass development. This same wave action may act directly on the plant as a destructive force, tearing-off leaves or scouring-out the root-rhizome system. Temperature may be a controlling factor by imposing high thermal stress on the shallow subtidal during the summer months. Seagrass adapted to low light intensities may be restricted by strong sunlight as the chlorophyll becomes saturated and broken down (Earll and Erwin, 1983). A combination of these factors is likely to provide the control to the upper limit of seagrass colonisation.

Price et al (1984) collected seasonal data on seagrass cover around Bahrain and stated that no seasonal trends in the data were apparent for any of the species. However, scrutiny of the data provided by Price et al (1984) show that, for H. uninervis at least, percentage cover values were always lower during the January-February sampling period and higher during April-May and September-October. Price et al surmised that the relatively high abundance of seagrass at Askar on the east coast was a result of the lower salinity values for that area, while the more limited occurrence on the west coast was a reflection of the higher salinities. However, it is known that H. uninervis grows in much higher salinities in Dawhat Salwah and in high salinity lagoons on the Saudi Arabian coastline (Jones et al, 1978) and chapter 2 reveals that tidal salinity fluctuations on the east coast can raise salinities as high as some of the west coast sites studied by Price et al (1984). Hence it is unlikely to be salinity which is constraining the overall percentage cover of seagrass on the west coast.

Basson et al (1977) list depth of water, the physical nature of the bottom substrate and water movement as being the three main factors controlling the occurrence of seagrass beds in the Gulf. Sheppard et al (1992) also suggest that depth must be an important factor and note that around Bahrain where water depths tend to be < 10m seagrasses are much more common than in the rest of the Gulf. There appears to be suitable substrate available all around Bahrain with a varied assortment of muds, sands and admixtures of the two liberally distributed around the coastline (Doornkamp et al, 1980). Water movement is a function of current velocity (which varies down the west coast from quite rapid movement around the Causeway to very reduced velocity at the western tip of the island - see chapter 2), winds and wave action. The latter will depend on depth as will light attenuation and so it is probable that water depth ultimately exerts a significant influence over the distribution of seagrass species in the Gulf and around Bahrain.

Because of their commercial and historical importance, the seagrass habitats around Bahrain should be given priority as far as immediate protection is concerned. They are of economic importance as a fisheries resource (Basson et al., 1977; Adams, 1976a and 1976b) and of cultural importance as they represent the livelihood and heritage of the fishermen of Bahrain. Also they are now of international scientific importance with the recent discovery of a herd of dugong representing probably the largest, if not the only, significant population of this endangered Gulf species (Preen, pers. comm; Vousden, pers. obs.). Biologically, the seagrass beds serve a twin role as both a major source of primary productivity in these waters and as a habitat representing a complex extension of the seabed in which many species including young commercial shrimp and fish can hide from predators. In view of the importance of seagrass communities around Bahrain a better understanding of the relationship between salinity, depth and seagrass distribution and growth is a priority.

Below 12m the seagrass community is replaced by either soft silts and muds in low velocity water (e.g. offshore south-western Bahrain) or mixed shell sand and gravel in areas of stronger current (e.g. north and north-west Bahrain, beyond the deep water channel). Similarly, in subtidal waters less than 2 m in depth seagrass generally becomes stunted and sparsely distributed. Consequently, around the south and east of Fasht al Adhm and many of the outlying islands there tends to be a belt of sand between low-tide and the 2 m depth contour. This sand is generally rich in blue-green algae and cyanobacteria representing sources of primary production with occasional macroalgae where rock or gravel provide a foothold.

On the west coast where water velocities are generally very low and depths reach at least 32 m, large areas of mud and mud with shell-gravel exist. In Tubli Bay, Khawr Al Qulayah and other low energy subtidal areas of the east coast, muds are also found. Although the economic importance of such areas is not immediately obvious, they provide a habitat for the adult penaeid shrimp and certainly play an important role during their spawning season (Al Attar, 1981). Basson et al., (1977) have shown that the subtidal muds have a characteristic flora and fauna and evidence suggests that diversity within this habitat type may be even higher than that found in the seagrass beds . Sand habitats are associated with a higher velocity water movement than mud, except where the mud is bound and stabilised by seagrass. They present a difficult environment for colonisation because of their inherently mobile nature and are also generally considered to be less productive than seagrass beds. However, Basson et al.,(1977), report a greater diversity of organisms associated with subtidal sand (638+ species) than with the seagrass system (530+ species). In shallower (less than 10 m) waters, this substrate can support a high primary productivity in the form of benthic diatoms and other microalgae and in depths below this the food chain may well start at the bacteria/detritivore level.

Around Bahrain, sublittoral exposed rock surfaces, boulders or any natural or artificial hard substrate which breaks the relief of an otherwise horizontal and 2-dimensional surface sand layer can produce an 'oasis' effect (Vousden, 1985b). The hard substrate provides a point of settlement for macroalgae, bivalve molluscs and other sedentary or sessile organisms. The two best examples of exposed rock habitat are to be found in the Hawar islands and in the northern entrance to Tubli Bay. In both cases coral is present but in very limited quantity (< 7% cover). In the Hawar islands hard surfaces are dominated by algae, in particular Sargassum. In the channel and northern interior of Tubli Bay, where currents are stronger, there is less algae and more filter-feeders with a prolific growth of a sessile, filter-feeding community..

The existence of these non-coralline hard substrates is inversely related to the same physical factors controlling the distribution of the corals. The balance of coral versus non-coral can be modified by very small changes in any or all of these controlling factors providing advantage either to the corals or to the other hard substrate organisms such as Sargassum, sponges or algal turfs. Exposure is important as much of the top of Fasht Al Adhm is very shallow and suffers from temperature stress both in summer and winter together with considerable wave action, especially along the northern edge. In the algal-dominated rocky subtidal around Hawar salinities are excessive and beyond the tolerance of all but the most hardy corals. At the northern tip of Hawar Porites survives as scattered colonies, but where salinities are in excess of 48 ppt it is the algae which thrive and dominate. This is also true of other non-coralline subtidal hard substrates found to the south west of Hawar at Janan. Here shallow water areas reach salinities of 55 ppt or more and there is little water exchange. Algae thrive in this area and corals are excluded in these extreme salinities. The reasons for a lack of coral dominance on the hard substrate found at the northern entrance to Tubli Bay is more difficult to resolve. Here algae are small and appear to be outcompeted by sponges in the tidal races found under the bridge. The bridge itself throws an area of shadow which may inhibit photosynthesis and discourage many of the more competitive algae. On an ebb tide there is a high sediment load carried out of the Bay from the mangrove and mudflats within and light attenuation may inhibit the growth of both the corals and algae whilst providing food for the filter-feeding community.

SEASONAL CHANGES

Generally, subtidal habitats are less affected by seasonal variations than intertidal habitats as a result of their submergence which reduces the effect of variations in temperature, desiccation and insolation. However, the shallow waters around Bahrain are still more prone to the effects of seasonal variations in temperature than are the deeper waters elsewhere in the Arabian Gulf. Seasonal wind patterns may also affect the shallower habitats causing increased wave action which can dislodge algae and cause considerable damage to shallow water coral communities. This wave action also increases sediment loads in the water which place additional pressure on corals which are already under stress from temperature extremes. Changes in water temperature and insolation certainly effect the distribution and percentage cover of algae and seagrass and their associated communities (Drew, 1980; McMillan, 1984).

The algal invasion of the coral during the winter season which was recorded for Bahrain during the present study has been previously noted for the offshore coral islands of Saudi Arabia (Basson et al., 1977) and more recently for reefs in Kuwait (Downing and Roberts, 1993) and the inshore reefs of Saudi Arabia (Vogt, 1994). This temporary algal overgrowth of the coral skeleton during periods of low water temperature in Bahrain (12-14° C) does not appear to have any long-term detrimental effects. The algal cover is sloughed off and the reef resumes its customary appearance once the temperature starts to rise again.

The seagrass beds are responsible for the major seasonal biotic variation within the subtidal zone, dying back significantly during the winter months. This regression in seagrass cover appears to be reflected in the seasonal life-cycles of organisms such as the shrimp, the pearl oyster and the dugong, all of which are dependent on the seagrass habitat at some stage in their lives. Shrimp spawning coincides with both seagrass abundance and the incidence of large quantities of Sargassum floating free in the late winter and early summer. The latter provides protection for early post-larvae (Al Attar, 1981), the former for later stages in the development of the shrimp.

This subtidal study provides the first information on the community structure and distribution of coral reefs and seagrass beds and other habitat types around Bahrain. This knowledge gained from the study combined with the results of the satellite remote sensing in chapter 5 allows the production of an accurate chart of subtidal habitat distributions (Volume 2) to compliment the intertidal habitat maps developed in chapter 3. The preparation of these subtidal habitat charts from the combined results from the remote sensing exercise and the habitat study data forms the subject of the next chapter.

This rapid general subtidal study inevitably contains shortfalls in the data collection. Principal amongst these are the lack of seasonal data for the seagrass habitats and a need to collect more representative data to allow study of the effects of salinity and depth on seagrass growth and distribution. There are many other factors which may and almost certainly do effect seagrass distribution and growth. Substrate type may well be important as may soil chemistry and grazing by herbivores. Hence a further and more detailed study of seagrass growth and distribution around Bahrain with the specific aim of resolving the problem of the effects of salinity and depth on the various species is the subject of chapter 6.

DETAILS OF DATA MATRIX FOR CORAL SITES

(See Table 4.2 for data matrix)

ROWS			COLUMNS		
ROW	SITE NUMBER	SITE NAME	COLUMN (variable number)	VARIABLE	MEASURE
1	55	Jarim N	1	*Acropora cf.formosa sp1&2*	% cover
2	56	Jarim W	2	*Cyphastrea monile*	% cover
3	57	Jarim SW	3	*Cyphastrea seralia*	% cover
4	58	NW Muharraq Patch Reefs	4	*Favia speciosa*	% cover
5	59	Khawr Fasht 8	5	*Platygyra daedalea*	% cover
6	60	Khawr Fasht 3	6	*Porites compressa*	% cover
7	61	NE Muharraq Fringe Reef	7	*Porites nodifera*	% cover
8	62	Dibal NW 8	8	*Acropora sp.3*	% cover
9	63	Dibal NW 6	9	Reef building bivalves	% cover
10	64	Dibal NW 2	10	Zoanthids	% cover
11	65	Sala N Slope	11	Calcareous red algae	% cover
12	66	Dibal Central W	12	Total coral species	Numbers
13	67	Jaradah WNW	13	Total coral cover	% cover
14	68	Jaradah NE	14	Depth	Metres
15	69	Jaradah SE	15	Salinity	Parts/1000
16	70	"Seistan" Wreck			
17	71	Fasht Adhm W Front 7m			
18	72	Fasht Adhm Channel			
19	73	Fasht Adhm W Front 3.5m			
20	74	Fasht Adhm, Central Front 10m			
21	75	Fasht Adhm, Central Front 8m			
22	76	Fasht Adhm Central Front 9			
23	77	Fasht Adhm Central Front 5			
24	78	Fasht Adhm, Central Front 10m			
25	79	Fasht Adhm, Central Front 1.5m			
26	80	Fasht Adhm Central Front 6			
27	81	"Half Tanker" Site, Fasht Adhm			
28	82	Fasht Adhm, Central Front 1m			
29	83	Fasht Adhm, Central Flat 1m			
30	84	"Mollusc Reef", SW of Fasht Adhm			
31	85	Ad Dur			
32	86	Fasht Bu Thur			
33	87	Hawar Ajirah			

Average temperature for subtidal sites = 33.6 degrees C. Standard deviation = 0.96.
Maximum temperature recorded = 35 degrees C. Minimum = 30.5 degrees C.

Species authorities given in Sheppard and Sheppard (1991)

TABLE 4.1

DATA MATRIX FOR CORAL SITES

See Table 4.1 for identification of columns and rows

ROWS	PRINCIPAL CORAL SPECIES (%ge Cover)								OTHER KEY BIOTA (%ge Cover)			TOTAL CORAL		PHYSICAL	
												Spp.	cover	Depth	PPT
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	0	0	1	0	10	0	0	3	6	4	12	2	43.7
2	1	1	0	1	0	0	10	0	0	0	10	4	12	3	43.7
3	1	0	0	1	1	0	1	0	0	1	20	6	5	3	50.2
4	1	1	1	1	1	1	0	0	0	5	15	9	5	3	43.7
5	1	2	1	1	1	6	1	1	0	0	0	17	45	8	50.2
6	1	1	0	1	1	1	1	1	0	1	20	9	1	3	50.2
7	2	0	1	1	1	1	0	0	0	0	1	9	5	3	43.7
8	1	0	0	1	1	1	0	0	0	0	0	6	7	8	43.7
9	0	0	0	0	1	1	1	0	0	1	30	3	5	6	43.7
10	0	1	0	1	1	0	15	0	0	1	15	4	15	2	43.7
11	0	1	0	0	0	0	1	0	0	0	10	3	3	4	50.2
12	20	1	1	1	4	1	0	1	0	0	7	12	45	8	43.7
13	15	1	0	1	1	0	1	1	0	0	1	8	20	3	43.7
14	40	1	0	1	3	0	1	1	0	0	0	7	50	2	43.7
15	15	0	0	1	1	0	0	0	0	0	1	5	20	2	43.7
16	0	1	1	1	0	1	0	0	0	0	0	16	1	18	43.9
17	65	0	1	1	0	10	1	1	0	0	10	11	65	7	43.9
18	1	1	1	4	1	0	1	0	0	0	0	13	10	9	43.7
19	75	0	0	1	1	1	0	1	0	0	10	5	80	3.5	43.9
20	1	1	1	6	4	8	4	1	0	0	0	19	30	10	43.7
21	75	1	1	1	1	8	0	5	0	1	5	13	90	5	43.9
22	15	1	1	1	5	20	1	2	0	0	1	14	75	10	43.9
23	5	1	1	1	1	12	1	1	0	0	0	17	60	8	43.9
24	1	1	1	5	1	20	1	0	0	0	0	18	50	9	43.9
25	0	0	1	0	1	0	1	0	0	0	5	5	5	1.5	43.9
26	8	1	3	10	22	8	12	1	0	0	0	14	70	6	43.9
27	65	1	1	1	1	1	1	0	0	0	5	8	65	6	43.9
28	0	1	1	0	1	0	1	1	0	0	5	7	2	1	43.9
29	0	0	1	0	1	0	0	0	0	0	2	4	2	1	44.3
30	1	1	0	0	1	0	0	0	10	0	1	7	1	1	44.3
31	0	1	0	0	1	1	40	0	0	0	3	4	45	2	46.3
32	0	0	0	0	0	0	7	0	0	0	10	1	7	3	50.5
33	0	0	1	1	1	0	65	0	5	0	5	4	70	3	50.5

TABLE 4.2

CORRELATION MATRIX SHOWING SIGNIFICANT CORRELATIONS BETWEEN VARIABLES AT CORAL STUDY SITES

RESULTS OF CORRELATION MATRIX
(All coral site data)

Degrees of freedom = 31
Where r>0.449 = 99% probability of correlation

VARIABLE	CORRELATED VARIABLES (r =)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 *Acropora cf.formosa sp1&2*															
2 *Cyphastrea monile*															
3 *Cyphastrea seralia*															
4 *Favia speciosa*			0.664												
5 *Platygyra daedalea*			0.679	0.784											
6 *Porites compressa*															
7 *Porites nodifera*															
8 *Acropora sp.3*	0.569														
9 Reef-building bivalves															
10 Zoanthids															
11 Calcareous red algae															
12 Total coral species		0.522	0.607	0.571		0.699					-0.456				
1 Total coral cover	0.683					0.571		0.596							
14 Depth						0.487						0.734			
15 Salinity															

TABLE 4.3

PRINCIPAL COMPONENTS FACTORING FOR VARIABLES AT CORAL STUDY SITES

PRINCIPAL COMPONENT FACTORING
(Using Equimax Rotation)

All coral and non-coral species, total number of coral species, total percentage cover of coral, depth and salinity

FACTORS	1	2	3	4	5	6	TOTAL
Factor variance	30.95%	13.07%	11.49%	9.15%	8.15%	6.78%	79.59%
Principal variables (numbers equivalent to variable numbers in table 4.1)	5 (85%) 4 (74.5%) 3 (62%)	1 (76%) 13 (74%) 8 (64%)	2 (72.5%) 12 (57%)	-10 (77%) -11 (42.5%)	15 (75%) 7 (48%)	-9 (62%)	

Figures in brackets represent total percentage variance for that variable accounted for by that factor. E.G. 85% of the overall variance of variable 5 within this data set has been accounted for by Factor 1.

TABLE 4..4

CANONICAL CORRELATION ANALYSIS OF CORAL DATA - Correlations between presence of individual biota and other variables

ANALYSIS	No.	EIGENVALUE	CORREL.	CHI-SQ.	D.F.	SIGNIF.	GROUP 1 VARIABLES	GROUP 2 VARIABLES
A. Number of coral spp. and total percentage coral cover against depth and salinity	1	0.5549	0.7449	23.9371	4	P=0.0001	Number of coral spp.(1.03) Total percentage coral cover(-0.10)	Depth(0.97) Salinity(-0.14)
B. 8 key spp. of coral against depth	1	0.3965	0.6296	13.6289	8	P=0.0920	var.1(0.01), var.2(0.23), var.3(0.50) var.4(0.56), var.5(-0.73), var.6(0.48) var.7(-0.23), var.8(-0.16)	Depth(1)
C. 8 key spp. of coral against salinity	1	0.227	0.4764	6.9512	8	P=0.5419	NO CORRELATION	NO CORRELATION
D. 8 key spp. of coral and 3 key non-coral components against depth, salinity, number of coral spp. and total percentage coral cover	1	0.9478	0.9735	133.291	44	P=0.0000	var.1(0.77), var.2(0.05), var.3(-0.06) var.4(-0.20), var.5(0.35), var.6(0.44) var.7(0.50), var.8(-0.02), var.9(-0.06) var.10(-0.04), var.11(-0.07)	Depth(0.05), Salinity(-0.06) Number of coral spp.(-0.20) Percentage coral cover(1.05)
	2	0.874	0.935	62.499	30	P=0.0005	var.1(-0.29), var.2(0.27), var.3(0.43) var.4(0.60), var.5(-0.62), var.6(0.17) var.7(-0.39), var.8(0.22), var.9(0.10) var.10(0.04), var.11(-0.12)	Depth(-0.26), Salinity(-0.07) Number of coral spp.(1.23) Percentage coral cover(-0.28)
E. 3 key-non coral components against depth, salinity, number of coral spp. and total percentage coral cover	1	0.3271	0.572	15.5269	12	P=0.2139	var.9(0.31), var.10(-0.38), var.11(1.09)	Depth(0.29), Salinity(0.49) Number of coral spp.(-0.94) Percentage coral cover(-0.05)

Variable numbers are as given in table 4.1, figures in brackets after variables = coefficients; D.F. = Degrees of freedom

TABLE 4.5

CLUSTER SITE STATISTICS - CORAL DATA

CLUSTER NOMINATIONS	
CLUSTER A ROWS:	1,17,18,23 (See Table 4.1 for equivalent site numbers)
CLUSTER B ROWS:	9,11
CLUSTER C ROWS:	3,5,8,20,21,22,27,28
CLUSTER D ROWS:	2,4,6,7,10,12,13,14,15,16,19,24,25,26,29,30,31,32,33,

		CLUSTER A	CLUSTER B	CLUSTER C	CLUSTER D	ALL SITES
SALINITY (Parts per thousand)	Mean	43.9	48.4	44.6	45.2	45.1
	Std	0.0	2.1	2.1	2.6	2.5
	Range	-	46.3-50.5	43.7-50.2	43.7-50.5	43.7-50.5
DEPTH (metres)	Mean	5.4	2.5	7.6	4.0	5.0
	Std	1.3	0.5	2.4	3.9	3.6
	Range	3.5-7.0	2-3	2-10	1-18	1-18
NUMBER OF CORAL SPECIES	Mean	8.7	4.0	14.8	7.2	8.7
	Std	9.3	0.0	3.7	4.3	5.0
	Range	5-13	-	7-19	3-22	1-19
TOTAL PERCENTAGE CORAL COVER	Mean	83.3	55.5	42.3	7.3	29.6
	Std	9.5	12.5	13.8	5.9	28.4
	Range	72-98	43-68	23-71	1-20	1-90

TABLE 4.6

DETAILS OF DATA MATRIX FOR SEAGRASS SITES

ROWS			COLUMNS		
ROW	SITE NUMBER	SITE NAME	COLUMN (Variable number)	VARIABLE	MEASURE
1	88	NE Transect NE	1	Cyanobacteria	% cover
2	89	NE Transect SC	2	Sponge sp. A	Mean No./sq.m
3	90	Muharraq NW Off	3	Sponge sp. B	Mean No./sq.m
4	91	Sanabis N Off	4	Pennatulid sp.	Mean No./sq.m
5	92	Jaradah S Off	5	Hydroid sp.	Mean No./sq.m
6	93	Fasht Adhm NW	6	Cerianthid sp.	Mean No./sq.m
7	94	Tonque NW Off	7	*Cerithium scabridum*	Mean No./sq.m
8	95	Fasht Adhm SW	8	*Pinna muricata*	Mean No./sq.m
9	96	Fasht Adhm S	9	*Pinctada radiata*	Mean No./sq.m
10	97	B-Q Transect UJ	10	Shrimp/Goby burrows	Mean No./sq.m
11	98	B-Q Transect W	11	Burrows (anon.)	Mean No./sq.m
12	99	B-Q Transect CW	12	*Linckia multiflora*	Mean No./sq.m
13	100	Tighaylib NW	13	*Clypeaster humilis*	Mean No./sq.m
14	101	Gabbari N Reef	14	Tunicate sp.	Mean No./sq.m
15	102	B-Q Transect E	15	*Phallusia nigra*	Mean No./sq.m
16	103	B-Q Transect Q	16	*Halodule uninervis*	% cover
17	104	Gabbari Cairn	17	*Halodule uninervis*	Leaf length
18	105	Twins S Off	18	*Halophila stipulacea*	% cover
19	106	Mashtan NW Arm	19	*Halophila stipulacea*	Leaf length
20	107	Mutarid NW	20	*Halophila ovalis*	% cover
21	108	Hawar W Off	21	*Halophila ovalis*	Leaf length
			22	Salinity (sector)	Parts per 1000
			23	Depth	Metres
			24	Number of key biotic components	Numbers
			25	Total seagrass cover	% cover

Average temperature for subtidal sites = 33.6 degrees C. Standard deviation = 0.96.
Maximum temperature = 35 degrees C. Minimum temperature = 30.5 degrees C.
Species authorities given in Jones (1986)

TABLE 4.7

DATA MATRIX FOR SEAGRASS STUDY SITES

See Table 4.7 for identification of columns and rows

	COLUMNS (BIOLOGICAL/PHYSICAL MEASUREMENTS)																								
	KEY BIOTIC COMPONENTS (%ge Cover or Numbers per Square metre)															SEAGRASS DATA (%ge Cover and Leaf Length)						PHYSICAL		TOTALS	
ROWS																						PPT	Depth	Key Biota	Seagrass %ge Cover
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	0	0	0	0	0	0	0	0	0	0	1.6	0	0	0	0	0	0	0	0	5	3	43.7	12	2	5
2	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-	43.7	18	2	1
3	0	0	0	0	0	1.6	0.1	0.8	0	0	0	0	0	0	0	18.2	8.8	2	4	3.5	2.2	43.7	5	6	23.7
4	60	0	1.3	0	0	0	0	0.8	0	0	0	0	0	1	0.8	2.6	-	0.6	6	1	2.8	43.7	11	8	4.2
5	0	0	0	0	0	0	0	0	5000	0.8	0	0.01	0	0.04	1.6	2.6	3.1	0	0	0.5	2	43.7	7	7	3.1
6	0	2.7	4	0	1.3	0	0	0	0	0	0	0	0	1.3	0	53.3	12	1.7	1.3	0	0	43.9	5	6	55
7	0	0	0	0	2.4	0	0	0.8	0	3.2	0	0.8	0	0.1	0	7.5	7.3	0	0	8.5	2.5	43.9	7	7	16
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.6	-	0.2	-	0	0	44.3	2	2	2.8
9	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6.7	31	5.9	0	0	44.3	1.7	3	36
10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	46.7	-	21.7	-	0	0	46.3	3	3	68.4
11	0	6.7	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	1.7	-	23.3	-	44.3	8	4	25
12	78	0	0	0	0	0	0	0	0	0	6.7	0	0	0	0	0	0	0.5	-	0	0	46.3	15	3	0.5
13	0	0	0	0.01	0.7	0.1	203	0	0	0	0	0	0	10	0	66.7	9.7	0	0	0	0	46.3	3	6	66.7
14	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	1.3	18.5	9	0	0	0	0	46.3	3	3	18.5
15	35	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	18	-	46.3	13	3	18
16	0	0	0	0	0	0	0	0.8	0	0.01	0	0	1.6	0	0	25	5.5	23	8.1	0	0	46.3	3	5	48
17	0	0	10.7	1.3	1.3	0	0	1.3	0	0	0	0	0	0.01	2.7	60	15.7	0.2	4.5	0.8	2.5	46.3	3	9	61
18	0	1.3	4	0	0	0	0	0	0	0	0	0	0	0.01	2.7	30	16.8	38.3	4.8	0	0	50.5	4	6	68.3
19	0	6.7	1.3	0	0.1	0	0	0	0	0	0	0	0	0.01	1.3	70	16.5	6.7	4.7	1.7	3	50.5	5	8	78.4
20	0	0.02	0	0	2.4	0	0.1	0	0	0	0	0	0	0	2.4	36	-	0	0	0	0	50.5	3	5	36
21	1	6.4	0	0	0	0	0	0	0	3.6	0	0	0	0	0	42	13.3	11	5.4	0	0	50.5	7.5	5	53

TABLE 4.8

CORRELATION MATRIX SHOWING SIGNIFICANT CORRELATIONS BETWEEN VARIABLES AT SEAGRASS STUDY SITES

(percentage cover of seagrass species, presence of non-seagrass biota, salinity and depth)

Degrees of Freedom = 19
Where $r>0.549$ = 99% probability of correlation

VARIABLE		CORRELATED VARIABLES (r =) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1 Cyanobacteria												0.616													
2 Sponge sp. A																									
3 Sponge sp. B					0.876											0.594									
4 Pennatulid sp.									0.613																
5 Hydroid sp.													0.589												
6 Cerianthid sp.																									
7 *Cerithium scabridum*															0.987										
8 *Pinna muricata*																									
9 *Pinctada radiata*																									
10 Shrimp/Goby burrows													0.635												
11 Burrows (anon)																									
12 *Linckia multiflora*																									
13 *Clypeaster humilis*																					0.756				
14 Tunicate sp.																									
15 *Phallusia nigra*																									
16 *Halodule uninervis*	cover																						0.559		
17 *Halodule uninervis*	leaf length	Not Included																							
18 *Halophila stipulacea*	cover																								
19 *Halophila stipulacea*	leaf length	Not Included																							
20 *Halophila ovalis*	cover																								
21 *Halophila ovalis*	leaf length	Not Included																							
22 Salinity																									
23 Depth																									
24 Number of Key Species		Not Included																							
25 Total Seagrass Cover		Not Included																							

TABLE 4.9

PRINCIPAL COMPONENTS FACTORING FOR VARIABLES AT SEAGRASS STUDY SITES

PRINCIPAL COMPONENTS FACTORING
(Using Equimax Rotation)

Percentage cover of seagrass species, presence of non-seagrass biota, salinity and depth.

FACTORS	1	2	3	4	5	6	7	8	Total
Factor Variance	19.33%	12.93%	11.7%	11.56%	9.05%	8.15%	6.33%	5.16%	84.21%
Principal variables (numbers equivalent to variable numbers in table 4.7)	4 (87%) 3 (86%)	14 (95%) 7 (93%)	11 (68%) 1 (63%)	13 (82%) 20 (77%)	12 (82%) 10 (65%)	22 (70%) 2 (56%)	-18 (81%)	9 (78%)	

Figures in brackets represent total percentage variance for that variable accounted for by that factor (to the nearest integer).
E.G. 87% Of the overall variance of variable 4 within this data set has been accounted for by Factor 1.

TABLE 4.10

CANONICAL CORRELATION ANALYSIS OF SEAGRASS BED DATA

ANALYSIS	No.	EIGENVALUE	CORREL.	CHI-SQ.	D.F.	SIGNIF.	GROUP 1 VARIABLES	GROUP 2 VARIABLES
A. Percentage cover of 3 Spp.of seagrass against salinity and depth	1	0.6127	0.7829	16.2931	6	P=0.0123	Percentage cover uninervis(0.82) Percentage cover stipulacea(0.49) Percentage cover ovalis(0.01)	Salinity (0.64) Depth (-0.63)
B. Leaf length of 3 spp. of seagrass against salinity and depth	1	0.4456	0.6675	10.1339	6	P=0.1191	Leaf length uninervis(0.87) Leaf length stipulacea(0.17) Leaf length ovalis(-0.48)	Salinity (0.68) Depth (-0.57)
C. Percentage cover of 3 spp. of seagrass against salinity	1	0.3952	0.6286	8.7995	3	P=0.0321	Percentage cover uninervis(0.87) Percentage cover stipulacea(0.47) Percentage cover ovalis(0.10)	Salinity(1)
D. Percentage cover of 3 spp. of seagrass against depth	1	0.3873	0.6223	8.5729	3	P=0.0355	Percentage cover uninervis(0.76) Percentage cover stipulacea(0.50) Percentage cover ovalis(-0.09)	Depth(-1)
E. Leaf length of 3 spp. of seagrass against salinity	1	0.3118	0.5584	6.5392	3	P=0.0881	Leaf length uninervis(0.86) Leaf length stipulacea(0.15) Leaf length ovalis(-0.55)	Salinity(1)
F. Leaf length of 3 spp. of seagrass against depth	1	0.2556	0.5056	5.1659	3	P=0.16	Leaf length uninervis(-0.88) Leaf length stipulacea(-0.19) Leaf length ovalis(0.39)	Depth(1)
15 key non-seagrass biota against salinity and depth	N/A	0.9027	0.9501	30.9952	30	P=0.4156	NO SIGNIFICANT CORRELATION	NO SIGNIFICANT CORRELATION
G. 15 key non-seagrass spp. against percentage cover of 3 spp. of seagrass	1	0.9503	0.9749	58.2185	45	P=0.0893	var.1(-0.56), var.2(0.57), var.3(-1.31), var.4(1.23) var.5(0.22), var.6(0.04), var.7(-3.69), var.8(0.19) var.9(0.004), var.10(-0.25), var.11(0.42), var.12(-0.16) var.13(-0.72), var.14(4.06), var.15(0.21)	Percentage cover uninervis(0.61) Percentage cover stipulacea(-0.66) Percentage cover ovalis(-0.48)
H. 15 key non-seagrass spp. against leaf length of 3 spp. of seagrass	1	0.9806	0.9902	74.5684	45	P=0.0037	var.1(-0.20), var.2(0.35), var.3(0.94), var.4(-0.05) var.5(0.04), var.6(0.51), var.7(0.86), var.8(-0.69) var.9(0.16), var.10(-0.08), var.11(0.14), var.12(0.64) var.13(-0.20), var.14(-0.53), var.15(-0.05),	Leaf length uninervis(1.09) Leaf length stipulacea(-0.84) Leaf length ovalis(0.06)

Variable numbers are as given in table 4.7, figures in brackets after variables = coefficients; D.F. = Degrees of Freedom

TABLE 4.11

CLUSTER SITE STATISTICS - SEAGRASS DATA

CLUSTER NOMINATIONS
CLUSTER A SITES: 7,8,9,10,11,12,16 (See Table 4.7 for equivalent site numbers)
CLUSTER B SITES: 2,3,15
CLUSTER C SITES: 1,4,5,6,13,14,17,18,19,20,21

			CLUSTER A	CLUSTER B	CLUSTER C	ALL SITES
SALINITY (Parts per thousand)		Mean	47.8	47.0	44.5	46.0
		Std	2.5	2.6	1.1	2.4
		Range	43.9-50.5	44.3-50.5	43.7-46.3	43.7-50.5
DEPTH (metres)		Mean	4.2	2.9	9.2	6.6
		Std	1.6	0.9	4.8	4.5
		Range	3-7.5	1.7-4	2-18	1.7-18
NUMBER OF KEY BIOTIC COMPONENTS		Mean	6.0	4.7	4.3	4.9
		Std	1.8	1.2	2.2	2.1
		Range	3-9	3-6	2-8	2-9
SEAGRASS SPECIES PERCENTAGE COVER	*H.uninervis*	Mean	53.5	20.0	4.7	23.2
		Std	11.8	10.8	6.8	24.0
		Range	36-70	5-30	0-18.5	0-70
	H. stipulacea	Mean	5.9	30.8	0.4	6.6
		Std	7.5	6.2	0.7	11.3
		Range	0-21.7	23-38.3	0-2	0-38.3
	H. ovalis	Mean	0.4	0.0	5.5	3.0
		Std	0.6	0.0	7.6	6.1
		Range	0-1.7	-	0-23.3	0-23.3
	Total cover	Mean	59.8	50.8	10.7	32.8
		Std	12.6	13.3	9.1	25.8
		Range	36-78.4	36-68.3	0.5-25	0.5-78.4

TABLE 4.12

ANALYSIS OF SEAGRASS SPECIES COMBINATIONS AT 21 SITES

ROW NUMBER	Ho	Hs	Hu	Ho/Hs	Ho/Hu	Hs/Hu	Ho/Hs/Hu
1	O	YES	YES	O	O	YES	O
2	O	YES	YES	O	O	YES	O
3	O	YES	YES	O	O	YES	O
4	YES	O	O	O	O	O	O
5	O	YES	O	O	O	O	O
6	YES	YES	O	YES	O	O	O
7	O	YES	YES	O	O	YES	O
8	O	O	YES	O	O	O	O
9	O	YES	YES	O	O	YES	O
10	YES	YES	YES	O	O	O	YES
11	O	YES	YES	O	O	YES	O
12	O	O	YES	O	O	O	O
13	YES	O	YES	O	YES	O	O
14	YES	O	YES	O	YES	O	O
15	O	YES	YES	O	O	YES	O
16	YES	YES	YES	O	O	O	YES
17	O	O	YES	O	O	O	O
18	YES	O	O	O	O	O	O
19	YES	O	O	O	O	O	O
20	YES	YES	YES	O	O	O	YES
21	YES	YES	YES	O	O	O	YES

(See Table 4.7 for equivalent site numbers)

TOTALS:							
Species Mix	Monosp. Ho	Monosp. Hs	Monosp. Hu	Dispp. Ho/Hs	Dispp. Ho/Hu	Dispp. Hs/Hu	Trispp. Ho/Hs/Hu
Number of sites	3	1	3	1	2	7	4
Depth range m	12-18	15	3	8	7	1.7-7	3-11
Salinity range ppt	43.7-46.3	46.3	46.3-50.5	44.3	43.7-43.9	43.9-50.5	43.7-50.5

Ho = *Halophila ovalis*
Hs = *Halophila stipulacea*
Hu = *Halodule uninervis*

YES = Present
0 = Absent

TABLE 4.13

FIGURE 4.1 DISTRIBUTION OF CORAL STUDY SITES AROUND BAHRAIN

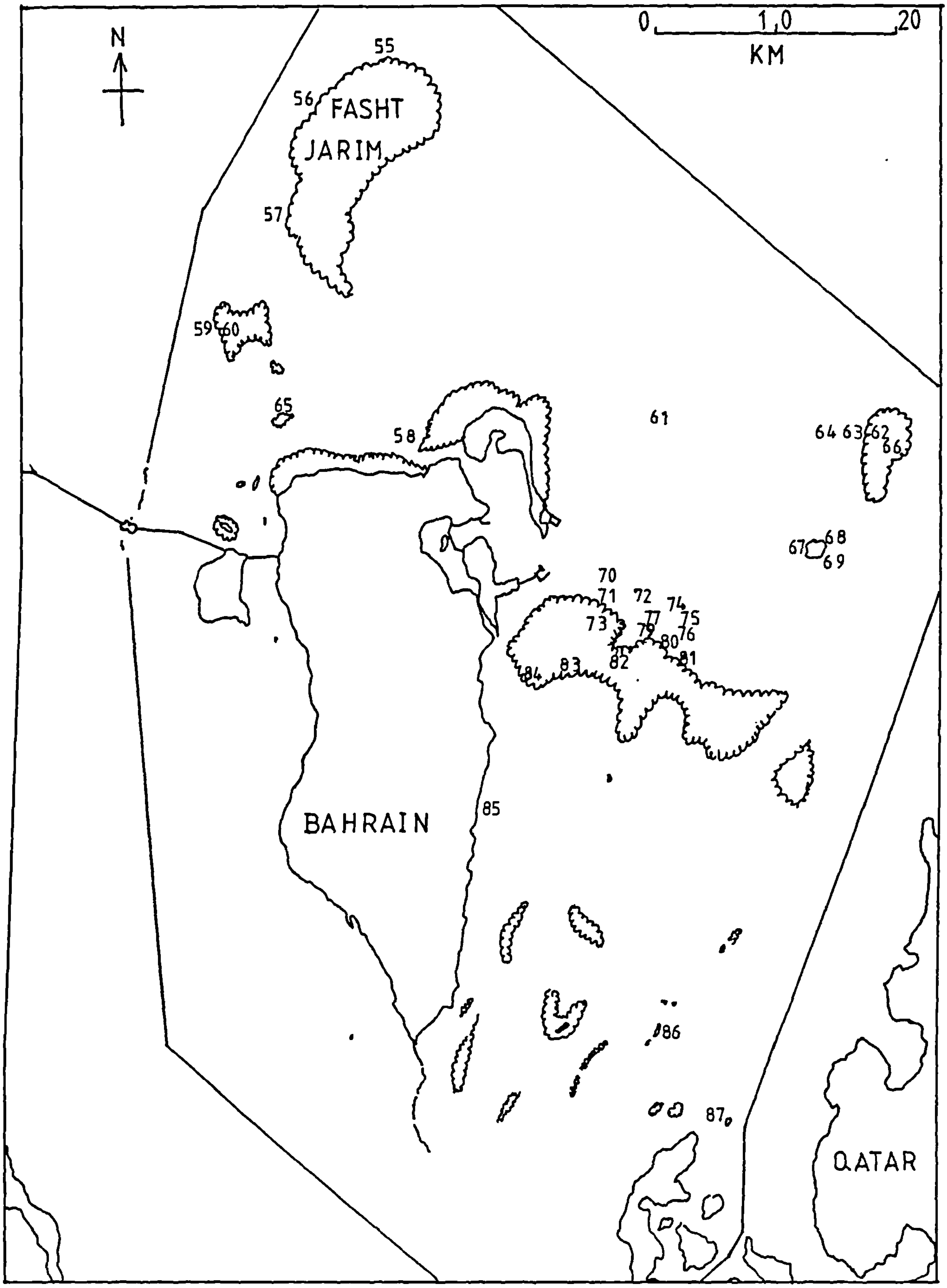


FIGURE 4.2 DISTRIBUTION OF SEAGRASS STUDY SITES AROUND BAHRAIN

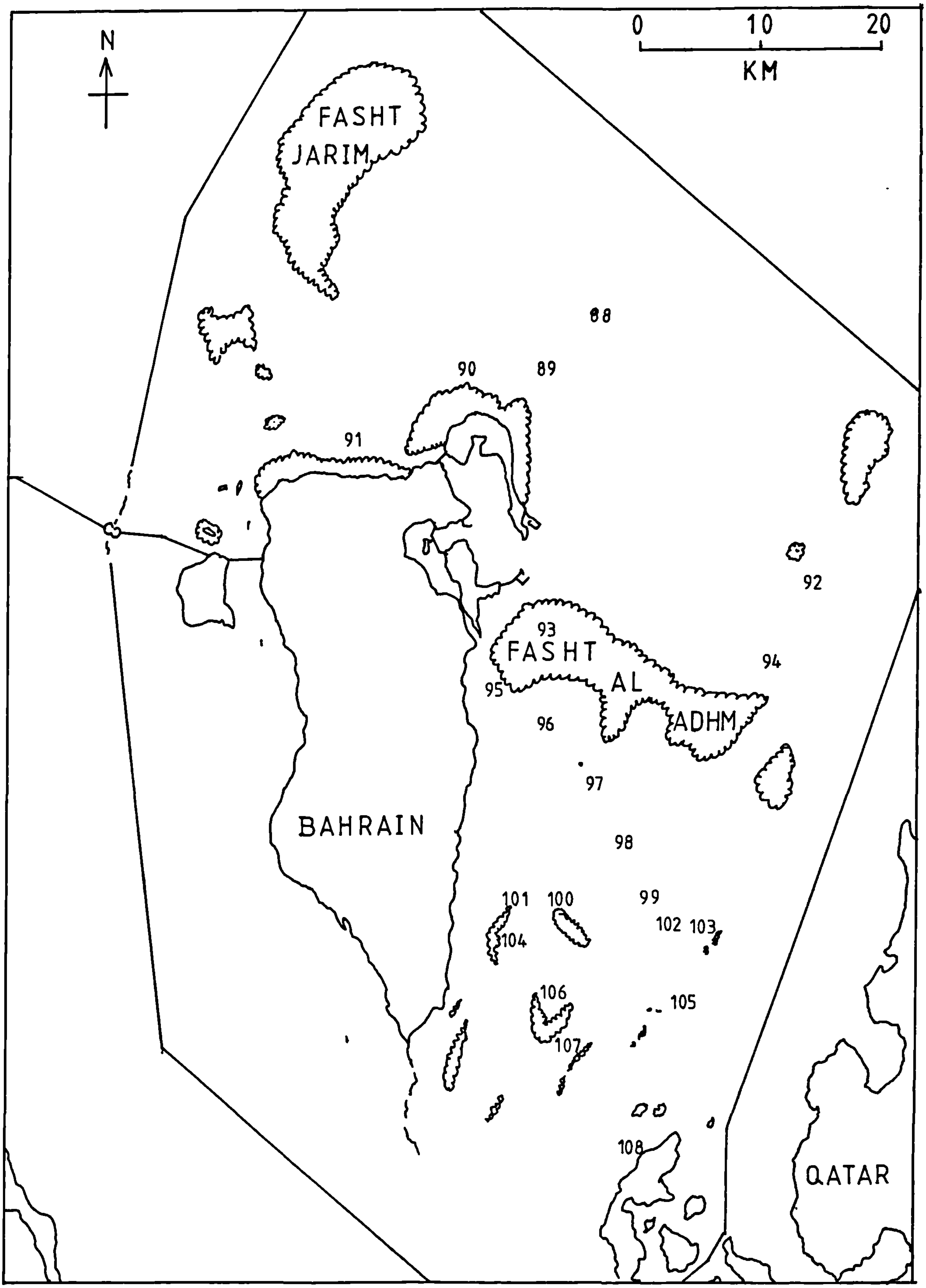


FIGURE 4.3 DISTRIBUTION OF OTHER SUBTIDAL SITES AROUND BAHRAIN PART ONE - NORTHERN BAHRAIN

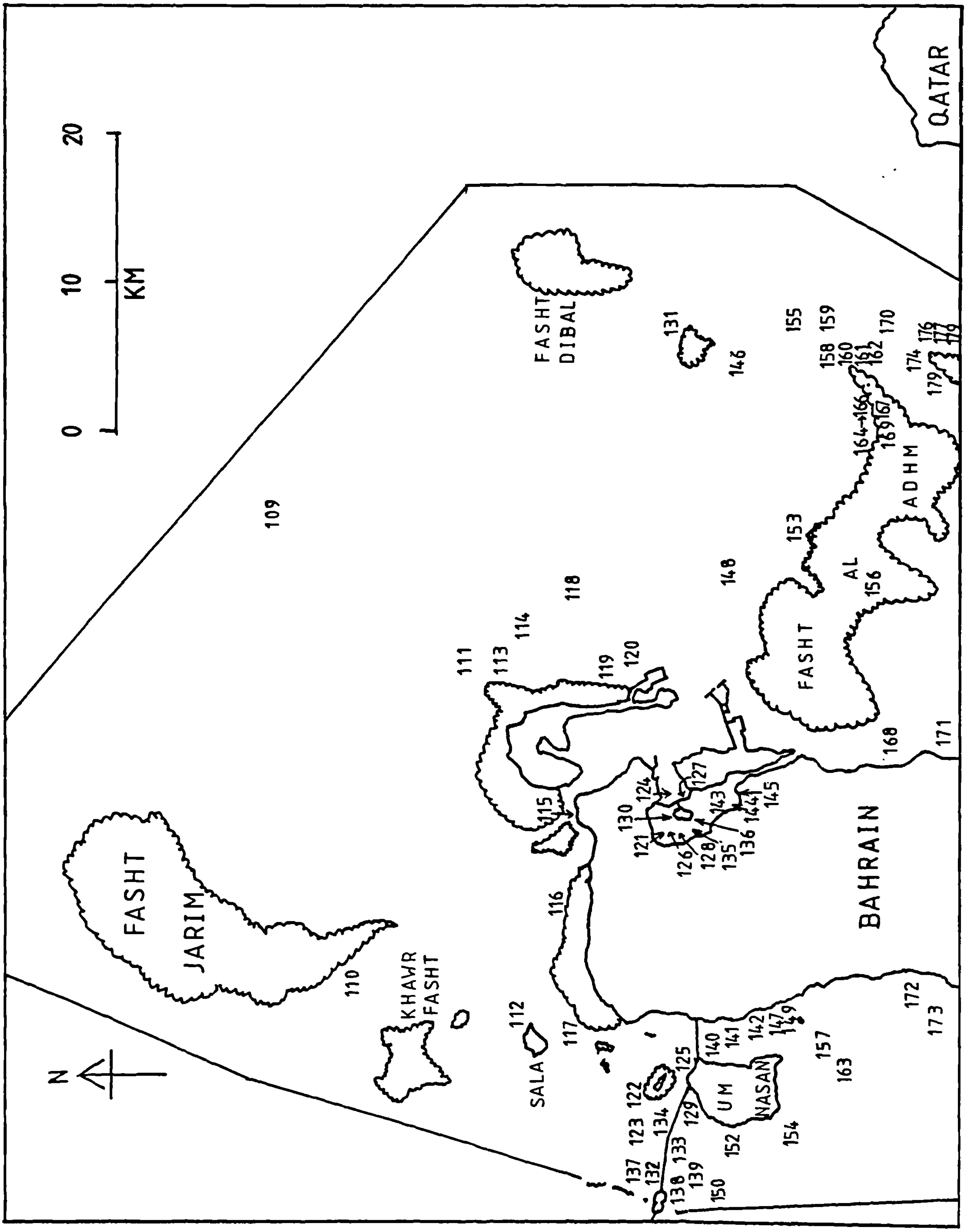


FIGURE 4.3 DISTRIBUTION OF OTHER SUBTIDAL SITES AROUND BAHRAIN (CONT'D) PART TWO - SOUTHERN BAHRAIN

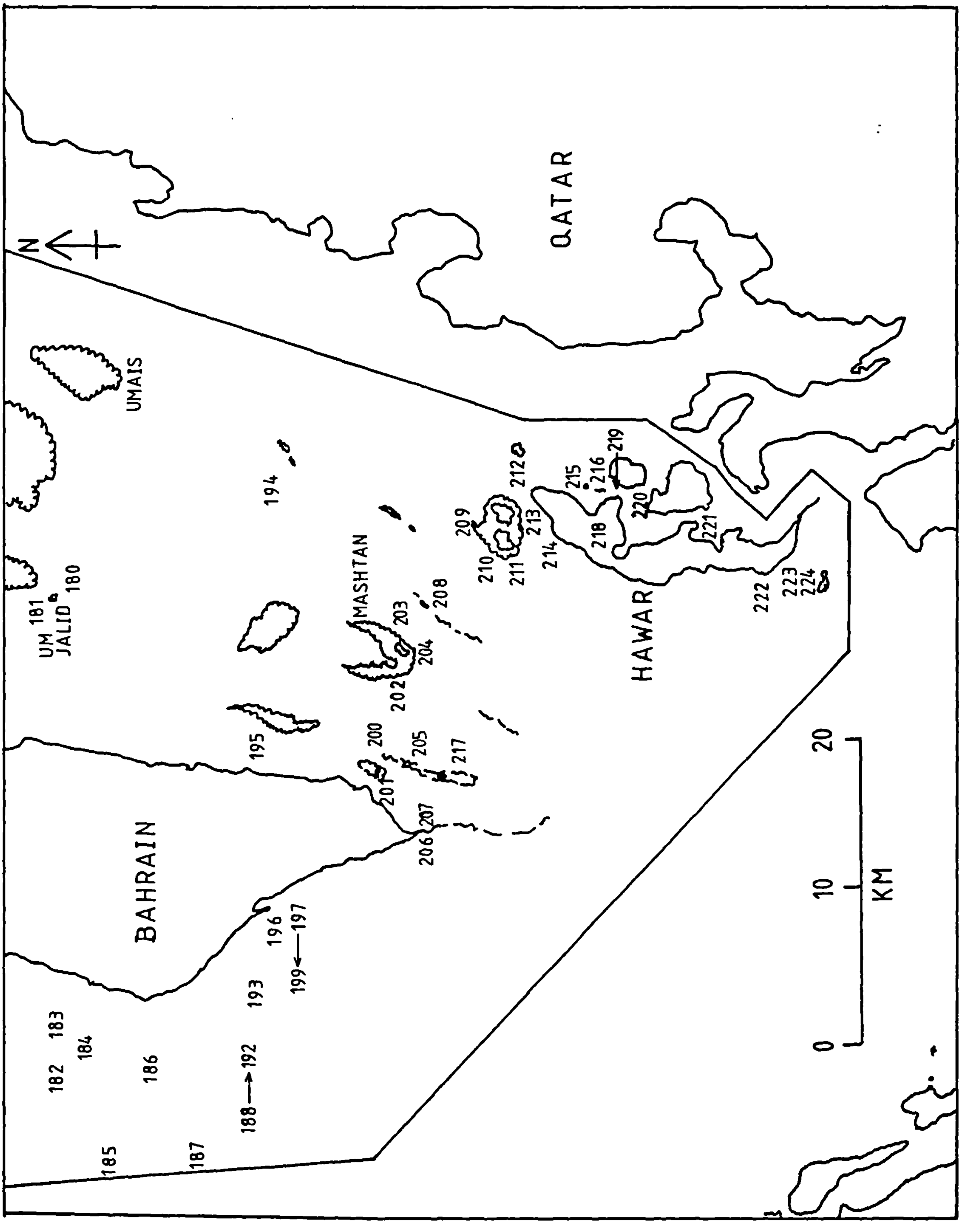


FIGURE 4.4 CLUSTER DIAGRAM OF 33 CORAL SITES

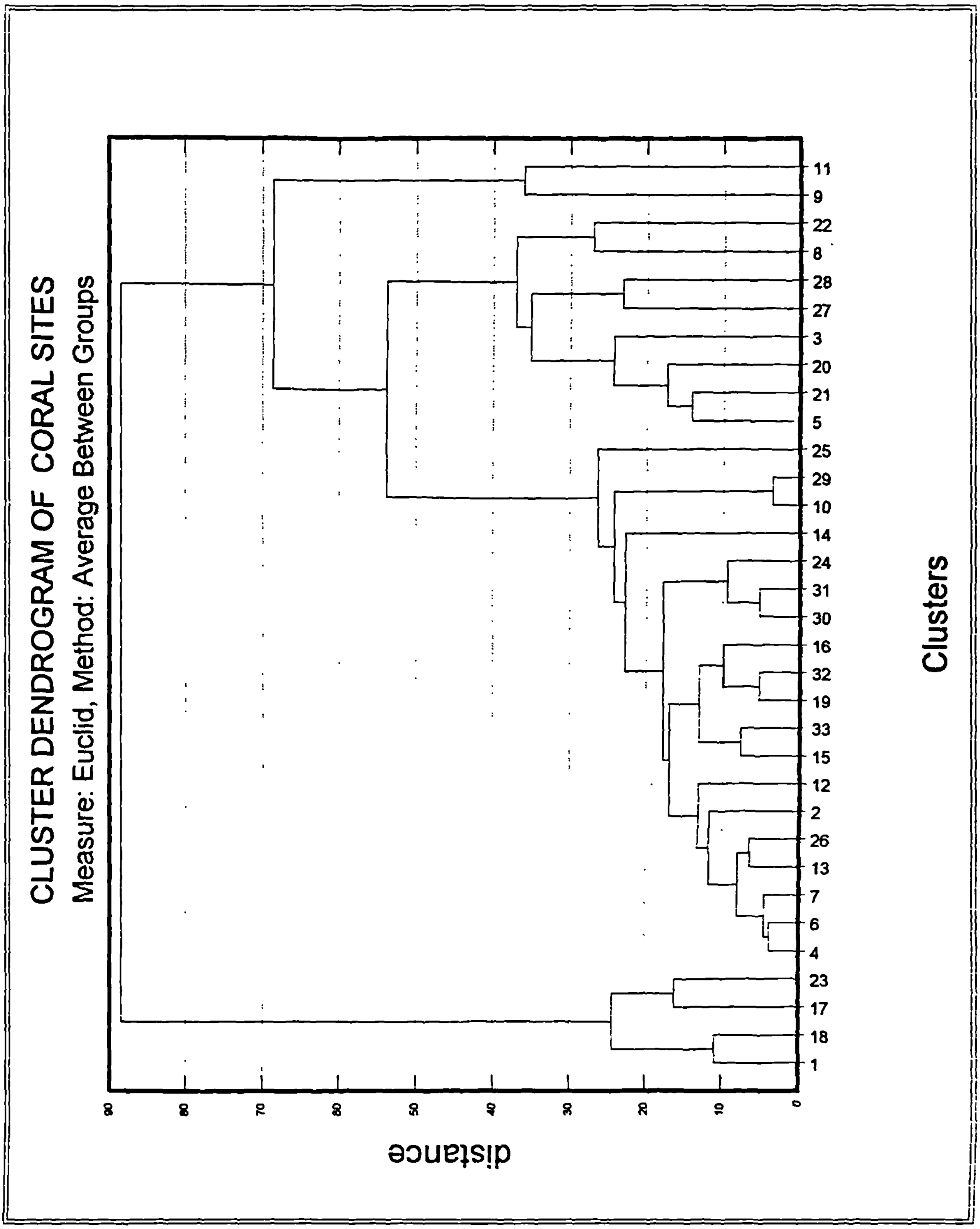
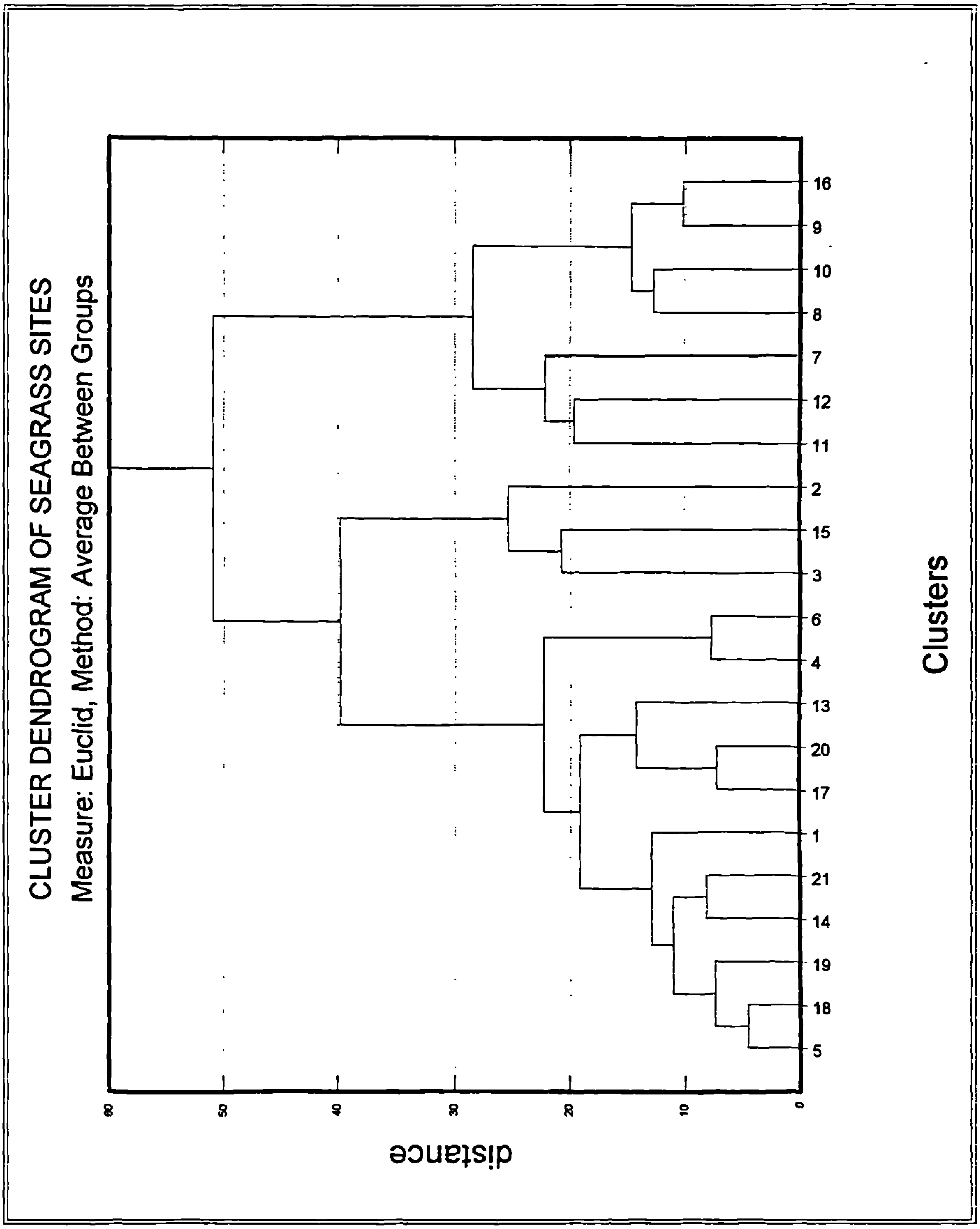


FIGURE 4.5 CLUSTER DIAGRAM OF 21 SEAGRASS SITES



SURVIVAL OF CORAL SPECIES WITH INCREASING SALINITY

SPECIES	SALINITY (parts per thousand) <41	<43	44-45	46	48	50	>50
60 coral species on reefs of Arabian Gulf (Burchard, 1979)	------------>						
27 coral Species on Fasht Adhm and north east reefs, Bahrain (Listed in appendix 4.3)	------------	--------->					N
							O
Coscinaraea monile	------------	------------	------->				N
Favia pallida	------------	------------	------->				E
Favites pentagona	------------	------------	------->				
Platygyra sinensis	------------	------------	------->				
Cyphastrea seralia	------------	------------	------------	------->			
Porites compressa	------------	------------	------------	------->	----- ? --->		
Platygyra daedalea	------------	------------	------------	------------	------->		
Acropora sp. 1	------------	------------	------------	------------	------->		
Favia speciosa	------------	------------	------------	------------	------->		
Favites chinensis	------------	------------	------------	------------	------->		
Leptastrea purpurea	------------	------------	------------	------------	------->		
Siderastrea savignyana	------------	------------	------------	------------	------------	------->	
Porites nodifera	------------	------------	------------	------------	------------	------->	
Cyphastrea microphthalma	------------	------------	------------	------------	------------	------->	

FIGURE 4.6

CHAPTER FIVE

REMOTE SENSING AND HABITAT MAPPING

CHAPTER 5 - REMOTE SENSING AND HABITAT MAPPING

INTRODUCTION

Remote sensing is a term used to describe the measurement, from a distance, of the spectral features of the Earth's surface and atmosphere. The instruments which make these measurements are normally carried by satellites or aircraft. These instruments measure the reflectance of electromagnetic energy wavelengths from the sun off the earth's atmosphere or surface. Certain wavelengths penetrate water and are then reflected back. These reflected wavelengths can provide useful information on the nature of the bed of a body of water. The possibilities for identifying biological habitat types associated with the beds of lakes and with the seabed are of particular interest to aquatic ecologists. Chen (1985) and Mather (1987) provide a good introduction to satellite remote sensing systems, the theory behind electromagnetic remote sensing, assessments of accuracy of remote sensing data and processing techniques used to create satellite imagery (the digital data processed to produce colour images of the target area).

The advantages of using remote sensing depend on the accuracy and reliability of the imagery which is developed from digital data provided by the remote sensing platform (in the present case Landsat 5). If such imagery is reliable then large areas of shallow seabed can be characterised in terms of their biological community saving time, energy and resources which would otherwise have to be expended in the field. This does not mean that remote sensing can ever entirely replace field work. On the contrary, the data and subsequent imagery developed from remote sensing techniques can only be as reliable as the initial field survey which must be carried out to provide ` training' data. This training data is used by remote sensing data analysts and imagery developers to allocate a specific character to a specific set of reflectance values. In the case of the present study the training data will be the accurate location of areas identified as `seagrass' or `coral reef', etc.

Remote sensing has been used for studying marine habitat types and distribution in other parts of the world, but this has usually involved only one or two habitat types in very shallow water. A full marine habitat characterisation throughout the entire territorial waters of a country has not previously been attempted. The aims of this remote sensing exercise is to accurately identify the distribution of as many different subtidal habitat types as possible in the waters around Bahrain.

Untawale, et al (1982) presents the successful use of aerial photography for studying the distribution of mangroves along the estuaries of Goa on the central-west coast of India, and Kelly (1980) gives a good review of remote sensing techniques used for identifying seagrass beds. However, most of the discussion is limited to the features which can be identified using aerial photography and very little touches on the use of electro-optical devices or satellites. Some aerial surveillance was undertaken over Bahrain's territorial waters (See chapter 4) but water clarity presented a problem in identifying and characterising all of the subtidal area. Aerial surveillance as a means of subtidal habitat identification throughout an area as large as Bahrain's territorial waters is not a realistic alternative to satellite remote sensing techniques. However, some of the data collected from the initial aerial surveillance was very useful in setting up the training data for the remote sensing exercise.

Elliot Smith (1975) used data from the earlier Landsat series (1, 2 and 3) to map coral reefs on the Australian Great Barrier reef. Aerial photography was used to provide training data and the merits of different bands (ranges of wavelengths of electromagnetic energy chosen for capture by the scanner on board the satellite) are discussed with respect to their ability to penetrate water and reflect back off the seabed. The value of creating satellite images from more than one band was identified. This work shows that imagery created from three bands rather than just one band permits a clear distinction between submerged and land targets and that this method is therefore preferable for general mapping of the entire reef-island-coastal zone complex. False classification of reef zones occurred where highly turbid waters were encountered and it was noted that information was lost due to the use of only single training sets (areas which had been positively identified as a particular reef type). Multiple training sets were recommended for each target so as to represent a fair range of variation for each zone. The costs of producing a Landsat characterisation image compared very favourably with the cost of the same product from aerial surveillance, the former approximating to 20 cents per km^2 and the latter being in the order of several dollars per km^2.

Both Landsat 4 and Landsat 5 were operational at the time of the study but Landsat 4 had experienced a number of problems with the power supply to the thematic mapper (see 'methods'). Cost limitations and time prevented a request for an image on a specific day. However a virtually cloud-free image of Bahrain and the surrounding waters taken from Landsat 5 in February of 1985 was located. Other satellite platforms which were in orbit at the time were not designed for collecting data at the scale required, their purpose being to scan whole ocean and continent systems. Landsat 5 had sufficient resolution to be able to pick out areas as small as 30 x 30 metres.

The first three bands of the thematic mapper (see 'methods') which is mounted on Landsat 5 are water-penetrating (Jupp, 1989) and therefore potentially useful for studying sub-surface features and water bathymetry. The MSS (multispectral scanner - see `methods') bands of both Landsat 4 and 5 have proved valuable in updating charts through the location of unknown reefs and shoals. Jupp (1989) demonstrated that the improved spatial and spectral resolution of the TM (thematic mapper) bands provided a greater resolution of water depth and bottom features. Several combinations of bands were tested. TM bands 1 and 2 were found to penetrate into the ocean water column most effectively. In the clear oceanic waters around the Bahamas, they found that band 1 could penetrate to 10-15 metres and band 2 to 4-5 metres. Band three was also considered to be useful, but only for very shallow water depths (0.5-3 metres maximum). These penetration depths were reduced in areas of more turbid water. Under conditions of exceptional water clarity band 1 of the TM has been found to penetrate as deep as 25 m (this is deeper than band 1 on the MSS due to the lower wavelengths available from the expanded band width) while band 2 can reach to between 7-18 m and band 3 as deep as 7 m (ERSAC, pers. comm). Successful reflectance of bands 1, 2 and 3 from such depths is unlikely for Bahrain considering the generally turbid nature of the water in many parts of the study area.

METHODS

Landsat 5 is equipped with a 4-channel Multispectral Scanner (MSS) capable of gathering image data in the visible and near-infrared spectrum (0.5-1.1 μm). In addition to this, it also carries a 7-channel scanner called a Thematic Mapper (TM) which scans visible reflected light as well as the near-, mid- and thermal-infrared spectrum (0.45-12.5 μm).

The Multispectral scanner is a line scanner which sweeps the ground below the satellite and builds up an image of the Earth's surface. The area scanned is 92.5 km to either side of the sub-satellite track. Because the spacecraft velocity is too high to permit the scanning of the image one line at a time, a total of six scan lines are viewed by the sensor for each sweep of the mirror that directs reflected light from the ground into the scanners. The MSS collects data in four spectral bands. The reflected light from the Earth's surface is directed by the oscillating mirror onto a fibre optics array which transmits the light to a series of filters. The filters split the incoming signal into four spectral bands. Each of the four MSS band-splitters has a set of six detectors which generate an analogue signal proportional to the incident light. This analogue signal is sampled every 9.96 μs and the signal is converted from analogue to digital form for transmission to a ground station.

The TM is also a line scanner, but samples seven bands which cover from the visible blue-green spectrum through to the thermal infrared. There are a number of other technical attributes which separate the TM scanner from the MSS scanner and a more detailed review can be found in Mather (1987). The TM scanner was selected for the imagery rather than the MSS for a number of reasons. The TM scanner provides greater ground resolution with a pixel (picture element) size of 30 x 30 m as compared to the MSS which can only resolve to 80 x 80 m. Furthermore, the greater sensitivity of the TM scanner to the slightly shorter blue-green reflectance wavelengths allows for deeper penetration of the water column than the MSS sensor therefore making it more applicable to seabed studies (Jupp, 1989). Table 5.1 shows the spectral range and applications for the seven Landsat TM bands. The first three bands of the TM onboard Landsat have been identified as most capable of water penetration (Jupp, 1989). The fourth band is useful in delineating boundaries between land and sea. Bands 5, 6 and 7 do not penetrate the water column, but are more useful in identifying terrestrial vegetation types from thermal signature and moisture levels.

Previous workers have shown the value of using multiple band imagery rather than using one single band. Using a regression of multiple bands to produce the imagery provides a greater capacity to cover a wider area of light reflectance values. In the context of the present study this allowed for the analysis of a wider range of water depths. Mather (1987) provides a useful explanation of the different results achieved from the same data by using univariate analysis of a single reflectance band as opposed to multivariate analysis of two or more reflectance bands. He concludes that the use of well-chosen and sufficient spectral bands is a necessity if different targets are to be successfully identified. It is not the targets (coral reefs, sea surface temperature, weather patterns, geological formations, etc) themselves that are detected directly by remote sensing: their nature is inferred from the property of the radiance measurements in comparison with radiance measurements from known objects.

Landsat 5 does a repeat cycle of global coverage every 16 days acquiring imagery at approximately 10.00 am local time and dividing it into scenes 185 km. x 185 km. The pixel size of 30 x 30 m allows images to be produced as a map down to a scale of 1:50,000. Any attempt to improve the scale to produce finer imagery causes the image to break up into its individual pixels (a phenomenon known as pixelation). Using the MSS imagery with its larger pixel size (56 x 79m) it is only possible to achieve a scale of 1:200,000 before pixelation occurs. Mather (1987) provides a detailed discussion on the spatial resolution capabilities of Landsat 5 in relation to pixel size. The illusion that higher resolution is necessarily better is a common mistake which should be avoided and begs the question "better than what?". Mather (1987) illustrate this point by explaining that a pixel size of 1 x 1m might be useful for small scale urban mapping but would prove unwieldy in the assessment of boundaries in a large spatial unit such as a town or city. Likewise, a spatial resolution of 10m would provide the user with an absurdly detailed exercise when mapping the sea surface temperature patterns of an ocean.

The data from the satellite is transmitted in a digitised form to a receiving station on the Earth via a Tracking and Data Relay Station (TDRS) in geostationary orbit over the equator. This digitised data (recorded on magnetic tape) can then be fed into a suitable computer for analysis and imagery extrapolation. This service was provided by the Environmental Remote Sensing Applications Centre (ERSAC) in Scotland, U.K. using a Prime/Gems computing/image processing unit. This consists of a Prime 550 11 computer system with 2 megabytes of high speed memory to reduce the amount of memory access time required, and 600 megabytes of back-up storage on fixed disk along with a Gems CRT visual display unit to convert the digital data to a pictorial screen image.

The image selected for the present study was one recorded on the 16th February, 1985. This was the only cloud-free TM image available for this area, and the fact that it was recorded in the winter period while the ground study was undertaken in the summer caused some initial uncertainties resulting in repeat field studies in the spring to verify seasonal differences. Two approaches were taken for the analysis and image projection of this scene. The first was to create a false colour image of the area and the second was to extrapolate this to an image which characterised the habitat types.

When three spectral bands are chosen for processing into a false colour composite one of each of these bands will be directed to the red, blue and green colour guns of a colour monitor (or the equivalent interfaces on a plotter or printer). Each pixel position is associated with three values. The vector {0,0,0,} means : no red, no green, no blue (i.e. black) whereas {255,0,0} means : maximum red, no green, no blue. The values forming the vectors are those extracted from the remotely-sensed image at the particular pixel location. If, for example, band one was directed to the red colour gun and the vector for a particular pixel location was {255,0,0}, this would cause the image to display maximum `red' or maximum level of band 1 with no reflectance from the other two bands. The maximum value of 255 is a result of the binary coding used for digital processing.

In reality there may be very little pure `band 1' and the total width of the bands is often much less than 255 units so that the range may only be, for example, 40-90 and a linear contrast stretch enhancement is used to pull the 40 value down to 0 and stretch the 90 up to 225 therefore giving a better contrast. Alternatively a false colour composite can be created using principal component analysis on a combination of any three of the available bands and combined onto colour film with exposures made through blue, green and red filters respectively to produce a simulated colour image. Because different bands enhance different physical phenomena dependent on their reflectance, various details will be enhanced in each colour. The linear contrast stretch enhancement technique retains the original information contained within the imagery, but substitutes what could be relatively narrow spectral band widths for a wider combination of colours which are more easily differentiated by the human eye. This is called a false colour image and it only uses certain bands of reflectance, not the whole spectrum. Mathers (1987) provides a more detailed and precise explanation of these techniques.

RESULTS

Production of the False Colour Image

To produce the false colour image used during this study (Volume 2, figure 2), the initial digital scene was subdivided into land and sea. TM bands 1,2 and 3 were then extracted for the sea and enhanced to give details of depth, sediment movement, water flow etc. TM band 4 was used to define the land/water boundary.

Because of the curvature of the Earth and the angle of the scanner at the time of recording, the image is distorted when generated as a flat picture on screen or photograph. To overcome this it was necessary to geometrically correct the data and the first step in this correction was the location of ground control points (GCPs). Large scale maps were referred to in order to identify areas of high contrast that will stand out in the satellite imagery, being careful to avoid any features that are likely to change over a short period of time. For the TM data a minimum of 5 or 6 such control points are necessary for each scene with the accuracy improving as more GCPs are added. Control points used for this study included trigonometrically-positioned survey points on the offshore islands and reefs at Mashtan, Hawar, Fasht Jarim, Um Nasan and Um Jalid and on the main island at Ras al Barr, Jebel al Dukhan, Bahrain Yacht Club and Zallaq.

Once these control points were established on both the control map and the image, regression analysis was performed on the two to generate a mapping transformation to convert the Landsat coordinates to a Universal Transverse Mercator map projection. After creating this mapping transformation a new grid of points were generated which did not align with the old set of points. A method of estimating intermediate values is required and re-sampling of the data was undertaken to re-orientate the image both with respect to its north-south alignment and to the pixel size which can be changed to more convenient dimensions. There are several methods which can be employed to arrive at the transformed image. In this study a linear interpolation was used. This creates a value for the individual distances from the pixel to the old grid points. These values were then used to correlate the pixel position in relation to the new grid point. This linear interpolation procedure is the one most commonly used as a balance of expense against accuracy. As a result of this re-orientation of the image the overall accuracy of the scene was calculated to be within 25 m (i.e. any point on the image should be no greater than 25 m in error with regard to it's true geographical position as shown on the original charts supplied by the State of Bahrain's Survey Directorate).

The false colour image (Volume 2, figure 2) contains a number of symbols shown below the picture which are of relevance to the remote sensing methodology. The centre of the original full scene is at 26.00^0 North and 50.93^0 East. Only the western half of this scene was required to obtain the necessary information for Bahrain's waters. This constitutes a considerable reduction in processing time as well as cost.

163/42 refers to the Path and the row respectively. The Path is the line along which the satellite is traversing and the Row refers to the number in sequence of the scene being recorded. Along a north-south Path of number 163 the image obtained was number 42 (i.e. the forty-second scene available along that particular Path). The next scene to the immediate south would have been given the coordinates of Path 163, Row 43 and alternatively the next scene to the immediate west of the image would have been Path 164, Row 42.

16th February, 1985 is the date upon which the image was recorded. The time would have been approximately 1000 hours local time. Band 123 refers to the TM bands used to produce the false colour image. Bands 1, 2, and 3 record reflections of light from the Earth's surface in the visible blue, visible green and visible red parts of the spectrum respectively. Sun Az refers to the sun's azimuth and EL to the sun's elevation. The azimuth represents the angle between the sun and the satellite at the point of the image on the earth's surface whilst the elevation is the sun's height above the horizon. The Orbit is the number of operational passes that the satellite has made over the poles since it was originally commissioned, in this case 5120 at the time of our imagery. Transformed UTM 39 refers to the geometric correction of the image onto the Universal Transverse Mercator projection using UTM zone 39 at Ain Al Abd in Qatar (each zone is 6 degrees of longitude in width). Top Left 420030 2930009 are the UTM grid coordinates at the top left- hand side of the image. Finally the pixel size is self-explanatory, the 30 x 30 m representing the size of each picture element or point reference.

Interpretation of the False Colour Image

Volume 2, figure 2 provides a very good representation of the geology and sediment regime around Bahrain. On the main island itself it is possible to identify some of the historic geological features associated with past coastlines. There is a distinct separation inland at around + 2 m (above mean sea level) which corresponds with the drowning of the desert in the latter part of the Holocene at around 6,300-7,000 BP (Doornkamp, 1980). Further inland the top ridge of the rim-rock stands out quite clearly running around the central depression at between + 30-40 m (above mean sea level).

To the west of the main island at Ras al Mumtallah (Volume 2, figure 1) lies the remnants of an old marine strait which used to separate a small island from the mainland. This has been identified by Doornkamp et al (1980) and shows up clearly in the imagery (Volume 2, figure 2). South of this moving down the west coast is an area of active accretion with much of the sand being carried down to Ras al Barr.

Off the west and south-west coast and running down to Hawar there is a clear zone of separation in the offshore waters. This moves away from the coast going south from Mumtallah, swings east around Ras al Barr and then drops south again towards Um Janan, off the southern end of Hawar. This line follows the 9-10 m contour almost precisely, and seems to relate very closely to a series of pronounced terraces throughout the Gulf which are a result of the periodic rise in sea level during the Flandrian transgression. However, this does not agree with the data relating to the flooding of the Gulf of Bahrain and Dawhat Salwah. This should not have occurred until sea level throughout the Gulf rose to -7.0 m (Doornkamp et al., 1980) and would have been a rather rapid transition. There are a number of possible explanations for this, such as the Bahrain Ridge having been relatively lower in height than previously thought and having been uplifted since (Doornkamp et al. show that there is evidence to support this), or that this submerged coastline represents a much earlier period in Bahrain's history prior to c.100,000 BP. Certainly the evidence suggests that Bahrain was an island before this period and then underwent a fall in sea level. It may be that this -9 m zone represents a coastline from an earlier sea level. Another possibility is that this line may, in fact, represent the line of the old Hasa terrace on which Bahrain sits and which used to connect it to the mainland of Saudi Arabia and Qatar. The satellite imagery has opened up a whole new area of research for marine geologists and sedimentologists.

The sand spit at Ras al Barr is very clearly marked on the imagery along with a number of other sand formations around the islands. There is an obvious spit running south from Fasht Jarim and a number of spits and bars in the channel between Saudi Arabia and the north-west of Bahrain. These show the predominantly north-south current in this area as do the numerous spits and bars on the south-east coast. Many of these islands and small reefs display sand bank formations both to the north and to the south suggesting a net active accretion on both the flood and ebb tide.

To the south-west of the image, stretching up the coast of Saudi Arabia and across most of Dawhat Salwah it is possible to see the shape of large sand formations on the sea bed. These are the remains of sand dunes which once covered this area of the Gulf of Bahrain when it was a desert and before the waters flooded it during the late Holocene. These have become compacted and stabilised on the sea bed by the action of carbonate muds. Small dune formations and sand ripples have been seen underwater off the west coast of Bahrain during field trips. Part of their present day stability is determined by the presence of seagrasses growing on the taller ridges of the dunes and ripples, thus preventing their erosion. Between the dunes and the ripples there are often areas of exposed rock and this combination provides for quite an unusual habitat.

Throughout the image the shallow reefs and sandbanks show up well. In fact, they are even clearer in the habitat classification image. Channels and intertidal flats are also very obvious mainly due to the high turbidity of these waters. Because of this high turbidity it is easy to pick out zones of erosion/accretion and also areas of recent dredging and reclamation. The recently reclaimed sites on the north coast at Sanabis and to the north-west at Budaiya stand out as regular grey areas and the effects of siltation caused by these reclamations can be seen along the adjacent coastline, especially at Sanabis. At Al Hidd, where there is a recently reclaimed causeway to serve the shipyard and the iron and steel mills, the area offshore, which was dredged to provide sand, can be clearly seen in the form of a cross.

Below Fasht Adhm, on the south eastern side, is an area of curious sedimentary characteristics. The water, here, appears to be very turbid and this is confirmed by helicopter observations. On the satellite image there appears to be an eddying effect which may be a result of tidal currents.

Another curious phenomenon is the presence of very regular grid lines across Fasht Jarim, Fasht Adhm and off Tighaylib. These appear to be the result of petrochemical exploration using a magnetometer and it is the first time that these features have ever been detected from satellite data.

Production of the Habitat Characterisation Image

To create an image depicting habitat types it is necessary to supply the computer with accurate information on areas of known habitat. The principle involved in producing a characterisation image is basically a matter of comparison between the pixel data captured and transmitted by the satellite and the actual habitat types known to be present for that corresponding area on the `ground'. Accurate and reliable training data are necessary to achieve an acceptable level of accuracy and problems can arise if such data are insufficient. The first attempt to produce a Habitat Characterisation Image was relatively unsuccessful as a result of insufficient training data and less than 15% of the study area was classified.

Several areas of training data are required for each habitat type that is to be mapped. Within each training area several pixels have to be confidently identified as being representative of a specific habitat. To classify seagrass distribution on the image, four or five areas taken from different parts of the image were used for training. Each area consisted of several pixels which the classifier was confident represented only a seagrass habitat. This was repeated for all the habitat types encountered. The computer then scanned the rest of the image for identical or similar pixel types. Where a pixel type does not fall immediately into one of the habitat categories the computer employs a `maximum likelihood' approach and assigns it to the nearest (most similar) category into which the pixel is most likely to fall.

The original training data used for creating the first habitat classification image was provided from local knowledge of the habitat types as well as information available from Price et al (1984). When it was realised that this training data was insufficient in quantity and not accurate enough, follow-up training data was provided using information collected specifically for that purpose with accurate position-fixing of precise habitat types. This process took several days in front of specialised equipment operated by trained imagery analysts during which time much refining of the boundaries of the training data and compromises between different habitat allocations were necessary. This highlighted the need for an ecologist with field experience in the area being classified to work closely alongside the satellite imagery specialist to produce an accurate and reliable product. Mather (1987) provides an excellent presentation on classification techniques.

To generate the habitat characterisation image only bands 1, 2 and 3 were used as information for the land was not required. Suspended sediment levels in Bahrain's waters presented a problem as they reduce the penetration of all three bands. The apparent colour of water depends on the size distribution, mineralogy and chemical composition of the sediment, as well as the absorption effect of any dissolved or organic material (Jupp and Mayo, 1986). But, in general, the brightness of the light which is backscattered into the field of view of the satellite sensor is directly related to the concentration of suspended sediments in the top few metres of the water column. Other workers have found that turbidity prediction by MSS is positively related to salinity (Khorram and Cheshire, 1985). It is almost inevitable that these two parameters (salinity and turbidity) can effect the prediction of habitat type from one area to another within an image.

Obviously, the accuracy of the information received by the satellite can also be upset by climatic factors such as sea state and cloud-cover, both of which can affect the penetration and back-scatter of light (Jupp and Mayo, 1985).

Medium smoothing is employed to get rid of noise. The process of imaging and scanning involves some blurring effects. A filtering technique is used to sharpen the image and remove background noise which might be the product of wave action, atmospherics or subtle, small-scale changes in the target. The technique involves comparing each pixel with the median value of neighbouring pixels. Those pixels which have larger or smaller values than their neighbourhood median values are respectively reduced or increased in value so that local detail is not lost. This technique of filtering is discussed in detail in Mathers (1987). Bearing in mind the maximum effective penetration of the TM bands (10-25 m in clear water), along with the restrictions imposed by high sediment levels, it was considered necessary to include a deep water element in the habitat classification. This deep water classification appears to include all depths of water greater than 12 m, but this probably extends deeper in certain areas of the image depending on local values of suspended sediment.

Volume 2, figure 10 shows the final satellite habitat classification depicting 8 different habitat types. These nominal habitat types are:

Seagrass > 30% cover:
Non-specific seagrass beds (any combination of the three species). This habitat covers much of the east coast south of Fasht Adhm, the shallow seas between Saudi Arabia and Bahrain north and south of the Causeway, large areas of the north coast, around Hawar and along the west coast in a strip running parallel to the shore. Definition is lost to the west of Hawar and south of Bahrain because of striping effects (see Mathers, 1987). This is partly a result of the algae-seagrass classification overlap (see discussion).

Algae > 30% cover:
Non-specific algae (any species). This classification is very strong down the northeast and eastern boundary of the image (see Volume 2, figure 10). This is a result of the algae-seagrass overlap. This overlap seems to be stronger in shallow waters. Around Mashtan there is a solid block of algal classification despite the fact the present studies have shown there to be quite high levels of seagrass in the area. This phenomenon is almost certainly a result of the timing of the imagery (winter) when the more prolific shallow water species (H. uninervis) dies back to a low percentage cover. As a result, the seagrass classification may well be concentrating on those species which do not drop in cover during the winter.

Sand:
This classification is effectively a combination of sand-associated habitats including fine to medium sand and sand interspersed with algae and seagrass.

Deeper water:
The need for this classification is explained in the text. Deeper water effectively covers all areas with water depths greater than 12 m.

Bright sands/silt:
This classification produced a very strong signal to the satellites detectors as a result of high levels of reflectance (hence the name allocated by the imagery analysts). In reality, this classification represents mainly coarse sands and `silt' is probably something of a misnomer.

Rock/rock with sand:
This represents the commonly-distributed habitat of rock with a thin layer of sediment over the surface. This is one of the most common coastal features around Bahrain,

Mud:
This is the shallow water muds and fine sediments which are not common. The small area of `mud' immediately north of the centre of Fasht Adhm is likely to be a mis-classification although the seabed in that area can be quite silty in patches.

Coral >30% cover:
This classification appears to represent living coral reef structures rather than just coral-associated habitats. It is strongest along the central front and northeastern arm of Fasht Adhm.

With all the sea area in the image classified in one way or another it was possible to statistically compare the confirmed habitat types from the field records for any one position with the `predicted' image classification.

The Subtidal Habitat Map

Volume 2, figure 10 represents the satellite Habitat Characterisation Image defining 8 different habitat types. Volume 2, figures 11 and 12 represent the final habitat map for Bahrain. This map is a more detailed interpretation of the subtidal habitat types employing additional data from the present study along with other field studies undertaken around Bahrain as well as information available from published bathymetric charts, the false colour image and helicopter surveillance and photography. The areas which are black represent the land out to the extreme low water spring tide contour. By analysis and incorporation of this additional information it was possible to expand the number of habitat types from the original 8 developed from the satellite imagery to a final figure of 12. These are:

1. Seagrass:
This classification remains much the same as for the satellite classification. However, after careful consideration of the algae/seagrass classification overlap the areas classified as seagrass have been strictly selected and it is considered more accurate to raise the percentage cover to 40%. It is clear from the distribution that seagrasses are a prolific and important habitat type around Bahrain. This classification includes seagrass community type A (as identified in chapter 4) and some of community type B, but probably not C where low percentage covers of seagrass and water depths would not be conducive with a strong reflectance signal for seagrass.

2. Mixed sands/seagrass/algae:
This encompasses much of the medium and fine sediments covered by 'sand' in the satellite classification. This includes soft substrate habitats with a patchy distribution in which areas of low cover seagrass (<30% cover) and sands with cyanobacteria/diatom populations might be found. Some of the seagrass community type C may be associated with this habitat classification.

3. Mixed sands and coral:
Medium to fine soft substrates with intermittent coral populations but not as reef structures. Cluster D coral community types (see chapter 4) would be found in this category along with some cluster B.

4. Medium to fine sands:
Sand (not coarse) is the dominant habitat type and this cannot strictly be considered to be a mixed habitat, although patchiness means that there are some intermittent and sparsely distributed other habitat types (at <20% cover) found associated with this classification.

5. Coarse sands:
A pure coarse sand habitat, mobile and with very little associated biota. This habitat is often associated with high- energy shallow reef areas.

6. Rock with soft veneer:
Limestone rock (either Evaporite 'faroush' or coralline in origin) with a thin layer of fine sediment supporting cyanobacteria and/or diatoms and/or macroalgae such as Hormophysa at low percentage cover. Seagrasses may be intermittent and also at low cover where the sediment layer is thick enough.

7. Coral dominated:
Those areas where coral is quite clearly the principal habitat cover and where a true reef structure exists. This is the habitat category which includes nearly all of the cluster A and most of the cluster C coral community types.

8. Algae dominated:
Areas where algae are the dominant biota. However, this may be macroalgae such as Hormophysa and Sargassum or it can be cyanobacteria or diatoms. In either case percentage cover is 30% or greater.

9. Rock/sand with coral/algae/seagrass:
A mixed habitat type transitional between type 3 and 6. The substrate consists of coralline or evaporite rock and/or shell-based sands with associated coral species, algae or seagrass. Some seagrass community type B can be found within this classification. This category includes some cluster D coral community types.

10. Shallow water muds:
The muddy habitats found in water depths of less than 14 metres.

11. Deep water muds:
The muddy habitats found waters with depths greater than 14 metres.

12. Deep water gravels:
Areas with a water depth greater than 14 metres and with a substrate (usually not too thick) consisting mostly of gravels or cobbles over a rocky seabed. A patchy distribution of Hormophysa and Pinctada spp. are characteristic biota.

After the final habitat classification image was produced (see Volume 2, figures 11 and 12) Two methods were employed to assess the accuracy of this imagery. The first was a computer database comparison between the `on-site' habitat descriptions for each site visited during the course of the Habitat Study (235 altogether) and the predicted habitat for that site as represented by the pixel values for that position on the habitat characterisation image. The second was a direct visual comparison created by using an accurate overlay of the study site positions onto the satellite habitat image. For the computer-based comparison, details of the predicted habitat type were obtained from ERSAC for a block of 25 pixels covering each field site. The pixel mean value was calculated, this being the average likelihood of any of the pixel's in a 25-pixel block belonging to a particular habitat category. Using a 25-pixel block allowed for any inaccuracies in on-site positioning (maximum error 50 m - see methods section of chapter 4) as well as the root mean square error for the geometric correction (Calculated to be an average of 25 m across the image). This gives a total maximum error of 75 m. Hence any characterised pixel identified as site A could actually be 75 m away from sites A in any direction but must lie in a circle with a diameter of 150 m with site A (as given by the Loran-C positioning equipment) at its centre. The pixel size is 30x30 m so a 25-pixel block (150x150 m) would cover the known field-site allowing for all possible inaccuracies. Thus for each field site there was a comparable pixel classification using the pixel mean value allowing an assessment of percentage accuracy. This was achieved by comparing each `actual' site classification on the database with its pixel-predicted classification.

In reality very few habitats are `pure' coral or `pure' seagrass. Usually an area consists of predominantly one habitat type, but with elements of others present to a lesser degree. To account for this a five-field habitat database was created with each element listed in order of priority from one to five. Thus, for example, an area which had a high percentage cover of seagrass interspersed with bare mud and occasional pockets of sand would be recorded in the first three fields as seagrass:mud:sand in that order.

Wherever the predicted habitat type agreed with the first field in the database a `positive' identification was scored. If there was little or no relationship between `recorded' and `predicted' habitats then a negative identification was allocated. But in a number of cases the `predicted' habitat would agree with the second or third habitat field and these sites would have to be researched in greater detail either by comparison with immediate neighbours, with previous data records or, where necessary, by a repeat visit for re-sampling. If any doubt still existed then the sites where classified as `negative' identification. Many of these poor correlations were found to be due to seasonal effects, the die-back of seagrass beds during the winter months being one obvious example. This was solved by re-sampling old `training' sites and adding some additional ones during the same time of year (February) as the satellite data was recorded.

For the `deep-water' pixel category, 12 m + was decided on as the cut-off point for the simple reason that all the field sites recorded as over 12 m had been predicted as deep water by the satellite. Shallower sites that received a satellite classification of deep water were considered to be a `negative' correlation.

The final result of this comparative analysis, was that out of 235 sites, 56 were rejected, leaving 179 sites for statistical comparison. 23 of these were a `negative-fit' and 156 were `positive-fit' leaving a final percentage accuracy of 87%. This in itself represents a significant accuracy for such a method. Table 5.2 lists a percentage accuracy for each satellite classification. Certain classifications such as coral and sands are very accurate indeed, while others are less accurate.

The other method of accuracy analysis, by transferring the site positions onto the image takes into account the fact that in the processing of the satellite data, the whole image has been `smoothed' or averaged. A transparent overlay was created with only the outline of the land areas and the UTM grid transposed onto it. All 235 sites were then carefully plotted and the transparency placed over the habitat image. A record of the `predicted' habitat type for each site was made from comparison of the site overlay onto the underlying classification and these were then compared to the `real' site data on the computer to produce a `positive' or `negative' correlation. In this case the accuracy attained was higher with 173 `positive' sites, 12 `negative' sites and 50 sites rejected as `unreliable' data. Thus, a sample size of 185 sites gave a percentage accuracy of 93.5%.

Of the 50-56 sites rejected as unreliable, 60% of these were rejected due to their close proximity to land resulting in interference (i.e. they were intertidal or sublittoral fringe sites). The majority of the rest were rejected as unreliable position fixing. The `smoothing' process of the computer can be seen to make a noticeable difference to the data. For example, small patches of mud or sand are smoothed over and lost so that the average habitat type over large areas is presented. After `smoothing' across the image by the computer, it is safe to say that one can reliably predict the average habitat type for any one area around Bahrain, but localised patchiness must always be considered.

The Priority Zone Maps

By using information available from other published studies (Vousden, 1985b; 1987) and unpublished field work along with the observations collected during the course of the present study it is possible to define areas of special scientific and commercial interest. These are presented as Volume 2, figures 13 and 14. The areas of scientific interest include feeding grounds for dugong and turtles (both of which are listed as endangered by the International Union for the Conservation of Nature and Natural Resources) as well as nesting, roosting and feeding areas for a variety of seabirds which are either endemic to, threatened or rare around Bahrain. The areas of commercial interest include nursery areas for commercial species (shrimp and fish), major areas of commercial fish concentration and recorded shrimp fishing grounds. Much of the identification for the areas concerned followed detailed discussion with local fishermen as well as knowledge gained from the present study, numerous turtle and dugong surveys, mangrove studies, reef monitoring projects, aerial surveillance and fishing trips during the period 1983-89. Much of the data from these projects is on file within the library of the Environmental Protection Technical Secretariat of the State of Bahrain.

Using the accumulated information and the maps of commercial and scientific interest a final Priority Zone Map (Volume 2, figure 15) was produced which defines three areas recommended for priority protection, conservation and management. These zones include areas which have been designated scientifically or commercially important, and which can also be defined as classic examples of their type; the last remaining representative of that habitat type; or are considered to be particularly vulnerable to disturbance. These areas are:

Priority Zone 1:

These zones should be allocated 'Full Protection' status and are for the immediate and absolute protection of endangered species and threatened habitat types which are commercially or scientifically important. Development in or adjacent to these zones should be discouraged. Public access should be controlled and restricted. Any disturbance should be limited and a policy of careful monitoring and management should be adhered to.

Priority Zone 2:

These zones have a lower level of protection than zone 1. They are intended as reserve zones for the long-term conservation of that type of area and the species which it supports within Bahrain's territorial waters. Development may be allowed, but it should be on a small-scale only and should be carefully controlled so as to avoid wide-scale disturbance. A policy of monitoring and supervision should be adopted to assess any effects of disturbance and correct any deleterious consequences.

Priority Zone 3:

These are the areas which are seasonally important. They cannot be allowed to deteriorate or be significantly altered between their seasonal periods of importance. From this point-of-view development needs to be limited, monitoring is necessary (especially prior to and during the critical season) and public access may have to be controlled during the critical season to prevent disturbance.

Description of the Recommended Priority Zones
(All figures refer to those in Volume 2)

Priority 1 Areas - Full Protected Status.
(Areas 1, 2 and 9 on figure 15):

A. The Hawar Islands:

A critically important nesting and feeding area for a number of coastal bird species including Flamingoes, Cormorants, Ospreys, Sooty Falcons and several species of Tern. This is also a highly productive nursery and feeding area for fish.

B. Mashtan Island and Surrounding Reef Area:

A rare example of an island with a true sandy intertidal and subtidal. It is also a regular breeding, nesting and feeding site for Ospreys. Only 6-8 breeding pairs of these magnificent predators have been recorded around Bahrain.

C. The Western and Southern Coastline of Tubli Bay:

This is a major feeding and roosting area for many species of coastal birds both endemic and migratory. It also represents the last remaining area of true mangrove habitat in Bahrain, a habitat which is now becoming increasingly rare throughout the Arabian Gulf region. Tubli Bay as a whole is an area of high productivity.

Synopsis of Priority 1 Areas

The Hawar Islands already enjoy a considerable amount of protection due to their strategic importance to local security forces. They also serve as a stock-holding area for Al Areen Wildlife Park. however, it is strongly urged that their reserve status should be made more formal and a protection and management strategy should be adopted. Incidents of the shooting of wildlife and the systematic destruction of nesting sites are not uncommon.

This is true also of the Osprey nesting site on Mashtan which is frequently disturbed and where broken eggs are commonly found.

The west and south coasts of Tubli Bay are in desperate need of protection. Already greater than 80% of Bahrain's total mangrove habitat has been destroyed by reclamation. These shallow, muddy habitat types are vital in the food chain of commercial species and as a nursery to a number of those species. Equally as important is the scientific and educational value of this unusual mangrove habitat.

Priority 2 Areas - Conservation Status (Areas 3, 5, 8, 10, 12 and 13 on figure 15):

A. East Coast Reef and Seagrass Zone:

A highly productive fishing ground and one of the principal shrimp-trawling areas. This zone stretches from the southern edge of Fasht Adhm down to Ras al Barr and across to the northern edge of the Hawar Islands. It is an area of rocky or coralline reefs, sand banks and prolific seagrass beds which support a vast assortment of fish life. These are also the principal feeding grounds for the Sea-Cow (Dugong dugon), a rare species of marine mammal. Over 700 of these unique mammals have been recorded in one herd within this area representing one of the largest assemblages of Dugong throughout its global range It is also a principal feeding area for nesting seabird colonies along the east coast of Bahrain and south of Hawar.

B. Northern Edge of Fasht Adhm:

This is an area of coral or coralline reef bordered by sand and seagrass and displaying relatively low salinities compared to the rest of Bahrain's waters. It supports large concentrations of reef fish which are both commercially and educationally important. It is also the main area of high coral diversity around Bahrain being one of the only areas supporting this habitat in any proliferation. It also falls within one of the areas that supports a sizeable population of turtles.

C. Inner, Northern and Eastern Tubli Bay:

This area has been discussed in many independent assessments of Bahrain's marine environment and has always been highlighted for its unique productivity and diversity of habitat types. It is a major nursery and breeding area for commercial fishery species and supports unique habitats found nowhere else around Bahrain and very rarely within the region.

D. The Outer Reefs of Jarada and Fasht Dibal:

A productive fishing area frequently used by commercial fishermen setting long drift nets. Also Fasht Dibal is another area of high coral diversity and cover.

Synopsis of Priority 2 Areas

These areas represent zones which are important both commercially (fisheries) and scientifically (endangered and vulnerable species or habitats). Tubli Bay is a sad example of a highly productive and rich area of the marine environment which is losing out to man's exploitation. Despite constant and strong pressure from environmental bodies (both national and international) this area has been systematically and recklessly destroyed by reclamation and development. A number of unique and rare habitat types can be found within Tubli Bay and the whole bay is of major commercial and scientific interest.

Most of the eastern and north-eastern coast and offshore area is a rich fishing ground of great commercial significance. It also contains two particularly important habitat types namely coral reefs and seagrass beds. The reefs are of importance because of the rich diversity of marine life which they support while the seagrass beds are an important habitat for commercially exploited species of fish and shrimp as well as vulnerable and endangered species such as turtles and particularly the Dugong. One of the major populations of this unique and threatened marine herbivore is found in these waters. Therefore, for both commercial and scientific reasons, Priority 2 areas require some measure of conservation, monitoring and general supervision.

Priority 3 Areas - Seasonal Management Status
(Areas 4, 6, 7 and 11 on figure 15):

A. South-Western Coastal Strip of Main Island:

This area supports the main west coast colonies of White-Cheeked Terns. These are the most significant breeding colonies in the area. Nesting takes place in the summer around June-August.

B. Eastern Coastal Strip - Sitra to Askar:

This is an important nesting and feeding area for both endemic and migratory birds. Once again, White-Cheeked Terns are known to have a breeding colony here but this is also of importance as it is the only recorded nesting area in the country for Saunder's Little Tern. Migrant Flamingoes also use this coastal strip as a feeding ground.

C. Island Nesting Sites:

These are the two islands of Jazirat Yusuf and Qasser al Qulayah. They also support nesting site for White-Cheeked Terns.

Synopsis of Priority 3 Areas

These areas represent mainly nesting or migratory feeding sites for seabirds. Over the last few years there has been an alarming fall in the number of nesting pairs of birds within the coastal zone. This is due to a variety of factors including development of the coastal strip, disturbance by man, traditional removal of eggs for food by local fishermen and the shooting of nesting birds or feeding parents. It is recommended that these areas should be given some seasonal protection and all-year-round management to prevent such interference.

DISCUSSION

Perhaps one of the best uses of the false colour imagery is the detection of geological and sedimentary phenomena. These also serve to highlight the current regime of the area as is immediately apparent when first observing the image. The direction of flow around the north end of the island and between Saudi Arabia and the north-west of Bahrain, as well as around Fasht Adhm and south down into Dawhat Salwah, stands out very clearly.

The false colour image also assists with the interpretation of the habitat classification image and with the extrapolation to the final subtidal habitat map. Careful scrutiny of the false colour image can help to define habitat boundaries which are otherwise unclear in the classification imagery.

The Habitat Classification Image (see Volume 2, figure 10) has provided classification for 100% of the scene. What should be remembered is that 20-25% of this classified image represents deeper water (>12-14 m). This does not present a problem when extrapolating to a final habitat map (Volume 2, figures 11 and 12) as the bottom types in these deeper waters are generally well known and probably of less significance from the point of view of protection as they are mostly outside of the sphere of industrial influence. However, the deep water classification is a consideration when reviewing the accuracy of the classified image as a whole.

The accuracy of this imagery has proved to be very good (>80%). It was feared at first that the colour classifications had simply followed certain lines of bathymetry and only represented a colour-coded hydrographic chart. However more detailed analysis of the classified image along with careful checks into the accuracy of the satellite predictions have shown that this is not the case and the colour-coding on the image is a true representation of the distribution of local habitat types.

There is, however, an apparent correlation between certain habitat types and the depth contours and this pattern is a logical one. Light available for photosynthesis is attenuated with depth. The generally turbid waters around Bahrain exacerbate this light extinction effect. As a consequence benthic productivity and those organisms which depend on light for photosynthesis (e.g. seagrass and corals) have depth limits below which levels of light are insufficient for the organism's photosynthetic needs. Seagrasses also require a soft substrate in which to root and where they have been noted as absent (both in the field study and on the classified map) it is often because the substrate is unsuitable. On the west coast, much of the inshore substrate consists of a thin layer of sediment over rock. The sediment is too thin to support seagrass. It is not until the 6-7 m mark that there is suitable substrate and at this depth out to 12-14 m the grassbeds are prolific. Seagrass does not follow bathymetry perfectly as can be seen by comparison of areas classified as seagrass. Around Tighaylib, Mutarid and Mashtan the colour code for seagrass on the habitat map (Volume 2, figure 10) stretches from 2 m down to 14 m when compared with local hydrographic charts. In other areas it is restricted to between 3-6 m and between 8-12 m depending on substrate types.

It should be noted that the 87-95% accuracy assigned to the habitat classification image is derived from a comparison with the actual site descriptions from the field sites. These field sites were selected for their biological significance rather than as an equal distribution of points for testing the accuracy of the image. As a consequence certain areas on the image have received less attention than others during the accuracy-testing procedure. The measure of accuracy therefore only applies to the areas studied and cannot be extrapolated throughout the whole area of the image.

Table 5.2 shows the individual percentage accuracies for each satellite classification. All of these values are close to or exceed the overall accuracy of the image. Seagrass falls slightly lower at 76%, and there were some problems at the imagery classification stage with misclassification between algae and seagrass. In the end a compromise was agreed which reduced the accuracy of the classification for these two habitat types in the north eastern corner and far eastern edge of the image. Any attempt to introduce a stronger seagrass classification to the computer imagery to improve the classification in the eastern and north-eastern regions tended to reduce the definition of the other classes throughout the image. This compromise was taken into account during the production of the final, 12-habitat map.

A more precise assessment of the accuracy might be achieved by excluding the 'deep water' classification. The detection of water greater than 15m deep might be expected to be highly accurate. However, the original assessment of 86.8% accuracy actually improves slightly to 88.1% if the 'deep water' class is removed. This can be calculated from table 5.2. The reason for this improvement in overall accuracy is that the 'deep water' class actually represents one of the less accurate categories (78%). Its removal would then inevitable increase overall accuracy. Where mis-classification has occurred for this category the sites were all greater than 7m deep and in areas of turbid water which would limit the penetration and reflectance of the spectral bands in the same way as deeper water and could explain the mis-classification.

The submerged dune structures in the southern Gulf of Bahrain and Dawhat Salwah that are apparent in the false colour image are equally obvious in this classified image due to the presence of seagrass on the tops of these structures. These dune structures appear to extend right across the southern edge of the image but this may be noise from the banding effects of the satellite imagery and requires field verification.

The classified image is even more accurate than the false colour image in detecting areas of reefs and shallow waters. In a number of cases the image clearly shows reef structures where local bathymetry charts only have them marked as a spot-position of shallow waters. In the south-east area of the image, to the north of the

Hawar islands and south-east of Mutarid, is an area that is shown on the most recent bathymetry charts as 6 spot-depths of between 2.0-2.5 m. On the classified image this area represents a significant sand bank which fits quite accurately over the spot-depths and gives a defined shape to an otherwise obscure shoal.

Further north the classified image predicts another sand shoal and careful inspection of the hydrographic charts shows a line of three spot-depths of between 1.8-2.4 m in waters otherwise 5-6 m deep, once more proving the accuracy of this imagery. In both cases the shoals appear as `ghosts' on the false colour image.

Therefore, not only does the classified imagery predict habitat types with exceptional accuracy, but it would also appear to be a major aid to bathymetry and has great potential for hydrographic applications.

It is important to remember that the final subtidal habitat map required local knowledge and the results of other field work (Volume 2, figures 11 and 12). The imagery processing technique requires smoothing and enhancement and the potential for patchy distribution of other habitat types within the predicted habitat classification must always be a consideration. Detailed knowledge of local habitat types and distributions is necessary to in order to translate the satellite habitat classification image accurately and to extrapolate from that image to the final subtidal habitat map. Coastal management specialists should not become too dependent on desk-top techniques such as remote sensing and classification imagery. Such technology can never fully replace field experience.

Several problems were encountered and a number of valuable lessons were learned during the exercise of creating the final habitat map. Any reduction in discrepancies in position-fixing when collecting training data and data to prove the accuracy of the image must be an advantage and the use of more accurate positioning gear, such as a trisponder network or differential GPS (Global Positioning System), should be a consideration. This would reduce on-site position error to a few metres at most and would therefore reduce the potential for overall error in position on the imagery to within 30 metres or so. Such a reduction in error becomes valuable when testing the accuracy of the classification. To this end, a reduction in the RMS (geometric correction) error on the satellite image would also be an advantage. The best way of achieving this is with a frequent and reliable network of ground-control points.

When `proving' the image by an overlay technique, accuracy of the image itself could be increased by expanding the scale to 1:50,000. This is within the capabilities of the imagery processing equipment, although there is a tendency towards pixelation. An increase in scale enhances position-fixing accuracy on the image.

One of the original mistakes made during this study was to commission the habitat classification image based on poor training data. The original intention was to use the satellite imagery to select the field-sites, but it became obvious that this approach is incorrect. As a result, the first habitat classification image only classified between 10-15% of the original area which, although of some use in site selection, fell far short of original expectations. This was rectified by ERSAC's generous agreement to re-run the habitat classification based on more precise habitat identification and more numerous areas of training data. This produced a more accurate second image (volume 2, figure 10) from which to create the final habitat map (volume 2, figures 11 and 12).

To provide good training data, therefore, one should select good examples of high cover, widespread habitat types. To supply the computer with reliable areas of, for example, seagrass distribution, one needs to identify a number of good sites supporting 60% (or greater) cover of seagrass stretching over as large an area as possible with as few interruptions by other habitat types as possible. Some examples of borderline habitat types may also be useful for accuracy assessment (i.e. low percentage cover seagrass tending towards a mud-type habitat).

During the classification process on computer it was discovered that the more habitat types one tries to extract from the imagery, the more likelihood there is of classification overlap. This was particularly noticeable between corals, seagrass and algae. It is a reflection on the reliability of this methodology that the computer does appear to be capable of distinguishing between fine sand, mud and silt with reasonable accuracy, a distinction that is often missed in the field by the eye of the human observer. A certain amount of balancing is necessary to achieve the best possible accuracy. The accuracy of one habitat type may have to be sacrificed in order to gain a better understanding of the distribution of another, less well-known habitat.

In conclusion, the use of satellite remote sensing techniques for subtidal habitat classification has shown itself to be a viable and accurate technique and one that can save many hours of fieldwork. Caution is necessary with regard to the need for field experience when interpreting the satellite classification. Once the accuracy of the habitat classification has been proven, the final subtidal map can be a valuable tool for coastal zone management. Knowledge of the distribution of the various habitat types provides a firm foundation upon which to base decisions regarding the protection and conservation of coastal resources within the frame work of sustainable coastal development.

LANDSAT 5 THEMATIC MAPPER SPECTRAL BAND SELECTION

BAND	WAVELENGTH (um)	SPECTRAL RANGE	APPLICATIONS
1	0.45 - 0.52	Blue	Coastal area mapping ; differ-entiation of soil and vegetation
2	0.52 - 0.60	Green	Reflectance by healthy green vegetation
3	0.63 - 0.69	Red	Chlorophyll absorption for plant species differentiation
4	0.76 - -0.90	Near IR	Water body delineation: biomass surveys
5	1.55 - 1.75	Near IR	Vegetation moisture measurements
6	10.4 - 12.5	Thermal IR	Thermal mapping; plant heat stress measurements
7	2.08 - 2.35	Middle IR	Hydrothermal mapping; geological mapping

TABLE 5.1

PERCENTAGE ACCURACY OF EACH HABITAT FROM SATELLITE CLASSIFICATION

HABITAT CLASS	ACCURACY
Seagrass >30% cover	76%
Algae >30% cover	84%
Sand	100%
Deeper water	78%
Bright sands / silt	87.5%
Rock / rock with sand	83%
Mud	86%
Coral >30% cover	100%

TABLE 5.2

CHAPTER SIX

THE EFFECTS OF WATER TEMPERATURE, SALINITY AND DEPTH ON THE DISTRIBUTION OF SEAGRASS SPECIES AROUND BAHRAIN

CHAPTER SIX

THE EFFECTS OF WATER TEMPERATURE, SALINITY AND DEPTH ON THE DISTRIBUTION OF SEAGRASS SPECIES AROUND BAHRAIN.

INTRODUCTION:

Seagrasses are marine angiosperms with a well-developed rhizome and root system belonging to the class monocotyledonae and constitute the only group of flowering plants able to withstand permanent submergence in a marine environment. They occur in a wide range of intertidal and subtidal marine and estuarine habitats and are found in virtually all seas except in polar areas (den Hartog, 1970: Jones et al, 1987; Sheppard et al, 1992: Erftemeijer, 1993). Seagrasses may occur as monospecific or mixed-species beds on a wide range of substrates from fine muds to coarse sands and broken coral fragments and in habitats ranging from the upper intertidal down to 80 m.

More than 50 species of seagrass in 12 genera have been described from two families, the Potamogetonaceae and the Hydrocharitaceae (den Hartog, 1970). Despite their common collective name, seagrasses are not true grasses, but are more closely related to pond weeds. Difference of opinion exists regarding the evolution of seagrasses, especially with respect to whether they have originated from freshwater angiosperms or not. The reader is directed to den Hartog (1970) for a more detailed discussion of the evolution of the seagrasses.

Halodule uninervis (Forsk.) Aschers, Halophila stipulacea (Forsk.) Aschers and Halophila ovalis (R. Br.) Hook. f.. are accepted as being present within the Arabian Gulf but within these species there has been a number of taxonomic revisions. Most of these are discussed by den Hartog (1970). These revisions have almost exclusively been based on characteristics of leaf size, shape and pattern. Much of the previous uncertainty regarding the taxonomic identity of the three species has been as a result of the highly plastic nature of their leaf morphology. This morphology varies greatly with differences in environmental variables such as salinity and water depth and after careful consideration of the effects of environment on morphology it has been concluded that the species of seagrass found within the Arabian Gulf and the coast of Bahrain are as above (Basson et al, 1977; McMillan, 1980; McMillan and Bridges, 1982; McMillan, 1983; Price et al, 1984, McMillan, 1986; Coppiens, pers. comm.).

A useful general introduction to the effects of physicochemical factors on seagrass distribution is given by Young and Kirkman (1975) who studied the composition of the various seagrass communities in Moreton Bay, Australia in relation to a number of environmental variables. They conclude that salinity, depth, turbidity and substrate are the four main factors determining the zonation of seagrass communities in that area. H. ovalis was found to withstand salinities down to 3 ppt (parts per thousand). Both H. uninervis and H. ovalis were found in littoral areas from the region of mangrove pneumatophores down to below the low tide mark and H. ovalis was found down to a water depth of 5 m, but only where light penetration was high. The findings of Young and Kirkman (1975) also indicate that a seagrass climax community is not necessarily monospecific and that neither H. ovalis or H. uninervis exist in monospecific beds. They also found that both H. ovalis and H. uninervis were much reduced in size in shallow waters.

Duarte (1991) reviewed seagrass depth limits from various studies around the world and found a relationship between the maximum colonisation depth for seagrass and light attenuation. H. ovalis and H. uninervis were seen to prefer a shallow range of between 2-12m while H. stipulacea reached depths of 50m.

In contrast, Erftemeijer (1993) records H. ovalis in depths from 10-35m and H. uninervis down to 'considerable depths' in the Indo-Pacific.

In studies of laboratory cultures of seagrass from the coast of Kenya, McMillan (1984) found that H. stipulacea is one of the most temperature-sensitive seagrass species. H. stipulacea only survived for one hour at 39^0 C whereas H. uninervis survived for 72 h at this temperature.

In the Red Sea waters of Sinai and Israel, H. stipulacea is found to show the widest ecological distribution in comparison to H. ovalis and H. uninervis (Lipkin, 1979). H. stipulacea survives over wide fluctuations of salinity and temperature in the Red Sea including small, shallow lagoons where temperature and salinity fluctuate markedly. Plants of this species found growing in dim light have larger, greener leaves in comparison to those growing in bright sunlight. Lipkin summarises the depth distribution for the three species in Sinai and Israel. H. stipulacea is found from 1 m down to 50 m, H. ovalis from 1-10 m and H. uninervis is generally restricted to between 1-6 m. H. stipulacea is seen to be the most common species and is prolific even at depths greater than 10 m while H. ovalis and H. uninervis are never seen at depths below 10 m. Lipkin also notes that both Halodule and Halophila can be found on a variety of substrates from fine muds to coarse sand. This is further confirmed by McMillan (1983). Burrel and Schubel (1979) conclude that while many seagrasses may prefer particular substrate textures, most can grow on a variety of substrates. In the Red Sea, all three species can be found growing in metahaline lagoons with recorded salinities of between 40-60 ppt (Jones et al, 1987).

Den Hartog's monograph on 'The Sea-grasses of the World' (1970) also describes the ecology of each species. He states that all three species can be found on a variety of substrates from fine muds through sands to coarse coral sands. In the Arabian Gulf, Basson et al (1977) found all three species of seagrass present on sand, silt or mud substrates. They noted that initial seagrass growth requires a mud to sand substrate after which the plant can extend laterally over less suitable substrates by trapping sediments. These authors also record H. uninervis and H. stipulacea in salinities of 56-58 ppt and up to 62 ppt. Sheppard et al (1992) found seagrass biomass in the Arabian Gulf to be correlated with depth as well as grain-size but not with season or salinity. Basson et al (1977) found that in the Arabian Gulf, the intense heat and radiation of the summer months prevents seagrass from growing above the lowest spring tides. Exceptions to this are recorded, but only in situations where the plants are protected from desiccation by wave action and, even in this situation, show small and stunted growth forms. Although occasional dense beds of seagrass are recorded down to 15 m, growth is generally sparse beyond 10m.

Extensive seagrass beds are to be found along the east and southeast coast of Bahrain from Askar down to the Hawar Islands and off the west coast south of Um Nasan (see volume 2, figures 11 and 12). The extent of these seagrass beds indicates that seagrass must play an important role in the productivity of local fisheries (Price et al, 1984). These authors found H. uninervis to be the most common species while H. stipulacea is recorded at a number of sites but never exceeds more than 30% cover. H. ovalis was only recorded from the area offshore from Askar on the east coast. The relatively high abundance of seagrass on the east coast in contrast to the more limited occurrence on the west coast was attributed to the higher salinity values recorded on the west coast (46-58 ppt). Salinities recorded on the east coast at Askar are between 42-46 ppt.

Analysis of data in chapter 2 of this thesis has highlighted extremes in environmental conditions in the waters around Bahrain. This study has also identified seagrass beds to be one of the principal marine habitat types associated with Bahrain (Chapter 4 and 5). Water quality data shows large seasonal fluctuations in temperature and extreme salinity levels representing some of the highest open water values in the world. Salinity values fluctuate considerably with tidal cycle and display significant spatial variation throughout Bahrain's coastal and offshore waters. Chapter 4 shows that either depth or salinity or possibly both acting in unison have an effect on seagrass species distribution and percentage cover around Bahrain. Multivariate analysis of the data supports a depth-dependent distribution of the three seagrass species, but also suggests a difference in salinity tolerance between the species.

It is recognised that other factors may affect the growth and distribution of seagrass. Although all three Gulf species are seen to grow on a wide variety of substrates this does not preclude the fact that substrate grain-size and chemistry may affect growth patterns and rates. However, without detailed and long-term work involving laboratory experiments and field transplantation studies it would be difficult to separate cause and effect. Wave action may have an influence over seagrass growth, but can also be dampened by the presence of seagrass beds which raise the level of the seabed considerably. Grazing will undoubtedly alter the biomass of seagrass beds, especially off the coast of Bahrain where there are large herds of herbivorous dugong. Competition between the three species of seagrass cannot be ruled out but such relationships are difficult to study and would again require detailed and long-term laboratory experiments in order to separate out any effects from the major environmental variables of temperature, depth and salinity. Field studies on competition would be difficult as certain species are never found in monospecific assemblages. Appendix 6.1 provides references to studies which have looked at other factors controlling seagrass growth and distribution.

Differences in opinion exist as to whether seagrass distribution changes seasonally around Bahrain and as to the depth ranges of the various species. In contrast to present studies, Price et al (1984) stated that no seasonal trends in seagrass cover are apparent. They also state that salinity probably effects seagrass distribution and cover. Lipkin (1979) suggests that Halophila ovalis is a shallow water species, never found below 10 m, and is rarely found in isolation from Halophila stipulacea or Halodule uninervis. Hence the aims of this chapter are to identify the relationship between the distribution of the three species of seagrass found in the waters around Bahrain and temperature, salinity and depth variations in an attempt to clarify some of these contradictions and uncertainties.

METHODS:

Site selection was based on the selection of seagrass beds in conditions of varying depth and salinity and, with summer and winter sampling periods included, to study the effects of seasonal temperature variations. Sites (see figure 6.1) were selected so as to include seagrass beds in water depths from the immediate subtidal (0.5m) down to approximately 12-13m, which is considered to be the cut-off point for seagrass survival (chapter 4). Beyond this depth there are only two records for seagrass and both represent 1% or less cover. Water depths quoted in the text relate to mean sea level.

Sites were identified to include areas with salinities ranging from a minima of 45 ppt (as are generally found to the north and east of the main island) to a maxima of 58 ppt (as are generally found to the south and west of the island). These salinity variations were identified in chapter 2. Actual salinities recorded at the time of sampling were included for reference only as fluctuations have been shown to be considerable over even one tidal cycle in some areas. For the statistical analyses mean sector salinities were used as in chapter 4 (see figure 2.3).

Samples were collected during the winter (13.5°-23.0° C) season when seagrass cover was seen to be at a minimum and during the spring-summer (30.5°-37.0° C) season when growth and expanded percentage cover were obvious. Depth, temperature and salinity data were collected using a Hydrolab Surveyor water quality probe (manufactured by Hydrolab Inc., Texas, U.S.A). Measurements were made at or very close (within 50cm) to the seabed.

Wherever possible, sites were chosen for ease of relocation, an important consideration around Bahrain where the coastline is often flat and nearly featureless. Some sites were beyond sight of land (e.g. Big Red Two) but had a navigation buoy close to hand. Others had only one reliable reference point or were so far from shore that any triangulation attempts proved to be relatively inaccurate for the purpose of repeatable sampling. Loran-C position-fixing equipment (Micrologic) was employed along with compass bearings where possible. This gave a repeatable accuracy of between 30-50 m.

All seagrass samples were collected by means of a stainless steel core sampler with a piston which incorporated a 0.5 mm mesh to retain the seagrass material. The core sampler was 20 cm in length and 12 cm in diameter. This took a sample 15 cm deep from the seabed. The core diameter size and depth of cores were selected following the results of using several core sampling tubes in a previous study (Price et al., 1984). Corer depth was also based on the results of this previous study and represented the normal maximum depth for seagrass rhizome/root systems for the local species, particularly Halodule uninervis which has the deepest root system of the three seagrass species encountered. This diameter of corer sampled an area of a little over 100 cm^2 (113.1 cm^2) and the material for construction was both readily available from local machine shops as well as being considered to be the maximum size/weight of apparatus which could be safely and effectively handled by a diver working alone underwater. Multiplication of the final weights of material retrieved from this sampler by a factor of 88.42 gave an equivalent figure for 1 m^2 of seabed.

The corer was pushed and rotated into the seabed by a diver and the material along one outside edge of the corer was removed. A plastic cap was placed over the lower end and the corer retrieved. After removal of loose substrate and other material from around the corer, a heavy duty, pre-coded (using waterproof marker pen) polythene bag was placed over the lower end of the corer and the piston depressed slowly to deposit the contents into the sample bag. The mouth of the bag was then sealed and the code number of the bag recorded against the site details on an underwater slate for transfer at the surface to a data notebook.

Core locations were randomly selected underwater by a diver in mid-water with eyes closed dropping a 0.25 m^2 quadrat at arms length. The core was then taken from the centre of the quadrat. Wherever possible, eight cores were taken from each station. This number of samples was selected on the basis of the limitations placed on the diver working at the maximum depth sampled (12.5 m) by the exertion of taking the sample, the weight of the material which had to be retrieved to the surface vessel and the air supply available to the diver. Site descriptions were also recorded on underwater slate for each station (see appendix 6.2).

Samples were refrigerated in cool boxes on the vessel and placed in a freezer in the laboratory to await processing. Freezing the samples had the added benefit of breaking down the glutinous muds often associated with seagrass beds. This assisted in the later stages of sieving and separating the plant material. Samples were washed and sieved through a 0.5 mm mesh-size sieve. This retained all of the living plant material and most of the detrital material. Living seagrass material was then separated into root/rhizome and leaf portions and then into species. Where seagrass leaves were found to be encrusted with calcareous material (carbonates and epiphytes) these were removed using weak hydrochloric or phosphoric acid (5% solution) as described by Patriquin (1973), Jacobs (1979), Zieman and Wetzel (1980) and Brouns (1987).

Leaves were counted and measured (length and number of leaves of each species) and the separate leaf and root/rhizome portion for each species were then washed to remove salt and other organic debris and dried at 100° C to constant weight (Harrison and Mann, 1975; Hulings, 1979; Brouns, 1987). The samples were then ashed to constant weight (maximum 6 hs) at 550° - 600° C as per Jacobs (1979) and Brouns (1987). Organic weight was calculated by subtracting the ash-free weight from the dry weight.

Multivariate statistical analyses were carried out using Principal Component Analysis, Principal Component Factoring and Canonical Correlation Analysis on Unistat IBM PC compatible statistical software package (Unistat (C) 1984-1993, UNISTAT Ltd., P.O. Box 383, London, N65UP). See chapter 4 for description of analysis techniques and references.

RESULTS

Table 6.1 presents ash-free weight data for 108 seagrass samples taken from 14 different sites between March 1988 and March 1989 along with temperature, depth and salinity for the sites. Appendix 6.3 gives the latitude and longitude coordinates for the sites and figure 6.1 provides a chart of the locations. Mean salinity values have been calculated at each site from the different values recorded at each visit. The mean sector salinities in which the site lies (as calculated in chapter 2) are also included in the table for comparison. These sector salinities are presented in table 2.1 and figure 2.3. In the following statistical analyses, both maximum and minimum salinity values and salinity range values were all substituted for mean salinity with no significant alteration to the outcome of the analyses. Original salinity values for each site at each visit are given in appendix 6.2.

The initial review of the data presented in table 6.1 shows a relationship between the number of species present at any one site and temperature. All records where the 3 species of seagrass were found together at one site were recorded when temperatures were greater than 21° C and most of them were at the 30° C or over range. Significant correlations between the 11 variables recorded in table 6.1 are presented in table 6.2. There are obvious strong correlations between the presence of leaf and of root/rhizome material for any species. The presence of H. uninervis and detrital material are both inversely related to depth so that more detritus and a greater percentage cover of H. uninervis would be expected in shallower waters. There are positive correlations between temperature, H. stipulacea, H. uninervis leaf and the number of species present at a site. As temperature rises seasonally, the overall biomass of H. stipulacea increases while H. uninervis responds with an increase in the leaf component only. The number of species present at a site is also seen to increase relative to season with more species present in the summer months. The number of species present at a site is related to the absence or presence of the two Halophila species rather than H. uninervis so that most monospecific sites are pure stands of H. uninervis. There are no significant correlations between the three species and this suggests that direct interspecific competition does not affect the presence or absence by weight of any of the three species of seagrass.

Principal Component Factoring (PCF) was performed on two separate sets of variables, one representing leaf material and the other representing root/rhizome material. The two could not be placed together in a PCF analysis as it is inevitable that the strongest relationships would be between root/rhizome complex and leaf (as was seen in the correlation matrix) and any other relationships between the presence of seagrass and the physical variables would be masked. The results of the PCF are presented in table 6.3 which shows that in the first data set (leaf material) a strong relationship exists between water depth and the presence of H. uninervis leaf material and detrital material.The presence of H. uninervis leaf material and detrital material is greater in shallow waters and decreases with depth. H. stipulacea leaf material is related to temperature and increases as temperature increases. In the second data set (root/rhizome material) H. uninervis root/rhizome shows a very strong inverse relationship to depth and H. stipulacea root/rhizome is positively related to temperature. This shows that H. uninervis is depth-dependent and more prolific in shallower water as is detrital seagrass material, while H. stipulacea shows more prolific growth during higher temperatures and is therefore seasonally influenced. Once again, the PCF confirms that there is no relationship between any one species of seagrass and the presence or absence of another species, at least on a leaf-to-leaf or a root/rhizome-to-root/rhizome basis.

Canonical Correlation Analysis (CANCOR) was performed on a number of data sets in order to extract the relationships between the group 1 (plant material measurements) variables and the group 2 (physical measurements) variables. Table 6.4 presents the results of the CANCOR. A number of highly significant relationships (>99.99% probability) are demonstrated in this table. CANCOR analysis A shows that both H. uninervis leaf and detrital material are inversely related to depth. H. stipulacea leaf is related to a mixed effect of the number of species present, water depth and water temperature. There is also a strong relationship between the absence of H. uninervis leaf material, the presence of H. uninervis root/rhizome material and a positive effect caused by the number of species present and the inverse effect of temperature.

Analysis B reveals that in conditions of higher temperature and shallow water there is a greater proportion of H. uninervis leaf material, while in conditions of higher temperature and deeper water it is the H. stipulacea and H. ovalis leaf material which increases.

Analyses C to E show that increasing temperature is related to an increase in H. uninervis leaf material and H. stipulacea leaf and root/rhizome material, while H. uninervis root/rhizome material shows a relative decrease with increasing temperature. H. ovalis root material also increases with rising temperature but not so significantly. The number of species present at a site also increases with a rise in temperature. An increase in water depth is related to a decrease in both H. uninervis leaf and root/rhizome material, H. stipulacea root/rhizome material and a decrease in the detrital material. H. stipulacea leaf material shows a slight increase with increasing water depth.

Table 6.5 presents the data collected from 90 samples on leaf number and leaf length along with temperature, depth and salinity. Initial analysis of the number of species present in a sample against the physical parameters measured supports an increase in number of species with rising temperature as was found in table 6.1.

Correlations between the 13 variables measured and presented in table 6.5 are given in table 6.6. There are inevitable correlations between the variables measured within species (e.g. Between H. uninervis leaf number, leaf length and the standard deviation in leaf length). All of the measurements for H. uninervis are inversely related to water depth, although the relationship between depth and the number of leaves for this species is noticeably stronger. The leaf length for H. stipulacea , on the other hand, is positively related to water depth. As the depth increases, the number of H. uninervis leaves decreases significantly with a related decrease in leaf length and the amount of variation in the length. In contrast, the leaf length of H. stipulacea can be seen to increase in deeper waters. An increase in the water temperature brings about an increase in the length and the variation in the length of leaves in both H. uninervis and H. ovalis and the number, length and variation in length of leaves in H. stipulacea. The number of seagrass species present at a site is positively related to all leaf measurements for H. stipulacea and H. ovalis and to the leaf length for H. uninervis. This suggests that where all three species are found together their leaves tend to be long rather than short and that the two Halophila species have more leaves with greater length variation under such conditions.

Table 6.7 presents the results of the PCF. Analysis is performed on three separate sets of variables. This is necessary as the three measurements of leaf characteristic (number, length and variation in length) are shown by the correlation matrix to be directly and strongly related and, if analysed together will mask other significant relationships between leaf measurements and measurements of water characteristics at each site.

In data set A, factor 1 represents the strong inverse relationship between the number of H. uninervis leaves and depth with the number of leaves decreasing as water depth increases. Factor 2 represents an increase in the number of H. stipulacea leaves with rising temperature and factor 3 reveals an inverse relationship between H. ovalis leaf number and salinity so that as salinity rises there is a reduction in the number of H. ovalis leaves.

In data set B, factor 1 represents the effects of rising temperature which increases the leaf length of the two Halophila species, factor 2 reveals that the leaf length of H. uninervis is also reduced with increasing water depth and factor 3 represents salinity alone and does not relate to any biological measurement.

In data set C, factor 1 represents an increase in the variation in the leaf length of H. stipulacea with rising temperature, factor 2 shows that the variation in the leaf length on H. uninervis is also reduced with increasing water depth and factor 3 once again represents only salinity.

Canonical Correlation Analysis (CANCOR) was performed on several data sets with the group 1 variables being the measurements of leaf number, length and standard deviation in length and the group 2 variables being number of species, temperature, depth and salinity . The results of this CANCOR are given in table 6.8.

CANCOR analysis A1 reveals a relationship between the number of seagrass species at a site and the length of leaves in H. stipulacea and H. ovalis. Where all three species are present then the Halophila spp. have longer leaves. A2 relates shallow water to a greater number of leaves in both H. uninervis and H. stipulacea. The leaf length of H. uninervis is also greater in shallow waters while the length of the H. stipulacea leaf increases with water depth. A3 suggests that at higher salinities (probably associated with higher temperatures) the number of leaves of H. ovalis is reduced while the length increases and H. uninervis shows an increase in the variation in leaf length. However, the probability of this relationship is only 84% (P=0.1580) and is not statistically significant.

Analysis B1 represents the inverse relationship between depth and the number and length of leaves for H. uninervis and the number of leaves for H. stipulacea while there is a direct relationship between depth and H. stipulacea leaf length. B2 shows the relationship between temperature and leaf length of the Halophila species. B3 suggests a relationship between the reduction in the number and an increase in the length of H. ovalis leaves, the increase in the variety of leaf length in H. uninervis and increasing salinity but, once again, the probability of this relationship being significant is only 93% (P=0.0658) which, although high, is less than the statistically acceptable. However, the change in emphasis between this data set and A3 is interesting. With the effect of temperature reduced in B3 from 0.54 to -0.01 (as compared to A3) there is a stronger relationship revealed between salinity (from 0.87 to 1.00) and H. ovalis leaf number (from -1.14 to -1.36) while the relationship to H. uninervis leaf length variability (from 0.92 to 0.87) and to H. ovalis leaf length (from 0.71 to 0.42) is weakened suggesting the relationships of the two latter variables were more closely tied to temperature in A3.

Analysis C shows that the number of H. uninervis leaves increases as the water becomes shallower. C reveals that the number of H. stipulacea (and, to a lesser extent, H. ovalis) leaves increases as temperature increases seasonally. C once again suggests a direct relationship between salinity and the number of H. ovalis leaves present at a site.

D1 relates the leaf length of both H. uninervis and H. stipulacea to temperature with lengths increasing as temperature rises seasonally. Analysis D2 confirms the H. uninervis leaf-length : water depth relationship found in B1.

The E1 data set indicates that as temperature rises seasonally there is an increase in variation in the length of leaves for all three species. E2 shows that depth also affects the variability in leaf length with that of H. uninervis being reduced and that of H. stipulacea being increased as water depth increases.

Data set F reveals a relationship between the length of H. ovalis leaves and temperature with the former increasing with a rise in the latter.

G compares the leaf variables with depth and confirms that as water depth increases, the number of leaves of both H. uninervis and H. stipulacea decreases, but the length of the H. stipulacea leaf increases.

Finally, data set H suggests a relationship between rising salinity and a reduction in the number of H. ovalis leaves along with an increase in their length much as in data set B3. However, as in B3 the probability level of the relationship is weak at 86.5% ($P=0.1345$) and cannot be considered to be significant although it does suggest an interesting future line of research.

In summarising these results it is possible to indicate the effects of each independent variable:

A. Temperature:

As temperature increases from winter to summer the following occurs:

1. A large increase in the leaf cover of H. uninervis with a slight reduction in the root/rhizome biomass. The increase in leaf material is due to a major increase in leaf length rather than the number of leaves.

2. An increase in both the leaf and root/rhizome cover of H. stipulacea. The increase in leaf material is result of an increase in both leaf number and length.

3. H. ovalis shows a relatively small alteration in overall cover compared to the other two species. However, there is a slight increase in leaf length and leaf biomass.

4. The number of species present at any one site can be expected to increase with rising seasonal temperature.

B. Depth:

Moving from shallower coastal waters to deeper offshore waters (maximum depth 12.5 m) the following will be noted:

1. A large reduction in both the root/rhizome and leaf mass of H. uninervis. The reduction in the leaf mass is a result of both reduced leaf length and leaf numbers.

2. A reduction in leaf number and an increase in the leaf length of H. stipulacea resulting in an overall increase in leaf biomass. Root/rhizome mass is reduced.

3. There is no noticeable variation in the leaf or root/rhizome mass or in the leaf measurements of H. ovalis as a result of changes in water depth.

4. The amount of seagrass detritus (dead leaf and root/rhizome material) associated with the seagrass bed is less in deeper waters.

C. Salinity:

Moving from less saline waters in to higher salinity the following occurs:

1. No alteration in the leaf or root/rhizome mass of any species.

2. A possibility of greater variation in the leaf length of H. uninervis.

3. A possibility of a slight reduction in the number of H. ovalis leaves along with an increase in their length.

D. Number of Seagrass Species:

In those areas where there are a greater number of species of seagrass it can be seen that:

1. This greater number of species is due to the additional presence of either H. stipulacea or H. ovalis or both species. This suggests that monospecific seagrass beds tend to be mainly H. uninervis.

2. Where more seagrass species are present there is less detrital seagrass material.

Table 6.9 presents average figures for the dry weight of seagrass in g m^{-2} which also equates to tonnes km^{-2}. These are compared with the findings of other relevant studies. Table 6.10 presents the average ash-free weights and their maxima and minima from the present study and relates these figures to a comparable study by Erftemeijer(1993). Table 6.11 shows the dry weight and the ash-free weight of seagrass in tonnes km^{-2}. Table 6.11 also gives values for tonnes of seagrass within Bahrain territorial waters based on the area represented as 'Seagrass Dominant (> 40% cover)' in the subtidal habitat maps (see Volume 2, Figures 11 and 12).

A comparison of the average summer and winter biomass for all seagrass beds (Table 6.10) reveals that the winter biomass represents only 54% of summer biomass. This is closely reflected by both H. uninervis and H. stipulacea which are reduced in winter to 55% and 52% of the summer biomass respectively. H. ovalis biomass shows a greater reduction in winter to only 34% of its summer biomass. This is further reflected in the value for the total living biomass of seagrass in the territorial waters of Bahrain(Table 6.11). Although the average value for total biomass throughout the year is 1.18×10^5 this rises to 1.57×10^5 in the summer and falls to 8.48×10^4 in the winter.

DISCUSSION:

One of the reasons for choosing the multivariate statistical methods used in the data analysis was in order to nullify the effect of other unrecorded influences on the seagrass data collected and to concentrate on the effects of temperature, depth and salinity . The importance of these three measurements is discussed in the introduction to this chapter. The fact that there may be an influence from, say, sediment type will not affect the findings of the multivariate analysis with regard to depth or salinity being an important factor.

Water temperature, as a reflection of the changes in season, affects the growth of all three species to some extent. H. ovalis shows very little response other than a slight increase in leaf length. The other two species respond more dramatically with a significant increase in leaf biomass. This is only to be expected as rising water temperatures and increased light levels herald the beginning of the growing season. The Halophila species re-colonise sites from which they have been absent in the winter. This results in an increase in the number of seagrass species present at any one site with rising temperature.

Water depth also has a significant effect on species distribution and growth patterns. H. uninervis is identified as a shallow water species and is replaced by H. stipulacea as depths increase. H. ovalis shows no statistically apparent trends related to depth down to 12.5 m. There is less detrital seagrass material to be found at depth. This is because most of the detrital material found in the samples was dead and decaying leaf and root/rhizome parts of H. uninervis which has been shown to be a predominantly shallow water species. Furthermore, it was noticed during the sample processing procedure that the detrital fraction was only barely negatively buoyant and easily resuspended by any agitation of the water. In the relatively shallow waters where H. uninervis predominates wave energy tends to wash such detrital material into the shallows. During the study large mounds of dead H. uninervis were recorded in late summer and during the winter transition along the strand line both on the main and offshore islands. These mounds were associated with the windward side of the islands and, in a number of cases, there were no beds of H. uninervis recorded in the surrounding subtidal for several kilometres. Halophila stipulacea detritus was also found along the strand line but in much smaller volumes.

In chapter 4, it was noted that between the intertidal zone and water depths of 2m seagrass is generally absent and where present it is stunted and sparsely distributed. However, during field expeditions for this more detailed study prolific seagrass beds were recorded in certain intertidal areas. These were nearly always associated with sheltered areas of the beach (e.g. inside the lee of the arrow-head fish traps at Galali on the northeast coast of Muharraq and in the sheltered and shallow `V' of the Mashtan island reef (off the southeast coast of the main island). This association between sheltered waters and intertidal/shallow water seagrass beds suggests that wave-action may be a contributory factor to the general absence of seagrass in waters which are less than 2m deep.

Salinity has no apparent effect on seagrass biomass around the coast of Bahrain. It may have some effect on growth pattern and leaf morphology. H. ovalis shows a tendency for an increase in leaf length in higher salinity waters although the trend was not statistically significant. It was noted in the field that H. ovalis leaf morphology at certain higher salinity sites was similar to that of H. stipulacea. At Middle Shoal (881004 -

see appendix 6.2) seagrass was recorded as having a leaf morphology similar to H. stipulacea but a root/rhizome and stem pattern more characteristic of H. ovalis. This requires further investigation to define exactly what is causing this effect and to statistically confirm any relationship between salinity and leaf length in H. ovalis.

Price et al. (1984) record no seasonal trends in seagrass cover around Bahrain and suggested that salinity differences around the coast may have a more significant effect on the distribution of seagrass. However, the six sites which they used were selected to act as monitoring stations and controls to assess the effects of the construction of the Saudi-Bahrain Causeway and as two of the sites were on rocky substrate they were never intended to provide information on seagrass distribution. In view of the sites selected it is unlikely that trends related to temperature or salinity would be apparent.

Analysis of the data from the present study reveals no trends in seagrass distribution which can be related to salinity. Basson et al (1977) record both H. uninervis and H stipulacea surviving in salinities up to 62 ppt in the Arabian Gulf and Jones et al (1987) recorded all three species in salinities up to 60 ppt. Basson et al (1977) discuss seasonal trends and water depth limits associated with seagrass off the Arabian Gulf coast of Saudi Arabia, but only as a habitat type and not as individual species. They note seasonal trends in seagrass beds per se, with the above-sediment portion of the seagrass bed at a minimum at the end of winter (mid February). Depth limits (both shallow and deep water) are also discussed but, once again, only in respect of seagrass as a habitat type and with no quantitative data analysed for individual species.

The present study identifies the distribution of the species with depth revealing that H. uninervis dominates the seagrass biomass in shallower waters while H. stipulacea is a more important component in deeper waters. H. ovalis has no obvious depth limitations within the confines of the study criteria (i.e. down to 12-13m). Both Basson et al (1977) and Sheppard et al (1992) consider the distribution of seagrass species in the Arabian Gulf to be strongly correlated with depth. However, Sheppard et al (1992) did not find any correlation with season. It is clear from visual observations that there is a massive die-back in seagrass cover during the colder months. This is reported by Basson et al (1977) but without quantitative data to support the observation.

Erftemeijer (1993) used CANCOR to compare seasonal environmental variables with biological variables in seagrass samples taken off the coast of Sulawesi in the Indo-Pacific. He found that, with the possible exception of porewater phosphate at one of the sites, the availability of dissolved nutrients showed no significant correlation with observed seasonal dynamics in seagrass variables (relative growth rates, biomass, C:N ratio, C:P ratio). Erftemeijer provides evidence that the porewater phosphate concentration is related to a significant drop in seagrass biomass as a result of seasonal die-back and a major part of the dead seagrass material being retained and decomposed *in situ* within the seagrass meadow.

The present study confirms a seasonal variation in seagrass distribution which mainly effects H. uninervis and to a lesser extent H. stipulacea. No significant direct interspecific relationships affecting biomass, leaf length or leaf number are apparent from the multivariate analysis (i.e. there is no evidence to suggest that the presence of one species of seagrass has a direct effect on the presence of another). However, indirect interspecific competition is a function of survival and growth under certain conditions, particularly depth and temperature, whereby one species is more suited to that set of conditions than is another. If direct interspecific relationships do exist they may be more subtle than the present data collection techniques can account for and a specific programme of data collection and analysis would be necessary to elucidate any further on this matter.

In addition to the overall relationships established between the three physical factors measured and the biomass of the three species, certain other effects on leaf length and abundance are apparent. H. stipulacea showed a significant increase in leaf length with depth which increased its overall leaf biomass. Lipkin (1979) notes that in dim light conditions the leaves of H. stipulacea are larger and greener compared to the leaves of this species found growing in bright sunlight. However, Lipkin (1979) also found that H. uninervis leaf width and length increased with water depth which appears to contradict the results of the present study. Statistical analysis of the data for the present study shows an overall reduction in both leaf length and number with increasing depth for H. uninervis Observation by the author during the course of the present study suggests that short, thin-leaved plants occur in the intertidal and very shallow water, while longer, wider leaved plants are found in the 1-5 m depth range. Below this the leaves of H. uninervis tend to be short and thin again. Jones et al (1987) also found that H. stipulacea had larger, greener leaves in dimly-lit waters. Hulings (1979) finds that the mean leaf length of H. stipulacea increased as water depth went from 5m to 25m while the number of leaves decreased which supports the findings of the present study.

Changes in leaf : root/rhizome biomass ratio are apparent in H. uninervis in relation to temperature and in H. stipulacea in relation to depth. As temperature rises from winter to summer, the leaf biomass of H. uninervis increases as leaf length increases and the root/rhizome biomass decreases. One explanation for this could be the movement of materials necessary for growth from the rhizome into the leaves to take advantage of optimum growth conditions provided by increased temperature and probably greater irradiance. H. stipulacea shows an increased leaf mass (as a result of increased leaf length) with increasing water depth. The change in leaf growth form could be a response to the need for a greater surface area of leaf in more dimly lit (deeper) waters in order to exploit the reduced quantity of light as a result of attenuation. Rhizome material may be reduced as a dense rhizome may be of less importance as an anchor in deeper waters with less wave energy. Basson et al, (1977) state that on sheltered beaches in the Western Arabian Gulf, Halophila and Halodule extend their distribution inshore to just below the low spring tide level, but that on an exposed shore these two species are limited by wave action to waters 2.5 - 4 m deep.

Drew (1980) studied the seagrasses of the Chagos Archipelago in the Indian Ocean and found that plants growing in still water appeared stunted and covered in filamentous cyanobacteria while plants growing in conditions of rapid water movement were luxuriant and showed rapid growth. Large areas of substrate normally found to be suitable for seagrass colonisation were completely devoid of these plants. Drew considered that this was either a factor of geographic isolation or excessive exposure to wind and waves. Drew also noted that H. stipulacea suffered from photoinhibition in shallow waters, displaying white leaves with contracted chloroplasts. This species was recorded in depths of less than 0.5m of water down to 40 m.

Price and Coles (1991) and Sheppard et al (1992) record that species of seagrass may be selectively associated with fine sediments. A review of their methods reveals that samples for grain-size analysis were taken in the upper 10-15 cm of the substrate supporting the seagrass bed. Burrel and Schubel (1979) cite a number of examples where sediment entrapment by the presence of seagrass has raised the level of the seabed by as much as several metres. Jones et al (1987) note that sediment trapping in a seagrass bed is selective with fine-grained sediments being deposited and accumulated as a result of the damping effect of the seagrass plant on water movement. This demonstrates that caution is necessary in the interpretation of grain-size analysis from seagrass beds lest 'effect' be mistaken for 'cause'. Any analysis of substrate preference by seagrasses should start with an uncolonised substrate and record the succession of colonisation by seagrass species over a period of time. Even then, colonisation may be affected by soil chemistry or other factors. Transplantation experiments in the laboratory may prove to be the most effective way of understanding the relationship between seagrass presence and substrate grain-size. The literature shows that most species of seagrass can be found growing on a variety of sediment types although species may display a 'preference' for a certain type of substrate (Bridges et al, 1982; Jones et al, 1987; Lipkin, 1979; McMillan, 1976, 1978, 1979, 1980, 1982). Basson et al (1977) found Halodule uninervis, Halophila ovalis and Halophila stipulacea growing on all sediment types from fine muds to coarse sands and coral fragments. The distribution and growth of seagrass species are more likely to be affected by soil chemistry than by sediment grain-size (Buesa, 1975; Jones et al, 1987, Penhale and Wetzel, 1983).

Grazing on the seagrass plant itself and on the associated epiphytes will also effect seagrass biomass. Randall (1965) and Ogden (1976) working in the Caribbean have shown that this a common phenomenon adjacent to coral reefs. Other authors working in the Red Sea and Indian Ocean record direct consumption of the live seagrass material to be relatively uncommon (Wahbeh and Mahasneh, 1985; Jones et al, 1987; Sheppard et al, 1992). Orth and Montfrans (1984) consider direct consumption of the seagrass plant to be minimal and less than 5% of the total production of seagrass. Ogden et al (1973) consider Caribbean seagrass beds to be unique for the numbers of organisms which feed almost exclusively on seagrass and associated epiphytes. There are many references to grazing by fish and invertebrates on Thalassia testudinum (Randall, 1965: Ogden et al 1973, von Westernhagen, 1973), which is the common species of seagrass in the Caribbean, but few studies have been undertaken to identify grazers on the three species of seagrass under consideration in the present work. It is possible that the species of seagrass present may influence the extent of grazing.

Wahbeh and Mahasneh (1985) list the urchin, Tripneustes gratilla and the Rabbit Fish , Siganus rivulatus as the principal grazers in the Gulf of Aqaba. Parrotfish and Surgeon fish are listed for the Caribbean (Ogden, 1976). In many cases these are recorded as grazing on the epiphytes rather than the seagrass leaf. Basson et al (1977) record Green turtles as major seagrass consumers. The dugong (Dugong dugon) is a common inhabitant of seagrass beds around Bahrain. This large marine mammal feeds almost exclusively on seagrass (Heinsohn, 1981) and large tracts of the seagrass beds around Bahrain are frequently disturbed by dugong feeding patterns (Preen, pers. comm; Vousden, pers. obs.). These animals are non-selective and feed on any seagrass species present (Heinsohn, 1981). Areas which have been disturbed are very obvious and easily avoided when sampling seagrass biomass. More complex sampling procedures would have to be developed to include the possible effects of grazing alongside the more obvious effects of temperature and depth on seagrass distribution.

This study has estimated values for standing crop and biomass and compares these values to those of other authors (Tables 6.9 and 6.10). Jones et al (1987) give figures for the standing crop (leaf only) for tropical seagrass beds which range from 20g to 8.1 kg dry weight m^{-2} but note that the smaller species of seagrass such as are found in the Arabian Gulf would fall into the lower end of this range, the higher end being reserved for the larger species which are not recorded in the Arabian Gulf. Both Lipkin (1979) and Wahbeh (1980) give more precise figures relating to the species under consideration in this study. Lipkin (1979) shows that communities dominated by Halophila stipulacea have an average standing crop (dry weight) of 330 g m^{-2}, those dominated by H. ovalis have an average dry weight of 35 g m^{-2} and those dominated by Halodule uninervis have a standing crop of 230 g m^{-2} dry weight. Wahbeh gives dry weights for H. stipulacea of 260 g m^{-2}, for H. ovalis of 10 g m^{-2} and 400 g m^{-2} for H. uninervis. Average dry weight values from the present study (table 6.9) are all much lower than the findings of other authors although the latter have only addressed the standing crop (above-ground) portion so there are no comparisons for the root-rhizome portion. Basson et al (1977) records a higher standing crop of seagrass for the Arabian Gulf coastline of Saudi Arabia, but the figure falls within the maximum and minimum range recorded for this study. Basson also notes that the standing crop dry weight for areas of seagrass with 100% cover off the coast of South Yemen was between 100-400g m^{-2}.

McRoy and McMillan (1979) point out that research into seagrass productivity has mainly been confined to the larger species such as Zostera marina and Thalassia testudinum which can support standing crops of 5 kg dry weight m^{-2} and greater than 8kg dry weight m^{-2}. Smaller species such as Syringodium sp. and Halodule sp. support a seasonal maximum standing stock of less than 500 g m^{-2} dry weight with an average of 100-200 g m^{-2}.

Table 6.10 compares ash-free dry weight values from the present study with those of two other authors. Brouns (1987) measured mixed seagrass beds consisting of Thalassia hemprichii, Cymodocea serrulata, C. rotundata, Syringodium isoetifolium, Halodule uninervis and Halophila ovalis in Papua New Guinea. The total annual mean ash-free dry weight of the above-ground biomass was 100g m^{-2} and the below-ground biomass was 529g m-2 AFDW. the maximum standing crop value was 136g m^{-2} AFDW. These figures are considerably higher than values from the present study which reflects the presence of larger seagrass species in the Pacific such as T. hemprichii which can form very dense and widespread seagrass beds. Erftemeijer (1993) gives biomass data in ash-free dry weights for H. ovalis and H. uninervis at different sites studied in Sulawesi and separates the data into above-ground and below-ground biomass. For H. uninervis, the average annual ash-free dry weight of both leaf and root in the present study are lower but the maximum recorded values are higher than Erftemeijer (1993). For H. ovalis both the average and maximum leaf and root weights from the present study are higher. The figures by Erftemeijer (1993) for total above- and total below-ground biomass (and therefore total overall biomass) are much higher (4 to 5 times greater) but other species are included in this assessment such as Enhalus acoroides and Thalassia hemprichii. These seagrass species have much larger leaves and a denser root/rhizome network than Halophila or Halodule. Figures based on just these last two species give a total above-ground biomass of 39 g m^{-2}, a total below-ground biomass of 174.1 3 m^{-2} with an overall biomass of 213.1 g m^{-2}. This compares with similar figures from the present study of 13.52 g m^{-2} (above-ground), 120.2 g m^{-2} (below ground) and an overall biomass of 133.72 g m^{-2}. The biomass figures given by Erftemeijer (1984) are still higher but with a much smaller margin (around 1.5 times greater).

Table 6.10 shows the ash-free dry weights from the present study separated into summer and winter values. Both of the above-ground and below-ground biomass vary noticeably between the seasons so that biomass values are twice as high in the summer. The figures for the average summer ash-free dry weights are 26.13g m^{-2} above-ground, 166.16g m^{-2} below-ground and a total biomass of 192.29g m^{-2}. These figures compare very closely to the findings of Erftemeijer (1993) in a fully tropical region where annual temperatures at the study sites varied between 26.5° C and 32.5° C.

Basson et al (1977) estimate that Tarut Bay ,with an area of 175 km $^{-2}$, supports a dry weight of 22.4 million kg of leaves (22.4 x 10^3 tonnes) or 128 tonnes km^{-2}. They base this figure on an average of 128 g dry weight of seagrass m^{-2}. This compares with the figures from the present study which show an average leaf dry weight throughout the year of 32.9 g m^{-2} (tonnes km^{-2}) . This equates to 26.9 million kg of leaves (26.9 x 10^3 tonnes) for the total territorial sea area (the study area) of Bahrain which constitutes 3672 sq. km (see table 6.11).

The present study also provides the figures for the detrital component together with figures for living seagrass tissue. These are the broken-off and decaying sections of leaf and root that were also present in the sample. This component represents a substantial quantity of additional organic matter available within the seagrass beds. In the summer this figure equates to at least 325.9 tonnes km^{-2} ash-free dry weight of seagrass organic debris and at least 26.6 x 10^3 tonnes within the total study area (territorial waters). If the detrital component and living biomass are added together during the summer season then the overall ash-free dry weight of seagrass material available to herbivores, detritivores and for decomposition into basic nutrients reaches 518.2 tonnes km^{-2} or 42.3 x 10^3 tonnes throughout the study area at any one point in time. However, these figures are almost certainly higher than estimated as an unknown amount will have been lost to detritivores and general decomposition. This is also true of the estimates for living seagrass biomass as some percentage will have been taken by grazers.

Basson et al (1977) found that values for the energy content of seagrass leaves from a number of studies are very similar and show little variation from one species to another. They estimated the average energy value of seagrass leaves to be 13 kJ g^{-1} dry weight. The average annual dry weight of leaves in the present study amounts to 32.9 tonnes km^{-2} or 26.9 x 10^3 tonnes throughout the study area. Using the estimated values from Basson et al (1977) the total energy content for average annual standing crop of seagrass in Bahrain's waters is 4.27 x 10^8 kJ km^{-2} or 3.5 x 10^{11} kJ for the entire study area.

The present study reveals that figures for the ash-free dry weight of standing crop and overall biomass can double in the summer. The overall seagrass material available for grazing and decomposition in the summer season amounts to 518 tonnes km^{-2} (at any one moment in time) which is equivalent to 423,206 tonnes throughout the study area. These figures must be seen as somewhat conservative as they only account for the area of the territorial sea which was classified as having greater than 40% cover of seagrass (817 km^{-2} - see chapter 5). There is another 2855 km^{-2} of seabed which represents other habitat types including seagrass beds with a percentage cover of less than 40%. Whittaker (1975) lists net annual primary production values of between 200-1,500 g m^{-2} a^{-1} for temperate grasslands and 500-4,000 m^{-2} a^{-1} for algal beds, reefs and estuaries. The figures from the current study represent the average values per unit area for single standing samples of one type of plant available throughout the year rather than annual production. The annual production of the seagrass plant as a result of the turn-over of leaf material is estimated to be 2-4 times greater than the standing crop (Basson et al, 1977). Orth and Montfrans (1984) state that the presence of seagrass can increase the surface area of seabed available for colonisation by epiphytes or epibenthic diatoms by a factor of between 5 and 19. So clearly there is a higher potential for net primary productivity in a m^2 of seagrass bed than is represented just by mass of the seagrass plant present at any one moment. To attempt to calculate the net annual productivity of a unit area of seagrass bed is a much more complex exercise and beyond the objectives of this study.

SUMMARY

This study demonstrates some of the relationships between temperature, depth, salinity and seagrass species distribution in the waters around Bahrain. It confirms the presence of three species of seagrass in the waters around Bahrain. It further clarifies a number of uncertainties and contradictions which exist in the literature. By incorporating the findings of the subtidal study (chapter 4) it is now possible to define the distribution of the three species in the waters around Bahrain in relation to the physical factors studied as follows:

Halodule uninervis:

A predominantly shallow water species dominant between 3.0 - 7.5m. As water depth increases the numbers of leaves per area of seabed and the average length of the leaves are reduced. Root/rhizome biomass also declines with increasing depth. This species shows a large seasonal response in growth as a result of variations in water temperature. As temperatures rise from winter into summer, leaf length increases significantly, but not the number of leaves. As a result leaf biomass rises dramatically while root/rhizome biomass shows a slight but noticeable reduction. This species can be found throughout the salinity range experienced around Bahrain and displays no variation in biomass that can be related to salinity changes, although there is evidence of greater variability in leaf length as a result of higher salinities.

Halophila stipulacea:

Found at all depths studied (Intertidal to 14m), but tends to dominate in shallow waters (1.7 - 4m) and in deeper waters (>7m). Also found at a low biomass among dominant H. uninervis at intermediate depths. Increasing water depth results in a reduction in leaf number, but an increase in leaf length resulting in an overall increase in leaf biomass. Root/rhizome biomass is reduced with water depth. A seasonal increase in water temperature results in greater leaf and root/rhizome cover with an increase in both leaf length and leaf number. This species exhibits no inhibition in growth patterns as a result of variations in salinity.

Halophila ovalis:

Where this species is present it shows no statistically significant alterations in biomass as a result of changes in water depth. Seasonal increases in temperature result in an increase in leaf length and root biomass but not on such a large scale as for the other two species.. Highest biomass values are recorded at depths of >7m where this species may dominate over H. uninervis and H. stipulacea, but recorded percentage cover never exceeds 23%. H. ovalis shows some preference for lower salinity water, only reaching its highest levels of recorded biomass where salinities are < 46 ppt. At higher salinities a reduction in the number of leaves is likely with a tendency for leaf morphology to alter so that leaves become elongated and less oval, bearing a closer resemblance to H. stipulacea

Total seagrass biomass throughout Bahrain effectively doubles in the summer (table 6.10). Both H. uninervis and H. stipulacea reflect this summer increase with an approximate duplication of their overall biomass from winter to summer. H. ovalis triples its winter biomass values in the summer but this has little effect on the overall seasonal increase in seagrass biomass because of the relatively small presence by weight of H. ovalis compared to the other two species. The total living biomass of seagrass throughout the territorial waters of Bahrain averages approximately 12 x 10^4 tonnes AFDW (Ash-free dry weight) throughout the year. This rises in summer to c. 16 x 10^4 and falls in winter to c. 8.5 x 10^4.

SEAGRASS ASH-FREE WEIGHT DATA MATRIX

SITE NUMBER	COLUMNS (BIOLOGICAL/PHYSICAL MEASUREMENTS)											
	SEAGRASS COVER IN GRAMS PER SQUARE METRE							NUMBER OF SPECIES PRESENT	PHYSICAL VARIABLES			
(See table 6.1)	Detritus (All species)	*H. uninervis* Leaf	*H. uninervis* Root	*H. stipulacea* Leaf	*H. stipulacea* Root	*H. ovalis* Leaf	*H. ovalis* Root		Temp.	Depth	Mean Site Salinity	Mean Sector Salinity
1	0	13.22	86.35	0	0	0	0	1	23	5	45.1	44.3
1	0	24.13	128.22	0	0	0	0	1	23	5	45.1	44.3
2	0	7.67	38.38	11.26	7.05	1.11	1.30	3	21	7	48.9	46.3
2	0	3.59	6.47	15.84	16.08	2.75	3.39	3	21	7	48.9	46.3
2	0	0.90	4.64	9.21	9.29	0	0	2	21	7	48.9	46.3
2	0	0	0	8.77	24.38	0.22	0.97	2	21	7	48.9	46.3
2	37.07	0	0	10.05	3.01	2.96	0.88	2	33.5	7	48.9	46.3
2	36.60	3.11	30.01	12.25	6.16	0	0	2	33.5	7	48.9	46.3
2	40.05	4.49	22.44	14.70	20.58	0	0	2	33.5	7	48.9	46.3
2	0.06	7.34	21.82	7.31	5.79	0	0	2	33.5	7	48.9	46.3
2	40.45	5.25	84.65	9.88	3.08	0	0	2	33.5	7	48.9	46.3
2	37.11	6.46	2.16	0	0	0	0	1	33.5	7	48.9	46.3
2	57.82	5.32	54.52	0	0	1.00	1.21	2	33.5	7	48.9	46.3
2	39.86	10.39	21.11	0	0	0	0	1	33.5	7	48.9	46.3
2	4.11	0.20	7.11	0	0	0	0	1	31	7	48.9	46.3
2	40.89	0.83	10.79	10.64	6.45	0	0	2	31	7	48.9	46.3
3	15.75	0	0	0	0	1.57	0.86	1	19.5	9	48.7	46.3
3	24.40	0	0	0	0	0.64	0.57	1	19.5	9	48.7	46.3
3	18.36	0	0	0.654308	0.999146	0	0	1	19.5	9	48.7	46.3
3	38.13	0	0	0	0	2.79	4.99	1	19.5	9	48.7	46.3
3	28.89	0	0	0.29	0.17	1.84	1.79	2	19.5	9	48.7	46.3
4	543.35	25.64	296.65	18.97	28.50	0.89	1.31	3	37	0.5	52.1	50.5
4	565.43	16.07	331.37	13.38	14.85	2.35	1.33	3	37	0.5	52.1	50.5
4	0	20.09	203.66	20.83	28.36	11.33	20.07	3	37	0.5	52.1	50.5
4	31.36	10.01	100.68	0	1.28	0	0	2	21.5	0.5	52.1	50.5
4	528.57	15.02	184.12	5.23	9.17	3.19	4.48	3	21.5	0.5	52.1	50.5
4	187.62	14.20	124.27	7.54	9.61	4.47	14.61	3	21.5	0.5	52.1	50.5
4	470.40	19.04	314.62	0	0	0	0	1	21.5	0.5	52.1	50.5
4	219.33	17.26	264.14	0	0	0	0	1	21.5	0.5	52.1	50.5
4	847.44	10.53	270.99	0	0	0	0	1	13.5	0.5	52.1	50.5
4	628.56	3.26	152.52	0.97	2.54	0	0	2	13.5	0.5	52.1	50.5
4	714.65	15.26	343.84	0	0	0.45	2.44	1	13.5	0.5	52.1	50.5
4	811.42	0.40	206.45	0	0	0	0	1	13.5	0.5	52.1	50.5

(Sector ppt = Mean salinity for the sector in which that site lies - See figure 2.3)

TABLE 6.1

SEAGRASS ASH-FREE WEIGHT DATA MATRIX

SITE NUMBER (See table 6.1)	COLUMNS (BIOLOGICAL/PHYSICAL MEASUREMENTS)											
	SEAGRASS COVER IN GRAMS PER SQUARE METRE							NUMBER OF SPECIES PRESENT	PHYSICAL VARIABLES			
	Detritus (All species)	*H. uninervis* Leaf	*H. uninervis* Root	*H. stipulacea* Leaf	*H. stipulacea* Root	*H. ovalis* Leaf	*H. ovalis* Root		Temp.	Depth	Mean Site Salinity	Mean Sector Salinity
5	817.32	20.52	370.90	0	0	0	0	1	35	1	51.5	50.5
5	749.07	0	0	25.01	34.28	0	0	1	35	1	51.5	50.5
5	429.63	0	0	7.98	16.21	0	0	1	35	1	51.5	50.5
5	672.88	53.80	452.84	0	0	0.72	1.14	2	35	1	51.5	50.5
5	330.45	71.97	476.63	2.95	1.79	3.64	2.25	3	35	1	51.5	50.5
5	130.91	7.50	117.02	19.29	34.16	0	0	2	35	1	51.5	50.5
5	399.07	30.67	282.40	16.35	20.95	4.05	4.06	3	35	1	51.5	50.5
5	557.51	28.03	282.61	9.55	9.94	1.74	7.03	3	35	1	51.5	50.5
5	401.50	11.16	288.61	0	0	0	0	1	13.5	1	51.5	50.5
5	502.30	8.58	245.52	0	0	0	0	1	13.5	1	51.5	50.5
5	644.35	13.33	202.64	0	0	0	0	1	13.5	1	51.5	50.5
5	282.92	35.09	298.68	0	0	0	0	1	13.5	1	51.5	50.5
6	393.05	18.73	94.22	0	0	10.42	6.3	2	30.5	3.5	52.6	50.5
6	362.15	15.81	98.26	5.94	1.6	0	0	2	30.5	3.5	52.6	50.5
6	362.16	29.02	89.3	0	0	0.8	18.01	2	30.5	3.5	52.6	50.5
6	279.92	17.3	159.76	0	0	0	0	1	30.5	3.5	52.6	50.5
6	303.95	16.12	51.17	0	0	0	0	1	30.5	3.5	52.6	50.5
6	427.63	23.22	106.2	0	0	4.72	3.07	2	30.5	3.5	52.6	50.5
6	336.42	13.17	115.3	0	0	0	0	1	30.5	3.5	52.6	50.5
6	279.51	16.02	176.82	0	0	0	0	1	30.5	3.5	52.6	50.5
7	77.27	15.08	27.92	11.15	7.41	0	0	2	32.5	5	56.2	50.5
7	*58.03*	*10.51*	*44.99*	*15.51*	*6.16*	0	0	2	32.5	5	56.2	50.5
7	73.87	28.52	73.16	2.97	0.41	0	0	2	32.5	5	56.2	50.5
7	116.28	7.00	44.02	30.81	19.43	0	0	2	32.5	5	56.2	50.5
7	74.41	3.59	30.55	0	0	0	0	1	17	5	56.2	50.5
7	63.72	3.51	25.57	0	0	0	0	1	17	5	56.2	50.5
7	57.02	2.44	16.63	0	0	0	0	1	17	5	56.2	50.5
7	73.19	0.33	9.84	0	0	0	0	1	17	5	56.2	50.5
7	68.60	0.64	7.22	3.20	2.34	0	0	2	17	5	56.2	50.5
7	53.72	1.60	16.73	0	0	0	0	1	17	5	56.2	50.5
7	63.50	1.39	29.95	0	0	0	0	1	17	5	56.2	50.5
7	50.90	0.29	14.06	0	0	0	0	1	17	5	56.2	50.5
8	0	0	0	7.61	6.22	0.96	0.99	2	20.5	7	54.0	50.5
8	0	0	0	14.27	19.25	0.33	0.57	2	20.5	7	54.0	50.5
8	0	0	0	0.67	0.35	0	0	1	20.5	7	54.0	50.5
8	0	0	0	6.18	6.56	0	0	1	20.5	7	54.0	50.5
9	2.11	0	0	2.44	4.20	0	0	1	32	10	57.8	50.5

(Sector ppt = Mean salinity for the sector in which that site lies - see figure 2.3)

TABLE 6.1 (Cont.d)

SEAGRASS ASH-FREE WEIGHT DATA MATRIX

SITE NUMBER (See table 6.1)	COLUMNS (BIOLOGICAL/PHYSICAL MEASUREMENTS)											
	SEAGRASS COVER IN GRAMS PER SQUARE METRE							NUMBER OF SPECIES PRESENT	PHYSICAL VARIABLES			
	Detritus (All species)	*H. uninervis* Leaf	*H. uninervis* Root	*H. stipulacea* Leaf	*H. stipulacea* Root	*H. ovalis* Leaf	*H. ovalis* Root		Temp.	Depth	Mean Site Salinity	Mean Sector Salinity
10	58.51	0	0	3.03	2.82	15.28	17.09	2	31.5	8	58.5	57.3
10	50.55	0	0	22.19	13.78	0.24	0.33	2	31.5	8	58.5	57.3
10	20.13	0	0	12.53	5.36	0	0	1	31.5	8	58.5	57.3
10	68.85	0	0	16.53	12.79	0	0	1	31.5	8	58.5	57.3
11	23.18	1.81	14.12	2.58	1.85	0.79	2.47	3	32.5	10	59.0	57.3
11	33.87	2.87	8.15	10.63	6.78	0	0	2	32.5	10	59.0	57.3
11	25.65	0.27	7.48	12.10	9.09	0	0	2	32.5	10	59.0	57.3
11	27.74	1.15	15.78	1.99	2.82	1.34	0.95	3	32.5	10	59.0	57.3
11	34.51	1.88	5.69	1.05	1.78	3.86	2.48	3	32.5	10	59.0	57.3
11	25.73	0.53	2.32	2.44	1.12	2.61	6.78	3	32.5	10	59.0	57.3
11	44.05	0.95	4.15	1.23	2.66	1.47	3.76	3	32.5	10	59.0	57.3
11	33.67	0.47	14.76	15.41	6.76	0	0	2	32.5	10	59.0	57.3
11	0.23	0	0	0.04	0.08	0	0	1	15	10	59.0	57.3
11	3.45	0	0	0.11	0.52	0	0	1	15	10	59.0	57.3
11	0.18	0	0	0.16	0.40	0	0	1	15	10	59.0	57.3
12	0	0	0	1.69	0.80	1.24	0.68	2	20.5	12.5	54.4	57.3
12	0	0	0	2.64	0.95	1.72	2.90	2	20.5	12.5	54.4	57.3
12	0	0	0	0.64	1.51	0	0	1	20.5	12.5	54.4	57.3
12	0	0	0	8.69	4.14	0	0	1	20.5	12.5	54.4	57.3
13	137.67	8.07	25.93	11.64	5.26	0	0	2	31	4.5	58.5	56.3
13	162.47	3.17	0.46	0	0	0	0	1	31	4.5	58.5	56.3
13	82.48	11.80	36.08	0	0	0	0	1	31	4.5	58.5	56.3
13	85.57	1.74	16.42	0	0	0	0	1	31	4.5	58.5	56.3
13	114.17	3.58	12.07	0	0	0	0	1	31	4.5	58.5	56.3
13	111.20	8.33	32.99	0	0	0	0	1	31	4.5	58.5	56.3
13	103.63	22.82	50.64	0	0	0	0	1	31	4.5	58.5	56.3
13	131.91	5.38	18.29	0	0	0	0	1	31	4.5	58.5	56.3
13	124.46	11.77	39.28	0	0	0	0	1	30.5	4.5	58.5	56.3
13	15.01	4.42	37.35	0	0	0	0	1	30.5	4.5	58.5	56.3
13	15.09	12.59	72.87	0	0	0	0	1	30.5	4.5	58.5	56.3
13	195.36	4.31	42.60	0	0	0	0	1	18.5	4.5	58.5	56.3
13	259.35	9.60	77.97	0	0	0	0	1	18.5	4.5	58.5	56.3
13	102.02	1.87	33.04	0	0	0	0	1	18.5	4.5	58.5	56.3
13	157.48	2.33	31.92	0	0	0	0	1	18.5	4.5	58.5	56.3
13	117.07	0.78	44.19	0	0	0	0	1	18.5	4.5	58.5	56.3
13	245.09	7.22	63.54	0	0	0	0	1	18.5	4.5	58.5	56.3
13	132.95	6.20	43.72	0	0	0	0	1	18.5	4.5	58.5	56.3
14	7.09	3.25	16.20	0	0	5.06	3.63	2	31	4.5	52.1	50.2

(Sector ppt = Mean salinity for the sector in which that site lies - see figure 2.3)

TABLE 6.1 (Cont.d)

CORRELATION MATRIX SHOWING SIGNIFICANT CORRELATIONS BETWEEN VARIABLES AT DETAILED SEAGRASS STUDY SITES

RESULTS OF CORRELATION MATRIX
(All seagrass data)

Degrees of freedom = 106
Where r > 0.254 = 99% probability of correlation

	VARIABLE		CORRELATED VARIABLE (r =) 1	2	3	4	5	6	7	8	9	10	11
1	Detritus												
2	*H. uninervis*	leaf	0.462										
3	*H. uninervis*	root	0.749	0.789									
4	*H. stipulacea*	leaf											
5	*H. stipulacea*	root				0.862							
6	*H. ovalis*	leaf											
7	*H. ovalis*	root						0.772					
8	Number of species					0.473	0.44	0.452	0.462				
9	Temperature			0.272		0.433	0.363			0.414			
10	Depth		-0.718	-0.546	-0.674								
11	Salinity												

TABLE 6.2

PRINCIPAL COMPONENTS FACTORING FOR VARIABLES AT DETAILED SEAGRASS STUDY SITES

PRINCIPAL COMPONENT FACTORING
(Using Equimax Rotation)

	A. Three species of seagrass leaf, detritus, temperature, depth and salinity			B. Three species of seagrass root, detritus, temperature, depth and salinity		
FACTORS	1	2	TOTAL	1	2	TOTAL
Factor variance	32.28%	22.73%	55.01%	36.26%	21.58%	57.83%
Principal variables	Depth -78.73%	Temperature 70.53%		Detritus 80.84%	*H. stipulacea* root 59.03%	
	Detritus 70.87%	*H. stipulacea* leaf 53.02%		*H. uninervis* root 79.83%	Temperature 56.87%	
	H. uninervis leaf 60.26%			Depth -77.48%		

Figures in brackets represent total percentage variance for that variable accounted for by that factor.
E.G. 78.73% of the overall variance in depth within the data set represented by A. has been accounted for by Factor 1.

TABLE 6.3

CANONICAL CORRELATION ANALYSIS OF DETAILED SEAGRASS STUDY SITES

Correlations between presence of species (by weight) and physical variables

ANALYSIS	No.	EIGENVALUE	CORRELATION	CHI-SQ.	D.F.	SIGNIFICANCE	GROUP 1 VARIABLES	GROUP 2 VARIABLES
A. Leaf and root for all 3 spp. and detritus against number of seagrass species present, temperature, depth and salinity	1	0.6579	0.8111	197.9547	28	P=0.0000	Ul(0.54), Ur(0.02), Sl(0.1), Sr(0.28), Ol(0.07),)Or(0.11), Detritus(0.45)	No. Spp.(0.44), Temp.(0.25), Depth(-0.85), Salinity(-0.06)
	2	0.4901	0.7000	89.8294	18	P=0.0000	Ul(0.33), Ur(-0.26), Sl(0.77), Sr(-0.17), Ol(0.36), Or(0.09), Detritus(-0.49)	No. Spp.(0.54), Temp.(0.42), Depth(0.52), Salinity(-0.02)
	3	0.1663	0.4078	21.7428	10	P=0.0165	Ul(-1.41), Ur(1.84), Sl(-0.28), Sr(0.17), Ol(-0.04), Or(0.61), Detritus(-0.77)	No. Spp.(0.79), Temp.(-0.96) Depth(0.07), Salinity(-0.20)
B. Leaf presence for all 3 spp. against temperature, depth and salinity	1	0.4490	0.6701	82.8315	9	P=0.0000	Ul(0.91), Sl(0.43), Ol(0.04)	Temp.(0.70), Depth(-0.69), Salinity(-0.17)
	2	0.1845	0.4296	21.2352	4	P=0.0003	Ul(-0.44), Sl(0.78), Ol(0.40)	Temp.(0.67), Depth(0.72), Salinity(-0.15)
C. Root presence for all 3 spp. against temperature, depth and saliity	1	0.4831	0.6950	85.9983	9	P=0.0000	Ur(0.98), Sr(0.19), Or(-0.03)	Temp.(0.18), Depth(-0.93), Salinity(-0.20)
	2	0.1569	0.3961	17.7786	4	P=0.0014	Ur(-0.24), Sr(0.88), Or(0.32)	Temp.(0.92), Depth(0.25), Salinity(-0.30)
D. Detritus presence and number of seagrass species present against temperature, depth and salinity	1	0.5293	0.7275	99.5415	6	P=0.0000	Detritus(0.98), No.Spp.(-0.20)	Temp.(-0.10), Depth(-1.0), Salinity(0.05)
	2	0.1842	0.4292	21.2533	2	P=0.0000	Detritus(0.21), No.Spp.(0.98)	Temp.(0.93), Depth(-0.09), Salinity(-0.34)
E. Leaf and root presence for all 3 Spp. against temperature, depth and salinity	1	0.5141	0.7170	123.9426	18	P=0.0000	Ul(0.31), Ur(0.68), Sl(-0.32), Sr(0.50), Ol(-0.12), Or(0.02)	Temp.(0.22), Depth(-0.93), Salinity(-0.20)
	2	0.3798	0.6163	50.5205	10	P=0.0000	Ul(1.01), Ur(-0.92), Sl(0.77), Sr(-0.08), Ol(0.35), Or(-0.16)	Temp.(0.97), Depth(0.21), Salinity(-0.08)

U = uninervis l = leaf
S = stipulacea r = root
O = ovalis

TABLE 6.4

LEAF NUMBER AND LENGTH DATA MATRIX

SITE NUMBER	SAMPLE NUMBER	*H. uninervis* Leaf count	*H. uninervis* Leaf mean length	*H. uninervis* Leaf std length	*H. stipulacea* Leaf Count	*H. stipulacea* Leaf mean length	*H. stipulacea* Leaf std length	*H. ovalis* Leaf count	*H. ovalis* Leaf mean length	*H. ovalis* Leaf std length	Number of seagrass species	TEMP DEGREES CELSIUS	DEPTH METRES	MEAN SITE SALINITY PPT	MEAN SECTOR SALINITY (See figure 2.3)
2	1	0	0	0	18	41.4	4.8	6	15.0	2.9	2	33.5	7	48.9	46.3
2	2	14	69.3	13.9	11	58.2	9.8	0	0	0	2	33.5	7	48.9	46.3
2	3	12	60.0	17.2	11	35.5	14.4	0	0	0	2	33.5	7	48.9	46.3
2	4	11	80.5	29.3	6	35.0	11.2	0	0	0	2	33.5	7	48.9	46.3
2	5	11	55.6	22.0	12	43.8	15.3	0	0	0	2	33.5	7	48.9	46.3
2	6	11	69.1	16.1	0	0	0	0	0	0	1	33.5	7	48.9	46.3
2	7	11	55.5	12.7	0	0	0	7	32.1	3.6	2	33.5	7	48.9	46.3
2	8	15	81.0	23.5	0	0	0	0	0	0	1	33.5	7	48.9	46.3
2	1	0	0	0	24	36.0	9.2	0	0	0	1	31	7	48.9	46.3
2	2	12	68.8	14.6	0	0	0	0	0	0	1	31	7	48.9	46.3
3	1	0	0	0	0	0	0	8	13.1	2.4	1	19.5	9	48.7	46.3
3	2	0	0	0	0	0	0	21	15.5	3.8	1	19.5	9	48.7	46.3
3	3	0	0	0	18	15.3	1.2	0	0	0	1	19.5	9	48.7	46.3
3	4	0	0	0	0	0	0	8	15.0	3.5	1	19.5	9	48.7	46.3
3	5	0	0	0	5	14.0	2.0	12	15.4	2.5	2	19.5	9	48.7	46.3
4	1	33	81.1	21.4	40	56.6	9.6	4	36.3	5.5	3	37	5	52.1	50.5
4	2	22	79.4	25.6	22	43.0	14.1	9	25.6	8.6	3	37	5	52.1	50.5
4	3	17	57.4	15.5	17	37.1	8.2	14	26.1	7.6	3	37	5	52.1	50.5
4	1	26	56.9	18.9	0	0	0	0	0	0	1	21.5	5	52.1	50.5
4	2	42	30.8	10.1	0	0	0	0	0	0	1	21.5	5	52.1	50.5
4	3	35	64.6	19.6	21	30.0	9.0	13	16.5	7.2	3	21.5	5	52.1	50.5
4	4	42	59.5	15.8	0	0	0	0	0	0	1	21.5	5	52.1	50.5
4	5	0	0	0	24	23.5	8.6	0	0	0	1	21.5	5	52.1	50.5
4	1	5	23.0	5.1	0	0	0	0	0	0	1	13.5	5	52.1	50.5
4	2	14	22.1	5.3	0	0	0	0	0	0	1	13.5	5	52.1	50.5
4	3	19	38.7	11.3	0	0	0	12	15.4	4.8	2	13.5	5	52.1	50.5
4	4	16	36.6	14.2	10	20.5	5.7	0	0	0	2	13.5	5	52.1	50.5
5	1	25	73.6	13.8	0	0	0	0	0	0	1	35	1	51.5	50.5
5	2	15	58.3	13.7	21	36.5	12.0	0	0	0	2	35	1	51.5	50.5
5	3	14	67.1	18.8	15	30.7	7.0	0	0	0	2	35	1	51.5	50.5

STD Length = Standard Deviation of Average Leaf length

TABLE 6.5

LEAF NUMBER AND LENGTH DATA MATRIX

SITE NUMBER	SAMPLE NUMBER	*H. uninervis* Leaf count	*H. uninervis* Leaf mean length	*H. uninervis* Leaf std length	*H. stipulacea* Leaf count	*H. stipulacea* Leaf mean length	*H. stipulacea* Leaf std length	*H. ovalis* Leaf count	*H. ovalis* Leaf mean length	*H. ovalis* Leaf std length	Number of seagrass species	TEMP DEGREES CELSIUS	DEPTH METRES	MEAN SITE SALINITY PPT	MEAN SECTOR SALINITY (See figure 2.3)
5	4	19	60.3	17.6	0	0	0	4	30.0	5.0	2	35	1	51.5	50.5
5	5	52	63.1	17.7	12	33.3	6.9	11	21.8	3.9	3	35	1	51.5	50.5
5	6	51	47.7	17.8	35	22.7	15.0	0	0	0	2	35	1	51.5	50.5
5	7	41	53.2	25.2	24	35.2	8.8	11	26.4	3.1	3	35	1	51.5	50.5
5	8	34	67.9	15.3	31	28.4	10.0	13	19.2	6.5	3	35	1	51.5	50.5
5	1	51	34.9	9.7	0	0	0	0	0	0	1	13.5	1	51.5	50.5
5	2	48	60.9	12.3	0	0	0	0	0	0	1	13.5	1	51.5	50.5
5	3	28	40.0	10.7	0	0	0	0	0	0	1	13.5	1	51.5	50.5
5	4	24	35.8	12.9	0	0	0	0	0	0	1	13.5	1	51.5	50.5
6	1	39	48.5	23.4	0	0	0	0	0	0	1	30.5	3.5	52.6	50.5
6	2	22	61.7	30.5	8	33.5	9.3	0	0	0	2	30.5	3.5	52.6	50.5
6	3	74	56.8	26.6	0	0	0	2	30.0	5.0	2	30.5	3.5	52.6	50.5
6	4	37	66.6	38.3	0	0	0	0	0	0	1	30.5	3.5	52.6	50.5
6	5	45	67.0	30.7	0	0	0	0	0	0	1	30.5	3.5	52.6	50.5
6	6	54	62.0	25.3	0	0	0	9	34.0	4.6	2	30.5	3.5	52.6	50.5
6	7	30	60.8	31.1	6	24.2	8.4	0	0	0	2	30.5	3.5	52.6	50.5
6	8	24	46.8	19.3	0	0	0	20	27.2	5.5	2	30.5	3.5	52.6	50.5
7	1	51	80.3	32.8	4	4.9	0.3	0	0	0	2	32.5	5	56.2	50.5
7	2	28	75.4	25.5	11	29.9	12.3	0	0	0	2	32.5	5	56.2	50.5
7	3	27	65.0	25.1	24	40.3	13.7	0	0	0	2	32.5	5	56.2	50.5
7	4	13	53.7	25.3	29	45.7	9.9	0	0	0	2	32.5	5	56.2	50.5
7	1	14	53.2	9.6	0	0	0	0	0	0	1	17	5	56.2	50.5
7	2	10	35.5	12.3	0	0	0	0	0	0	1	17	5	56.2	50.5
7	3	13	38.9	23.1	0	0	0	0	0	0	1	17	5	56.2	50.5
7	4	3	10.0	4.1	0	0	0	0	0	0	1	17	5	56.2	50.5
7	5	4	41.3	5.5	0	0	0	0	0	0	1	17	5	56.2	50.5
7	6	10	75.0	13.8	0	0	0	0	0	0	1	17	5	56.2	50.5
7	7	7	56.4	9.9	11	33.2	10.5	0	0	0	2	17	5	56.2	50.5
7	8	6	43.3	15.2	0	0	0	0	0	0	1	17	5	56.2	50.5
10	1	0	0	0	26	38.1	7.9	0	0	0	1	31.5	8	58.5	57.3
10	2	0	0	0	0	0	0	16	37.2	8.1	1	31.5	8	58.5	57.3

STD Length = Standard Deviation of Average Leaf Length

TABLE 6.5 (Cont.d)

LEAF NUMBER AND LENGTH DATA MATRIX

SITE NUMBER	SAMPLE NUMBER	*H. uninervis* Leaf count	*H. uninervis* Leaf mean length	*H. uninervis* Leaf std length	*H. stipulacea* Leaf count	*H. stipulacea* Leaf mean length	*H. stipulacea* Leaf std length	*H. ovalis* Leaf count	*H. ovalis* Leaf mean length	*H. ovalis* Leaf std length	Number of seagrass species	TEMP DEGREES CELSIUS	DEPTH METRES	MEAN SITE SALINITY PPT	MEAN SECTOR SALINITY (See figure 2.3)
10	3	0	0	0	29	34.0	13.6	0	0	0	1	31.5	8	58.5	57.3
10	4	4	62.5	55.9	31	42.9	10.1	2	14.0	1.0	3	31.5	8	58.5	57.3
11	1	7	72.1	8.0	5	39.0	3.7	3	30.0	4.1	3	32.5	10	58	57.3
11	2	9	49.4	18.6	24	44.2	11.4	0	0	0	2	32.5	10	58	57.3
11	3	7	61.4	14.6	13	37.7	9.3	0	0	0	2	32.5	10	58	57.3
11	4	4	47.5	18.2	6	47.5	10.3	6	23.3	4.7	3	32.5	10	58	57.3
11	5	4	47.5	13.5	4	47.5	10.3	7	32.1	5.3	3	32.5	10	58	57.3
11	6	1	30.0	0	6	42.5	12.5	5	34.0	4.9	3	32.5	10	58	57.3
11	7	3	46.7	2.4	3	46.7	6.2	6	35.0	5.0	3	32.5	10	58	57.3
11	8	5	44.0	11.6	12	41.3	7.9	6	40.0	4.1	3	32.5	10	58	57.3
11	1	0	0	0	3	10.0	4.1	0	0	0	1	15	10	58	57.3
11	2	0	0	0	1	13.0	0	0	0	0	1	15	10	58	57.3
13	1	32	50.0	27.3	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	2	20	48.8	27.8	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	4	12	53.3	26.1	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	5	17	67.1	29.3	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	6	39	64.5	29.0	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	7	54	63.3	25.3	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	8	66	73.8	30.5	0	0	0	0	0	0	1	31	4.5	58.3	56.3
13	1	24	46.0	15.2	0	0	0	0	0	0	1	30.5	4.5	58.3	56.3
13	2	36	63.6	14.8	0	0	0	0	0	0	1	30.5	4.5	58.3	56.3
13	1	15	44.0	16.3	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	2	19	54.2	19.2	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	3	16	56.9	18.4	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	4	20	68.5	27.6	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	5	19	58.2	23.7	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	6	12	35.4	9.9	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
13	7	11	27.3	9.1	0	0	0	0	0	0	1	18.5	4.5	58.3	56.3
14	1	14	56.8	13.8	0	0	0	18	24.2	4.8	2	31	4.5	52.1	50.2

STD Length = Standard Deviation of Average Leaf Length

TABLE 6.5 (Cont.d)

CORRELATION MATRIX SHOWING SIGNIFICANT CORRELATIONS BETWEEN LEAF LENGTH, LEAF NUMBER AND PHYSICAL VARIABLES AT DETAILED SEAGRASS STUDY SITES

(All seagrass leaf length and leaf number data)

Degrees of freedom = 88
Where r > 0.267 = 99% probability

	VARIABLE	MEASUREMENT	CORRELATED VARIABLE 1	2	3	4	5	6	7	8	9	10	11	12	13
1.	*H. uninervis*	leaf number													
2.	*H. uninervis*	leaf length	0.521												
3.	*H. uninervis*	std of leaf length	0.533	0.752											
4.	*H. stipulacea*	leaf number													
5.	*H. stipulacea*	leaf length				0.765									
6.	*H.stipulacea*	std of leaf length				0.795	0.902								
7.	*H. ovalis*	leaf number													
8.	*H. ovalis*	leaf length							0.731						
9.	*H. ovalis*	std of leaf length					0.272		0.833	0.909					
10.	Number of seagrass species			0.317		0.526	0.757	0.661	0.461	0.689	0.661				
11.	Temperature			0.441	0.380	0.432	0.519	0.499		0.368	0.319	0.528			
12.	Depth		-0.641	-0.385	-0.362		0.333								
13.	Salinity														

TABLE 6.6

PRINCIPAL COMPONENTS FACTORING FOR SEAGRASS LEAF NUMBER AND LENGTH VARIABLES AT DETAILED STUDY SITES

PRINCIPAL COMPONENTS FACTORING (Using Equimax Rotation)												
	A. Number of leaves for each species, temperature, depth and salinity				B. Leaf length for each species, temperature, depth and salinity				C. Standard Deviation in leaf length for each species, temperature, depth and salinity			
FACTORS	1	2	3	TOTAL	1	2	3	TOTAL	1	2	3	TOTAL
Factor Variance	28.01%	25.73%	18.89%	72.64%	32.74%	25.38%	17.15%	75.27%	29.57%	24.80%	18.18%	72.54%
Principal variables	*H. uninervis* -81.37%	*H. stipulacea* 67.76%	*H. ovalis* -56.53%		*H. stipulacea* 65.95%	*H. uninervis* 77.11%	Salinity 96.40%		*H. stipulacea* 59.73%	*H. uninervis* -64.93%	Salinity 85.42%	
	Depth 80.68%	Temperature 73.62%	Salinity 66.19%		*H. ovalis* 45.69%	Depth -54.29%			Temperature 75.22%	Depth 65.94%		
					Temperature 60.76%							

TABLE 6.7

CANONICAL CORRELATION ANALYSIS OF SEAGRASS LEAF NUMBER AND LENGTH DATA FROM DETAILED STUDY SITES

ANALYSIS	No.	EIGEN VALUE	CORREL.	CHI-SQ.	D.F.	SIGNIF. (P=)	GROUP 1 VARIABLES AND COEFFICIENTS	GROUP 2 VARIABLES AND COEFFICIENTS
A. Leaf number, length and standard deviation in length for each species against number of species, temperature, depth and salinity	1	0.9370	0.9680	317.8635	3	0.0000	leaf number *uninervis* (0.03), leaf length *uninervis* (0.22), leaf std *uninervis* (0.12), leaf number *stipulacea* (-0.03), leaf length *stipulacea* (0.53), leaf std *stipulacea* (0.16), leaf number *ovalis* (0.14), leaf length *ovalis* (0.46), leaf std *ovalis* (-0.02),	Number of species(0.84) Temperature(0.25) Depth(0.06) Salinity(0.00)
	2	0.5849	0.7648	91.2426	24	0.0000	leaf number *uninervis* (0.57), leaf length *uninervis* (0.49), leaf std *uninervis* (-0.09), leaf number *stipulacea* (0.57), leaf length *stipulacea* (-0.77), leaf std *stipulacea* (0.24), leaf number *ovalis* (0.13), leaf length *ovalis* (-0.04), leaf std *ovalis* (0.11),	Number of species(-0.07) Temperature(0.36) Depth(-0.95) Salinity(0.04)
	3	0.1761	0.4197	19.1852	14	0.1580	leaf number *uninervis* (-0.36), leaf length *uninervis* (-0.36), leaf std *uninervis* (0.92), leaf number *stipulacea* (-0.10), leaf length *stipulacea* (0.04), leaf std *stipulacea* (-0.15), leaf number *ovalis* (-1.14), leaf length *ovalis* (0.71), leaf std *ovalis* (-0.10),	Number of species(-0.36) Temperature(0.54) Depth(0.10) Salinity(0.87)
B. Leaf number, length and standard deviation in length for each species against temperature, depth and salinity	1	0.5930	0.7700	144.3955	27	0.0000	leaf number *uninervis* (0.50), leaf length *uninervis* (0.54), leaf std *uninervis* (0.00), leaf number *stipulacea* (0.55), leaf length *stipulacea* (-0.58), leaf std *stipulacea* (0.29), leaf number *ovalis* (0.15), leaf length *ovalis* (0.16), leaf std *ovalis* (-0.18),	Temperature(0.59) Depth(-0.83) Salinity(0.04)
	2	0.4994	0.7067	70.4940	16	0.0000	leaf number *uninervis* (-0.33), leaf length *uninervis* (0.06), leaf std *uninervis* (0.33), leaf number *stipulacea* (-0.14), leaf length *stipulacea* (0.65), leaf std *stipulacea* (0.10), leaf number *ovalis* (0.00), leaf length *ovalis* (0.69), leaf std *ovalis* (-0.8),	Temperature(0.81) Depth(0.56) Salinity(0.04)
	3	0.1474	0.3839	13.292	7	0.0658	leaf number *uninervis* (-0.19), leaf length *uninervis* (-0.53), leaf std *uninervis* (0.87), leaf number *stipulacea* (-0.21), leaf length *stipulacea* (-0.06), leaf std *stipulacea* (-0.28), leaf number *ovalis* (-1.36) leaf length *ovalis* (0.42), leaf std *ovalis* (0.59),	Temperature(-0.01) Depth(-0.09) Salinity(1.00)
C. Leaf number for each species against temperature, depth and salinity	1	0.4826	0.6947	81.1167	9	0.0000	leaf number uninervis (0.98), leaf number stipulacea (0.32), leaf number ovalis (-0.01),	Temperature(0.47) Depth(-0.91) Salinity(-0.05)
	2	0.2299	0.4794	24.9093	4	0.0001	leaf number uninervis (-0.17), leaf number stipulacea (0.79), leaf number ovalis (0.52),	Temperature(0.80) Depth(0.42) Salinity(-0.42)
	3	0.0283	0.1681	2.4951	1	0.1142	leaf number uninervis (-0.18), leaf number stipulacea (0.54), leaf number ovalis (-0.86),	Temperature(0.38) Depth(0.13) Salinity(0.91)

TABLE 6.8

CANONICAL CORRELATION ANALYSIS OF SEAGRASS LEAF NUMBER AND LENGTH DATA FROM DETAILED STUDY SITES

ANALYSIS	No.	EIGEN VALUE	CORREL.	CHI-SQ.	D.F.	SIGNIF. (P=)	GROUP 1 VARIABLES AND COEFFICIENTS	GROUP 2 VARIABLES AND COEFFICIENTS
D. Leaf length for each species against temperature, depth and salinity	1	0.4819	0.6942	88.2017	9	0.0000	Leaf length uninervis(0.52) Leaf length stipulacea(0.63) Leaf length ovalis(0.37)	Temperature(0.99) Depth(0.10) Salinity(0.01)
	2	0.3117	0.5583	32.1377	4	0.0000	Leaf length uninervis(-0.86) Leaf length stipulacea(0.50) Leaf length ovalis(0.18)	Temperature(-0.14) Depth(0.99) Salinity-0.23
E. Standard deviation in leaf length for each species against temperature, depth and salinity	1	0.4559	0.6752	74.4402	9	0.0000	Standard deviation in leaf length uninervis(0.67) Standard deviation in leaf length stipulacea(0.56) Standard deviation in leaf length ovalis(0.40)	Temperature(0.99) Depth(-0.16) Salinity(0.08)
	2	0.2291	0.4787	22.5323	4	0.0002	Standard deviation in leaf length uninervis(-0.75) Standard deviation in leaf length stipulacea(0.55) Standard deviation in leaf length ovalis(0.29)	Temperature(0.13) Depth(0.91) Salinity(-0.48)
F. Leaf number, length and standard deviation in length for each species against temperature	1	0.5276	0.7263	62.6127	9	0.0000	Leaf number uninervis(0.04), leaf length uninervis(0.38), leaf std. uninervis(0.24), leaf number stipulacea(0.22), leaf length stipulacea(0.18), leaf std stipulacea(0.26), leaf number ovalis(0.12), leaf length ovalis(0.64), leaf std ovalis(-0.35)	Temperature(1)
G. Leaf number, length and standard deviation in length for each species against depth	1	0.5605	0.7487	68.6477	9	0.0000	Leaf number uninervis(-0.60), leaf length uninervis(-0.42), leaf std. uninervis(0.19), leaf number stipulacea(-0.53), leaf length stipulacea(0.84), leaf std stipulacea(-0.18), leaf number ovalis(-0.14), leaf length ovalis(0.25), leaf std ovalis(-0.00)	Depth(1)
H. Leaf number, length and standard deviation in length for each species against salinity	1	0.1510	0.3886	13.6715	9	0.1345	Leaf number uninervis(-0.30), leaf length uninervis(-0.59), leaf std. uninervis(0.89), leaf number stipulacea(-0.30), leaf length stipulacea(0.22), leaf std stipulacea(-0.30), leaf number ovalis(-1.36), leaf length ovalis(0.47), leaf std ovalis(0.57)	Salinity(1)

TABLE 6.8 (Cont.d)

COMPARISON OF SEAGRASS DRY WEIGHTS WITH OTHER AUTHORS

		SEAGRASS COVER IN GRAMS PER SQUARE METRE (TONNES PER SQUARE KILOMETRE)									
		Detritus	*H. uninervis* Leaf	*H. uninervis* Root	*H. stipulacea* Leaf	*H. stipulacea* Root	*H. ovalis* Leaf	*H. ovalis* Root	Total Above Ground	Total Below Ground	Total Biomass
From Vousden (present thesis)	Average	357	16.89	149.82	12.5	14.97	3.47	6.98	32.87	171.78	204.65
	STD	454.22	32	155.86	10.59	15.65	3.25	7.27	45.83	178.78	224.62
	Maximim	2334.47	255.14	631.2	40.59	69.07	16.22	30.91	311.95	731.2	1043.13
	Minimum	0.2400	0.37	2.4	0.1	0.11	0.33	0.26	0.8	2.78	3.57
Basson et al (1977)	Average	**	**	**	**	**	**	**	128	**	**
Lipkin (1979)	Average	**	230	**	330	**	35	**	**	**	**
Wahbeh et al (1980)	Average	**	400	**	260	**	10	**	**	**	**
Jones et al (1987)	Maximim	**	**	**	**	**	**	**	8100	**	**
	Minimum	**	**	**	**	**	**	**	20	**	**

** = No data collected or species not present at site sampled.

STD = Standard Deviation

TABLE 6.9

COMPARISON OF SEAGRASS ASH-FREE DRY WEIGHTS WITH OTHER AUTHORS

			SEAGRASS COVER IN GRAMS PER SQUARE METRE (TONNES PER SQUARE KILOMETRE)									
			Detritus	*H. uninervis* Leaf	*H. uninervis* Root	*H. stipulacea* Leaf	*H. stipulacea* Root	*H. ovalis* Leaf	*H. ovalis* Root	Total Above Ground	Total Below Ground	Total Biomass
From Vousden (present thesis)	Average	Annual	229.54	12.40	118.42	4.57	5.70	1.12	1.78	18.09	125.91	144.00
		Winter	149.26	7.52	87.48	3.34	3.89	0.53	1.00	11.39	92.36	103.75
		Summer	325.88	18.27	155.55	6.04	7.88	1.83	2.73	26.13	166.16	192.29
	STD	Annual	229.03	13.66	126.18	6.62	9.42	2.34	4.15	15.67	127.04	139.51
		Winter	187.75	8.45	102.61	4.74	6.29	1.10	2.76	8.53	100.71	106.04
		Summer	236.83	16.90	140.95	8.10	11.79	3.11	5.21	18.29	142.71	158.27
	Maximim	Annual	817.32	71.97	476.63	30.81	34.28	11.33	20.07	78.57	480.66	559.23
		Winter	644.35	35.09	314.62	15.84	24.38	2.78	14.61	35.09	314.62	333.77
		Summer	817.32	71.97	476.63	30.81	34.28	11.33	20.07	78.57	480.66	559.23
	Minimum	Annual	0.06	0.20	0.46	0.04	0.10	0.30	0.19	0.20	0.35	1.03
		Winter	0.18	0.29	5.30	0.04	0.01	0.31	0.57	0.20	0.35	1.03
		Summer	0.60	0.27	0.46	1.05	0.41	0.30	0.19	0.64	7.11	7.31
Brouns (1987)		Average	--	--	--	--	--	--	--	100.00	529.00	629.00
		Maximum	--	--	--	--	--	--	--	136.00	--	--
Erftemeijer (1993)		Average	--	38.00	172.50	--	--	1.00	1.60	*95.33	*573.00	*669.00
		STD	--	22.50	115.50	--	--	1.00	0.50	*45.00	*320.00	*362.00
		Maximim	--	51.00	180.00	--	--	1.00	2.00	*145.00	*991.00	*1137.00
		Minimum	--	25.00	165.00	--	--	1.00	1.00	*44.00	*172.00	*217.00

* = Totals include other, larger seagrass species found at same sites as *H. uninervis / H. stipulacea*

- - = No data collected or species not present at sites sampled. STD = Standard deviation

TABLE 6.10

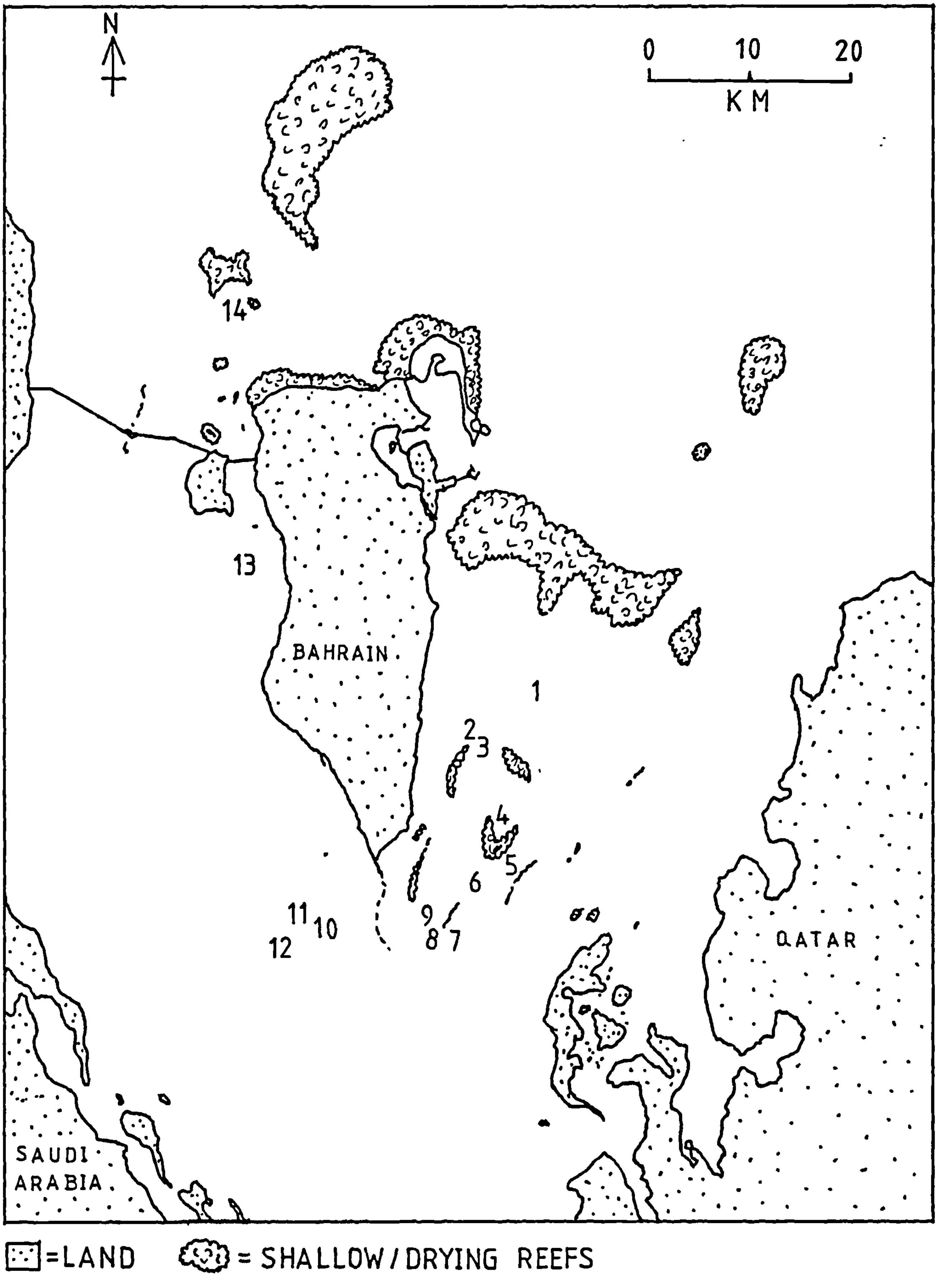
WEIGHT OF SEAGRASS PER SQUARE KILOMETRE AND PER TERRITORIAL WATERS OF BAHRAIN FOR SEAGRASS BEDS WITH GREATER THAN 40% COVER

		Total Above-ground (Standing Crop)	Total Below-ground (Root-Rhizome)	Total Biomass	Total Detritus
Tonnes per square kilometre (Annual Averages)	Dry Weight	32.9	171.8	204.6	357
	Ash-free Weight	18.1	125.9	144	229.5
Tonnes within territorial waters (Annual Averages)	Dry Weight	2.69E+04	1.40E+05	1.67E+05	2.92E+05
	Ash-free Weight	1.48E+04	1.03E+05	1.18E+05	1.88E+05
	AFDW Winter	9.31E+03	7.55E+04	8.48E+04	1.22E+05
	AFDW Summer	2.13E+04	1.36E+05	1.57E+05	2.66E+05

AFDW = Ash-free Dry Weight

TABLE 6.11

FIGURE 6.1 LOCATION OF DETAILED SEAGRASS STUDY SITES



CHAPTER SEVEN

GENERAL CONCLUSIONS

CHAPTER SEVEN

GENERAL CONCLUSIONS

The aim of this study was to seek a better understanding of the presence and distribution of coastal habitat types around Bahrain, particularly with respect to water temperature, water depth and salinity as previous authors have only recognised the general effects of these three physical attributes on coastal habitat types around Bahrain.

This study shows that extreme fluctuations in water temperature are associated with two seasons of summer and winter. These water temperature fluctuations place some marine organisms under extreme stress. Seawater salinities fluctuate on a tidal cycle with higher salinities experienced on a falling and low tide. There is also a seasonal element to salinity fluctuations in shallow waters and the intertidal zone with higher salinities associated with higher insolation (and hence evaporation) in the summer months. This area of the Arabian Gulf has some of the highest open water salinities in the world. The effects of man-made discharges are a cause for concern as many organism and habitats may already be under considerable natural stress. Monitoring of water quality and habitat distribution is considered to be essential to avoid long-term and irreversible damage.

The intertidal zone in particular is marked by extremes in temperature and high salinities resulting in a relatively sparse biota. The large seasonal changes in temperature and salinity range provide an explanation for many of the differences in biotic character seen between Bahrain and the northern and southern Arabian Gulf. Bahrain has few undisturbed shorelines with the north coast showing the greatest degree of perturbation (e.g. oil spills, coastal reclamation, sewage discharges). Despite these perturbations the lower shore and shallow sublittoral zones are regions of high productivity with primary productivity being mainly benthic in origin. Rocky shores are restricted in macroalgal cover while the immediate subtidal zone is often marked by the presence of corals. Small tidal ranges and topography prevent the sorting of sand material and the development of typical sand beaches. Muddy shores are rare and there is an absence of some classic muddy shore inhabitants due to the limited extent of this habitat type. Where mangrove is present, the highest diversity of muddy coastal macrofauna is recorded. Significant seasonal changes in the biota of the intertidal are obvious and should not be confused with any deterioration in habitat quality related to man-made effects.

The subtidal is characterised by the presence of seagrass beds and scattered coral growth with little true coral reef. Coral growth is constrained by extremes of water temperature and by high levels of salinity and turbidity. Water depths control the local distribution of coral species. Only the hardiest of coral species can survive the wide seasonal water temperature fluctuations and the generally shallow, high salinity waters of Bahrain. As a consequence, reef growth and development cannot be compared directly with typical reef growth elsewhere. The presence of additional man-made stresses (dredging and reclamation, industrial discharges) represent a concern not only to Bahrain but to reefs in neighbouring countries which are down-current and which may be dependent on planktonic larvae from Bahrain. Three species of seagrass are confirmed for Bahrain. The distribution and growth pattern of these seagrass species are effected seasonally by temperature and geographically by depth. High salinities appear to have little effect on seagrass distribution, but some effect on morphology (patterns of leaf growth in particular). Three principal community types are identified. Because of their commercial significance and their importance to some endangered species, seagrass beds should be given priority for protection.

This study has shown the value of using remote sensing methods to produce habitat classification maps. It has further established that a high level of accuracy (>80%) can be achieved by using such methods. Several other valuable uses of remote sensing techniques have been identified which can assist coastal planners and marine surveyors. These uses include the location of reefs and shoal areas in uncharted waters and the identification of areas of coastal accretion and erosion. The use of remote sensing techniques can save many man-hours in the field and provides a readily repeatable approach to coastal zone monitoring and survey.

In view of the commercial and conservational value of the seagrass habitat and its relatively widespread cover of the seabed around Bahrain, more detailed studies on seagrass distribution were undertaken. These studies confirm and define the relationship between the biomass cover of seagrass and the three principal physical water column characteristics which are most obviously effecting subtidal habitat distribution around Bahrain (temperature, depth and salinity). This has assisted in clarifying uncertainties and contradictions in the literature regarding the effect of these physical characteristics and elucidated the general distribution pattern of seagrass species around Bahrain. The data collected also provides dry weight and ash-free dry weight values for seagrass biomass in the study area.

The study as a whole has developed an approach to creating a baseline catalogue of the critical marine biological resources of an otherwise unsurveyed national coastline. It has produced an initial species list of marine biota for Bahrain (see appendix 7.1). It has instigated a data collection programme to identify the principal water quality characteristics which are controlling the distribution of the biological resources. It has developed and evaluated a low man-power methodology for mapping coastal habitat types which can be easily repeated at selected intervals for monitoring purposes.

The results of this study show the need for both seasonal and long-term coastal management in the waters around Bahrain. These should include the declaration of specific management areas with respect to conservation and species protection. They should further include a well-designed and implemented approach to the monitoring and control of coastal development with a view to sustainable resource management. This management and monitoring should take into consideration the need for repeated surveys of the same or similar nature as the present study in order to identify any trends in coastal degradation. A repeat survey every five to ten years would be advisable.

CHAPTER EIGHT

APPENDICES

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
NE Transect N	850818	26.26.00	50.45.00	2923739	475072	No Data	34	42	1
NE Transect NC	850818	26.24.00	50.43.50	2920052	472571	No Data	34	42	1
NETransect SC	850818	26.21.00	50.42.00	2914520	470065	No Data	34.2	42	1
Khawr Fasht	880330	26.20.87	50.22.86	2914510	438076	28.6	21.8	44.9	5
Khawr Fasht	890403	26.20.87	50.22.86	2914510	438076	18.7	19.9	47.5	5
Vidal Buoy	880330	26.20.00	50.45.00	2928070	475350	26.1	21.1	42.2	1
Vidal Buoy	870502	26.20.00	50.45.00	2928070	475350	No Data	26.4	44.5	1
Muharraq	870129	26.18.20	50.40.70	2909570	468169	No Data	18	44	1
Muharraq	850822	26.18.20	50.40.70	2909357	467890	No Data	34.5	45	1
Ne Transect S	850818	26.18.20	50.40.70	2909357	467890	No Data	34.2	42	1
Sanabis N Off	850822	26.16.20	50.31.10	2905715	451904	No Data	34.5	46	1
Sala N Off	850822	26.16.14	50.26.90	2906112	444916	No Data	34.5	50	5
AH Transect C	850803	26.14.50	50.43.30	2902517	472201	No Data	32.5	44	1
Mina Al Manama	870128	26.14.25	50.34.50	2902263	457515	No Data	18.3	45	1
Mina Al Manama	870129	26.14.25	50.34.50	2902263	457515	No Data	18	43	1
Mina Al Manama	850730	26.14.25	50.34.50	2902095	457551	No Data	33.5	45	1
Ras Abu Subh	850729	26.13.22	50.27.26	2900232	445486	35	33	46	1
Budaiya	850723	26.13.00	50.26.90	2899836	444889	36	35.5	46	5
AH Transect E	850803	26.13.00	50.45.50	2899741	475858	No Data	32.5	44	1
Al Azl	850730	26.12.78	50.39.47	2899365	465817	36	33	45	1
AH Transect W	850803	26.12.50	50.41.90	2898831	469862	No Data	32.5	43	1
Al Muwaylighah	850731	26.12.15	50.34.11	2898219	456882	37	33	45	2
Causeway N 2km	850827	26.11.97	'50.21.77	2897974	436338	No Data	34	54	5
Sitra Causeway North	870211	26.11.65	50.35.20	2897453	458684	No Data	17.4	43	2
Sitra N. Bridge	870129	26.11.65	50.35.20	2897453	450334	No Data	17.9	43	2
Sitra Causeway North	870129	26.11.65	50.35.20	2897453	458684	No Data	17.9	43	2
Sitra Causeway North	870209	26.11.65	50.35.20	2897453	458684	No Data	18.5	43	2
Um Nasan NW	850827	26.11.30	50.22.20	2896733	437049	No Data	No Data	55	5

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Nabih Salih N	850731	26.11.30	50.35.00	2896647	458366	34.5	32	42	2
Jaradah	850807	26.11.30	50.54.60	2896584	491007	38	33.5	42	1
Sitra Causeway Mid	870129	26.11.00	50.35.22	2896250	458717	No Data	17.8	43	2
Sitra Causeway Mid	850731	26.11.00	50.35.22	2896250	458717	37	32	45	2
Causeway N	850729	26.10.90	50.27.10	2895958	445206	No Data	33	46	5
Causeway North	860312	26.10.75	50.27.20	2895788	445324	No Data	19.8	56	5
Nabih Salih S	850731	26.10.60	50.35.00	2895355	458362	No Data	32	45	2
Centre Island SE	850827	26.10.30	50.20.00	2894906	433375	No Data	No Data	56	7
Causeway 1 km S	850827	26.10.25	50.21.75	2894799	436290	No Data	No Data	56	7
Sitra Causeway South	870129	26.10.24	50.35.95	2894844	459937	No Data	19.9	43	2
Jurdab	850731	26.10.20	50.33.60	2894625	456027	36	33	46	2
Causeway South	860312	26.09.69	50.26.80	2893527	444656	No Data	19.5	56.5	7
Causeway S	850824	26.09.50	50.26.80	2893376	444695	No Data	34	60	7
Jaradah S Off	850807	26.09.20	50.53.20	2892709	488672	No Data	33.5	43	1
Ras Sanad	850725	26.08.90	50.35.30	2892216	458851	No Data	34	45	2
Al Ak	850802	26.08.79	50.37.04	2892010	461753	36	33	47	2
Jasrah s 2km	850824	26.08.70	50.27.05	2891900	444522	38	34	60	7
Fasht Adhm N Dp	850728	26.08.70	50.45.40	2891804	475677	No Data	33	42	2
Tubli South Channel	870209	26.08.40	50.36.90	2891140	461523	No Data	19.5	42	3
Tubli South Channel	870125	26.08.40	50.36.90	2891140	461523	No Data	26	43	3
Tubli South Channel	870122	26.08.40	50.36.90	2891140	461523	No Data	17.6	44	3
Tubli South Channel	870211	26.08.40	50.36.90	2891140	461523	No Data	17.4	42	3
Tubli South Channel	870121	26.08.40	50.36.90	2891140	461523	No Data	16.4	43	3
Al Hamalah	850824	26.08.00	50.26.90	2890606	444850	38	34	60	7
Fasht Adhm Nw	850805	26.08.00	50.41.80	2890525	469676	No Data	33.7	45	2
Al Baynay S	850827	26.07.80	50.18.88	2895044	431594	No Data	No Data	55	7
Um Nasan West	860312	26.07.80	50.20.40	2890030	433968	No Data	20	60	7
Um Nasan W	850827	26.07.80	50.20.40	2890288	434018	No Data	No Data	56	7
Sitra Jetty	870121	26.07.80	50.38.00	2890030	463360	No Data	18	44	2

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Sitra Dhow Port	870121	26.07.80	50.38.00	2890030	463360	No Data	17.9	44	2
Sitra Dhow Port	870124	26.07.80	50.38.00	2890030	463360	No Data	No Data	44.3	2
Um Nasan SW Coast	850827	26.07.50	50.23.50	2889709	439181	No Data	38	No Data	7
Bandar Al Dar	870121	26.07.30	50.38.15	2889105	463611	No Data	18.2	44	2
Bandar Al Dar	870122	26.07.30	50.38.15	2889105	463611	No Data	18.5	45	2
Um Nasan SW(MT)	850827	26.07.27	50.23.47	2889287	439126	39	38	56	7
N. Of Half Tanker	890403	26.07.00	50.46.22	2888550	477387	20.4	20.4	43.4	2
Tonque Nw Off	850807	26.07.00	50.53.00	2888649	488335	No Data	33.4	43	2
Khalid's Marina	870125	26.06.80	50.38.22	2888180	463727	No Data	27	44	3
Khalid's Marina	870203	26.06.80	50.38.22	2888180	463727	No Data	22	43	3
BYC Basin	870203	26.06.72	50.38.10	2888032	463527	No Data	22	43	3
BYC Basin	870209	26.06.72	50.38.10	2888032	463527	No Data	23.5	43	3
BYC Basin	870121	26.06.72	50.38.10	2888032	463527	No Data	18.1	45	3
BYC Basin	870208	26.06.72	50.38.10	2888032	463527	No Data	21	44	3
BYC Basin	870123	26.06.72	50.38.10	2888032	463527	No Data	21.1	43	3
BYC Basin	870128	26.06.72	50.38.10	2888032	463527	No Data	19.5	43	3
BYC Basin	870122	26.06.72	50.38.10	2888032	463527	No Data	18.7	45	3
BYC Basin	870129	26.06.72	50.38.10	2888032	463527	No Data	19	43	3
BYC Basin	870125	26.06.72	50.38.10	2888032	463527	No Data	29.5	45.2	3
BYC Basin	851125	26.06.72	50.38.10	2888032	463527	No Data	No Data	45	3
BYC Basin	870124	26.06.72	50.38.10	2888032	463527	No Data	No Data	45	3
BYC Basin	870211	26.06.72	50.38.10	2888032	463527	No Data	19.4	43	3
BYC Basin	870126	26.06.72	50.38.10	2888032	463527	No Data	No Data	43	3
BYC Channel	870123	26.06.70	50.38.13	2887995	463577	No Data	21.6	43	3
Crown Buoy	870123	26.06.66	50.39.00	2887921	465030	No Data	18.1	42	3
Ras Zawayyid	870125	26.06.53	50.37.75	2887681	462943	No Data	25	44	3
Flamingo Bay	870125	26.06.40	50.37.40	2887440	462358	No Data	30	45	3
LLPH Seaward	870209	26.06.20	50.37.87	2887070	463143	No Data	19.7	44	3
LLPH Seaward	870125	26.06.20	50.37.87	2887070	463143	No Data	28	45	3

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
LLPH Seaward	870203	26.06.20	50.37.87	2887070	463143	No Data	23	44	3
LLPH Seaward	870214	26.06.20	50.37.87	2887070	463143	No Data	18.9	45	3
LLPH Seaward	870211	26.06.20	50.37.87	2887070	463143	No Data	19.2	43	3
LLPH Seaward	870128	26.06.20	50.37.87	2887070	463143	No Data	19	44	3
LLPH Seaward	870122	26.06.20	50.37.87	2887070	463143	No Data	17.7	45	3
Sitra Gate	890402	26.06.08	50.38.75	2886848	464613	19.6	19.8	43.2	3
Sitra Gate	880329	26.06.08	50.38.75	2886848	464613	19.2	20.7	43.5	3
Sitra Gate	861101	26.06.08	50.38.75	2886848	464613	No Data	28	44	3
Um Nasan SW Off	850827	26.06.00	50.20.00	2886968	433334	No Data	34.2	58	7
Zallaq Tower	890313	26.05.60	50.27.00	2885960	444990	No Data	18.7	59	7
Zallaq Tower	860519	26.05.60	50.27.00	2885960	444990	28.7	25.5	59	7
West Yasuf N	850827	26.05.00	50.24.00	2885090	439993	No Data	34.4	55	7
West Yasuf N	850825	26.05.00	50.24.00	2885090	439993	No Data	34.4	55	7
Tonque Ne	850807	26.05.00	50.52.50	2884958	487499	No Data	33.5	43	2
West Yasuf S	850827	26.04.50	50.24.00	2884167	439988	No Data	No Data	55	7
Askar North	870125	26.04.35	50.37.33	2883648	462241	No Data	23	46	3
Ras Abu Jarjur	870125	26.04.20	50.32.32	2883370	453874	No Data	27.5	48	3
Ras abu Jarjur 300M	870202	26.04.17	50.37.42	2883315	462391	No Data	23	44	3
Ras abu Jarjur 300M	870219	26.04.17	50.37.42	2883315	462391	No Data	19.5	45	3
Ras abu Jarjur 500M	870202	26.04.17	50.37.44	2883315	462425	No Data	23	44	3
Fasht Adhm S	850730	26.04.10	50.43.00	2883322	471659	No Data	30.5	44	3
Askar N	850721	26.04.00	50.37.20	2891310	462024	45	31	49	3
Ras abu Jarjur Se	870202	26.04.00	50.37.45	2883000	462442	No Data	21	44	3
Askar Offshore	870202	26.03.52	50.38.20	2882112	463694	No Data	22	45	3
Zallaq N	850727	26.03.40	50.29.00	2882101	448315	No Data	32	55	7
Askar South	870129	26.03.40	50.37.20	2881890	462024	No Data	21	45	3
Askar South	870209	26.03.40	50.37.20	2881890	462024	No Data	21.2	44	3
Askar South	870208	26.03.40	50.37.20	2881890	462024	No Data	23	43	3
Askar South	870211	26.03.40	50.37.20	2881890	462024	No Data	17.5	44	3

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Askar South	870125	26.03.40	50.37.20	2881890	462024	No Data	23	44	3
Askar South	870124	26.03.40	50.37.20	2881890	462024	No Data	No Data	45.8	3
Askar South	870126	26.03.40	50.37.20	2881890	462024	No Data	20	44	3
Askar South	870203	26.03.40	50.37.20	2881890	462024	No Data	27	43	3
Askar South	870128	26.03.40	50.37.20	2881890	462024	No Data	19.5	44	3
Askar South	870122	26.03.40	50.37.20	2881890	462024	No Data	17.6	45	3
Big Red 1	861029	26.03.20	50.39.10	2881520	465197	No Data	27.5	45	3
Big Red 1	890320	26.03.20	50.39.10	2881520	465197	No Data	20.6	47.1	3
Big Red 1	861101	26.03.20	50.39.10	2881520	465197	No Data	27.8	44	3
Big Red 1	870126	26.03.20	50.39.10	2881520	465197	No Data	20.3	45	3
Big Red 1	880329	26.03.20	50.39.10	2881520	465197	22	21.2	44.3	3
Mosque Island 300M N	870202	26.03.15	50.37.87	2881428	463143	No Data	22	43	3
Zallaq Old Jetty	850825	26.03.00	50.27.00	2881376	444978	No Data	No Data	56	7
Zallaq Bapco Jetty	850825	26.03.00	50.28.60	2881365	447646	No Data	32	55	7
Mosque Island 300M W	870202	26.03.00	50.37.70	2881150	462859	No Data	22	43	3
Mosque Island 300M W	870219	26.03.00	50.37.70	2881150	462859	No Data	19.5	43	3
Mosque Island	860511	26.03.00	50.37.95	2881150	463277	32.5	27.7	44	3
Mosque Island 150M S	870202	26.02.90	50.37.95	2880965	463277	No Data	22	43	3
Zallaq	880330	26.02.80	50.28.80	2880780	447996	23.2	20.6	53.8	7
Zallaq	870128	26.02.80	50.28.80	2880780	447996	No Data	19	56	7
Zallaq	870129	26.02.80	50.28.80	2880780	447996	No Data	18	53	7
Zallaq	890403	26.02.80	50.28.80	2880780	447996	17.8	19.6	55.2	7
Ras Hayyan North	870126	26.02.80	50.37.35	2880780	462275	No Data	No Data	44	3
Ras Hayyan North	850802	26.02.80	50.37.35	2880946	462234	40	30	46	3
Ras Hayyan (Lagoon)	870211	26.02.80	50.37.75	2880780	462943	No Data	19.2	44	3
Ras Hayyan (Lagoon)	870203	26.02.80	50.37.75	2880780	462943	No Data	22	44	3
Ras Hayyan (Lagoon)	870208	26.02.80	50.37.75	2880780	462943	No Data	20.5	45	3
Ras Hayyan (Lagoon)	870126	26.02.80	50.37.75	2880780	462943	No Data	No Data	48	3
Ras Hayyan (Lagoon)	870209	26.02.80	50.37.75	2880780	462943	No Data	20	45	3

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Ras Hayyan (Lagoon)	870125	26.02.80	50.37.75	2880780	462943	No Data	21.5	44.1	3
Ras Hayyan	870126	26.02.80	50.37.90	2880780	463193	No Data	No Data	46	3
Ras Hayyan Offshore	870202	26.02.80	50.38.25	2880780	463778	No Data	22	43	3
Um Jalid Nw	850816	26.01.70	50.44.10	2878888	473485	No Data	34	45	3
Um Jalid Se 2Km	870126	26.01.70	50.44.10	2878745	473847	No Data	20	45	3
Um Jalid	870127	26.01.53	50.43.38	2878431	472645	No Data	22.5	44	3
Um Jalid	870508	26.01.53	50.43.38	2878431	472645	No Data	No Data	45	3
Um Jalid	851125	26.01.53	50.43.38	2878431	472645	No Data	No Data	45	3
Um Jalid	860309	26.01.53	50.43.38	2878431	472645	No Data	24	44	3
Al Jazair Off	850825	26.01.50	50.26.00	2878615	443298	No Data	No Data	56	7
Um Jalid Se	850816	26.01.48	50.43.29	2878888	473485	40	34	45	3
Um Jalid 200M South	870219	26.01.48	50.43.29	2878338	472494	No Data	19.4	41.5	3
B-Q Transect Uj	850801	26.01.30	50.43.80	2878151	472983	No Data	33	43	4
North Jaww	870131	26.01.00	50.38.00	2877450	463360	No Data	24	45	3
North Jaww	870219	26.01.00	50.38.00	2877450	463360	No Data	19.3	44	3
Jaww	870124	26.00.10	50.37.90	2875785	463193	No Data	No Data	44.6	3
Jaww Prison	870131	26.00.00	50.37.55	2875600	462609	No Data	24	45	3
L Jazair S Off	850825	2555.00	50.29.00	2866596	448254	No Data	34	55	8
Um Jalid Ese 8Km	870126	25.59.60	50.48.12	2875160	480560	No Data	20.5	45	3
Ras Nawmah Off	850825	25.59.50	50.26.00	2874000	443278	No Data	No Data	55	8
Zallaq S	850727	25.59.30	50.28.65	2874536	447702	No Data	32	55	7
West Deeps N	850825	25.59.00	50.21.00	2874039	434937	No Data	34.1	55	8
B-Q Transect W	850801	25.59.00	50.44.90	2873902	474809	No Data	32	44	3
Ad Dur	850810	25.58.70	50.36.60	2857327	459744	37	33.5	45	3
Big Red 2	860309	25.58.20	50.42.50	2872570	471175	No Data	21	44	3
Big Red 2	861029	25.58.20	50.42.50	2872570	471175	No Data	28	45	3
Big Red 2	890320	25.58.20	50.42.50	2872570	471175	No Data	20.3	47.5	3
Big Red 2	861101	25.58.20	50.42.50	2872570	471175	No Data	28	45	3
B-Q Transect Cw	850801	25.56.80	50.46.26	2869837	477071	No Data	32.2	44	4

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
West Coast Deeps	850825	25.56.00	50.20.00	2868510	433240	No Data	33.8	55	8
Ad Dur Off 2.5 Nm	870319	25.55.50	50.37.00	2867575	461690	No Data	No Data	44	3
Gabbari N. Pole	860309	25.55.10	50.40.00	2866835	467000	No Data	21	50	4
Tigaylib Nw	850805	25.55.10	50.41.90	2866714	469788	No Data	33	44	4
B-Q Transect Ce	850801	25.54.90	50.47.40	2866327	478968	No Data	32.2	48	4
Ras Al Qurayn	850722	25.54.80	50.36.60	2866280	461275	35	34	48	6
Ras Al Mumtallah	850728	25.54.30	50.30.70	2865293	451087	38	31.4	65	8
Ras Al Mumtallah	870303	25.54.30	50.30.70	2865355	451169	No Data	26.5	56	8
Gabbari Rock	890402	25.54.20	50.39.40	2865170	465698	20.8	20.2	46.5	4
Gabbari Rock	850810	25.54.20	50.39.40	2865063	465610	No Data	34.5	45	4
Gabbari Rock	881207	25.54.20	50.39.40	2865170	465698	No Data	21.1	50	4
Gabbari Rock	890320	25.54.20	50.39.40	2865170	465698	No Data	20.2	48.4	4
Gabbari Rock	880803	25.54.20	50.39.40	2865170	465698	No Data	33.6	48.1	4
Gabbari Rock	880329	25.54.20	50.39.40	2865170	465698	24.5	21.4	45.4	4
B-Q Transect E	850801	25.53.80	50.48.70	2864293	481135	No Data	32.3	46	4
B-Q Transect Q	850801	25.53.80	50.50.20	2864290	483639	No Data	32	46	4
Gabbari S. Cairn	850810	25.53.20	50.38.90	2863219	464771	No Data	34	45	4
Gabbari S. Cairn	870319	25.53.00	50.38.90	2862950	464863	No Data	No Data	46	4
Mumtallah W Off 7	850825	25.52.00	'50.25.00	2861087	441553	No Data	34.5	60	8
Mumtallah W Off 12	850825	25.52.00	50.23.00	2861102	438213	No Data	34.1	55	8
Mumtallah S Off	850825	25.52.00	50.31.00	2861046	451572	No Data	34.6	55	8
Big Red 3	860123	25.51.60	50.48.00	2860360	480360	No Data	No Data	50	4
Big Red 3	861029	25.51.60	50.48.00	2860360	480360	No Data	28	45	4
Big Red 3	861101	25.51.60	50.48.00	2860360	480360	No Data	28	45	4
Big Red 3	860603	25.51.60	50.48.00	2860360	480360	No Data	31	45	4
Twins S Off	850810	25.50.60	50.50.56	2858383	484233	No Data	35	47.5	6
Had al Jamal jetty	850810	25.50.00	50.35.90	2857327	459744	37	33.5	48	6
Mashtan W Arm	850805	25.50.00	50.41.70	2857301	469432	No Data	33.7	45	6
Mashtan North	890206	25.48.48	50.41.00	2854488	468670	No Data	13.3	50	6

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN, 1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Mashtan North	880914	25.48.48	50.41.00	2854488	468670	No Data	37	54	6
Mashtan North	850805	25.48.48	50.41.00	2854535	468256	43	33.5	50	6
Mashtan South	890320	25.48.36	50.40.90	2854266	468503	No Data	19.6	52.5	6
Mashtan South	890206	25.48.36	50.40.90	2854266	468503	No Data	13.3	48	6
Mashtan South	881207	25.48.36	50.40.90	2854266	468503	No Data	21	50.8	6
Mashtan South	860309	25.48.36	50.40.90	2854266	468503	No Data	21	50	6
Mashtan South	880914	25.48.36	50.40.90	2854266	468503	No Data	35	55	6
Mashtan South	850805	25.48.36	50.40.90	2854535	468256	43	33.5	50	6
Mashtan South	870319	25.48.36	50.40.90	2854266	468503	No Data	No Data	48	6
Ras Al Barr West	850801	25.48.08	50.33.87	2852354	456554	32	35	52	6
Ras Al Barr West	870303	25.48.08	50.33.87	2853748	456463	No Data	24.5	48	6
Ras Al Barr East	850801	25.48.08	50.33.98	2852354	456554	32	35	52	6
Ras Al Barr East	870303	25.48.08	50.33.98	2853748	456647	No Data	23.5	50	6
Mutarid Nw	850805	25.47.30	50.42.90	2852313	471426	No Data	33.2	49	6
Mutarid S.300M	850811	25.46.92	50.42.35	2851614	470505	No Data	No Data	No Data	6
Gharbiyah N	850811	25.46.40	50.46.50	2850640	477439	No Data	35	49.5	6
East Al Hul	881206	25.45.00	50.34.45	2848050	457432	No Data	21.7	56.8	6
Gharbiyah Trans A	850811	25.45.00	50.45.60	2848059	475930	No Data	36	No Data	6
Gharbiyah Trans B	850811	25.45.00	50.45.60	2848059	475930	39	36	52	6
Middle Shoal	890402	25.44.80	50.38.30	2847680	463861	20.5	19.7	53.4	6
Middle Shoal	880329	25.44.80	50.38.30	2847680	463861	22	20.9	52.6	6
Middle Shoal	880803	25.44.80	50.38.30	2847680	463861	No Data	33.7	51.9	6
West Al Hul	880329	25.44.40	50.30.20	2846940	450334	19.1	20.1	54	8
West Al Hul	890217	25.44.40	50.30.20	2846940	450334	No Data	15.1	58.6	8
West Al Hul	890402	25.44.40	50.30.20	2846940	450334	21	19.6	54.7	8
West Al Hul	880803	25.44.40	50.30.20	2846940	450334	No Data	33.2	59.3	8
Ajirah	850820	25.44.39	50.49.38	2846923	482247	No Data	36	48	6
Ajirah (MT)	850821	25.44.39	50.49.39	2846923	482263	38	36	48	6
Hawar Nw Jetty	861018	25.43.70	50.48.12	2845645	480560	No Data	31.5	48	6

APPENDIX 2.1 SITE POSITIONS, TEMPERATURE AND SALINITY DATA FOR BAHRAIN,1985 - 1989.

Data collected at various times of day. Sea temperatures measured in top 1 metre of water column

SITE NAME	DATE	LATITUDE	LONGITUDE	UTM NORTHINGS	UTM EASTINGS	AIR TEMP Deg.C.	SEA TEMP Deg. C	SALINITY ppt	SECTOR (see Fig. 2.3)
Hawar Nw Jetty	861029	25.43.70	50.48.12	2845645	480560	No Data	27	47	6
Hawar Nw Jetty	861022	25.43.70	50.48.12	2845645	480560	No Data	30.5	46.5	6
Hawar Nw Jetty	861101	25.43.70	50.48.12	2845645	480560	No Data	27	48	6
Hawar Coastguard	850813	25.43.30	50.46.60	2844918	477596	No Data	34	48	6
Hawar W Off	850805	25.42.28	50.44.16	2852313	469900	No Data	33	50	6
Hawar Back Island	850820	25.42.00	50.47.95	2842515	479849	No Data	36.6	49	6
Jazur Bu Sadad	850820	25.40.60	50.46.00	2839937	476584	No Data	39	62	6
Bandar Nakhiah	850813	25.37.10	50.45.00	2833480	474899	36	34	58	6

APPENDIX 2.2 : VERTICAL SALINITY PROFILES - BAHRAIN, 1988-89

SECTOR (see Fig. 2.5)	DATE	SITE NAME	SAMPLE TIME (hours)	SAMPLE DEPTH (Metres)	TEMPERATURE (Degrees C)	SALINITY (Parts Per Thousand)
6	880329	Middle Shoal	1545	1.0	20.9	52.6
				2.0	-	52.8
				5.0	-	54.0
				7.7	-	54.1
6	880803	Middle Shoal	1415	0.2	33.7	51.9
				4.0	32.7	58.5
6	881206	East Al Hul	1230	1.0	21.7	56.8
				2.7	21.3	57.7
6	881206	S.E. Of Mashtan	1500	1.2	21.5	52.3
				3.5	-	54.9
6	881206	S.E. Of Mashtan	1625	1.1	21.4	54.0
				2.9	21.5	54.5
6	881206	W.N.W. Of Mashtan	1130	1.1	21.3	52.8
				4.7	21.3	53.0
6	881207	Mashtan South	745	0.7	20.6	51.2
				2.5	20.7	52.8
6	890320	Mashtan South	1100	0.5	19.6	52.5
				4.7	19.6	53.8
6	890402	Middle Shoal	1515	1.0	19.7	53.4
				2.0	-	53.5
				5.0	-	54.4
7	880330	Zallaq Tower	940	1.0	20.6	53.8
				2.0	-	53.7
				5.0	-	53.6
				7.0	-	53.7
7	890313	Zallaq Tower	1330	1.0	18.7	59.0
				4.5	18.6	59.3
7	890403	Zallaq Tower	600	1.0	19.6	55.2
				2.0	-	55.1
8	880329	West Al Hul	1745	1.0	20.1	54.0
				2.0	-	54.2
				5.0	-	54.1
				12.5	-	54.4
8	880803	West Al Hul	1200	0.5	33.2	59.3
				5.0	32.7	59.0
				10.0	32.6	59.0
8	890217	West Al Hul	1230	1.0	15.1	58.6
				5.0	15.0	58.5
				10.0	14.9	58.5
8	890402	West Al Hul	1545	1.0	19.6	54.7
				2.0	-	54.8
				5.0	-	54.6
				8.2	-	54.7

APPENDIX 2.3

RAW CURRENT METER DATA FROM SOUTHWEST MASHTAN 8TH - 13TH MARCH, 1989.

Current meter position = Lat. 25.46.10 N, Long. 50.38.51 E. Meter depth 3.5 m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG. MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1240	890308	18.1	66	29	56.0	51.7
1310	890308	17.6	68	22	43.9	52.7
1340	890308	17.3	67	25	42.6	53.3
1410	890308	17.2	67	25	40.7	53.5
1440	890308	17.1	67	28	41.7	53.6
1510	890308	17.1	67	28	41.2	53.6
1540	890308	17.2	67	30	38.7	53.6
1610	890308	17.0	67	25	34.8	53.8
1640	890308	17.0	66	28	27.1	53.9
1710	890308	16.9	66	22	19.9	53.9
1740	890308	17.0	66	9	9.0	54.0
1810	890308	17.0	66	219	5.8	53.9
1840	890308	17.5	66	198	10.7	53.3
1910	890308	17.7	67	192	25.5	52.7
1940	890308	17.4	67	194	41.5	53.3
2010	890308	17.7	69	199	38.1	52.7
2040	890308	18.0	71	203	41.9	52.4
2110	890308	18.4	73	205	42.9	51.8
2140	890308	18.7	74	202	44.8	51.3
2210	890308	19.2	70	196	43.1	50.1
2240	890308	19.5	68	201	38.8	49.4
2310	890308	19.4	67	230	19.9	49.8
2340	890308	19.6	67	325	5.3	49.2
10	890309	19.5	67	16	12.9	49.5
40	890309	18.9	67	30	27.3	50.6
110	890309	18.1	67	24	40.5	52.1
140	890309	17.3	69	22	47.9	53.3
210	890309	17.0	69	27	41.1	53.7
240	890309	17.1	68	28	39.6	53.6
310	890309	17.0	68	22	31.5	53.7
340	890309	17.0	68	25	35.1	53.8
410	890309	17.0	67	23	32.4	53.8
440	890309	16.9	67	22	25.4	53.9
510	890309	17.0	67	28	20.5	53.9
540	890309	17.0	67	351	6.2	53.8
610	890309	17.3	67	213	5.3	53.4
640	890309	17.5	67	200	22.2	53.0
710	890309	17.4	67	193	38.8	52.8
740	890309	17.3	72	207	44.5	53.0
810	890309	17.5	75	205	43.9	52.7
840	890309	17.8	77	209	44.1	52.2
910	890309	18.2	78	206	46.9	51.4
940	890309	18.7	76	208	46.4	50.3
1010	890309	19.3	72	208	45.5	49.3
1040	890309	19.5	68	203	39.4	48.9
1110	890309	19.8	68	197	29.4	48.5
1140	890309	19.8	68	252	10.3	48.5
1210	890309	19.7	67	8	7.3	48.6
1240	890309	19.7	67	16	22.6	48.8
1310	890309	18.5	67	28	38.4	51.0
1340	890309	17.8	69	19	45.7	52.4

APPENDIX 2.3 **RAW CURRENT METER DATA FROM SOUTHWEST MASHTAN 8TH - 13TH MARCH, 1989.**

Current meter position = Lat. 25.46.10 N, Long. 50.38.51 E. Meter depth 3.5 m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG. MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1410	890309	17.4	69	26	40.8	53.1
1440	890309	17.4	69	26	41.0	53.1
1510	890309	17.4	68	24	37.5	53.2
1540	890309	17.5	68	23	35.3	53.2
1610	890309	17.5	68	25	30.9	53.2
1640	890309	17.3	67	31	33.0	53.5
1710	890309	17.2	67	31	27.2	53.6
1740	890309	17.3	67	24	21.2	53.6
1810	890309	17.2	67	192	6.0	53.6
1840	890309	17.5	67	181	4.3	53.4
1910	890309	17.6	67	197	13.4	53.3
1940	890309	18.3	67	193	31.4	52.0
2010	890309	17.8	68	194	41.6	52.6
2040	890309	17.9	70	200	38.5	52.5
2110	890309	18.1	73	203	41.7	52.2
2140	890309	18.7	73	207	43.9	51.1
2210	890309	18.9	75	201	46.6	50.8
2240	890309	19.5	72	197	43.4	49.8
2310	890309	20.0	68	192	39.4	48.7
2340	890309	20.0	67	198	26.0	48.4
10	890310	20.0	67	333	5.5	48.6
40	890310	19.9	67	13	15.5	48.5
110	890310	19.6	67	26	35.9	49.3
140	890310	18.4	67	23	37.3	51.6
210	890310	17.6	68	27	46.9	53.0
240	890310	17.5	68	26	42.9	53.4
310	890310	17.5	68	29	36.8	53.4
340	890310	17.4	67	30	33.5	53.5
410	890310	17.4	68	24	30.6	53.5
440	890310	17.4	68	29	29.9	53.5
510	890310	17.5	67	27	29.3	53.6
540	890310	17.5	67	30	23.8	53.6
610	890310	17.5	67	29	13.8	53.7
640	890310	17.6	67	216	3.7	53.5
710	890310	17.8	67	198	13.1	53.3
740	890310	18.3	67	187	31.6	52.8
810	890310	17.8	68	197	42.6	52.8
840	890310	17.8	72	198	43.9	52.6
910	890310	18.0	75	207	43.5	52.2
940	890310	18.5	77	208	45.7	51.2
1010	890310	19.0	77	206	46.0	50.1
1040	890310	19.5	76	209	44.7	48.9
1110	890310	19.9	70	207	41.9	48.3
1140	890310	20.2	68	212	36.6	47.7
1210	890310	20.2	67	207	22.8	47.7
1240	890310	20.1	68	11	5.1	48.0
1310	890310	20.0	67	23	23.9	48.2
1340	890310	19.0	67	21	40.2	50.2
1410	890310	18.1	69	21	41.0	52.5
1440	890310	17.8	69	22	38.7	53.2
1510	890310	17.7	69	28	41.3	53.3

APPENDIX 2.3 **RAW CURRENT METER DATA FROM SOUTHWEST MASHTAN 8TH - 13TH MARCH, 1989.**

Current meter position = Lat. 25.46.10 N, Long. 50.38.51 E. Meter depth 3.5 m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG. MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1540	890310	17.8	68	28	40.1	53.3
1610	890310	17.8	68	27	42.5	53.2
1640	890310	17.8	68	31	44.6	53.5
1710	890310	17.7	68	29	42.5	53.6
1740	890310	17.7	67	26	38.7	53.6
1810	890310	17.7	67	23	30.4	53.7
1840	890310	17.7	67	23	14.4	53.7
1910	890310	17.7	67	193	5.7	53.6
1940	890310	18.2	67	205	13.2	52.4
2010	890310	18.3	69	199	33.6	52.3
2040	890310	18.1	76	206	39.9	52.6
2110	890310	18.1	77	205	41.4	52.5
2140	890310	18.8	79	212	46.4	50.9
2210	890310	19.4	81	221	56.2	49.5
2240	890310	19.7	78	220	53.0	48.7
2310	890310	20.1	74	214	48.4	47.6
2340	890310	20.2	70	214	42.2	47.3
10	890311	20.3	69	219	32.7	46.9
40	890311	20.4	68	227	16.3	46.6
110	890311	19.4	68	31	6.6	49.7
140	890311	19.0	68	23	34.2	50.5
210	890311	18.1	70	23	48.4	52.6
240	890311	17.9	70	26	45.7	53.1
310	890311	17.6	70	27	42.4	53.6
340	890311	17.5	72	32	40.2	53.7
410	890311	17.5	73	32	46.5	53.7
440	890311	17.5	73	26	46.9	53.6
510	890311	17.4	70	24	43.7	53.8
540	890311	17.3	70	40	41.2	53.8
610	890311	17.3	69	28	39.6	53.8
640	890311	17.2	68	22	28.6	53.9
710	890311	17.2	68	31	14.0	53.9
740	890311	17.3	68	245	5.2	53.8
810	890311	17.6	68	207	13.5	53.1
840	890311	17.7	72	199	33.2	52.8
910	890311	17.6	77	223	41.6	53.1
940	890311	18.0	79	211	39.0	52.2
1010	890311	18.9	80	218	44.5	49.9
1040	890311	19.4	80	221	50.9	48.8
1110	890311	19.6	80	215	51.4	48.0
1140	890311	19.7	80	207	50.7	47.7
1210	890311	19.9	75	216	46.9	48.2
1240	890311	20.0	69	220	36.3	47.2
1310	890311	20.1	68	220	16.4	47.0
1340	890311	19.6	68	30	8.3	48.5
1410	890311	17.7	69	27	36.7	53.2
1440	890311	17.6	69	25	46.1	53.3
1510	890311	17.3	72	22	45.7	53.6
1540	890311	17.2	72	33	44.2	53.8
1610	890311	17.1	74	25	46.0	53.8
1640	890311	17.1	75	29	46.9	53.8

APPENDIX 2.3 RAW CURRENT METER DATA FROM SOUTHWEST MASHTAN 8TH - 13TH MARCH, 1989.

Current meter position = Lat. 25.46.10 N, Long. 50.38.51 E. Meter depth 3.5 m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG. MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1710	890311	17.0	73	29	47.1	53.9
1740	890311	17.0	71	22	44.7	53.9
1810	890311	17.0	70	28	43.9	53.8
1840	890311	17.1	69	27	39.7	53.8
1910	890311	17.0	68	33	33.3	53.9
1940	890311	17.0	68	30	27.8	53.9
2010	890311	17.1	68	22	12.8	53.9
2040	890311	17.4	68	173	6.3	53.1
2110	890311	17.6	68	200	16.0	52.4
2140	890311	17.3	72	193	27.8	53.2
2210	890311	17.4	77	215	30.1	53.0
2240	890311	17.7	79	216	33.0	52.1
2310	890311	18.3	79	209	37.3	50.8
2340	890311	18.8	76	227	40.1	49.9
10	890312	19.4	74	216	36.3	48.0
40	890312	19.5	69	222	31.0	47.3
110	890312	19.3	68	269	15.9	47.8
140	890312	18.7	68	29	5.9	49.9
210	890312	17.8	68	26	31.9	52.1
240	890312	17.1	68	18	42.0	53.6
310	890312	17.0	68	25	45.7	53.8
340	890312	17.0	68	21	43.7	53.9
410	890312	17.0	70	25	42.3	54.0
440	890312	17.0	71	22	44.8	54.0
510	890312	17.0	71	28	45.5	53.9
540	890312	17.0	71	26	43.8	54.0
610	890312	16.9	69	29	42.1	54.0
640	890312	17.0	69	21	37.4	54.0
710	890312	17.0	68	18	32.3	53.9
740	890312	17.0	68	19	27.5	53.9
810	890312	17.1	68	15	16.7	53.8
840	890312	17.4	68	30	7.4	53.0
910	890312	17.4	68	182	7.1	52.7
940	890312	17.4	68	193	18.1	52.7
1010	890312	17.4	68	204	28.1	52.9
1040	890312	17.4	68	212	33.1	52.9
1110	890312	17.5	68	211	31.1	52.8
1140	890312	18.1	72	204	33.3	51.2
1210	890312	18.1	72	211	37.5	50.7
1240	890312	18.6	70	214	33.7	49.5
1310	890312	19.0	68	212	28.1	48.7
1340	890312	19.1	68	175	13.0	48.5
1410	890312	18.8	68	48	4.4	49.5
1440	890312	18.5	68	30	27.8	50.4
1510	890312	17.8	68	34	42.0	52.5
1540	890312	17.4	68	30	45.0	53.4
1610	890312	17.2	68	30	41.5	53.9
1640	890312	17.1	69	32	46.6	53.9
1710	890312	17.1	69	32	47.0	54.0
1740	890312	17.1	69	27	46.1	53.9
1810	890312	17.1	69	24	44.4	53.9

APPENDIX 2.3 RAW CURRENT METER DATA FROM SOUTHWEST MASHTAN 8TH - 13TH MARCH, 1989.

Current meter position = Lat. 25.46.10 N, Long. 50.38.51 E. Meter depth 3.5 m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG. MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1840	890312	17.1	68	23	43.0	53.9
1910	890312	17.1	68	21	39.2	53.9
1940	890312	17.1	67	28	35.7	53.8
2010	890312	17.1	67	20	25.9	53.9
2040	890312	17.1	67	22	13.0	53.9
2110	890312	17.4	67	237	7.1	53.2
2140	890312	17.3	67	201	8.2	53.4
2210	890312	17.1	67	200	28.4	53.5
2240	890312	17.1	69	207	36.9	53.6
2310	890312	17.2	70	202	39.1	53.4
2340	890312	17.3	74	210	36.1	53.1
10	890313	17.7	75	204	35.1	51.9
40	890313	18.2	74	217	40.5	50.8
110	890313	18.4	70	229	35.8	50.1
140	890313	18.5	68	222	28.1	49.7
210	890313	18.3	67	347	8.8	50.1
240	890313	18.2	67	31	5.6	50.4
310	890313	17.6	67	31	23.5	52.3
340	890313	17.3	67	24	37.4	53.3
410	890313	17.3	67	27	42.3	53.1
440	890313	17.2	67	22	40.9	53.4
510	890313	17.2	68	21	41.5	53.6
540	890313	17.2	68	26	41.1	53.7
610	890313	17.2	68	26	41.0	53.7
640	890313	17.1	68	26	39.8	53.7
710	890313	17.1	68	25	38.1	53.8
740	890313	17.1	67	28	31.5	53.8
810	890313	17.2	67	26	24.5	53.8
840	890313	17.3	67	19	17.2	53.6
910	890313	17.5	67	25	12.3	53.2
940	890313	17.5	67	44	4.0	52.7
1010	890313	17.5	68	190	4.9	52.8

APPENDIX 2.4 **RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989**

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1430	890308	17.7	63	78	6.8	53.0
1500	890308	17.7	63	100	10.1	53.0
1530	890308	18.8	63	42	4.0	51.3
1600	890308	18.1	63	133	4.2	52.1
1630	890308	18.5	63	122	10.6	52.2
1700	890308	18.7	63	104	11.6	52.0
1730	890308	18.6	63	82	9.4	51.9
1800	890308	18.4	63	75	5.2	51.8
1830	890308	18.6	63	122	6.4	52.1
1900	890308	18.6	63	136	8.0	52.0
1930	890308	18.4	64	137	11.7	52.3
2000	890308	18.3	63	142	11.2	52.4
2030	890308	18.0	64	257	4.4	52.8
2100	890308	18.3	64	67	2.7	52.5
2130	890308	17.8	64	267	2.9	53.0
2200	890308	18.0	64	268	4.1	52.8
2230	890308	18.3	64	307	3.1	52.7
2300	890308	17.8	64	309	3.4	52.8
2330	890308	17.6	64	352	4.1	53.1
0	890309	17.4	64	3	10.9	53.3
30	890309	17.2	64	344	10.4	53.5
100	890309	17.4	64	8	8.7	53.2
130	890309	17.5	64	19	9.6	53.2
200	890309	17.3	64	98	4.2	53.4
230	890309	17.4	64	109	4.7	53.2
300	890309	17.7	64	83	7.3	52.9
330	890309	18.2	64	103	6.9	52.4
400	890309	18.1	64	97	7.7	52.4
430	890309	18.3	64	115	7.9	51.9
500	890309	18.4	64	128	8.4	51.8
530	890309	18.4	64	159	7.5	51.7
600	890309	18.5	64	244	7.3	51.3
630	890309	18.5	64	253	6.6	51.2
700	890309	18.6	64	252	6.6	51.2
730	890309	18.5	64	263	5.9	51.2
800	890309	18.5	64	264	7.3	51.3
830	890309	18.5	64	290	7.3	51.2
900	890309	18.5	64	315	7.0	51.2
930	890309	18.5	64	331	8.7	51.3
1000	890309	18.4	64	357	9.8	51.4
1030	890309	18.2	64	330	8.7	51.8
1100	890309	18.3	64	13	8.3	51.7
1130	890309	18.1	64	5	11.2	52.1
1200	890309	17.9	64	19	17.0	52.4

APPENDIX 2.4 RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1230	890309	17.8	64	14	15.9	52.6
1300	890309	17.8	64	10	12.4	52.6
1330	890309	17.8	64	21	11.2	52.6
1400	890309	17.9	64	73	8.8	52.6
1430	890309	17.9	64	74	7.2	52.5
1500	890309	18.5	64	103	9.0	51.6
1530	890309	18.6	64	103	18.0	51.5
1600	890309	18.6	64	118	15.7	51.6
1630	890309	18.6	64	122	13.4	51.6
1700	890309	18.7	64	87	11.6	51.8
1730	890309	18.8	64	82	11.0	51.5
1800	890309	18.8	64	101	11.0	51.5
1830	890309	18.8	64	102	10.2	51.5
1900	890309	18.8	64	122	7.7	51.5
1930	890309	18.7	64	121	7.1	51.7
2000	890309	18.6	64	116	6.6	51.8
2030	890309	18.7	64	137	7.0	51.6
2100	890309	18.7	64	139	8.3	51.6
2130	890309	18.7	64	85	4.9	51.7
2200	890309	18.6	64	67	6.8	51.7
2230	890309	18.0	64	260	6.4	52.4
2300	890309	18.3	64	310	6.2	52.0
2330	890309	18.0	64	265	7.0	52.4
0	890310	17.9	64	310	7.3	52.5
30	890310	17.7	64	299	9.3	52.7
100	890310	17.4	64	359	11.1	53.1
130	890310	17.4	64	54	13.5	53.1
200	890310	17.5	64	49	10.0	53.0
230	890310	17.8	64	83	8.0	52.7
300	890310	17.5	64	95	7.4	53.0
330	890310	17.9	64	110	8.1	52.4
400	890310	18.4	64	97	9.7	51.7
430	890310	18.5	64	111	8.4	51.7
500	890310	18.7	64	303	8.2	51.0
530	890310	18.7	64	276	8.7	51.0
600	890310	18.7	64	245	6.5	50.9
630	890310	18.7	64	198	7.5	50.8
700	890310	18.8	64	301	7.3	50.7
730	890310	18.7	64	232	5.8	50.8
800	890310	18.7	64	236	6.7	51.0
830	890310	18.7	64	252	10.7	50.9
900	890310	18.8	64	259	8.3	50.9
930	890310	18.7	64	268	5.7	51.0
1000	890310	18.7	64	306	6.6	51.1

APPENDIX 2.4 **RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989**

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
1030	890310	18.6	64	300	8.2	51.4
1100	890310	18.4	64	312	9.8	51.7
1130	890310	18.1	64	20	10.6	52.2
1200	890310	18.2	64	12	12.9	52.2
1230	890310	18.1	64	19	13.5	52.3
1300	890310	18.0	64	27	13.4	52.4
1330	890310	18.0	64	28	10.4	52.4
1400	890310	18.0	64	45	9.5	52.5
1430	890310	18.1	64	71	9.8	52.2
1500	890310	18.2	64	81	10.2	52.0
1530	890310	18.1	64	60	9.8	52.3
1600	890310	18.3	64	109	9.9	52.0
1630	890310	18.3	64	117	12.8	52.0
1700	890310	18.3	64	86	11.0	52.1
1730	890310	18.5	64	106	11.8	51.7
1800	890310	18.5	64	115	15.2	51.7
1830	890310	18.6	64	103	15.4	51.6
1900	890310	18.4	64	141	13.2	51.9
1930	890310	18.5	64	126	11.0	51.8
2000	890310	18.4	64	138	8.4	51.9
2030	890310	19.0	64	148	9.3	51.1
2100	890310	18.2	64	133	8.3	52.3
2130	890310	18.0	64	340	7.1	52.6
2200	890310	18.1	64	215	5.4	52.4
2230	890310	18.0	64	11	6.1	52.6
2300	890310	18.1	66	344	6.5	52.5
2330	890310	17.9	66	334	6.5	52.6
0	890311	17.8	66	352	7.5	52.8
30	890311	17.8	66	350	8.3	52.9
100	890311	17.9	66	352	8.9	52.8
130	890311	17.4	66	3	11.5	53.2
200	890311	17.4	66	14	13.8	53.2
230	890311	17.3	66	18	15.8	53.3
300	890311	17.6	66	55	12.8	52.9
330	890311	17.8	66	66	10.6	52.8
400	890311	18.2	66	62	12.5	52.5
430	890311	18.5	66	44	13.3	51.9
500	890311	18.5	66	72	12.6	51.9
530	890311	18.4	66	88	13.5	52.2
600	890311	18.5	66	94	14.0	51.9
630	890311	18.5	66	88	12.7	51.9
700	890311	18.6	66	121	10.8	51.6
730	890311	18.6	66	136	15.6	51.6
800	890311	18.8	66	136	17.1	51.4

APPENDIX 2.4 **RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989**

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
830	890311	18.7	66	141	16.7	51.6
900	890311	18.5	66	138	16.4	51.8
930	890311	18.7	66	162	12.1	51.5
1000	890311	18.7	66	146	8.2	51.6
1030	890311	18.5	66	49	8.9	51.8
1100	890311	18.1	66	54	8.2	52.4
1130	890311	18.6	66	58	8.7	51.8
1200	890311	18.6	66	66	10.0	51.9
1230	890311	17.9	66	353	11.0	52.7
1300	890311	17.4	66	3	11.6	53.2
1330	890311	17.2	66	22	14.3	53.4
1400	890311	17.0	66	7	12.0	53.6
1430	890311	16.9	66	23	14.0	53.6
1500	890311	17.0	66	20	14.5	53.6
1530	890311	17.0	66	40	12.2	53.6
1600	890311	16.9	66	36	13.1	53.6
1630	890311	16.9	66	37	14.3	53.6
1700	890311	17.0	66	41	14.3	53.6
1730	890311	17.1	66	49	13.8	53.5
1800	890311	17.1	66	59	14.9	53.6
1830	890311	17.7	66	98	17.4	53.1
1900	890311	17.5	66	96	23.7	53.3
1930	890311	17.5	66	98	24.7	53.3
2000	890311	17.4	66	93	20.7	53.3
2030	890311	17.4	66	89	15.2	53.3
2100	890311	17.4	66	76	13.2	53.3
2130	890311	17.4	66	99	9.3	53.4
2200	890311	17.4	66	105	7.3	53.4
2230	890311	17.6	66	139	7.9	53.1
2300	890311	17.8	66	145	8.0	52.8
2330	890311	17.7	66	143	8.3	53.1
0	890312	17.9	66	166	5.1	52.7
30	890312	17.9	66	90	6.6	52.9
100	890312	17.9	66	50	5.1	52.8
130	890312	17.9	66	38	4.3	52.9
200	890312	17.8	66	42	5.1	52.9
230	890312	17.7	66	80	4.5	53.1
300	890312	17.7	66	97	7.4	53.2
330	890312	17.4	66	47	6.8	53.3
400	890312	17.4	66	56	6.2	53.3
430	890312	17.4	66	102	7.8	53.3
500	890312	17.9	66	111	14.9	53.0
530	890312	18.2	66	89	15.2	52.5
600	890312	18.6	66	64	14.5	51.7

APPENDIX 2.4 RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
630	890312	18.5	66	64	15.5	52.0
700	890312	18.5	66	80	14.5	51.9
730	890312	18.3	66	103	14.1	52.0
800	890312	18.3	66	100	12.4	52.1
830	890312	18.4	66	110	12.6	52.1
900	890312	18.4	66	108	12.4	52.2
930	890312	18.5	66	149	9.1	52.1
1000	890312	18.7	66	143	9.8	52.1
1030	890312	19.0	66	152	12.6	52.0
1100	890312	18.5	66	179	10.3	52.5
1130	890312	18.0	66	200	6.8	52.8
1200	890312	18.2	66	145	5.8	52.7
1230	890312	18.1	66	204	6.2	52.7
1300	890312	18.0	66	66	7.5	52.9
1330	890312	18.7	66	82	10.5	52.5
1400	890312	18.5	66	71	9.2	52.8
1430	890312	17.8	66	354	6.8	53.1
1500	890312	17.7	66	355	7.2	53.2
1530	890312	17.5	66	27	7.9	53.3
1600	890312	17.5	66	42	9.2	53.3
1630	890312	17.4	66	57	10.2	53.4
1700	890312	17.5	66	86	10.8	53.4
1730	890312	17.4	66	87	11.6	53.5
1800	890312	17.5	66	51	11.6	53.4
1830	890312	17.5	66	54	10.7	53.4
1900	890312	17.5	66	67	11.2	53.4
1930	890312	17.6	66	78	14.8	53.4
2000	890312	17.7	66	84	17.5	53.3
2030	890312	17.8	66	86	18.5	53.3
2100	890312	17.8	66	91	13.8	53.3
2130	890312	17.9	66	111	9.6	53.3
2200	890312	17.8	66	140	6.7	53.3
2230	890312	18.0	66	124	10.0	53.1
2300	890312	17.9	66	111	8.6	53.2
2330	890312	17.9	66	104	7.0	53.2
0	890313	17.8	66	92	5.2	53.3
30	890313	18.0	66	100	6.5	53.1
100	890313	18.2	66	55	5.9	53.0
130	890313	18.1	66	11	2.9	53.0
200	890313	18.2	66	17	3.3	53.0
230	890313	18.2	66	13	6.0	52.9
300	890313	18.2	66	13	8.0	52.9
330	890313	17.9	66	40	7.9	53.2
400	890313	18.0	66	68	5.6	53.2

APPENDIX 2.4

RAW CURRENT METER DATA FROM WEST AL HUL 8TH - 13TH MARCH, 1989

Current meter position = Lat. 25.42.51 N, Long. 50.33.45 E. Meter depth 6m.

TIME	DATE	TEMP DEG. C	PRESSURE KG/SQCM	CURRENT DIRECTION DEG.MAG.	CURRENT SPEED CM/SEC	SALINITY PARTS PER THOUSAND
430	890313	17.8	66	49	5.9	53.3
500	890313	17.7	66	71	5.8	53.3
530	890313	17.8	66	82	6.0	53.2
600	890313	18.0	66	110	6.4	53.2
630	890313	18.2	66	119	9.8	53.0
700	890313	18.2	66	129	14.2	53.1
730	890313	18.4	66	134	19.7	53.0
800	890313	18.5	66	122	17.3	52.8
830	890313	18.4	66	97	19.8	52.1
900	890313	18.4	66	108	23.6	52.4
930	890313	18.4	66	110	23.4	52.4
1000	890313	18.5	66	106	21.9	52.5
1030	890313	18.6	66	122	23.2	52.6
1100	890313	18.6	66	140	15.0	52.8

APPENDIX 3.1

POSITION AND SAMPLE DATES FOR ALL INTERTIDAL SITES (SUMMER AND WINTER)

SITE NUMBER	DATE	SITE NAME	LATITUDE	LONGITUDE
1	850730	Ad Dayr	26.16.95	50.37.08
2	850730	Galali	26.15.84	50.39.42
2	860227	Galali	26.15.84	50.39.42
3	850730	Muharraq Bridge N	26.14.95	50.36.30
4	850730	Mina Al Manama	26.14.23	50.34.65
5	850729	Portuguese Fort	26.14.03	50.31.45
6	850729	Ras Abu Subh	26.13.22	50.27.26
7	850723	Budaiya	26.12.81	50.26.70
7	860226	Budaiya	26.12.81	50.26.70
8	850730	Al Azl 1Km S	26.12.78	50.39.47
9	860224	Al Muwaylighah	26.12.15	50.34.11
9	850731	Al Muwaylighah	26.12.15	50.34.11
10	850731	Khawr Mugla Tubli	26.12.00	50.34.63
11	850731	Sitra Causeway E	26.11.50	50.35.50
11	860224	Sitra Causeway E	26.11.50	50.35.50
12	850731	Nabih Salih N	26.11.20	50.35.03
13	850731	Jidd Al	26.10.76	50.34.00
14	850729	Causeway North	26.10.75	50.27.20
15	850731	Nabih Salih S	26.10.60	50.34.90
16	850731	Jurdab	26.10.45	50.34.38
17	850807	Jaradah	26.10.40	50.53.94
18	850824	Causeway South	26.09.69	50.26.80
19	860305	Ras Sanad Outer	26.09.16	50.34.73
20	860305	Sanad Sub Flats	26.09.12	50.35.22
21	850725	Ras Sanad Inner	26.09.00	50.35.44
21	860224	Ras Sanad Inner	26.09.00	50.35.44
22	850802	Al Ak	26.08.79	50.37.04
23	850824	Jasrah S 2Km	26.08.70	50.27.05
24	850824	Al Hamalah	26.08.09	50.27.45
25	850827	Um Nasan SW	26.07.27	50.23.47
26	860225	Askar North + 1Km	26.04.35	50.37.33
27	850721	Askar N	26.04.20	50.37.30
28	850727	Zallaq North	26.03.40	50.29.00
29	850802	Askar South	26.03.40	50.37.20
30	850825	Zallaq Jetty	26.03.12	50.29.00
31	850802	Ras Hayyan	26.02.80	50.37.35
31	860225	Ras Hayyan	26.02.80	50.37.35
32	850816	Um Jalid NW	26.01.52	50.43.31
32	860309	Um Jalid NW	26.01.52	50.43.31
33	850816	Um Jalid SE	26.01.48	50.43.29
33	860309	Um Jalid SE	26.01.48	50.43.29
34	860301	Zallaq South	25.59.30	50.28.65
34	850727	Zallaq South	25.59.30	50.28.65
35	850810	Ad Dur	25.58.07	50.37.00
36	850722	Qurayn 5Km S	25.54.40	50.36.60
37	850728	Al Mumtallah	25.54.30	50.30.85
38	850810	Had Al Jamal Jetty	25.49.70	50.35.26
39	850805	Mashtan North	25.48.48	50.41.00
39	860309	Mashtan North	25.48.48	50.41.00
40	850805	Mashtan South	25.48.36	50.40.90
40	860309	Mashtan South	25.48.36	50.40.90
41	850801	Ras Al Barr W	25.48.08	50.33.87
42	850801	Ras Al Barr E	25.48.08	50.33.98
43	860309	Qasar Noon	25.47.28	50.36.18

APPENDIX 3.1

POSITION AND SAMPLE DATES FOR ALL INTERTIDAL SITES (SUMMER AND WINTER)

SITE NUMBER	DATE	SITE NAME	LATITUDE	LONGITUDE
44	850811	Mutarid 300M S	25.47.10	50.42.57
45	850811	Gharbiyah Trans B	25.45.15	50.45.70
46	850811	Gharbiyah Trans A	25.44.92	50.45.75
47	850821	Ajirah	25.44.39	50.49.39
47	860302	Ajirah	25.44.39	50.49.39
48	850813	Hawar Cg Fort	25.43.23	50.47.22
49	850821	Back Island North	25.42.00	50.47.93
49	860302	Back Island North	25.42.00	50.47.93
50	850821	Back Island South	25.41.63	50.47.82
51	860302	Shamaliyah NW	25.40.22	50.47.60
52	850821	Jazur Bu Sadad	25.40.18	50.45.92
53	860302	Shamaliyah SW	25.38.95	50.46.70
54	850813	Bandar Nakiah S	25.37.10	50.45.85

APPENDIX 4.1 SUBTIDAL SURVEY SITES SUMMER 1985 AND WINTER 1986

(* = Coral Study sites, ** = Seagrass Study sites. 109 - 224 = Rapid Survey sites

SITE NUMBER	SITE NAME	SEASON	LATITUDE	LONGITUDE
55 *	Fasht Jarim N	Summer	26.32.28	50.31.90
56 *	Fasht Jarim W	" "	26.30.85	50.28.57
57 *	Fasht Jarim SW	" "	26.25.43	50.26.31
58 *	Muharraq NW	" "	26.15.00	50.34.00
59 *	Khawr Fasht 8m	" "	26.20.87	50.22.86
60 *	Khawr Fasht 3m	" "	26.20.87	50.22.86
61 *	Muharraq NE	" "	26.18.20	50.40.70
62 *	Dibal NW 8m	" "	26.17.28	50.54.45
63 *	Dibal NW 6m	" "	26.17.28	50.55.40
64 *	Dibal NW 2m	" "	26.17.28	50.56.27
65 *	Sala N Slope	" "	26.15.00	50.28.00
66 *	Dibal Central W	" "	26.15.20	50.54.79
67 *	Jaradah WNW	" "	26.11.40	50.53.40
68 *	Jaradah NE	" "	26.11.40	50.54.48
69 *	Jaradah SE	" "	26.10.60	50.54.10
70 *	Seistan Wreck	" "	26.09.50	50.43.50
71 *	Fasht Adhm W Off	" "	26.09.25	50.42.10
72 *	Fasht Adhm Channel	" "	26.09.08	50.44.20
73 *	Fasht Adhm W Front	" "	26.08.68	50.42.23
74 *	Fasht Adhm CF 10m	" "	26.08.18	50.46.67
75 *	Fasht Adhm CF 8m	" "	26.07.96	50.46.83
76 *	Fasht Adhm CF 9m	" "	26.07.50	50.46.70
77 *	Fasht Adhm C Front	" "	26.07.25	50.45.38
78 *	Fasht Adhm C Front	" "	26.08.22	50.46.62
79 *	Fasht Adhm CF 1.5m	" "	26.07.19	50.45.20
80 *	Fasht Adhm CF 6m	" "	26.07.00	50.45.70
81 *	Half Tanker	" "	26.06.61	50.46.22
82 *	Fasht Adhm CF 1m	" "	26.06.50	50.44.65
83 *	Fasht Adhm Flat 1m	" "	26.06.30	50.42.26
84 *	Fasht Mollusc Reef	" "	26.04.90	50.39.70
85 *	Ad Dur	" "	25.58.70	50.36.60
86 *	Fasht Bu Thur	" "	25.48.95	50.45.85
87 *	Hawar Ajirah	Winter	25.44.58	50.49.25
88 **	NE Transect NC	Summer	26.24.00	50.43.50
89 **	NE Transect SC	" "	26.21.00	50.42.00
90 **	Muharraq NW Off	" "	26.18.10	50.36.10
91 **	Sanabis N Off	" "	26.16.20	50.31.10
92 **	Jaradah S Off	" "	26.09.20	50.53.20
93 **	Fasht Adhm NW	" "	26.08.00	50.41.80
94 **	Tonque NW Off	" "	26.07.00	50.53.00
95 **	Fasht Adhm SW	" "	26.04.90	50.39.70
96 **	Fasht Adhm S	" "	26.04.10	50.43.00

APPENDIX 4.1 SUBTIDAL SURVEY SITES SUMMER 1985 AND WINTER 1986

(* = Coral Study sites, ** = Seagrass Study sites. 109 - 224 = Rapid Survey sites

SITE NUMBER	SITE NAME	SEASON	LATITUDE	LONGITUDE
97 **	B-Q Transect UJ	" "	26.01.30	50.43.80
98 **	B-Q Transect W	" "	25.59.00	50.44.90
99 **	B-Q Transect CW	" "	25.56.80	50.46.26
100 **	Tighaylib NW	" "	25.55.10	50.41.90
101 **	Gabbari N Post	" "	25.55.00	50.40.00
101 **	Gabbari N Post	Winter	25.55.00	50.40.00
102 **	B-Q Transect E	Summer	25.53.80	50.48.70
103 **	B-Q Transect Q	" "	25.53.80	50.50.20
104 **	Gabberi S Cairn	Winter	25.53.20	50.38.90
104 **	Gabbari S Cairn	Summer	25.53.20	50.38.90
105 **	Twins S Off	" "	25.50.60	50.50.56
106 **	Mashtan NW Arm	" "	25.50.00	50.41.70
107 **	Mutarid NW	" "	25.47.30	50.42.90
108 **	Hawar W Off	" "	25.42.28	50.44.16
109	NE Transect N	" "	26.26.00	50.45.00
110	Fasht Jarim S	" "	26.22.50	50.27.62
111	NE Transect S	" "	26.18.20	50.40.70
112	Sala N Off	" "	26.16.14	50.26.90
113	Galali	" "	26.15.84	50.39.42
113	Galali	Winter	26.15.84	50.39.42
114	AH Transect C	Summer	26.14.50	50.43.30
115	Mina al Manama	" "	26.14.25	50.34.50
116	Portuguese Fort	" "	26.14.20	50.31.28
117	Budaiya	" "	26.13.00	50.26.80
117	Budaiya	Winter	26.13.00	50.26.80
118	AH Transect E	Summer	26.13.00	50.45.50
119	Jazirat al Azl	" "	26.12.50	50.39.00
120	AH Transect W	" "	26.12.50	50.41.90
121	Al Muwaylighah	" "	26.12.20	50.34.00
121	Al Muwaylighah	Winter	26.12.20	50.34.00
122	Jiddah WSW	Summer	26.12.10	50.23.00
123	Causeway N 2 km	" "	26.11.97	50.21.77
124	Tubli N Channel	Winter	26.11.75	50.35.33
125	Jiddah S Off	Summer	26.11.70	50.22.60
126	Khawr Mugla Tubli	" "	26.11.50	50.33.60
127	Sitra Causeway E	Summer	26.11.50	50.35.50
127	Sitra Causeway E	Winter	26.11.50	50.35.50
128	Tubli Deeps	Winter	26.11.46	50.34.50
129	Um Nasan NW	Summer	26.11.30	50.22.20
130	Nabih Salih N	" "	26.11.30	50.35.00
131	Jaradah	" "	26.11.30	50.54.60
132	Bridge 4 N	" "	26.11.00	50.23.00

APPENDIX 4.1 SUBTIDAL SURVEY SITES SUMMER 1985 AND WINTER 1986

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SITE NUMBER	SITE NAME	SEASON	LATITUDE	LONGITUDE
133	Causeway Under	" "	26.10.90	50.21.80
134	Causeway N	" "	26.10.90	50.27.10
135	Tubli SE al Ak	" "	26.10.70	50.34.90
136	Nabih Salih S	" "	26.10.60	50.35.00
137	Al Baynay	" "	26.10.37	50.18.93
138	Central Island SW	" "	26.10.30	50.19.50
139	Central Island SE	" "	26.10.30	50.20.00
140	Causeway S 1km	" "	26.10.25	50.21.75
141	Jurdab	" "	26.10.20	50.33.60
142	Causeway S	" "	26.09.50	50.26.80
143	Ras Sanad Offshore	Winter	26.09.15	50.35.00
143	Ras Sanad Offshore	Summer	26.09.15	50.35.00
145	Ras Sanad Sub Flats	Winter	26.09.12	50.35.22
144	Ras Sanad Inshore	Winter	26.09.00	50.35.44
144	Ras Sanad Inshore	" "	26.09.00	50.35.44
146	Jaradah S Off	Summer	26.09.00	50.53.00
147	Al Jasrah S	" "	26.08.70	50.26.70
148	Fasht Adhm N DP	" "	26.08.70	50.45.40
149	Al Hamalah	" "	26.08.00	50.26.90
150	Al Baynay S	" "	26.07.80	50.18.88
151	Um Nasan W	" "	26.07.80	50.20.40
152	Um Nasan SW Coast	" "	26.07.50	50.23.50
153	Hajaz ENE 550m	" "	26.07.00	50.46.90
154	Um Nasan SW OFF	" "	26.06.00	50.20.00
155	Tonque Trans 5	" "	26.06.00	50.53.00
156	Fasht Adhm Flat 1m	" "	26.05.85	50.43.40
157	West Yasuf N	" "	26.05.00	50.24.00
158	Tonque NE	" "	26.05.00	50.52.50
159	Tonque Trans 4	" "	26.05.00	50.53.00
160	Tonque West 4	" "	26.04.88	50.52.00
161	Tonque West 3	" "	26.04.66	50.52.00
162	Tonque West 2	" "	26.04.51	50.52.00
163	West Yasuf S	" "	26.04.50	50.24.00
164	Tonque Bay 2	" "	26.04.50	50.51.00
165	Tonque Bay 3	" "	26.04.50	50.51.00
166	Tonque 1m	" "	26.04.48	50.52.10
167	Tonque W 1	" "	26.04.41	50.52.00
168	Askar North + 1Km	Winter	26.04.35	50.37.33
169	Tonque Bay 1	Summer	26.04.20	50.51.00
170	Tonque Trans 3	" "	26.04.00	50.53.00
171	Askar N	" "	26.04.00	55.37.20
172	Zallaq N	" "	26.03.40	50.29.00

APPENDIX 4.1 SUBTIDAL SURVEY SITES SUMMER 1985 AND WINTER 1986

(* = Coral Study sites, ** = Seagrass Study sites. 109 - 224 = Rapid Survey sites

SITE NUMBER	SITE NAME	SEASON	LATITUDE	LONGITUDE
173	Zallaq Old Jetty	" "	26.03.00	50.28.60
174	Tonque Trans 2	" "	26.03.00	50.53.00
175	Ras Hayyan	" "	26.02.80	50.37.35
175	Ras Hayan	Winter	26.02.80	50.37.35
176	Ghumays Trans 3	Summer	26.02.72	50.53.95
177	Ghumays Trans 2	" "	26.02.61	50.53.95
178	Ghumays Trans 1	" "	26.02.52	50.53.95
179	Tonque W Trans 1	" "	26.02.00	50.53.00
180	Um Jalid SE	" "	26.01.60	50.43.50
180	Um Jalid SE	Winter	26.01.60	50.43.50
181	Um Jalid NW	Summer	26.01.60	50.43.70
181	Um Jalid NW	Winter	26.01.60	50.43.70
182	Al Jazair off	Summer	26.01.50	50.26.00
183	Zallaq South	Winter	26.01.50	50.28.85
183	Zallaq South	Summer	26.01.50	50.28.85
184	Ras Nawmah Off	" "	25.59.50	50.26.00
185	West Deeps N	" "	25.59.00	50.21.00
186	Al Jazair Off	" "	25.56.87	50.26.64
187	West Coast Deeps	" "	25.56.00	50.20.00
188	Jazair S Transect 2	" "	25.55.24	50.26.75
189	Jazair S Transect 3	" "	25.55.24	50.27.26
190	Jazair S Transect 1	" "	25.55.22	50.26.38
191	Jazair S Transect 5	" "	25.55.22	50.27.59
192	Jazair S Transect 4	" "	25.55.06	50.27.23
193	Al Jazair S Off	" "	25.55.00	50.29.00
194	B-Q Transect CE	" "	25.54.90	50.47.40
195	Ras al Qurayn	" "	25.54.80	50.36.60
196	Ras al Mumtallah	" "	25.54.30	50.30.70
197	Mumtallah W Off 7m	" "	25.52.00	'50.25.00
198	Mumtalah W Off 12m	" "	25.52.00	50.23.00
199	Mumtallah S Off	" "	25.52.00	50.31.00
200	Qasar Noon N Off	" "	25.50.24	50.37.91
201	Hadd al Jamal	" "	25.50.00	50.35.90
202	Mashtan SW Off	" "	25.48.79	50.39.64
203	Mashtan North	" "	25.48.48	50.41.00
203	Mashtan North	Winter	25.48.48	50.41.00
204	Mashtan South	Summer	25.48.36	50.40.90
204	Mashtan South	Winter	25.48.36	50.40.90
205	Qasar Noon E Off	Winter	25.47.45	50.36.55
206	Ras al Barr W	Summer	25.47.30	50.34.00
207	Ras al Barr E	" "	25.47.30	50.34.00
208	Mutarid S 300m	" "	25.46.92	50.42.35

APPENDIX 4.1 SUBTIDAL SURVEY SITES SUMMER 1985 AND WINTER 1986

(* = Coral Study sites, ** = Seagrass Study sites. 109 - 224 = Rapid Survey sites

SITE NUMBER	SITE NAME	SEASON	LATITUDE	LONGITUDE
209	Gharbiyah N	" "	25.46.40	50.46.50
210	Gharbiyah Trans A	" "	25.45.00	50.45.60
211	Gharbiyah Trans B	" "	25.45.00	50.45.60
212	Jazirat Ajirah	Summer	25.44.39	50.49.38
212	Jazirat Ajirah	Winter	25.44.39	50.49.39
213	Gharbiyah S Off	" "	25.44.02	50.45.95
214	Hawar Coastguard	" "	25.43.30	50.46.60
215	Back Island North	Winter	25.42.00	50.47.95
215	Back Island North	Summer	25.42.00	50.47.95
216	Qasar Noon E In	" "	25.41.27	50.36.39
217	Jazur Bu Sadad	" "	25.40.60	50.46.00
218	Shamaliyah NW	Winter	25.40.22	50.47.60
218	Shamaliyah SW	Winter	25.38.95	50.46.70
219	Bandar Nakhiah	Summer	25.37.10	50.45.00
220	Hawar SW Off	" "	25.35.65	50.43.30
221	Janan N Off	" "	25.34.23	50.43.57
222	Janan N Coast	" "	25.33.59	50.43.81

APPENDIX 4.2

BRIEF DESCRIPTION OF THE CORAL AND CORAL REEF SITES SURVEYED

This includes the major reefs, or fashts, around Bahrain whether or not they can be correctly regarded as living coral reefs at the present time. It also includes some areas where corals occur on non-reef, artificial and soft substrates. Locations are the approximate positions on which the reefs are centered.

(NB. Salinity measurements are single readings taken immediately subsurface in August, 1985.)

Name: Fasht Dibal **Position:** 26° 15' N, 50° 56.50' E.
No. of Sites: 4 **Depths Surveyed:** NW (2m, 6m, 8m) Central W (8 m).
Salinity: 42 ppt at all sites

Description:
Gentle slopes exist along the entire western side. Shallow parts are generally almost devoid of live coral, although numerous recently killed colonies were seen, especially of Acropora. At the shallowest site on the NW transect, Porites nodifera provided 15% cover, but deeper on this reef there is less coral. At the Central West site there is more coral. Acropora dominates and provides a 20% cover. Only 13 species of coral were found on this reef in the survey.

Name: Qit Al Jaradah **Position:** 26° 11' N, 50° 54' E.
No. of Sites: 3 **Depths Surveyed:** NE (0-3 m), WNW (0-3 m), SE (0-3 m).
Salinity: 42 ppt at all sites

Description:
Gentle slope all around. Corals are found at all depths between low water and 4 m, then sand covers the substrate to at least 7 m deep. This is merely a thin layer in the south, but thicker sand which supports some seagrass is found on other sides of this reef. Where there is coral, this is dominated at all sites by Acropora which may reach 40% cover, but for the most part the reef has a low coral diversity (11 species). However, it contains the only substantial growths of Stylophora pistillata seen in Bahrain. Large areas of the reef flat are covered by sand, which forms emergent banks in the south.

Name: Between Qit Al Jaradah and Fasht al Adhm **Position:** 26° 09' N, 50° 53' E.
No. of Sites: 2 **Depths Surveyed:** Shallow, < 3m
Salinity: 42 ppt.

Description:
Horizontal substrate with a thin cover of sand. Currents were strong on both occasions when this area was examined, and the sand layer was mobile. A few corals are attached to the substrate beneath the thin sand layer, mainly Siderastreids and Acropora, together with the alga Sargassum. There was also a very sparse scattering of the seagrass Halodule uninervis in places.

Name: Fasht Jarim
Position: 26 27' N, 50 30' E.
No. of Sites: 4
Depths Surveyed: N (2m), W (3m), SW (3m), S (2m).
Salinity: 44 ppt.

Description:
Very extensive, gentle slopes all around this large reef. Despite this there is very limited hard substrate since sand is reached at depths of about 3-4 m, or shallower in the south where sand commenced from the low tide level and supported extensive seagrass beds at 2 m deep. There is a very low coral diversity for such a large reef (7 species) and very low coral cover (<2%) on all observed areas. The water was exceptionally turbid at the time of the visit, with a visibility of less than 3 m in most parts. North and west sites showed evidence of numerous, recently killed corals, especially Acropora and Porites.

Name: Khawr Fasht
Position: 26^0 21' N, 50^0 24.5' E.
No. of Sites: 2
Depths Surveyed: N (1-3 m, 8 m).
Salinity: 48 ppt on the surface, thermocline at 4 m with cooler water beneath of unrecorded salinity.

Description:
A gentle slope initially, followed by a 10° slope to 6 m, then horizontal substrate with about 50% sand cover. The shallower regions are largely devoid of coral and have a 50% cover of filamentous green algae. The deeper site on this reef slope, by contrast, revealed 17 species of coral and a coral cover of 45%. The dominant coral genus is Porites, which formed numerous colonies over 2 m diameter. At this site, several groups of fish were seen (eg. Scaridae, Acanthurus) in an abundance not seen elsewhere in Bahrain.

Name: Sala
Position: 26^0 16' N, 50° 26' E.
No. of Sites:
Depths Surveyed: North and east of reef, surface to 4 m.
Salinity: 50 ppt.

Description:
This small reef was almost entirely devoid of living corals. Three species only were seen on the north and west sides, providing a total cover of no more than 2%. Other biota was also scarce. Green filamentous algae covered only 3% of the rock, while encrusting red algae covered 10%. The remainder of the surface was bare rock, with a fine film of sediments. The form of the reef was typical of a living reef with steep fore-reef slopes, and the form of its rocky outcrops suggested that at least one of the species present, Porites nodifera, had recently been much more abundant. The high salinity of the water surrounding this reef is sufficient to account for its present paucity of fauna.

Name: Northwest of runway, Muharraq Island.
No. of Sites: 1
Salinity: 45 ppt.

Position: 26° 15' N, 50° 34' W.
Depths Surveyed: 0-3 m deep.

Description:
This site has the topography of a complex fringing reef and series of shallow patch reefs around northwest Muharraq Island. At the time of the visit it was largely devoid of corals, however, which together with filamentous green algae provided less than 5% cover each. Encrusting red algae provided 15% cover. A total of only nine coral species existed at the time of the survey, and there were also large patches of zoanthids. It shares many of the characteristics of Sala (above) especially in its topography of fairly steep reef slopes and in the presence of numerous, recently dead colonies of Porites. As with Sala, this suggests that the present paucity of life is a recent development.

Name: Site northeast of Muharraq Island
No. of Sites: 1
Salinity: 42 ppt.

Position: 26°18.2' N, 50°40.7' E.
Depths Surveyed: 0-3 m deep.

Description:
A flat rock platform with a thin cover of coarse sand. Strong currents ensure that this site is scoured by mobile sediment, which is reflected in its low (5%) cover of corals. The prominent species are Acropora and Plesiastrea. Algal cover is minimal (<1%), and no Sargassum was observed.

Name: Soft substrate northeast of Muharraq Island.
No. of Sites: 2
Salinity: 42 ppt.

Position: 26° 25' N, 50° 42' E.
Depths Surveyed: 15 and 18m deep.

Description:
A flat muddy substrate, without seagrass. The mud was colonised by the free living, ahermatypic coral Heterocyathus heterocostatus at about 1-3 m^{-2}.

Name: Wreck of Seistan
No. of Sites: 1
Salinity: 44 ppt.

Position: 26° 9.5' N, 50° 43.5' E.
Depths Surveyed: 15 - 18m deep.

Description:
The wreck provides a substrate of metal plates, which support numerous corals. These include some species not found elsewhere in the present survey and not found previously in Bahrain, in particular, Paracyathus and Culicia. In addition to these the coral fauna, although low in cover, is relatively diverse.

Name: "Mollusc reef", rear of Fasht al Adhm
No. of Sites: Entire reef
Salinity: 45 ppt.

Position: 26° 4.9' N, 50° 39.7' E.
Depths Surveyed: 1 m

Description:
This small patch reef was found in the lee of Fasht al Adhm in an area of very high turbidity. Corals are few, but the reef has an average 10% cover of the bivalve mollusc Chama pacifica. This species is strongly cemented onto rock and while one valve is lost on death the other remains, forming further substrate. The reef graded into fine, soft substrate at about 1 m deep, where seagrass was present.

Name: Fasht Bu Thur
No. of Sites: Entire patch reef
Salinity: 46 ppt.

Position: 25° 48.7' N, 50° 47' E.
Depths Surveyed: 3 m

Description:
A small patch reef about 100 m in diameter arising from a seagrass bed and sand at 3 m deep. Porites nodifera colonies form this small reef, and cover 65% of its surface. Only 3 other coral species are present. The bivalve Chlamys ruschenbergerii is very abundant amongst the columns of Porites.

Name: Ad Dur
No. of Sites: Entire patch reef
Salinity: 45 ppt.

Position: 25° 55.5' N. 50° 37' E.
Depths Surveyed: 3 m

Description:
A small patch reef of not more than 100 m diameter arising from sand at about 3 m deep. Porites nodifera dominates the community, covering 40% of the substrate, and forming the reef itself. Only 3 other coral species were present.

Name: Fasht al Adhm
No. of Sites: 14 Total

Position: 26° 05' N, 50° 45' E.
Depths Surveyed: Various

Transect 1: 3 sites on longitude 50° 42'. — 3.5m and 7m on fore reef slope, lm on back reef

Transect 2: 11 sites near longitude 50° 46'.

3 sites on reef flat	1 m.
1 site	5 m.
2 sites	6 m.
2 sites	8 m.
2 sites	9 m.
1 site	10 m.

Salinity: 42 ppt on all sites deeper than 3 m.
45 ppt on the reef flat of transect 2.
45 ppt on back reef site of transect 1.

Description:
This large reef was surveyed in some detail by Barratt and Ormond (1985) and the present work aimed not to duplicate the latter survey. Instead, the work done on it was intended to provide a sound reference to permit an assessment of all the reefs of Bahrain, and to place Fasht al Adhm in this context. Maps in Barratt and Ormond (1985) show locations of the major habitats on Fasht al Adhm. However, observations in this survey do not agree closely with the latter in some important respects.

In general, the central third of the fore reef slope has the highest diversity and/or cover of corals. Shallow parts are poor in both features, but both increase with increasing depth according to the pattern described in the chapter. To both the east and west of this central section, the dominant coral is Acropora whose cover is very variable but which is commonly over 40%, intermixed with patches and larger expanses of sand. This extends to the west as far as 50° 43' at least; and as far east as 50° 53' at least. It is possible that the map in Barratt and Ormond (1985) is rather misleading as it suggests a significantly smaller region of good coral growth. In part this is an unfortunate consequence of the cover classes selected in their survey and their implication that cover of less than 50% is in some way less rich than cover values of over 50%. In fact, highest diversity values are generally found with coral cover of just under 50%.

The reef flat is devoid of much coral growth, although various depressions support Acropora and several species of Faviid in particular. The hard substrate supports substantial amounts of filamentous green algal growth. Barratt and Ormond (1985) remark that this area is of low biological value. In relative terms this is clearly true with respect to diversity. However, this region of many reef flats is commonly that which fixes nitrogen the most rapidly and which has a productivity as high as any other part. In such cases there are few resident fauna to utilise the nutrients which instead are swept off and utilised in the back reef regions. This is probably the case with Fasht al Adhm, but this has not been confirmed.

In the back reef regions of transects 1 and 2 there is an increased diversity compared with the reef flat, but still a very low coral cover. One area, dominated by bivalves and termed "mollusc reef" is described separately in this appendix.

The coral composition and cover values of all species at the principal sites of this survey are given in a appendix 4.3. The eastern part of the Fasht was briefly examined after the initial study was completed. Details gained were insufficient to include these sites in the main analysis, and the data obtained is given here. Comprehensive searches for all species were not conducted. Instead observations were made to determine which species dominated.

SITE		DEPTH (M)	SUBSTRATE CHARACTER
50°53.95'E,	26°2.52'N	1.5	Rubble
	26°2.61'N	6	Sand, seagrass
	26°2.72'N	7	Sand
50°53'E,	26°2.00'N	6	30% dead coral, sargassum, sand
	26°3.00'N	5	Rubble, 30% Acropora, 5% P. compressa
	26°4.00'N	5	Rubble, 20% Acropora, 5% P. compressa
	26°5.00'N	5	Sand/rubble, 25% Acropora,
	26°6.00'N	6	Sand

50°52.1'E,	26°4.48'N	1	50% Acropora, 5% P. nodifera
50°52'E,	26°4.41'N	1	15% P. nodifera, 60% green algae
	26°4.51'N	5	40% Acropora, 5% P. nodifera
	26°4.66'N	5	40% Acropora
	26°4.88'N	8	99% sand
50°51'E,	26°4.20'N	1	20% Acropora, 15% Platygyra
	26°4.50'N	5	40% Acropora, mostly dead + rubble
	26°4.50'N	11	Sand

High coral cover exists extensively over the eastern quarter of Fasht al Adhm. Subjective impressions indicated that overall diversity is not as great as in the central section, but this is not uncommon in Acropora dominated substrates.

In conclusion, Fasht al Adhm contains very large expanses of corals in a moderately varied arrangement of different assemblages. The present survey suggests that the extent and variety of corals is significantly greater than could be suggested with the methods of Barratt and Ormond (1985). Further searches using accurate position fixing apparatus is required to determine this over the remainder of the reef, particularly in the relatively unstudied western side.

APPENDIX 4.3

CORALS OF BAHRAIN

The following list includes all species of corals found in Bahrain during this survey. Checks were also made to discover whether other, earlier studies have obtained species record not found in the present survey, but it appears that the few earlier surveys have been concerned with identification only to genus. The list is annotated where necessary to provide a clearer description of the coral and their locations on the reefs of Bahrain.

ORDER SCLERACTINIA

Family - THAMNASTERIIDAE

Psammocora contigua (Esper)
This is a small branching form with calices of about 1-2 mm diameter. Fairly common below 5 m deep.

Family - POCILLOPORIDAE

Stylophora pistillata (Esper)
In Fasht al Adhm and reefs in the northwest of Bahrain this species, which is usually very common in the Indian Ocean region, was extremely rare or absent. It was found on Fasht Dibal and Qit Al Jaradah in greater abundance.

Family - ACROPORIDAE

Acropora sp 1
This large, "stag's horn" species is extremely abundant in depths of between 2-5 metres on several of the reefs, particularly Fasht al Adhm where it forms a cover of over 80% over thousands of square metres.

Acropora sp 2
This species co-occurs with species No. 1 and is distinguished by its more tabular growth form and by its thinner branches. These two species cannot be separated on the basis of their fine structure but only on their growth form. Small samples of species No. 2 usually have thinner branches.

Acropora sp 3
This species is readily distinguished from both of the above. It has a smaller, bushy growth form, and its corallites are much broader and more prominant, with oval or dimidiate apertures.

Family - SIDERASTREIDAE

Siderastrea savignyana - Edwards and Haime

Pseudosiderastrea tayamai - Yabe and Sugiyama

Anomastrea irregularis - Marenzeller

Coscinaraea monile - (Forskal)

Family - PORITIIDAE

Porites lutea - Edwards and Haime

Porites compressa - Dana

This is a common species below about 5 m deep. It forms colonies exceeding 2 m in diameter and characterised by large, thick spires. It may provide a cover of over 20% in some areas, particularly Fasht al Adhm.

Porites nodifera - Klunzinger

This is a widespread species, usually occuring in shallower water than the above, and it is abundant in small, localised patches off East Bahrain such as Gabbari and Fasht Bu Thur where salinity is high. In these areas it is the principal reef builder. Its growth form is one of small, nodule-like spires, often heavily colonised by the bivalve Chlamys ruschenberqerii.

Porites (Porites) ?murrayensis - Vaughan

Family - FAVIIDAE

Favia speciosa (Dana)
Favia pallida (Dana)
Favia favus (Forskal)

Favites chinensis (Verrill)
Favites pentaqona (Esper)
Favites sp 1

An uncommon species the size of F. chinensis. Only one specimen has been collected, and is inadequate for the determination of the species.

Platygyra daedalea (Ellis and Solander)

Some specimens are large enough to be mistaken for P. lamellina and the latter species is recorded for the Gulf by Burchard (1979); indeed in the Red Sea Scheer and Pillai (1983) consider the two species to be synonyms. However, in most regions they are distinct, and specimens of the Bahrain species fit P. daedalea as in Veron et al (1977).

Platygyra sinensis (Edwards and Haime)

A species found mostly in very shallow water, this may be mistaken for a Favites because of its largely monocentric calices.

Plesiastrea versipora (Lamarck)

Many examples of this common species showed very large corallites, which reach the size of those of Montastrea annuligera, with which small samples could be confused. There is a tendency towards intratentacular budding as noted by Burchard (1979).

Leptastrea purpurea (Dana)

Cyphastrea microphthalma (Lamarck) Cyphastrea serialia (Forskal)

Family - RHIZANGIIDAE

Culicia cf. rubeola (Quoy and Gaimard)

A small, ahermatypic species forming colonies in dark areas, most especially in crevices, and seen in greatest abundance on the wreck of the Seistan at 18 m deep.

Family - MUSSIDAE

Acanthastrea echinata (Dana)

A very uncommon species in Bahrain, and found only in very small colonies of less than 10 calices each.

Family - CARYOPHYLLIDAE

Paracyathus sp 1.

A common, solitary, ahermatypic coral which is common in deeper water, most conspicuously on the wreck of the Seistan.

Heterocyathus heterocostatus Harrison

This is a very abundant species found on silty sand and mud to the north and east of Bahrain. It is not usually found with seagrass. Scheer and Pillai (1983) have synonymised this species with H. aequicostatus. However, the Bahrain species always has a flared calice in common with the type from Karachi, and is dissimilar in appearance to H. aequicostatus. It is the only free-living coral found in Bahrain.

Family - DENDROPHYLLIDAE

Turbinaria peltata (Esper)

This species has calices of over 4 mm diameter. Both this and the next species usually occur in water over 10 m deep.

Turbinaria crater (Pallas) Foliaceous, with smaller calices than the above.

APPENDIX 4.4

HABITAT DESCRIPTIONS FOR SOFT-BOTTOM/MOBILE SUBTIDAL SITES

Information on locations, salinities and water depth are accessible from the data matrix (See Tables 4.7 and 4.8). Also further details on flora and fauna present can be found within the matrix. (C) indicates sites at which core samples were taken for infaunal analysis.

Site 1 (850722b) (C)

Occasional seagrass (H. uninervis and H. stipulacea); little surface fauna, infauna dominated by polychaetes and molluscs.

Site 2 (850730p) (C)

H. stipulacea dominant seagrass species, up to 80% cover, H. uninervis less common (<10% cover); both seagrasses with heavy epiphytic algal growth; blue-green algae abundant, especially where seagrass absent; no conspicuous macrofauna, though asteroid (Astropecten polyacanthus phragmorus) and anemone
present on sand near seagrass; infauna dominated by polychaetes and small bivalves.

Site 3 (850801p) (C)

2 seagrass species (H. uninervis and H. stipulacea) up to 60% cover, and sand. Brown algae (Padina sp.) patchily distributed over sand; bivalve (Pinna sp.) and sand dollar (Clypeaster humilis) most conspicuous macrofauna; infauna including polychaetes, molluscs, crustaceans and ophiuroids (Amphioplus (Lymanella) sp.); occasional reef/rock patches containing various oysters, and also artificial structure containing hydroids and tunicate species (e.g. Phallusia nigra).

Site 4 (850801t)

Sparse H. ovalis (up to 40% cover) on soft, gelatinous mud coated with blue-green algae (up to 60% cover); occasional sand dollars (C. humilis) and very occasional "volcanoes"; infauna dominated by polychaetes and small bivalves.

Site 5 (850801u)

Mud with extensive blue green algae/benthic microflora (up to 85% cover) and very sparse (<1% cover) H. stipulacea: burrows and occasional "volcanoes" present, otherwise no conspicuous biological features; infauna dominated by polychaetes and small bivalves.

Site 6 (850801r)

Silty mud and seagrass dominated by H. ovalis (up to 40% cover) and some H. stipulacea (<5% cover); purple sponges and sand dollars (Clypeaster humilis) most conspicuous macrofauna; infauna dominated by polychaetes and small molluscs.

Site 7 (850801s)

Dense seagrass beds in silty mud, dominated by H. uninervis (up to 100% cover)with dense epiphytic algae; occasional H. stipulacea,dense in patches (60% cover); purple sponges most conspicuous macrofauna.

Site 8 (850805u)

Dense monospecific seagrass beds of H. uninervis (up to 80% cover) over sand, with white epiphytic tunicates dominant and gastropods (Cerithium scabridum) common; other fauna include cerianthid anemones, penatulids (uncommon), crustaceans (Cymodoce, Squilla and crabs); occasional rocks with attached hydroids also present.

Site 9 (850805t)

Seagrass bed on silty sand, dominated by H. uninervis (>50% cover) and occasional H. stipulacea (5% cover), both with dense epiphytic algal covering; including hydroids, at least 3 sponge species (including red sponge, blue/purple Haliclona, grey sponge) and tunicates (Phallusia nigra and Didemnum sp. epiphytic on seagrass).

Site 10 (850805s)

Seagrass bed on silty mud, represented by 3 seagrass species, but H. uninervis dominant (70% cover); encrusting biota dominant, including hydroids, at least 2 sponge species (red sponge, blue Haliclona) and tunicates (Didemnum sp.).

Site 11 (850805q) (C)

Dense seagrass bed in silt, dominated by H. uninervis (up to 80% cover with heavy epiphytic algal growth) and some H. stipulacea (up to 30% cover, without epiphytes); red sponge and epizoic ophiuroids (Ophiothrix savignyi) most conspicuous macrofauna, and shrimp/goby burrows also present.

Site 12 (850805p)

Moderately dense seagrass bed, consisting of H. uninervis (up to 50% cover, with notably heavy epiphytic algal growth, as well as some drifted H. stipulacea; hydroid dominant macrofauna, cerianthids and orange sponge also present; occasional rocks present with attached tunicates (Phallusia nigra).

Site 13 (850807q)

Subtidal rock with sand veneer up to 5 cm thick and thin stands of seagrass (H. uninervis and H. ovalis up to 30% cover, the former with epiphytic algae); shrimp/goby burrows and large bivalves (Pinna sp.) most conspicuous sand fauna, with hydroids and tunicates also present.

Site 14 (850807p)

Subtidal rock/coral, with thin veneer of sand and moderately well distributed seagrasses (H. uninervis and H. ovalis), but stands of both thin (<5% cover); predominantly sand macrofauna; oyster spat (probably Pinctada) on seagrass blades (and on Sargassum attached to rocks), shrimp/goby burrows and tunicates; cerianthid anemones, sand dollars (Echinodiscus auritus) and tests of other echinoids (Metalia townsendi and Temnopleurus toreumaticus) also present; spider crabs included in infauna; other fauna mostly associated with rocky substrates.

Site 15 (850810r)

Silt with dense seagrass bed (H. uninervis and H. stipulacea) up to 60-75% cover, but with little epiphytic algal growth; surface macrofauna represented by 2-3 sponge species (red, purple/brown species and Haliclona sp.), epizoic tunicates, anemones (Cassiopeia andromeda), asteroids (Asterina burtoni) and tunicates (Phallusia nigra).

Site 16 (850810q)

Silty sand with dense seagrass bed containing 3 species (with little epiphytic algal growth), but dominated by H. uninervis (up to 90% cover); some areas containing both seagrass and brown algae (Hormophysa triquetra); blue sponge (Haliclona sp.) predominant; other conspicuous macrofauna included cerianthid anemones, hydroids, penatulids and tunicates (Phallusia nigra and epiphytic species).

Site 17 (850810P)

Substrate coral sand, patches of seagrass (H. uninervis up to 60% cover), outcrops of reef corals/rocks with dense attached brown algae (Padina sp.); little macrofauna apparent on sand or seagrass, except occasional pen shell (Pinna sp.) and cerianthid anemones and tunicates (Phallusia nigra).

Site 18 (850818c)

Silt with very sparse seagrass (H. ovalis <1% cover); strong surface current and little surface biota, except loose algal drift including Avrainvillea sp. and hydroids; test of heart urchin (Metalia townsendi) also observed.

Site 19 (850818b) (C)

Silty sand with very sparse seagrass (H. ovalis <5% cover); cerianthid anemones and hermit crabs in ceriths and occasional large burrows representing most conspicuous surface biological features; infauna diverse and represented by polychaetes, molluscs, amphipods and ophiuroids (Ophiura kinbergi)

Site 20 (850822c) (C)

Sandy silt with seagrass bed of 3 species, H. uninervis most abundant (up to 40% cover); pen shells (Pinna sp.) and ceriths (Cerithium scabridum) most conspicuous macrofauna; infauna dominated by polychaetes and molluscs; nearby dead coral reef containing few reef coral species.

Site 21 (850822b)

Sandy silt with extensive cover (up to 80%) cyanobacteria/benthic microflora and very sparse (<5% cover) seagrass - all 3 species; blue sponge (Haliclona), pen shells (Pinna sp.) and tunicates (Phallusia nigra and red species) most conspicuous macrofauna.

APPENDIX 6.1 — REFERENCES TO STUDIES LOOKING AT OTHER FACTORS CONTROLLING SEAGRASS GROWTH AND DISTRIBUTION

AUTHOR(S)	DATE	FACTORS STUDIED	GEOGRAPHICAL AREA	MENTION OF ARABIAN GULF SPECIES
Basson et al	1977	Exposure, wave action, depth, irradiance, substrate.	Arabian Gulf	Ho, Hs, Hu
Bridges et al	1982	Wave action, water movement, substrate, depth, exposure.	Australia	
Buesa	1974	Irradiance, temperature, substrate grain-size.	Cuba	
Bulthius	1983a	Irradiance.	Australia	Hs
den Hartog	1970	Exposure	The World	
Dennison and Alberte	1982	Irradiance.	Various	
Drew	1979	Irradiance, depth.	Various	Hs
Drew	1980	Water velocity.	Indian Ocean	
Duarte	1991	Depth limits.	Various	
Hammer	1971	Hydrostatic pressure.	Various	
Hulings	1979	Depth, interspecific seagrass competition.	Jordan	Ho, Hs, Hu
Isaac and Isaac	1968	Exposure	Kenya	
Jacobs	1979	Depth, temperature, irradiance.	France	
Johnstone	1975	Exposure	Papua New Guinea	
Jones et al	1987	Substrate, exposure, depth.	Red Sea	Hs, Hu
Kikuchi	1980	Water velocity.	Temperate	
Koch	1974	Photoinhibition.	Caribbean	
Lipkin	1979	Depth, salinity, temperature, substrate, light, grazing, exposure, epiphytes.	Sinai, Israel	Ho, Hs, Hu
McMillan	1976	Substrate type	Caribbean	
McMillan	1978	Substrate type	Caribbean	
McMillan	1979	Substrate type	Caribbean	
McMillan	1980	Substrate type	Tropical	
McMillan	1982	Substrate type	Tropical	
McRoy and McMillan	1979	Sediment chemistry.	Various	
Ogden	1976	Grazing	Caribbean	
Ogden et al	1973	Grazing	Caribbean	
Orth	1977	Substrate grain-size and sorting.	Various	
Patriquin	1972	Sediment chemistry.	Caribbean	
Penhale and Wetzel	1983	Substrate chemistry	Temperate	
Peterson et al	1984	Water velocity.	Temperate	
Price and Coles	1991	Sediment characteristics.	Arabian Gulf	Ho, Hs, Hu
Randall	1965	Grazing	Caribbean	
Sand-Jensen	1975	Irradiance, temperature.	Denmark	
Sheppard et al	1992	Salinity, depth, substrate, grain-size, season, nutrients	Arabian Gulf	Ho, Hs, Hu
Short	1980	Photoinhibition.	Various	
Van Breedveld	1975	Substrate type and chemistry.	Caribbean	
Wiginton and McMillan	1979	Depth, irradiance, light quality.	Caribbean	
Young and Kirkman	1975	Salinity, depth, turbidity, substrate, currents, wave action, exposure.	Australia	Ho, Hs, Hu

Full references available in Bibliography.
Ho = Halophila ovalis, Hs = Halophila stipulacea, Hu = Halodule uninervis

APPENDIX 6.2

SITE DESCRIPTIONS - DETAILED SEAGRASS STUDY SITES FROM CHAPTER 6

These are the site descriptions for each station where biomass and leaf size/number data has been collected. Note that where Station numbers are repeated, site descriptions have changed along with the date. Percentage cover has been estimated by eye using a 0.25 m^2 quadrat.

Station 1: **Big Red Two** Date: 880413 Time: 1400 h

Temp.	Depth	Salinity
23.0°C	5.0 m	45.1 ppt

Tidal State: Flooding. 2 h and 15 min after LW, 3 h and 5 min before HW.

Overall percentage cover:	80%	
Percentage representation:	H. uninervis	100%
	H. stipulacea	0%
	H. ovalis	0%

A monospecific bed of H. uninervis. This is an area next to a large navigation buoy which is frequently used by the Bahrain Coastguard as a mooring for protecting access to the Hawar Islands. Consequently the seabed is often in the shadow of these large vessels and frequently disturbed. Substrate is coarse sand. Current quite strong (> 1 knot).

Station 2: **Gabbari Rock** Date: 880329 Time: 1532 h

Temp.	Depth	Salinity
21.0°C	7.0 m	49.1 ppt

Tidal State: Flooding. 3 h after LW, 1 hr and 55 min before HW.

Overall percentage cover:	90%	
Percentage representation:	H. uninervis	30%
	H. stipulacea	40%
	H. ovalis	30%

Low leaf length for all 3 species. Leaves relatively free of any fouling. Current approximately 0.5 knots. Substrate is coarse sand covered by silt. Occasional tube-worms. General community description is seagrass - Clypeaster sp. - sponge habitat interspersed with algae on hard surfaces.

Station 2: **Gabbari Rock** Date: 880803 Time: 1615 h

Temp.	Depth	Salinity
33.5°C	7.0 m	48.2 ppt

Tidal State: Ebbing. 5 h and 35 min after HW, 1 h and 15 min before LW.

Overall percentage cover:	25%	
Percentage representation:	H. uninervis	65%
	H. stipulacea	30%
	H. ovalis	5%

H. ovalis rare and small-leaved. Dominance of the other two species varies over a small area, mostly mixed H. uninervis and H. stipulacea. Substrate very coarse, difficult to core. Free-rolling H. stipulacea common. Current strong, visibility less than 3 metres. Sponges and tube-worms also present among seagrass.

Station 2: **Gabbari Rock** Date: 881004 Time: 1145 h

Temp.	Depth	Salinity
31.0°C	7.0 m	49.5 ppt

Tidal State: Flooding. 5 h after LW, 55 mins before HW.

Overall percentage cover:	70%	
Percentage representation:	H. uninervis	80%
	H. stipulacea	10%
	H. ovalis	10%

Most seagrass is heavily fouled. Some of the H. stipulacea have healthy-looking leaves other examples are coiled at the end. Visibility < 2 m. Substrate small grain-size with a silty, anoxic surface. 50 m away the substrate is more sandy and there is a healthy H. stipulacea bed.

Station 3: **Gabbari Rock** Date: 890308 Time: 0945 h

Temp.	Depth	Salinity
19.5°C	9.0 m	48.7 ppt

Tidal State: Ebbing. 2 h and 50 min after HW, 5 h before LW

Overall percentage cover:	15%	
Percentage representation:	H. uninervis	0%
	H. stipulacea	5%
	H. ovalis	95%

Seabed covered in drifting algae.

Station 4: **Mashtan North** Date: 880914 Time: 1530 h

Temp.	Depth	Salinity
37.0°C	0.5 m	54.0 ppt

Tidal State: Flooding. 40 min after LW, 5 h and 45 min before HW.

Overall percentage cover:	100%	
Percentage representation:	H. uninervis	45%
	H. stipulacea	40%
	H. ovalis	15%

H. uninervis in shallow areas (0.1 m) very stunted. In slightly deeper water (0.2 - 0.3 m) H. uninervis heavily fouled with algae. At 0.5 m less fouling and H. stipulacea now apparent. At 0.8 - 1.0 m the substrate is much softer and muddy (upper shore has coarse substrate) with healthy, long-leaved H. uninervis and H. stipulacea.

Station 4: **Mashtan North** Date: 881206 Time: 1530

Temp.	Depth	Salinity
21.5°C	0.5 m	52.3 ppt

Tidal State: Flooding. 4 h and 30 min after LW, 2 h and 40 min before HW.

Overall percentage cover:	100%	
Percentage representation:	H. uninervis	75%
	H. stipulacea	15%
	H. ovalis	10%

H. uninervis dominates shallow waters to 0.5 m deep with 100% cover and 100% fouling by epiphytes. In 0.8 - 1.0 m water depth, all 3 species present at 100% cover. Substrate thick with rhizomes, spongy to walk on.

Station 4: **Mashtan North** Date: 890206 Time: 1000 h

Temp.	Depth	Salinity
13.5°C	0.5 m	50.0 ppt

Tidal State: Ebbing. 2 h and 50 min after HW, 4 h and 45 min before LW.

Overall percentage cover:	35%	
Percentage representation:	H. uninervis	85%
	H. stipulacea	5%
	H. ovalis	10%

Very reduced growth compared with 880914 and 881206. Mostly just H. uninervis but with brown, stunted leaves often consisting only of the mid-vein.

Station 5: **Mashtan South** Date:880914 Time: 1415 h

Temp.	Depth	Salinity
35.0°C	1.0 m	55.0 ppt

Tidal State: Ebbing. 6 h and 55 min after HW, 35 min before LW.

Overall percentage cover:	75%	
Percentage representation:	H. uninervis	85%
	H. stipulacea	10%
	H. ovalis	5%

Shallow subtidal (0.8 m) mainly H. uninervis with occasional interspersed H. ovalis and H. stipulacea. Further offshore (1.2 - 1.4 m) more H. stipulacea noticeable. H. uninervis leaves in shallow water are black/brown while in deeper water they are green.

Station 5: **Mashtan South** Date:890206 Time: 1030 h

Temp.	Depth	Salinity
13.5°C	1.0 m	48.0 ppt

Tidal State: Ebbing. 3 h and 20 min after HW, 4 h and 15 min before LW.

Overall percentage cover:	40%	
Percentage representation:	H. uninervis	85%
	H. stipulacea	10%
	H. ovalis	5%

Very reduced seagrass cover compared with 880914. Leaves on south side in shallows now stunted and brown.

Station 6: **Mashtan Offshore** Date: 880713Time: 1700 h

Temp.	Depth	Salinity
30.5°C	3.5 m	52.6 ppt

Tidal State: Flooding. 3 h and 40 min after LW, 2 h and 10 min before HW.

Overall percentage cover:	75%	
Percentage representation:	H. uninervis	80%
	H. stipulacea	10%
	H. ovalis	10%

Substrate mostly soft silt and mud.

Station 7: **Middle Shoal** Date:880803 Time:1415 h

Temp.	Depth	Salinity
32.5°C	5.0 m	58.5 ppt

Tidal State: Ebbing, 2 h and 45 min after HW, 3 h and 45 min before LW.

Overall percentage cover:	35%	
Percentage representation:	H. uninervis	75%
	H. stipulacea	22.5%
	H. ovalis	2.5%

Substrate coarse but loose and easy to core. No surface rhizomes. Large salinity gradient from surface to seabed. Surface salinity only 52 ppt. Gradient between -1.0 and -2.5 metres. Tide falling, higher salinity water from Dawhat Salwah flowing beneath less dense lower salinity water already at site. Patches of Avrainvillae spp. amongst seagrass.

Station 7: **Middle shoal** Date:890308 Time: 1445 h

Temp.	Depth	Salinity
17.0°C	5.0 m	53.9 ppt

Tidal State: Low Water.

Overall percentage cover:	35%	
Percentage representation:	H. uninervis	85%
	H. stipulacea	15%
	H. ovalis	0%

H. uninervis leaves heavily fouled. Substrate very loose, very easy to core. Very strong current.

Station 8: **Middle Shoal** Date: 880329 Time: 1645 h

Temp.	Depth	Salinity
20.5°C	7.0 m	54.0 ppt

Tidal State: Flooding. 4 h and 55 min after LW, 1 h and 15 min before HW.

Overall percentage cover:	90%	
Percentage representation:	H. uninervis	0%
	H. stipulacea	70%
	H. ovalis	30%

Substrate is coarse, shelly sand, Seagrass leaves covered in fine sediment. Sponges large, common and actually growing around and completely surrounding live leaves of seagrass. Water very clear.

Station 9: **Middle Shoal** Date: 881004 Time: 1400 h

Temp.	Depth	Salinity
32.0°C	10.0 m	57.8 ppt

Tidal State: Ebbing. 1 h and 15 min after HW, 6 h and 30 min before LW.

Overall percentage cover:	10%	
Percentage representation:	H. uninervis	0%
	H. stipulacea	85%
	H. ovalis	15%

Substrate is coarse shell and silt covered by loose shelly sand. Difficult to core. H. stipulacea has unusual growth pattern. In some cases the leaf shows classic H. stipulacea morphology but root/rhizome and stem
more characteristic of H. ovalis.

Station 10: **West Al Hul** Date: 881004 Time: 1710 h

Temp.	Depth	Salinity
31.5°C	8.0 m	58.5 ppt

Tidal State: Ebbing. 3 h and 55 min after HW, 4 h and 35 min before LW.

Too dark to record percentage covers. Seagrass looks like H. stipulacea with very elongated stem but only one or two leaves per shield. Roots originate from nodes. Substrate muddy, soft sediment, easy to core. Little to no current. Core samples revealed that seagrass present was mainly H. stipulacea but with some H. ovalis.

Station 11: **West Al Hul** Date: 880803 Time: 1200 h

Temp.	Depth	Salinity
32.5°C	10.0 m	59.0 ppt

Tidal State: Ebbing, 30 min after HW, 6 h and 50 min before LW.

Overall percentage cover:	35%	
Percentage representation:	H. uninervis	16%
	H. stipulacea	64%
	H. ovalis	20%

Surface substrate is coarse sand and shell, difficult to core. Roots of seagrass very shallow (even H. uninervis). Rhizome of H. stipulacea often above surface of substrate. No noticeable current. Avrainvillae spp. (alga) common.

Station 11: **West Al Hul** Date: 890217 Time: 1300 h

Temp.	Depth	Salinity
15.0°C	10.0 m	59.0 ppt

Tidal State: Low Water

Overall percentage cover:	5%	
Percentage representation:	H. uninervis	0%
	H. stipulacea	85%
	H. ovalis	15%

Substrate is silt in shell-gravel. What little seagrass present is nearly all H. stipulacea with very sparse H. ovalis. H. stipulacea had brown leaves covered in a fine layer of silt or with epiphytic fouling. Dead H. stipulacea leaves lying on seabed. No current. Lots of Rhizostoma Sp. (jellyfish).

Station 12: **West Al Hul** Date: 880329 Time: 0630 h

Temp.	Depth	Salinity
20.5°C	12.5 m	54.4 ppt

Tidal State: Ebbing. 55 min after HW, 6 h before LW.

Overall percentage cover:	60%	
Percentage representation:	H. uninervis	0%
	H. stipulacea	65%
	H. ovalis	35%

Substrate is coarse, loose material covered in fine sediment. Leaves clean with no fouling. Rhizomes exposed. No algae. Seagrass is the only obvious biotic element present. One very small patch of H. uninervis noted but only 5 leaves. Water very clear. No noticeable current.

Station 13: **Zallaq Tower** Date: 880713 Time: 1300 h

Temp.	Depth	Salinity
31.0°C	4.5 m	57.0 ppt

Tidal State: Ebbing, 1 h after HW, 2 h before LW.

Overall percentage cover:	25%	
Percentage representation:	H. uninervis	85%
	H. stipulacea	15%
	H. ovalis	0%

No H. ovalis present. Coarse surface substrate, firm but easy to core.

Station 13: **Zallaq Tower** Date: 881005 Time: 0700 h

Temp.	Depth	Salinity
30.5°C	4.5 m	59.1 ppt

Tidal State: Ebbing. 1 h and 40 min after HW, 4 h and 25 min before LW.

Overall percentage cover:	70%	
Percentage representation:	H. uninervis	98%
	H. stipulacea	2%
	H. ovalis	0%

Seagrass distribution patchy, both short leaves and long leaves. Leaves heavily fouled. Substrate is silt and seagrass detritus on surface, shell, sand and mud underneath. Where H. stipulacea is present, the rhizome is thick and the leaf shield extends along the length of the rhizome.

Station 13: **Zallag Tower** Date: 890313 Time: 1330 h

Temp.	Depth	Salinity
18.5°C	4.5 m	59.3 ppt

Tidal State: Ebbing. 1 h and 40 min after HW, 6 h and 45 min before LW.

Overall percentage cover:	50%	
Percentage representation:	H. uninervis	99.5%
	H. stipulacea	0%
	H. ovalis	>0.5%

H. uninervis now thinned out and not so dense as in 880713 and 881005. Substrate varies from tightly packed coarse sand to very loose, mixed material.

Station 14: **Khawr Fasht** Date: 881004 Time: 1130 h

Temp.	Depth	Salinity
31.0°C	4.5 m	52.1 ppt

Tidal State: High Water

Overall percentage cover:	75%	
Percentage representation:	H. uninervis	70%
	H. stipulacea	0%
	H. ovalis	30%

Continuous, even cover of seagrass, not patchy. Ratio of H. uninervis to H. ovalis varied from 90:10 to 50:50 over a distance of 10m. Both species display healthy, green leaves with no fouling. Substrate very silty and anoxic, easy to core. Visibility < 1.5 m.

APPENDIX 6.3

SITE COORDINATES
SEAGRASS DETAILED STUDY SITES

SITE NUMBER	SITE NAME	DEPTH (Metres)	LATITUDE	LONGITUDE
1	Big Red Two	5	25.58.22	50.42.54
2	Gabbari Rock	7	25.55.08	50.40.10
3	Gabbari Rock	9	25.54.92	50.40.18
4	Mashtan North	0.5	25.48.78	50.40.32
5	Mashtan South	1	25.48.62	50.40.44
6	Mashtan Offshore	3.5	25.47.98	50.40.83
7	Middle Shoal	5	25.44.78	50.38.52
8	Middle Shoal	7	25.44.92	50.38.25
9	Middle Shoal	10	25.44.98	50.38.16
10	West Al Hul	8	25.44.85	50.30.72
11	West Al Hul	10	25.44.83	50.30.28
12	West Al Hul	12.5	25.44.80	50.30.03
13	Zallaq Tower	4.5	26.05.78	50.27.08
14	Khawr Fasht	4.5	26.20.87	50.22.86

See figure 6.1 for locations on map

APPENDIX 7.1

SPECIES LIST FOR BAHRAIN

This is a list of all the biota which have been positively identified to genera or species during the course of the present study. Authorities given in Newton, 1955; Basson et al, 1977; Basson, 1979, Jones, 1986a; Walker, 1987.

PLANTS:

* = Algal taxa previously reported from Bahrain (Compiled by Dr. Philip W. Basson)

** = Algal taxa representing new records for Arabian Gulf at the time of collection (1985-86) as verified by Dr. P. Basson.

CHLOROPHYTA

Ulotrichales

Chaetophoraceae

Entocladia
Entocladia viridis = Endoderma viride *

Phaeophila
Phaeophila dendroides *

Ulvales

Ulvaceae

Enteromorpha
Enteromorpha clathrata
Enteromorpha compressa * (conspecific)
Enteromorpha flexuosa (conspecific)
Enteromorpha intestinalis ** (conspecific)

Ulva
Ulva lactuca
Ulva reticulata

Cladophorales

Cladophoraceae

Chaetomorpha
Chaetomorpha aerea *
Chaetomorpha capillaris *
Chaetomorpha linum *

Cladophora
Cladophora dalmatica
Cladophora echinus *

Cladophora koiei *
Cladophora nitellopsis *
Cladophora sericoides *

Rhizoclonium
Rhizoclonium kochianum

Siphonocladales

Siphonocladaceae

Cladophoropsis
Cladophoropsis zollingeri

Valoniaceae

Dictyosphaeria
Dictyosphaeria cavernosa

Valonia
Valonia utricularis

Dasycladales

Acetabulacea
Acetabularia calyculus

Caulerpales

Caulerpaceae

Caulerpa
Caulerpa sertularioides
Caulerpa sertularioides forma farlowii

Udoteaceae

Avrainvillea
Avrainvillea amadelpha forma montagneana

PHAEOPHYTA

Ectocarpales

Ectocarpaceae

Ectocarpus
Ectocarpus cryptophilus *

Giffordia
Giffordia mitchellae *

Sphacelariales

Sphacelariaceae

Sphacelaria
Sphacelaria furcigera *
Sphacelaria tribuloides

Dictyotales

Dictyotaceae

Dictyota
Dictyota divaricata *

Padina
Padina gymnospora

Chordariales

Corynoploeaceae

Myriactula
Myriactula arabica *

Spermatochnaceae

Nemacystus
Nemacystus decipiens *

Dictyosiphonales

Punctariaceae

Colpomenia
Colpomenia sinuosa var. sinuosa *

Hydroclathrata
Hydroclathrus clathratus

Fucales

Cystoseiraceae

Cystoseira
Cystoseira myrica *
Cystoseira trinodis = Cystophyllum muricatum *

Hormophysa
Hormophysa triquetra *

Sargassaceae

Sargassum
Sargassum acutifolium *
Sargassum vulgare var. angustifolium *
Sargassum boveanum *
Sargassum cervicorne *
Sargassum crassifolium *

Sargassum decurrens *
Sargassum heteromorphum
Sargassum latifolium = Sargassum asperifolium =
Sargassum vulgare var. latifolium *

CYANOPHYTA

Chroococcales

Chroococcaceae

Anacystis
Anacystis marina *

Chroococcus
Chroococcus minutus = Coccochloris stagnina *

Chamaesiphonales

Hydrococcaceae

Hyella
Hyella caespitosa = Entophysalis deusta *

Xenococcus
Xenococcus acervatus = Entophysalis conferta *

Nostocales

Nostocaceae

Microchaete
Microchaete grisea = Calothrix crustacea *

Oscillatoriaceae

Lyngbya
Lyngbya epiphytica = Schizothrix calcicola *

Microcoleus
Microcoleus tenerrimus = Schizothrix tenerrima *
Microcoleus vaginatus **

Oscillatoria
Oscillatoria corallinae = Microcoleus lyngbyaceus *

Spirulina
Spirulina subsalsa
Spirulina tenerrima = assigned to the bacteria *

Rivulariaceae

Calothrix
Calothrix confervicola = Calothrix crustacea *

Schizothrix
Schizothrix mexicana **

Stigonematales

Nostochopsidaceae

Mastigocoleus

Mastigocoleus testarum *

RHODOPHYTA

Goniotrichales

Goniotrichaceae

Chroodactylon

Chroodactylon ornatum = Asterocytis ornata *

Erythropeltidales

Erythropeltidaceae

Erythrocladia

Erythrocladia irregularis = Erythrocladia subintegra

Erythrotrichia

Erythrotrichia carnea

Acrochaetiales

Acrochaetiaceae

Acrochaetium

Acrochaetium bahreinii *

Nemaliales

Helminthocladiaceae

Liagora

Liagora ceranoides

Gelidiellaceae

Gelidiella

Gelidiella acerosa

Corallinales

Corallinaceae

Fosliella

Fosliella farinosa = Melobesia farinosa *

Jania

Jania rubens *

Jania pumila *

Lithothamnion
Lithothamnion sp.

Cryptonemiales

Hypneaceae

Hypnea
Hypnea cornuta
Hypnea valentiae *

Solieriaceae

Sarconema
Sarconema furcellatum

Rhodymeniales

Champiaceae

Champia
Champia parvula

Ceramiales

Ceramiceae

Anotrichium
Anotrichium tenue = *Griffithsia tenuis*

Centroceras
Centroceras clavulatum

Ceramium
Ceramium codii **
Ceramium cruciatum
Ceramium fastigiatum forma *flaccidum*
Ceramium flaccidum = *Ceramium transversale*
Ceramium luetzelburgii
Crouaria
Crouaria attenuata

Spyridia
Spyridia filamentosa *

Dasyaceae

Dasyopsis
Dasyopsis pilosa

Rhodomelaceae

Acanthophora

Acanthophora spicifera

Chondria
Chondria dasyphylla *

Digenea
Digenea simplex *

Herposiphonia
Herposiphonia secunda forma tenella = Herposiphonia tenella *

Laurencia
Laurencia obtusa *
Laurencia papillosa
Laurencia glandulifera

Leveillea
Leveillea jungermannioides

Polysiphonia
Polysiphonia crassicollis *
Polysiphonia kampsaxii *
Polysiphonia variegata

NB: Since compiling this list, Amadelpha riukiuensis has been identified from one of the samples. This has only previously been recorded in Japan and Mauritius

ANTHOPHYTA

Authorities as in den Hartog, 1970; Jones 1986a.

Avicennia marina
Halocnemon strobilaceum
Phragmites communis
Arthrocnemon macrostachyum
Juncus rigidus
Salicornia sp.

Hydrocharitacea:

Halodule uninervis

Potamogetonacea:

Halophila stipulacea
Halophila ovalis

ANIMALS:

PORIFERA

Halichondria sp.
Haliclona sp.
Gellius sp.

COELENTERATA

Authorities as in Burchard, 1979; Downing, 1985; Sheppard and Sheppard, 1985; Jones 1986a; Sheppard et al, 1992.

CLASS:- HYDROZOA

Thyroscyphus fruticosus
Dynamena crisioides
Halocordyle pennaria
Ventromma halecoides
Zoobotryon verticillatum
Diopatra sp.

CLASS:- SCYPHOZOA

ORDER:- Rhizostomae
Cassiopeia andromeda
Rhizostoma sp.

CLASS:- ANTHOZOA

ORDER:- Actinaria
Stoichactis sp.
Cerianthus sp.

ORDER:- Scleractinia

Family:- Acroporidae
Acropora cf. formosa
Acropora spl?
Acropora sp2?
Acropora sp3

Family:- Caryophyliidae
Heterocyathus heterocostatus
Paracyathus sp.

Family:- Dendrophylliidae
Turbinaria crater
Turbinaria peltata

Family:- Faviidae

Cyphastrea microphthalma
Cyphastrea seralia
Favia favus
Favia pallida
Favia speciosa
Favites chinensis
Favites sp.
Favites pentagona
Leptastrea purpurea
Platygyra daedalea
Platygyra sinensis
Plesiastrea versipora

Family:- Mussidae

Acanthastrea echinata

Family:- Pocilloporidae

Stylophora pistillata

Family:- Poritidae

Porites compressa
Porites lutea
Porites cf. murrayensis
Porites nodifera

Family:- Rhizangiidae

Culicia sp.

Family:- Siderastreidae

Anomastrea irregularis
Coscinaraea monile
Pseudosiderastrea tayamai
Siderastrea savignyana

Family:- Thamnasteriidae

Psammocora contigua

ANNELIDA

Authorities as in Basson et al. 1977; Jones, 1986a.

Polychaeta:

Pomatoleios kraussi
Serpulorbis sulcatus

ARTHROPODA

Authorities as in Basson et al, 1977; Al Attar, 1981: Jones and Clayton, 1983: Jones, 1986a

Class:- CRUSTACEA

Sub class:- Cirripedia

Chthamalus malayensis
Euraphia sp. nov?
Balanus amphitrite
Balanus tintinnabulum

Sub class:- Malacostraca

Order:- Mysidacea

Gastrosaccus kempi
Rhopalophthalmus sp.

Order:- Stomatopoda

Gonodactylus chiragara chiragara
Squilla sp.

Order:- Tanaidacea

Leptochelia savignyi
Malacanthura sp. juv.

Order:- Isopoda

Excirolana sp. nov.
Excirolana orientalis
Eurydice peraticus
Metacirolana rotunda
Cirolana parva
Lanocira gardineri
Cirolana sp.
Tylos maindroni
Cymodoce sp. nov.

Order:- Amphipoda

Hyale perieri
Orchestia platensis
Leucothoe spinicarpa
Ampelisca brevicornis
Ampelisca scabripes
Ceradocus rubromaculatus
Ceradocus serratus
Elasmopus rapax
Stenothoe valida
Dexamine spinosa
Maera quadrimana
Gammaropsis atlantica
Lysianassa ceratina
Grandidierella bonniroides
Metaprotella sandalensis
Thipotella amica
Aeginellopsis arabia
Cymadusa filosa
Ligia italica

Order:- Decapoda

Penaeus semisulcatus
Metapenaeus stebbingi

Section - Caridae

Family:- Alpheidae

Alpheus lobidens
Alpheus djeddensis

Family:- Hippolytidae

Hippolyte ventricosa
Hippolyte kraussiana
Hippolyte sp.

Family:- Palaemonidae

Palaemon pacificus

Family:- Upogebidae

Upogebida rhadames
Upogebida savignyi

Section - Anamura

Family:- Paguridae

Paguristes perspica
Dardanus tinctor
Diogenes avarus
Diogenes sp.

Family:- Porcellanidae

Petrolisthes rufescens
Petrolisthes carinipes
Platycheles natalensis

Section - Brachyura

Hyastenus planasius
Cyphocarcinus minutus
Acanthonyx limbatus
Micippa cf. margaritifera

Family:- Ocypodidae

Metaplax indicus
Ilyoplax frater
Ocypode rotundata
Nasima dotilliformis
Scopimera crabricauda
Macrophthalmus depressus
Macrophthalmus grandidieri
Macrophthalmus telescopicus
Macrophthalmus dilatus sulcatus?

Family:- Portunidae

Thalamita prymna
Thalamita poissoni
Portunus pelagicus

Family:- Xanthidae

<u>Heteropanope</u> <u>laevis</u>
<u>Xantho</u> <u>exaratus</u>
<u>Actaea</u> <u>savignyi</u>
<u>Pilumnus</u> <u>verspertilio</u>
<u>Eurycarcinus</u> <u>orientalis</u>

Family:- Grapsidae

<u>Metopograpsus</u> <u>messor</u>

Class:- PYCNOGONIDAE

<u>Anoplodactylus</u> <u>glandulifer</u>
<u>Ammothella</u> <u>indica</u>

<u>MOLLUSCA</u>

Authorities as in Smythe, 1972, Basson <u>et</u> <u>al</u>, 1977; Price <u>et</u> <u>al</u>, 1984; Jones et al, 1986a.

= Also recorded by Smythe (1972)

PVO = Also recorded by Price <u>et</u> <u>al</u> (1984)

AMPHINEURA

Chitonidae

<u>Chiton</u>?

SCAPHOPODA

Dentaliidae

<u>Dentalium</u> <u>octangulatum</u>
<u>Dentalium</u> <u>longitrorsum</u>
<u>Dentalium</u> <u>politum</u> (PVO)

GASTROPODA

Pulmonata

<u>Doriopsilla</u> <u>miniata</u>
<u>Onchidium</u> sp.

Patellacea

<u>Patella</u> sp.
<u>Patella</u> sp. (PVO)
<u>Diodora</u> ?<u>bombayana</u>
<u>Diodora</u> <u>imbricata</u>
<u>Diodora</u> <u>funiculata</u> (PVO)
<u>Diodora</u> <u>rupelli</u> (S)
<u>Diodora</u> <u>quadriradiata</u> (S)
<u>Fissurella</u> ?<u>townsendi</u>

Trochacea

Calliostoma sp
Euchelus asper (S)
Trochus erythraeus
Trochus niloticus
Monilea obscura
Monodonta vermiculata
Minolia gradata
Minolia holdsworthiana (S)
Turbo coronatus
Turbo sp 1
Turbo sp 2
Tectus sp.
Gibbula declivis
Phasianella solida (PVO)
Phasianella jasplidea (S)
Phasianella sp.
Tricolia fordiana (PVO, S)
Priotrochus obscura

Neritacea

Smaragdia rangiana
Smaragdia souverbiana (PVO)

Littorinacea

Rissoina distans (S)
Littorina ?scabra
Nodilittorina ?millegrana
Nodilittorina subnodosa (S)

Cerithiacea

Turritella maculata
Turritella columnaris (PVO)
Turritella fultoni (PVO)
Turritella torulosa (PVO)
Vermetus sulcatus
Planaxis sulcatus
Planaxis sp.
Clypeomous bifasciatum (PVO)
Pirinella conica
Pirinella caillaudi (S)
Cerithium cingulata
Cerithium caeruleum
Cerithium rugosum
Cerithium scabridum
Cerithium morus (S)
Cerithium petrosum (S)
Cerithium rupelli (S)
Rhinoclavis kochi
Rhinoclavis sordidula (PVO)
Rhinoclavis fasciatum (S)
Cerithiopsis binduorum (S)
Dialia sulcifera (S)
Dialia semistriata (S)
Alaba virgata (S)

Naticacea

Natica lineata
Natica vitellus

Strombacea

Strombus decorus (S)

Cypraeacea

Cyprea turdus (S)
Cyprea gracilis (S)

Muricacea

Hexaplex kuesterianus
Murex scolopax
Thais mancinella
Thais savignyi
Thais carinifera (S)
Thais pseudohippocastanum (S)
Thais tissoti (S)
Thais margariticola (S)
Cronia konkanensis
Drupa tuberculata (S)

Buccinacea

Mitrella blanda
Nassarius arcularis plicatus
Nassarius (Niotha) stolatus
Nassarius deshayesianus (PVO)
Nassarius pullus (PVO)
Fusinus arabicus (S)
Fusinus sp. (PVO)

Volutacea

Ancilla castenea
Ancilla cinnamomea (S)
Ancilla fasciata (S)
Ancilla sp.1
Ancilla sp.2 (PVO)
Marginella mazagonica (S)
Marginella juv.

Acteonacea

Bulla ampulla
Atys cylindrica
Melampus luridus (PVO)

Pyramidellacea

Otopleura mitralis
Turbonilla icela (S)
Siphonaria rosea (S)

Fresh water gastropod

Melania tuberculata

BIVALVIA

Arcacea

<u>Anadara</u> <u>urypigmelana</u> (PVO, S)
<u>Anadara</u> <u>ehrenbergi</u> (PVO)
<u>Arca</u> <u>lacerata</u> (S)
<u>Arca</u> <u>plicata</u> (S)
<u>Arca</u> sp.
<u>Barbatia</u> sp 1
<u>Barbatia</u> sp 2
<u>Barbatia</u> sp 3
<u>Barbatia</u> <u>obliquata</u> (PVO)
<u>Barbatia</u> <u>helbingi</u> (S)

Mytilacea

<u>Brachydontes</u> <u>variabilis</u>
<u>Lithophaga</u> <u>malaccana</u>
<u>Modiolus</u> <u>auriculatus</u>

Pinnacea

<u>Pinna</u> <u>bicolor</u>
<u>Pinna</u> <u>atropurpurea</u> (S)
<u>Pinna</u> <u>muricata</u>

Pteriacea

<u>Pinctada</u> <u>radiata</u>
<u>Pinctada</u> <u>margaritifera</u> (PVO)
<u>Pinctada</u> juv. (?<u>radiata</u>)
<u>Malleus</u> <u>regulus</u>
<u>Isognomen</u> <u>legumen</u> (S)
<u>Isognomon</u> <u>dentifera</u> (S)
<u>Plicatula</u> <u>plicata</u> (S)

Pectinacea

<u>Chlamys</u> <u>ruschenbergerii</u>
<u>Chlamys</u> <u>senatorius</u>
<u>Spondylus</u> <u>?hystrix</u> (PVO)
<u>Spondylus</u> <u>aculeatus</u> (S)
<u>Spondylus</u> <u>gloriandus</u> (S)
<u>Spondylus</u> <u>townsendi</u> (S)

Ostreacea

<u>Crassostrea</u> c.f. <u>margaritacea</u>
<u>Ostreacea</u> sp 2
<u>Ostreacea</u> sp 3

Trigoniacea

<u>Lucinidae</u> juv.
<u>Lirga</u> <u>semperiana</u> (PVO)
<u>Anodontia</u> <u>edentula</u> (PVO, S)
<u>Codakia</u> <u>fischeriana</u> (PVO)
<u>Loripes</u> <u>fischeriana</u> (S)

Chamacea

<u>Chama</u> <u>aspera</u>
<u>Chama</u> <u>pacifica</u>

Carditacea

Cuna sp (S)
Cardita sp
Mytilicardita gubernaculum (S)

Cardiacea

Trachycardium lacunosum
Trachycardium maculosum (S, PVO)
Laevicardium papyraccum (S, PVO)
Cardiacea juv.

Mactracea

Mactra olorina (S)

Tellinacea

Tellinacea juv.
Moerella sp 1 (PVO)
Moerella sp 2 (PVO)

Veneracea

Dosina sp
Circe calypyga
Circe corrugata (PVO)
Circe scripta (PVO, S)
Timoclea farsiana (PVO)
Timoclea sp (S)
Timoclea juv
Dosinia hepatica (PVO)
Tivela damaoides (P W)
Bassina callophyla (PVO)
Gari maculosa (P W)
Gari rosea (PVO)
Gari occidens (S)
Gafrarium arabicum (S)
Gafrarium callipygeum (S)
Gafrarium divaricatum (S)
Meretrix meretrix (S)
Sunetta effossa (S)
Venerupia deshaysei (S)
Ancilla castanca

Bivalve 1
Bivalve 2
Bivalve 3
Bivalve 4
Bivalve 5

Bivalve juv 6
Bivalve juv 7
Bivalve juv 8
Bivalve juv 9
Bivalve juv 10
Bivalve juv 11
Bivalve juv 12
Bivalve juv 13
Bivalve juv 14
Bivalve juv 15

Bivalve juv 16
Bivalve juv 17
Bivalve juv 18
Bivalve juv 19
Bivalve juv 20

ECHINODERMATA

Authorities as in Price, 1982.

CLASS:- ASTEROIDEA

Family:- Asterinidae
Asterina burtoni

Family:- Asteropectinidae
Astropecten polyacanthus phragmorus

Family:- Ophidiasteridae
Linckia multifora

Family:- Oriasteridae
Pentaceraster mammillatus

CLASS:- OPHIUROIDEA

Family:- Amphiuridae
Amphioplus sp.
Amphiura fasciata

Family:- Ophiactidae
Ophiactis savignyi

Family:- Ophiotrichidae
Ophiothela danae
Ophiothrix savignyi
Ophiothela venusta

Family:- Ophionereidae
Ophionereis dubia

Family:- Ophiuridae
Ophiura kinbergi

CLASS:- ECHINOIDEA

Family:- Astryclypeidae
Echinodiscus auritus

Family:- Cidaridae
Prionocidaris baculosa

Family:- Clypeasteridae
Clypeaster humilis

Family:- Diadematidae
Diadema setosum

Family:- Echinometridae
Echinometra mathaei

Family:- Brissidae
Metalia townsendi

CLASS:- HOLOTHURIOIDEA

Family:- Holothuriidea
Holothuria (Cystipus) rigida
Holothuriidae sp.

UROCHORDATA

Authorities as in Jones, 1986a.

Ascidiacea:

Polyclinum constellatum
Phallusia nigra
Didemnum candidum (may be more than one sp. present)
Styela canopus

PISCES

Authorities as in Basson *et al*, 1977; Linden, 1982; McCain *et al*, 1984; Jones 1986a.

Epinephelus tauvina
Cryptocentrus cryptocentrus
Aphanius dispar
Siganus spp.
Pomacanthus maculosum
Acanthopagrus bifasciatus
Pseudochromis persicus
Scomberomorus commersoni
Sardinella sp.
Stolephorus sp.
Istiophorus platypus
Thunnus sp.

REPTILIA

Authorities as in Gallagher, 1971.

Squamata:

Hydrophis cyanocinctus

Chelonia:

Chelonia mydas
Eretmochelys imbricatus bissa

MAMMALIA

Authorities as in Basson *et al*, 1977.

Sirenia:

Dugong dugon

Odontoceti:

Sousa sp.

CHAPTER NINE

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BIBLIOGRAPHY

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