Analysis of the space–time variation of emperor (Lethrinus) in Omani waters

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Abstract

Coverage within the scientific literature regarding both the general ecology of the family Lethrinidae (emperor fish) and spatially focused analyses for this group of species in Omani waters in particular has been limited to date. The contribution of this study is a systematic analysis of the space-time patterns in distribution of emperor in Omani waters, with particular reference to the Arabian Sea, in relation to environmental variables. The longer-term context of the work is the improvement of fisheries management, so that maximum sustainable yields can be attained.

Geographical Information Systems (GIS) are used to provide a qualitative description of the relationships between monthly fish distribution and abundance (based upon commercial and traditional catch records) with monthly data on sea surface temperatures, salinity and water depth for the period 1996-2004. In addition a General Additive Model (GAM) is used to provide quantitative descriptions of the spatial relationships between the distribution of emperor abundance and the environmental variables. Further, both GIS and GAM methodologies are used to identify and explain space-time patterning in the spawning season of Lethrinus nebulosus in the Arabian Sea. GIS techniques are used to analyse the spatial performance of the models and to provide an independent verification of the GAM results. In regard to spawning data collected as part of a recent biological survey (2000-2001), the work evaluates typical space-time patterns in the spawning season for Lethrinus nebulosus in Omani waters and further explores both the relationship between spawning and maturation and controls on maturation.

Analysis shows that the emperor is more abundant in the southwest of the Omani sector of the Arabian Sea than the northwest; temporally, the peak season for high abundance of emperor lies between September and December. Additionally, the GAM fitted data clearly indicates a seasonal effect on Gonado Somatic Index whereby the most strongly positive effect is during August to October and the starting point of the first sexual maturity is a length of around 35 cm.
Dedication

To my beloved husband, Ali Al-Riyami, for his patience, encouragement, understanding and love throughout my studentship.

To my son, Aktham, for his intelligence, understanding and help throughout my studies.

To my daughter, Alaa, for her beauty, patience and encouragement.

To my little son, Sulaiman; may he always be so joyful and cheerful.

To my parents, Mr Sulaiman Al-Kharusi and Mrs Tala Al-Lamki, for their love and support.
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A special note of thanks goes to Maria Desouza, for her unwavering support throughout my study and her help with looking after the children. Last but not least, I would like to thank my brothers, sisters, the rest of my family and friends for their constant support during my studies. Many thanks.
Glossary

Cephalopod  A marine animal of phylum Mollusca, Class Cephalopoda. The class includes squid, octopus and nautilus.

Demersal  Bottom-living. Living in some association with the sea floor.

Exclusive  The 200 miles EEZ in which a coastal state exercises extensive resource ownership and management rights

Fishery (Fisheries)  The combination of fishermen, fishing vessel and gear involved in catching a fish stock or species within a given area and in a particular way.

Fork length  The length of a fish measured from the tip of the snout to the fork of the caudal fin.

Gonads  Reproductive organs (ovary or testis)

$L_{50}$  Size at sexual maturation ($L_{50}$) is estimated as the size at which 50% of individuals classify as mature stages.

Otolith  Hard calcareous ear-stones which in fish are used as hearing and balancing organs.

Pelagic  Free-swimming or drifting in the open sea.

Polychaete  Marine bristle worms, including lugworm and sandworm or clam worm.

Protandry  Beginning life as a male and then changing to female.

Protogyny  Beginning life as a female and then switching to male.

Gonochoristic-  Fish that maintain the same sex throughout their entire lifespan.

Total length  The length of the fish measured from the tip of the snout to the tip of the longer lobe.

Wilayat  An administrative division or province.

Zooplankton  Animals which drift freely in the water column; animal plankton.
### Abbreviations

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>AIC</td>
<td>Akaike Information Criterion</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced very-high-resolution radiometer</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>CPUE</td>
<td>Catch per unit effort</td>
</tr>
<tr>
<td>df</td>
<td>Degrees of freedom</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
</tr>
<tr>
<td>ER</td>
<td>Entity Relation</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>GAM</td>
<td>Generalized Additive Model</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical information system</td>
</tr>
<tr>
<td>GSI</td>
<td>Gonado Somatic Index</td>
</tr>
<tr>
<td>Kg</td>
<td>Kilograms</td>
</tr>
<tr>
<td>Km</td>
<td>Kilometres</td>
</tr>
<tr>
<td>MAF</td>
<td>Ministry of Agriculture and Fisheries</td>
</tr>
<tr>
<td>MSFC</td>
<td>Marine Science and Fisheries Centre</td>
</tr>
<tr>
<td>MT</td>
<td>Metric tonnes</td>
</tr>
<tr>
<td>NM</td>
<td>Nautical miles</td>
</tr>
<tr>
<td>ppt</td>
<td>Parts per thousand</td>
</tr>
<tr>
<td>psu</td>
<td>Particle salinity unit</td>
</tr>
<tr>
<td>RO</td>
<td>Rial Omani (Currency)</td>
</tr>
<tr>
<td>RS</td>
<td>Remote Sensing</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>SSS</td>
<td>Sea Surface Salinity</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
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<tr>
<td>°C</td>
<td>Degree Celsius</td>
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1.1 Introduction

This thesis focuses on the distribution in space and time of emperor fish in Omani waters during the period between 1996 and 2004, in relation to environmental variables. The work is situated in the context of an ongoing requirement for the fisheries sector to manage fish in a sustainable manner and seeks to develop a spatial model that reveals the relationship between emperor catch and environment. Methodologically, geographical information systems (GIS) and generalised additive models (GAM) are the key structures used in this study.

This introductory chapter is divided into five main sections. Section 1.2 introduces the general study area. Section 1.3 introduces the research context of the study; the aims and objectives are described in Section 1.4. In Section 1.5 explains the way in which this study is structured.

1.2 The study area

The Sultanate of Oman lies on the south-eastern corner of the Arabian Peninsula between latitudes 16° 40' and 26° 20' N and longitudes 51° 50' and 59° 40' E. It has a coastline of 3,165 km (NSA, 2003) and is bordered by three different bodies of water: the Arabian Sea, the Gulf of Oman and the Arabian Gulf (Persian Gulf) (Figure 1-1). Oman is the third largest country in the Arabian Peninsula and occupies a total land area of 309,000 km$^2$ (about 119,500 sq mi). The country is
bordered by the United Arab Emirates (UAE) and Saudi Arabia to the west and the Republic of Yemen to the south.

The particular focus area for this study is located in the Gulf of Oman and the Arabian Sea, between 17° 30' and 26° 00' N, and 53° 00' and 59° 30' E (Figure 1-1). This area is notable in that it is a unique tropical basin which has a semi-annual cycle (Kumar et al., 2001a; Weller et al., 2002; Bohm et al., 1999) and the strongest annual variability in water circulation in the world (Esenkov et al., 2003).

Figure 1-1 Location of Sultanate of Oman in Arabian Peninsula (Google Earth, August-2006)
1.3 Research context

The fisheries sector has always been of great importance to the Sultanate of Oman, providing a significant source of employment and food; more than 150 species of fish and crustaceans have been identified in Omani waters (Al-Abdessalaam, 1995). Prior to the discovery and subsequent exploitation of oil in the late 1960s, the fishing sector supported approximately 80% of the population, and even today around 50% of Omanis rely upon fishing as a source of income. This sector also retains its prominence within the limits of renewable economic resources (Ministry of Information, 1999). Total landings in 2004 were 165,078 metric tons (MT) with a value of approximately 75.23 million Omani Rial (RO) (100 million sterling pounds) of this total, trawler landings accounted for 25,782 MT, while landings from traditional vessels were 139,236 MT. With regard to distribution, around 20% of the total landings were made in the Gulf of Oman and 80% in the Arabian Sea.

The emperor is an important commercial reef fish (demersal fish) in the Sultanate of Oman, locally referred to as Sheiry (Figure 1-2). Emperor are caught by both industrial trawlers and the traditional fishing sector. Total landings of emperor during 2004 were 10,300 MT with a value of RO 48,000,000. Emperor contribute around 6.2% to the total landings and 6.4% to the total value of the fisheries economy. In addition, the emperor fish contributes approximately 24% of the total demersal landings in terms of both quantity and value (MAF, 2004).
The initial impetus to carry out this study on fisheries in Oman began when serious concerns were repeatedly raised about the sustainability of demersal stocks and the welfare of the traditional fishery sector, especially in the light of frequent reports of large numbers of foreign vessels trawling in closed areas. In the 1990s the Omani fisheries sector saw a decline in both total catch and fish landings, as well as a reduction in the size of the individuals caught in Omani waters. The specific reasons for this decline in Oman's landings are not known. Hence, further study is necessary to determine the influence of environmental factors, overfishing and the exploitation of these resources, given the paucity of information available on fish biology, distribution, spawning season and spawning grounds, in order to assist the Ministry of Agriculture and Fisheries of Oman (MAF) to develop an informed fisheries infrastructure with the ability to regulate the fisheries by reaching the maximum sustainable yield and improving fisheries management. To do this, MAF has funded several projects to explore the factors affecting the Omani fish population. As an Omani governmental project, the research reported in this thesis is situated within this political context.
The focus of this study is on the Lethrinidae family and on *Lethinus nebulosus* (Forsskål, 1775) in particular. In addition to its importance in Oman, the Lethrinidae family is globally one of the most commercially important groups of tropical and subtropical fish in three major oceans (Randall, 1987; Beets and Hixon, 1994; Sluka and Reichenbach, 1996). Despite this, the literature on this family is sparse, particularly in relation to Omani waters.

This study derives its importance from the fact that it may be considered the first study in the Arabian Sea and the Gulf of Oman to address the spatial distribution of fish in general and of emperor in particular. The limited number of studies in this field provides a sufficient reason to study this fish in the Arabian Sea, which has the strongest annual variability in circulation in the world (Esenkov et al., 2003), and both types of fishery activity are concentrated in the Arabian Sea more than in the Gulf of Oman. Moreover, the results should shed light on a number of essential issues related to the distribution in space and time of emperor. To recap, the results of this study may be of value for other studies of different types of fish in the same study area or in other tropical and subtropical waters.

### 1.4 Aims and objectives

The principal aim of this study is to map and analyse spatio-temporal patterns of Lethrinidae distribution in Omani waters in relation to different environmental factors. Thus, it will map and analyse spatial and temporal patterns of adult emperor distribution in Omani waters in relation to different environmental variables. The longer-term context of the work is the improvement of fisheries
management so that maximum sustainable yields can be attained. This study in particular asks:

1) What are the spatial and temporal distribution patterns of Lethrinidae?

2) Is there a relationship between Lethrinidae distribution and environmental factors such as sea surface temperature, salinity, geographical location (latitude and longitude) and bathymetry?

3) When is the spawning season for *Lethrinus nebulosus* in the Arabian Sea? What environmental conditions are associated with the maturation of *Lethrinus nebulosus* in the Arabian Sea?

1.5 Organisation of the thesis

This thesis comprises six chapters, which provide an explanation of the research process to answer the questions posed above (Section 1.4).

Chapter 2 begins by examining the state of research into the emperor species studied in this thesis; it also reviews existing studies that have employed a GIS, Remote Sensing (RS) and non-parametric statistics such as GAM to model the abundance of marine fishery resources.

Chapter 2 starts by outlining the structure and characteristics of the sources of fisheries catch data used in the study, then introduces the secondary geographical and environmental data. Next, this chapter introduces the main elements of
methodology for describing and explaining the spatial and temporal relationships between distributions of emperor abundance and environmental variables.

Chapter 4 presents a qualitatively explanatory analysis of the relationships found between emperor abundance and associated environmental factors (SST, SSS geographic locations and depth) in the waters of Oman. Results for emperor catch patterns are discussed.

Building on Chapter 4, Chapter 5 examines the influence of environmental variables on emperor abundance and the spawning season of *Lethrinus nebulosus* from a quantitative perspective. This chapter also presents an assessment of the models, their accuracy and validation data.

In Chapter 6, the significant findings of the study are presented, discussed and summarised. Additionally, suggestions are made for the further development of this approach as the first application of GIS and GAM techniques to studies of the emperor fish.
Figure 1-3 Organization of the thesis
Chapter 2 : Literature Review

2.1 Introduction

This chapter reviews the state of research into the emperor species, through the application of the Geographical Information System (GIS), Remote Sensing (RS) and non-parametric statistics such as Generalised Additive Models (GAMs) to marine fisheries.

It begins with an overview of general studies of the emperor in Section 2.2. In Section 2.3 describe the environmental condition in Omani waters. Section 2.4 explores application of the GIS and RS to marine fisheries, while Section 2.5 highlights the uses of univariate data sets commonly found in ecological or environmental studies and non-parametric GAM techniques. Section 2.6 deals with studies of marine fisheries which have applied a combination of all three techniques: GIS, RS and GAMs. Section 2.7 summarises the chapter.

2.2 Overview of general studies of the emperor, Lethrinidae

The emperor fish, also known as pig face bream, is a scavenger belonging to the Lethrinidae family and known locally as Sheiry. The focus of this section is on the genus of emperor fish called Lethrinus and the spangled emperor (Lethrinus nebulosus) species (Forsskål, 1775) in particular (Figure 2-1). This is because for the genus Lethrinus, there is a paucity of information on patterns of distribution and abundance, while Lethrinus nebulosus is the most common lethrinid and an
important commercial species in the line fisheries of Omani waters, with little information on the biology of spawning aggregations.

Figure 2-1: Spangled emperor (*Lethrinus nebulosus*). Photo taken by David Harasti [www.scuba-equipment-usa.com/marine/JAN05/imaq](http://www.scuba-equipment-usa.com/marine/JAN05/imaq) (28/July/2006)

2.2.1 General biological aspects of the emperor

Species of the family Lethrinidae are widely distributed in the coastal waters of the tropical and subtropical Indo-Pacific region (Young and Martin, 1982; Carpenter and Allen, 1989). The family consists of two subfamilies, the Lethrininae and the Monotaxinae, the latter containing four genera and the former just one genus, *Lethrinus*, which has twenty-eight species (Carpenter and Allen, 1989; see Appendix 1). In the present study, *Lethrinus* and *L. nebulosus* are the focus. This genus contains some of the most common and economically important commercial and artisanal tropical demersal fish species (Carpenter and Allen, 1989), including in the study area. Lethrinids occur mainly in the tropical and
subtropical Indo-Pacific region and only one species of *Lethinus* occurs in the
tropical eastern Atlantic (Randall, 1995).

A number of studies have documented the biological aspects of the Lethrinidae
family, including age, growth and mortality, as well as food and feeding habits, in
different regions: the Pacific and Indian Oceans, the Red and Arabian Seas, and
the Arabian Gulf region, for example Walker (1975, 1978); Aldonov and Druzhinin
(1978); Al-Sayed *et al.* (1988); El-Gammal (1988); Ibrahim *et al.* (1988a);
Morales-Nin (1988); Sharma (1990); Brown and Sumpton (1998); Laursen *et al.*
(1999). However, these bodies of research into the reproductive biology of the
genus *Lethinus* are restricted to only a few species of the family Lethrinidae, as
will be discussed below.

### 2.2.1.1 Growth and population

There are a number of factors which might be expected to affect growth, such as
location, water temperature and food (Medley *et al.*, 1993). For instance, Medley
*et al.*, (1993) found that the growth parameters of emperor *L. nebulosus* had a
wide range of values over different locations.

Generally, *L. nebulosus* is a large tropical species reaching 80.0 cm total length
and 8.4 kg total weight (Randall, 1995); the maximum age of an individual
estimated from the count of opaque bands in the Arabian Gulf was found to be 14
years (Grandcourt *et al.*, 2006). However, Ezzat *et al.*, (1992) reported the growth
of *L. nebulosus* in the Arabian Gulf waters off Dammam at 7 years old, while the
length was 39.70 cm and weight 8 Kg. Furthermore, Al-Abdessalaam, (1995)
reported that, *L. nebulosus* in Omani waters can reach around 75cm total length and corresponding to about 4 years of age.

Pilling *et al.*, (2000) estimated the rate of growth of other species, such as *L. mahsena*, in the tropical Indian Ocean and found it varied depending on the time of sampling during the year and the age of the fish. The rate of growth between ages 1-5 years was fast, while at age 6 and above it was slow. Wassef, (1991) examined two species of genus *Lethrinus*, *L. mahsena* and *L. lentjan*, in the Red Sea and found that the maximum size of *L. lentjan* was 42cm, while that of *L. mahsena* was 47cm.

Williams *et al.*, (2003) examined other species such as *Lethrinus miniatus* on the Great Barrier Reef in Australia, concentrating on age estimation and rates of somatic and otolith growth, and found a direct linear relationship between otolith and fork length. However, although these studies determined the size of spatial patterns on the species by using otolith growth and somatic growth, there were no direct explanations of the fundamental factors driving the regional patterns, despite their great importance in fish growth studies.

### 2.2.1.2 Feeding behaviour

A number of studies on food and feeding habits have been carried out on Lethrinids in the Pacific Ocean, the Red Sea and the Arabian Gulf, such as those by Walker, (1975, 1978) and El-Gammal, (1988), suggesting that they are bottom-feeding, they have strong jaws and their dentition and body form reflect their feeding specificity (Carpenter and Allen, 1989), the type of food depending mainly on the type of lateral jaw and type of teeth. Carpenter's (1996) study of the
relationship between the body shape of the *Lethrinus* and feeding mode suggested that the ontogenetic series may provide evidence for the evolution of these feeding types. Lo Galbo *et al.*, (2002) also examined the evolution of the three primary feeding types in 20 species of *Lethrinus*. For example, the diet of *L. nebulosus*, *L. harak* and *L. lentjan* are mainly composed of molluscs, crustaceans, polychaetes and echinoderms, suited to their molariform or submolariform teeth (Carpenter, 1996; Fischer and Bianchi, 1984). As for other species, Bhikajee, (2004) found that *L. Mahsena* feeds on same foods as *L. nebulosus*: crustaceans, molluscs and echinoderms. In addition, Nasir, (2001) reported that the *L. lentjan* feeds on polychaetes, bivalves, crabs and fish.

### 2.2.1.3 Reproduction

Many species of reef fish form spawning aggregations of large numbers of mature fish, which travel to a specific location at a specific time (Domeier and Colin, 1997; Colin *et al.*, 2003). As with other representatives of the family Lethrinidae, *L. nebulosus* is a protogynous hermaphrodite, with sexual transformation from female to male occurring over a wide range of sizes (Ebisawa, 1990; Young and Martin, 1982). Also, McIwain *et al.*, (2006) report that the L50 for *L. nebulosus* was not significantly different between sexes. Nzioka, (1979) has described the probable spawning seasons of some Lethrinid species in East African waters by observing the seasonal occurrence of the mature stages of these species. Generally, Lethrinids are considered to have long spawning seasons, running from spring to at least early autumn, with peaks occurring in different seasons.

The spawning seasonality of different Lethrinid species varies widely (Carpenter and Allen, 1989). For example, Ebisawa, (1990) reports that the spawning of *L.*
*L. nebulosus* occurs during March to April in Okinawan waters, while Nzioka, (1997) observed that the spawning of *L. nebulosus* has two peaks from March to April and October to November off the east coast of Africa. *L. nebulosus* was also found on the North Western Shelf of Australia, with a prolonged spawning season extending from September to February (Kuo and Lee, 1990). Moreover, Grandcourt (2006) found a peak in the Gonado Somatic Index (GSI) for *L. nebulosus* females in April and noted that the main spawning period lasted until the end of May in the southern Arabian Gulf, while Mcllwain *et al.*, (2006) found one peak in the spawning of females and males of *L. nebulosus* between October and December in the Arabian Sea, in Omani waters.

Other studies of different species, such as by Kulmiye *et al.*, (2002), have examined the reproductive biology of the *Lethrinus harak* species in Kenyan waters and found a prolonged spawning season extending from October to April, with peaks during October and February, and a length at maturity estimated to be 24.2 and 26.4 cm. Bhikajee, (2004) investigated the reproductive biology of *Lethrinus mahsena* at St. Brandon (Mauritius) and found that the length at maturity was estimated to be 30 cm, with spawning taking place no later than in the month of September every year, which indicates that the species is annually productive. In the Red Sea it was found that peaks in sexually mature females for *L. lentjan* occur in January and from April to May (Kedidi *et al.*, 1984), while in the New Caledonian Lagoon it was observed that the spawning of the same species was during August and September (Loubens, 1980b).

On the other hand, Sumpton and Brown (2004) identified in *Lethrinus miniatus* an extended spawning season from July to November in the southern Great Barrier.
Reef, Australia. Similarly, Williams et al., (2006) identified a peak spawning period for the same species between July and October on the Great Barrier Reef. Ebisawa, (1997) found that *Lethrinus rubrioperculatus* spawned from May to October in waters off the Ryukyu Islands, while *Lethrinus atkinsoni*, was found to have a spawning season from April to November in the Ryukyu Island waters (Ebisawa, 1999).

Despite the many studies conducted in many parts of the world to investigate the reproductive biology of the genus *Lethrinus*, they are restricted to a few species of the family Lethrinidae; it is especially notable that in the Arabian Sea and Gulf of Oman, knowledge of the biology of spawning of the family is lacking.

### 2.2.1.4 Habitat

*Lethrinus* mostly inhabit coral and rocky reefs and occur in coastal waters up to 100 metres depth, preferring sandy or rubble substrate habitats (Al-Abdessalaam, 1995; Carpenter and Allen, 1989; Kailola et al., 1993).

The spangled emperor *Lethrinus nebulosus* is distributed throughout the Indo-West Pacific, from the Red Sea and East Africa to southern Japan and Samoa (Carpenter and Allen, 1989; Grandcourt et al., 2006). It is found in a variety of habitats including coral reefs, sea grass beds and mangroves, from near shore to a depth of 75 m (Randall, 1995; Forster, 1984; Williams and Russ, 1994).

Newman and Williams, (1996) used fish traps to describe the broad-scale patterns of distribution and abundance of *Lethrinus* species along the continental shelf of the central Great Barrier Reef. One characteristic they found was that *Lethrinus*
prefer shallow shelf waters of less than 100 m. Newman et al., (1997) went on to use visual censuses to quantify the distribution and abundance of Lethrinus at the same location in three different deeper water assemblages and the results were the same. However, neither of these studies examined the longer-term temporal stability of the observed spatial patterns.

Additionally, Newman and Williams, (2001b) used both methods —visual censuses and fish traps— in the same study area, and concluded that the Lethrinids are primarily demersal species that are associated strongly with hard substrata and deeper-water feeding; therefore their distribution may be highly correlated with structure and shelter. Indeed, these findings on Lethrinus distribution support other studies (Al-Abdessalaam, 1995; Carpenter and Allen, 1989; Kailola et al., 1993) in different regions, in which it was found that Lethrinus species are generally at lower abundance on inshore reefs than on reefs of the mid-shelf depth. Hixon and Beets, (1989) suggest that depth preferences may also overlap with the selection of large shelter and that this could be the major factor in the depth distribution of Lethrinus.

Overall, the different studies noted above have used different methods associated with Lethrinidae distribution patterns, investigating their growth and reproductive biology and also identifying spawning seasons in some regions. However, the focus of these studies was on the distribution of the Lethrinus. Their relationships to other environmental variables are still in early stages of research, and existing studies indicate many gaps. It is this research gap that the current research seeks to fill, i.e. the relationship between the distribution of the emperor fish and its
abundance with reference to environmental variables such as sea surface temperature, salinity and depth.

In fact, since the studies reported used neither GIS nor GAM techniques, nor considered the relationship of environmental variables such as sea temperature or sea salinity with spatial and temporal distribution patterns and the biology of emperor, this research will apply these two techniques. They will be used to study the spatial and temporal distribution patterns of emperor and the spawning season of *L. nebulosus* in Omani waters to explore the possibility of a relationship between the fish and their environment.

2.3 Environmental conditions in Omani waters

The Arabian Sea is one of the most complex marine regions (Richardson *et al.*, 2006) and it comes under the influence of seasonal variations in conditions (Savidge *et al.*, 1990). There are two different water masses in the study area, which is characterised by strong upwelling-favourable southwest winds accompanied by cloud cover during the SW monsoon, which occurs from May to September. These conditions have been confirmed by various investigations (Kindle, 2001; Schott, 1983; Prasad, 2004; Quraishie, 1984); the upwelling is more intense when at its peak in July (Rao *et al.*, 2005) and is associated with a reduction in SST. The monsoon then reverses to the north-easterly direction, with moderate winds and clear skies, from November to February (Arnone *et al.*, 2000; Flagg and Kim, 1998).
The Gulf of Oman is strongly influenced by outflow from the Arabian Gulf, but not directly affected by the seasonal upwelling during the SW monsoon (Bohm et al., 1999). The SST images show a plume of Gulf water flowing along the Gulf of Oman to Ra’s Al-Hadd at the mouth of the Gulf of Oman, i.e. where it joins the Arabian Sea (Figure 2-2). Flagg and Kim (1998) discovered that the Ra’s Al-Hadd Jet has two types of eddy: an anticyclonic eddy forms when the northward Oman coastal currents reaches Ra’s Al-Hadd, where the flow turns offshore to the northeast; and a cyclonic eddy occurs when a current driven southward to Ra’s Al-Hadd turns offshore to the southeast, this feature also being referred to as the Ra’s Al-Hadd Jet (Johns et al., 1999).

This jet separates relatively cool water (25-26°C) found in the central Arabian Sea from warmer water greater than 30°C found within the Gulf of Oman and the northern Arabian Sea (Shi et al., 2000) (Figure 2-2). During summer the SW monsoon causes strong currents and a productive upwelling with deeper mixing, bringing colder, less saline water to the surface mixed layer and most of the deep water upwelling across the 500 m depth, which compensates for the loss of water in the upper 500-m layer (Shi et al., 1999). These features are capable of exporting cool water rich in nutrients hundreds of kilometres offshore (Brink et al., 1998). Additionally, NOAA / AVHRR satellite imagery shows that the SST during the SW monsoon in the Arabian Sea is lower than in the Gulf of Oman waters by approximately 5°C and reaches a minimum value in the Arabian Sea in July, while in the Gulf of Oman it reaches a minimum value in January. However, the winter NE monsoon winds produce onshore flow and stratification of the water column, with warmer surface water and a shallower mixed layer (Kumar et al., 2001).
Figure 2-2 Movement of filaments extending from the Arabian Sea and the Gulf of Oman to Ra’s al Hadd.

In this study the sea bottom temperature and sea bottom salinity were not considered for analysis, because during both SW and NE monsoons the mixed layer depths increase to a maximum of less than 80 metres and the difference between surface and bottom temperatures within this depth is very small, at 0.02 to 0.1°C (Weller et al., 2002). In addition, Forster, (1984) notes that the fluctuation of temperature at moderate depth (50-60 metres) varies between 2°C and 3°C. Moreover, Kumar et al., (2001) examined the evolution of physical, chemical and biological fields in the Northern Arabian Sea during the NE monsoon and observed that the SST was uniform at mixed layers at a depth of less than 30 metres. Indeed, Esenkov et al., (2003) observed that the mixing of layers in the Arabian Sea occurs between depths of 40–50 metres and 150–300 metres and that large quantities of water are exchanged between these areas, but SST appears to be of very low variation. Similarly, Esenkov et al., (2002) studied the features of
Chapter-2

subsurface circulation of water in the western Arabian Sea at mixed layer depths and found that this circulation had a strong impact on the surface.

Kumar and Narvekar, (2005) analysed the seasonal variability of the properties of mixed layers in the central Arabian Sea and found that the analysis of profiles indicated matching with the SST distribution, but did not appear to have any specific trends during the SW monsoon. Weller et al., (2002) also suggested a reduction in salinity below the mixed layer and that advection plays an important role in controlling salinity during the southwest monsoon. In addition, Esenkov et al., (2002) observed that salinity values differed only by 0.1 practical salinity units (psu) in the undercurrent depth. As a result, sea bottom temperature and sea bottom salinity data were not considered in this study.

2.4 Applications of the Geographical Information System and Remote Sensing in marine fisheries

Marine GIS has been used in many ways to gather data from oceans and seas and to integrate information on different environment variables. The aim of this section is to provide an overview of how GIS and RS can be used to deal with issues in marine fisheries.

2.4.1 Applications of GIS in Marine fisheries

GIS is basically an integrated computer-based system which allows the input of digital geo-referenced data to produce maps, plus other textual, graphical and tabular output. The essential usefulness of GIS, however, lies in its ability to manipulate data in a large number of ways and to perform various analytical
functions so as to produce outputs that can contribute to a faster and more efficient decision-making process in fisheries (Fisher and Rahel, 2004).

GIS has been used for the analysis of marine fish habitats (e.g. Kendall et al., 2004; Chen et al., 2005). Isaak and Hubert, (1997) provide information on GIS capabilities in the analysis of fisheries. Fisheries professionals are increasingly using GIS as a resource management tool, because it is a useful technique for studying fish resources and allows integration between fisheries production, fishing areas, aggregation areas, spawning grounds and oceanographic features (Nishida et al., 2001). Indeed, the GIS technique provides useful information on various issues such as spatial and temporal fish distribution, locating spawning areas, spawning time, whole habitats, aggregation areas and migration areas, especially when integrated with methods for spatial data analysis such as environmental data (Meaden, 2000; Valavanis et al., 2002). Subsection 2.3.3 will discuss the use of GIS technology in fisheries and the integration of RS data within GIS as an important element in marine GIS development.

Valavanis, (2002) has categorised marine GIS applications into three overlapping types: coastal, oceanographic and fisheries. Taking a more process-based approach, Meaden, (2000) identifies three major components of fisheries for GIS applications: (1) the dynamics of marine objects (species populations); (2) the dynamics of marine processes (upwelling); and (3) the vertical dimension. This chapter illustrates several different applications of GIS in fisheries. For example, Valavanis et al., (2002) have approached the development of marine GIS applications in fisheries as an important introduction to species life-history data. The FAO Fisheries Department has produced a series of publications focusing on the necessary skills, such as procedures for mapping marine resources (Meaden,
1996), a revision of the growing need for GIS and its applications to marine fisheries. More recently it has also organized workshops at regional level for the purpose of discussing the use of GIS as a decision support for the management of fisheries, such as the International Symposium on GIS in Fishery Science and the Fisheries GIS Symposium 1999. Figure 2-3 shows the relationships between four categories which are usually recognised but which overlap (Nishida and Booth, 2001).
Alakhzami, (2000) explored the applications of GIS techniques to marine fisheries in Omani waters. He used two types of fisheries data: traditional and commercial (long-lines and trawlers). The spatial integration of the methods was twofold, the point and the area, to display data at different levels of management and decision making. The results indicate that the concentration of pelagic fish was in the northern part of Omani waters, in the Gulf of Oman, while the demersal fish were concentrated more in the southern part of the Arabian Sea. However, this study was unable to explain the relationship between the environment and the distribution of the fish. Similarly, Riolo, (in press) has shown that a geographic information system can analyse and visualize temporal and spatial data in the context of long line fishery in American Samoa. Abella et al., (2001) used GIS in the Tyrrhenian Sea to measure the spatial distribution and abundance of different
commercial species caught by trawlers. Verdoit et al., (2003) also used GIS to examine the spatial and temporal distribution of white fish in the Celtic Sea.

2.4.2 Applications of Remote Sensing in marine fisheries

It is widely recognized that oceanographic environmental factors such as temperature, salinity, depth and colour have an influence on the distribution of fishery resources and shapes of marine ecosystems (Sharp et al., 1983; Pierce et al., 2001; Pierce et al., 2002). Thus, the understanding of the marine environment and modelling of the dynamics of water masses—upwelling, surface and underwater currents, convergence and diffusion—are essential because of their influence on fish habitat and fish distributions so have been explored as proxies for the identification of productive habitats.

Along with the recognition that environmental factors have an influence on fish habitat, the field of remote sensing has gained increasing attention during the past years. Satellites and other RS technologies, with their advantages of spatial, spectral and temporal availability of data, present information on a fairly large geographic scale and their analyses can provide real-time guidance for processing. They are also useful for the acquisition of information on fisheries including resources, location and dynamics (Simpson, 1994).

Remote sensing has gained increasing importance in studies of marine systems; it has numerous applications from a fisheries management perspective and its high archival imagery makes for long-term analysis. One of the greatest advantages of using RS data for monitoring fisheries is its ability to generate information in-spatial
and temporal domains, which is crucial for successful analysis. Researchers have noted that fish distribution is not influenced by only one variable but by a variety of biotic and abiotic factors, especially sea temperature, which is affected by other environmental factors such as water circulation and in turn determines food availability. This concurs with comments from others researchers such as Rose et al., (1994), who believe that one factor cannot be a good proxy for fish distribution patterns or other biological studies. Additionally, numerous articles have addressed the statistically significant correlation between fish distribution and environmental variables (Cushing, 1982; Bell and Putter, 1958).

Satellite systems such as the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) have produced oceanographic information data such as ocean surface temperature and these data from the AVHRR positioned on the weather satellites of the National Oceanographic and Atmospheric Administration (NOAA) have proved highly useful for studying the ocean surface (Cotos et al., 1993). Particular attention has been paid to the detection and monitoring of SST variability and upwelling of cold, nutrient-rich benthic waters from the ocean floor, since these areas represent the richest fisheries (Cotos et al., 1993).

A number of studies have used different satellite data such as sea surface temperature, since determination of spatial variation of SST and upwelling may contribute to a better understanding of dynamic processes, thus providing a sound scientific basis for fisheries operations (Simpson, 1994). For example, Wilson-Diaz et al., (2001) analysed the variability in SST derived from the AVHRR Pathfinder to examine the inter-annual variability in the climatologically of SST data in the
Arabian Sea, providing the description of the environmental dynamics of Omani waters which has been discussed in Chapter 2 Section 2.3. Luis and Kawamura, (2003) used AVHRR to address seasonal and temporal SST variability along the West India shelf in order to explore the relationship between SST and atmospheric forcing, heat fluxes and wind stress, which could affect fish habitats. SST data obtained from AVHRR data has also been used to examine the influence of surface thermals in the study of squid in Falkland Islands waters (Waluda et al., 2001).

Given the vital importance for the protection, management and sustainability of species of mapping their environmental variation, and the recognition that remote sensing data alone is not sufficient for many fisheries analyses, there is a clear need for RS to be merged with GIS. Therefore, several studies on the spatial and temporal dynamics of fish populations have used a combination of the two technologies. This combination will be discussed in the following subsection.

2.4.3 Combined application of GIS and RS in Marine Fisheries research

Within fisheries research, the integration of remote sensing technology and geographical information systems plays a rapidly increasing role in the field of marine fisheries development (Valavanis, 2002). They have also already been successfully applied to map the distribution of species (Bello et al., 2005) and have proven to be powerful tools for the evaluation of coastal and marine habitats and an essential aid in fisheries studies (Green et al., 2000). Although the direct detection of fish stocks would appear difficult, different techniques are currently under development, as described by Butler et al., (1988).
Overall, the number of studies of applications of GIS using RS in fisheries has been growing significantly during the last few years (Meaden and Kapetsky, 1991). Simpson, (1994) discusses some of the potential benefits to be gained from increased use of RS and GIS in operational fisheries oceanography, and of the combination of the two technologies to overcome the limitations of satellite data used alone. The spatial and temporal patterns of fish species resource dynamics could be examined through the use of GIS (Valavanis, 2002) because analysing RS-based environmental variables within GIS technology can reveal information about the geographical distribution and life history of species (Simpson, 1994; Meaden, 2000; Waluda et al., 2001). Additionally, Wilkinson, (1996) and Hinton, (1996) have reviewed issues in the integration of GIS and RS data for environmental applications and noted that there is increasing use of GIS for the storage, manipulation and visualisation of RS data. The uses of satellite imagery to derive bio-geophysical parameters, e.g. SST, salinity and chlorophyll (CHL) are also becoming increasingly important within marine fisheries oceanographic research (Valavanis et al., 2004).

Table 2-1 Combination of RS and GIS in marine fisheries

<table>
<thead>
<tr>
<th>Reference:</th>
<th>Type of Fish</th>
<th>Geographical Area</th>
<th>Tools</th>
<th>Type of Data</th>
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<tbody>
<tr>
<td>Eastwood et al., (2001)</td>
<td>Sole</td>
<td>South Atlantic</td>
<td>GIS/RS</td>
<td>Daily fishery data</td>
</tr>
<tr>
<td>Wright et al., (2000)</td>
<td>Lesser sandeel</td>
<td>North Sea</td>
<td>GIS/RS</td>
<td>Survey data</td>
</tr>
<tr>
<td>Bello et al. (2005)</td>
<td>Lobster</td>
<td>Yucatan, México</td>
<td>GIS/RS</td>
<td>Field Survey</td>
</tr>
</tbody>
</table>
At this point it is appropriate to refer to some case studies in order to demonstrate the ability of GIS and RS to handle huge amounts of data from different sources and apply them to marine fisheries. Although several studies using GIS and RS have focused on spatial and temporal dynamics, these have tended to concern pelagic and cephalopod more than demersal fish species. Table 2-1 shows examples of applications of GIS and RS to demersal species. Examples applying to other species include Lee et al., (1999), who used the GIS technique and RS to create monthly distribution maps for three types of tuna in the Indian Ocean and investigated the high abundance areas with SST data derived from AVHRR and CHL concentrations by overlaying maps. A discriminant function analysis was also applied to predict the catch per unit of effort (CPUE) and abundance of the three species of tuna, based on monthly distribution patterns.

Studies of spatial and temporal dynamics through GIS and RS have been also used for mapping spawning grounds of species such as sole (Eastwood et al., 2001) and, cuttlefish (Valavanis et al., 2001), and GIS has been used for mapping the distribution of the habitat of the lesser sandeel (Wright et al., 2000). Zheng, (2001) also used GIS to describe the spatial patterns of whiting abundance, haddock and cod distribution in relation to environmental factors in UK water. Buck and Anderson, (2001) analysed spatial and temporal distribution of pink shrimp, walleye pollock and arrowtooth flounder against environmental conditions in Kodiak Island, Alaska. Valavanis, (2002) also used satellite imagery and AVHRR to map SST and SSS, in order to reveal areas having minimum and maximum environmental values. Furthermore, Gordoa et al., (2000) analysed monthly and spatial patterns of the Namibian hake catch and its relationship with environmental
seasonality, using commercial data from bottom trawl fishery logbooks and weekly SST data obtained from NOAA. Results showed that the Namibian hake has a strong seasonal pattern which correlates with the environmental seasonality.

Castillo et al., (1996) used GIS to analyse the distribution of sardine, anchovy and jack mackerel based on acoustic information on the geographical and spatial distribution of the three species relative to physical oceanographic conditions, surface temperature and salinity off northern Chile. It was observed that the distributions of species were influenced by the presence and intensity of thermal fronts. Abookire et al., (2000) used GIS to map fish distribution in relation to SST and salinity in Alaska. Nakken, (1994) and Rose et al., (1994) used GIS to observe the cause of trends and fluctuation in Arcto-Norwegian cod and the recruitment of cod stock, which was positively related to the inflow of Atlantic water into the fisheries.

Other studies have used GIS and RS to study the effect of Atlantic currents on fish; for example, Helle and Pennington, (1999) note that the highest abundance of juvenile cod coincided with the areas of highest zooplankton biomass, which may be associated with the strong inflow of warm Atlantic water. In a similar study, Begg et al., (1999) found a broad distribution of cod species during spring, with a move to deeper waters during summer, while haddock moved to deeper waters during autumn.

The GIS and RS techniques were also used by Foucher et al., (1998) to study spatial and temporal patterns in other species such as Octopus vulgaris, grouper and sea bream on the Senegalese continental shelf; they used both artisanal and
industrial trawler data. Similarly, Demarcq and Faure, (2000) used GIS and RS (Meteosat) to identify the spatial structure of upwelling off the West African coast and estimated environmental impacts on *Octopus vulgaris* in Mauritania, while Piatkowski *et al.*, (2001) overviewed various studies using GIS to reveal the interaction of cephalopods with their environment.

Other researchers have demonstrated the relationship between environmental variables and cephalopod abundance and biology in UK waters; for example, Pierce *et al.*, (1998) used GIS to describe temporal and spatial patterns of cephalopod distribution and abundance patterns in the North Sea, while Waluda and Pierce, (1998) used GIS and RS to test hypotheses regarding the spatial distribution and to identify spawning locations of the squid *Loligo forbesi* and *Loligo vulgaris* in the northern north-east Atlantic. The relationships between squid distribution and sea temperature and salinity in the North Sea were examined by overlaying maps of squid abundance, landings per unit effort (LPUE) and oceanographic variables, using correlation and multiple regression analysis. Similarly, Dawe *et al.*, (2000) used GIS and focused on environmental influences on another squid (*Illex illecebrosus*) in the northwest Atlantic Ocean. The results of the analyses indicated that squid abundance was positively related to oceanographic regime. Other studies elsewhere have also used GIS and analysed SST data to reveal distribution and spawning areas of the cephalopod *Todarodes pacificus*, for example, in the East China Sea and the south-western Sea of Japan (Kiyofuji *et al.*, 1998; Sakurai *et al.*, 2000). Xavier *et al.*, (1999) demonstrated the ability of GIS to produce an atlas of the distribution of 21 species of cephalopod in the Southern Ocean. Similarly, Valavanis *et al.*, (2002) demonstrated how GIS
techniques can reveal different spatial and temporal patterns of cephalopod dynamics with the integration of RS.

An investigation of the possible relationships between coastal upwelling variability and sardine and horse mackerel recruitment dynamics off the west coast of Portugal was carried out using GIS and RS by Santos et al., (2001), who confirmed that the variability of upwelling conditions and spawning season are crucial factors in the recruitment dynamics. Valavanis et al., (2004) used GIS to define areas of high productivity by integrating the time series of monthly satellite images of SST distribution derived from AVHRR with monthly fisheries production data such as CPUE of Sardine pilchardus, Engraulis encrasicolus, Loligo vulgaris and Illex coindetii in the Eastern Mediterranean. Additionally, Brown and Nocross, (1999) used both ground and satellite SST data to define the spatial and temporal distribution of herring juveniles in Prince William Sound.

Previous studies illustrate that GIS and RS techniques were useful in studying the integration of different species with environmental factors and in analysing the spatial and temporal features of fish abundance to provide more details of intra- and inter-annual variations in their distribution and abundance and to quantify how SST affects species distribution and migration along different coasts (Wang et al., 2003; Mathews et al., 2001; Nishida et al., 2001; Pena et al., 2001).

The successful combined use of GIS and RS techniques in the numerous studies cited above justifies their application in this research, although it can be seen that there have been relatively few applications to demersal species and to Lethrinus species in particular.
2.5 Models of Marine Species Abundance

Statistical models are potentially important tools in the prediction of species distribution and abundance based on environmental variables (Ahmadi-Nedushan et al., 2006). Modelling is also a useful tool to roughly mimic the structuring and functioning of an ecosystem, but the ability to model individual distribution patterns, populations and ecosystems depends on the modelling techniques and computing power available (Giske et al., 1998). Several studies have been carried out to assess associations between fish distribution and different environmental variables which may influence fish habitat; several models could be used to provide quantitative descriptions of and predictions about marine fisheries, and to relate fish abundance to the habitat variables.

This section first explores some of the different models used in fisheries research. For example, Xiao et al., (2004) overview the use of GAM, GLM and GLMM in fisheries science and of progress in the field. Beamish and Lowartz, (1996) used multi-linear regression (MLR), while Brosse et al., (1999) used two models: MLR and artificial neural network (ANN) to assess the influence of environmental variables on the spatial distribution and abundance of six fish populations. Eastwood et al., (2003) used quantile regression(RQ), which is a linear model, to model the spatial distribution of sole in the Dover Strait, while Sobrino et al., (2005) used Spearmans rank to assess how young fish recruitment is affected by estuarine fishery activities. Wang et al., (2003) also used the Spearmans rank technique to examine intra- and inter-annual variations of cuttlefish distribution and abundance in the English Channel. Moreover, Principle Component Analysis (PCA) has been used by Zheng et al., (2001) to define areas of similar seasonal
patterns of whiting abundance in Scottish waters. GLMs have been used extensively in fisheries studies to investigate abundance (Nishida and Chen, 2004; Royer et al., 2006) and standardization of CPUE (Battaile and Quinn II, 2004).

ANNs have been shown to be efficient for non-linear data; while their use in fisheries applications has been limited, it includes the modelling of fish species richness (Guegan et al., 1998), presence/absence (Mastrorillo et al., 1997; Maravelias et al., 2003), abundance (Lek et al., 1996; Brosse et al., 1999) and production (Chen and Ware, 1999). MLR is also used in ecology analysis, but it has a drawback in the relationships between dependent and independent variables, because they are always non-linear (James and McCulloch, 1990). Furthermore, MLR is not appropriate when assumptions of normality, linear relationships and constant variance of errors are violated (Ahmadi-Nedushan et al., 2006), while GLM is an extension of linear models that does not force data into unnatural scales, and thus allows for non-linearity variance structures in the data.

On the basis of previous studies, it was found that not all of these techniques can be used to predict the probability of occurrence of fish in relation to environmental variables. GLM, GAM and ANN can produce models of high predictive value, while Spearmans rank can be used for correlation between variables but not for prediction. PCA is a common technique for finding patterns in data having similarity in high dimensions; when, used for modelling fish distribution it requires absence datasets only and can transform the variables into a smaller set of linear combinations (Dillon and Matthew, 1984; Manly, 1994). Although using both GLM and GAM techniques in the same study is not common, there are some examples: Cardinale and Svedang, (2004) tested a final GAM model for cod recruitment and
abundance with GLM in the North Sea, while Fox et al., (2000) fitted GLM to cod, sole and plaice in the Irish Sea to test whether the GAM models were significantly better than the GLM ones.

From the above it can be concluded that GLM, GAM, MLR and ANN are all appropriate tools for both prediction and explanation of ecological relationships at various spatial scales and for aquatic resources, but a major limitation on the use of neural networks is that they require large amounts of data for analysis (Silvert and Baptist, 1998). Another problem with neural networks is that there may be multiple solutions to the neural network using common estimation techniques (Hinton and Maunder, 2004). This is a serious problem, because in most ecological applications data are usually very inadequate and limited. It is therefore essential to find ways of making these analytical tools more efficient so that they can be used in situations where the amount of data is small. Ultimately, the choice of modelling technique should depend on the nature of available data and on the specific study aims. Ahmadi-Nedushan et al., (2006) review some statistical models and present their respective advantages in different contexts. Table 2-2 shows options for different models to be used in marine fisheries analysis.

Table 2-2 Options for different models used for marine fisheries

<table>
<thead>
<tr>
<th>Model</th>
<th>Non-linearity</th>
<th>Analysis/explanatory task</th>
<th>Prediction task</th>
<th>Non parametric</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAM</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLM</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANN</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spearmans rank</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RQ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Small sample

Large data
Therefore, Generalized Additive Models (GAMs) were chosen for use in this study, because they appear to be the most flexible in expressing relationships between explanatory variables and response variables such as CPUE and GSI. While the use of GAMs in fisheries studies is less common than that of GLMs, their use has increased substantially over the last decade (Venables and Dichmont, 2004) and GAMs have recently shown particular promise in modelling relationships between fish distribution/abundance data and environmental factors (Barratt et al., 2002).

GAMs are found in some software packages, such as S-PLUS, R, SAS and Brodgar. For example, GAMs analyses have been carried out using Brodgar software, Highland Statistic Ltd (Sacau et al., 2005), S-PLUS (Begg and Marteinsdottir, 2002) and R software (Leathwick et al., in press). GAMs are an effective and flexible technique for conducting nonlinear regression analysis in studies of fisheries. GAMs represent an extension to the range of application of GLMs by allowing non-parametric smoothers in addition to parametric forms, combined with a range of link functions.

This section therefore reviews studies of the various applications of GAMs in different species to correlate the relationship between fish and environmental factors. GAMs were first proposed by Hastie and Tibshirani, (1990) as a non-parametric, non-linear regression technique by which functional relationships can be determined quickly (Jongman et al., 1995). Regressions were fitted by using GAM techniques which have been increasingly used over the last decade (Hastie et al., 2001) and have led to a growing sophistication in the methods used to analyse relationships between fish distribution, abundance and causative
environment factors (Guisan and Zimmermann, 2000; Rogers, 1992; Guisan et al., 2002; Fromentin et al., 1998).

GAMs were first applied to fisheries by Swartzman et al., (1992); for most analyses, sequences of statistical techniques were applied similar to those in Table 2-3. GAM techniques have been applied to demersal species and other fisheries resources; for example, Swartzman et al., (1992) used GAM to analyse the geographical variations in the distributions of five ground fish in the eastern Bering Sea. Two models were used; the first used depth and temperature as covariates and the second model added other two covariates, latitude and longitude, along with depth and temperature. These covariates have been used in their analyses by many researchers, such as Booth, (1998), Wright et al., (2000) and Hedger et al., (2004).

Extensive use of statistical models (GAMs) permits the specification of the error distribution, such as Gaussian, binomial, gamma or Poisson. Each of these distributions allows a variety of link functions to connect the mean with the additive predictor (Maravelias et al., 2000), after which the type of error distribution will be chosen according to appropriate data (O'Brien and Rago, 1996). Non-parametric logistic models for binary data and non-parametric log-linear models for Poisson error distribution were assumed by Swartzman et al., (1992), Smith et al., (2005), Booth, (1998), Begg and Marteinsdottir, (2002) and Simpson and Walsh, (2004), because it was considered appropriate for random count data and estimating the fit of models by calculating the pseudo–R² with the p-values. Bellido et al., (2001), Hedger et al., (2004) and Daskalov, (1999), on the other hand, used Gaussian (normal) distribution, assumed the homogeneity of the residual from the fitted
model and tested by plotting residuals against the predicted values of the identity function using p-values.

Commonly, models were fitted using a stepwise procedure such as the Akaike Information Criterion (AIC) (Akaike, 1973) to determine the best model fit; a lower value denotes a better fit for GAM. The AIC value provides a quantitative measure of model fit and allows direct comparison of GAM and linear models. For example, Zheng et al., (2002) used the GAM stepwise procedures to determine a set of significant covariates based on the analysis of deviance in a study of the abundance of whiting (Merlangius merlangus) in the northern North Sea. Simpson and Walsh, (2004) modelled the spatial-temporal distribution of yellowtail flounder on the Grand Bank using a stepwise procedure to determine the best fitting model based on the AIC, where the lowest AIC statistic gave the best combination of parameters for the final model. Maravelias et al., (2000), Gimona and Fernandes (2002), Walsh et al., (2005), Daskalov, (1999), Cardinale and Svedång, (2004) and Sacau et al., (2005) also used a stepwise procedure for evaluating alternative models in terms of the AIC.

An additional measurement of model fit is based on a pseudo-coefficient $R^2$, which is used for calculating the goodness of the model fit; for example, Zheng et al., (2002), Simpson and Walsh, (2004) and Begg and Marteinsdottir, (2002) measured model fit based on a pseudo-coefficient of determination ($R^2$), which was the fraction of the total variation accounted for by the model. Where pseudo-$R^2$ is higher than 50%, it indicates how the covariates are affecting the spatial distribution abundance (Swartzman et al., 1992), but the disadvantage of $R^2$ is that the higher the $R^2$, the more explanatory variables are used (Zuur et al., 2006).
Cross-validation is another useful estimation to assess the optimal degrees of freedom for smoothers (Wood and Augustin, 2002). Jensen et al., (2005), Trenkel et al. (submitted) and Smith et al., (2005) used cross-validation in their studies.

GAMs have become widely used in marine sciences to predict abundance (Swartzman et al., 1994; Sacau et al., 2005) and also to model relationships of stock recruitment with environmental factors (Cardinale and Arrhenius, 2000; Cardinale and Svedang, 2004). Welsh et al., (1996) recommended modelling the data using a two-stage procedure; two-stage GAMs are an extension of the basic structure in which first the response variable is modelled as a binomial variable (presence/absence) and secondly the presence is modelled as a Gaussian or Poisson distribution (Jensen et al., 2005). The first stage is to model the presence/absence in GLM or GAM and usually with a logistic link, and the second stage is to model with normal distribution such as Poisson; if the model indicates overdispersion then it turns to the quasi-Poisson. Commonly, quasi-Poisson distribution is assumed when accounting for dispersion in the model either more or less than 1. Barratt et al., (2002), Trenkel et al. (2004) and Portela et al., (2005) selected quasi-Poisson distribution in their analyses.

A two-stage GAMs approach has been used in fisheries by Sacau et al. (2005), Barratt et al., (2002), Bellido, (2002), Stoner, (2001) and Jensen et al., (2005) to examine relationships between species and environmental variables. GAMs were also applied to examine environmental and cod distribution data by specifying a binomial distribution (Begg and Marteinsdottir, 2002). Wright et al., (2000) also used GAM to examine the relative significance of physical factors in influencing the distribution of the lesser sandeel Ammodytes marinus in the North Sea. The
data sets were analysed by specifying a binominal distribution of error with a log link function, while abundance data were specified by using gamma distribution and log link functions.

A common theme that is apparent is that the majority of the studies referred to were not of demersal species; they are, however, related to the study fish (emperor). Indeed, there is similarity of data structure and methods of approach among all types and species. Initially, the researchers attempted to fit generalized additive models into different software using a starting model that included all predictor variables as smoothing terms, and which was then simplified as required using a step-wise procedure to determine a set of significant covariates based on analysis of deviance. An additional measure of model fit used is $R^2$, which is the fraction of the total variation accounted for by the model, and the AIC was used to select the best model. Also, cross-validation was used to verify the optimal degrees of freedom for each smoother. The approaches were illustrated using underlying statistical distributions from the exponential family, such as Gaussian, Poisson, quasi-Poisson, binomial or gamma distributions. Examples of different models used in marine fisheries are shown in Table 2-3.
Table 2-3 Examples of techniques used for statistical analysis (GAM) in marine fisheries

<table>
<thead>
<tr>
<th>Type of Fish</th>
<th>Location</th>
<th>Variables</th>
<th>Technique</th>
<th>Type of data</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demersal species</td>
<td>Alaska (GOA)</td>
<td>Distance, lat, long and bottom temp</td>
<td>AIC, ( R^2 )</td>
<td>Survey data</td>
<td>Mueter &amp; Norcross, (2002)</td>
</tr>
<tr>
<td>Sparid fish</td>
<td>South Africa</td>
<td>Temp, Depth, dissolved ( O_2 ), log</td>
<td>Poisson</td>
<td>Survey data</td>
<td>Booth, (1998)</td>
</tr>
<tr>
<td>Whiting</td>
<td>Scottish waters</td>
<td>SST, SBT depth and currents</td>
<td>AIC/ ( R^2 )</td>
<td>Fishery landings</td>
<td>Zheng et al., (2002)</td>
</tr>
<tr>
<td>Whiting, Anchovy, Horse mackerel Sprat</td>
<td>Black Sea</td>
<td>SST, Sea level, pressure, river runoff, wind speed and wind cubed</td>
<td>Gaussian/ AIC/</td>
<td>Survey data</td>
<td>Daskalov, (1999)</td>
</tr>
<tr>
<td>Squid</td>
<td>Northeast Atlantic</td>
<td>Depth, SST, sea pressure, wind direction, wind speed and solar flux</td>
<td>Gaussian and gamma</td>
<td>Commercial data</td>
<td>Denis, (2002)</td>
</tr>
<tr>
<td>Cod</td>
<td>Finnmark Norway</td>
<td>Long, lat, time and depth</td>
<td>Quasi-Poisson</td>
<td>Acoustics data</td>
<td>Trenkel, (2004)</td>
</tr>
<tr>
<td>Squid</td>
<td>Southwest Atlantic</td>
<td>Depth, SST, long, lat, year, month, moon and sky</td>
<td>Binomial / Quasi-Poisson</td>
<td>Commercial data</td>
<td>Sacau, (2005)</td>
</tr>
<tr>
<td>Herring</td>
<td>Shetland, North Sea</td>
<td>SSS, SST, long, lat, type of seabed, depth &amp; zooplankton</td>
<td>Gamma</td>
<td>Survey data</td>
<td>Maravelias, (2001)</td>
</tr>
<tr>
<td>Squid</td>
<td>Scottish waters</td>
<td>Ovary weight, month, gland weight</td>
<td>Gaussian</td>
<td>Market &amp; commercial landing</td>
<td>Smith, (2005)</td>
</tr>
<tr>
<td>Pollock</td>
<td>Bering Sea</td>
<td>Long, lat, water mass, depth and temperature</td>
<td>Poisson</td>
<td>Survey data</td>
<td>Swartzman et al. (1994)</td>
</tr>
<tr>
<td>Cod</td>
<td>Icelandic waters</td>
<td>Lat, long, SST, SBT</td>
<td>Binomial, Poisson/AIC</td>
<td>Survey data</td>
<td>Begg et al., (2002)</td>
</tr>
</tbody>
</table>

From the studies reviewed above it can be seen that GAM techniques were most widely used and were successfully applied to fish survey data. Denis et al., (2002) were the first to apply these techniques to commercial fishery data, and the focus of this thesis is also on commercial fishery data. No survey data were available for the study area, except for two years of biology data. Nevertheless, the main
objective of the Denis et al., (2002) study was to prove whether GAM techniques could explain and model the abundance of fish as survey or commercial data. Indeed, Denis et al., (2002) and other researchers such as Sacau et al., (2005) showed by their results that GAMs could be applied to both types of data.

Reviewing the above analyses confirms that GAMs provide reasonable fits to the spatial distribution and were found to be suitable tools for application in fisheries research. They are also very powerful tools in explanatory analysis, allowing non-parametric smoothers in addition to parametric forms, combined with a range of link functions, and can be applied to a much wider range of data analysis problems, such as those where the data is sparse. The following section will review the application of three techniques, GIS, RS and GAM, as the best combination to identify spatial and temporal patterns in the composition of fish communities.

2.6 Combined application of GIS, RS and GAMs in Marine Fisheries research

Although previous case studies have highlighted the ability of GIS to overlay different information sources at one time, they have also shown that GIS has limitations, which it is essential to overcome by the integration of GIS and analytical tools such as GAMs and database software like ORACLE and MS Access (Pierce, 2001), thus allowing for the improvement of spatial analyses and ultimately leading to better and more effective analysis (Carocci, 2006). Analysis of fish habitats has become more sophisticated, especially combining statistical models of fish distribution and abundance with environmental factors, because GAM applications provide quantitative information on the spatial relationships from
Chapter-2

a mathematical point of view and these models can be used to produce predictions of fish abundance in spatial and temporal domains (Quinn and Keough, 2002).

In order to verify in detail spatial and temporal relationships between fish distributions and a variety of environmental parameters, the best approach is to combine these technique in one study. For example, Zheng et al, (2002) used GIS, GAM and RS techniques to describe the relationships of the spatial patterns of whiting abundance and environmental variables. Techniques combining the application of GIS and GAM were also used by Pierce et al., (2001) to investigate the spatial and temporal distribution of cephalopod resource dynamics in relation to environmental variables, while Barratt et al., (2002) used statistical methods and environmental parameters were obtained from RS and integrated into GIS.

Similarly, Sacau, (2005) used both GIS and GAM techniques to describe variation in Illex argentinus abundance in relation to the geographical and environmental variables using RS data. Leathwick et al., (in press) also used GAM and GIS to analyse relationships between fish species richness and a set of functionally based environmental predictors, including primary productivity. Fox et al., (2000), for their part, used fish catch data and environmental variables in combination with the GIS technique and GAMs to investigate the spatial and temporal patterns in the spawning areas of cod, sole and plaice in the Irish Sea. Table 2-4 shows some examples of using three techniques in Marine fisheries analysis.

The integration of GIS with other quantitative techniques for mapping and modelling fishery habitats is a promising aspect of this relatively new method.
Moreover, the use of GIS combined with environmental models has become widespread as a method of visualizing and mapping the results of habitat modelling (Stoner et al., 2001), as a qualitative description of spatial patterns and to confirm the results revealed by GAMs, such as in the work of Jensen et al., (2005) Zheng et al., (2002) and Barratt et al., (2002). Remote sensing is invaluable as a tool for measuring variables that were not or could not be measured in the field (Brown et al., 2000; Clark et al., 2003). The GAM techniques are useful to provide a quantitative description of the relationships between fish abundance and environmental conditions. The conclusion is that the integration of GIS software and a statistical package will help in overcoming the limitations of the analysis (Pierce et al., 2001).

Table 2-4 Examples of previous studies using three techniques in studies of marine fisheries resources

<table>
<thead>
<tr>
<th>Paper</th>
<th>Geographical area</th>
<th>Variables</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacau, (2005)</td>
<td>Southwest Atlantic</td>
<td>Long, lat, SST, month, year</td>
<td>Squid</td>
</tr>
<tr>
<td>Zheng et al. (2002)</td>
<td>North Atlantic</td>
<td>SST, depth, SBT</td>
<td>Whiting</td>
</tr>
<tr>
<td>Bigelow et al., (1999)</td>
<td>North Pacific</td>
<td>SST, lat, long</td>
<td>Swordfish and blue shark</td>
</tr>
<tr>
<td>Mueter and Norcross, (2002)</td>
<td>Gulf of Alaska</td>
<td>Depth, lat, long, bottom temp and gear type</td>
<td>Demersal fish</td>
</tr>
<tr>
<td>Barratt et al., (2002)</td>
<td>Australia</td>
<td>Depth, month and SST</td>
<td>Orang rougy &amp; yellowfin tuna</td>
</tr>
<tr>
<td>Booth, (1998)</td>
<td>South Africa</td>
<td>Long, lat, depth, temp</td>
<td>Sparid fish</td>
</tr>
<tr>
<td>Agenbag et al., (2003)</td>
<td>South Africa</td>
<td>Long, lat, depth, SST</td>
<td>Pelagic fish</td>
</tr>
</tbody>
</table>

2.7 Summary

In this chapter, three major topics have been discussed: general studies of the emperor fish, applications of RS and GIS in marine fisheries and applications of GAM in marine fisheries. It is clear from previous studies that there is little information on emperor species, especially in the study area. It is also clear that
the identification of environmental factors that influence the spatial distribution, abundance and spawning of emperor have not been researched using GIS, RS or GAMs.

This chapter has also discussed the potential of satellite imagery analyses and GIS tools for incorporating the spatial analysis of different marine resources. It is believed that the potential of these tools for the evaluation of fishing resources is evident and the data from these different technologies (GIS, RS and GAM) can be used to facilitate the collection of data, its calculation and analysis, and to display the results. Nishida and Booth, (2001) summarize the situation of GIS application in fishery science. Figure 2.4 shows that more than 90% of applications of GIS are qualitative analyses, which involve simple mapping and overlay in ecological research. However, the combination of GIS with quantitative analysis is increasingly being used in fisheries research.

Figure 2-4 Summary of the current situation of GIS application to fishery science (Nishida and Booth, 2001).
Source: http://www.esl.co.jp/Sympo/1st/sympo7_3.htm
3.1 Introduction

"Mapping the fishery and the resources should be among the priority tasks when planning for fisheries management and should not be postponed until 'complete' information is available, since redundancies or blanks in the information base will more readily appear in the process of elaboration" (Caddy and Garcia, 1986) p.32.

Certainly, any management system falling under the overall heading of "Fisheries" or "Marine Resources" could not possibly function without having access not only to large amounts of data, but also to data from a wide variety of sources in a potentially huge array of formats (Meaden and Do Chi, 1996). In the context of the above statement, this chapter reviews the primary source of data, its characteristics and the techniques used to develop the study from data collection to analysis. It begins with an overview of the fisheries data (Section 3.2), describing its structure and characteristics, as well as the techniques of collection and calculation for both types of fisheries (traditional and industrial) considered in this study. In Section 3.3, the secondary (mapped survey and environmental) data are introduced, based on and derived from remotely sensed imagery and discusses the preparation of fisheries and environment data (Data Management). The main elements of the methodology used to describe the spatial and temporal relationships between distributions of emperor abundance and environmental variables are explained in Section 3.4 and include suitable tools that can allow the nature of these relationships to be explored, such as Geographical Information Systems (GIS) and non-parametric statistics in the form of Generalised Additive
Models (GAMs). Section 3.5 considers the spatial interpolation method and assesses the accuracy of the models. Section 3.6 concludes and summarises the chapter.

3.2 Data requirements for marine fisheries resources GIS

Geographical information systems cannot function properly without sufficient data, in terms of both quantity and quality, as they affect the functionality, the visual quality and results of the GIS (Meaden and Chi, 1996) and an important factor in organizing a database is the information or data collected, including its source, format and quality.

Hence, it is important to describe the status of the data, which will be highlighted in Subsections 3.2.1 and 3.2.2 prior to an examination of the methodology. This section will thus describe the data sources used in this study, the characteristics of the data and the data type requirements.

3.2.1 Fisheries data

For centuries Oman has run a fleet of sea vessels based in small coastal fishing communities. The combination of open seas and high productivity led to a varied fishing industry and trading in a wide variety of commercially important species. Since the early 1970s the fleet has been modernised and the fisheries sector has expanded. The Ministry of Agriculture and Fisheries (MAF) has taken a number of steps to develop the commercial and traditional fisheries sectors, as fishing is considered to be the most important economic activity following oil. Irrespective of
these positive developments, fisheries activities in the Sultanate of Oman remain classified into two major sectors: (1) the artisanal or traditional sector and (2) the industrial sector (both trawlers and long-liners) (Figure 3-1).

![Conceptual diagram of the fisheries sector in the Sultanate of Oman](image)

**Figure 3-1** Conceptual diagram of the fisheries sector in the Sultanate of Oman

### 3.2.1.1 Illustration of artisanal fishing methods employed in Oman

In the traditional fisheries sector, it is estimated that there are 32,437 fishermen using 13,943 boats (MAF, 2004), which land at 84 villages (landing sites) (Figure 3-3). These villages are grouped into a number of Wilayat, and the Wilayat are further grouped into six regions. Figure 3-2 indicates the main regional landing sites along the coastline of the Sultanate of Oman: Musandam, Al Batinah, Muscat, Al Sharqiya, Al Wusta and Dhofar. The traditional fishing areas are located less than 10 nautical miles from the shoreline and are not restricted by either fishing area or catch quota. The contribution of these regions to total catch is shown in Table 3-2, with the Sharqiya region making the highest contribution to total catch. This may be due to the fact that this region has the highest number of
dhows, which are relatively large and so allow the fishermen to spend longer at sea. On other hand, the table shows that the Al-Wusta region makes the highest contribution to the emperor catch, followed by Dhofar, while Musandam has the smallest total and emperor catches.

Boats in the traditional fisheries are of five major types: fibreglass, houri, dhow (launch), shasha and aluminium. Houris are wooden vessels of between 8 and 10 metres in length, while shashas are locally designed vessels made of palm fronds, between 3 and 4 metres in length. Fibreglass vessels range in length from 8 to 10 metres and are now mainly used along the coast of Oman, steadily replacing houri (Figure 3-5). While the majority of these vessels are powered by outboard diesel engines, the dhows, which are wooden vessels of between 15 and 25 metres in length, are powered by inboard diesel engines (Al-Harthy, 2002).

Table 3-1 summarises the total number of local fishermen and boats including types of boat by Wilayat for all regions in the Sultanate of Oman. Appendix 2 shows the growth in number of boats and fishermen by Wilayat between 2000 and 2004. Most fishermen use a combination of three fishing methods: hand lines, traps and gill nets, depending on the target species and season. Different gear may be used for catching the same species; traps, gill nets and hand lines are all used for catching demersal species, which are the focus of this thesis.
Figure 3-2 Main regional landing sites along the coastline of the Sultanate of Oman
### Table 3-1: Traditional fishery sector: numbers of boats and fishermen by Wilayat for all regions during 2004 (Source: MAF, 2004)

<table>
<thead>
<tr>
<th>States</th>
<th>Shasha</th>
<th>Aluminium</th>
<th>Launch</th>
<th>Houri</th>
<th>Fibreglass</th>
<th>Total No. of Boats</th>
<th>No. of Fishermen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Musandam Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bukha</td>
<td>0</td>
<td>12</td>
<td>1</td>
<td>11</td>
<td>130</td>
<td>154</td>
<td>332</td>
</tr>
<tr>
<td>Khasab</td>
<td>0</td>
<td>13</td>
<td>96</td>
<td>196</td>
<td>797</td>
<td>1102</td>
<td>2528</td>
</tr>
<tr>
<td>Daba</td>
<td>0</td>
<td>3</td>
<td>14</td>
<td>10</td>
<td>244</td>
<td>271</td>
<td>590</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>28</td>
<td>111</td>
<td>217</td>
<td>1171</td>
<td>1527</td>
<td>3450</td>
</tr>
<tr>
<td><strong>Al-Batinah Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shinas</td>
<td>262</td>
<td>20</td>
<td>32</td>
<td>63</td>
<td>465</td>
<td>842</td>
<td>1743</td>
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<tr>
<td>Liwa</td>
<td>46</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>124</td>
<td>185</td>
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<td>Sohar</td>
<td>139</td>
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<td>Saham</td>
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<td>20</td>
<td>0</td>
<td>25</td>
<td>464</td>
<td>784</td>
<td>1576</td>
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<tr>
<td>Al-Khaburah</td>
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<td>1</td>
<td>0</td>
<td>2</td>
<td>345</td>
<td>384</td>
<td>917</td>
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<tr>
<td>Al-Suwaiq</td>
<td>211</td>
<td>14</td>
<td>0</td>
<td>2</td>
<td>699</td>
<td>926</td>
<td>2010</td>
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<tr>
<td>Al-Musn’aah</td>
<td>8</td>
<td>3</td>
<td>0</td>
<td>10</td>
<td>323</td>
<td>344</td>
<td>853</td>
</tr>
<tr>
<td>Barka</td>
<td>9</td>
<td>11</td>
<td>0</td>
<td>17</td>
<td>530</td>
<td>567</td>
<td>1398</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>986</td>
<td>84</td>
<td>36</td>
<td>182</td>
<td>3488</td>
<td>4776</td>
<td>10562</td>
</tr>
<tr>
<td><strong>Muscat Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>7</td>
<td>5</td>
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<td>237</td>
<td>538</td>
</tr>
<tr>
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<td>5</td>
<td>11</td>
<td>544</td>
<td>561</td>
<td>1228</td>
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<td>Quraiyat</td>
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<td>0</td>
<td>16</td>
<td>436</td>
<td>457</td>
<td>1009</td>
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<td>14</td>
<td>12</td>
<td>59</td>
<td>1772</td>
<td>1858</td>
<td>4127</td>
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<td><strong>Al-Sharqiyyah Region</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Jalaan Bani Bu Hassan</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>23</td>
<td>227</td>
<td>262</td>
<td>705</td>
</tr>
<tr>
<td>Jalaan Bani Bu Ali</td>
<td>0</td>
<td>14</td>
<td>27</td>
<td>53</td>
<td>779</td>
<td>873</td>
<td>2245</td>
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<tr>
<td>Sur</td>
<td>0</td>
<td>46</td>
<td>199</td>
<td>134</td>
<td>598</td>
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<tr>
<td>Masirah</td>
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<td>61</td>
<td>73</td>
<td>334</td>
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<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>79</td>
<td>296</td>
<td>283</td>
<td>1937</td>
<td>2596</td>
<td>7279</td>
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<tr>
<td><strong>Al-Wusta Region</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mahoot</td>
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<td>1</td>
<td>32</td>
<td>16</td>
<td>658</td>
<td>707</td>
<td>1568</td>
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<td>Al-Duqum</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>438</td>
<td>450</td>
<td>951</td>
</tr>
<tr>
<td>al-Jazir</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>41</td>
<td>331</td>
<td>389</td>
<td>853</td>
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<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>23</td>
<td>38</td>
<td>58</td>
<td>1427</td>
<td>1546</td>
<td>3373</td>
</tr>
<tr>
<td><strong>Dhofar Region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salalah</td>
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<td>14</td>
<td>4</td>
<td>624</td>
<td>702</td>
<td>1557</td>
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<td>Rakhyut</td>
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<td>0</td>
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<td>35</td>
<td>89</td>
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<tr>
<td>Dhalkut</td>
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<td>9</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>79</td>
<td>195</td>
</tr>
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<td>Mirbat</td>
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<td>8</td>
<td>6</td>
<td>4</td>
<td>147</td>
<td>165</td>
<td>370</td>
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<tr>
<td>Taqah</td>
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<td>2</td>
<td>1</td>
<td>107</td>
<td>132</td>
<td>301</td>
</tr>
<tr>
<td>Sadah</td>
<td>0</td>
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<td>8</td>
<td>1</td>
<td>239</td>
<td>257</td>
<td>569</td>
</tr>
<tr>
<td>Shalaim &amp; Hallaniyat</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>267</td>
<td>270</td>
<td>565</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
<td>114</td>
<td>32</td>
<td>10</td>
<td>1484</td>
<td>1640</td>
<td>3646</td>
</tr>
<tr>
<td><strong>Total Regions</strong></td>
<td>987</td>
<td>342</td>
<td>525</td>
<td>809</td>
<td>11279</td>
<td>13943</td>
<td>32437</td>
</tr>
</tbody>
</table>
Figure 3-3 Traditional landing ports and fishing areas within 10 nautical miles of the coastline

Figure 3-4 Percentage of different traditional boats used in all regions of Oman in 2005
**Figure 3-5** Examples of different types of local boats that are used in the Sultanate of Oman

**Table 3-2** The relative importance of regional landing sites in terms of their contribution to total catch

<table>
<thead>
<tr>
<th>Region</th>
<th>Contribution to total catch</th>
<th>Contribution to emperor catch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Wusta</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Dhofar</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Sharqiya</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Al-Batinah</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Muscat</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Musandam</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
3.2.1.1.1 MAF methods of data collection and calculation for traditional fisheries

MAF has set three methods for the collection and calculation of fisheries data; based on the FAO technical report (Sparre, 2000), each method has a different format according to the data source. Since 1989 the traditional fisheries data has been collected using time schedules based in the four regions of Musandam, Al-Batinah, Muscat and Al-Sharqiya. In contrast, the directorates of Al-Wusta and Dhofar have set their own programmes according to the season and catch. For the frequency of collection of data per village per month, see Appendix 3.

Because of the varied nature of the coastline and the many landing sites, the trained MAF staff (data collectors) record data from most of the landing sites using two different schedules: a) vessel landing log-sheets and b) sampled vessel landing log-sheets, which were designed by the statistics department of MAF, as shown in Figure 3-6 a & b. MAF uses log-sheets (a) to record the vessel's landing date, start time and end time of data collection, region, landing site, vessel sequence number, time of landing, type of vessel, licence number of the vessel, number of crew and whether the vessel is sampled or not; and (b) to record the sampled vessel's landing date, region, landing site, vessel sequence number, fishing time, crew number (number of fishermen), species code, total numbers of species, average weight per piece of the species and total weight of species in kilogrammes, self consumption, gear type (code and numbers) and price per unit.
Figure 3-6 a & b: Example of vessel landing log-sheet and sampled vessel landing log-sheet.

The Fisheries Statistics Section has set methods for the estimation of daily and monthly catches in terms of effort and value from the log sheets, and since 2000 this data has been transferred from the original dBase IV format to ORACLE (Alakhzami, 2000). Data collected for one landing site during one day is used to estimate the total landing for particular landing sites by species. The total daily catch data is also estimated, as are the monthly and annual catches.

Catch Per Unit Effort (CPUE) data have often been used to obtain a relative index of the abundance of fish stock by standardizing nominal CPUE using various statistical methods (Nishida and Chen, 2004) and many aspects of the fishery can
be monitored by utilizing CPUE analysis. CPUE can be defined as a ratio commonly used to eliminate temporal and regional trends in fish stock abundance (Morgan and Burgess, 2006). The catch may be expressed as the number or weight of the entire catch, while the unit effort is the measured volume of fishing energy, which usually refers to the uniformly designed time when the fishing gear is deployed in the water. The units of effort are dependant on the type of fishing gear, vessels fishing days, trawl or gillnet hours used. The CPUE can be applied to any effort data available. Therefore, traditional catch was estimated as CPUE kg per fishing trip (kg/trip) and the formulae applied to estimate traditional landings by day and month which are given in Appendix 4, together with the estimation of CPUE.

3.2.1.1.2 Traditional fisheries data problems

There are several problems related to the primary data, which was collected between 1996 and 2004. These will now be illustrated, together with a discussion of the solutions applied before the data could be used.

The primary data has several problems with regard to traditional fisheries; for example, the design of the database used between 1987 and 1999 was different from that used from 2001 to date in a number of respects. First, the relationship structure was designed, but with no attributes associated with relationships types. In addition, the entity values were defined differently, so that in the earlier database the boat type value was defined as text, while in the later one it was defined numerically. Furthermore, in the landing site entity, some names were spelt differently. As a result of this, when designing the relational database for traditional fishery, it was essential initially to solve the problems highlighted when
using Microsoft Access 2003, by modifying the table design, adding, deleting fields, changing some field names, setting the primary key, formatting data fields and sorting by creating queries such as SELECT, FROM and WHERE. Traditional fishing areas are within 10 nautical miles of the coast, as mentioned earlier, and they usually operate in three directions, e.g. north, west and east from the landing site/port. A number of ports are close to each other, which lead to overlapping of some fishing areas, and the absence of navigation aids such as Global Positioning System (GPS) creates difficulties in estimating actual fish catch and defining the location. To solve these problems, intersecting methods have been employed. For details of the methods discussed above see Appendix 4.

### 3.2.1.2 Fishing by industrial trawlers

Industrial fishing vessels have been permitted to operate since 1989; Ministerial Decree No. 4/94 sets the rules for industrial fishing vessels chartered by Omani fishing companies (Al-Kharusi, 1999 see Appendix 6), which hold licences for industrial fishing allowing them to operate in Omani waters within specified quotas. Table 3-3 presents examples of quotas for both demersal and pelagic fish types for each Omani fishing company.

The industrial vessels are categorised into two types according to their fishing methods: (a) trawlers, which use trawl nets to catch the species living on the seabed of the continental shelf (demersal species), and (b) long-lines, which catch large pelagic species (especially yellow fin tuna). They both operate on the high seas, which the MAF has divided into a series of square blocks denoting fishing areas. Locations of the main fishing grounds of the trawler fleet have been divided
into blocks of 30 by 30 nautical miles and each block sub-divided into areas of 10 square nautical miles (Figure 3-7). The minimum fishing depth at which vessels may operate is 50 metres. Vessels must not operate in the same area for more than three days continuously. This study focuses on trawlers only within the industrial sector, because emperor is a demersal species and hence not fished using long-lines.

Table 3-3 The eleven Omani fishing companies and their quotas in tons for pelagic and demersal fisheries per year. Source MAF, 2004

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Demersal quota ton/year</th>
<th>Pelagic quota ton/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omani Fisheries Co.</td>
<td>20000</td>
<td>30000</td>
</tr>
<tr>
<td>Oman Sea Co.</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>Gulf of Oman Fishing Co.</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>Sadeh Marine Products</td>
<td>2000</td>
<td>5000</td>
</tr>
<tr>
<td>Protein Products Int.</td>
<td>2000</td>
<td>8000</td>
</tr>
<tr>
<td>Dhofer Fisheries Ind. Co.</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>Al-Maiber Trading</td>
<td></td>
<td>5000</td>
</tr>
<tr>
<td>Ahmed Adullah Al-Sadoon</td>
<td></td>
<td>5000</td>
</tr>
<tr>
<td>Omani Saudi Food Canning Factory</td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>Sheik Khalid bin Mustahil Al-Maashani and Sheik Mohammed bin Mohammed Al-Maashani</td>
<td></td>
<td>5000</td>
</tr>
<tr>
<td>Total</td>
<td>28000</td>
<td>75500</td>
</tr>
</tbody>
</table>
Figure 3-7  Fishing areas for trawler vessels located in the southern part of the Sultanate of Oman

3.2.1.2.1 MAF data structures of collection and calculation for industrial fishing

On each trip trawlers operate for up to 35 days, and the captain of the vessel is obliged to fill in a fishing report that includes the name of the vessel, voyage number, the date of fishing, type of species / code (from among 50 different possibilities), fishing location, total weight of catch in kilogrammes and the total number of boxes per species per date. Figure 3-8 shows an example of a fishing operation log-sheet for a trawler. This report requires approval by the onboard
observer, after which it is submitted to the MAF at the end of each trip and checked again by land observers when the vessel unloads the catch at the port.

The data is stored as total catch per month per species, regardless of the fish location; hence an important phase of this study was to design a geographically referenced database before proceeding to the second phase of data management, which is discussed in a later Section (3.3). However, the calculation for the trawler CPUE has been calculated in a different way from traditional CPUE. This is because of the nature of the catch methods shown above and the current availability of the average number of fishing days per trip. Thus, the measurement of effort used here is fishing days, so that the estimation of CPUE is as follows:

$$\text{CPUE (kg / day)} = \frac{\text{Total catch in kilograms per fishing day}}{\text{Number of fishing days}}$$

---

**Figure 3-8** Example of the log sheet for data collection of commercial trawler
3.2.1.2.2 Problems with industrial fisheries data

This section examines some of the problems related to the commercial (trawler) fisheries data collected between 1996 and 2004, the main one being that the original format was presented as hard copy, as only annual total catches were stored in a computer. Another is that the blocks shown in Figure 3.7 represent large areas. The major tool for solving these problems was a specially designed database which converted all locations into known coordinates (latitude and longitude) in decimal degree units and allowed for the manual input of data with the use of a keyboard. A further problem concerned the availability within MAF of data which had been moved from place to place or misplaced. For this reason, the data was mostly available from 1996.

3.2.1.3 Biological data for Lethrinus nebulosus

In order to define the spawning season of Lethrinus nebulosus, reproductive biology materials were studied for the Arabian Sea, which is within the study area. All biological materials were collected by the working group in the Marine Science and Fisheries Centre (MSFC).

3.2.1.3.1 MSFC methods of data collection and calculation for biological materials

Owing to a lack of information available on fish biology in general and emperor in particular, such as distribution and spawning season, the MSFC has set methods of collection and measurement of Lethrinus nebulosus data in accordance with FAO descriptions of biological data sampling and measurement methods.
*Lethrinus nebulosus* specimens were collected monthly between January 2001 and December 2002 from the traditional fisheries landing ports of Ra's Duqm and Shalalah, located in Al-Wusta and Dhofar regions (Figure 3-3). During this period around 1281 specimens were collected; mostly from lines and drift gillnet fishing gear. The measurements were taken as follows: total length, total weight, sex, liver weight, gonad weight, maturity stage and eviscerated weight. All this data was stored in an Excel spreadsheet.

3.2.1.3.2 **Biology data problems**

Statistical analysis was carried out using the Brodgar 2.4.3 software package (www.brodgar.com), which cannot read data in certain formats from Excel. For example, characters such as *, & and # had to be avoided and zero values replaced by 'N/A'. Similarly, nominal variables such as 'yes/no', colours or months had to be transformed to numerical values. For example, for stomach content, 'yes' was converted to 1, and the code for an empty stomach, 'no', was converted to 0. The same principle holds with variables for months: 1 for January to 12 for December. Thus, the original (hard copy) biological data was redesigned in a special format in MS Excel 2003.

3.2.2 **Environmental data**

Oceanographic conditions in specific areas, such as water temperature, currents and water salinity, can be integrated to derive useful variables and procedures (Pierce *et al.*, 1998; Valavanis *et al.*, 2004). The relationships among such variables as temperature, salinity and currents can be influenced by ocean
condition factors such as ocean circulation (currents and winds). Moreover, latitude and longitude have an impact on the location and presence of fish (Zheng et al., 2002; Begg and Marteinsdottir, 2002). Remote sensing data is useful in detecting fishing patterns and monitoring the spatio-temporal distribution of different fish species. Researchers have used satellite images acquired by different sensors in a variety of spatial, spectral and temporal resolutions, such as the Seasat, Coastal Zone Colour Scanner (Simpson, 1994), NOAA and MODIS, and integrated them into a GIS for further analysis.

The environmental data products such as SST and SSS used in this study were derived from data recorded by the Advanced Very-High-Resolution Radiometer (AVHRR) on board satellites of the National Oceanographic and Atmospheric Administration (NOAA). The Sea Surface Temperature (SST) data are available from the Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Centre (JPL PO.DAAC) (http://podaac.jpl.nasa.gov/poet), while the Sea Surface Salinity (SSS) products were obtained from the Naval Research Laboratory’s Navy Coastal Ocean Model (NCOM) (ftp://ftp7300.nrlssc.navy.mil/pub/lsmedstad/out/). Both SST and SSS data were selected for the same period as the emperor catch data. The specifications of remote sensing procedures are explained in Subsection 3.2.2.2.

The Dissolved Oxygen (DO) and pH data were obtained from the Marine Ecology Section, Marine Science and Fisheries Centre, MAF, in Oman; however, this information was accessible for only two years (2001 and 2002) and therefore was used only for biological analysis of Lethrinus nebulosus within that period.
These environmental data are fundamental to this study because they provide the environmental factors responsible for the availability, catch and spatio-temporal distribution of fish species.

3.2.2.1 Outline of geography & bathymetry

The geographical database, a secondary map in the form of hard copy and a digital map, were obtained from the National Survey Authority, National Hydrographic Office in Oman on a scale 1:1 500 000. The maps covered the whole area of the Sultanate of Oman from longitude 53° 00' to 63° 00' E and from latitude 13° 00' to 28° 00' N, although this study focuses on the coastal zone, the Gulf of Oman and the Arabian Sea. This map was used to extract the coastline; boundaries, bathymetry and major towns located along the coastline were identified and digitised. This will be discussed in the following methodology section.

3.2.2.2 Sea Surface Temperature and Sea Surface Salinity

Two types of remote sensing data, SST and SSS, were derived from the 5-channel AVHRR on board the NOAA-7, 9, 11, 14, 16 and 17 polar orbiting satellites. All data products were available from 1985 to the present time in a variety of spatial and temporal resolutions, map projections and formats. There are obtainable daily, 8-day and monthly averaged data for both the ascending pass (daytime) and descending pass (night time) on equal-angle grids of 8192 pixels/360 degrees (nominally referred to as the 4km spatial resolution), 4096 pixels/360 degrees and 720 pixels/360 degrees (54km resolution and 0.5 degree resolution) (http://podaac.jpl.nasa.gov/poet).
Satellite estimates of SSTs are made by converting the radiance measured in the infrared channels to brightness temperature and then using a multi-channel technique to calculate SST to within ±0.5°C (http://podaac.jpl.nasa.gov/poet). The AVHRR Pathfinder datasets Version 5.0 (Pathfinder V5) contains separate files, which are obtainable in the HDF-SDS (scientific dataset) and GeoTIFF formats, and are available from 1985 to the present time. This study used monthly compositions for the nine years 1996-2004.

The SSS archival data are updated daily at the Naval Oceanographic Office (NAVOCEANO) with atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS), assimilation of salinity profiles via the MODAS and climatology based on input from the operational 1/8° MODAS 2D SST nowcasts. Salinity was computed from the derived temperature using local climatological relationships between temperature and salinity (http://www.ocean.nrlssc.navy.mil/global_ncom).

3.3 Data management

Section 3.2 has explored the acquisition of secondary data and its importance for this study of spatial and temporal distribution of the emperor species. Table 3-4 summarises the characteristics and sources of fish data. Both remote sensed environmental parameters and biological data were used in this study. This section discusses the preparation of fisheries data, emperor catch data (traditional and trawlers), biological catch data and environmental data for input to GIS prior to review by analytical methods.
Table 3-4 Summary of fishery and environmental datasets included in GIS and GAM analysis

<table>
<thead>
<tr>
<th>Data sets</th>
<th>Characteristic</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary emperor catch data - artisanal &amp; trawler fisheries and effort</td>
<td>Daily, monthly catch CPUE kg/trip for traditional and CPUE kg/day for trawlers for period 1996-2004</td>
<td>Statistics department at MAF</td>
</tr>
<tr>
<td>Secondary <em>Lethrinus nebulosus</em> biology data</td>
<td>Monthly catch during 2001-2002</td>
<td>Marine Science and Fisheries Centre at MAF</td>
</tr>
<tr>
<td>pH and DO</td>
<td>Monthly data for two years 2001 - 2002</td>
<td>Marine Ecology Section Marine Science and Fisheries Centre at MAF</td>
</tr>
</tbody>
</table>

The main objective of designing a database is to create an accurate representation of the data and its relationships. To meet these objectives it is essential to identify suitable relations (Connolly and Begg, 2002). When undertaking the design of a database for a relational system it is important to normalise the data, the principal rationale being to eliminate redundant information. In addition, data management is made easier and, in particular, future changes to table structure are simplified.

Both graphical / spatial and non-graphical / non-spatial databases are required for the GIS analysis. The display and analysis of spatial information has been greatly enhanced with GIS, which combine layers of geographic features with an associated database of attributes to form a composite map (Rogers and Bergersen, 1996). Therefore, structuring data is the most fundamental stage of
building any GIS, as it is the real method for organising and storing data in the database (Meaden and Chi, 1996). Further information on the importance of data management has been highlighted by Bernhardsen, (1992) and by Burrough and McDonnell, (2000). The spatial data, such as vector data structure and raster data structure, is usually held within the GIS, while the non-spatial data is stored externally using software such as Excel, Oracle or dBase (Meaden and Chi, 1996). In this study, Microsoft Access 2003 (MS Access) was used for building the non-spatial GIS database. With personal computers becoming increasingly powerful and affordable, GIS has become an attractive tool for facilitating analysis of spatial questions in fisheries research and management.

3.3.1 Fisheries database

The traditional fisheries landing data for emperor was extracted from a database held by the Oman Fishery Statistic Department, MAF for a period of nine years from 1996 to 2004, using MS Access. The industrial trawler fishery data was used in its original hardcopy (logbook sheets) format (Figure 3-8) and was obtained from the Oman Fishery Statistic Department, MAF for the same period as the traditional data.

Biological data for *Lethrinus nebulosus* was used for two years: 2001 and 2002. It was extracted from the MSFC using an MS Excel 2003 spreadsheet. The trawler catch of emperor refers to one type of gear, while the traditional catch refers to all types of gear used by local fishermen.

Before structuring the database for fisheries data and conducting further analysis it is important to illustrate the method used to calculate CPUE for both types of
fishery. In this study the emperor data for the trawler catch was calculated differently from the traditional catch, because each type of fishing activity requires a different amount of effort. According to Sparre, (2000), effort can be measured in many ways, depending on types of fleet and gear used (Hilborn and Walters, 1992). It was noted that comparing the catch from different types of fishing can be misleading as a basis of stock assessment management. Therefore, the trawler CPUE was calculated as total catch over all blocks divided by fishing days and expressed as CPUE kg/day. On the other hand, in Appendix 4, the example of traditional CPUE calculation for emperor is explained and expressed as CPUE kg/fishing trip. The specific structure of the databases for the three types of fishery is set out in the following three subsections (3.3.1.1-3).

These relational database structures were created not only for this research but for the future use of the MAF, which sponsored this research; hence, some of these attributes are not considered at this point.

Data structure is based on three components: a structure part, a manipulating part and a set of integrity rules. Fisheries data model files were built and stored in three different files using MS Access. Each data type differs in its characteristics; this section considers each fishery type individually (Figure 3-9).
3.3.1.1 The relational database for traditional fisheries

The Entity Relation (ER) model is an important step in designing database applications (Elmasri and Navathe, 2004). In this case it was designed on the basis of collecting log-sheets for the traditional landing sites, traditional vessel logs and traditional sampled logs, as shown in Figure 3-6 a & b. The ER model for the traditional fishery file identifies entities and their associated attributes in order to describe the relationships between these entities and attributes (Figure 3-10). It identifies and associates the attributes with entities as shown in Table 3-5 and is converted into a relational database structure in MS Access.
Figure 3-10 The Entity Relation conceptual schema diagram for the datasets of traditional fisheries
Table 3-5 Description of Entity Relation schema for traditional fisheries

<table>
<thead>
<tr>
<th>Relational Name</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region-Description</td>
<td>Region-Code and Region-Name</td>
</tr>
<tr>
<td>Landing-Site/Port</td>
<td>Landing-site-code, Landing-site-name, Latitude, Longitude, Total-boats, Region-Code and Depth</td>
</tr>
<tr>
<td>Fish-Description</td>
<td>Fish-Code, Fish-English-name, Fish-Scientific-name, Fish-Group-code, Fish-Subgroup-code and Fish-Picture</td>
</tr>
<tr>
<td>Boat-Description</td>
<td>Boat-Code, Boat-Type, Boat-licence-number and Boat-Picture,</td>
</tr>
<tr>
<td>Gear-Description</td>
<td>Gear-Code and Gear-name</td>
</tr>
<tr>
<td>Trip-Information</td>
<td>Date, Boat-licence-number, Boat-Type, Boat-crew-number, Boat-hours, Gear-code, Gear-unit, Gear-size, Gear-hours</td>
</tr>
<tr>
<td>Sampled-Details</td>
<td>Landing-site-code, Date, Boat-Licence-number, Fish-code, Total average weight, Total weight, Number of pieces, Unit price, Kg price, Landing time, Self weight, User ID and Value</td>
</tr>
</tbody>
</table>

Referring to Figure 3-10, the seven relational database files created for the traditional fisheries data are: Region-Description, Landing-Site/Port, Fish-Description, Boat-Description, Gear-Description, Trip-Information and Sampled-Details. Each of these relational databases contains a list of attributes, which gives details of the data, as shown in Table 3-5. All the detailed information of region codes and landing villages codes are given in Appendix 5.

3.3.1.1.1 Defining relationships of traditional fisheries

The purpose of defining relationships is to coordinate the retrieval of information in the different tables. A relational model has cardinality relationships which are usually related in three ways: one-to-one, one-to-many or many-to-many. The main advantage of a relational database is when queries, forms and reports can be created to display information from different tables at once. To relate tables, one attribute must be a unique value in every record: this is called a primary key.
Chapter-3

(Connolly and Begg, 2002; Andersen, 2003). In one-to-many relationships, the field or attribute in the original relation is a 'primary key', while in the second relation the attribute is a 'foreign key', which does not have a unique value.

Thus, a primary key is the candidate key that is selected to identify tuples\(^1\) uniquely within the relation, there is no primary key with a null value, because the primary key value that is used to identify the individual attributes is a relation which cannot be identified if there are null values (Connolly and Begg, 2002). Null value here does not mean that the value is zero, but denotes the absence of a value, and it can cause implementation problems in calculus.

Usually, the primary key is highlighted in some way; for example, the primary key in Figure 3-10 (Fish-Code) is underlined and in Figure 3-11 the primary key is in bold. This means that each type of fish has been given a unique code. In addition, for the primary key in the relational file Landing-Site/Port, each landing-site/port has a unique identity code called Landing-site-code, also relational file Trip-Information has primary key, Boat-Licence, as each boat can make more than one trip and can differ from fishing hours. When an attribute appears in more than one relation, it usually represents a relationship between tuples of the two relations. According to Connolly and Begg, (2002), a foreign key is "an attribute, or set of attributes, within one relation that matches the candidate key of some (possibly the same) relation". For example, Gear-Code is the primary key in the Gear-Description relation and a foreign key in the Trip-Information relation. The values of these two attributes must match because they play an important role in

\(^1\) A tuple is a row of relations
manipulating data, which will be discussed under Structured Query Language (SQL) in the examples section.

![Diagram of a relational database system for traditional fisheries](image)

**Figure 3-11** Structure of relational database system for traditional fisheries

### 3.3.1.2 The relational database for the trawlers fisheries

#### 3.3.1.2.1 Data modelling using an ER model for trawler fisheries

It is very important to note that trawler fisheries data is not survey sample data. Thus, the ER model for the trawler fisheries was structured on the basis of information in the catch logbook (Figure 3-8) and fishing vessel licence, which are issued to each vessel before operating in Omani waters by the MAF Department of Fisheries Surveillance and Licenses. Figure 3-12 shows the structure of ER modelling for the demersal fisheries; it also identifies and associates the attributes with entities as shown in Table 3-6. The next step is to convert the ER model into a relational database in MS Access.
Figure 3-12 The Entity Relation conceptual schema diagram for the datasets of trawlers fisheries
### Table 3-6 Description of Entity Relation for trawler fisheries

<table>
<thead>
<tr>
<th>Relational Name</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company-Description</td>
<td><strong>Company-Code</strong> and Company-Name</td>
</tr>
<tr>
<td>Vessel-Description</td>
<td><strong>Vessel-code</strong>, Vessel-name and Company-Code</td>
</tr>
<tr>
<td>Vessel-Trip-Information</td>
<td><strong>Trip-Number</strong>, Vessel-Code, Voyage-Number Call-sign, Licence-Number, Captain-name, Captain-Licence-Number, Departure-date, Arrival-date, Total-catch, Total-Discard and others.</td>
</tr>
<tr>
<td>Fish-Description</td>
<td><strong>Fish-Code</strong>, Fish-English-name, Fish-Scientific-name, Fish-Picture</td>
</tr>
<tr>
<td>Catch-Description</td>
<td>Record-Number, Fishing-Date, Fish-Code, Fishing-Area, Latitude, Longitude, Voyage-Number, Trip-Number, Total-Catch, Start-fishing-Time, End-fishing-Time, Depth and Temperature</td>
</tr>
<tr>
<td>Fishing-block-area</td>
<td><strong>Area-Code1</strong>, Latitude and Longitude</td>
</tr>
<tr>
<td>Fishing-sub-block-area</td>
<td>Fishing-Area, Area-Code1, Latitude, Longitude and Depth</td>
</tr>
</tbody>
</table>

As noted above, the nature of fishing activities and data collection differ between industrial and traditional fisheries. Hence, the seven relational databases have been structured differently for the trawler fisheries, as follows: Company-Description, Vessel-Description, Vessel-Trip-Information, Fish-Description, Catch-Description, Fishing-block-area and Fishing-sub-block-area. It is important to note that these last two relational files were created because trawler fishing activity areas are divided into blocks and sub-blocks, as noted in Subsection 3.2.1.2.

#### 3.3.1.2.2 Defining relationships for trawler fisheries

Similar to traditional relational files, the primary key in the relational files has a unique value and is underlined. Each relational file has a primary key; for example, the primary key in the relational file Vessel-Trip-Information is Trip-Number, as each vessel can make more than one trip in a year (Figure 3-13).
3.3.1.3 The database for the biological data

3.3.1.3.1 The relational database for the biological fisheries data

Similar to traditional relational files and demersal relational files, the primary key in the relational files also has a unique value and is underlined. Each relational file has a primary key; for example, the primary key in the relational file Biological Master is a Biological ID, as each fish could have more than one biological detail (Figure 3-14).

3.3.1.3.2 Defining relationships of biological fisheries

This biological fisheries data was generated by empirical research, although it was used for the quantitative analysis in the Excel format. It is expected that this database will be of great value for future research by the MSFC and thus it was important to include the data modelling for the biological data.
3.3.1.4 Example of Query by Design and SQL manipulations to retrieve data and calculate catch.

Presented here are some examples of retrieving and presenting information with queries from the database for the total catch of emperor in the Dhofar region during 2002. When building a query using Query By Example (QBE), in the design grid (Figure 3-15), within the criteria cell or row of the Region-Code column, the code of the region is entered. In this case the Dhofar ID is 3 and in the criteria cell for the date column, the expression is specified as "between#01/01/2002# and#31/12/2002#".

In the criteria cell of the Fish-Code column the expression is specified by the code LET for the Lethrinus species. The last expression is the sum of total catch column; entered under the total catch field is the total cell (Sum) from the drop-
down option list. This display summarises the total catch in the Dhofar region during 2002 in a new table called sum of total catch in Dhofar region, which will be displayed on the Polygons traditional-fishing-area map. This displays each parameter as prompted in a separate dialogue box. At the same time, in the background, MS Access builds equivalent SQL statements which can be viewed in Figure 3-16. These have three clauses in addition to the SELECT command: FROM, INNER JOIN and WHERE, in order not to cause any Cartesian product of the number of records in the table.

![Microsoft Access - [Query]](Query1.png)

**Figure 3-15** Example of query parameter in the criteria row Region-Code, Date and Fish-Code

```
SELECT [Region-Description].[Region-Code], [Landing-Site/Port].Latitude, [Landing-Site/Port].Longitude, [Sample-Details].Date, [Sample-Details].[Fish-code], [Sample-Details].[Total-weight]
FROM ([Region-Description] INNER JOIN [Landing-Site/Port] ON [Region-Description].[Region-Code] = [Landing-Site/Port].[Region-Code]) INNER JOIN ([Fish-Description] INNER JOIN [Sample-Details] ON [Fish-Description].[FISH-CODE] = [Sample-Details].[Fish-code]) ON [Landing-Site/Port].[Landing-site-code] = [Sample-Details].[Landing-site-code]
WHERE ((([Region-Description].[Region-Code]) In (3)) AND ((([Sample-Details].Date) Between #1/1/2002# And #1/31/2002#) AND ((([Sample-Details].[Fish-code]) In ("LET"))).
```

**Figure 3-16** Example of expressions in the SQL SELECT statements
3.3.2 Geographical Information System database

3.3.2.1 Geography & bathymetry

Typical options are required to support GIS applications in digital mapping. Digitising is the conversion or transformation of features from hardcopy maps into a digital format. In addition, digitising can create and edit features such as shapefiles and coverages on digital maps with ArcMap. These features are automatically recorded and stored as spatial data.

The digital map of the Sultanate of Oman mentioned in Subsection 3.2.1 is on a scale of 1:1 500 000, and was obtained from the National Hydrographic Office, Royal Navy of Oman. The traditional landing ports, fishing areas and trawler fishing areas have been created as new shapefiles in digital map format. Also, several types of coverage, feature types and variables were set up according to the nature of the information used in this study (Table 3-7). The map of Oman was divided into two parts: the northern part, covering the Gulf of Oman, and the southern part, covering the Arabian Sea. The digitising was focused along the coastline of the country, the marine area, the Exclusive Economic Zone (EEZ), which is 59 km$^2$ (Alakhzami, 2000), and digitised bathymetry data measured in metres using line features. The Editor Function with Sketch and Edit tools was used to create these features, which have several types of coverage and were set up according to the nature of the information stored (de Graaf et al., 2003).
Table 3-7 Summary of the coverage types and their variables mapped associated in this study.

<table>
<thead>
<tr>
<th>Coverage</th>
<th>Feature Type</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing sites</td>
<td>Points</td>
<td>Traditional-landing-site-Code (ID)</td>
</tr>
<tr>
<td>Coastline</td>
<td>Poly-line</td>
<td>Coastline area</td>
</tr>
<tr>
<td>Traditional Fishing areas</td>
<td>Polygons</td>
<td>Poly-traditional-fishing-area</td>
</tr>
<tr>
<td>Trawler Fishing areas</td>
<td>Polygons</td>
<td>Poly-trawler-fishing-area</td>
</tr>
<tr>
<td>Depth</td>
<td>Lines</td>
<td>Depth ID</td>
</tr>
<tr>
<td>Sea Surface Temperature</td>
<td>Polygons</td>
<td>SST ID</td>
</tr>
<tr>
<td>Sea Surface Salinity</td>
<td>Polygons</td>
<td>SSS ID</td>
</tr>
</tbody>
</table>

For the landing ports, each location was digitised as a point feature type and each landing site was labelled with the same ID code as given in the database table in Appendix 5. Traditional fishing activity areas were digitised differently, as the local fishermen usually make their trips in one of three directions from their local ports: north, east or west up to around 11 nautical miles (NM) / 20 kilometres (km) in each direction, which means that the original fishing area is around 800 km². Some landing ports are closer than 11 NM to each other, which lead to overlapping in some places, amounting to around 20% of the total fishing area. Therefore, traditional fishing activity areas for each port have been digitised as polygons and areas which overlap have the original landing site / port ID code replaced with a new ID code. For example, Figure 3-17 shows that the landing port Ra’s Duqum (74) is located between landing port Nafun (77) and the landing port Shuair (76), so that their fishing areas will overlap. Hence Ra’s Duqum (74) and Shuair (76) have been given a different ID code (7777). Moreover, the catch for overlapping areas was calculated differently from that of original areas (Alakhzami, 2000), as is evident from Appendix 4.
On the other hand, commercial trawler fishing areas have been divided into blocks of 10 square nautical miles, as noted above, and digitised as polygon features. Each block has been given the same reference ID number as in the original secondary data map, with the location by latitude and longitude. Re-projecting the data was required to avoid error and distortion. Table 3-8 gives details of the main characteristics of the Sultanate of Oman map. The general outlook of the output coverage after editing the Sultanate of Oman map is shown in Table 3-8 Figure 3-3.

**Figure 3-17** Interaction area between two ports
3.3.2.2 Sea Surface Temperature and Sea Surface Salinity

Monthly SST and SSS data are available in different formats; in this study two types were used: Arc-Grid ASCII and ASCII. Thus, monthly SST and SSS data have been downloaded as Arc-Grid ASCII format and then converted into GRID, which is appropriate for GIS analysis using ArcMap. Additionally, all monthly data were converted into monthly long-term averages for nine years, and then the cell statistic function was applied through the spatial analysis tool to calculate the mean of the values of each cell in both sets of data. In order to simplify and make the data clearer to analyse, all continuous data was classified according to the minimum and maximum average values in the original data. Thus, SST values were divided into 13 classes (from 21 to 33°C) while the SSS values were divided into 6 classes ranging from 34 to 39 ppt. As for the data downloaded for statistical analysis in ASCII format, the sea depth measured in metres was divided into six classes. Additionally, pH and DO (mg/l) data for the period from January 2001 to December 2002 were obtained from MSFC. This information was used for biological analysis. Following this, all environmental data was linked into GIS as well as used in GAM analysis. Section 3.4 will explore both methods.
3.3.2.3 Linking the database tables into Geographical Information Systems shapefiles

The principal aim of this section is to describe the procedure for joining and relating data into ArcMap and displaying the information on a map. As noted above, the advantage of using MS Access is that it allows users to view, add, update and analyse without changing the original data. As a result, all queries were made prior to exporting data to dBase format, then joining tables for display of point data into ArcMap. Although MS Access could be linked directly into ArcMap, it was considered preferable to export into dBase, because any modification in the original data would not then affect the output of ArcMap.

It is essential to ensure the quality of data, because when exporting or importing the data into other applications it is often possible to interpret the formatted text in numerous ways, which can result in errors. The data is stored in a geodatabase and as the relationship classes have already been defined, there is no need to establish a relationship in ArcMap. The relationship classes will automatically be available when a layer is added that participates in a relationship class to the map (ESRI, 2003).

A number of maps were generated to display SST, SSS and bathymetric data versus CPUE of emperor, and to reveal overall trends to support the visual exploratory analysis of spatial patterns in distribution and abundance of catch against a background of individual coverages of SST, SSS and bathymetry. Plots were analysed on season-by-season and aggregate annual bases to reveal spatial as well as temporal features of emperor distribution. ArcMap provides a method that can associate attribute data stored in MS Access or other databases with
geographic features: this is "join", which allows attributes to be appended from an MS Access table onto a Shapefiles table, based on a common attribute in both tables. For example, there was a need to show total emperor catch for each landing site on the map. The table of the digital landing site/ports had been given a unique ID and the table (resulting from as shown in Figure 3-16) of total catch of emperor for all years had been given the same ID number, so these catch attribute would then be associated with the correct landing site when mapped as point or polygon (ESRI, 2003). This method was used for displaying total catch and other average results at each point for landing sites and also for trawling areas.

3.4 Analytical methods

Given that the aim of this study is to analyse the spatial and temporal distribution of emperor and to reveal the relationship between environmental variables and emperor distribution, this necessitates the use of both qualitative and quantitative methods of analysis. Since GIS is a powerful tool and has specially designed functions to integrate and manipulate geographically referenced data, mapping, analysing and visualising the spatial patterns and relating fish catch data with environmental factors, it can provide qualitative descriptions of spatial patterns with statistical models such as GAM. On the other hand, GAMs constitute a powerful technique for defining and quantifying the intricate multidimensional relationships between biotic and abiotic variables (Cardinale and Arrhenius, 2000), as well as revealing quantitative spatial relationships between fish distribution and environmental variables. Therefore, it is appropriate to use these two techniques to describe the spatial relationship between Lethrinidae distribution and
abundance in Omani waters and to identify the spawning season of *Lethrinus nebulosus* (Figure 3-18).

A number of previous fisheries researchers have already used these techniques and found them to be appropriate tools for fisheries studies (Maravelias *et al.*, 2000; Denis and Robin, 2001; Barratt *et al.*, 2002; Guisan *et al.*, 2002). Therefore, the GAM technique was used to analyse quantitative information on the spatial and temporal relationships between emperor abundance and environmental variables from a mathematical viewpoint. GIS techniques have also been used in marine fisheries for analysing the spatial and temporal patterns of fish abundance, distribution and relationships with environmental factors (e.g. Eastwood *et al.*, 2001; Valavanis, 2002; Eastwood *et al.*, 2003; Valavanis *et al.*, 2003; Bello *et al.*, 2005). Moreover, GIS can be used to provide geographical information on the basis of GAM results (Zheng, 2001).

![Figure 3-18 Merging spatial and non-spatial data for analytical methods](image-url)
3.4.1 Use of Geographical Information System for handling datasets

GIS operations were conducted using ArcMap, and in this research, it was used for a general qualitative explanation and description of spatial seasonal trends of both environmental variables and fish abundance by overlaying fish data and environmental data. GIS was also used to present geographic information based on the results revealed by GAMs, because although GAM plots can illustrate the quantitative spatial relationships between response and explanatory variables, they cannot show the spatial patterns. Consequently, the use of GIS technique was vital to present the spatial information.

3.4.1.1 Application of GIS to environmental factors

Initially, monthly SST and SSS data were processed and mapped individually in order to ensure the classification of the spatial and temporal distribution of SST and SSS anomalies. This was followed by monthly averages for SST and SSS data, calculated and converted to long-term averages for the period from January 1996 to December 2004 and intersected into GIS. Twelve monthly average maps were then created to display patterns of SST and SSS in order to reveal the spatial and temporal distribution of SST and SSS variation in Omani waters, because the seasonal SST, SSS and bathymetry patterns are very important for the biotic and abiotic factors influencing the distribution and habitat of marine species. Many authors (Rose et al., 1994; Solanki and Dwivedi, 1998; Zheng et al., 2002; Valavanis et al., 2004) have noted that SST has the greatest influence on fish distribution, although SST itself could be affected by other environmental factors, such as geographical location and ocean circulation.
3.4.1.2 Application of GIS to fisheries data with environmental variables

3.4.1.2.1 Mapping the general spatial distribution of emperor catch in Omani waters

It was essential to describe patterns of emperor distribution to reveal general trends as the first step in studying the fish ecology and biology of the new area. Therefore, both types of fishery, traditional and commercial, were combined to give the total catch of emperor for nine years, which was measured in kilogrammes, plotted and mapped. This method was designed to give a preliminary or general indication of the possible location of emperor abundance.

3.4.1.2.2 Mapping the annual emperor abundance

A number of maps were generated to display spatial distribution of emperor in Omani waters. Maps for individual years for both types of fisheries were displayed, measured as CPUE kg/day and CPUE kg/trip.

3.4.1.2.3 Examining spatial and temporal distribution of emperor abundance and its relationship to the SST, SSS and bathymetry

Other maps of both types of fishery were generated to display spatial distribution of emperor abundance measured as CPUE kg/day and CPUE kg/trip versus depth and to show monthly means of SST and SSS. These maps made use of long-term average datasets. The main aim was to reveal the spatial and temporal distribution of emperor in relation to environmental factors.

GIS modelling is the process of looking at characteristics from a number of layers for each location to solve different problems (ESRI, 2001). Under this concept, a
series of sequential spatial monthly queries were made each month in areas with high CPUE, an SST range of 26-27°C and a depth of less than 100 metres, following the suggestion of authors who had studied emperor living in areas where SST was 27°C, including Al-Abdessalaam, (1995), Randall, (1995), Newman and Williams, (2001b) and others, such as Carpenter and Allen, (1989) and Al-Abdessalaam, (1995), who reported that emperor were found in rocky areas and at a depth of less than 100 metres.

3.4.2 Generalised additive modelling (GAM)

As stated at the beginning of this section, the model was designed to explore emperor distribution spatially and temporally and was strongly focused on gathering the data required for geographical analysis. This subsection describes the GAM process. The literature review in Chapter 2 highlighted a number of research issues relating to the use of GAM to model environmental effects and spatial distribution in marine fisheries. Most of these concern environmental factors which have a significant impact on marine fisheries. Nonetheless, much remains to be explored about the environmental effects and spatial distribution, particularly on marine fisheries in Omani waters. The statistical analysis of GAMs can be conducted using a range of software, such as the S-Plus R language, SAS and Brodgar packages. In this study the GAM was carried out with the aid of Brodgar 2.5.2 software (www.brodgar.com) for conducting a GAM analysis using covariate data held in GIS and R (Bivand and Gebhardt, 2000); (Venables and Dichmont, 2004) to calculate the predictions and probabilities. Smith et al., (2005), Sacau, (2005) and Barratt et al., (2002) describe it as a public domain statistical package based on R and explicitly designed for ecological
applications. All data was imported from Excel into Brodgar and organized according to data objective. Two smoothing functions are available in Brodgar: \( s \) (cubic spline) and \( lo \) (loess), which can be used on their own or mixed with parametric functions. In this study a cubic smoothing spline method was chosen to smooth the variables, using cross validation to find the optimal degrees of freedom (df) for each model.

As noted earlier, GAM has the ability to deal with non-linear relationships between an independent variable and multiple predictors at the same time. In GAMs, the notion of linearity is extended to include fundamental probability distribution from the progeny of major exponential models, for example Poisson, gamma, Gaussian, quasi-Poisson and binomial distribution (Maravelias et al., 2000).

GAM methods and their application have previously been described by Hastie and Tibshirani, (1990). The general form of GAM is given by the equation 1

\[
g(\mu) = \alpha + \sum_{i=1}^{n} f_i(X_i) + \varepsilon
\]  

(equation 1)

where \( g(\mu) \) is the response variable, \( Xi \) is the explanatory variable, \( \alpha \) represents the intercept term in the fitted model, \( fi \) is the non-parametric function of the explanatory and \( \varepsilon \) is the error. The SST and depth data are available for every year and month in all study areas and were considered as the explanatory variables in addition to locations (latitude and longitude). Figure 3-19 summarises the main steps of model validation, starting from data exploration techniques, in order to verify and investigate the shape of the data and the relationship of the variables to the application of the GAM technique by means of appropriate model
selection, by examining the dispersion and calculation of a modified version of the Akaike Information Criterion (AIC).

Data exploration and non linear regression

- Start
- Data exploration
  - Normality
    - QQ-plots
    - Histograms
  - Collinearity
    - Pair-plots & Cop-plots
  - Outliers
    - Dot-plots & Box-plots
- Is data linear or non linear?
- Non linear relationship
  - Transformation needed?
  - Yes
    - Generalized additive modelling
      - Poisson distribution
        - verify over-dispersion $p > 1$ OR $p < 1$
      - Quasi Poisson distribution model apply
  - No
  - Transformation needed?
    - No
    - Generalized additive modelling
      - Stepwise producer AIC values
        - OK
        - Print & Publish

Figure 3-19 Summary of model validation for generalized additive modelling
3.4.2.1 Application of GAM model to emperor catch data

This section will show how GAMs were used to model the spatial relationships between the georeferenced emperor abundance and environmental variables in Omani waters in two stages: (1) Fitting GAM to emperor fishery data on CPUE, (2) Fitting a GAM to monthly long-term average emperor abundance data and (3) Fitting GAM to *Lethrinus nebulosus* data for two years biological data. Each of these three response variables were modelled to see if they could be explained, predicted by any of the covariate environmental datasets.

3.4.2.1.1 Preliminary examination of the data

In order to achieve this it is essential as a first step in any analysis of univariate techniques to investigate the shape of the data. Hastie and Tibshirani, (1990) and Zuur et al., (2006) have suggested several procedures which could be followed as a first step prior to commencing the use of GAM, including data exploration. This step allows for screening of data, revelation of data set characteristics and detection of outliers, as GAM could be sensitive to their effect on the residuals, because the smoother takes residuals into account. In this study, while plotting the scatterplots for traditional and trawlers fisheries data there evidence that one point was an outlier. In order to check the model for any effect of this one point, the model was run with and without the outlier. In addition, visualisation of the relationships between the explanatory variables and whether they are linear or non-linear is important (Swartzman et al., 1994). All these techniques should be applied to untransformed data.
Therefore, to begin with, all data in this study was plotted using various approaches such as scatterplots, dot plots, pair plots and box plots, in order to detect the outliers, distinguish the type of relationship between variables and identify any collinearity. Pair plots were found to be the best tool, because they showed pair-wise scatterplots that can be used to detect relationships between variables and detect variables that have collinearity (Swartzman et al., 1992). Collinearity in the predictors is an additional problem associated with stepwise model selection (Brauner and Shacham, 1998), because a common observation is that two highly correlated predictors can both appear non-significant, even though each would explain a significant proportion of the deviance if considered individually (Guisan et al., 2002).

3.4.2.1.2 The GAMs fitted to the emperor catch data

After examining the pair-plots and scatterplots with the aim of investigating the spatial relationships between emperor abundance and environmental factors, the GAM model for analysis of the monthly long-term average data was specified using month, latitude, longitude, SST and bathymetry as putative explanatory variables and CPUE as the response variable. The GAM was formulated to examine environmental effects on the relative abundance as follows:

\[ \text{CPUE} \sim + s(\text{Month}) + s(\text{Latitude}) + s(\text{Longitude}) + s(\text{SST}) + s(\text{Depth}) \]

with family quasi-Poisson distribution and log link function.

When comparing models to data, the primary concern is to estimate parameters, construct confidence intervals around the estimates, determine the goodness-of-fit of the model to the data, compare alternative models and select the most
appropriate one. There are many steps for comparing models of data, as shown in the steps below.

Initially, Poisson regression was used because it is considered appropriate for random count data (Begg and Marteinsdottir, 2002) with log link function and where models have different degrees of freedom and/or smoothers are required for the model (Zuur et al., 2006). In addition, estimation of dispersion in a model is important because "sometimes, the increasing spread in count data is even larger than can be modelled with the mean-variation relationship of the Poisson distribution" (Zuur et al., 2006).

Hence, over-dispersion (p) was estimated in the GAM model with a log-link function. The estimation of the over-dispersion factor was then used to judge whether the underlying distribution was really Poisson. In the case of a true Poisson distribution, the over-dispersion factor is 1. So if clustering occurs and it is larger than 1 or in the case of avoidance where p<1 or p>1 the Poisson distribution should be changed into a quasi-Poisson distribution in a GAM model (Swartzman et al., 1992; Zuur et al., 2006). Accordingly, in this study the quasi-Poisson model was applied in order to avoid potentially misleading, calculations and interpretations.

An addition, finding the optimal GAM model involves two aspects, namely the selection of explanatory variables and the df of the smoother for each explanatory variable.
Measurement of the best model fitted was based on examining the value of pseudo R-square (see equation 2), which describes the fraction of the total variation explained by a model by (Swartzman et al., 1992). Where pseudo R-square is greater than 50%, the fit is significant and variables have an effect on spatial distribution. However, R-square should not be used to compare models with different data transformations, because R-square can be high for certain non-linear models, even when the regression presents a poor fit with the data (Zuur et al., 2006).

\[ R^2 = 1 - \frac{\text{residual deviance}}{\text{null deviance}} \]  

(equation 2)

Cross-validation was calculated automatically using the Brodgar software package to estimate the optimal degrees of freedom for each smoother. The explanatory variable added to the model at each step resulted in the highest significant (p-value) test corresponding to the percentage of confidence intervals less than zero when reduction in residual deviance was compared with the previous model. The calculation of deviance is explained as follows:

\[ \text{Deviance explained} = \frac{(\text{Deviance}_\text{null} - \text{Deviance}_\text{residual})}{\text{Deviance}_\text{null}} \]  

(equation 3)

Deviance (D) is the difference between the log-likelihood of the saturated model and that of the fitted model. This is also one of the measurements which could help to determine how well the model fits: a small value of deviance indicates a good fit, see equation 3 but this measurement will not be used in this study except in GAM fitted to fishery catch data Subsection 5.3 because using \( R^2 \), AIC and p-value were adequate to measure the model.
Therefore, all models in this study were evaluated for measures such as R-square and the deviance reduction as measured with the chi-square statistic, as well as a step-wise procedure and evaluation in terms of the AIC (Akaike, 1973). Automatic procedures, such as stepwise regression used for fitting GAMs, were considered to be high-variance operations, because they can allow selection of the best predictors from a list of pre-specified possible predictors based on terms of the value of the AIC (Hastie and Tibshirani, 1990; Zuur et al., 2006) (see equation 4). This was used automatically in the Brodgar software package, in order to establish the significance of individual explanatory variables in the models (Guisan and Zimmermann, 2000). These models were evaluated to select the best final model by dropping predictors as parameters in the formula and the final model was then selected with the lowest AIC (Ferguson et al., 2005). There are two formulas that can be used to measure AIC:

\[
AIC = -2 \log (\text{Likelihood}) + 2 \times df
\]

OR

\[
AIC = (\text{Deviance} + 2 \times df) / n
\]

(equation 4)

The GAM output plots are shown as the best fitting smoothers for the effects of all the explanatory variables included in the model. The dotted lines represent the 95% confidence intervals and the tick marks on the x-axis called rug indicate the number of data points available for different values of x. The partial components, as represented by y-values on the GAM plots, express the relationship between the link function of the response variable and each of the variables included in the model.
3.4.2.1.3 Application of GAM to Lethrinus nebulosus (spawning)

In order to evaluate and determine fish reproduction, several spawning period parameters were examined for *Lethrinus nebulosus*: length at first maturity, gonad phase and the Gonado Somatic Index (GSI). The most common parameter used in biological studies is the GSI see equation 5, because it is the method which most successfully indicates the reproduction period and length at first maturity; it is considered to be a real indicator of maturity. Thus, these two parameters, GSI and gonad phase, were used in this study. GSI was calculated as follows:

\[
GSI = \frac{(GW)}{(BW)} \times 100
\]  
(equation 5)

Where GW is the gonad weight of *Lethrinus nebulosus* in grammes and BW is the total weight of the body.

Data was analysed separately for males and females. A GAM was then used to examine the temporal distribution of the spawning season for *Lethrinus nebulosus* and also to examine any environmental effects on distribution of *Lethrinus nebulosus*. GAM analysis was specified using month, SST, SSS, pH, DO and total length of *Lethrinus nebulosus* as explanatory variables and GSI as the response variable, while geographical location and depth were not considered, because the samples were collected from known areas. The final model for GSI was formulated as:

\[
GSI \sim + s(\text{Month}) + s(\text{Total Length}) + s(pH) + s(SST) + s(\text{DO}) + s(SSS)
\]
GAM statistical analyses were also applied to *Lethrinus nebulosus* to examine the GSI, Ovary phase (female) and Testis phase (male) data and all procedures were carried out as above in Subsection 3.2.4.1.

### 3.5 A Two stage GAM to account for the sparsity of the observation data

The next stage in this study was to make an estimation of the model accuracy. It needs to be emphasised that the crucial goal of most fish habitat modelling studies is not only to describe the trends in the modelled data, but also to make predictions which are valid for given temporal and spatial scales. GAM fitted models can be used to predict abundance in any areas of interest and relate this to the explanatory variables. Observations of catch are often characterised by a large number of zeros in space and time, which makes it difficult to model this phenomenon in one stage and could account for the small proportion of variance explained (Bellido, 2002; Sacua, 2005; Welsh *et al.*, 1996) in some models.

Therefore, it was sensible to use two-stage GAM models (Heilborn, 1994) in order to relate data of monthly emperor commercial catches for the period concerned (1996-2004) with environmental variables. A two stage GAM model was fitted in this study to cover the trawler fishing area in Arabian Sea and to predict abundance from SST, geographic location and depth.

Four environmental variables were chosen for the models as being considered appropriate and available: depth, SST, latitude and longitude. The monthly datasets were then applied to a two-stage model. The first stage was to model the
emperor distribution as measured by CPUE in terms of presence or absence, so that the CPUE data was converted into binary form (1 and 0 respectively), using binomial distribution with 'logit' link function. The second stage was to use the CPUE data for the areas of presence with Gaussian error distribution and 'identity' link function.

In the first stage of modelling, a binomial distribution model provided estimations of the probability of emperor presence issue on a geographic basis, while the second stage (Gaussian distribution) quantified the strength of this presence. The outputs of the two-stage model, probability and prediction, were multiplied in order to estimate expected abundance.

Furthermore, separate GAMs of the emperor catch data for only 2005 were developed and new environmental data were predicted in order to test monthly data patterns and to compare them with the original models. This year data used for validation was checked if there is any unusual in respect to range of environmental parameters. Based on these GAM models were constructed with R v 2.2.1 language software, mgcv package, applying a cubic spline smoother and default degrees of freedom (Hastie, 1991; Venables and Ripley, 1997). The models were also built by the stepwise method to remove insignificant variables and to maintain a level of significance is less than 0.001. The continuous probability grids of emperor presence was then generated from the GAMs and transferred to ArcGIS-9 software (ArcMap) (ESRI) to plot the results. The GAM fitted used to estimate environmental effects on relative emperor abundance used the following equations in R language software in three models quasi-Poisson, Gaussian and binomial:
1) Binomial error distribution model

gam (presence ~ s(Latitude)+s(Longitude)+s(SST) +s(Depth),family= binomial (logit))
test1 = list (Latitude = Latitude, Longitude = Longitude, SST = SST)
validation1 = logit (predict (model1, test1))
valid <- data. frame (validation1)
write. table (valid,"output1.txt")

2) Gaussian error distribution model

gam (rCPUE ~ s(Latitude)+s(Longitude)+s(SST) +s(Depth), family = Gaussian)
test2 = list (Latitude = Latitude, Longitude = Longitude, SST = SST)
validation1 = (predict (model2, test2))
valid <- data. frame (validation1)
write. table (valid,"output2.txt")

3) Quasi-Poisson error distribution model

gam(rCPUE ~ s(Latitude)+s(Longitude)+s(SST),family =negative. binomial(2))
test3 = list (Latitude = Latitude, Longitude = Longitude, SST = SST)
validation1 = (predict (model3, test3))
valid <- data. frame (validation1)
write. table (valid,"output3.txt")

3.6 Summary

This chapter began by describing the data requirements and characteristics, and the techniques used to carry out this study of fisheries and environment. An overview of the empirical approaches used in this thesis is illustrated and summarised in Figure 3 - 20. This demonstrates the approach taken to spatial data handling within this study. General issues concerning problems related to the
primary data used in this study were also discussed. Section 3.2 explored the acquisition of secondary data and its importance for this study, focussing on the spatial and temporal distribution of the emperor species.

Using the GIS technique greatly assisted in presentation of the spatial information, as it can be used to integrate and manipulate geographically referenced data. Data management or the structuring of data was shown to be the most fundamental stage before mapping, analysing and visualising the spatial patterns and relating the fish catch data to the environmental factors. Section 3.3 explained the preparation of data on fisheries (traditional and trawlers), emperor catch, biological factors, and the environmental data stored in GIS. The database used was MS Access. The structuring of the database for fisheries data was explained as ER diagrams and the method used to calculate CPUE for both types of fisheries data was described. Queries were illustrated for calculating the fish catch at different locations and the means of holding this information geo-referenced on GIS shapefiles was described.

In Section 3.4.1, the application of GIS for overlaying the fish catch data and the environmental variables was discussed and an illustration given of the outcome of the analysis is usual exploratory using GIS. Next, it was noted that GAM is a powerful technique which provides quantitative spatial relationships between fish distribution and environmental variables. The ability to deal with non-linear relationships between an independent variable and multiple predictors at the same time was highlighted. GIS was also used to represent geographic information based on the results revealed by GAM, because although GAM plots can illustrate the quantitative spatial relationships between response and explanatory variables, they cannot show the spatial patterns explicitly.
Creating Relational Tables in Access Database

ArcGIS Shapefiles

Out put:
- Maps of predicted emperor
- Maps of estimated abundance

Management Consideration

Out put:
- Maps of probability of emperor
- Maps of estimated abundance

GIS data e.g. (bathymetry)

Digitising Oman hard copy Map & adding into digital new shapefiles

Spatial geographic factors for analysis

R/S data e.g. (SST, SSS)

Archive Data of emperor catch data 1996-2004

Biological data of *Lethrinus nebulosus* 2001-2002

Out put:
- Maps of probability of emperor
- Maps of estimated abundance

Merge Spatial and Non spatial data

Analytical methods (GIS & GAM) Apply fishery data and environments into GAM model and GIS display

Figure 1: Generic steps of GIS-based empirical modelling
Chapter 4 : Spatial and Temporal Description of Emperor Distribution in Omani Waters

4.1 Introduction

This chapter examines the spatial and temporal distribution of emperor abundance in Omani waters. The overall objective is to reveal the location and abundance of emperor in relation to environmental factors in the waters of Oman. The approach is mainly used GIS technique.

As discussed in Chapter 3, the secondary data on fish catches and the environment were collected between 1996 and 2004 and are important for this analysis. This information includes the monthly mean catch of commercial trawlers and artisanal fishing vessels, bathymetry, monthly mean Sea Surface Temperature (SST), and monthly mean Sea Surface Salinity (SSS).

The study area stretches from longitude 53° to 63° E and latitude 13° to 24° N. For each type of map, coverage was created differently: SST was divided into 13 classes measured in degrees Celsius (°C), SSS was divided between 34 and 39 parts per thousand (ppt) and the bathymetry data into 7 classes in meters (m), while the emperor catch was measured using Catch Per Unit Effort (CPUE), in kilograms per fishing trips (kg/trip) for traditional fisheries and kilograms per fishing day (kg/day) for trawler fisheries. The disparities in measurement units are discussed in Chapter 3, Sections 3.2.1.1.1 and 3.2.1.2.1.
This chapter is divided into nine sections. Seasonal patterns of SSS and SST in the Northwest Arabian Sea and the Gulf of Oman are discussed in Section 4.2. Section 4.3 explores the general spatial distribution of emperor abundance in Omani waters, while its annual distribution is examined in Section 4.4. Section 4.5 investigates the spatial and temporal distribution of emperor abundance and its relationship to SST, Section 4.6 does so for SSS and Section 4.7 explores its relationship to bathymetry. Section 4.8 discusses the relationships of SST, SSS and bathymetry with the distribution of emperor abundance on a qualitative basis. Finally, Section 4.9 summarises the chapter.

4.2 Seasonal SST and SSS patterns in the Gulf of Oman and the Northwest Arabian Sea

Generally, the sizes of fish populations in the oceans are influenced by several factors, such as water temperature, salinity and dissolved oxygen, which is regularly changed by the seasonal coastal upwelling that occurs in the area under study (Sharp, 1988). Changes in temperature can be associated with spatial and temporal changes in distribution and relative abundance of species (Buck and Anderson, 2001). While SST is considered the most important single factor determining fish production in the oceans (Barratt et al., 2002; Peirce et al., 2003), fish distribution patterns cannot be explained by the influence of one factor alone (Rose et al., 1994). SST can, however, have both a direct and an indirect effect on fish habitat. SST variations play an important role in the genesis of oceanographic processes such as monsoon movements (Ali Khan et al., 2004), and influence both biotic and abiotic factors which affect the distribution of marine species. Therefore, examining annual and seasonal variations in water temperature, salinity
and upwelling are important, because they may be related to fish distribution, as suggested, for example, by the work of Banse (1968), who investigated water properties and their effects on demersal fish. He found that upwelling was related to the seasonal changes in water mass and water circulation in the Arabian Sea, in turn affecting fish stocks. Such processes are discussed at length in Chapter 2.

The specific aim of this section is to examine the seasonal, spatial and temporal variability of SST and SSS in Omani waters with remote sensing data from the Advanced Very High Resolution Radiometer (AVHRR), before examining how the relationships between these variations affect fish distribution. This region is known to be influenced by the southwest (SW) and northwest (NW) monsoons, with the strongest spatial variability in SST and SSS during the SW monsoon, involving changes in SST up to 5°C over 200 kilometres (Vecchi et al., 2004). Chapter 2, Section 2.3 described the structure and mechanisms of such variability in the Gulf of Oman and the Northwest Arabian Sea during the monsoon season. Neither sea bottom temperature nor sea bottom salinity was considered for analysis in this study, for reasons detailed in Chapter 2.

4.2.1 Spatial distribution of Sea Surface Temperature

In general, the spatial patterns of monthly long-term average SST between the Arabian Sea and the Gulf of Oman are strikingly different and great seasonal changes can be seen (Figure 4-1). The range of SST is from below 21°C to above 33°C in both the Gulf of Oman and the Arabian Sea.

In the Arabian Sea, it was observed that the SST variability levels appear with annual regularity between April and October. During early April, the SST gradually
decreases from south to north during the SW monsoon, attaining its trough value of less than 23°C, which it reaches in mid-June and early August, at location 17° to 20° N and 55° to 58° E. This location is near the landing ports of Hasek and Sarab, close to the coast (Figure 4-1), where there is a clear variation of the mean SST, which increases gradually from low values of 23°C in the inshore area of the Arabian Sea to 26.7°C in the offshore area at the same latitude. This may be attributed to the cooling of the landmass in the north and the flow of cold air from the land, as well as the influence of upwelling (Morrison, 1997; Shi et al., 2000). Upwelling is important during the SW monsoon in the Arabian Sea (Kumar et al., 2001) and results in a gradual increase in the SST, extending over a greater offshore distance, reaching 26°C. This event is followed by the secondary warming of the SST in December, when it reaches 27°C because of the weak winds and hot sun (Arnone et al., 1997; Lee et al., 1998); furthermore, Prasad and Ikeda, (2002) have confirmed that humidity plays an important role in the heat budget of the northern Arabian Sea during winter.

In the Gulf of Oman during the SW monsoon, SST shows an increase from 26° to higher than 33°C. During this period, from early June to late August, the SST value reaches a maximum of higher than 33°C because of the wind-driven circulation patterns in the Arabian Sea, and the spreading of the cold water from the south of Oman to the Gulf of Oman is ineffective (Ali Khan et al., 2004). During the NE monsoon, the SST in the Gulf of Oman continues to decrease and reaches a minimum of 23°C during January. This suggests that the Arabian Sea has great influence on the dynamic water circulation in the study area, as has been described in several studies detailed in Chapter 3 (Weller et al., 1998; Brink et al., 1998; Shi et al., 2000; Kindle and Arnone, 2001). Conversely, Figure 4-1b shows
the SST to be much more uniform within the area (Gulf of Oman and Arabian Sea) between November and February, when the changes in SST are very small and do not exceed 1°C to 2°C.
Figure 4-1 Spatial distribution of monthly mean Sea Surface Temperature in the Gulf of Oman and the Arabian Sea derived from AVHRR data, January-December.
4.2.2 Spatial distribution of Sea Surface Salinity in Omani waters

Generally, the monthly long-term average SSS variability levels range between less than 34 ppt and higher than 37 ppt and can be seen to extend from the Gulf of Oman to the Arabian Sea (Figure 4-2). The SSS is rather uniform in the Arabian Sea (i.e. 54° 21' E, 16° 21' N) during the SW monsoon, with a range between 34 and 35 ppt. The SSS values in the Arabian Sea gradually decrease towards south from the Gulf of Oman, where the SSS monthly mean during July and August shows a decrease to a minimum of 34 ppt, while during the NE monsoon (December and January) the monthly mean of SSS values increases to a maximum of 36.5 ppt.

The monthly long-term average of SSS in the Gulf of Oman during the SW monsoon (April to September) ranges between less than 35 ppt and greater than 37 ppt at the north end of the Gulf of Oman (Musandam). It is clear that during July and November the monthly long-term average of SSS differs between four broad areas of the Gulf of Oman. At the northern part of the Gulf of Oman (the Strait of Hormuz), SSS reaches its highest values at 38 ppt, while at the southern corner (Ra’s Al-Hadd) it is only 35 ppt. Between these two areas, SSS values range between 36 and 37 ppt (Figure 4-2). From January to June the monthly long-term average of SSS values ranges between 35 and 37 ppt, while at Ra’s Al-Hadd, where the Gulf of Oman meets the Arabian Sea, the annual SSS range is only from 35 to 36 ppt.
Figure 4-2 Spatial distribution of monthly mean of Sea Surface Salinity in the Gulf of Oman and Arabian Sea, January-December
4.3 Mapping the spatial catch of emperor in Omani waters

Mapping the total catch of emperor is essential in describing patterns in their spatial distribution and abundance, and as the first step in studying their ecology and biology in the area. Therefore, the aim of this section is to map the total catch of emperor for nine years, in order to reveal in general the spatial distribution in Omani waters. The datasets used are based on the combined catches by both fisheries, i.e. traditional and commercial, and are measured in kilograms.

Figure 4-3 illustrates the general spatial distribution patterns of the total catch of emperor for both types of fishery. It is quite clear that the emperor are widely distributed in Omani waters and most of the high catch areas are found in the Arabian Sea rather than in the Gulf of Oman. In particular, the highest abundance is in the Al-Wusta and Dhofar regions between 16° and 20° N, where the catch ranges between 1000 and 19,400 kg. The highest catch among the traditional fisheries is found in the Al-Wusta region, near the Ra’s Madrakah area, while the highest catch for trawlers is 700 kg and is concentrated between the areas of Ra’s Duqm, Ra’s Madrakah and Lakbi (Figure 4-3). Furthermore, the Sharbithat and Shuwaimiyah areas located in the Dhofar region (between 56° 40' E, 18° 26' N and 54° 33' E, 16° 55' N) also have a high catch, ranging between 4,600 tons and 8,000 tons.

It is important to note that under the national regulations, commercial fishing vessels are allowed to catch a certain quota in a year (Table 3-3), while traditional fishing boats are allowed to fish throughout the year with no limits. Therefore, in
the Arabian Sea area, catches by trawlers are quite low compared to the traditional catches.

Since it is recognised that spatial trends in fish distribution vary between these areas, and that catches are higher in the Arabian Sea than in the Gulf of Oman, it is necessary to explore these trends in more detail in order to understand whether these variations are a result of the fishing effort or of the environmental effects on emperor, and this examination will begin by concentrating on the Arabian Sea.
Figure 4-3 Spatial distribution of total emperor catch in kilograms in Omani waters, 1996-2004, with bathymetry.
4.4 Spatial distribution of annual emperor catch in the Arabian Sea

Mapping average CPUE for emperor gives a more precise view of the possible distribution of fish; hence, as a first step the annual average CPUE values for traditional and trawler fisheries were plotted to explore general patterns of emperor abundance in the Arabian Sea. In the second step, nine maps for each type of fishery were created in order to reveal the spatial distribution of emperor abundance in the Arabian Sea. Different maps were created for traditional fisheries (Figure 4-6) and trawlers (Figure 4-7) because of the different units used to measure CPUE: kilograms per trip (kg/trip) for the former and kg/day for the latter. Although the same scale was used, the calculations were different, and these are discussed in Chapter 3, sections 3.2.1.1.1 and 3.2.1.2.1.

Annual average for traditional fisheries was quite steady during 1996-2000, rising only slightly from the lowest value of 2.4 kg/trip in 1996, while in 2001 there was a very high peak of 32 kg/trip, followed by a relatively rapid decline to 15 kg/trip in 2004 (Figure 4-4).

Figure 4-4 Annual average catch (CPUE) for traditional fishery
Figure 4-6 shows the spatial distribution of emperor abundance for traditional fisheries during the nine years 1996-2004. Generally, the average CPUE ranged between zero and 40 kg/trip at most landing ports. The figure shows that the average CPUE was comparatively high from 2001 to 2004, ranging between 38 and 290 kg/trip, while from 1996 to 2000 it ranged between 0.26 and 13 kg/trip. The CPUE at Ras-Madrakah was higher than at other landing ports; for instance, in 2001 it reached 290 kg/trip and in 2003 it was 115 kg/trip. CPUE was also relatively high at Sharbithat and Soqrah, at more than 100 kg/trip.

Average CPUE for trawlers showed a somewhat different pattern of fluctuation between 1996 and 2004. The lowest value, 3.6 kg/day in 1998, was followed by the highest average CPUE of 22.4 kg/day in 1999, falling back to 12 kg/day in 2001 and declining steadily to 6.5 in 2004, so that levels in 2002 to 2004 were approximately the same as in 1996-7, but not as low as in 1998.

The changing patterns of annual emperor abundance according to trawler catch in different seasons are shown in Figure 4-5. It is apparent that these patterns vary from year to year. Figure 4-7 shows that in 2004 at the location 17° 73' N, 56° 4' E, the highest average CPUE was 112 kg/day, while the lowest was 15 kg/day in 1998 and for the remaining years average values ranged between 20 and 98 kg/day.
Generally, these patterns show that for both types of fishery the average CPUE values were high during the period from 2000 to 2004. Also, around the areas of Ra's Madrakah and Soqrah (17° 73' to 18° 73' N and 56° 4' to 57° 59' E), there was a high frequency of high average CPUE values. However, in order to confirm the reasons for all these variations of CPUE, further examination of these areas is needed by comparing the monthly means of CPUE with those of SST, SSS and bathymetry. Therefore, the next section will examine the SST, SSS and depth values and their relationship with CPUE.
Figure 4-6 Spatial distribution of annual emperor catch in the Arabian Sea for traditional fisheries (1996-2004)
Figure 4.7 Spatial distribution of annual emperor catch in the Arabian Sea for trawler fisheries (1996-2004)
4.5 Analysis of sea surface temperature in relation to the distribution of emperor abundance

After analysing the spatial distribution of monthly long-term averages of SST, mapping the spatial distribution of total catch and mapping annual CPUE of emperor in Omani waters, it is important to explore and analyse the spatial and temporal distribution of emperor abundance in relation to SST in the Arabian Sea. Hence, twelve maps of CPUE for each type of fishery were created and overlaid with monthly long-term average SST. Figures 4-8 a & b present the monthly long-term average CPUE (kg/trip) for traditional fisheries and Figures 4-9 a & b present the monthly long-term average CPUE (kg/day) for trawlers, overlaid with monthly long-term average values for SST measured in °C. A number of observations can be made concerning both types of fishery, on the basis of these figures:

1. The spatial distribution of emperor appears in all months, although their distributions vary in CPUE.
2. The spatial distribution of emperor abundance appears higher in the northwest of the Arabian Sea.
3. The temporal distribution of emperor appears to be highest in the months between August and December.

Section 4.2.1 discussed the spatial patterns of SST in the study area, including large seasonal changes between summer and winter time. Figure 4-1 a & b shows that from April to September, there is a consistent trend in SST values, which decreases from high to low temperature values. During this period, the monthly patterns of both CPUE measurements show fluctuations. Figures 4-8 a & b show a
high abundance of emperor from August to November, measured by CPUE ranging between 0.5 and 100 kg/trip. It is clear that low traditional CPUE values are widespread from March to July, ranging between 0.5 and 20 kg/trip, with low values of CPUE between 20 and 60 kg/trip in areas such as Sharbithat and Marbat.

Generally, the trawler CPUE values in this area range between 0.5 and 20 kg/day, but low CPUE values are clearly seen during March, with widespread distribution between 0.5 and 10 kg/day, few values ranging between 10 and 40 kg/day, and mean values of SST in the range 25.9°C to 26.7°C from inshore to offshore. Figures 4-9 a & b show that CPUE values increase from August to December, with the highest emperor abundance values in October, November and December, when most CPUE values are between 10 and 80 kg/day and mean values of SST range between 25.9 and 28.1°C from inshore to offshore. Although during April and May the mean SST ranges between 26.5 and 27°C, there are lower values of CPUE than in August, when the mean SST ranges between 23 and 25.6°C. During these months, which have low CPUE values with less spread, there are one or two areas where CPUE is more than 100 kg/day.

This indicates that low SST values may be the reason for low CPUE figures during the SW monsoon period and higher CPUE values after the monsoon has finished. Nonetheless, the overall relationship between spatial and temporal distribution patterns of emperor abundance and SST cannot be fully explained at this stage. The reasons for the variation in the distribution of emperor abundance during different months at different SST levels will be discussed further in Section 4.7, while an analysis of the influence of SST on distribution of emperor abundance will be offered in Chapter 5.
Figure 4-8 (a) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SST for traditional fisheries, January-June
Figure 4-8 (b) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SST for traditional fisheries, July-December.
Figure 4-9 (a) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SST for trawler fisheries, January-June.
Figure 4-9 (b) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SST for trawler fisheries, July-December
4.6 Analysis of Sea Surface Salinity in relation to the distribution of emperor abundance

This section analyses the spatial and temporal distribution of emperor abundance patterns in relation to SSS. This is essential, because identified variation in SSS has potentially an important effect on the habitat of fish, owing to the considerable monthly variation in SST, as described in Section 4.2.1. Figures 4-10 a & b display the monthly long-term average CPUE patterns for the traditional catch overlaid with monthly long-term SSS averages, while Figures 4-11 a & b provide the same for the trawler catch. The following observations may be made from the maps:

- SSS values fluctuate between 36 and 36.5 ppt in the Arabian Sea.
- SSS patterns are much more steady and constant than SST patterns.
- High CPUE values occurred during the months of September to December, corresponding to low SSS values.

Figures 4-10 a & b and Figures 4-11 a & b show the overall mean SSS patterns and emperor abundance values, which are fairly analogous to the SST patterns. The SSS value changes from the southwest to the northwest of the Arabian Sea starting in April, when it decreases from 36.5 ppt to reach a minimum of 35.5 ppt in July and August. This is followed by values of SSS between <34 and 35 ppt when there is high abundance of emperor in September and December. The results of the upwelling phenomena in Omani waters have been presented in detail by Weller et al. (2002) and Esenkov et al. (2003). Although these patterns are visually evident, they show no clear relationship with emperor abundance distribution, because the mean SSS values vary over a very small range; therefore this will not play an important role in further examining whether the relationship between SSS and CPUE has an effect on the distribution of emperor abundance.
Figure 4-10 (a) Spatial distribution of long-term average emperor in the Arabian Sea in relation to SSS for traditional fisheries, January-June
Figure 4-10 (b) Spatial distribution of long-term average emperor in the Arabian Sea in relation to SSS for traditional fisheries, July-December
Figure 4.11 (a) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SSS for trawler fisheries, January-June
Figure 4-11 (b) Spatial distribution of long-term average emperor abundance in the Arabian Sea in relation to SSS for trawler fisheries, July-December
4.7 Analysis of the distribution of emperor abundance in relation to depth

Bathymetric analysis of the study area allows the spatial distribution of emperor to be explored. The literature suggests that the emperor species usually occurs in waters of less than 100 metres in depth (Carpenter and Allen, 1989; Randall, 1995; Al-Abdessalaam, 1995; Sato, 1978). Figure 4.12 shows the average CPUE distribution of emperor abundance for traditional and trawler fisheries overlaid with bathymetry. Analysis of this data shows that higher CPUE values of more than 10 kg/day or kg/trip were found mostly in areas of less than 100 metres depth, i.e. latitude 18° to 19° N and longitude 57° 35' to 57° 50' E (Figure 4-12; the 100-metre depth contour is shown in red). Indeed, in areas with water more than 200 metres deep there was hardly any catch. These patterns clearly indicate that as depth increases, the CPUE value decreases to less than 5 kg/day or kg/trip. These results, which support the findings of other researchers that genus *Lethrinus* occur in waters less than 100 metres deep, will be examined in greater detail in Chapter 5 in order to clearly establish whether depth really has a significant effect on the distribution of emperor abundance.
Figure 4-12 Spatial distribution of total average emperor abundance in the Arabian Sea for both types of fishery (traditional kg/trip and trawler kg/day) in relation to bathymetry.
4.8 Discussion of the relationship between the distribution of emperor abundance and environmental variables

The approach used to analyse the qualitative description of spatial and temporal patterns of emperor abundance in relation to environmental variables was through a geographical information system (GIS). The spatial patterns of SST in the Arabian Sea are completely different from those in the Gulf of Oman, and start to change in late April, these changes ending in September. This indicates that the study area is affected by upwelling (Morrison, 1997), which has an effect on the ambient temperature, nutrient richness and the availability of food to fish.

The analysis paid particular attention to the spatial and temporal patterns of SST distribution in the Arabian Sea during and after the SW monsoon period, which reflects the effect of the distribution of emperor abundance. It indicated that the annual patterns of emperor abundance seem not to be precisely the same in terms of CPUE in the same place every year; and high abundance is always more likely to occur in the Arabian Sea than in the Gulf of Oman.

Earlier GIS analyses discussed in Section 4.2.1 have shown obvious seasonal variations in the spatial patterns of SST in the Arabian Sea and the Gulf of Oman, between the seasons of the SW and NE monsoons. The spatial distribution of SST was very clear; for example, the mean SST of the northwest Arabian Sea during winter reached 23°C, while in summer it reached around 27°C. Seasonal patterns are clearly present in the Omani waters: during April and June CPUE values for both types of fishery were low, while emperor abundance was high for both types of catch after the monsoon period (September to December). These results
support the hypothesis that the upwelling which accompanies the SW monsoon has the effect of reducing SST, leading to low emperor abundance.

Many studies have noted that for different species of fish there are significant relationships between fish abundance and temperature. Indeed, the influence of SST variation on distribution and abundance of fish has been noted widely in the literature; for example, Fox et al., (2000) reported a negative relationship between cod abundance and the occurrence of warm water, a positive relationship with cold water and an absence of relationship at intermediate water temperature. Similarly, Zheng, (2001) found haddock abundance in winter in the northern North Sea to be positively related to spatial distribution of SST. Moreover, the apparent influence of SST in the northern North Sea on the coastal fishery has been reported by Pierce and Boyle, (2003), who suggest that this could be an indication that SST affects *Loligo forbesi* recruitment. The researchers have noted that there are differences in the spatial relationships between environmental variables, especially SST and marine abundance, and that in those areas which have high seasonal variations a relatively strong effect is observed on marine species.

However, at present there is a scarcity of literature in all parts of the world on the spatial and temporal variation of emperor abundance. There has also been little evidence to support the existence of a relationship between the distribution of emperor abundance and variation in SST or SSS. Forster, (1984), analysed 19 demersal species, including *Lethrinus nebulosus*, in Aldabra (Indian Ocean). His findings showed that temperature and fish distribution were related, with the fish occurring in areas of upwelling, where the temperature ranged between 24.3 and 27.8°C. This is further supported by Newman and Williams, (2001b), who
observed the highest abundance of *Lethrinus nebulosus* at an average temperature of 27°C on the central Great Barrier Reef during July; but they made no further reference to the relationship between the emperor and the environmental variation. McIlwain *et al.*, (2006) note the relative abundance of *Lethrinus nebulosus* in the Arabian Sea with a rise in SST to between 25.7 and 27°C. Their findings, which show catches to be low during the months of June, July and August, when the SST is less than 23°C, support the findings of the research presented here. It is particularly important to point out here that although in May and June the effort for both types of fishery was higher than or similar to that of the period from November to January, the CPUE was in fact low. The findings of earlier research and the current research clearly support the view that emperor is mostly found in the SST range of 25°C to 27°C.

Thangaraja *et al.*, (1995) studied the hydrobiology of the waters off Oman and conclude that sea temperature; depth and salinity are major environmental factors affecting fish distribution. However, they focused on the abundance of emperor eggs and larvae rather than that of adult fish. According to their findings, the Arabian Sea is a good spawning ground and the Gulf of Oman is the best nursery ground for most of the fish species that occur in Omani waters (Thangaraja and Al-Aisry, 2001). These findings will be of particular importance for the examination of the emperor spawning season in Chapter 5.

On examining the salinity issue, it was observed that patterns in the study area show low variation of 36.0 to 36.5 ppt between the months of September and February. This is supported by Weller *et al.*, (2002), who observed the salinity at the surface during the SW monsoon in the Arabian Sea as being quite uniform and
dropping from 36.5 to 36 ppt. Prasad, (2004) reports that the SSS in the Arabian Sea gradually increases towards the north, reaching a maximum of 36.5 psu and decreasing to a minimum of 34.5 psu. In addition, Esenkov et al., (2002) observed the distribution of salinity in the Arabian Sea as of low variability. Similarly, Kumar and Narvekar, (2005) found that surface salinity ranged from 36 to above 36.4 psu in the Arabian Sea, while Thangaraja et al., (1995) reported values between 35.5 and 36.5 ppt; and Han and McCreary, (2001) showed that the low values of SSS enter the Arabian Sea from the Indian Ocean. Although a relationship is suggested between distributions of marine species abundance and salinity, there are limited findings on the influence of salinity on fish in general, with no direct association found. For example, Pierce and Boyle, (2003) examined whether interannual variation of squid was related to SSS and other environmental variables, but found that SSS was not a significant variable.

These findings of low variation of SSS and previous studies indicating that salinity does not directly influence the marine species suggest that the influence of salinity on emperor abundance is not significant. Therefore, the association between distribution of emperor abundance and the salinity variable will not be further investigated.

The investigation of the distribution of emperor in relation to depth confirms that in general *Lethrinus* species were found in depths of less than 200 metres. It is evident that different species of emperor favour habitats at different sea depths. These patterns are supported by studies on the central Great Barrier Reef by Newman and Williams, (1996), who investigated assemblages of *Lethrinus* spp, finding that they commonly appear at a depth of 30-40 metres and that *Lethrinus*. 
*miniatus* frequently occur at depth of 128 metres. Furthermore, Williams and Russ, (1994) suggest that *Lethrinus nebulosus* occur on the Great Barrier Reef in inshore waters at a depth of 50 metres. Forster, (1984) examined the distribution of fish at Aldabra (Indian Ocean) in relation to bottom temperatures between the depths of 100 and 300 metres, and found that emperor were not being caught below a depth of 75 metres. Additionally, Koranteng, (2001) suggests that depth appears to be the most significant variable in demersal assemblages in Ghana.

These findings are supported by Sato, (1978), Randall, (1995) and Al-Abdessalaam, (1995), who have reported that most Lethrinidae species are found in waters less than 100 metres deep. The GIS analysis of spatial abundance patterns shows that emperor tend to aggregate in areas less than 200 metres deep, but the depth preferences may overlap with the type of ground and this could be a significant factor in the distribution of lethrinid abundance (Hixon and Beets, 1989). However, the traditional fishermen are active throughout the year and mostly operate within 20 kilometres from the landing port in three directions, in areas where the water is less than 100 metres deep; these areas provide a suitable habitat for the emperor, which is consistent with the high catch in the Arabian Sea at a depth of less than 200 metres.

The above analysis of visual detection shows the long-term averages of the spatial and temporal distribution of emperor in Omani waters to be associated with SST and depth by using GIS, which provides a good indication of where and when the emperor occurs. Nevertheless, there is still a need to ascertain whether SST and depth are significant factors in the distribution of emperor abundance. It is suggested that the use of spatial statistics may highlight some of the relationships.
between environment and distribution of marine species abundance (Swartzman et al., 1992; Denis et al., 2002; Pierce and Boyle, 2003). Therefore, the approach followed in this chapter is considered to facilitate further research such as quantitative analysis in order to test the hypothesis and validate the findings. In Chapter 5 spatial statistics of the General Additive Model will be used to study the relationship between the spatial and temporal distribution of emperor and the environmental factors.

4.9 Summary

This chapter has provided general information on the distribution of emperor abundance in Omani waters and in particular analysed the spatial and temporal distribution derived from data relating to traditional and trawler fisheries in the Arabian Sea. This was done in relation to simultaneous measures of SST, SSS and depth, using GIS techniques, which allow the display and overlay in real time of different environmental variables. This study used qualitative techniques to describe the relationships between these environmental factors and the spatial patterns of emperor abundance as measured by CPUE. The analyses show the following results:

(a) In the Arabian Sea, there is clear and strong seasonal variability of SST and SSS during the winter and summer monsoons.

(b) The Arabian Sea has a maximum SST of 27°C in December and a minimum of 23°C in July, while the SSS is fairly uniform, fluctuating between 36 and 36.5 ppt.

(c) In terms of spatial distribution, emperor abundance is concentrated more in the northwest of the Arabian Sea, from longitude 57° 30' to 58° 30' E and from...
latitude 18° to 20° N, than in the southwest; and CPUE is high in areas where the sea is less than 200 metres in depth.

(d) In terms of temporal distribution, emperor CPUE is low in June and high from September to January.

The spatial and temporal patterns of CPUE against SST and depth variables suggest the usefulness of further quantitative analysis.
Chapter 5 : GAM Analysis of Emperor Distribution in Omani Waters

5.1 Introduction

Generalised Additive Modelling (GAM) is a non-parametric regression technique offering the advantages over conventional regression techniques that it makes fewer assumptions and is independent of particular functional relationships in the underlying statistical distribution of the data (Hastie and Tibshirani, 1990).

The aim of this chapter is therefore to examine the influence of environmental variables, to analyse the quantitative relationships between these variables and emperor abundance data and to identify the spawning season. In order to do this, statistical reconstruction of the spatial distribution of *Lethrinus nebulosus* and the temporal distribution of its spawning season in relation to sea surface temperature (SST), depth and geographic locations (latitude and longitude) were modelled using GAM techniques; this is the most suitable technique for this study, since it allows an exploration of nonlinear relationships between the catch data as response variable and multiple explanatory (independent) variables.

This chapter has been divided into 8 sections. Descriptive of statistics and scatterplots are presented in Section 5.2, while Section 5.3 shows the results of GAMs fitted to emperor fishery data averaged over nine years 1996-2004. Section 5.4 presents the results for GAMs fitted to environmental variables related to long-term monthly averages of emperor fishery data. Section 5.5 examines the relationships between the maturation of the gonads (ovaries, testes) as indicated
by the Gonado Somatic Index (GSI) of *Lethrinus nebulosus* and ambient environmental factors. Section 5.6 mapping predict distribution of emperor in the Arabian Sea, compare and validate the accuracy of different models using R language and Brodgar software. Section 5.7 discusses the results of these GAMs in relationship to the distribution of emperor abundance. Finally, Section 5.8 summarises the chapter.

5.2 Descriptive statistics and scatterplots for both types of fishery, 1996-2004

The previous Chapter 4 has presented qualitative analyses of the relationships of the spatial distribution of emperor abundance with the environmental variables SST, SSS bathymetry and geographical locations in the Arabian Sea. It was observed that these environmental variables might be important factors affecting emperor distribution, but it was not concluded how they could have a significant effect. It is in this context that the present section examines the effects of environmental variables on the distribution of emperor abundance.

In order to assess the relationship between emperor abundance as measured by catch per unit effort (CPUE) and explanatory variables, scatterplots were used to visualize and to confirm the non-linearity of the relationships between the explanatory variables and the CPUE data. The major explanatory variables used to analyse this model are: year, month, sea surface temperature (SST, degrees Celsius), depth (metres), latitude and longitude (decimal degrees).

Scatterplots confirm the non-linearity of the relationships between CPUE and environmental variables (Figures 5-1 a-f and 5-2 a-f). The data range variation of
CPUE was not high, except for one point which was found to be high; so this point was examined to see if it affected the model. However, the scatterplot analysis suggests the following relationships: emperor abundance for traditional fisheries appears to be low during 1997, 1998 and 1999, reaching its highest values in 2001 (Figure 5-1a), whereas in terms of seasonal variation it appears to be high during August, September, October and November (Figure 5-1b), with lowest values in May and June. Equivalent plots for trawler fisheries indicate that CPUE appears to be lowest during 1996 and 1998 (Figure 5-2a), while seasonally it falls to minimum values in March and reaches high values from August to December (Figure 5-2 b).

The highest emperor abundance values were associated with an SST range higher than 24°C and less than 28.5°C for both traditional and trawler catch (Figures 5-1c and 5-2c). The highest emperor abundance for both types of fishery was found in depths of 30 to 200 metres and low abundance in deeper water, at more than 200 metres (Figures 5-1d and 5-2d). Also, emperor abundance was greatest between latitudes 17°.50' and 20° N and longitudes 56°.50' and 58 °.50' E (Figures 5-1 e-f and 5-2 e-f); it decreased with increasing distance outside these coordinates.
Figure 5-1 Scatterplots for traditional fisheries, showing the relationships between emperor abundance / CPUE (kg/trip) and (a) year, (b) month, (c) SST (°C), (d) depth (m), (e) latitude and (f) longitude (decimal degrees).
Figure 5-2 Scatterplots for trawler fisheries, showing the relationships between emperor abundance / CPUE (kg/day) and (a) year, (b) month, (c) SST (°C), (d) depth (m), (e) latitude and (f) longitude (decimal degrees).
5.3 GAMs fitted to emperor fishery catch data with different explanatory variables

This section examines a preliminary application of GAMs to describe the variation of emperor abundance in Omani waters with relation to environmental variables. The discussion in Chapter 4 on geographical information systems (GIS) analysis pointed out that within the study area, emperor abundance is higher in the Arabian Sea than in the Gulf of Oman, with SST also showing seasonal changes during the monsoons.

In order to examine these matters and demonstrate the relationship between emperor abundance distribution during all nine years for traditional and trawler fisheries and environmental variables, GAM was applied at this stage with stepwise elimination, using the cubic spline and a quasi-Poisson distribution function with log link; the degree of smoothing was determined by the degrees of freedom (df) with cross validation, which produced moderate smoothing of the relation between numerical abundance and factors of interest (Hastie and Tibshirani, 1990; Venables, 1994).

The final GAM model formula for the 1996-2004 fishery catch data was as follows:

\[
\text{CPUE} \sim s(\text{Year}) + s(\text{Month}) + s(\text{SST}) + s(\text{Depth}) + s(\text{Latitude}) + s(\text{longitude}),
\]

with 95% confidence intervals, where \( s \) is a cubic smoothing spline, family is quasi-Poisson and the link function is log. Table 5-1 and Table 5-2 list the numerical output for the best model fits with the explanatory variables. Table 5-1 presents the results of best model fit of GAM for all years and for both types of fishery using predefined rules such as the pseudo-\( R^2 \), percentage of deviance.
explained, degrees of freedom and Akaike Information Criterion (AIC), which gives an indication of the goodness of the GAM model fit. Where the pseudo-\(R^2\) is greater than 50% it appears that the variable affects the spatial distribution (Swartzman et al., 1992). For example, the pseudo-\(R^2\) value for the emperor CPUE for trawlers is 0.50 and for traditional fisheries it is 0.53, which indicates a significant effect of the variables in this model on the spatial distribution of emperor CPUE. Also, the 'deviance explained' term examines the goodness of the fit as the ratio between explained deviance and the total deviance (Hastie and Tibshirani, 1990). For example, the commercial and traditional fisheries the model explained 54% and 63% of the total deviance respectively (Table 5-1).

<table>
<thead>
<tr>
<th>R^2</th>
<th>Dev-explained</th>
<th>df</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trawler</td>
<td>Traditional</td>
<td>Trawler</td>
</tr>
<tr>
<td>0.50</td>
<td>0.53</td>
<td>54%</td>
</tr>
</tbody>
</table>

Table 5-2 shows the optimum GAM results, where all the explanatory covariates included were significant at p-values < 0.001. When the GAM model was applied to both types of fishery data, the main effect was for the explanatory variables of month, year, latitude, longitude and SST were significant, while depth was not a significant explanatory variable.
Table 5-2. Analysis of optimum GAM for fish catch (CPUE) with six explanatory variables

<table>
<thead>
<tr>
<th>Exploratory Variables</th>
<th>Degrees of freedom (df)</th>
<th>Traditional</th>
<th>Trawlers</th>
<th>Traditional</th>
<th>Trawlers</th>
<th>Traditional</th>
<th>Trawlers</th>
<th>Chi.sq ($\chi^2$)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>4</td>
<td>4</td>
<td>52.4</td>
<td></td>
<td>49</td>
<td></td>
<td></td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Month</td>
<td>4</td>
<td>8</td>
<td>54.1</td>
<td>150.6</td>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Latitude</td>
<td>4</td>
<td>7</td>
<td>173.84</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Longitude</td>
<td>1</td>
<td>7</td>
<td>30</td>
<td>50</td>
<td>0.011</td>
<td>0.03049</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>4</td>
<td>3</td>
<td>73.86</td>
<td>20</td>
<td>&lt; 0.001</td>
<td>0.017396</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST</td>
<td>4</td>
<td>8</td>
<td>33</td>
<td>1045</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

5.3.1 GAMs fitted for traditional emperor fishery data

GAM results for the traditional fishery data are shown in Figure 5-3 a-e. The plots illustrate the non-linear relationship between the response variable CPUE kg/trip and each explanatory variable individually. The y-axis indicates zero, negative and positive effects: an adjusted y-value less than zero indicates a negative effect and a value more than zero indicates a positive effect on the response variable. The optimal GAM model for CPUE contained a smoothing function for year (df = 4 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of year (Figure 5-3a) indicates that the most strongly negative effect occurred in 1998 and the most strongly positive effect in 2001.

The optimal GAM model for CPUE also contained smoothing functions for month, (df=4 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of month (Figure 5-3b) indicates a clear seasonal effect on CPUE: there is a decrease from March to June and an increase from July to October; then, after the maximum is reached, there is a decrease to the end of the year (Figure 5-3b). The optimal GAM model for CPUE containing a smoothing function for SST, df = 4 and
p-value < 0.001 (Table 5-2). The smoother for the partial effect of SST (Figure 5-3c), indicates that SST has a positive effect on emperor abundance between 25°C and 27°C. The optimal GAM model for CPUE contained a smoothing function for depth (df = 4 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of depth indicates that depth has a positive effect on CPUE between 50 and 100 metres depth and a negative effect at depths greater than 100 metres (Figure 5-3d). The optimal GAM model for CPUE contained a smoothing function for latitude (df = 4 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of latitude indicates that the partial effect of CPUE decreases with increasing latitude; for example, the most positive effect on abundance was observed at locations between latitude 18° and 19° N, while the most negative effect was at latitudes higher than 22° N (Figure 5-3 e). In terms of longitude there is also a negative relation at higher than 22° N (Figure omitted) and the optimal GAM model for CPUE contained a smoothing function for longitude (df = 1 and p-value = 0.011) (Table 5-2).
Figure 5-3 GAM smoothing curves fitted to partial effects of explanatory variables on emperor abundance (CPUE kg/trip), as a function of (a) year, (b) month, (c) SST (°C), (d) depth (m), (e) latitude and (f) longitude (decimal degrees).
5.3.2 GAMs fitted for trawler fishery data

The plots in Figure 5-4 a-e demonstrate the optimal GAM model results from the trawler fishery CPUE data. The GAM plots illustrate the non-linear relationship between the response variable (CPUE kg/day) and each explanatory variable. The optimal GAM model for CPUE contained smoothing functions for year, (df = 4 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of year (Figure 5-4a) indicates that the most strongly positive effect occurred in 1999 and the most strongly negative effect in 1996. The optimal GAM model also contained a smoothing function for month (df = 8 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of month indicates a clear seasonal effect on abundance, which decreases from January to April, then increases from May to the end of the year (Figure 5-4b). The optimal GAM model for CPUE contained a smoothing function for SST (df = 8 and p-value < 0.001) (Table 5-2). The smoother for the partial effect of SST (Figure 5-4c) indicates that the SST has a positive effect on CPUE between 25°C and 27°C (Figure 5-4c). The optimal GAM model for CPUE contained a smoothing function for depth (df = 3 and p-value = 0.017) (Table 5-2); the smoother for the partial effect of depth indicates that it has a negative effect on abundance at depths greater than 200 metres and a positive effect at depths of less than 100 metres (Figure 5-4d). The optimal GAM model for CPUE contained a smoothing function for latitude (df = 7 and p-value < 0.001) (Table 5-2) and the smoother for the partial effect of latitude indicates that CPUE decreases with increasing latitude; for example, the most positive emperor abundance was observed at latitude 17° N and the most negative effect at latitudes higher than 22° N (Figure 5-4e). In terms of longitude, CPUE increased from longitude 57°.50' E and the smoother for the partial effect of longitude shows
a negative effect at longitudes higher than 58.5° E (Figure 5-4 f); the optimal GAM model for CPUE contained a smoothing function for longitude (df = 7 and p-value = 0.030) (Table 5-2).
Figure 5-4 GAM smoothing curves fitted to partial effects of explanatory variables on emperor abundance (CPUE kg/day), as function of (a) year, (b) month, (c) SST (°C), (d) depth (m), (e) latitude and (f) longitude (decimal degrees)
5.4 GAMs fitted to monthly long-term average emperor data

The models used here for quantitative analysis focus on long-term average data. From Section 5.3 on the preliminary application of GAM fits, it is noticeable that there are partial relationships between emperor abundance and the explanatory variables of year, month, SST, depth, latitude and longitude. In order to verify these hypotheses, this section examines the relationships between emperor abundance and environmental variables by taking the monthly long-term averages of all 108 months of data. This conversion to monthly long-term averages was to allow a general description of spatial and seasonal trends of emperor abundance with environmental variables. In Chapter 3, a method was discussed using a stepwise procedure, and it was noted that it is vital to assess models in terms of the AIC, p-values and $R^2$ to ensure the best or good enough fits of explanatory variables in the model. Therefore, Table 5-3 lists the results of the best fits of GAM numerical output with SST, latitude, longitude and depth Model-1. And in order to conform the hypothesis of Model-1 was compared with Model-2 without explanatory variables SST and or latitude.

Table 5-3 Table 5-3 Model-1 results and Figure 5-5 (a-c) show that for all months $R^2$ was greater than 50%; nevertheless, $R^2$ was not compared between models. The AIC values were used to compare between the goodness of fit of the models and the model with the lowest AIC values chosen.

The interaction of depth with latitude and SST during April, May, September, October, November and December appears to produce high AIC values; therefore depth was dropped as a parametric component. The significance p-values of GAM
for all months for depth also show that it did not have an effect on emperor abundance: the p-values were relatively high in all months except July.

Table 5-3 Degrees of freedom, p-values, $R^2$ and AIC values of the best GAM models fitted to emperor abundance (CPUE) for long-term averaged data by month

<table>
<thead>
<tr>
<th>Month</th>
<th>SST</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>Model-1</th>
<th>Model-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df</td>
<td>p-value</td>
<td>df</td>
<td>p-value</td>
<td>R²</td>
<td>AIC</td>
</tr>
<tr>
<td>January</td>
<td>4</td>
<td>0.000</td>
<td>5</td>
<td>0.000</td>
<td>1</td>
<td>0.006</td>
</tr>
<tr>
<td>February</td>
<td>2</td>
<td>0.373</td>
<td>6</td>
<td>0.000</td>
<td>1</td>
<td>0.090</td>
</tr>
<tr>
<td>March</td>
<td>1</td>
<td>0.000</td>
<td>7</td>
<td>0.000</td>
<td>2</td>
<td>0.120</td>
</tr>
<tr>
<td>April</td>
<td>1</td>
<td>0.046</td>
<td>3</td>
<td>0.006</td>
<td>7</td>
<td>0.035</td>
</tr>
<tr>
<td>May</td>
<td>2</td>
<td>0.523</td>
<td>1</td>
<td>0.154</td>
<td>6</td>
<td>0.001</td>
</tr>
<tr>
<td>June</td>
<td>4</td>
<td>0.138</td>
<td>6</td>
<td>0.129</td>
<td>1</td>
<td>0.676</td>
</tr>
<tr>
<td>July</td>
<td>5</td>
<td>0.000</td>
<td>6</td>
<td>0.000</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>August</td>
<td>2</td>
<td>0.000</td>
<td>6</td>
<td>0.000</td>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>September</td>
<td>4</td>
<td>0.000</td>
<td>4</td>
<td>0.050</td>
<td>3</td>
<td>0.009</td>
</tr>
<tr>
<td>October</td>
<td>4</td>
<td>0.052</td>
<td>4</td>
<td>0.027</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>November</td>
<td>4</td>
<td>0.000</td>
<td>4</td>
<td>0.000</td>
<td>3</td>
<td>0.080</td>
</tr>
<tr>
<td>December</td>
<td>4</td>
<td>0.000</td>
<td>4</td>
<td>0.000</td>
<td>1</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Key: $\xi$ = error for parametric component

The explanatory variable latitude shows an influence during January, February, March, April, July, August, November and December, when p-values were <0.001, while during April, May, June, September and October it did not have influence on emperor abundance, as p-values were > 0.001.

The explanatory variable SST can be seen to have no influence on emperor abundance during February, March, April, May, June and October, when p-values were < 0.001 (Table-5-3), whereas in July, August, September, November, December and January the SST did have an influence on long-term averages of emperor abundance, as p-values < 0.001.
The results of smoothing for the partial effect of SST, latitude, longitude and depth are demonstrated in Figure 5-5 (a-c) and are discussed here in detail. The GAM plots show the best fitting smoother with 95% confidence limits for the effects of explanatory variables on average emperor abundance (CPUE). The smoother for the partial effect of SST (Figure 5-5 a) shows a very slightly positive effect over a small range of SST between 24.5°C and 25.3°C. Figure 5-5 (a) for month of January also shows that emperor abundance was high between latitudes 17° N and 19° N, decreasing with increasing latitude above 20° N, which indicates a negative effect of high latitude. The smoother for the partial effect of longitude indicates increasing abundance with increasing longitude. Although there is only a slight indication of the effect of longitude, the most positive effect is between 57°.50' E and 58°.50' E.

During February the smoother for the partial effects of SST and longitude show no influence on emperor abundance, with p-values of 0.373 and 0.090 respectively (Table 5-3). In terms of latitude, the effect was similar to that during January: average emperor abundance decreased with increasing latitude (Figure 5-5 a c).

The best GAM models for average emperor abundance had a smoothing function for degrees of freedom of the explanatory variables, and depth was fitted as a parametric component (Table 5-3). It is also noticeable that during March and April the smoother for the partial effect of SST shows a negative effect (Figure 5-5 a) also shows that emperor abundance was high between latitudes 17° N and 20° N, which was a slightly extended location compared to January, with a decrease at increasing latitude above 20° N; this again indicates a negative effect of high latitude. Similarly, the smoother for the partial effect of longitude during March...
Chapter-5

indicates decreasing average emperor abundance with increasingly easterly longitude (Figure 5-5 a), while during April longitude was not highly influential.

During May and June the smoothers for the partial effects of SST, latitude and longitude indicate a negative effect for all these explanatory variables (Figure 5-5 b), except that during May longitude had a positive effect: emperor abundance increased with increasing longitude, as it had during January and February.

During July and August there was a clear positive influence of the explanatory variables SST, latitude, longitude and depth on average emperor abundance, except that during August depth had a negative effect (Figure 5-5 b).

During September the smoother for the partial effect of SST (Figure 5-5c) indicates that the strongest effect on average emperor abundance occurred between 24.5°C and 26.5°C, above which there was a negative effect. The smoother for the partial effect of latitude indicates that the greatest effect occurred above 22° N; while for longitude the most negative effect occurred above 59° E.

During October and November the smoother for the partial effect of SST (Figure 5-5c) indicates that the greatest effect on average emperor abundance occurred between 27°C and 28.5°C, while the smoother for the partial effect of latitude (Figure 5-5 c) indicates that most negative effect occurred at latitudes above 20° N. The smoother for the partial effect of longitude during October also shows a negative effect at longitudes above 58° E, whereas during November it was fitted as a parametric component.
Finally, the best model for the average emperor abundance during December contained a smoothing function for SST and latitude (df = 4), and longitude and depth were fitted as parametric components. The smoother for the partial effect of SST (Figure 5-5 c) indicates a positive effect between 26°C and 27°C, while that for latitude shows a negative effect where latitude is above 20° N.

In order to confirm that latitude and SST are the most explanatory variables in relation to emperor abundance, Model 1 was evaluated through a second model, Model 2. In Table 5-3, it can be clearly seen in Model-2 that $R^2$ dropped down significantly for every month except for June, which was same, and during October where $R^2$ was higher. Furthermore, AIC values were seen to increase, thus, the most important explanatory variables in the model are SST and latitude for the spatial distribution of emperor in this study area.
Figure 5-5 (a) Results of GAM smoothing curves (solid lines) with 95% confidence limits, fitted to partial effects of the explanatory variables on the response variable (CPUE) from January to April.
Figure 5-5 (b) Results of GAM smoothing curves (solid lines) with 95% confidence limits, fitted to partial effects of the explanatory variables on the response variable (CPUE) from May to August.
Figure 5-5 (c) Results of GAM smoothing curves (solid lines) with 95% confidence limits, fitted to partial effects of the explanatory variables on the response variable (CPUE) from September to December.
5.5 GAM fitted to *Lethrinus nebulosus*

This section provides a detailed description of models used for examining the relationship between maturation measured through the development of the reproductive organs (ovaries, testes) by the Gonado Somatic Index (GSI) and environmental factors such as SST, month, latitude, longitude, bathymetry, pH, dissolved oxygen (DO) and length of the *Lethrinus nebulosus* as explanatory variables, in order to explore the timing of the spawning season and to examine how these variables influence the spawning of this species.

Table 5-4 shows how models were constructed following a stepwise procedure, then compared with the final model by dropping predictors as parametric in the formula and selecting the final model in terms of the lowest AIC value (Ferguson *et al.*, 2005) and a high R$^2$ value. Table 5-5 lists the best model fits with month, total length and pH as the possible explanation for male and female GSI data for two years. The results indicate that the best fit of the GAM model occurs where pseudo R$^2$ is highest and AIC value is lowest.

**Table 5-4 Summary of the models used for males and females of *Lethrinus nebulosus***

<table>
<thead>
<tr>
<th>Model</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>GSI +s(Month) + s(Total-Length) + s(pH) + s (SST) + s (DO) + s (SSS)</td>
</tr>
<tr>
<td>Model 2</td>
<td>GSI +s(Month) + s(Total-Length) + s(pH) + s (SST) + s (DO) + SSS</td>
</tr>
<tr>
<td>Model 3</td>
<td>GSI +s(Month) + s(Total-Length) + s(pH) + s (SST) + DO + SSS</td>
</tr>
<tr>
<td>Model 4</td>
<td>GSI +s(Month) + s(Total-Length) + s(DO) + SST + pH + SSS</td>
</tr>
<tr>
<td>Males</td>
<td></td>
</tr>
<tr>
<td>Females</td>
<td>GSI +s(Month) + s(Total-Length) + s(pH) + SST + DO + SSS</td>
</tr>
</tbody>
</table>
**Table 5-5** Sequential goodness of fit of GAMs measured with GSI for males and females

<table>
<thead>
<tr>
<th>Models</th>
<th>exploratory variables</th>
<th>Male</th>
<th></th>
<th></th>
<th>Female</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R-sq</td>
<td>Deviance explained</td>
<td>df</td>
<td>p-value</td>
<td>AIC</td>
<td>R-sq</td>
</tr>
<tr>
<td>Model 1</td>
<td>Month</td>
<td>0.56</td>
<td>59.6%</td>
<td>7.1</td>
<td>3.87 e-05</td>
<td>0.76</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>Total length</td>
<td>3.1</td>
<td>&lt; 2.2 e-16</td>
<td>1</td>
<td>0.794</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>1</td>
<td>0.450</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>5.6</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>1</td>
<td>0.364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSS</td>
<td>6.5</td>
<td>1.32 e-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total length</td>
<td>8.3</td>
<td>&lt; 2.2 e-16</td>
<td>6.2</td>
<td>0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>4.5</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>9</td>
<td>2.75 e-15</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>7.5</td>
<td>&lt; 2.2 e-16</td>
<td>7.2</td>
<td>&lt; 2.2 e-16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total length</td>
<td>3.1</td>
<td>&lt; 2.2 e-16</td>
<td>6.2</td>
<td>0.016</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>2.1</td>
<td>0.271</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>2.1</td>
<td>0.271</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>6.9</td>
<td>2.17 e-05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total length</td>
<td>8.7</td>
<td>&lt; 2.2 e-16</td>
<td>8.5</td>
<td>&lt; 2.2 e-16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>5.6</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**5.5.1 Males**

Chapter 3 Subsection 3.4.2.2 indicated how the GSI was calculated; here, the same procedure will be applied to examine the GSI and testis phase representing the reproductive organs in detail in order to determine and to define the length at first sexual maturity and the spawning season of *Lethrinus nebulosus* males.
5.5.1.1 Gonado Somatic Index

Model 4 (Table 5-5) is the best GAM model for the male GSI, and the explanatory variables used are month, total length and DO, as indicated above. Generally, the temperature, salinity and pH variables do not have a significant effect on the GSI of males. The model used a quasi-Poisson distribution for males as the final formula, as shown below (1):

$$\text{GSI} \sim + s(\text{Month}) + s(\text{Total-Length}) + s(\text{DO}) + \text{SST} + \text{pH} + \text{SSS}$$  \hspace{1cm} (1)

The optimal GAM model for GSI contained smoothing functions by month (df = 7) total length (df = 8) and DO (df = 5). Salinity, temperature and pH were fitted as parametric components. The smoother for the partial effect on GSI of the month (Figure 5-6a) shows that the effect is relatively low during January and decreases to the strongest negative effect during March, while the most strongly positive effect is from the beginning of August to the end of October, immediately after which it decreases again. The model therefore indicates that in the Arabian Sea *Lethrinus nebulosus* is affected by seasonal factors.

The partial effect of total length (Figure 5-6b) increases with GSI (although non-linearly), with a point of starting maturity for *Lethrinus nebulosus* around 35 cm. This suggests that the maturation of *Lethrinus nebulosus* in the Arabian Sea starts at a length of 35 cm, while at a length of 60 cm GSI begins to drop. On the other hand, the partial effect of DO (Figure 5-6c) begins to increase at 6.5 mg/L and reaches a maximum at 7.5 mg/L, with a negative effect thereafter.
Figure 5-6 Partial plots of GAM smoothing curve, for best model of *Lethrinus nebulosus* male GSI fitted to partial effect of explanatory variables.

5.5.1.2 Testis phase

The results for testis phase show that the best model is the one with the highest $R^2$ (0.63) and lowest AIC value (0.79), while using as explanatory variables month, total length, SST and pH. The analysis shows almost the same results as for GSI, noted above, although the smoother for the partial effect of month indicates a slight difference from the GSI seasonal effect: for testis phase there are two
positive effect peaks, in May and from August to the end of September, with the most negative effect being observed during March. Thus the results indicate that the best GAM model for testis contained a smoothing function for month (df = 8), total length (df = 6), temperature (df = 7) and pH (df = 3), while salinity and DO were fitted as parametric variables.

The partial effect of total length (Figure 5-7b) on the testis phase was positive at around 35 cm. This result confirms that GSI maturation of *Lethrinus nebulosus* in the Arabian Sea starts at a length of 35 cm and falls off at 60 cm. On the other hand, the smoother for the partial effect of pH is negative at values higher than 8.5 (Figure 5-7c), while the smoother for the partial effect of SST indicates a negative effect occurring at SST of less than 25°C.

![Figure 5-7](image)

*Figure 5-7* Partial plots of GAM smoothing curve, for best model of *Lethrinus nebulosus* male testis phase fitted to partial effect of explanatory variables.
5.5.2 Females

5.5.2.1 Gonado Somatic Index

Having examined the GSI for males, this section will attempt to do the same for females. The best GAM fits for GSI in females indicates that the best model is the one with the highest $R^2$ of above 50%, although $R^2$ was 40% and deviance explained is higher than 50% with the lowest AIC value (Table 5-5). Indeed, model 4 is the best fit, with the explanatory variables of month, total length and pH, while SST, salinity and DO variables had no significant effect on GSI for females. The model used for females is a quasi-Poisson distribution (2):

$$GSI \sim + s(\text{Month}) + s(\text{Total-Length}) + s(pH) + \text{SST} + \text{DO} + \text{SSS} \quad (2)$$

The optimal GAM model for female GSI contained smoothing functions by month (df = 8), total length (df = 6) and pH (df = 6). Salinity, SST and DO were fitted as parametric components (Table 5-5). The smoother for the partial effect of month (Figure 5-8a) shows that from January to the end of July GSI has the strongest negative effect, while the strongest positive effect occurs from August to the end of October, immediately after which it decreases again. Comparing these results with the male model (Figure 5-6a) the same period of negative effect is seen. This clearly indicates a seasonal effect on GSI, with the partial effect of total length (Figure 5-8b) increasing with GSI. The starting point of the first sexual maturity for females is the same as that for male maturity, at a length of around 35cm. Nevertheless, the smoother for the partial effect of pH (Figure 5-8c) shows that it is negative at pH values above 7.8, as seen in the case of males.
Figure 5-8 Partial plots of GAM smoothing curve for best model of *Lethrinus nebulosus* female GSI fitted to partial effect of explanatory variables

5.5.2.2 Ovary phase

The results for the ovary phase point to the best model being that with the highest $R^2$ of 0.62 and the lowest AIC value of 0.79. The best GAM model for the ovaries contained a smoothing function for month (df = 8), total length (df = 7), SST (df = 3), pH (df = 5) and SSS (df = 5), while DO was fitted as a parametric variable.

The analysis of the best GAM fits for ovaries in females were observed when using as explanatory variables month, total length, SST, pH and SSS. The results
were similar to the smoother for partial effect of month for both GSI females and males and also for the testis results. Three major results can be observed from this analysis. First, the most positive effect occurred from August to the end of September (Figure 5-9a). Second, the partial effect of total length (Figure 5-9b) on the ovary phase was also positive around 35 cm. These results clearly indicate that the maturation of *Lethrinus nebulosus* in the Arabian Sea starts at a length of 35 cm and falls off at 60 cm. The third observation is that the smoother for the partial effect of pH (Figure 5-9c) showed it decreasing with a negative effect of 8.3; that for the partial effect of SST also showed a negative effect below 26°C, while for SSS it was clear that it did not have any significant effect on the ovary phase (p-value = 0.04) (Figure 5-9e).
Figure 5-9 Partial plots of GAM smoothing curve, for best model of ovary phase fitted to partial effect of explanatory variables
5.6 Two stage modelling for prediction distribution of emperor in the Arabian Sea to compare, validate and assessing the accuracy of models.

The aim of this section is to examine a complete view of the monthly distribution patterns of emperor abundance. The models used in this section will estimate the probability of emperor presence on a geographic basis and will examine their actual presence in the Arabian Sea.

5.6.1 Data to predict distribution

Data sets for 1996-2004 were utilised for the two stages of analysis, binomial and Gaussian. First the CPUE data was converted to binary form and used with five environmental variables to predict presence. Then data with non-zero CPUE was used as present abundance. Chapter 3, Section 3.5 sets out the method which is followed in this section.

Table 5-6 shows the best GAM models using binomial and Gaussian error distribution of fishery data for 1996-2004 and the most significant explanatory variables in the models. These data will be compared with independently observed data for 2005.
Table 5-6 List of Binomial and Gaussian error distribution GAM approaches for the period 1996-2004 and best $R^2$ for the best GAMs fitted to CPUE (kg/day)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Binomial</th>
<th>Gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2 = 15$</td>
<td>$R^2 = 25$</td>
</tr>
<tr>
<td></td>
<td>AIC = 0.98</td>
<td>AIC = 424</td>
</tr>
<tr>
<td>df</td>
<td>p-value</td>
<td>df</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>-------</td>
</tr>
<tr>
<td>Month</td>
<td>4</td>
<td>3.4951e-05</td>
</tr>
<tr>
<td>SST</td>
<td>6</td>
<td>&lt; 2.22e-16</td>
</tr>
<tr>
<td>Longitude</td>
<td>7</td>
<td>5.1351e-06</td>
</tr>
<tr>
<td>Latitude</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>Depth</td>
<td>2</td>
<td>8.927e-10</td>
</tr>
<tr>
<td>Gaussian</td>
<td>CPUE ~ + s (Month) + s (Latitude) + s (Longitude) + s (Depth) + s (SST)</td>
<td></td>
</tr>
<tr>
<td>Binomial</td>
<td>PA ~ + s (Month) + s (Latitude) + s (Longitude) + s (Depth) + s (SST)</td>
<td></td>
</tr>
</tbody>
</table>

5.6.1.1 Presence and absence model (binomial) for 1996-2004

For the binomial approach, the percentage of variance $R^2$ in emperor occurrence explained is 15%. For binomial error distribution, GAMs fitted to emperor CPUE shows that in the optimal GAM for month, df = 4 and p-value < 0.001. The smoother for partial effect of month indicates that it is an important variable with a seasonal effect, the most positive effect being in August and October, and the most negative effect in March and April (Figure 5-10). The optimal GAM for SST has df = 6 and p-value < 0.001 (Table 5-6). The smoother for partial effect of the SST variable also shows that it is an important factor and the most significant variable in this model; and it seems that the emperor preferentially occurs in areas where SST ranges between 25 and 27°C. The longitude is also significant (df = 7 and p-value < 0.001) (Table 5-6); a positive effect on CPUE occurs between longitude 57°.50' E and 58°.50' E. Neither latitude nor depth were important explanatory variables, however (df = 2 and p-value > 0.001).
Figure 5-10 Results of GAM regression binomial of CPUE 1996-2004. Effects of explanatory variables (a) month (b) SST (c) latitude (d) longitude and (e) depth.
5.6.1.2 Abundance CPUE 1996-2004 model (Gaussian)

For the Gaussian approach the percentage of variance $R^2$ in emperor occurrence explained is 25%. For Gaussian GAMs fitted to emperor CPUE, the smoother for the partial effect of month (Figure 5-11a) indicates a seasonal effect at its most positive from August to October, with a negative effect occurring in March and April; it seems to be an important variable (df = 5 and p-value < 0.001). Regarding the smoother for the partial effect of SST (Figure 5-11b), this indicates a positive effect in the range between 25 and 27°C. The SST variable seems to be the most important in the Gaussian model for the spatial distribution of emperor (df = 8 and p-value < 0.001) (Table 5-6). On the other hand, none of the three explanatory variables latitude, longitude or depth was important in terms of error distribution or of p-value.
Figure 5-11 GAM regression Gaussian of CPUE 1996-2004. Effects of explanatory variables (a) month (b) SST (c) latitude (d) longitude and (e) depth
5.6.2 Probability monthly distribution prediction for independent data for year 2005

Environmental data for 2005 was used to predict monthly probabilities of presence and estimates of abundance by using two GAM approaches (binomial, Gaussian) for presence abundance and a quasi-Poisson model was used to validate these two models.

Table 5-7 Results of binomial tests to compare probability prediction of occurrence both GAM models Gaussian and quasi-Poisson for independent year 2005

<table>
<thead>
<tr>
<th>Variable</th>
<th>Binomial</th>
<th>Gaussian</th>
<th>Quasi-Poisson</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2 = 20$</td>
<td>$R^2 = 20$</td>
<td>$R^2 = 40$</td>
</tr>
<tr>
<td></td>
<td>AIC = 1.2</td>
<td>AIC = 1.98</td>
<td>AIC = 0.96</td>
</tr>
<tr>
<td>df</td>
<td>p-value</td>
<td>df</td>
<td>p-value</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>Month</td>
<td>$\epsilon$</td>
<td>$\epsilon$</td>
<td>5</td>
</tr>
<tr>
<td>SST</td>
<td>5</td>
<td>3.7468e-07</td>
<td>5</td>
</tr>
<tr>
<td>Longitude</td>
<td>8</td>
<td>0.000</td>
<td>7</td>
</tr>
<tr>
<td>Latitude</td>
<td>4</td>
<td>0.017</td>
<td>$\epsilon$</td>
</tr>
<tr>
<td>Depth</td>
<td>6</td>
<td>0.004</td>
<td>$\epsilon$</td>
</tr>
</tbody>
</table>

Key: $\epsilon$ = error for parametric component

Table 5-7 shows the results of the binomial model used to estimate and compare the probability of occurrence of two GAM models, Gaussian and quasi-Poisson. The SST effect is present in all three models. The optimal three GAM models for CPUE contained a smoothing function for SST (df = 5 and p-value > 0.001) (Table 5-7). The smoother for the partial effect of SST (Figure 5-4c) indicates that the SST has a positive effect on CPUE between 25°C and 27°C (Figure 5-12c), which
means that the most positive effects of SST on emperor abundance are again in the range between 25°C and greater than 26°C. The probabilities were divided into 5 groups from 0 to 1. Figure 5-12 shows the probability prediction estimates of emperor abundance distribution for 2005.

**Figure 5-12** GAM fitted to presence/absence, Gaussian and quasi-Poisson models, fitted to partial effects of predictor variable SST for emperor abundance year 2005
5.6.3 Mapping probability, prediction and estimated expected abundance

Once the models had been generated, the CPUE index of emperor was interpolated by applying the fitted model absence and presence, exported from R to ArcGIS, to illustrate seasonal variation. Figure 5-13 shows the spatial interpolation of model outputs of the distribution of probability of emperor presence for each month of independent year 2005. Seasonal distribution patterns can be seen in Figure 5-13: during September, October, December and January there is high probability, in a sequence interrupted only by the month of November, when the probability is low, as it is in the remaining months, particularly March, May and June.

On the other hand, Figure 5-14 shows the spatial interpolation of predictions provided by the model output of CPUE (kg/day). Again, a seasonal distribution pattern can be seen: predictions of CPUE more than 1 kg/day are more abundant from August to January, while between February and July the predictions of CPUE are lower, except during June.

The estimated expected abundance patterns (multiplying absence/presence by abundance in kg/day) are quite similar to the predictive abundance, with high values between August and January. These results suggest that there is a strong seasonal effect on emperor distribution, as shown in Figure 5-15.

Furthermore, spatial interpolation of the model output predictions of emperor abundance for fish data 1996-2004 using model quasi-Poisson, also was clear that there is potential patterns of seasonal distribution of abundance in the Arabian Sea (Figure 5-16). This clarifies that environmental variable of great important to emperor distribution abundance.
Figure 5-13 Map of probability distribution (presence/absence) estimated by month from January to December using GAM binomial distribution for independent data 2005
Figure 5-14 Map of prediction of relative emperor abundance (CPUE kg/day) from January to December using the GAM Gaussian distribution for independent data 2005
Figure 5-15 Map of expected emperor abundance from January to December multiplied probability by prediction independent data 2005
Figure 5-16 Map of prediction of relative emperor abundance (CPUE kg/day) from January to December using the GAM quasi-Poisson distribution, fishery data 1996-2004
5.6.4 Assessing the accuracy of the models

This section examines the accuracy of the models' spatial and temporal predictions against fishing operation records, comparing predicted with actual values. Assessing the accuracy of the predictive models as described in Section 5.6 above is essential in examining any model errors produced from fishing records. This process was undertaken in respect of the Gaussian model used to predict emperor abundance for each fishing block. Figure 5-17 presents the relationship between predicted abundance and average trawler CPUE; the predicted abundance, shown on the X-axis, ranges between zero and above ten kg/day. From Figure 5-17 the model appears to perform reasonably well, because could be assumed that when the CPUE is low, the prediction also is low.

Figure 5-17 Relationship between predicted abundance of emperor from the Gaussian model and catch per unit effort from trawlers catch in the Arabian Sea independent year 2005.
5.7 Discussion of GAM results and the relationship with the distribution of emperor abundance on a quantitative basis

The approach used to analyse the quantitative description of spatial and temporal distribution of emperor abundance in relation to environmental variables was through generalised additive models (GAMs). The GIS technique was then used as an auxiliary to provide information that could not be seen from the statistical GAM analysis.

The use of GAM in this study allowed the visualisation of often non-linear relationships between explanatory variables on one hand and on the other nine-year means, monthly long-term averaged data and maturation parameters. The results were found to be interesting for the Arabian Sea. The GAM models demonstrate that the relationships between abundance and both SST and latitude are positive, highly variable and non-linear, with high abundance values at SST between 25 and 27°C and low values at SST less than 24°C.

Further approach has been taken is GAM models applied describe relationships between to maturation and environment variables in *Lethrinus nebulosus*. The $R^2$ explained 61.7% of variation in the response variable for males and 52% for females. Variation in the GSI was significantly affected by season for males and females (p-value < 0.001), month and total length being the most important explanatory variables. The spawning period of *Lethrinus nebulosus* was well defined following the SW monsoon during September and October, when the water temperature was between 25 and 27°C, and then declined progressively in November. This offers support to some studies which have connected the
spawning patterns to seasonal conditions and food supply (Thangaraja, 1995; Robertson, 1991). In both males and females, GSI continued to increase with increasing total length, starting at 35 cm, which could be interpreted as an indication of the growth of emperor and maturation through life. In this study, it appears that spawning and environmental conditions are significantly correlated. This confirms the results of Thangaraja and Al-Aisry, (2001), who found that the peak abundance of *Lethrinus* eggs and larvae was in warmer water. Their findings also indicted that the Arabian Sea is a good spawning ground. However, it could be concluded that SST was not a significant factor in the spawning of *L. nebulosus*. In addition, the observed match in the GSI peaks between the two sexes indicates no significant difference (p-value > 0.05), indicating that this species is protogynous and protandrous, these finding also supported by the view of Grandcourt *et al.*, (2006).

The two-stage GAM modelling approach also aimed to explain emperor distribution and abundance. Results indicate that environmental variables do influence distribution and abundance in the Arabian Sea. In particular, the effect of SST is associated with the effect of upwelling (Morrison, 1997). Higher catches of emperor were predicted from September to January in the Gaussian model and also the estimated abundance. The presence/absence model also found the CPUE of emperor to be highest during the same months. These results suggest that the emperor has a preferred range of temperature around 25°C to 27°C; thus, abundance increases in the Arabian Sea under favourable SST conditions. These results support the earlier analysis in Sections 5.3 and 5.4 which showed that emperor has preference for a water temperature of 27°C.
Using presence/absence and presence only models is very useful for avoiding the problem of controlling the large proportion of zero values in the data. This model for the first time allowed prediction of the probability distribution of emperor abundance in the Arabian Sea on the basis of monthly data for 2005 and monthly average data for nine years. Therefore, modelled monthly data for 2005 provide an estimate of abundance distribution using spatial environmental datasets. Results from GAM models and GIS output of both datasets – mean values for the nine years 1996-2004 and independent data for 2005, suggest that the predictions of emperor occurrence in the Arabian Sea were higher from August to January, where there is great seasonal change, whereas in the monsoon season between April and late July abundance was low; and this could be an indication of the influence of upwelling on emperor distribution and abundance. The results from the GAM models were clear and suggest that a factor affecting distribution and abundance of emperor in the Arabian Sea is SST that emperor preferred a range of SST between 25 and 27°C. The other variable was significant for emperor distribution and abundance is georeferenced location (latitude).

Indeed, the combination of GIS and GAM analysis methods has an important approach for spatial and temporal analysis in this study, in understanding, prediction and visualization of emperor resources in relation to environmental variation in spatial and temporal measurements. All model results indicate that emperor abundance is correlated positively with SST and geographic location. The presence or absence as well as the abundance of emperor in this study area are determined by temporal environmental variables. A major observation from a synthesis of the model results is that high CPUE for emperor occurred at SST between 25 and 27°C. These findings support previous studies that emperor prefer
water at a temperature of 27°C (McIlwain et al., 2006; Forster, 1984; Newman and Williams, 1997). The likely causal mechanisms linking SST and abundance of emperor, which dwell on the sea floor, is monsoon.

The seasonal monsoon in the Arabian Sea could be the significant factor with respect to the emperor spatial and temporal distributions. All these findings relating to environmental conditions and emperor abundance, suggest that GIS and GAM are more informative technique than traditional regression for exploring and testing spatial relationships between emperor CPUE and the environment and geographical attributes could explain an important for the distribution patterns, the high emperor CPUE at latitude between 17° and 20° N and longitude 57°.50' and 58°.50' E.

Furthermore, the finding of relationships between the environmental variable, geographical location and emperor distribution abundance allow a prediction of abundance of these species. The latitude effect is thought to indicate favourable fishing grounds (see Figure 5-4 e and Figure 5-10). The models applied in this study explained a significant percentage of the variation in presence and abundance of emperor in the areas where the species was recorded. GAM models yielded $R^2 = 20\%$ for binomial and Gaussian distributions whereas quasi-Poisson gave an $R^2 = 40\%$, and the AIC value for quasi-Poisson was the lowest. This indicates that the quasi-Poisson distribution performs forms best model. Also, this model allows the evaluation of possible fundamental mechanisms underlying possible relationships and suggests that successful fishery prediction is a realistic target.
5.8 Summary

This chapter has analysed quantitatively the spatial and temporal distribution of emperor abundance in the Arabian Sea, derived from CPUE data for both traditional and trawler fisheries for 1996-2004 in relation to environmental variables: sea surface temperature, depth, latitude and longitude, using both generalised additive models and GIS.

GAMs were fitted to average CPUE for nine years, long-term average CPUE for trawler catch, two years' biological data and independent year 2005 catch data. GAM fitted to the data for the Arabian Sea shows that the partial relationships between SST, latitude and emperor apparently have an important influence on the spatial distribution of emperor, especially from September to January, where the SST is between 26°C and 28°C, when emperor abundance is high, and from April to July, when the relationship between emperor abundance and SST is negative.

Variation in GSI was significantly affected by season for both males and females. GSI peaked in the spawning season, which occurred during September and October. The maturity of *Lethrinus nebulosus* starts when individuals are around 35 cm in length.

According to the presence and absence model, the probability of occurrence of emperor is widespread in all months, but is greatest from September to January; at sea surface temperatures between greater than 25°C and 27°C. The prediction model indicates a large abundance of emperor in the Arabian Sea corresponding roughly to the original data for 1996-2004, predicting high abundance during June, August, September, October, December and January.
Chapter 6 : Conclusion

6.1 Introduction

This research has presented a number of important results and a number of issues have been highlighted which need to be carefully considered in relation to the spatial and temporal distribution of emperor in Omani waters. This study had three main objectives: first, to identify the spatial and temporal distribution patterns of emperor in Omani waters; secondly to examine the relationships between emperor distribution and environmental factors such as sea surface temperature, salinity, bathymetry and geographical location; and thirdly to identify the spawning season of the *Lethrinus nebulosus* and examine the relationships between maturation and environmental factors.

This chapter presents an overall summary of the different aspects of this study. Two major areas are covered: preparation of the marine fisheries database, in Section 6.2, and progress achieved in this study, in Sections 6.3, 6.4 and 6.5, as follows.

➢ A general spatial and temporal description of the distribution of emperor abundance in Omani waters and in particular in the Arabian Sea, using the GIS technique;

➢ An examination of the relationships between abundance and environmental variables in the Arabian Sea, using GAM as a statistical tool, and identification of the spawning season of *Lethrinus nebulosus*;

➢ The importance of this study to the management of fisheries.
The chapter closes with a number of suggestions for future work to improve understanding of the spatial and temporal distribution of emperor or other marine fish, in Section 6.6.

6.2 Database management system

In developing this research study, an effort was made to include data from a wide variety of sources by collecting data from both traditional and industrial types of fishery, for a period of nine years, as well as bathymetric and environmental data such as sea surface temperature (SST) and salinity (SSS). The problems associated with the aims of this study were discussed in the Chapter 3 section on database design. This research gathered two types of fishery data from January 1996 to December 2004, and two years of biological data for Lethrinus nebulosus from January 2001 to December 2002. Methods of preparation of both types of data fishery and biological data were given in Chapter 3. The idea of using MS Access 2003 was to store and hold the spatial, temporal and attributes data and was successful, because each type of data was collected and formatted differently, as discussed in Chapter 3. Additionally, ArcGIS was used to store organise the spatial data with environmental SST, SSS and depth data. The data for both types of fishery were then linked into ArcGIS and overlaid with environmental data in order to produce spatial and temporal maps of emperor abundance. The results are summarised in Section 6.3
6.3 Spatial and temporal distribution of emperor abundance in Omani waters: GIS analysis

This study systematically analysed the spatial and temporal distribution of emperor in relation to environmental variables in the Sultanate of Oman waters, with particular reference to the Arabian Sea, based on data from both traditional and commercial fisheries, using the Geographical Information Systems (GIS) technique.

The spatial and temporal analysis reveals important environmental characteristics of the emperor habitat, whose seasonal changes affect emperor abundance in the Arabian Sea. The seasonal and spatial patterns of emperor abundance also illustrate differences within the study area. A very interesting SST characteristic was found in the Arabian Sea with respect to the spatial location of the catch per unit effort (CPUE). The CPUE of emperor was higher in the Arabian Sea than in the Gulf of Oman, particularly in the northwest of the Arabian Sea between latitudes 17° and 19° N and longitudes 55° and 57° 30' E. Temporal analysis revealed that between April and late June emperor CPUE for both types of fishery indicates low abundance along the coast of the Arabian Sea for a variety of reasons.

6.3.1 With sea surface temperature

GIS analyses of the spatial SST patterns show that there are clear differences in SST values between the Arabian Sea and the Gulf of Oman during winter and summer. In winter the temperature in the Arabian Sea is much higher than in the
Gulf of Oman. For example, during July SST values were very clearly different in the two locations.

SST is affected by other environmental variables and this area is in particular characterised by two types of monsoon, which is consistent with the reports by Bohm *et al.*, (1999) and Schott *et al.*, (2002), who describe the seasonality of the upwelling that occurs in the Arabian Sea. The relatively low SST in the Arabian Sea in summer time may be a sign that the SST is greatly affected by the upwelling phenomenon.

The qualitative GIS analysis reveals spatial and temporal relationships between the distribution of emperor abundance in the Arabian Sea and seasonal variation in SST, whereby monthly long-term averages of emperor abundance are positively related to monthly long-term averages of SST data. Thus, CPUE for trawlers reaches high values of more than 100 kg/day at temperature values between 25°C and 27°C, and CPUE for the traditional fishery exceeds 100 kg/trip. Between April and June, by contrast, the CPUE is low for both types of fishery, declining to less than 10 kg/trip or /day at temperature values less than 25°C. This concurs with the findings of authors who have reported high emperor abundance at average temperatures between 24.3°C and 27.8°C (Newman and Williams, 2001b). Furthermore, high CPUE for both types of fishery between September and December in the Arabian Sea may be related to rich nutrients and food availability, because after the SW monsoon in the study area the primary productivity (nutrients) is rich in after the SW monsoon (Kumar *et al.*, 2001; Thangaraja, 1995).
Several researchers have described relations between temperature and distribution abundance for various marine species (Peirce, 1998; Bellido, 2002; Zheng, 2001; Begg and Marteinsdottir, 2002) and suggested that seasonal cycles linked to environmental variables constitute an important factor in explaining the variability in distribution and abundance of marine species. Nevertheless, it has to be pointed out that this current study is the first to describe the spatial and temporal distribution of emperor in Omani waters and to present evidence of the effects of SST on emperor distribution in the Arabian Sea.

6.3.2 With sea surface salinity and depth

Although the spatial relationships between SST and emperor distribution and abundance were clear and visible, it was also important to examine other environmental variables such as SSS and depth. The spatial relationship between emperor distribution and SSS was negative and non-significant. This reflects other studies on spatial patterns of other demersal species such as cod, where salinity was not found to be an important factor (Begg et al., 1999). Pierce and Boyle, (2003) also found that SSS was not a significant variable for the abundance of squid.

As for depth, it was found that in all seasons emperor were concentrated in areas where the depth is less than 200 metres. This finding is supported by the literature reporting that the emperor species usually occurs in waters of depth less than 100 metres (Carpenter and Allen, 1989; Randall, 1995; Al-Abdessalaam, 1995; Sato, 1978). Other studies have found that depth is a significant factor for species such as cod (Begg and Marteinsdottir, 2002). However, it is very difficult to separate the effects of physical and biological factors from those of human activities on the
spatial and temporal distribution of emperor, because as mentioned before, local fishermen are fishing throughout the year and they do not have the equipment necessary to fish in deeper water areas more than 20 nautical miles from their landing ports. Thus, at this stage it was difficult to conclude that depth is a significant variable, and a further analysis was undertaken to examine how the depth variable has influenced the emperor distribution.

6.4 Examining the relationships between fish abundance and environment variables using GAM analysis

It was essential to examine the influence of environmental variables, to analyse the quantitative relationships between environmental variables and emperor abundance for the nine-year datasets, then to test the datasets in the different theoretical distribution models which were developed: quasi-Poisson, binomial and Gaussian.

6.4.1 GAM fitted for fishery data 1996-2004

Preliminary results for both types of fishery from scatterplot analysis confirmed that there was non-linearity in the relationships between CPUE and environmental variables. They also suggested that emperor CPUE was high from August to November, with lowest values from May to June. Furthermore, high emperor abundance was associated with an SST range between 24°C and 28°C.

Results from both the GAM fitted analysis using a quasi-Poisson distribution, for the 1996-2004, and the monthly long-term average datasets show that percentage of deviance explained (pseudo-$R^2$) is greater than 50%, which means that the
explanatory variables appear to affect the spatial distribution of abundance. There is a strong seasonal effect in both datasets: high CPUE was found during the period from August to January; in addition, the GAM model revealed that the relationship between emperor abundance and SST is nonlinear, with highest values of CPUE being found for SST between 25°C and 27°C. Previous studies showed that emperor preferred to live within this same range of temperature (McIlwain et al., 2006). A measure of geographic location, latitude, was also a significant covariate affecting the spatial distribution of the abundance of emperor: in both types of datasets emperor abundance was greater between 17° and 20° N. Evidence from the fitted GAM models shows adequately that the suggested relationship of emperor CPUE with these two variables was rather stable in different models.

6.4.2 GAM fitted for Lethrinus nebulosus (spawning season)

GAM techniques have only recently been employed to examine the maturation process; even now, very few marine biologists studying spawning have so far applied the GAM method in marine species such as squid (Smith et al., 2005; Sacau et al., 2005). To date, published work detailing emperor fish spawning aggregation and spawning behaviour has been based on few species and different ways of applying the methods. Using GAM models allowed for the first time the application of quantitative patterns to the analysis of Lethrinus nebulosus maturity in order to describe relationships between maturation and environmental variation in the Arabian Sea.

From the GSI results for both males and females, a clear seasonal effect emerges, the highest maturity stages were found in September and October. From previous
Chapter-6

studies, *Lethrinus nebulosus* spawning has been reported to be from October to December in the Arabian Sea (McIlwain et al., 2006), which suggests that emperor mature one month later than has been found in this study. Furthermore, the Arabian (Persian) Gulf was defined as the spawning ground during April and May (Grandcourt et al., 2006).

### 6.4.3 Two-stage model to predict distribution monthly average of emperor CPUE in the Arabian Sea

The spatial distribution patterns of fishery data and monthly long-term averages of emperor in the Arabian Sea were found to be significantly related to environmental variables over nine years. Two-stage GAMs have also been used in this study to explain the distribution of emperor CPUE. As suggested by Barry and Welsh (2002) and Barratt et al. (2002), modelling firstly with binomial and then Gaussian or Poisson could avoid the problem of zeros values.

The results of analysis of two models Binomial and Gaussian demonstrate which variable has the most influence on the patterns of probability and prediction of species abundance. The GAM results show that SST and month are the variables most strongly affecting the probability distribution (p-value < 0.001) and that the highest probability of emperor presence is at SST ranges between 25 and 27°C.

### 6.4.4 Monthly probability distribution and prediction for independent data 2005

Modelling allowed the prediction of spatial distributions for 2005 on a monthly spatial basis, and the results were compared with presence as indicated by 1996-
2004 fishery data. From these models the seasonal distribution patterns were clear and quite similar. GAM modelling of fishery data using the monthly long-term average, monthly mean average 1996-2004 and independent data 2005, showed consistent results in the Arabian Sea, the spatial distribution of emperor is positively related to SST and geographical location. The probability of presence was positive throughout the year, but the predicted abundance was highest from August to January. Results from predicted maps of expected abundance for 2005, when compared with maps predictions of quasi-Poisson for 1996-2004, fit quite well in terms areas of both low and high prediction.

However, it should be noted that there is the potential for other types and life stages of emperor to respond to different environmental factors, specifically SST and depth variables. This would also affect these models and the resultant spatially interpolated predictions of abundance, which reflect the relative availability of emperor with respect to variation in the fishing activities. Hence, there would be changes in predictions in space and time indicated in the relative availability of emperor. This study paid particular attention to the GAM modelling results of Subsection 5.6 showing that the best error model fits for the data in this study between the three error models Binomial, Gaussian and quasi-Poisson was quasi-Poisson.

Results from the GAM supports the GIS evidence that SST and latitude variables are the main environmental factor in this study area, among those analysed affecting the distribution and abundance in both types of datasets. However, in the Arabian Sea the effect of SST could be associated with the effects of upwelling in this study area. Indeed Weller et al., (1998) suggested that the temporal and
spatial changes of SST in the Arabian Sea are because of upwelling by the water circulation. Therefore, in the monsoon season sea temperature is uniform at a depth greater than 30 metres because of mixed layers.

6.5 The significance of this study to fisheries management

The analysis of the spatial and temporal (seasonal) distribution of commercially important species presented in this thesis has provided a range of very important information for the fisheries sector, because the two different fishery sectors in the Sultanate of Oman, artisanal and commercial (trawlers), involve different levels of management, such as protecting fishing areas, limiting fishing seasons and exploring new fishing areas.

Marine scientists often assess habitats to understand the distribution and relative abundance of marine resources. Because of the spatial nature of habitats and associated temporal changes, however, assimilating data using traditional analytical methods is often difficult. Geographic information systems are proving to be effective tools in helping to address problems inherent in the analysis of spatial data. GIS can be used to effectively collate, archive, display, analyze and model spatial and temporal data. Additionally, by combining dissimilar data types, such as socio-political boundaries, sea bed types and fish distributions, for example, resource managers can use GIS to make informed management decisions. In this way, GIS provides resource managers with a means to integrate scientific data with prevailing cultural values and traditions. This study has linked terrestrial and marine data to create a broad spatial and temporal database that will be used in a variety of ways such as evaluating natural processes, permitting and monitoring coastal development and assessing environmental impacts.
6.6 Future related research possibilities

Although the research presented in this study was based on fishery data, which could be biased to some extent because of mis-reporting and the fact that some important data on environmental variables is missing, it was able to highlight important information on the emperor, as concluded earlier. Thus, it is appropriate to make suggestions for future research which could improve the work in direct relation to the methods used this study. In addition, a number of further research studies using GIS and statistical techniques, which need not be directly related to emperor but to other demersal species, or indeed any other marine resources, will be suggested as follows:

➢ Further research should extend the investigation the distribution of individual emperor species.

➢ This study has indicated spatial heterogeneity, therefore, in order to reveal spatial heterogeneity in the distribution of emperor at different life stages in Omani waters it is suggested for follow up studies to utilise survey data; using this method could be useful to identify areas where juvenile fish are concentrated and suggest appropriate restricted areas and closed seasons.

➢ For the traditional fishery, different types of data should be collected according to the different species, such as type of gear, numbers of crew, engine power and hours of fishing. Such information might provide a more precise basis for the calculation of CPUE.
Future analysis should use only one type of fleet and one type of gear, which would be more efficient.

Recording the location of fishing activity by global positioning systems is very important for the spatial and temporal distribution of fish, because it gives better location accuracy (Meaden and Kemp, 1997; Rogers and Bergersen, 1996).

Recording other data for commercial vessels, such as depth at which fish have been caught, trawling speed, time of trawling, size of the gear and mesh, are also important for calculating CPUE.

It would be useful to examine fishing grounds where there was no fishing activity at all. This could help to find out if there is any species in other places.

There are a number of limitations to use fishery data since it may be misreported. Therefore, it is suggesting for further analysis should be performed on a combination of commercial and other fish survey data, to provide a better understanding of the species habitat.

Records should be kept of monthly temperature, salinity, dissolved oxygen and depth of water at the time of fishing activities in particular with commercial vessels.
Exploiting three-dimensional graphics is important to address some of the fundamental problems limiting the scalability of two-dimensional displays.

From a biological perspective, the findings here suggest that further research taking into account the relative age of emperor (to provide the relationship between age and maturation) might be fruitful. If, for example, emperor are more vulnerable to capture during spawning aggregations, the prevention of over-harvesting in that particular period would be a consideration within a sustainable management plan (Al-Kharusi and Jarvis, submitted).

Finally, this research highlights for the first time a set of conditions in the Arabian Sea allowing us to present the situation of commercial and artisanal emperor catch data in the Sultanate of Oman. In addition, this study has examined and compared these estimation distributions with actual catch of emperor as a measure of abundance. The application of GIS and GAM shows the benefits that could be derived from the use of such tools, in order to achieve the maximum advantage from them, although research is currently still in its early stages with respect to incorporating other environmental variables such as wind, sea bottom temperature and sea bottom salinity at the actual time of fishing.

It is hoped that the analyses presented in this thesis will help to persuade decision makers in the fisheries sector of the benefits that could be obtained from the wider use of GIS. The wider benefit to the Sultanate of Oman of a more effective system is that it will improve the likelihood of the right decisions being taken.
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Classification of subfamilies and genera of family Lethrinidae (Carpenter & Allen, 1989).
**Appendix 2:**

Traditional Fishery, number of fishermen and boats by Wilayat

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<tr>
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231
Table: Schedules for collecting artisanal data per month (MAF, 2004)

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<td>Muttrah</td>
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<td>Quriyat</td>
<td>7 times am &amp;pm</td>
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<td>Quriyat</td>
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<tr>
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<td>Muttrah</td>
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</tr>
<tr>
<td></td>
<td>Shinas</td>
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<td>Al-Batinah</td>
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</tr>
<tr>
<td></td>
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<td>10 times am and 4 times on beach seen am - pm</td>
</tr>
<tr>
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<tr>
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<td>11 times am and 4 times on beach seen am - pm</td>
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<td></td>
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<td>Al-haffa</td>
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Appendix 4:

Calculations for estimating artisanal fishery catch and effort

A) Example for Daily Monthly catch and CPUE

1) Example for the daily catch:

Total catch estimation in one Wilaya by species, boats, fishermen and participation rate of fleet in species.

Date of sampling: 5/09/1993, Sampling site: Muttrah, Fishing boat: Fibreglass

Species sampled: emperor

Table shows data recorded for on particular day in landing site (Muttrah)

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Estimation of emperor during day 05/09/1993:

Total catch * total landing boats/sampled boats = Catch/day =

395*60/20 = 1185 kg

Estimating numbers of FG boats landings emperor

Boats recorded the catch * landing boats/ sampled boats = Number of boats/day =

5* 60/20 = 15 boats

Estimation numbers of fishermen landing emperor

Total number of crew * landing boats/ sampled boats = Number of fishermen/day =

12*60/20 = 36 fishermen

Participation rate of the fleet in fishing emperor

Numbers of boats recorded the catch per day/ total boats at landing site =

Participation rate =

15/140 = 0.107 P
2) Estimation for monthly catch

Example for the monthly estimation in Muttrah: species, boats, fishermen and participation rate of fleet in species

Total catch at landing site * total days in a month / total sampled days at landing site

Total catch/month = (1185 + 2251 + 2199) * 30 / 3 = 56345 kg

Estimation numbers of boat-days landing

Total numbers of sampled boats * total days in a month / total sampled days at landing site

Total boats/month = (15 + 18 + 18) * 30 / 3 = 1220

Estimation mean Participation rate of the fleet in fishing

Total Participation rate / total sampled days at landing site.

The participation rate/month = (0.107 + 0.129 + 0.129) / 3 = 0.1217

3) Example on daily catch effort

On 16-04/00 the data collector in Al-Batinah region observed 48 boats landed in Barka. He sampled 16 of boats; two of the sample boats landed emperor used drift gill nets. The estimation of catch effort and value of each species by boat type, gear type and area for daily calculation as follows:

Table shows two of sample boats landed Yellowfin Tuna used same gear type

<table>
<thead>
<tr>
<th>Number-of sample-boats landing</th>
<th>Catch of sample</th>
<th>Number-of gear units-on sampled boat</th>
<th>Number-of fishermen-on sampled boat</th>
<th>Number-of boat hours on samples boats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellowfin tuna</td>
<td>Boats</td>
<td>Value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10.8</td>
<td>11.880</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>10.0</td>
<td>12.500</td>
<td>7</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td>20.8</td>
<td>24.380</td>
<td>13</td>
<td>4</td>
</tr>
</tbody>
</table>

The number of boats used type of gear landed emperor on date 16-04/00 =

Total number of boats landed / Total number of boats sampled * Number of sample boat landing emperor with type of gear

Numbers of boats used same gear = (48 / 16) * 2 = 6

Catch of yellowfin tuna by boat used same gear =

Total number of boats landed / Total number of boats sampled * Total catch of emperor by sampled boat with type of gear
Catch of emperor by boat used same gear =
(48/16)*20.8 = 62.4

The value of emperor landed by boat used same gear on 16/04/00 =
Total number of boats landed/ Total number of boats sampled* Total catch value
of sample boat landing emperor with type of gear used

Value of emperor landed by boat used same gear =
(48/16)*24.380 = 73.140

The numbers of fishermen landed emperor used same gear =
(48/16)*4 =12

The number of same gear used =
(48/16)*13 = 39

The number of boat hours landed emperor used same gear =
(48/16)*23 =69

4) Example catches effort monthly

The estimation of effort and value of each species by boat type, gear type and
area for monthly:

Table shows daily sampled month April for Yellowfin Tuna landed by boats
used same gear type for two days

<table>
<thead>
<tr>
<th>Date</th>
<th>Daily number of boats</th>
<th>Daily catch</th>
<th>Daily value</th>
<th>Daily number of fishermen days</th>
<th>Daily number of gear</th>
<th>Daily number of boat hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/4</td>
<td>3</td>
<td>13.3</td>
<td>6.933</td>
<td>6</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>16/4</td>
<td>6</td>
<td>62.4</td>
<td>73.140</td>
<td>12</td>
<td>39</td>
<td>69</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>75.7</td>
<td>80.073</td>
<td>18</td>
<td>56</td>
<td>91</td>
</tr>
</tbody>
</table>

Number of boats landed emperor used same gear for the month of April is:
30/2*9 = 135

The catch of emperor by boats used same gear in April is:
(30/2)* 75.7 = 1135.5

The value of emperor landed by boats used same gear in April is:
(30/2)*80.073 = 1201.095

The number of fishermen days landed emperor used same gear in April is:
(30/2)*18 = 270

The number of gill nets unit days used to land emperor in April is:
(30/2)*56 = 840
The number of boats hours landed emperor used same gear in April is:

\[(30/2) \times 91 = 1365\]

The Value per fisherman per day using gill nets in April is: Value of Catch for month / fishermen days for month = 1201.095/ 270 = Rial Omani 4.4 /day. Estimated in = £ 6.00/day

B) Measuring the Catch per overlap areas

Example on measuring amount of catch for the overlapping areas

1) Assuming each fishing area is around 800 km²

The overlapping between Ra’s Duqum and Shuair ports is 20% in each area west and east

Calculate size of new fishing area:

The new size \((800 \times 20\%) = 160\) km²

The overlapping area of 20% = 160 km²

2) Calculating new weight for the catch is the same method of calculating overlapping area.

Catch for landing port Ra’s Duqum ID (74) = 700 kg
Catch for landing port Shuair ID (776) = 200 kg

New weight catch for new ID port 777 is:

\[700 \times 20\% = 140\] kg
\[200 \times 20\% = 40\] kg
\[140 + 40 = 180\] kg for the port 7777
Appendix 5:

Region names Villages and their codes

<table>
<thead>
<tr>
<th>Region name</th>
<th>Region Code (ID)</th>
<th>Village name</th>
<th>Village Code (ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscat</td>
<td>1</td>
<td>Seeb</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Muttrah</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Muscat</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sidab</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quriyat</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dugmar</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bima</td>
<td></td>
</tr>
<tr>
<td>Al-Batinah</td>
<td>4</td>
<td>Barka</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Swadi</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Musanaa</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Widam Al-Sahel</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Suwaiq</td>
<td>35</td>
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<tr>
<td></td>
<td></td>
<td>Al-Khaburah</td>
<td>34</td>
</tr>
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<td></td>
<td></td>
<td>Saham</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sohar</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harmoul/Liwa</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shinas</td>
<td>30</td>
</tr>
<tr>
<td>Musandam</td>
<td>2</td>
<td>Khasab</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hana</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nadhi</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bukha</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Gari</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Port-Dabba</td>
<td>9</td>
</tr>
<tr>
<td>Sharqiyah</td>
<td>5</td>
<td>Sur beach</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kalhat</td>
<td>43</td>
</tr>
<tr>
<td></td>
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<td>Tiwi</td>
<td>44</td>
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<td></td>
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<td>Fins</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Ras Al-Hadd</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ras Al-Ruwais</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Askhrah</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Asilah</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Daffah</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ruwais</td>
<td>53</td>
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<tr>
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<td>Garoon</td>
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<td></td>
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<td>Masirah</td>
<td>59</td>
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<td></td>
<td>Al-Aejah</td>
<td>64</td>
</tr>
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<td></td>
<td></td>
<td>Ras Asia</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gshar Al-Shek</td>
<td>60</td>
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<td></td>
<td>Al-Haar</td>
<td>61</td>
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<td></td>
<td></td>
<td>Haql</td>
<td>62</td>
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<tr>
<td>Region name</td>
<td>Region Code (ID)</td>
<td>Village name</td>
<td>Village Code (ID)</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
<td>--------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Al-Wusta</td>
<td>6</td>
<td>Film zakhar</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Khlouf</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sarab</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saidrah</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Al-Nakda</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Ras Al-Duqm</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ras Al-Mudrakah</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shuair</td>
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<td>Haitam</td>
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<td>Daythab</td>
<td>83</td>
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<td></td>
<td>Ajwairah</td>
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<td></td>
<td>Soqrah</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lakbi -Port</td>
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</tr>
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<td></td>
<td></td>
<td>Mader</td>
<td>81</td>
</tr>
<tr>
<td>Dhofar</td>
<td>3</td>
<td>Raysut</td>
<td>16</td>
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<td></td>
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<td></td>
<td></td>
<td>Al-Haffa</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maghsail</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Taqah beach</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marbat</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hasek</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sadah Beach</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hadbeeen</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shrabitat</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shuwaimiyah</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Halaniyat</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rakhuit beach</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dhalkut beach</td>
<td>29</td>
</tr>
</tbody>
</table>
Appendix 6: Published papers
FISHERIES MONITORING, CONTROL AND SURVEILLANCE IN THE SULTANATE OF OMAN

Lubna H. Al Kharusi


Published in
FAO/NORWAY GOVERNMENT COOPERATIVE PROGRAMME
GCP/INT/648/NOR – Field Report C-3 (En) 47
Rome, September 2000
COUNTRY PAPER 1.

FISHERIES MONITORING, CONTROL AND SURVEILLANCE
IN THE SULTANATE OF OMAN

by

Lubna H. Al Kharousi
Marine Science and Fisheries Centre
Directorate General of Fisheries
Ministry of Agriculture and Fisheries

INTRODUCTION

This paper discusses the status of fisheries in Oman and the factors affecting the utilization and conservation of living aquatic resources. It deals with the role of government institutions concerned with protection of these important resources, and the departments, activities, laws and regulations designed to ensure well managed and controlled fisheries. The paper deals also with violations and how to control them, and reviews some basic issues encountered in fisheries management, monitoring and surveillance in Oman.

The Sultanate of Oman is one of the most important countries in the Arab world with regard to fishing and fisheries production. The coastline extends over 1,700 km, and the fisheries sector is considered as the most important non-oil source of national income. The fisheries sector plays a vital role in Oman’s economy, with an average annual production of 119,000 t.

The fisheries sector in Oman has witnessed rapid progress since 1976, when the Directorate General of Fisheries was established under the Five-Year Plan. During this period, as the competent authority responsible for the control of artisanal and industrial fisheries in Oman, the Department of Fisheries Affairs of the Directorate General of Fisheries has been responsible for the implementation of the Marine Fishing Law and Protection of Living Aquatic Resources, and its Executive Regulation and all the Ministerial Decrees and Circulars issued within the frame of the marine fishing law.

Aims of this paper

The primary aims of this paper are to:

➢ Provide information regarding the fisheries sector in Oman.
➢ Review fisheries status and assess the fisheries monitoring, control and surveillance (MCS) system.
➢ Define areas where enhancement and strengthening is required.
➢ Discuss ways for improvement and development of fisheries MCS and for establishment of a sound database that can assist in realization of future aims of fisheries development.

Contents of the paper

1. Fisheries control and surveillance in Oman.
2. The legal framework of fisheries.
3. Fisheries control, protection and development.
4. Types of violations.
5. Conclusion.

FISHERIES CONTROL AND SURVEILLANCE

Fisheries management
The Department of Fisheries Affairs of the Directorate General of Fisheries is responsible for follow-up and implementation of the provisions of fisheries control and surveillance laws and regulations. The following organizational chart of the Directorate General of Fisheries Resources shows the sections of the Department of Fisheries Affairs:

Sections and activities of the Department of Fisheries Affairs

Fishing Licence Section
➢ Issuance and renewal of fishing licences.

Surveillance Section
➢ Surveillance of industrial fishing vessels to check location, depth, and fishing equipment.
➢ Surveillance of coastline to check the validity of fishing licences as well as licences of boats and vessels.
➢ Monitoring of fisheries companies and factories.
➢ Monitoring of border checkpoints.
➢ Monitoring of landings.

Violations Sections
➢ Ensure compliance with Marine Fishing Law and its Executive Regulations, and inspection of fishing licences and equipment.
➢ Record violations and follow up actions on the same.
➢ Represent the Directorate General of Fisheries Resources before criminal courts with regard to violations of marine fishing law.
➢ Follow up the execution of judgements issued by criminal courts.
FISHERIES IN THE SULTANATE OF OMAN

Fisheries in the Sultanate are divided into industrial and artisanal (traditional) fisheries.

Artisanal fisheries

The artisanal fishing sector uses vessels and boats not exceeding 10 t capacity. It is considered as the most important sector exploiting fisheries resources and the main pivot for development of fisheries activities in Oman.

Industrial fisheries

By "industrial fisheries" are meant the fishing activities of industrial fishing fleets in the interest of licensed Omani fisheries companies, for which certain quotas are allocated. These fleets work on the high seas in defined fishing areas away from areas allocated for artisanal fishing.

IMPORTANCE OF THE FISHERIES SECTOR IN TERMS OF FISH QUANTITIES AND VALUE

Total fish production during 1997 was 119 000 t, of which 34 600 t (29%) came from the industrial fishing sector and 84 000 t (71%) from the traditional sector.

Table 1. Distribution of traditional fishermen by region (1993 - 1997)

<table>
<thead>
<tr>
<th>Year</th>
<th>Musandam</th>
<th>Batinah</th>
<th>Muscat</th>
<th>Sharqia</th>
<th>Wusta</th>
<th>Dhofar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>1 150</td>
<td>5 880</td>
<td>2 480</td>
<td>5 336</td>
<td>1 935</td>
<td>3 125</td>
<td>19 706</td>
</tr>
<tr>
<td>1994</td>
<td>1 150</td>
<td>5 880</td>
<td>2 480</td>
<td>5 336</td>
<td>1 935</td>
<td>3 125</td>
<td>19 706</td>
</tr>
<tr>
<td>1995</td>
<td>2 944</td>
<td>8 547</td>
<td>3 022</td>
<td>5 314</td>
<td>2 443</td>
<td>2 219</td>
<td>24 489</td>
</tr>
<tr>
<td>1996</td>
<td>3 038</td>
<td>8 837</td>
<td>3 151</td>
<td>5 571</td>
<td>2 629</td>
<td>1 345</td>
<td>25 575</td>
</tr>
<tr>
<td>1997</td>
<td>3 064</td>
<td>9 027</td>
<td>3 252</td>
<td>5 757</td>
<td>2 701</td>
<td>2 395</td>
<td>26 047</td>
</tr>
</tbody>
</table>

The commercial fishing sector is currently represented by six companies: Oman Fisheries Company; Oman Sea Company; Gulf of Oman Fishing International Company; Protein Products International Company; Sadah Sea Products Company; and Dhofar Fisheries Products Company. Their annual production during 1995-1997 was estimated at 28 700 t from demersal and pelagic species. Oman Fisheries Company is considered the most important company of the six, and it was established by Royal Decree No.79/1987, issued on 8/12/87.

The current activities of these companies are concentrated on demersal and large pelagic species of high economic value, especially tuna (Table 2).

Table 2. Quotas allocated to commercial fisheries companies in Oman

<table>
<thead>
<tr>
<th>Company</th>
<th>Demersal quota</th>
<th>Large pelagic fishes quota (tuna)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oman Fisheries Company</td>
<td>20 000</td>
<td>30 000</td>
</tr>
<tr>
<td>Oman Sea Company</td>
<td>2 000</td>
<td>5 000</td>
</tr>
<tr>
<td>Gulf of Oman Fishing International Company</td>
<td>2 000</td>
<td>5 000</td>
</tr>
<tr>
<td>Protein Products International Company</td>
<td>2 000</td>
<td>5 000</td>
</tr>
<tr>
<td>Sadah Sea Products Company</td>
<td>2 000</td>
<td>5 000</td>
</tr>
<tr>
<td>Dhofar Fishing Products Company</td>
<td>--</td>
<td>3 000</td>
</tr>
</tbody>
</table>
THE LEGAL FRAMEWORK OF FISHERIES

Due to the important role of the fisheries sectors in the national economy, the Government of Oman is giving care and concern to control and conservation of fisheries resources to ensure their optimal utilization. One result of this care and attention was the issuing of the Marine Fishing and Protection of Living Aquatic Resources Law, in May 1981, in accordance with Royal Decree No. 53, and this was followed by the issuance of Executive Regulations for the law, in 1982, later amended by a Ministerial Decree in 1994.

Significance of the Law on Marine Fishing and Protection of Living Aquatic Resources

The Law contains different chapters dealing with the organization and protection of fisheries resources, the most important of which are mentioned below.

**Regulation of fisheries**

This chapter of the law deals with regulations and conditions related to licences; fees; specifications of fishing vessels; permitted equipment and gear; substances harmful to the growth, reproduction or migration of living aquatic resources; etc.

**Fisheries protection and development**

This chapter deals with protection of living aquatic resources during their breeding and reproductive seasons, including provisions regarding prohibition of construction of dams or other barriers that block the movement of living aquatic resources, using methods and tools harmful to the eggs or young of living aquatic resources, etc.

**Handling, marketing and processing**

This chapter deals with the conditions and specifications of means used for fish transport, specifications of fish markets, and sanitary conditions for fish processing and marketing.

**Protection and development of living aquatic resources**

The provisions of this part of the Executive Regulation stipulate that all juvenile fish should be returned to the sea if found among the catch. It also prohibits the catching of turtles, crustaceans and shellfish species of economic importance, during their breeding and reproduction seasons.

**Control of fishing activities**

The provisions of this part determine areas where fishing is prohibited, e.g., areas adjacent to petroleum or military facilities, and bans the use of mechanical fishing gears and trawlers unless a permit is obtained for the same.

**Preservation, transport and marketing of living aquatic resources**

This part deals with the issuance of licences for processing, transport and marketing of living aquatic resources, and specifies sanitary conditions for selling the same in the market.

FISHERIES SURVEILLANCE, CONTROL AND PROTECTION

According to the authorization given to the Ministry of Agriculture and Fisheries by the Marine Fishing Law and its Executive Regulation, the Ministry has responsibility for the management, conservation and protection of fisheries.

The fisheries surveillance activities of the Ministry include:

- Surveillance on board fishing vessels.
- Landings surveillance.
- Coastal surveillance.
Surveillance at border checkpoints.

Surveillance of companies and factories.

Besides the Ministry of Agriculture and Fisheries, there are other government bodies assisting in and contributing to surveillance activities, and there is continuous coordination between them and the Ministry. These governmental bodies include:

- **Royal Oman Police** The Coastguard patrol vessels assist in fisheries surveillance operations through continuous patrolling trips, and reports are sent to them regarding violating vessels so that they can take necessary actions towards the seizure of violators at sea.

- **Royal Navy of Oman** The Royal Navy of Oman performs regular patrolling operations and the Ministry is informed of any violations detected of fishing laws and regulations in Omani territorial waters.

- **Royal Air Force of Oman** Aircraft of the Royal Air Force of Oman are used to monitor, locate and track fishing fleets and detects violations, and reports on the same are sent to the Ministry.

**Surveillance of commercial fishing vessels**

The control of commercial fisheries includes the issuance of vessel sailing permits, which contain information regarding the vessel, fishing area, fishing gear and equipment, and types of resources to be harvested, in addition to deployment of one or more of the Ministry's surveillance officers on board each demersal fishing vessel.

**Controlling the number of fishing vessels and duration of fishing trips**

The number of fishing vessels and the duration of each fishing trip has been determined by the Ministry of Agriculture and Fisheries in order to organize and control production.

- The maximum duration of a fishing trip for demersal fishing vessels is 35 days.
- The maximum duration of a fishing trip for large pelagic fishing vessels is 60 days.

**Control of fish species that may be thrown back to the sea and fisheries resources not allowed to be harvested**

Originally, 16 fish species were specified as species that could be thrown back to the sea if found among the catch during fishing operation.

Thereafter, a Ministerial Decision (No. 42/98) was issued amending Article 17 of the Executive Regulations, and according to this no fish species can be returned to the sea if it comes in the catch.

Industrial fishing vessels are not allowed to harvest lobster, abalone, shrimps, cuttlefish, octopus, whales and other marine mammals, sea turtles and kingfish, in line with the Sultanate policy favouring the protection of such resources from overexploitation.

The harvest of some of the abovementioned species is restricted to artisanal fishermen only.

**Control of fishing nets and equipment**

With regard to demersal fishing vessels, the stretched mesh size for the main net, including the wings, shall not be less than 210 mm and for the codend the mesh size shall not be less than 110 mm, and no doubling of nets is allowed.

Large pelagic fishing vessels are allowed to use longlines only.
Control of landing operations:
It is obligatory for each fishing vessel to submit, at the end of each fishing trip, a production report showing type and quantity of catch, and each vessel should comply with the standard weight of each box (20 kg).

Quantities stated in production reports are verified by the relevant officials of the ministry, and in the event of any discrepancies in weights, the difference shall be deducted from the company's allocated quota.

Control of permitted fishing areas for industrial fishing vessels
Industrial fishing vessels are restricted to fishing in specified fishing areas, as mentioned hereunder.

- Demersal fishing vessels should fish in areas between latitude 21°00"N and longitude 55°45"E, at least 10 n.mi. from the coastline and in depths not less than 50 m.

- Large pelagic fishing vessels should fish in areas between latitude 24°45"N and longitude 54°00"E, and at least 20 n.mi. from the shore.

Control of artisanal fisheries
Coastal fisheries control
Coastal fisheries control covers all surveillance activities carried out in different coastal areas in order to ensure that fishers comply with the provisions of the Marine Fishing Law and its Executive Regulations. Surveillance operations are carried out by surveillance teams of the Department of Fisheries Affairs. Article 21 of the Executive Regulations divides the fishing grounds into six main areas:

- Governorate of Musandam with its administrative boundaries.
- Batinah Region: from Wilayat Shinas to Wilayat Barka.
- Muscat Governorate from Wilayat AlSeeb to the coast of Makalah Waber at Wilayat Qurayat.
- Sharqiya Region from the end of Makalah Waber coast to Ruwais coast.
- Al-Wusta Region from the end of Ruwais coast to Wilayat Al-Jazir.
- Governorate of Dhofar from Sharbatat coast to the border with the Republic of Yemen.

Control of fish resources not allowed to be harvested during certain seasons
The Marine Fishing Law prohibits the catching of fish species of high economic value during their breeding and reproductive seasons (Article 14 of Marine Fishing Law). This includes lobster and abalone. Also, Article 12 of the Executive Regulations stipulates that all fishermen shall immediately return to the sea all live juvenile fish found among shrimps and fish catches.

Provisions of Article 16 of the Executive Regulations of the Marine Fishing Law prohibit the throwing of any shark part into the sea or on the shore. It also prohibits the separation of shark fins and tails.

Article 19 of the Executive Regulations prohibits the collection or export of oysters, shells and/or coral unless a licence is obtained from the competent authority.

Control of the use of prohibited fishing nets and equipment
Chapter Five of the Executive Regulations of the Marine Fishing Law deals with regulations regarding the use of some kinds of fishing gear, and equipment for the protection and development of living aquatic resources. They also protect the marine environment against the use of specific fishing gear and equipment, e.g., gillnets and monofilament nets.
Control of the employment of expatriates in artisanal fisheries

Article 46 of the Executive Regulations of the Marine Fishing Law forbids the employment of expatriate labourers in the traditional fishing sector, with the exception of large wooden fishing vessels, where two expatriates are allowed to be employed, one as a marine equipment mechanic and the other as a diesel technician.

Control of border checkpoints

This includes the inspection of fish consignments intended for export to ascertain that the consignment contains only species permitted at that season. Also, inspection is carried out to ascertain the hygienic and sanitary condition of fish and to check the validity of the licences for fish transport and marketing.

Inspection of fisheries companies and factories:

The inspectors of the Ministry pay inspection visits to companies working in the field of fish export, import or processing and to manufacturers of fishing boats and equipment, to ascertain compliance with relevant fisheries laws and regulations.

Violations in the fisheries sector

Industrial fishing sector

Typical problems found in the sector include:

- Straying outside the designated fishing area.
- Non-adherence to the stipulated duration of fishing trip.
- Using illegal nets and equipment.
- Discarding species of little market value.

Total violations recorded for industrial fishing vessels in the period 1990-1997 were about 275, i.e., about 40 violations annually, with a maximum of in 1993, when a total of 142 violations were committed by the Oman Fisheries Company fleet. Tables 3 and 4 show the number and type of violations detected among commercial fishing fleets.

Table 3. Number of violations by commercial fishing vessels

<table>
<thead>
<tr>
<th>Year</th>
<th>Oman Fisheries</th>
<th>Oman Sea</th>
<th>Gulf of Oman Fishing International</th>
<th>Protein Products International</th>
<th>Sadah Sea Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1991</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1992</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1993</td>
<td>142</td>
<td>21</td>
<td>-</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>1994</td>
<td>13</td>
<td>1</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1995</td>
<td>26</td>
<td>4</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1996</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1997</td>
<td>13</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>220</td>
<td>31</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4. Types of violation

<table>
<thead>
<tr>
<th>Year</th>
<th>Company</th>
<th>Discarding marketable fish</th>
<th>Use of illegal nets</th>
<th>Fishing in unauthorized area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>Oman Fisheries Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Oman Sea Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Gulf of Oman Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>1995</td>
<td>Oman Fisheries Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Oman Sea Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Gulf of Oman Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>1996</td>
<td>Oman Fisheries Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>1997</td>
<td>Oman Fisheries Co.</td>
<td>+</td>
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</tr>
<tr>
<td></td>
<td>Gulf of Oman Co.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Artisanal fisheries sector

Violations in this sector include:

- Harvesting of fish resources in closed seasons.
- Use of prohibited fishing nets and gear.
- Harvesting of egg-carrying (berried) lobsters and catching of undersize fish species.
- Export of prohibited shark fins.
- Employment of expatriates in fishing activities.
- Use of unlicensed fishing boats.
- Non-compliance with requirements for vessel identification number plates on both sides of the boat.
- Failure to have a valid fishing licence and fishing practice licence.
- Fishing in unauthorized fishing areas.
- Non-provision of marine safety aids.
- Exporting fish and shark fins abroad during closed seasons.

Conclusions and recommendations

From this review, it is clear that the Sultanate of Oman has taken important steps with regard to fisheries management. However, and despite the achievements realized, there is still scope for more work to be done concerning fisheries control and surveillance. The most important challenges facing the relevant authorities in this field include processing and collating the vast quantities of information and data needed for the establishment of a database to assist in decision making, in addition to insufficiency of available observers. This is considered an important missing link in the surveillance and control system, which weakens capabilities, and reduces the results that can be expected. Therefore the enhancement of fisheries supervisory bodies is a necessary element in any fisheries development plan in Oman.

It is important to provide the best and optimal ways and means for fisheries management control and surveillance, and hence it is recommended that this workshop discuss optimal factors for modernization of fishing gear and fishing methods, and development of fisheries management, control and surveillance.
Analysis of the space-time variation of emperor (Lethrinus) in the Arabian sea, 1996-2004

Al-Kharusi L.H. and Jarvis C.H

Paper presented at the Third International Symposium on GIS/ Spatial Analyses in Fishery and Aquatic Sciences Shanghai Fisheries University, Shanghai, China
Analysis of the space–time variation of emperor (*Lethrinus*) in the Arabian sea, 1996–2004

Al-Kharusi L.H.¹ and Jarvis C.H.¹

Abstract

This study report results from the space–time mapping of the distribution of emperor (*Lethrinus* sp.) in Omani waters. Fisheries data concerning catch and fishing effort from both commercial trawlers and traditional vessels were obtained from the Statistical Department of the Oman Ministry of Agriculture and Fisheries for the period 1996–2004. In order to support the modelling of relationships between fish abundance and the environmental conditions, monthly sea surface temperatures (SST) from environmental remote-sensing data were downloaded from the PO-DAAC physical oceanographic website. Additionally, sea surface salinity estimates were obtained from the Naval Coastal Ocean Model of the Naval Research Laboratory, and bottom bathymetric data was digitised from Omani charts.

Geographical information systems software was used to provide a qualitative description of the relationships between fish abundance and SST and water depth on a monthly basis for the 9-year period. Spatially, emperor is more abundant in the southwest of the Omani sector of the Arabian Sea than the northwest; temporally, the peak season for high abundance is between September and February. Geographical analyses for this group of species and for others in the Arabian Sea have not previously been well described.

A general additive model is used to explain the environmental variation in emperor abundance. The possible explanatory variables include year, month, latitude, longitude, SST and depth; the final best overall model included all variables except longitude.

Keywords

Emperor (*Lethrinus*), general additive model (GAM), geographical information system (GIS), sea surface temperature (SST), sea surface salinity (SSS).
1. Introduction

The family Lethrinidae, commonly known as emperor or scavenger, contains some of the most common and economically important commercial and artisanal tropical demersal fish species (Carpenter and Allen, 1989). Despite its economic importance there is generally a paucity of information on the environmental context for fish of this family. Authors such as Carpenter and Allen (1989), Al-Abdessalaam (1995) and Wray (1979) have reported that emperor usually inhabit coral and rocky reefs and sandy or rubble substrata in coastal waters down to 100 metres (m) depth. The preferred habitat and depth range varies with the species.

This paucity of literature on Lethrinidae is particularly the case in regard to Omani waters, the focus of this paper; only a few studies from neighbouring countries are available. McLlwain et al. (2006) describe the reproductive characteristics of the six species most commonly caught by the trawlers in the Arabian Sea, one of which was *Lethrinus nebulosus*. Wassef (1991)—who studied the growth rate of *Lethrinus lentjan* and *Lethrinus mahsena* in the Red Sea—is among others (e.g. Ezzat et al., 1992; Pilling et al., 2000) who examined growth and maturation rates. However, the majority of studies for Oman and beyond do not consider the effects of environmental factors on these species. At 24% of overall catch, emperor is the most common and highly-valued commercial genus in the Sultanate of Oman; hence, from an economic perspective, further work is warranted on the preferred environmental conditions supporting the catch. While Oman’s emperor landings have been rising steadily post-2002 (Ministry of Agriculture and Fisheries, 2004), reasons for earlier significant fluctuations are unknown, and warrant study.
This study maps and analyses the spatial and temporal distribution of adult Lethrinidae in Omani waters in relation to environmental variables. The longer-term context for the work is to improve fisheries management and maintain a sustainable yield. This study in particular asks:

- What are the spatial and temporal distribution patterns of Lethrinidae?
- Is there a relationship between Lethrinidae distribution and environmental factors such as sea surface temperature (SST), salinity, geographical locations and depth?

In order to answer these questions, both qualitative analysis within a geographical information system (GIS) and quantitative methods in the form of a generalised additive model (GAM) were used. GAMs were first used to analyse fish distribution by Swartzman et al., (1992), and later by other researchers such as Daskalov, (1999) and Pierce et al. (2001); their use has increased significantly in recent years. GAM is an appropriate form of model in this context since the method is able to deal with non-linear relationships between an independent variable (emperor abundance) and multiple predictors (spatial, temporal and environmental) at the same time.

2. Material and Methods

2.1 Study area

The study area is located in the Arabian Sea, between 17°30' and 24°00' North (N) and 53°00' and 59°30' East (E) (Map 1). The Arabian Sea is influenced by two types of monsoons—the Southwest (SW) monsoon from May to October and the Northeast (NE) monsoon from November to March. This area has the strongest annual variability in water circulation in the world (Esenkov et al., 2003). During summer the SW monsoon causes strong currents and productive upwelling with deeper mixing, bringing colder, less-saline water to the surface mixed layer. These features are capable of exporting cool water, rich in nutrients, hundreds of kilometres (km) offshore (Brink et al., 1998; and Morrison, 1997). Advanced High Resolution Radiometer (AVHRR) satellite imagery shows that the SST during the SW monsoon in the Arabian Sea is cooler than in the Gulf of Oman waters. The winter (NE) monsoon winds produce onshore flow and stratification of the water column, with warmer surface water and a shallower mixed layer.
2.2 Data sets

Table 1 shows the characteristics and sources of the data sets for the remotely-sensed environmental parameters and emperor catch data used in this study. The complete government record of fishery catch data from commercial trawling vessels for 1996–2004 was obtained from the Statistics Department of the Ministry of Agriculture and Fisheries of Oman. These data included daily and monthly catch by commercial fishing vessels (trawlers), and fishing effort. Catch per unit of effort—CPUE; kg/day, calculated as total catch over all fishing blocks divided by fishing days—is used as an index of abundance. The fishing blocks have been divided into blocks of 30*30 nautical miles, each block sub-divided into nine areas of 10 * 10 nautical miles. The emperor CPUE data sets were imported from a custom-designed Microsoft Access™ database and integrated into ArcGIS™, and located using the centroid sub-block of 10*10 nautical miles registered Omani commercial fishing areas.

Using a GIS, a time series of monthly satellite images of SST distribution for the period from 1996 to 2004 was derived from AVHRR at a spatial resolution of 4 km and measured in degrees Celsius (°C). In addition, time series of modelled monthly sea surface salinity (SSS) were derived from the Naval Research Laboratory Navy Coastal Ocean Model for the same period, at a spatial resolution of one-eighth degree and measured in parts per thousand (ppt). Bathymetry data for the study area, also measured in metres, was digitised from Omani charts.

Sea-bottom temperature and sea-bottom salinity were not considered for analysis owing to strong monsoonal advection in the study region (Forster, 1984). This advection plays an important role in reducing salinity through the upwelling of less-saline water from depth during the SW monsoon, and results in mixed temperature layers in depths ranging between 50 m and 200 m (Forster, 1984).

2.3 Exploratory GIS analysis

After analysing the spatial distribution of SST, mapping the spatial distribution of total catch, and mapping annual CPUE of emperor in Omani waters, the spatial and temporal distributions of
emperor abundance in relation to SST in the Arabian Sea were explored visually within a GIS. Plots were analysed both season-by-season and on an aggregated annual basis to capture temporal as well as spatial features of distribution of emperor.

Additionally, monthly averages of SSS and the emperor CPUE were plotted and analysed using similar methods. Similar analyses exploring the spatial distribution of emperor with bathymetry were also undertaken, because the literature suggests that the emperors usually occur in waters shallower than 100 m (Carpenter and Allen, 1989; Randall, 1995; Al-Abdessalaam, 1995).

2.4 Statistical modelling

General additive models (Hastie and Tibshirani, 1990) were used to analyze the non-linear relationships between the environmental variables and CPUE. Models were fitted using the Brodgar 2.4.8 software from Highland Statistics Ltd (www.brodgar.com). The general form of GAM adopted for this study is given by Equation (1):

$$g(\mu) = \alpha + \sum_{i=1}^{n} f_i(X) + \varepsilon$$

Equation (1)

where $g(\mu)$ is the response variable, also defined as the link function, for the CPUE; $X_i$ is the explanatory variable; $\alpha$ represents the intercept term in the fitted model; $f_i$ is the smoothing function of the explanatory variable; and $\varepsilon$ is the error term. The degree of smoothing is established using the degree of freedom (df) associated with the smoothing function variable. The cubic spline smoother method was used to smooth the variable and estimate the optimal df, using cross validation.

Initial exploratory analysis using dot plots and pairs was undertaken to reveal characteristics of the data sets, and scatterplots were used both to visualise the type of relationship between variables and to identify outliers. The possible explanatory variables included year, month, SST, depth, latitude and longitude, for all years’ data, the dotted lines represent the 95% confidence limits and the tick-marks on the x-axis indicate the number of data points available for different values of x. The partial components, as represented by y-values on the general-additive-model plots, express the
relationship between the link function of the response variable and each of the variables included in the model.

Subsequently, models were fitted within the software package Brodgar using a forward stepwise procedure. A cubic spline quasi-Poisson distribution with log link function, appropriate for avoiding over-dispersion, was used to model abundance, with the aim of producing moderate smoothing of the relationship between emperor numerical abundance and factors of interest. The 'best' model was selected using the Akaike Information Criterion (AIC; Equation 2), where the model with the lowest AIC was considered most optimal.

\[
AIC = -2 \log \text{(Likelihood)} + 2 \times df
\]  
Equation (2)

Adequacy of model fit was assessed by a pseudo-coefficient \( R^2 \) of residual determination, defined as the fraction of the total deviance explained by the model (Equation 3).

\[
R^2 = 1 - \frac{\text{residual deviance}}{\text{null deviance}}
\]  
Equation (3)

GAM models were subsequently also developed using long-term monthly average data, to allow further detailed analysis of spatial and seasonal trends in abundance of emperor with environmental variables. GAM output plots were visualised by month, using the best fitting smoothers for all explanatory variables included in the model.

3. Results

3.1 Spatial catch of emperor in Omani waters

The emperor is widely distributed in Omani waters, but most are found in the Arabian Sea. Map 1 illustrates the general spatial distribution patterns of the total catch of emperor for trawler fisheries, based upon approximately 16 500 catch records between 1996 and 2004 collated from commercial trawlers in Omani waters. The highest catches were located between 17°00' N and 20°00' N.

3.2 Analysis of SST in relation to the distribution of emperor abundance
Maps 2a and 2b show the spatially-referenced variation in monthly mean CPUE from the commercial emperor fisheries, with monthly mean values for SST. From the maps the following observations can be made:

- emperor catch appears in all months, though the distribution of CPUE varies; and
- the temporal distribution of emperor appears to be highest in the months between August and January.

From April to October, maps 2a and 2b show a consistent spatial trend in SST, decreasing from high to low temperatures. During this period, the monthly patterns of CPUE show some degree of fluctuation. During March the commercial CPUE is at its lowest, with levels reaching 10 kg/day in only three locations, near Ra's Duqm and Sharbithat. In these months too, SST ranged from 25.9°C inshore to 26.7°C offshore. CPUE increases from July to December. The highest widespread emperor distribution is in November and December, abundance reaching a high of >100 kg/day, when the SST ranges between 26°C and 28°C.

Low SST values may be the reason why the lowest CPUE figures arise during the SW monsoon period and the highest after the monsoon finishes. Nonetheless, the overall relationship between spatial and temporal distribution patterns of emperor abundance and SST cannot be fully explained at this stage, but are examined in the GAM analysis.

3.3 Analysis of SSS in relation to the distribution of emperor abundance

Generally, the SSS levels are more than 34 ppt and less than 37 ppt. This variability extends from the Gulf of Oman to the Arabian Sea. SSS is, however, relatively uniform in the Arabian Sea (that is, 54°62'E. and 16°21'N), with a range between 35 and 36.5 ppt. Perhaps surprisingly, given previous research literature on the importance of SSS to emperor distribution, no discernable visual relationship was found between emperor distribution and SSS.

3.4 Analysis of the distribution of emperor abundance in relation to depth
Map 1 shows the average CPUE distribution of emperor abundance in the Arabian Sea, and maps 2a and 2b show the long-term monthly average distribution of emperor abundance (CPUE), overlaid against bathymetry. The analysis of depth relative to distribution of emperor abundance shows that the higher CPUE values (more than 10 kg/day) were found in areas of less than 100 m depth, namely 18°00' to 19°00' N and 57°35' to 57°50' E. Indeed, in areas of more than 200 m depth there was hardly any catch. These patterns clearly indicate that in the Arabian Sea, as bathymetry increases beyond 200 m, the CPUE value decreases to less than 5 kg/day. These results support the findings of other researchers that *Lethrinus* species occur between shallow waters and 100 m depth. Depth is examined in greater detail in sections 3.7 and 3.8 below, in the report of the results from the GAM analyses.

3.5 Descriptive statistics and scatterplots, 1996–2004

Analysis using dot plots and scatterplots indicated non-linear relationships between emperor abundance (CPUE) and environmental variables (Figure 1). The emperor CPUE appeared to be higher during 1999 and lower during 2001, with minimum values during March and June, and higher catch rates from August to December.

Analysis of the data indicates interesting results: the higher emperor abundance values were largely associated with an SST range above 24.5 °C and lower than 28.5 °C (Figure 1c). Furthermore, the majority of emperor abundance appears to occur at depths below 200 m (Figure 1d). The most intense emperor abundance is located between 17 30' and 20° N, and between 56°30' and 58 30' E (figures 1e and 1f).

3.6 GAMs fitted to long-term (1996–2004) emperor-fisheries data

The results for the best GAM model fit for the long-term (1996–2004) trawler-vessel data provided a pseudo-$R^2$ of 54%, with 68% of the deviance explained (df=25), and an AIC value of 15.63. Taken together, these metrics suggest a model of reasonable fit, significant at $P<0.001$. Analysis of
deviance indicated that year, month, latitude, depth and SST all play a significant part in the model (p<0.001).

3.7 GAMs fitted to long-term-average data from emperor trawling vessels

The GAM plots (figures 2a–2e) demonstrate the smoothing functions, for all explanatory variables, within the optimal monthly GAM model results, against trawler-fishery CPUE data. Longitude was found to have high co-linearity with latitude and therefore was subsequently removed.

The smoothed partial effect of year indicates highest CPUE during 1999 and lowest in 1996 (Figure 2a). A clear seasonal effect on the CPUE is seen in the partial effect of month, with a negative effect from February through April (Figure 2b). Figure 2c suggests that the partial effect of SST at less than 25°C is negative, whereas above 26°C and less than 29°C it is positive. Emperor abundance is greatest in depths shallower than 200 m—in particular in 50–100 m—and decreases with increasing depth (Figure 2d). However, the 95% confidence limits on this variable are broad. Latitude had a strong negative partial effect south of 17° 00' N, and a slight positive effect between 17° 30' N and 20° N (Figure 2e).

3.8 GAMs fitted to long-term-average emperor data by month

As was the result for the non-seasonal model, the influence of the explanatory variable depth was largely non-significant (except for July p<0.01, Table 2) and general showed high AIC values and non-significant results (p>0.05). In contrast, the importance of latitude was strong in all months except May and June. Between July and January, there is a significant influence (p<0.01) of SST on average emperor abundance.

The form of smoothing for the partial effect of SST, latitude and depth (where relevant) is shown month-by-month for July to December—the important catch months (figures 3a–3e). The GAM model for July and August included explanatory variables SST, latitude and depth as significant influences on average emperor abundance, with the depth relationship in August having a negative effect on average emperor abundance (figures 3a and Table 2).
For the best model for September, smoothing for the partial effect of SST suggests that temperatures between 24.5 °C and 26.5 °C have the strongest positive effect on average emperor abundance, whereas there is a negative effect for SSTs above 27 °C. Smoothing for the partial effect of latitude indicates that it has its strongest influence on abundance at locations north of between 17.5° N and 20° N. The shapes of the smooths were similar during October (Figure 3c) and November (Figure 3d) for the partial effect of SST; this indicates a stronger effect on the average emperor abundance at higher temperatures more than 28.5 °C. During December, the smoothing for the partial effect of SST (Figure 3e) indicates a positive effect for ranges of SST values: between 25.5 °C and 27 °C; as with October and November, latitude has a negative effect north of 20° N. Clearly, the fitted GAM models captured adequately the relationships that were suggested from the explanatory analysis of the scatterplots.

Overall, while depth has an explanatory role in some months, the most important explanatory variables in this analysis of long-term monthly emperor-abundance data for the Arabian Sea are latitude and SST.

4. Discussion

From the visual overlay of spatial and temporal patterns of emperor distribution (as determined by CPUE) in the Omani sector of the Arabian Sea relative to environmental variation, high CPUE occurs in areas where the SST ranges between 25.5 °C and 28.0 °C, while low abundance occurs in areas where the SST is less than 25.0 °C. Relationships between fish distribution and temperature have been found in many studies of different species (for example, Wang et al., 2003; Zheng et al., 2002; and Barratt et al., 2002). However, there is a paucity of information on spatial and temporal variation of emperor globally, and little previous evidence explicitly supporting the existence of a relationship between emperor distribution/abundance and SST variation. Forster, (1984) analysed 19 species in Aldabra (Indian Ocean), one of the species being Lethrinus nebulosus. His general findings showed a relationship between temperature and fish distribution, the fish of this group occurring in areas of upwelling and in the temperature range of 24.3–27.8 °C. However, these
results were not specific to *Lethrinus nebulosus*. Newman and Williams, (2001) observed that in the central Great Barrier Reef region the highest abundance of *Lethrinus nebulosus* was found during average temperatures of 27 °C. GAMs allowed us to investigate seasonal patterns, visually observed by month, and show a statistically significant relationship between SST and emperor CPUE in October–December with temperatures of 25–27 °C. In seeking to explain the model results for emperor and SST, it is important to note in passing that between June and August there are very rough seas; the level of fishing effort may be affected by this adverse physical environment.

Following the analysis of emperor distribution relative to SST, the results of the relationship between emperor CPUE distribution and SSS were also examined. The SSS patterns in this area showed a variation from 36.0 to 37.7 ppt with little visual association to be made with the higher CPUE of emperor found during the months of September and February 2004. Relatively little is known concerning the influence of salinity on fish, but the range of variation here is low and hence is arguably relatively uniform in the context of its effect on emperor physiology. The high co-linearity of salinity with temperature in upwelling areas is a further factor that may have particularly affected the quantitative modelling process.

On examining the distribution of emperor relative to depth, it was noted that *Lethrinus* were found predominantly in depths ranging from shallow waters to 100 m. These observed patterns are supported by studies on the central Great Barrier Reef (Newman and Williams, 1996; Newman and Williams, 2001) that found that *Lethrinus* spp. were characteristic of shallow waters. These findings are echoed at a number of locations elsewhere (Forster, 1984; Randall, 1995; Al-Abdessalaam, 1995; and Koranteng, 2001). It is possible that depth preferences may overlap with seabed type, which could be a significant factor in the depth distribution of *Lethrinus*. However, a sampling issue is the more likely cause of this result in the context of GAM analyses based on data from trawling vessels, since the full “environmental space” for depth is not covered adequately in this study.
Further sampling issues affecting the results presented here also relate to the issues of environmental space and the use of catch data rather than full-coverage research data. Clearly, the use of catch data is practical, and provides relatively high volumes of data for analysis. However, bias in regard to the reach of boats, inaccuracies in landing data due to problems of underreporting in traditional-fishery domains, and the discarding of commercial catch because of quota limits, are all issues that must be acknowledged.

While the results presented are positive in regard to seasonality and temperature relative to emperor distribution and abundance (as measured by CPUE), further work is required in regard to the model validation by season. The spatial projection of the GAM model and cross-validation of the model in regard to CPUE data collected will be an important further step. Additionally, while the GAM method has provided a useful basis for analyses, comparison with other non-linear modelling methods—such as a feed-forward back-propagation neural network model—and an examination of their relative spatial performance would be of interest. From a biological perspective, the findings here suggest that further research that takes into account the relative age of emperor (to provide the relationship between age and maturation) might be fruitful. If, for example, emperor are more vulnerable to capture during spawning aggregations, the prevention of over-harvesting in that particular period would be a consideration within a sustainable management plan.

References


Table 1.

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<td>Sea surface temperature</td>
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<td>PO-DAAC physical oceanographic website 4 km resolution</td>
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GIS—geographic information system
GAM—general additive model
CPUE—catch per unit of effort
Table 2.

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£ error for parametric component
SST—sea surface temperature
AIC—Akaike information criterion
GAM—general additive model
CPUE—catch per unit of effort
Table 1. Summary of characteristics of the data sets that are included in GIS and GAM, and their sources, for the period 1996–2004

Table 2. Degrees of freedom (df), p-values, R-squared values ($R^2$) and AIC values of the best GAM fitted to emperor abundance (CPUE), for long-term averaged data, by month.

Figure 1(a–f). Scatterplots showing the relationships between long-term (1996–2004) average emperor abundance (CPUE—kg/day) and: (a) year; (b) month; (c) SST (°C); (d) depth (m); and (e) latitude and (f) longitude (decimal degrees).

Figure 2 (a–e). Results of general-additive-model smoothing curves fitted to partial effects of explanatory variables on long-term (1996–2004) average emperor abundance (CPUE—kg/day), as a function of: (a) year; (b) month; (c) sea surface temperature (°C); (d) depth (m); and (e) latitude (decimal degrees). Solid lines are the fitted linear model and dashed lines represent 95% confidence intervals.

Figure 3 (a–e). Results of general-additive-model smoothing curves (solid lines), fitted to partial effects of the explanatory variables on response-variable long-term (1996–2004) emperor abundance (CPUE), months July–December.

Map 1. Spatial distribution of emperor relative to sea depth, in the Arabian Sea, based on total trawler catch between 1996 and 2004.

Map 2(a). Spatial distribution, from January to June, of the long-term (1996–2004) monthly average emperor abundance (CPUE; kg/day) in the Arabian Sea in relation to sea surface temperature (SST; °C).

Map 2(b). Spatial distribution, from July to December, of the long-term (1996–2004) monthly average emperor abundance (CPUE; kg/day) in the Arabian Sea in relation to sea surface temperature (SST; °C).
Map (1)
Map 2 (a)
Map 2 (b)
Figure 1
Figure 3 (a–e).
Analysis of the space–time variation of emperor (*Lethrinus*) in the Arabian sea, 1996–2004

Al-Kharusi L.H.¹ and Jarvis C.H.¹

Abstract

This study report results from the space–time mapping of the distribution of emperor (*Lethrinus* sp.) in Omani waters. Fisheries data concerning catch and fishing effort from both commercial trawlers and traditional vessels were obtained from the Statistical Department of the Oman Ministry of Agriculture and Fisheries for the period 1996–2004. In order to support the modelling of relationships between fish abundance and the environmental conditions, monthly sea surface temperatures (SST) from environmental remote-sensing data were downloaded from the PO-DAAC physical oceanographic website. Additionally, sea surface salinity estimates were obtained from the Naval Coastal Ocean Model of the Naval Research Laboratory, and bottom bathymetric data was digitised from Omani charts.

Geographical information systems software was used to provide a qualitative description of the relationships between fish abundance and SST and water depth on a monthly basis for the 9-year period. Spatially, emperor is more abundant in the southwest of the Omani sector of the Arabian Sea than the northwest; temporally, the peak season for high abundance is between September and February. Geographical analyses for this group of species and for others in the Arabian Sea have not previously been well described.

A general additive model is used to explain the environmental variation in emperor abundance. The possible explanatory variables include year, month, latitude, longitude, SST and depth; the final best overall model included all variables except longitude.
Keywords
Emperor (*Lethrinus*), general additive model (GAM), geographical information system (GIS), sea surface temperature (SST), sea surface salinity (SSS).

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1. Introduction

The family Lethrinidae, commonly known as emperor or scavenger, contains some of the most common and economically important commercial and artisanal tropical demersal fish species (Carpenter and Allen, 1989). Despite its economic importance there is generally a paucity of information on the environmental context for fish of this family. Authors such as Carpenter and Allen (1989), Al-Abdessalaam (1995) and Wray (1979) have reported that emperor usually inhabit coral and rocky reefs and sandy or rubble substrata in coastal waters down to 100 metres (m) depth. The preferred habitat and depth range varies with the species.

This paucity of literature on Lethrinidae is particularly the case in regard to Omani waters, the focus of this paper; only a few studies from neighbouring countries are available. McLlwain *et al.* (2006) describe the reproductive characteristics of the six species most commonly caught by the trawlers in the Arabian Sea, one of which was *Lethrinus nebulosus*. Wassef, (1991)—who studied the growth rate of *Lethrinus lentjan* and *Lethrinus mahsena* in the Red Sea—is among others (e.g. Ezzat *et al.*, 1992; Pilling *et al.*, 2000) who examined growth and maturation rates. However, the majority of studies for Oman and beyond do not consider the effects of environmental factors on these species. At 24% of overall catch, emperor is the most...
common and highly-valued commercial genus in the Sultanate of Oman; hence, from an economic perspective, further work is warranted on the preferred environmental conditions supporting the catch. While Oman’s emperor landings have been rising steadily post-2002 (Ministry of Agriculture and Fisheries, 2004), reasons for earlier significant fluctuations are unknown, and warrant study.

This study maps and analyses the spatial and temporal distribution of adult Lethrinidae in Omani waters in relation to environmental variables. The longer-term context for the work is to improve fisheries management and maintain a sustainable yield. This study in particular asks:

- What are the spatial and temporal distribution patterns of Lethrinidae?
- Is there a relationship between Lethrinidae distribution and environmental factors such as sea surface temperature (SST), salinity, geographical locations and depth?

In order to answer these questions, both qualitative analysis within a geographical information system (GIS) and quantitative methods in the form of a generalised additive model (GAM) were used. GAMs were first used to analyse fish distribution by Swartzman et al., (1992), and later by other researchers such as Daskalov, (1999) and Pierce et al. (2001); their use has increased significantly in recent years. GAM is an appropriate form of model in this context since the method is able to deal with non-linear relationships between an independent variable (emperor abundance) and multiple predictors (spatial, temporal and environmental) at the same time.

2. Material and Methods
2.1 Study area

The study area is located in the Arabian Sea, between 17°30' and 24°00' North (N) and 53°00' and 59°30' East (E) (Map 1). The Arabian Sea is influenced by two types of monsoons—the
Southwest (SW) monsoon from May to October and the Northeast (NE) monsoon from November to March. This area has the strongest annual variability in water circulation in the world (Esenkov et al., 2003). During summer the SW monsoon causes strong currents and productive upwelling with deeper mixing, bringing colder, less-saline water to the surface mixed layer. These features are capable of exporting cool water, rich in nutrients, hundreds of kilometres (km) offshore (Brink et al., 1998; and Morrison, 1997). Advanced High Resolution Radiometer (AVHRR) satellite imagery shows that the SST during the SW monsoon in the Arabian Sea is cooler than in the Gulf of Oman waters. The winter (NE) monsoon winds produce onshore flow and stratification of the water column, with warmer surface water and a shallower mixed layer.

2.2 Data sets
Table 1 shows the characteristics and sources of the data sets for the remotely-sensed environmental parameters and emperor catch data used in this study. The complete government record of fishery catch data from commercial trawling vessels for 1996–2004 was obtained from the Statistics Department of the Ministry of Agriculture and Fisheries of Oman. These data included daily and monthly catch by commercial fishing vessels (trawlers), and fishing effort. Catch per unit of effort—CPUE; kg/day, calculated as total catch over all fishing blocks divided by fishing days—is used as an index of abundance. The fishing blocks have been divided into blocks of 30*30 nautical miles, each block sub-divided into nine areas of 10 * 10 nautical miles. The emperor CPUE data sets were imported from a custom-designed Microsoft Access™ database and integrated into ArcGIS™, and located using the centroid sub-block of 10*10 nautical miles registered Omani commercial fishing areas.

Using a GIS, a time series of monthly satellite images of SST distribution for the period from 1996 to 2004 was derived from AVHRR at a spatial resolution of 4 km and measured in degrees
Celsius (°C). In addition, time series of modelled monthly sea surface salinity (SSS) were derived from the Naval Research Laboratory Navy Coastal Ocean Model for the same period, at a spatial resolution of one-eighth degree and measured in parts per thousand (ppt). Bathymetry data for the study area, also measured in metres, was digitised from Omani charts.

Sea-bottom temperature and sea-bottom salinity were not considered for analysis owing to strong monsoonal advection in the study region (Forster, 1984). This advection plays an important role in reducing salinity through the upwelling of less-saline water from depth during the SW monsoon, and results in mixed temperature layers in depths ranging between 50 m and 200 m (Forster, 1984).

2.3 Exploratory GIS analysis
After analysing the spatial distribution of SST, mapping the spatial distribution of total catch, and mapping annual CPUE of emperor in Omani waters, the spatial and temporal distributions of emperor abundance in relation to SST in the Arabian Sea were explored visually within a GIS. Plots were analysed both season-by-season and on an aggregated annual basis to capture temporal as well as spatial features of distribution of emperor.

Additionally, monthly averages of SSS and the emperor CPUE were plotted and analysed using similar methods. Similar analyses exploring the spatial distribution of emperor with bathymetry were also undertaken, because the literature suggests that the emperors usually occur in waters shallower than 100 m (Carpenter and Allen, 1989; Randall, 1995; Al-Abdessalaam, 1995).

2.4 Statistical modelling
General additive models (Hastie and Tibshirani, 1990) were used to analyze the non-linear relationships between the environmental variables and CPUE. Models were fitted using the
Brodgar 2.4.8 software from Highland Statistics Ltd (www.brodgar.com). The general form of
GAM adopted for this study is given by Equation (1):

\[ g(\mu) = \alpha + \sum_{i=1}^{n} f_i(X_i) + \varepsilon \]  

Equation (1)

where \( g(\mu) \) is the response variable, also defined as the link function, for the CPUE; \( X_i \) is the explanatory variable; \( \alpha \) represents the intercept term in the fitted model; \( f_i \) is the smoothing function of the explanatory variable; and \( \varepsilon \) is the error term. The degree of smoothing is established using the degree of freedom (df) associated with the smoothing function variable. The cubic spline smoother method was used to smooth the variable and estimate the optimal df, using cross validation.

Initial exploratory analysis using dot plots and pairs was undertaken to reveal characteristics of the data sets, and scatterplots were used both to visualise the type of relationship between variables and to identify outliers. The possible explanatory variables included year, month, SST, depth, latitude and longitude, for all years’ data, the dotted lines represent the 95% confidence limits and the tick-marks on the x-axis indicate the number of data points available for different values of x. The partial components, as represented by y-values on the general-additive-model plots, express the relationship between the link function of the response variable and each of the variables included in the model.

Subsequently, models were fitted within the software package Brodgar using a forward stepwise procedure. A cubic spline quasi-Poisson distribution with log link function, appropriate for avoiding over-dispersion, was used to model abundance, with the aim of producing moderate smoothing of the relationship between emperor numerical abundance and factors of interest. The ‘best’ model was selected using the Akaike Information Criterion (AIC; Equation 2), where the model with the lowest AIC was considered most optimal.

\[ AIC = -2\log (\text{Likelihood}) + 2*df \]  

Equation (2)
Adequacy of model fit was assessed by a pseudo-coefficient $R^2$ of residual determination, defined as the fraction of the total deviance explained by the model (Equation 3).

$$R^2 = 1 - \frac{\text{residual deviance}}{\text{null deviance}} \quad \text{Equation (3)}$$

GAM models were subsequently also developed using long-term monthly average data, to allow further detailed analysis of spatial and seasonal trends in abundance of emperor with environmental variables. GAM output plots were visualised by month, using the best fitting smoothers for all explanatory variables included in the model.

3. Results

3.1 Spatial catch of emperor in Omani waters

The emperor is widely distributed in Omani waters, but most are found in the Arabian Sea. Map 1 illustrates the general spatial distribution patterns of the total catch of emperor for trawler fisheries, based upon approximately 16,500 catch records between 1996 and 2004 collated from commercial trawlers in Omani waters. The highest catches were located between $17^\circ00'\text{N}$ and $20^\circ00'\text{N}$.

3.2 Analysis of SST in relation to the distribution of emperor abundance

Maps 2a and 2b show the spatially-referenced variation in monthly mean CPUE from the commercial emperor fisheries, with monthly mean values for SST. From the maps the following observations can be made:

- emperor catch appears in all months, though the distribution of CPUE varies; and
- the temporal distribution of emperor appears to be highest in the months between August and January.

From April to October, maps 2a and 2b show a consistent spatial trend in SST, decreasing from high to low temperatures. During this period, the monthly patterns of CPUE show some degree of fluctuation. During March the commercial CPUE is at its lowest, with levels reaching
10 kg/day in only three locations, near Ra’s Duqm and Sharbithat. In these months too, SST ranged from 25.9°C inshore to 26.7°C offshore. CPUE increases from July to December. The highest widespread emperor distribution is in November and December, abundance reaching a high of >100 kg/day, when the SST ranges between 26°C and 28°C.

Low SST values may be the reason why the lowest CPUE figures arise during the SW monsoon period and the highest after the monsoon finishes. Nonetheless, the overall relationship between spatial and temporal distribution patterns of emperor abundance and SST cannot be fully explained at this stage, but are examined in the GAM analysis.

3.3 Analysis of SSS in relation to the distribution of emperor abundance

Generally, the SSS levels are more than 34 ppt and less than 37 ppt. This variability extends from the Gulf of Oman to the Arabian Sea. SSS is, however, relatively uniform in the Arabian Sea (that is, 54°62' E. and 16°21' N), with a range between 35 and 36.5 ppt. Perhaps surprisingly, given previous research literature on the importance of SSS to emperor distribution, no discernable visual relationship was found between emperor distribution and SSS.

3.4 Analysis of the distribution of emperor abundance in relation to depth

Map 1 shows the average CPUE distribution of emperor abundance in the Arabian Sea, and maps 2a and 2b show the long-term monthly average distribution of emperor abundance (CPUE), overlaid against bathymetry. The analysis of depth relative to distribution of emperor abundance shows that the higher CPUE values (more than 10 kg/day) were found in areas of less than 100 m depth, namely 18°00' to 19°00' N and 57°35' to 57°50' E. Indeed, in areas of more than 200 m depth there was hardly any catch. These patterns clearly indicate that in the Arabian Sea, as bathymetry increases beyond 200 m, the CPUE value decreases to less than 5 kg/day. These results support the findings of other researchers that Lethrinus species occur
between shallow waters and 100 m depth. Depth is examined in greater detail in sections 3.7 and 3.8 below, in the report of the results from the GAM analyses.

3.5 Descriptive statistics and scatterplots, 1996–2004

Analysis using dot plots and scatterplots indicated non-linear relationships between emperor abundance (CPUE) and environmental variables (Figure 1). The emperor CPUE appeared to be higher during 1999 and lower during 2001, with minimum values during March and June, and higher catch rates from August to December.

Analysis of the data indicates interesting results: the higher emperor abundance values were largely associated with an SST range above 24.5 °C and lower than 28.5 °C (Figure 1c). Furthermore, the majority of emperor abundance appears to occur at depths below 200 m (Figure 1d). The most intense emperor abundance is located between 17°30' and 20° N, and between 56°30' and 58°30' E (figures 1e and 1f).

3.6 GAMs fitted to long-term (1996–2004) emperor-fisheries data

The results for the best GAM model fit for the long-term (1996–2004) trawler-vessel data provided a pseudo-$R^2$ of 54%, with 68% of the deviance explained (df=25), and an AIC value of 15.63. Taken together, these metrics suggest a model of reasonable fit, significant at $P<0.001$. Analysis of deviance indicated that year, month, latitude, depth and SST all play a significant part in the model ($p<0.001$).

3.7 GAMs fitted to long-term-average data from emperor trawling vessels

The GAM plots (figures 2a–2e) demonstrate the smoothing functions, for all explanatory variables, within the optimal monthly GAM model results, against trawler-fishery CPUE data.
Longitude was found to have high co-linearity with latitude and therefore was subsequently removed.

The smoothed partial effect of year indicates highest CPUE during 1999 and lowest in 1996 (Figure 2a). A clear seasonal effect on the CPUE is seen in the partial effect of month, with a negative effect from February through April (Figure 2b). Figure 2c suggests that the partial effect of SST at less than 25°C is negative, whereas above 26°C and less than 29°C it is positive. Emperor abundance is greatest in depths shallower than 200 m—in particular in 50–100 m—and decreases with increasing depth (Figure 2d). However, the 95% confidence limits on this variable are broad. Latitude had a strong negative partial effect south of 17° 00' N, and a slight positive effect between 17° 30' N and 20° N (Figure 2e).

3.8 GAMs fitted to long-term-average emperor data by month

As was the result for the non-seasonal model, the influence of the explanatory variable depth was largely non-significant (except for July p<0.01, Table 2) and general showed high AIC values and non-significant results (p>0.05). In contrast, the importance of latitude was strong in all months except May and June. Between July and January, there is a significant influence (p<0.01) of SST on average emperor abundance.

The form of smoothing for the partial effect of SST, latitude and depth (where relevant) is shown month-by-month for July to December—the important catch months (figures 3a–3e). The GAM model for July and August included explanatory variables SST, latitude and depth as significant influences on average emperor abundance, with the depth relationship in August having a negative effect on average emperor abundance (figures 3a and Table 2).

For the best model for September, smoothing for the partial effect of SST suggests that temperatures between 24.5 °C and 26.5 °C have the strongest positive effect on average
emperor abundance, whereas there is a negative effect for SSTs above 27 °C. Smoothing for the partial effect of latitude indicates that it has its strongest influence on abundance at locations north of between 17.5° N and 20° N. The shapes of the smooths were similar during October (Figure 3c) and November (Figure 3d) for the partial effect of SST; this indicates a stronger effect on the average emperor abundance at higher temperatures more than 28.5 °C. During December, the smoothing for the partial effect of SST (Figure 3e) indicates a positive effect for ranges of SST values: between 25.5 °C and 27 °C; as with October and November, latitude has a negative effect north of 20° N. Clearly, the fitted GAM models captured adequately the relationships that were suggested from the explanatory analysis of the scatterplots.

Overall, while depth has an explanatory role in some months, the most important explanatory variables in this analysis of long-term monthly emperor-abundance data for the Arabian Sea are latitude and SST.

4. Discussion

From the visual overlay of spatial and temporal patterns of emperor distribution (as determined by CPUE) in the Omani sector of the Arabian Sea relative to environmental variation, high CPUE occurs in areas where the SST ranges between 25.5 °C and 28.0 °C, while low abundance occurs in areas where the SST is less than 25.0 °C. Relationships between fish distribution and temperature have been found in many studies of different species (for example, Wang et al., 2003; Zheng et al., 2002; and Barratt et al., 2002). However, there is a paucity of information on spatial and temporal variation of emperor globally, and little previous evidence explicitly supporting the existence of a relationship between emperor distribution/abundance and SST variation. Forster, (1984) analysed 19 species in Aldabra (Indian Ocean), one of the species being Lethrinus nebulosus. His general findings showed a relationship between temperature and fish distribution, the fish of this group occurring in areas of upwelling and in the temperature range of 24.3–27.8 °C. However, these results were not specific to Lethrinus nebulosus.
Newman and Williams, (2001) observed that in the central Great Barrier Reef region the highest abundance of *Lethrinus nebulosus* was found during average temperatures of 27 °C. GAMs allowed us to investigate seasonal patterns, visually observed by month, and show a statistically significant relationship between SST and emperor CPUE in October–December with temperatures of 25–27 °C. In seeking to explain the model results for emperor and SST, it is important to note in passing that between June and August there are very rough seas; the level of fishing effort may be affected by this adverse physical environment.

Following the analysis of emperor distribution relative to SST, the results of the relationship between emperor CPUE distribution and SSS were also examined. The SSS patterns in this area showed a variation from 36.0 to 37.7 ppt with little visual association to be made with the higher CPUE of emperor found during the months of September and February 2004. Relatively little is known concerning the influence of salinity on fish, but the range of variation here is low and hence is arguably relatively uniform in the context of its effect on emperor physiology. The high co-linearity of salinity with temperature in upwelling areas is a further factor that may have particularly affected the quantitative modelling process.

On examining the distribution of emperor relative to depth, it was noted that *Lethrinus* were found predominantly in depths ranging from shallow waters to 100 m. These observed patterns are supported by studies on the central Great Barrier Reef (Newman and Williams, 1996; Newman and Williams, 2001) that found that *Lethrinus* spp. were characteristic of shallow waters. These findings are echoed at a number of locations elsewhere (Forster, 1984; Randall, 1995; Al-Abdessalaam, 1995; and Koranteng, 2001). It is possible that depth preferences may overlap with seabed type, which could be a significant factor in the depth distribution of *Lethrinus*. However, a sampling issue is the more likely cause of this result in the context of GAM analyses based on data from trawling vessels, since the full “environmental space” for depth is not covered adequately in this study.
Further sampling issues affecting the results presented here also relate to the issues of environmental space and the use of catch data rather than full-coverage research data. Clearly, the use of catch data is practical, and provides relatively high volumes of data for analysis. However, bias in regard to the reach of boats, inaccuracies in landing data due to problems of underreporting in traditional-fishery domains, and the discarding of commercial catch because of quota limits, are all issues that must be acknowledged.

While the results presented are positive in regard to seasonality and temperature relative to emperor distribution and abundance (as measured by CPUE), further work is required in regard to the model validation by season. The spatial projection of the GAM model and cross-validation of the model in regard to CPUE data collected will be an important further step. Additionally, while the GAM method has provided a useful basis for analyses, comparison with other non-linear modelling methods—such as a feed-forward back-propagation neural network model—and an examination of their relative spatial performance would be of interest. From a biological perspective, the findings here suggest that further research that takes into account the relative age of emperor (to provide the relationship between age and maturation) might be fruitful. If, for example, emperor are more vulnerable to capture during spawning aggregations, the prevention of over-harvesting in that particular period would be a consideration within a sustainable management plan.

References


<table>
<thead>
<tr>
<th>Data sets</th>
<th>Characteristics</th>
<th>Source</th>
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<tr>
<td>Emperor catch and effort data</td>
<td>Daily, monthly catch from January 1996 to December 2004</td>
<td>Statistics Department, Ministry of Agriculture and Fisheries of Oman</td>
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<tr>
<td>Sea surface salinity</td>
<td>Advanced High Resolution Radiometers monthly data, 1996–2004</td>
<td>PO-DAAC physical oceanographic website 4 km resolution</td>
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<td>Modelled sea surface salinity</td>
<td>Naval Research Laboratory Navy</td>
<td>ftp://ftp7300.nrlssc.naw.mil</td>
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</table>

GIS—geographic information system  
GAM—general additive model  
CPUE—catch per unit of effort
Table 2.

<table>
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<th>Month</th>
<th>Explanatory variables</th>
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<td>December</td>
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ε error for parametric component

SST—sea surface temperature

AIC—Akaike information criterion

GAM—general additive model

CPUE—catch per unit of effort
Table 1. Summary of characteristics of the data sets that are included in GIS and GAM, and their sources, for the period 1996–2004

Table 2. Degrees of freedom (df), p-values, R-squared values ($R^2$) and AIC values of the best GAM fitted to emperor abundance (CPUE), for long-term averaged data, by month.

Figure 1(a–f). Scatterplots showing the relationships between long-term (1996–2004) average emperor abundance (CPUE—kg/day) and: (a) year; (b) month; (c) SST (°C); (d) depth (m); and (e) latitude and (f) longitude (decimal degrees).

Figure 2 (a–e). Results of general-additive-model smoothing curves fitted to partial effects of explanatory variables on long-term (1996–2004) average emperor abundance (CPUE—kg/day), as a function of: (a) year; (b) month; (c) sea surface temperature (°C); (d) depth (m); and (e) latitude (decimal degrees). Solid lines are the fitted linear model and dashed lines represent 95% confidence intervals.

Figure 3 (a–e). Results of general-additive-model smoothing curves (solid lines), fitted to partial effects of the explanatory variables on response-variable long-term (1996–2004) emperor abundance (CPUE), months July–December.

Map 1. Spatial distribution of emperor relative to sea depth, in the Arabian Sea, based on total trawler catch between 1996 and 2004.

Map 2(a). Spatial distribution, from January to June, of the long-term (1996–2004) monthly average emperor abundance (CPUE; kg/day) in the Arabian Sea in relation to sea surface temperature (SST; °C).
Map 2(b). Spatial distribution, from July to December, of the long-term (1996–2004) monthly average emperor abundance (CPUE; kg/day) in the Arabian Sea in relation to sea surface temperature (SST; °C).
Map (1)
Map 2 (b)
Figure 2 (a-e).
Figure 3 (a–e).