DOCTOR OF PHILOSOPHY

The biology, population dynamics and fishery management of the blue swimming crab, Portunus pelagicus (Linnaeus, 1758), in Bahraini waters : (Crustacea: Decapoda; Brachyura; Portunidae).

Al-Rumaidh, Mohammed

Award date:
2002

Awarding institution:
Bangor University

The biology, population dynamics and fishery management of the blue swimming crab, *Portunus pelagicus* (Linnaeus, 1758), in Bahraini waters.

(Crustacea : Decapoda : Brachyura : Portunidae)

A thesis submitted to the University of Wales - Bangor,

by

Mohammed Juma Al-Rumaidh
B.Sc., M.Sc.

in candidature for the degree of Doctor of Philosophy

School of Ocean Sciences
University of Wales - Bangor
Menai Bridge
Anglesey LL59 5EY,
United Kingdom

July 2002

Dedication

to the memory of my beloved sister Deena (1956-1997),

may Allah's mercy be upon her

Contents

Page

Chapter 5, Biometric relationships

Chapter 6, Population dynamics

Tables

Page

Chapter 6, Population dynamics

Figures

Page

Chapter 2, Materials & methods

Page

Chapter 3, Hydrology

Chapter 4, Reproductive biology

Chapter 5, Biometric relationships

Chapter 6, Population dynamics

Photographs

ACKNOWLEDGEMENTS

I am sincerely grateful to my supervisors Dr. Graham Walker, Reader, and Dr. Andy Yule, Lecturer, of the School of Ocean Sciences, University of Wales - Bangor, for their suggestions, criticisms and guidance throughout the field work, data analysis and write-up of this thesis. Their ready assistance whenever I approached them was of great support, which enabled me to complete this work.

I am obliged to the Bahrain Centre for Studies and Research (BCSR) for the Scholarship that was offered to me, and I wish to express my appreciation to Dr. Salman Al-Ziani, Secretary General, and Dr. Abdulrahman Musaiger, Director, Environmental and Biological Research Programme, of BCSR for their interest and strong support of this study. Also, I am grateful to the Islamic Development Bank, Kingdom of Saudi Arabia, for their financial support. Without the funds that were provided by both organisations, I would not have been able to undertake the Ph.D. study.

I am grateful to Dr. Ebrahim Abdulqader, National focal Point for the "Gulf Corporation Council (GCC) Shrimp Resources Survey", for giving me free access to join the survey's activities and collect the crab samples for the present study. My sincere thanks are also extended to Mr. Husain Al-Ali and Ali Al-Ali, owners of the trawling dhow that was used during the sampling programme, for giving all the crab catches absolutely free of charge. I am indebted to Mr. Ahmad Al-Shaikh and Mr. Ali Shoaib, technicians at BCSR for their keen interest and efficient involvement in the field and laboratory works. I also wish to thank Mr. Ali Shoaib for giving me free access to the crabs caught by the barrier trap, which belongs to his family. I thank Mr. Vinod Kumar and Ms. Rebecca Sims of the GIS and Remote Sensing Department, BCSR, for their help in processing the longitude and latitude data needed for the trawling programme.

I extend special thanks to Prof. Waheeb Al-Naser, Dean of College of Science, and Dr. Hashim Al-Saeed, Associate Professor (X-chairman of Biology Department), Biology Department, of Bahrain University, for allowing me to use the departmental laboratory facilities. Also, I thank Dr. Abdulradha Shams, Senior Marine Biologist, Directorate of Fisheries, for allowing free access to the photographic equipment at the National Mariculture Station, Bahrain.

My best wishes go to my dear friend Mr. Adnan Al-Azri, Ph.D. student at the School of Ocean Sciences, University of Wales - Bangor, for friendship whilst in Bangor. I wish him a happy life and success in his career.

I take this opportunity to express my sincere love to my parents for their encouragement and taking care of my family during my studies. My deep love is always to my children Farah; Osama, Abdulrahman and Yasmeen, who I missed greatly during my studies in the UK. My gratitude and appreciations are expressed to my beloved wife for her understanding; moral support; encouragement, standing beside me throughout and also for taking care of our children and household responsibilities during my absence. To her I express my endless love and sincere respect.

SUMMARY

Aspects of the biology of the swimming crab, *Portunus pelagicus* (Linnaeus, 1758), were investigated from trawl catches from offshore fishing grounds in Bahraini waters (designated areas A [northern], B [north-eastern] and C [southern], a total area of 1636 km^2) and inshore grounds (traps) around Bahrain over 14 months. *P. pelagicus* were found over a considerable range of temperatures (16-35 °C) and salinities (39-57‰). The abdomen of female crabs shows a distinct change in shape at about 7 cms carapace width (CW), when the pubertal moult takes place. In male crabs the shape of the abdomen remains unchanged throughout life. Breeding season lasts from March to November, with peck numbers of ovigerous females between June and September. Sex ratio analysis has shown that mature female crabs migrate from the shallow waters of areas A and C to the deeper water of area B. Since 73% of all ovigerous females caught were in area B, it was designated the major spawning ground. Females spawn at least twice throughout life and fecundity reaches as high as 1.54 million eggs $brood^{-1}$. Larvae were found over a more restricted temperature (31-35 °C) and salinity range (40-48‰) than the adults. Certain regions of areas A, C and the whole of area D (west) have been identified as the major nursery grounds. Two recruitment periods were identified – a short period (June-July) and a much longer period (December-April). Relative abundance (crabs km^{-1} trawled) varied spatially and seasonally being high during the summer months and low during winter through to spring. CW of crabs in areas A and B exhibits isometric growth with carapace length (CL). In area C, however, both dimensions indicated allometric growth with relatively shorter CL in the larger crabs. Male crabs were found to be relatively heavier than females at 2 cms CW, becoming more so above 6 cms CW. The growth rate for both genders ranged from 0.5 to 2.5 cms CW $month^{-1}$. Base-line recommendations for the crab fishery management in Bahrain from this study include - minimum size limits, banning the capture of ovigerous crabs, banning fishing in the nursery areas as well as modifications to fishing gear.

Chapter 1

General introduction

1. GENERAL INTRODUCTION

1.1 Portunid crabs

Portunid crabs are a tropical to sub-temperate crustacean group (Garth and Stephenson, 1966), widely spread around the world. However, their abundance differs from one region to another as the ecology and life history of each species can vary greatly with latitude and living environment (Tables 1.1 & 1.2) (Garth and Stephenson, 1966; Stephenson, 1972; Soltanpour-Gargari *et al.*, 1989; Ingle, 1992). Table 1.1 highlights that crabs belonging to the subfamily PORTUNINAE occur in all the oceans around the world.

Table 1.1. Distribution of Portunidae subfamilies world-wide

	Geographical Region		
Subfamily	Indo-West-Pacific	Pacific Coast of America	North-eastern Atlantic
Carcininae	*		*
Polybiinae	*		*
Caphyrinae	*		
Catoptrinae	*		
Portuninae	*	*	*
Podophthalminae	*		
Macropipinae	*	*	

Table 1.2. Geographical distribution of the commercial species of portunid crab based on the FAO statistical catches and landings data for 1992.

		Fishing area								
English name	Scientific name	21	27	31	37	41	51	57	61	71
Sand crab	*Portunus pelagicus*						*	**		**
Gazami crab	*Portunus tritubeculatus*								**	
Mud crab	*Scylla serrata*						*	**		**
Swimming crab	*Portunus spp.*		**	*	*					*
Blue crab	*Callinectes sapidus*	**		**						

Table 1.2 Continued

English name	Scientific name	Fishing area 21	27	31	37	41	51	57	61	71
Dana swimcrab	*Callinectes danae*					**				
Mediterranean shore crab	*Carcinus aestuarii*				*					
Green crab	*Carcinus maenas*	*	*							

* denotes to catch less than 1,000 mt.
** denotes to catch more than 1,000 mt.

Key to Fishing areas (Table 1.2)
21 North-western Atlantic
27 North-eastern Atlantic
31 Western Central Atlantic
37 The Mediterranean
41 South-western Atlantic
51 Western Indian Ocean
57 Eastern Indian Ocean
61 North-western Pacific
71 Western Central Pacific

1.2 Swimming crab, *Portunus pelagicus* (Linnaeus, 1758)

1.2.1 Systematics

1.2.1.1 Synonyms

Cancer pelagicus: Linnaeus (1766), *Neptunus pelagicus*: De Haan (1833), Milne-Edwards (1861), Miers (1866), *Lupea pelagicus*: Milne-Edwards (1834), Barnard (1950).

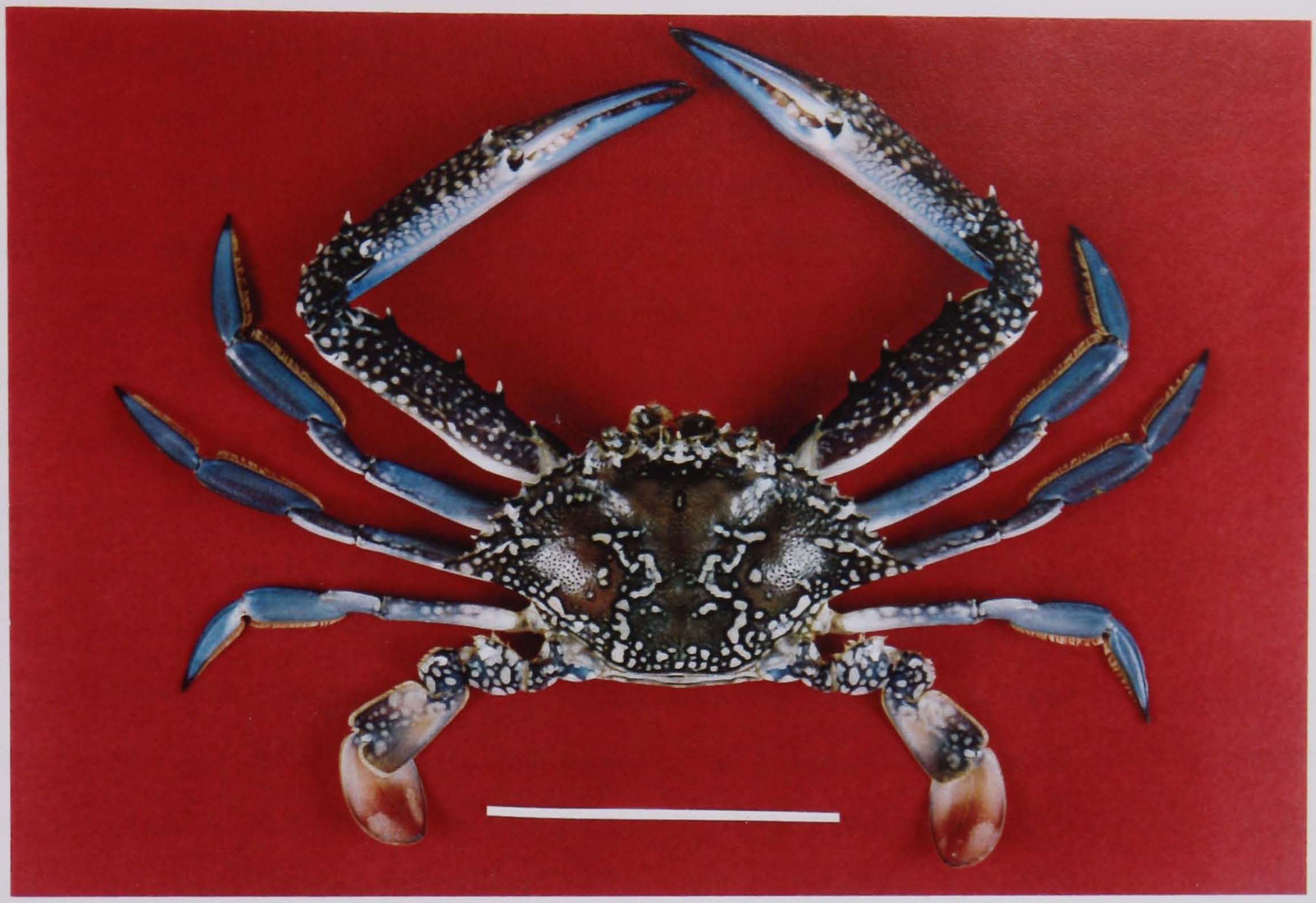
1. 2.1.2 Taxonomic history

In the earlier literature, the genus *Portunus* was long known as *Neptunus* de Haan 1833, however, the misidentification was corrected by the International Commission on Zoological Nomenclature in 1956. Therefore, the genus commonly known as *Neptunus* de Haan 1833, became *Portunus* Weber, 1795 (Stephenson and Campbell, 1959). Translation of its name from the Latin is *Portunus* meaning "god of harbours" and *pelagic* meaning "of the ocean" (Lewis and Short (1879) as cited by Gribble and Thorne, 1998).

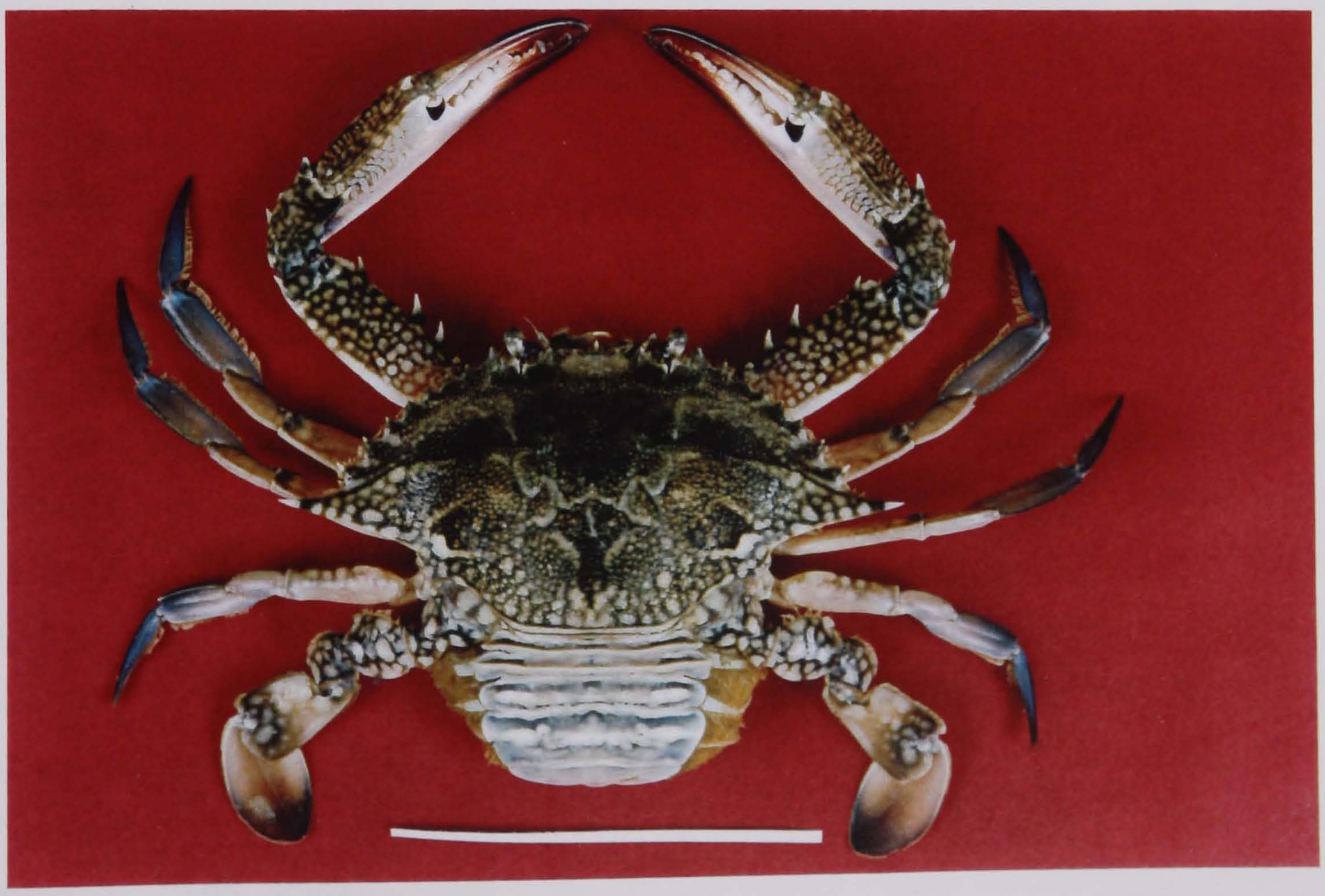
1.2.1.3 Description

Portunus pelagicus (Linnaeus,1758) (see photographs 1.2 and 1.2), is a portunid crab belonging to the family PORTUNIDAE Rafinesque, 1815. This family is made up of the group known as the swimming crabs (Stephenson, 1972). Many studies have dealt with this family from a systematic point of view for more than a century, which indicates its importance among the Decapoda. The Portunidae is one of the major families within the infraorder BRACHYURA Latreille, 1803, the "true crabs", which are considered strong and powerfully built with a heavy exoskeleton. The carapace is flattened and rounded, forming the typical crab-shaped body, and the abdomen is much reduced and folded forward under the carapace. The antennae are usually short, and the front thoracic limbs are modified to form chelipeds which possess at their ends the prehensile claw or chela, while the other 4 pairs of thoracic limbs (pereiopods) are variously developed, ending normally in a single dactyl (Campbell, 1994). These crabs are able to regenerate the chelae propodus in event of loss (Huxley and De Beer (1934) as cited by Evian, 1971). The major characteristics of the PORTUNIDAE, are the morphological adaptations of the most posterior pereiopods into paddle-like structures for swimming, whereas the three more anterior pairs retain their original walking function. In other brachyuran families all four pairs of thoracic appendages are used for walking (White and Spirito, 1973). Classification of *P. pelagicus* is as follows:

Phylum ARTHROPODA
Superclass CRUSTACEA Pennant, 1777
Class MALACOSTRACA Latreille, 1806
Subclass EUMALACOSTRACA Grobben, 1892
Superorder EUCARIDA Galman, 1904
Order DECAPODA Latreille, 1803
Infraorder BRACHYURA Latreille, 1803
Section BRACHYRHYNCHA Borradaile, 1903
Family PORTUNIDAE Rafinesque, 1815
Genus PORTUNUS Weber, 1795
Species PORTUNUS PELAGICUS (Linnaeus, 1758)



Photograph 1.1. Dorsal view of a mature male *Portunus pelagicus*. Scale bar equals 10 cms.



Photograph 1.2. Dorsal view of an ovigerous female *Portunus pelagicus*. Scale bar equals 10 cms.

A detailed key for *P. pelagicus* has been given by Stephenson and Campbell (1959) and Stephenson (1972), with the former summarising the major characteristics of the genus as: (1) broad carapace; (2) nine anterolateral teeth marginally on the carapace, of which the final lateral spines are greatly expanded. *P. pelagicus* is distinguished from the closely related species *Portunus sanguinolentus* Herbst, 1796, which is also found in the Arabian Gulf, but not as commonly as *P. pelagicus*, by the presence of a spine at the far end of the posterior border of the segment of the chelipeds (Chhapgar 1957) and the absence of the reddish brown spots surrounded by a bluish white rim (Carpenter *et al.*, 1997). A key to the *Portunus* species in the Arabian Gulf region is given by Apel and Spiridonov (1998) .

A striking difference in colour is shown between males and females of *P. pelagicus*. Male crabs from Bombay, India, are recorded as being pinkish purple, with extensive irregular white spots with the tips of the chelae and the distal segments of the legs purple; females are sand-coloured (Chhapgar, 1957). In Australia, the legs of males range from blue to lilac with white mottling, the carapace purplish-brown with pale mottling (Stephenson and Campbell, 1959) and females are brownish in colour (Anon, 1978). In Bahrain, the legs of males are blue, whereas the overall body of female crabs ranges between yellowish-brown, brown and greenish depending on habitat (Al-Rumaidh, 1995). The pigmentation in males varies between adults and juveniles and in adults there are also regional differences in pigmentation (Stephenson, 1972).

1.2.2 Geographical distribution

Portunus pelagicus, is one of the commercially exploited edible crabs, distributed widely throughout the Indian and West-Pacific Oceans, ranging from South and East African coast, Tanzania, Mozambique, Madagascar, the Red Sea, Gulf of Aden, Socotra through the Gulf of Oman, Arabian Gulf, Pakistan, India, Sri Lanka to Thailand, Singapore, Indonesia, Philippines, China, Japan and on to Australia (south-east Queenslad and western Australia), northern New Zealand, New Caledonia and Tahiti (Stephenson, 1972; Potter *et al.*, 1987; Trainor, 1990; Al-Rumaidh, 1995; Beckley *et al.*, 1995; Apel and Spiridonov, 1998). It is also found in the Red Sea and the eastern Mediterranean, where it has migrated in through the Suez Canal (Abdel Razek, 1988; Apel and Spiridonov, 1998). Although mainly a tropical and subtropical species, it is also reported in temperate regions

(Thomson, 1951; Pillay and Nair, 1971; Penn, 1977; Smith, 1982; Potter *et al.*, 1983). The various common names for the crab in different languages, reported in the literature are: (in English) Sand Crab; Blue Crab; Blue Swimming Crab or Manna Crab; (in Japanese) Taiwan Gazami; (in Filipino) Alimasag; Suga suga; Kasag; Lampay; and Dawat; (in Arabic): Gubgub, Saratan Sabih, in the Arabian Gulf and Caboria in Egypt, all of which indicates its wide distribution and importance in the stated regions. In western Australia this species is commonly known as the blue manna, however, this local name is somewhat inappropriate as the blue colouring is confined to the male and even then variation occurs in different localities (Anon, 1970).

1.2.3 *Portunus pelagicus* fishery around the Indian and West-Pacific Oceans

P. pelagicus supports substantial commercial and recreational fisheries throughout its range (Prasad and Tampi, 1951; Thomson 1951; Smith, 1982; Potter *et al.*, 1983). Nevertheless, *P. pelagicus* fisheries vary in intensity not only between regions, but also between sub-regions within the same country. In Australia, *P. pelagicus* of the Gulf of Carpentaria (tropical) are not fished commercially, whereas in Moreton Bay (subtropical) they are heavily exploited (Weng, 1992 and Sumpton *et al.*, 1994a). Furthermore, around Torrens Island, Australia, *P. pelagicus* is found in large numbers from late spring to early autumn and supports an intensive local fishery (Neverauskas and Butler, 1982). In India, *P. pelagicus* supports a thriving crab fishery at certain places, whereas its importance in others is negligible. However *P. pelagicus* is extensively fished and supports a fairly lucrative commercial fishery in the Chilka Lake (Chopra, 1939), near Mandapam (Prasad and Tampi, 1951; James, 1966), Zuari Estuary (Dhawan *et al.*, 1976), and in the Pulicate Lake (Joel and Raj, 1981), with the fishing season differing from one place to another but occurring mainly during the non-monsoon season (Table 1.3). Prasad and Tampi (1953) and Radhakrishnan and Samuel (1980) have reported that the crab fishery in India is not recognised as a major industry, although it is a source of income to many fin fishermen particularly during the off-season. Prasad and Tampi (1951) gave two reasons why the crabs are not commercially important in India - (1) the extreme perishable nature of the commodity and lack of adequate transportation and (2) there was no great demand as the population has not developed a taste for crab meat.

Table 1.3. *Portunus pelagicus* fishing seasons in India waters.

Region	Fishing season	Reference
Mandapam	February – May	Prasad and Tampi (1951)
Madras	March – June	Prasad and Tampi (1951)
Palk Bay, Gulf of Mannar	December – June	Prasad and Tampi (1951)
Tirupalakudi	Whole year	Prasad and Tampi (1951)
Zuari Estuary	December – April	Dhawan *et al.* (1976)
Manglore Coast	October – May	Manohara Ram and Chandra Mohan (1978)
Sikka	May – September	Patel *et al.* (1979)

In 1992 *P. pelagicus* contributed 12.8% in the total world catch of portunid crabs (FAO, 1992). Sumpton *et al.* (1994a) reported that the *P. pelagicus* fishery in Moreton Bay, which forms the major commercial catch in Queensland, was worth in excess of $A2 million (equivalent to £ 739,345) annually. The fishery in Kagoshima Bay, Japan, is very lucrative because of the high market price of 2000 yen kg^{-1} (equivalent to £ 11.00 kg^{-1}) (Kawamura *et al.*, 1995). In the Arabian Gulf, berried females (= ovigerous females – those carrying an egg mass attached to the pleopods) of this species fetch high market prices (Carpenters *et al.*, 1997). The retail price for such female crabs in the Bahrain fish market goes as high as BD. 1 kg^{-1} (i.e. £ 1.90) twice the price of male crabs. In the Mediterranean, Abdel Razek (1988) noted that the *P. pelagicus* fishery, centred in Alexandria, Egypt, had grown considerably and is being intensively exploited. The variety of fishing gear used around the Indo-Pacific Ocean for catching *P. pelagicus* is presented in Table 1.4.

Table 1.4. Different types of fishing gear used for catching *P. pelagicus* in Australia, Japan, India and Bahrain.

Region	Fishing gear	Source
South-west of western Australia	Drop net, 200 yards long and 1 yard deep, mesh size < 3 inch.	Thomson (1951) and Anon (1970).
	Gill net	Melville-Smith *et al.* (1999)

Table 1.4 Continued

Region	Fishing gear	Source
Gulf of Carpentaria Moreton Bay, Australia.	*Small-mesh bream trawl.*	Stephenson *et al.* (1982).
	Otter trawl net, mesh size 42 mm.	Weng (1987).
	Pot (Cylindrical shape, diameter 90 cms; height 30 cms approximately).	Sumpton *et al.* (1989).
	Twin 7.3 metre Yankee Doodle otter trawl net with a 38 mm mesh opening	Sumpton *et al.* (1989); Shields (1992).
	Twin otter trawl, 11 metre headrope length with a 45 mm mesh opening.	Weng (1992).
Kagoshima Bay, Japan	*Rectangular trap*, 60 cms long, 20 cms high; *and Hemispheric trap*, 70 cms long, 35 cms high.	Kawamura *et al.* (1995).
Palk Bay, India	*Gill net* (local name: nandu valai, means crab net), 300 feet long, and two feet high, used along the in-shore waters.	Prasad and Tampi (1951); Ameer Hamsa (1973).
Great Nicobar Island, India	Surface net	Premkumar and Danial (1971).
Manglore, India	*Trawl net.*	Manohara Ram and Chandra Mohan (1978).
Sikka, India	*AD net* (Stake net), made of cotton no. 4.	Patel *et al.* (1979).
Thailand	*Bottom gill net,* 10 cms mesh size; *Trap*, 60 X 45 X 20 cms	Yoodee (1984).
Bahrain	*Barrier trap* and *Gargoor* (coastal areas); and *Otter trawl net* with a 30 mm mesh opening.	Al-Rumaidh (1995).

1.2.4 *Portunus pelagicus* fishery management and regulations

Management regulations are essential for conservation and perpetuation of crustacean fisheries (Kuris and Lafferty, 1992). The standard management practices on commercial species include restrictions on: (1) number of individuals per catch, (2) minimum size (carapace length or carapace width), (3) sex (male only), (4) effort (number of fishing days), (5) closed areas, (6) closed season "during breeding periods" and (7) fishing gear. In Australia, *P. pelagicus* fishery regulations are not common throughout the continent. Anon (1970) has reported that the legal minimum size (carapace width) for male crabs was 127 mm, whereas others have reported it as 150 mm. However, in other areas, the minimum size for males is even smaller and harvesting of females is also permitted (Potter *et al.*, 1987). Kawamura *et al.* (1995) found that male *P. pelagicus* were more attracted to a bait of sugarcane and fish than females, from which they concluded that the use of sugarcane helps in conserving the females and consequently sustaining the *P. pelagicus* population. In India, although *P. pelagicus* is extensively fished at Chilka Lake, near Mandapam, Zuari Estuary and Pulicate Lake, the fishery is neither organised nor regulated (Dhawan *et al.,* 1976). From work on lobsters, Addison and Bannister (1994) have suggested conventional fisheries measures for crustacean stock management stating that "minimum size increases, or reduction in catch or in fishing effort, can promote "enhancement" of stocks by reducing fishing mortality, by increasing survival or by increasing the number of egg-bearing females in the stock". Enforced and recommended regulations of *P. pelagicus* populations in different parts of the world, are presented in Table 1.5.

However, although the fishery regulations were designed to conserve stocks, the management measures have also, inadvertently, given protection to parasitised crabs. Infected females and males smaller than 150 mm carapace width are usually thrown back into the sea (Stephenson and Campbell, 1959) and consequently cause more spread of infection among the population. In Moreton Bay for instance 10-15% of the *P. pelagicus* catch is infected with the rhizocephalan barnacle parasite *Sacculina granifera* (Lester, 1978). For the last 18 years, however, the fishermen of Queensland, Australia, have been allowed to keep and sell all parasitised crabs as the meat appears not to be affected by the parasite (Lester, 1980). The Australian fisheries authorities took measures in response to Lester (1978) who recommended a further two methods to minimise the impact of such parasite infection on the fishery - (1) increasing fishing pressure and (2) determining the most vulnerable point in the parasite life-cycle where it could be combatted.

Table 1.5. Enforced and recommended management regulations of *Portunus pelagicus* around Australia, Japan and India.

Region	Regulation	Status	Reference
Moreton Bay, Australia	**1.** Limiting the number of pots used by commercial fishermen and recreational fisherman to 50 and 4, respectively; **2.** A total ban on the landing of females; **3.** a minimum size limit of 150 mm carapace width (CW) for males; **4.** Amateur fishermen using drop nets are prohibited from using more than ten drop nets in any one day.	Enforced	Thomson, 1951; Sumpton *at al.*, 1989; Potter *et al.*, 1987; Potter *et al.*, 1991; Weng, 1992.
Kagoshima Bay, Japan	Fishermen are permitted to use 60 crab traps per vessel.	Enforced	(Kawamura *et al.*, 1995).
Manglore Coast, India	Conserving berried females from February – March.	Recommended	Manohara Ram and Chandra Mohan (1978).

The influence of parasitism on the hosts, especially those of commercial importance, produce considerable loss to the industry (Phillips, 1978). Lester (1980) has given a number of examples on the losses of some crustacean fisheries because of parasitism. Referring to *P. pelagicus*, he reported that the loss to the industry in Moreton Bay, was estimated at about $ 60,000 (equivalent to £ 22,180) a year.

It is important to emphasise here that understanding life history, determining accurate estimates of size at sexual maturity, breeding season, as well as the general ecology of the species, are essentially important tools for establishing sound fishery regulations to facilitate the rational exploitation of the marine resource (Chopra, 1939; Prasad and Tampi, 1953; Abdel Razek, 1988).

1.2.5 Habitat

P. pelagicus is found in a variety of habitats from the intertidal zone to a depth of around 65 m and from estuaries to open sea, although it prefers to live on sandy and muddy bottoms (Campbell and Stephenson, 1970; Stephenson, 1972; Manohara Ram and Chandra Mohan, 1978; Sumpton *et al.*, 1989). Prasad and Tampi (1953) reported that *P. pelagicus* at Mandapam, India, prefers a mixed substratum of sand and mud. Confirmation comes from Dhawan *et al.* (1976), in their ecological study in the Zuari Estuary, India, wherein they found that *P. pelagicus* tend to prefer a loamy habitat, i.e. a type of substratum neither sandy nor clay. The crab prefers salinities between 30-40‰ (Kurata and Midorikawa, 1975; Potter *et al.*, 1983) so Gray *et al.* (1990) grouped it with the high salinity species, which can withstand salinity as high as 45‰ (Todd, 1995). However, Chopra (1939) reported that *P. pelagicus* could acclimatise to living in freshwater for at least part of the year around Chilka Lake, India, which would suggest that the species has remarkable salinity tolerance (euryhaline).

P. pelagicus is nocturnal, burrows in the soft sediment during the day and exhibits peaks of activity during the night, moving about and feeding (Edgar, 1990). Stephenson *et al.* (1982) reported that *P. pelagicus*, *P. hastatoides*, and *P. sanguinolentus* all had higher catch rates at dusk than at midday.

1.2.6 Life history

Detailed information on the life history of *P. pelagicus* is limited and scattered in the literature. Nevertheless, the life-cycle is generally typical of marine crab species. Males and females form breeding pairs and successful mating is determined by maturity, moult stage and elaborate courtship.

In general, whole adult biology of *P. pelagicus* is temperature dependent, i.e. below certain temperatures movement and feeding are limited and vary between the sexes. Thus, at 19 °C, 90% of males remain active but only 45% of the females. Sumpton and Smith (1990) reported *P. pelagicus* to be most active at temperatures of 25 °C and above. Earlier investigations on crabs showed that sexual maturity occurs at a certain size and is accompanied by a series of morphological changes, considered to be secondary sexual characteristics, which occur usually after the pubertal moult (Hartnoll, 1974). The changes are more significant in females with changes to the abdomen, pleopods, and sternum (Hartnoll, 1974) and Adb EL-Hamid (1988) reports the change in the abdominal flap from a triangular shape to that of a wide semicircle. In males the T-shaped abdominal apron does not change significantly at maturity (Abdel Razek, 1988), but the main internal feature is the appearance of the vas deferens (Ryan, 1967a). Furthermore, changes in the colour of the chelae at maturity are often observed, usually from a light bluish to dark prominent blue in males and to a dark brown colour in females (Abdel Razek, 1988; Reeby *et al.*, 1990; Al-Rumaidh, 1995). The onset of maturity in the males is always at a smaller size (carapace width) compared to females (Table 1.6).

Table 1.6. Size at sexual maturity of male and female *Portunus pelagicus* in different world regions, given in carapace width (mm).

Region	Wild		Reared		Reference
	Males	Females	Males	Females	
India	-	108	-	-	Prasad and Tampi (1953)
India	-	77	-	-	Devi (1985)
Philippines	37	40	-	-	Batoy *et al.* (1987)
Japan	64	7-	67	80	Yatsuzuka and Meruane (1987)
Egypt	-	90-100	-	-	Abdel Razek (1988)
Egypt	60	-	-	-	Abdul EL-Hamid (1988)
India	87	-	-	-	Reeby *et al.* (1990)
Gulf of Carpentaria, Australia	70	80	-	-	Weng (1992)
Moreton Bay, Australia	80	80	-	-	Weng (1992)
	81	81	-	-	Shields and Wood (1993))
Bahrain	70	80	-	-	Al-Rumaidh (1995

Yatsuzuka and Meruane (1987) reported that *P. pelagicus* in Japan takes almost 4 months to attain maturity and that wild stocks attain maturity earlier than those reared in the laboratory, presumably due to better and varied feeding conditions in the natural environment. Abd EL-Hamid (1988) reported that males in Egypt attain sexual maturity within 18-19 moults following the first true crab stage. Information on size at first maturity is not only of scientific interest but also of practical value as it serves as an important tool in the study of population dynamics and the management of any commercially exploited resource (Prasad and Tampi, 1954; Campbell and Fielder, 1986; Abdel Razek, 1988; Abd EL-Hamid, 1988; Jacob *et al.*, 1990 Reeby *et al.*, 1990).

As is normal in Crustacea, the moulting and reproductive cycles in *P. pelagicus* are closely linked and mating in *P. pelagicus* only occurs between a hard-shelled male and soft-shelled female, immediately after she moults (Hartnoll, 1969; Fielder and Eales, 1972; Abd EL-Hamid, 1988; Weng, 1992; Shields and Wood, 1993; Kangas, 2000), as is common in the Portunidae (see Table 1.7).

Table 1.7. Species of portunid crabs with soft shelled females and hard shelled males at mating.

Species	Investigated by
Callinectes sapidus	Churchill (1919) as cited by Hartnoll (1969), and Van Engel (1958).
Carcinus maenas	Broekhuysen (1936) as cited by Hartnoll (1969), Cheung (1966), Reid *et al.* (1994).
Portunus sanguinolentus	George (1963) as cited by Hartnoll (1969), Ryan (1967b).
Portunus trituberculatus	Oshima (1938) as cited by Hartnoll (1969).
Thalamita crenata	Ryan (1966).
Podophthalmus vigil	Ryan (1966).
Portunus pelagicus	Al-Rumaidh (1995).

The male is attracted to copulate with the female by a sex pheromone released by the female just before she enters ecdysis. Kittredge and Takahashi (1971) suggested that the pheromone was 20-hydroxyecdysone, although Ryan (1966) had reported that it is released through excretory pores. Eales (1974), however, stated the pheromone source remained unknown. Gleeson (1980) suggested that males probably detect a sex pheromone in the water via chemoreceptors on the outer flagella of the antennules. Working on *Carcinus* *maenas*, Reid *et al.* (1994) reported that males of this species were only able to recognise 53% of pre-moult females when offered a choice, which is no better than chance.

Investigations indicate that the courtship is a prolonged process. In the genera *Portunus* and *Callinectes*, the male carries the female clasped beneath him for 4-10 days before she moults in the position called "Cradle-Carry" (Hartnoll, 1969; Kangas, 2000). Ingles and Braum (1989) reported that mating behaviour consists of three typical phases. First is the precopulation phase wherein the male lifts the female using his 3rd pereiopods while the female accommodates for this by folding her pereiopods towards her carapace so avoiding touching the substratum. This phase lasts for three days and both animals feed during this time. The male continues carrying the pre-moult female until ecdysis is imminent, then he releases her in order to allow her to moult, which lasts 30 minutes. He remains close keeping a distance of about 30 cms assisting her during the process, guarding and protecting her from predators for a few days after mating, as she can not defend herself during this period due to her soft body (Fielder and Eales, 1972). Two hours after moulting, the pair resume the precopulation position, but now the female has been turned over into the ventral-to-ventral position. The mating crabs maintain this position for 2 hours and 40 minutes, after which with copulation finished the crabs separate. Ameer Hamsa (1979 and 1982) has observed *P. pelagicus* moulting under laboratory conditions, and reported four stages in the cycle, viz. premoult, moulting, postmoult, and intermoult, and described them. The crab ceases feeding 2-3 days prior to the moult and the actual process of shedding takes place only at night and is completed within 12-15 minutes. The newly moulted crab does not eat for 1-2 days, due to the soft mouthparts and the cuticle hardens completely in 5-6 days. When hardened and able to swim effectively, the copulated females move to deeper waters to spawn. In *P. pelagicus*, the transferred sperm is stored by the female until the eggs are laid, at which time fertilisation occurs (Smith, 1982). Reid *et al.* (1994) found that males of *Carcinus maenas* > 65 mm carapace width (CW), prefer to copulate with females ranging from 38-43 mm CW, rather than the larger females (50-58 mm CW).

Spawning season of *P. pelagicus* varies from one region to another (Table 1.8), depending on latitude where the temperature and other physical factors play a major role.

Abdul EL-Hamid (1988) reported that egg-laying in Egyptian waters usually takes place within 1-2 months of mating. He further emphasized the effect of temperature on the occurrence of egg-laying, so that if crabs mate during the winter egg-laying can be delayed until the following spring when the sea is warmer. Similarly, in temperate waters female *P. pelagicus* store sperm until the water temperature is high enough for egg-laying (Todd, 1995). In Ragay Gulf, Philippines, Ingles and Braum (1989) reported that female *P. pelagicus* lay eggs 13 days after copulation and the eggs hatch after 5-6 days incubation at 29.5 °C. The variation in the breeding seasons presented in Table 1.8 is thought to be controlled largely by temperature, but other environmental factors may also be important (Potter *et al.*, 1983 and Campbell and Fielder, 1986). Unfortunately, none of the scientists listed in Table 1.8 reported the temperature range in their publications.

Potter *et al.* (1983) reported two colours for the egg mass (known as sponge) of *P. pelagicus*, i.e. yellow and grey. Campbell and Fielder (1988) have graded the egg mass by colour into two categories: orange and black indicating immature and mature eggs, respectively. In the closely related species, *Scylla serrata*, the egg mass changes colour from greyish-yellow to brown to brownish-black to dark as the yolk is utilised during embryonic development and the progressive formation of the chromatophores and the eyes darken the colour (Marichamy and Rajapackiam, 1984; Prasad and Neelakantan, 1989). A few hours before the eggs hatch the female migrates to deeper water with more constant temperature and oxygen saturation levels essential for a successful hatch (Anon, 1978). Tests showed that hatching of eggs was most successful in 100% oxygen-saturated water, however, hatching could occur in water with an oxygen concentration as low as 41% but at more limited rates (Meagher, 1970). Females of *P. pelagicus* spawn up to 0.7- 2 million eggs per batch (Yatsuzuka, 1962; Meagher, 1970; Ingles and Braum, 1989; Campbell and Fielder, 1988; Todd, 1995), equivalent to that of the closely related species, *Callinectes sapidus*, which spawns 1-2 million eggs per batch (Tagatz, 1968). The eggs hatch to the first of a series of four zoeal larval stages. The fourth zoeal stage metamorphoses to a single megalopa stage, which becomes benthic in existence (Kurata and Midorikawa, 1975; Anon, 1978; Shinkarenko, 1979). On metamorphosis to the first crab stage, the young crabs migrate to shallow waters where they undergo a series of 11 juvenile instars culminating in the mature adults (Yatsuzuka and Meruane, 1987). In Australia, it was realised that the time taken by the different stages might vary in the sea. Some 83 to 136 days pass between the time of hatching and when the young crabs first appear in the Leschenault inlet (Anon, 1978).

Table 1.8. Egg-laying seasons of *Portunus pelagicus* in different regions across its geographical range.

Region	Region	Spawning season	Reference
Northern hemisphere	Egypt	Winter, spring, summer and autumn.	Bawab and El-Shereif (1987)
	Egypt	Winter and spring (peak in April).	Abdel Razek (1988)
	Bahrain	Spring (peak in May), autumn (November) and winter (December).	Al-Rumaidh (1995)
	Cochin, India	Winter, Spring and summer.	Pillai and Nair (1973)
	India	Winter.	Ameer Hamsa (1978b)
	India	Winter and spring	Devi (1985)
	Tosa-Uranouchi inlet, Japan	Spring and autumn	Yatsuzuka (1962)
	Japan	Spring and summer	Yatsuzuka and Meruane (1987)
	Philippines	Winter and summer	Botay *et al.* (1987)
	Philippines	Winter-spring, and summer-autumn	Ingles and Braum (1989)
Southern hemisphere	Leschenault inlet, Australia.	Spring	Anon (1978)
	Peel-avey,Australia	Summer	Potter *et al.* (1983)

The life-cycle of *P. pelagicus* is quite similar to that of *Callinectes sapidus*, which has been extensively studied. Tagatz (1968) summarised the life-cycle of *C. sapidus* along the east coast of Florida, where matings were commonly observed from 11-215 km offshore, however, primary mating areas were sited in near-shore waters. Females of *C. sapidus* mate once (Van Engel, 1958; Gleeson, 1980), but males may mate during each of their last three growth stages (Van Engel, 1958). Mating occurred in January-February, March-July and October-December. After mating the females in the inshore waters migrate to deeper waters for spawning which occurs within 1 to 2 months. The larval stages consist of 8 zoeal stages which develop through the first two stages within a few kilometres of the shore. Development after stage 2 takes place further offshore. Some larvae return to inshore waters as megalopae. Costlow and Bookhout (1959) reported that development of a *C. sapidus* zoea to the megalopa takes approximately 30 days in Chesapeake Bay, U.S.A., whereas in the laboratory it required 31-49 days.

1.2.7 Larval development

Identification of planktonic crab larvae is of prime importance in order to study early life histories of the crabs in nature (Kurata and Midorikawa, 1975). Most current literature deals largely with larval development, especially for species with commercial value, declining fishery, or suitable for culture (Marichamy and Rajapackiam, 1984). Ingle (1992) has described the complete larval stages, reared in the laboratory, of 9 out of 16 portunid crabs found in the north-eastern Atlantic Ocean, viz.: *Liocarcinus holsatus*, *Liocarcinus marmoreus*, *Liocarcinus pusillus*, *Liocarcinus depurator*, *Liocarcinus arcuatus*, *Liocarcinus corrugatus*, *Liocarcinus henslowii*, *Necora puber*, and *Bathynectes longipe*. All have 5 zoeal stages and 1 megalopa. The other portunid species studied in terms of their larval development are presented in Table 1.9.

Table 1.9. Portunid crabs reared in the laboratory for larval development studies.

Species	Investigated by
Portunus sanguinolentus	Kurata and Midorikawa (1975)
Portunus spinicarpus	Bookhout and Costlow (1974) as cited by Greenwood and Fielder (1979)
Portunus rubromarginatus	Greenwood and Fielder (1979)
Portumnus latipes	Paula (1988)
Callinectes similis	Bookhout and Costlow (1977) as cited by Greenwood and Fielder (1979)
Callinectes sapidus	Costlow and Bookhout (1959); Costlow *et al.* (1959)
Ovalipes ocellatus	Costlow and Bookhout (1966) as cited by Rice (1979)
Macropipus maroreus	Goldstein (1971) as cited by Krishnan and Kannupandi (1990)
Scylla serrata	Ong Kah Sin (1964); as cited by Fielder and Greenwood (1979) Marichamy and Rajapackiam (1984)
Thalamita crenata	Prasad and Tampi (1953); Krishnan and Kannupandi (1990)
Thalamita danae	Fielder and Greenwood (1979)

A number of studies have followed the larval development of *P. pelagicus* in Australia (Shinkarenko, 1979; Campbell and Fielder, 1988), Japan (Yatsuzuka, 1962; Kurata and Midorikawa, 1975; Yatsuzuka and Sakai, 1980; Yatsuzuka and Meruane, 1987) and Philippines (Motoh *et al.*, 1978; Ingles and Braum, 1989). All report that the larval stages of *P. pelagicus* consist of 4 zoeae and 1 megalopa, but Prasad and Tampi (1953), from India, have reported that the 3rd zoea directly metamorphoses into the megalopa. It is most likely that the latter authors were working on another species, as the larvae of many marine animals are very similar in the early stages which can lead to confused identification (Anon, 1970). Nevertheless, the 4 zoeal stages of *P. pelagicus* can be distinguished from each other by the number of abdominal somites (Yatsuzuka, 1962). Shinkarenko (1979) reported that the larval stages of *Portunus pelagicus* and *Portunus spinicarpus* have similar types and locations of major setae and it is difficult to distinguish between the larvae of *P. pelagicus* and *Scylla serrata*. The zoeae of the latter two species are easily distinguished (see Table 1.10). Table 1.11 summarises the lengths of the zoeal stages of 6 portunid species, derived from Yatsuzuka (1962), Kurata and Midorikawa (1975), Paula (1988), and Ingle (1992).

In laboratory conditions, *P. pelagicus* larvae survive well when reared on a diet of *Artemia* nauplii at temperatures between 20 and 25 °C and salinities between 30 and 40‰. Larval development is completed in 2 to 3 weeks under these conditions (Meagher, 1970; Motoh *et al.*, 1978). Anon (1970) found that each zoeal stage lasts approximately 3-4 days, and the megalopa around 7-8 days, followed by a series of crab stages each of some 8-14 days. Being carnivorous, *P. pelagicus* zoeae are usually reared in the laboratory on *Artemia* nauplii, whereas at the megalopa stage small pieces of prawn, fish, and mussels can be supplemented (Prasad and Tampi, 1953; Yatsuzuka, 1962).

Table 1.10. Comparison of the diagnostic morphology of the antennule, scaphognathite and maxilliped exopods of all the zoeal stages of *Portunus pelagicus* (*P.p.*) and *Scylla serrata* (*S.s.*) (after Shinkarenko, 1979).

Zoeal stage	Antennule aesthetascs		Scaphognathite setae		Maxilliped exopods natatory setae	
	P.p.	*S.s.*	*P.p.*	*S.s.*	*P.p.*	*S.s.*
I	2	3	4	4	4, 4	4, 4
II	7	4	8	8	8, 8	6, 6
III	5, 1	4	18	15-17	10, 10	8, 9
IV	5,4	4, 2	26-30	25-27	14, 14	10, 11-12
V	-	?	-	45-50	-	12-16, 14-15

Table 1.11. Comparison of length of larval stages reported in portunid crabs

Species	Zoea T.T. (mean in mm)								Megalopa
	I	II	III	IV	V	VI	VII	VIII	C.L.
Callinectes sapidus	0.85	0.9	1.2	1.25	1.6	1.7	2.39	2.6	1.8
Liocarcinus corrugatus	1.55	1.65	2	2.55	2.9	-	-	-	x
Bathynectes maravigna	2	2.9	3.65	-	5.1	-	-	-	x
Carcinus maenas	1.38	1.75	2.14	2.37	-	-	-	-	1.33
Portumnus latipes	1.58	1.96	2.43	2.93	-	-	-	-	1.8
Portunus pelagicus	1.25	1.7	2.04	2.19	-	-	-	-	2.3
Portunus sanguinolentus	0.9	1.1	1.5	1.9	x	x	-	-	x

x = Data not available, C.L. Carapace length in mm.
T.T. = Average distances between the tip of the rostral spine to the tip of the dorsal spine.

1.2.8 Effect of salinity and temperature on larval development

Water temperature and salinity play a special role in regulating the distributions of crab species. They have a direct effect on egg development and subsequent hatching, as well as on larval development which takes place under a relatively narrower range of salinity and temperature, indicating the importance of these environmental factors in the survival of these animals during their early stages. Apart from the tolerance to high temperature (Neverauskas and Butler, 1982), the literature dealing with the effect of salinity and temperature on larval development of *P. pelagicus* is absent. Nevertheless, exposing adult crabs to temperatures of 22°, 25°, 28° and 30 °C, at a constant salinity of 35 ± 2.5‰ Neverauskas and Butler (1982) found that the upper incipient lethal temperature for *P. pelagicus* is near 39.5 °C. A number of studies on the effect of salinity, temperature and the combined effects of salinity and temperature under the controlled conditions of the laboratory have been described for the larvae of several crab species, e.g. *C. sapidus* by Sandoz and Rogers (1944) as well as Costlow (1967), *Panopeus herbstii* by Costlow *et al.* (1962), *Rhithropanopeus harrisii* by Costlow *et al.* (1966), *Sesarma cinereum* by Costlow *et al.* (1971) and many others. Richmond and Woodin (1996) have investigated the effects of short-term fluctuations in salinity on planktonic invertebrate larvae in estuarine habitats, where salinity can drop to below 20‰ in 6 hours, and found that salinity reduction affects growth rate, which results in smaller larvae. In the laboratory, Sandoz and Rogers (1944) found that development and hatching of *C. sapidus* eggs takes place under a relatively wide range of salinity and temperature and pointed out that the optimum range of salinity for hatching of eggs was 23-28‰ and eggs failed to hatch within the temperature range of 19-29 °C. The indication that *C. sapidus* prefers less saline conditions is confirmed by earlier reports that the adults migrate to less saline waters before copulation (Churchill, (1942) as cited by Costlow *et al.*, 1966). *C. sapidus* is well known for its marked tolerance to salinity changes throughout its life-cycle (Haefner and Shuster, 1964; Norse, 1978). Nagaraj (1993) has demonstrated a similar tolerance by *Carcinus maenas* zoeae to a wide range of temperatures and salinities.

1.2.9 Growth

Somatic growth for certain crab species continues throughout life so there may be no final definitive size. The growth rate usually changes with age, starting relatively high and decreasing as the animal grows bigger (Hartnoll, 1974). In contrast, it is reported that *C. sapidus* continued to grow when it was large (Gray and Newcombe (1938) as cited by Sather, 1965).

The rate of moulting in *P. pelagicus* throughout the zoeal stages follows "Brooks' Law" (Yatsuzuka, 1962) and growth (increase in carapace width) at each subsequent development stage of the maturing animals takes a "stepwise" pattern (Yatsuzuka and Meruane, 1987; Mortimer and Miller, 1994). However this pattern applies to length, it does not for weight. In almost all the literature cited, scientists do not specify size and growth, where size could be: length of a body dimension, weight, volume, dry weight, or organic weight, which are all interrelated. The same principle is also applied for growth where the three major types are: somatic, reproductive and storage. Using the terms size and growth without specifying what they refer to does not serve any purpose and leads to confusion. Several methods have been used for estimating the rates of growth. Beside modal progression analysis, biologists are often interested in estimating growth parameters from the von Bertalanffy curve which is a commonly used tool in fisheries research to model the growth of an organism (James, 1991).

Al-Rumaidh (1995) has reported growth parameter values for L_∞ and K of male *P. pelagicus* from Bahrain as 156 mm total carapace width (TCW) and 1.3 $year^{-1}$ respectively. No investigations on these values of this species have so far been attempted elsewhere, despite its importance for fisheries and aquaculture. However, the above mentioned K value indicates the high growth rate this species has in this part of the world, which further suggests the superb adaptation of this species to the harsh marine environments around Bahrain, particularly with reference to the high salinity which can reach 57‰. Estimating growth rates from size frequency analysis from field observations, showed that growth rates for male and female *P. pelagicus* recorded in Bahrain are 6.4 mm and 4 mm TCW $month^{-1}$, respectively (Al-Rumaidh, 1995), which agree with figures from India, at around 6.8 mm TCW $month^{-1}$ for males and 6.4 mm TCW $month^{-1}$ for females (Devi, 1985). Abdel Razek (1987) reported that the rate of growth of *P. pelagicus* in Mediterranean Egyptian waters varied from 5 mm TCW $month^{-1}$ at about 10 °C to 16.7 mm TCW $month^{-1}$ at about 30 °C. The average growth in the wild is 11.7 mm TCW $month^{-1}$ and 12 mm TCW $month^{-1}$ under culture conditions. Although these growth values are important, none of the above mentioned scientists has given their variability, hence, these monthly averages are not very meaningful. The similar growth rates reported for crabs in Bahrain and India are satisfying as the Arabian Gulf is linked directly to the Indian Ocean and the same climatic and environmental conditions prevail in both regions. Devi (1985) found that male and female *P. pelagicus* in India attain 76.5 mm and 81.5 mm TCW respectively, within one year (TCW is the distance between the tips of the two large lateral spines). Reared in the laboratory, *P. pelagicus* measuring between 11 and 25 mm TCW in carapace width and attained a marketable size of 140-145 mm TCW after 12 moults in a period of 14 months (Ameer Hamsa, 1982).

Variation in environmental variables such as temperature, salinity and pH influence growth to a large extent. Several workers studying *Callinectes* have observed a negative correlation between the size of crabs and salinity where they occur. They assume that crabs in low salinity absorb more water when they moult and, thus, increase in size faster than crabs in water of higher salinity (Cargo, 1958; Van Engel 1958; Fischler, 1959; Tagatz, 1965). This phenomenon has also been reported for *P. pelagicus* from Alexandria, Egypt (Abdel Razek, 1987) and Bahrain (Al-Rumaidh, 1995), where the rate of growth (at least in TCW) in the latter is much lower due to the high saline conditions, unlike the former, in the Mediterranean, with lowered salinity due to the proximity of the Nile delta. The changes in temperature in summer and winter are well marked in temperate waters where there is rapid growth during summer and negligible growth in the winter. Sather (1969) reported that temperature influences the moulting frequency in crabs and Hill (1975) stated that growth of crabs is mainly a summer phenomenon. Batoy *et al.* (1987) reported that *P. pelagicus* is able to withstand considerable variations in temperature, but is more active at 25 °C and above (Sumpton and Smith, 1990).

Working on the susceptibility of larval and juvenile instars of crustaceans to toxicity, Weis *et al.* (1992), Mortimer and Miller (1994), Mortimer and Connell (1995) have demonstrated the inhibition of growth in crabs that are exposed to sublethal concentrations of hydrocarbons (e.g. dithiocarbamates and chlorobenzenes) and heavy metals (e.g. chromium, nickel and copper). Mortimer and Miller (1994) have summarised the effects of these contaminants on *P. pelagicus* as: inhibiting larval moulting, increasing the duration of the larval development period and reducing the size achieved by successive juvenile instars. Mortimer and Connell (1995) reported that chlorobenzenes reduced the growth rate by up to 50%. Hilmy *et al.* (1985) reported that mature individuals of *P. pelagicus* were less sensitive to both zinc and copper toxicity than juveniles and of all crabs tested mature females were the more tolerant to both toxicants. They concluded that copper was about 6-7 times more toxic than zinc (Table 1.12), however, Aboul Naga (1996) found that zinc had a higher LD_{50} than copper at mean level of 17.68 ± 3.74 and 0.155 ± 0.029 mg l^{-1}, respectively for *P. pelagicus*.

Table 1.12. Median lethal concentrations (LC_{50}s) for juvenile and mature *P. pelagicus* exposed to zinc and copper for 96 hours. After Hilmy *et al.* (1985).

		96-h (mg/l)	
Maturity Status	Gender	Zinc	Copper
Juvenile	Females	12.16	2.16
	Males	12.49	1.04
Mature	Females	22.38	3.89
	Males	18.62	3.27

As crabs have the ability of regenerating limbs, it was found by Weis *et al.* (1992) that heavy metals such as chlorophenols and dithiocarbamates inhibit regeneration, however, they reported that these contaminants had no effect on moulting in shrimp. Surprisingly they also found that DDT (organic pesticide) accelerates regeneration and moulting when presented in sub-lethal doses. Ameer Hamsa (1982) has demonstrated that *P. pelagicus* is able to start regeneration of limbs after about 4-7 days following loss and to have a completely regenerated normal-sized limb at the next moult.

1.2.10 Feeding biology

Knowledge of the natural diet of an animal species is essential for studies of its ecology, nutritional requirements and potential for culture (Williams, 1981). Hence, various studies had been carried out to determine types of food eaten, quantitative dietary importance of prey types, as well as establishing means to estimate prey abundance and capture rates.

Feeding rates of crabs and other decapod crustaceans are affected directly both by environmental and physiological variables such as temperature and moult condition (Williams and Hill, 1982). Sumpton and Smith (1990) reported that there was no significant effect on food consumption rates by *P. pelagicus* within the temperature range 16.5-26 °C. Chittleborough (1975) reported that crabs do not feed for 2-6 days prior to moulting, after which abstinence continues for a few days, depending on the seawater temperature, until the mouthparts harden. Stage of moult also influences both the quantity and type of food eaten by *Portunus pelagicus*. At immediate post-moult stage *P. pelagicus* and *S. serrata* fill their renewed gastric mill with small pieces of bleached mollusc shell, coral fragments and other calcareous material (Hill, 1976; Williams, 1982).

Type of food depends on crab size and the efficiency of its mouthparts and other appendages. As the habitat of *P. pelagicus* ranges from shallow water down to depths of 65 metres (Stephenson, 1972; Manohara Ram and Chandra Mohan, 1978; Sumpton *et al.*, 1989), and because of their mobility, this species forages widely even onto tidal flats (Peterson, 1991). Five extensive studies have examined the stomach contents of *P. pelagicus*, viz. Patel *et al.* (1979) and Sukumaran and Neelakantan (1997a) from India; Williams (1982), Wassenberg and Hill (1987) and Edgar (1990) from Australia. However, both Edgar (1990) and Sukumaran and Neelakantan (1997a) have noted that information on the feeding biology and ecology of *P. pelagicus* is somewhat limited, despite its wide geographical range. Chopra (1939) reported that crabs generally are scavengers and Prasad and Tampi (1953) have referred to *P. pelagicus* in particular as "scavengers and cannibals". Nevertheless, Patel *et al.* (1979) were the first to investigate feeding in *P. pelagicus* in detail. Later, Williams (1982) worked on the natural food and feeding behaviour of *P. pelagicus* around Moreton Bay, Australia and found that type of prey varied quantitatively and qualitatively between intertidal and subtidal crabs, but was similar between the sexes at both levels. She also reported that *P. pelagicus* changes to larger prey as they grow. Patel *et al.* (1979), Williams (1982) and Sukumaran and Neelakantan (1997a) have reported *P. pelagicus* as a bottom feeding carnivore, eating a wide variety of sessile and slow-moving invertebrates with molluscs as the major prey item in all habitats (see Table 1.13). Edgar (1990) reported that *P. pelagicus* is a selective and wider-ranging predator, moving quite long distances to find prey. Although Williams (1982) identified *Zostera* and various species of macroalgae in the gut contents of *P. pelagicus*, she suggested that the plants entered the crab accidentally along with the food, as prey are gleaned from amongst the algae and seagrass. At Cliff Head, western Australia, the seagrass was as low as 10.2% of the volume of foregut contents, as estimated by Edgar (1990), who also reported that specimens *P. pelagicus* lacking chelae were almost exclusively herbivorous. Fragments of brown algae and seaweed were also frequently obtained in the diet of *P. pelagicus* around Alexandria, Egypt (Abdel Razek, 1988).

Sukumaran and Neelankantan (1997a) have found that prey preference depended upon crab size. Juvenile *P. pelagicus* (< 80 mm CW) had a strong preference for crustaceans (51.3%) followed by molluscs (38.8%) and small adults (80-100 mm CW) preferred crustaceans and molluscs but in lower proportions, 43% and 25.8%, respectively, whereas crustaceans were the principal food for larger adult crabs (> 100 mm CW). In laboratory maintenance, zoeae of *P. pelagicus* were fed various planktonic larvae, and the megalopae with small pieces of prawn, fish and mollusc muscle, whereas adult crabs were fed on fish fillets (Williams, 1986; Sumpton and Smith, 1990; Potter *et al.*, 1991).

Methods vary for estimating prey preference, as it is difficult to identify the prey from observations of stomach contents (Williams, 1981). Hyslop (1980) reviewed the methods for estimating and analysing the stomach contents of fishes, as prey occurrence, prey number, prey volume, prey weight and a number of unhelpful subjective methods. Williams (1981) has applied two semi-quantitative scoring methods for measuring the relative importance of natural food eaten by *P. pelagicus* - the Points Method and the Occurrence Method. The Points Method is suitable for foods that are ingested in large recognisable pieces or in their entirety, but is not recommended for food that consists of a high proportion of soft tissue. The Occurrence Method is a measure of the regularity of inclusion of a food in the diet of a population. Nevertheless, the latter method is appropriate for most food. Williams (1981) further pointed out that the morphology of each prey item and the way in which it is manipulated prior to ingestion, however, affects the accuracy of the Points Method and to lesser extent the percentage occurrence of some types of food. Patel *et al.* (1979) determined the volume of stomach contents of *P. pelagicus* by the displacement method, pouring the stomach contents into a pre-filled measuring cylinder (see Kimball and Helm, 1971).

Table 1.13. Major prey items for adult *Portunus pelagicus*.

Region	Type of food	Reference
Moreton Bay, Australia	**Intertidal zone**: Hermit crabs, various gastropods, gammarid amphipods, chitons. **Subtidal zone**: Bivalves and ophiuroids.	Williams (1982).
Cliff Head, western Australia	**Unvegetated habitat**: Polychaetes, bivalves, crustacean exuviae.	Edgar (1990).
Alexandria, Egypt	Molluscs (clams, mussels and cephalopods), crustaceans (mostly shrimps, small crabs, amphipods, barnacles).	Abdel Razek (1988).
Karnataka, India	Crustaceans, molluscs, fishes, zooplankton, phytoplankton.	Sukumaran and Neelakantan (1997a).
Hong Kong	Infaunal bivalves	Lee (1996).

For comparison, the quantitative analysis of the percentage of the volume that each prey item makes to the total volume of the stomach contents of *P. pelagicus* in Australia and India is presented in Table 1.14 where crustaceans generally make up the single, largest proportion of the contents.

Wassenberg and Hill (1987) reported that *P. pelagicus* uses a zigzag search pattern to find food using a mean point-to-point velocity of 290 m h^{-1} (8 cms s^{-1}) and can fill its foregut in about 8 minutes and clear it completely in about 6 hours. Fish bone apparently takes longer at about 24 hours. *Scylla serrata*, however, clears its gut of organic tissue after 12 hours, but fish bone and shell are retained in the gut for 2-3 and 5-6 days, respectively (Hill, 1976).

Table 1.14. Percentage composition of prey items as volume from the stomach contents of *Portunus pelagicus* from Australia and India.

	Stomach contents							
Region	Crustaceans	Molluscs	Polychaetes	Fish remains	Detritus	Zooplankton	Phytoplankton	Source
Sikka, India	24.97	24.96	-	9.43	-	0.65	0.95	Patel *et al.* (1979).
Cliff Head, W. Australia	31.6	-	16.1	-	-	-	-	Edgar (1990).
Karnataka, India	42.6	20	-	20.4	4.7	-	-	Sukumaran and Neelankantan (1997a).

1.2.11 Tagging and Migrations

Detailed knowledge of population dynamics of commercially important species, particularly population size, mortality rates and migration rates have proven crucial in determining regulations and management protocols for their rational exploitation (Chopra, 1939; Prasad and Tampi, 1953; Abdel Razek, 1988). Tagging / marking techniques have become a regular field practice to characterise populations in their natural habitats. Tagging marine animals has a history back 150 years since it was first introduced by the Danish fishery biologist G.G. Peterson, who tagged plaice with numbered bone discs (see Beverton, 1963). In the interim, fisheries biologists have developed many types of tags and used them to estimate migration, growth, mortality and population size. Various types of tags have been applied to portunid crabs and these are presented in Table 1.15.

As far as tagging *P. pelagicus* is concerned, only two investigations have been reported from Australia so far, but the results were poor for both. Williams (1986) tagged the crabs using Floy-67 anchor tags inserted at the posterior margin of the body, between the dorsal and ventral sections of the carapace, midway between the midline and the left lateral extremity of the posterior carapace margin. Tagging was applied on crabs > 100 mm CW, but the return was only 4%. She found that opaque scar tissue approximately 2 mm in thickness formed in the muscle around the insertion point of the tag. However, laboratory observations have shown that *P. pelagicus* is capable of retaining the floy tag through a moult, but the work concluded that the tag's impaired visibility which makes it unsuitable. Williams (1986) suggested that the tags were qualitatively adequate but quantitatively useless. Potter *et al.* (1991) tagged *P. pelagicus* with Floy-68BA anchor tags using an applicator gun at the insertion position described by Williams (1986). The Floy-68BA resulted in increased crab recapture in the wild with up to 15% returns, although it did reduce the short-term survival of crabs in the laboratory due to bacterial infection, unlike Floy-67 tag use where the short-term mortality was recorded as quite low. Williams (1986) did not specify whether such mortality was due to the tagging or the laboratory conditions. Potter *et al.* (1991) found that Floy-68BA tags were not suitable for field growth studies. Generally speaking, tagging *P. pelagicus* has proven difficult and the results are not reliable if crabs are tagged across the carapace (S. de Lestang, pers. comm.). The Western Australian Marine Research Laboratories, have been tagging *P. pelagicus* using a Hallprint TNA-1 (spaghetti tag with nylon T-bar) inserted into the branchial cavity on the suture line, but there is still ongoing work on testing other tag insertion sites (R. Melville-Smith pers. comm.). In addition to these conventional tagging methods, scientists have now begun using more advanced techniques for tracking crab movements using transmitter tags. Gribble and Thorne (1998) have applied this technique on *P. pelagicus* for investigating its movements during the tidal cycle. The tracking system consists of small ultrasonic tags, directional hydrophone and ultrasonic receiver. The ultrasonic tag is glued and wired to the posterior part of the dorsal carapace of the crab and the authors were able to estimate the average rate of movement at 0.8 to 3.7 m min^{-1}, with a maximum speed of 23 m min^{-1}, with tidal currents assisting in such movement. It is recommended that any conventional tagging programme should be associated with publicity, coupled with rewards for returned tags, as these are vital in obtaining meaningful and reliable data (Hayes, 1963; Williams, 1986; Estrella and Morrissey, 1997).

Table 1.15. Different types of tags used for crabs and lobsters.

Crustacean	Tag	Applied on	Reference
	Floy-67 anchor tag	Swimming crab *Portunus pelagicus*	Williams (1986)
	Floy-67 anchor tag	Mud crab *Scylla serrata*	Hill (1975)
	Floy-67BA anchor tag	*Portunus pelagicus*	Potter *et al.* (1991)
	Floy-68B tag	*Scylla serrata*	Hyland *et al.* (1984)
	Ultrasonic tag	*Portunus pelagicus*	Gribble and Thorne (1998)
Crabs	Plastic carapace tag	Blue crab *Callinectes sapidus*	Judy and Dudley (1970)
	Suture-tag method	Shore crab *Carcinus maenas*	Gomes (1991)
	Spaghetti-type FT-2dart tag	Deep-sea red crab *Geryon maritae*	Melville-Smith (1987)
	Floy anchor tag	King crab *Paralithodes camtschatica*	Meyer (1974)
	Floy anchor tag	Tanner crab	Meyer (1974)
	Floy anchor tag	*Chionoecetes bairdi*	Meyer (1974)
	Modified SphyrionTags: Subcarapace tag and Abdomen tag.	Spiny lobster *Homarus americanus*	Scarratt (1970)
	Sphyrion anchor tag	Spiny lobster *Homarus americanus*	Scarratt and Elson (1965); Robichaud and Campbell (1995); Moriyasu *et al.* (1995); Estrella and Morrissey (1997).
Lobsters	Floy-68B "Spaghetti" tag	Spiny lobsters: *Panulirus cygnus*, *P. argus*, *P. ornatus*.	Phillips *et al.* (1992)
	Floy-68BC Spaghetti Tag with a nylon t-bar	*Panulirus guttatus*	Evans and Lockwood (1994)
	Visible implant fluorescent elastomer (VIFE)	*Homarus gammarus*	Uglem *et al.* (1996)

Table 1.15. Continued

Crustacean	Tag	Applied on	Reference
Lobsters	Western rock lobster Tag.	*Panulirus cygnus*	Melville-Smith and Chubb (1997)
	Hallprint TBA-1 internal anchor tag	*Panulirus cygnus*	

1.2.12 Parasites and symbionts infesting crabs

Many parasites and symbionts have been reported to infect crabs with the most common, which is known to cause a considerable change in behaviour and morphology of the host, being members of the rhizocephalan family Sacculinidae. Rhizocephalan barnacles are all parasites, mainly of decapod crustaceans (Bocquet-Vedrine 1972 and Overstreet (1983) as cited by Alvarez *et al.*, 1995), which have a highly modified life-cycle compared to free-living barnacles. Most of the parasitological work on portunid crabs has focused on the American blue crab, *Callinectes sapidus*, because of its economic importance, and on the green shore crab, *Carcinus maenas* Pennant, because of its wide range and accessibility. Cavolini first described *Sacculina* in 1787. It is a rhizocephalan parasite of the order Cirripedia (Tattersall, 1920; Day, 1935). There are eight families in two suborders, the Kentrogonida, which includes the Sacculinidae and the Akentrogonida. Boschma (1955) arranged the species of Sacculinidae in six genera, viz. *Sacculina*, *Heterosaccus*, *Sesarmaxenos*, *Drepanorchis*, *Loxothylacus* and *Ptychascus*. He gave a detailed key to the Sacculinidae including the genus *Sacculina*. He also pointed out that the Sacculinidae are often not host-specific and their host may also carry more than one parasite species. All species of Rhizocephala parasitise marine and a few freshwater Crustacea (Boschma, 1955; Høeg and Lützen, 1995). The fact that the production of a *Sacculina* externa has an influence on the host moulting and consequently its growth is well documented. Potts (1909) reported that the moulting of the host is prevented after the externa erupts onto the outside of the host, which was also confirmed by Day (1935). Lester (1978) reported that *Sacculina granifera* stunts the growth of *P. pelagicus*, such that few infected crabs reach marketable size. Phillips and Cannon (1978) have summarized the effects of *Sacculina granifera* on male *P. pelagicus* as colour changes from mottled blue to brown reminiscent of females, marginal setae of the abdomen increase in length, less rigid mechanism locking the abdomen to the sternum, normally fused abdominal segments become separate, chelar propodus shorten and the abdomen becomes broader, all changes towards the female morphology. No obvious external morphological changes were evident in parasited female crabs. Furthermore, Day (1935) and Phillips and Cannon (1978) found the parasite preferentially infects immature crabs and diverts the energy for sexual maturation towards its own fecundity.

The most common parasite of *P. pelagicus* is *Sacculina granifera*. However Boschma (1973) reported that *P. pelagicus* in south India is commonly parasited by another rhizocephalan *Heterosaccus indicus*, whereas Devi (1985) reported that *P. pelagicus*, *P. sanguinolentus* and *S. serrata* from Kakinada, India were free from rhizocephalan infection. Thomson (1951) first noticed sacculinid infection of *P. pelagicus* in Australian waters and Boschma (1973) described and named the species as *Sacculina granifera* infecting this crab in Australia. A number of works have been carried out on the effect of this parasite on *P. pelagicus* in Moreton Bay, Australia, where *P. pelagicus* is fished commercially (Phillips, 1978; Bishop and Cannon, 1979; Shields, 1992; Weng, 1992; Shields and Wood, 1993; Sumpton *et al.*, 1994a). Thomson (1951) found the rhizocephalan infection rate within Moreton Bay, Australia, varied with locality ranging from 4 to 29%. Phillips and Cannon (1978) reported that infection is merely a "seasonal occurrence". Potter *et. al.* (1983) found that the average monthly infection rates varied from 1-10%, but at times infection in some areas exceeded 30%.

Another organism infecting *P. pelagicus* is the dinoflagellate *Hematodinium australis* which is responsible for a terminal disease (Hudson and Shields, 1994). *Hematodinium* spp have been reported from a number of commercially important crab species, including *Callinectes sapidus* (Newman and Johnson, 1975), *Cancer irroratus* and *C. borealis* (Maclean and Ruddell, 1978), *Chionoecetes bairdi* and *C. opilio* (Meyers *et al.*, 1987; Meyers, 1990). The dinoflagellate invades the haemolymph of the crustaceans (Hudson and Adlard, 1994) and ultimately results in host death. Hudson and Shields (1994) reported that the sternae and ventral surfaces of badly diseased crabs often had a chalky white appearance, whereas the internal organs appeared milky and the hepatopancreas and gills become cream in colour as opposed to yellow and translucent yellow. *Hematodinium*-like dinoflagellates cause the so-called Bitter Crab Disease (BCD) in *C. bairdi* and *C. opilio* (Meyers *et al.*, 1987; Meyers, 1990).

The microsporidian *Ameson* sp. is another source of infection for *P. pelagicus*. It invades the striated muscle cells and thus influences crab flesh quality that becomes dry, fibrous and unpalatable when cooked, otherwise the infected crabs appear normal and display no obvious external signs of infection (Sumpton, 1994). Other parasites and symbionts of *P. pelagicus* are presented in Table 1.16.

Table 1.16. A list of common parasites, infectious agents, symbionts and an epizoite of *Portunus pelagicus.*

Species	Location	Reference
Barnacle	Outer carapace	Newman and Ross (1976)
Chelonibia patula (Ranzani)		
Rhizocephala		
Sacculina granifera	Ventral abdomen only	Boschma, 1973
Thompsonia dofleini	Ventral sides of the body such as abdomen; merus.	Jesperson and Lutzen (1992).
Epizoic		
Gill-dwelling *Octolasmis angulata*	Middle and ventral regions of the branchial chamber.	Joal and Sanjeeva, Raj (1981).
Viruses		
White spot syndrome baculovirus	N/A	Lo *et al.* (1996).
white spot syndrome virus	N/A	Supamattaya *et al.* (1998).

Table 1.16 Continued

Species	Location	Reference
Nemertean		
Carcinonemertes mitsukurii	Eggs	Shields (1993), Shields and Wood (1993).
Nicothoid copepod		
Choniosphaera indica	*Eggs*	Gnanamuthu (1954) cited by Shields and Wood, (1993).

1.2.13 Nutritive value

Although *P. pelagicus* in particular and other commercial portunid crabs in general enjoy a wide distribution within the Indo-Pacific region (the Mediterranean to some extent) reports of the nutritive value of these edible crabs are meagre. Even in countries where the fishery is of substantial economic importance, such as Australia, where it is considered to be one of the tastiest treats available from its waterways (Todd, 1995) little is known of its biochemical composition. Only five investigations have been reported, two from the Indo-Pacific and three from the Mediterranean. The most extensive studies are by Srinivasagam (1979) and Siddiquie *et al.* (1989). The former investigated the carbohydrate, protein, lipid and moisture contents of the meat of *P. pelagicus*, *P. sanguinolentus*, *Scylla serrata*, and *Charybdis cruciata,* (see Tables 1.17 and 1.18). Srinivasagam (1979) only gave the ranges of biochemical composition (see Table 1.18) with no variability of the data, which leaves the values somewhat meaningless. Nevertheless, data in Table 1.18 show that the biochemical composition of *P. pelagicus* does not vary much with sex or berried condition.

Table 1.18 summarises Srinivasagam's (1979) findings where low carbohydrate contents were reported. Srinivasagam (1979) and Hilmy *et al.* (1988b) concluded that this crab meat could serve as an excellent source of nutrition because of its high protein component. Siddiquie *et al.* (1989) have found that *P. pelagicus* has the most nutritious meat compared with other crabs, viz. *S. serrata* and *P. sanguinolentus*, as its carbon to nitrogen ratio was the lowest. The data also indicated that the nutritive value of body and claw meats of male *P. pelagicus* is higher than in females. Muscle tissue in male *P. pelagicus* from Alexandria, Egypt, was found to be composed of 46.7% of the total dry

Table 1.17. Mean values of carbohydrate, protein, lipid and moisture contents recorded in the meat of four portunid crab species from Porto Novo waters, India, derived from Srinivasagam (1979). Values are given as percentages of wet weight.

Species	Wet weight (g)	Carapace width (mm)	Carbohydrate	Protein	lipid	Moisture
Portunus pelagicus	138.3	112.6	0.14	15.65	9.67	73.33
Portunus sanguinolentus	75.9	104	0.16	13.87	8.66	75.41
Scylla serrata	212.4	105	0.15	14.68	7.38	76.41
Charybdis cruciata	152	105.3	0.17	12.25	9.48	74.13

weight, with 62.5% of that leg meat and 37.5% shoulder meat (Badawi, 1971). Furthermore, Badawi (1971) also reported that the raw meat is composed of an average of 10.3% protein; 0.67% oil; 86% moisture; and 1.96% ash. In India, the wet weight of muscle, in the size group 110-184 mm CW, ranged from 24.6-32.5 g. for males and 22.3-25.3 g. for females, with averages of 28 and 24 g, respectively (Ameer Hamsa, 1978a). The muscle and hepatopancreas play a major role in the energy and metabolic cycles of crabs, muscle acting as a store for glycogen (Hilmy *et al.*, 1986). The hepatopancreas is the organ associated with digestion (Dionysius *et al.*, 1993), absorption and storage (Slattery *et al.*, 1989). Glycogen contents in the muscle, hepatopancreas and gonads of *P. pelagicus* are shown in Table 1.19. Hilmy *et al.* (1986) detected marked variation in the total glycogen content of muscle tissue in *P. pelagicus* in relation to maturity and sex, suggesting that the higher values for females in all organs, except muscle, is for satisfying the requirements of oocyte maturation and egg-laying (Table 1.19) and concluded that in *P. pelagicus* the intermediary metabolism centres mainly on glycogen without giving more details.

Table 1.18. Mean values of carbohydrate, protein, lipid and moisture contents in the meat of male, female, and berried female of *Portunus pelagicus* from Porto Novo waters, India, derived from Srinivasagam (1979). Values are given in percentage of wet weight and the ranges are given in parentheses.

Gender	Wet weight (g)	Carapace width (mms)	Carbohydrate	Protein	Fat	Moisture
Male	127.9	114	0.15 (0.1-0.2)	16.17 (14-21)	7.61 (6-9)	74.83 (70-88)
Female	147.4	112	0.15 (0.1-0.2)	16.99 (14-21)	10.66 (7-14)	70.60 (69-72)
Berried female	139.5	112	0.11 (0.1-0.1)	13.79 (13-14)	10.75 (10-11)	74.55 (74-75)

Table 1.19. Glycogen content (mg glycogen/g dry weight) in different organs of male and female of *Portunus pelagicus*. Summary of data given by Hilmy *et al.* (1986).

Gender	Muscle	Hepatopancreas	Gonad
Male	7.5-66.6	10.5-16	10.8-25.5
Female	10.52.3	13-32	13.1-40

1.2.14 Handling and storage

Special care in handling and storage of crabs should be taken by the industry once the catch is on board the fishing vessel in order to deliver crabs to consumers in good condition. Slattery *et al.* (1989) have reported on the degradation of the meat of *P. pelagicus* through a process called "Mushiness" caused by heat-labile proteolytic enzymes originating in the hepatopancreas, turning the firm and resilient flesh soft and friable. "Mushiness" takes place if crabs are stored raw (fresh), frozen, or in refrigerated brine, so adequate cooking of crabs as soon as possible after capture at temperatures higher than 70 °C for 10 minutes is the best method to prevent the development of "mushiness", since temperatures > 70 °C denature the autolytic enzymes. However, Radhakrishnan and

Samuel (1980) reported that fresh-frozen crab meat remained in good condition for about 51 weeks at –23 °C. Ameer Hamsa (1978b) has reported that fishermen and retail sellers in the fish markets in areas around the Gulf of Mannar, India, arrange crabs upside down, i.e. ventral side up. Apparently the method helps to keep crabs fresh for more than 10 hours. The presence of parasites and epifauna can severely affect a crab's nutritional value. It is believed in India that crab meat has got a medicinal value, wherein Bombay crab curry is a reputed cure for asthma, chronic fevers and is often used during recovery from malaria (Chopra, 1939). Although Thomson (1951) stated that crabs infected with *S. granifera* are usually quite edible and palatable, Potter *et. al.* (1983) reported that the parasite makes crabs unmarketable as the flesh is stained during cooking by discolouration from the hepatopancreas. Sumpton *et al.* (1989) also noted that infected crabs do not moult and hence often carry a heavy infestation of epizoic organisms which makes them aesthetically unacceptable for sale.

1.3 Swimming crabs around the Arabian Gulf and Bahraini waters

P. pelagicus is widely found in Arabian Gulf waters and is one of 48 portunid crabs reported from the Gulf (Apel and Spiridonov, 1998). The other major portunid species commonly referred to in the literature from the Gulf are: *Charybdis hellerii* (A. Milne Edwards, 1876); *Charybdis natator* (Herbst, 1794); *Thalamita admeta* (Herbst 1803); *Thalamita crenata* Ruppell, 1830 and *Portunus sanguinolentus* (Herbst, 1783) (Basson *et al.*, 1981; Jones, 1986; Carpenter *et al.*, 1997). Titgen (1982) has reported that *P. pelagicus* is the only brachyuran crab being commercially fished in the Arabian Gulf (cited by Apel and Spiridonov, 1998), which explains the absence of other portunid species from the FAO yearbooks for catches and landings (FAO, 1985 and 1992).

P. pelagicus has made an important contribution to Bahrain commercial fisheries, with a rapid increase in the landings during recent years. In 2000, its contribution was 2,380 metric tons (20% of the total marine fish catch), with revenue of Bahraini Dinar 308,000/- (i.e. £ 574,000) (DOF, 2001). It is also important as bait for the wire trap, artisanal fishing gear, known locally as "Gargoor", similar to lobster/crab pots in other countries. Despite the commercial value of this species in Bahrain, basic biological and fishery information is lacking not only from the territorial waters but also from the entire Arabian Gulf, hence, no legislation exists for managing the fishery. Nowadays the crab fishery in Bahrain is under heavy year round exploitation, with the exception of the period from mid-March until the end of June, the annual closed season for the shrimp fishery in Bahrain waters. Any protection of the crab fishery is thus indirect and based on the biology and needs of another species. The present importance of the *P. pelagicus* fishery demands that any management policy should be based on its particular needs and habits rather than having to rely on those of another species.

The aim of this chapter was to review the literature on portunid crabs in order to develop background information. The review has revealed that research effort and biological information on *P. pelagicus* around the Arabian Gulf region, are lacking, with only a single investigation from Bahrain. This study addresses this lack of basic knowledge for *P. pelagicus* in the unique waters around Bahrain.

1.4 Specific aims and objectives

Apart from the landing data of *P. pelagicus* that are recorded on a regular basis by the Directorate of Fisheries, Bahrain, nothing is known about the biology of this species in this part of the world. There is also a complete lack of fishery management for this crustacean resource. Bearing these facts in mind, this investigation was undertaken to achieve the following objectives:-

1. To investigate the population dynamics of *P. pelagicus* within the territorial waters of the Kingdom of Bahrain in terms of - growth, sex ratio, nursery grounds, recruitment, relative abundance, biomass and migrations.

2. To study the reproductive biology particularly size at first maturity, breeding and spawning seasons, fecundity and larval biology.

3. To investigate the morphometric changes in *P. pelagicus* as the crabs grow.

4. Investigate the temperature and salinity annual cycles in relation to their influence on many of the aforementioned.

Achieving this set of objectives should allow rational management protocols which will facilitate the successful exploitation of the *P. pelagicus* resource around Bahrain and near-shore environments of adjacent countries.

Chapter 2

Materials and methods

2. MATERIALS AND METHODS

2.1 Study area and sampling stations

2.1.1 Offshore fishing grounds

The survey was carried out within the territorial waters of the Kingdom of Bahrain. Survey operations were restricted within areas ranging from 25° 42.00' to 26° 33.00' N and 50° 21.00' to 50° 57.00' E (Fig. 2.1) where the major fishing grounds for crustacean resources are situated. Being a vast area with different habitats, wherein the abundance and distribution of benthic marine life varies, the study area was divided into grids, each 31 km^2. For simplicity, these grids were coded as to their positions within the study area (see Fig. 2.1).

The arrangement of the grids was coordinated by the Shrimp Resources Survey Project of the Arabian Gulf States. The study area fell naturally into three distinct sub-areas, representing the northern (A), north-eastern (B) and southern(C), fishing grounds (see Fig. 2.1). The northern and north-eastern waters were considered as two sub-areas (A and B), due to the nature of their respective seabed and water depth characteristics. The transition line between sub-areas A and B was defined according to the crab catches of March-April 1999, wherein the crab size composition of grids BF was most similar to the western catches while the BG catches more closely resembled the remaining more eastern catches. Sub-grouping the study area in this way was fundamental in order to obtain comprehensive and detailed data of the population dynamics of *Portunus pelagicus* in Bahraini waters. However the sub-area to the west of Bahrain Island extending from **King Fahad Causeway** in the north to **Ra's al Barr** in the south, is not included in the Gulf Shrimp Project as it is not normally commercially fished, but was included in the present investigation as sub-area D. Two stations were fixed in sub-area D, based on the fishermens' knowledge of the crab grounds (see Fig. 2.1). The sub-areas (hereafter designated areas) are described as follows:

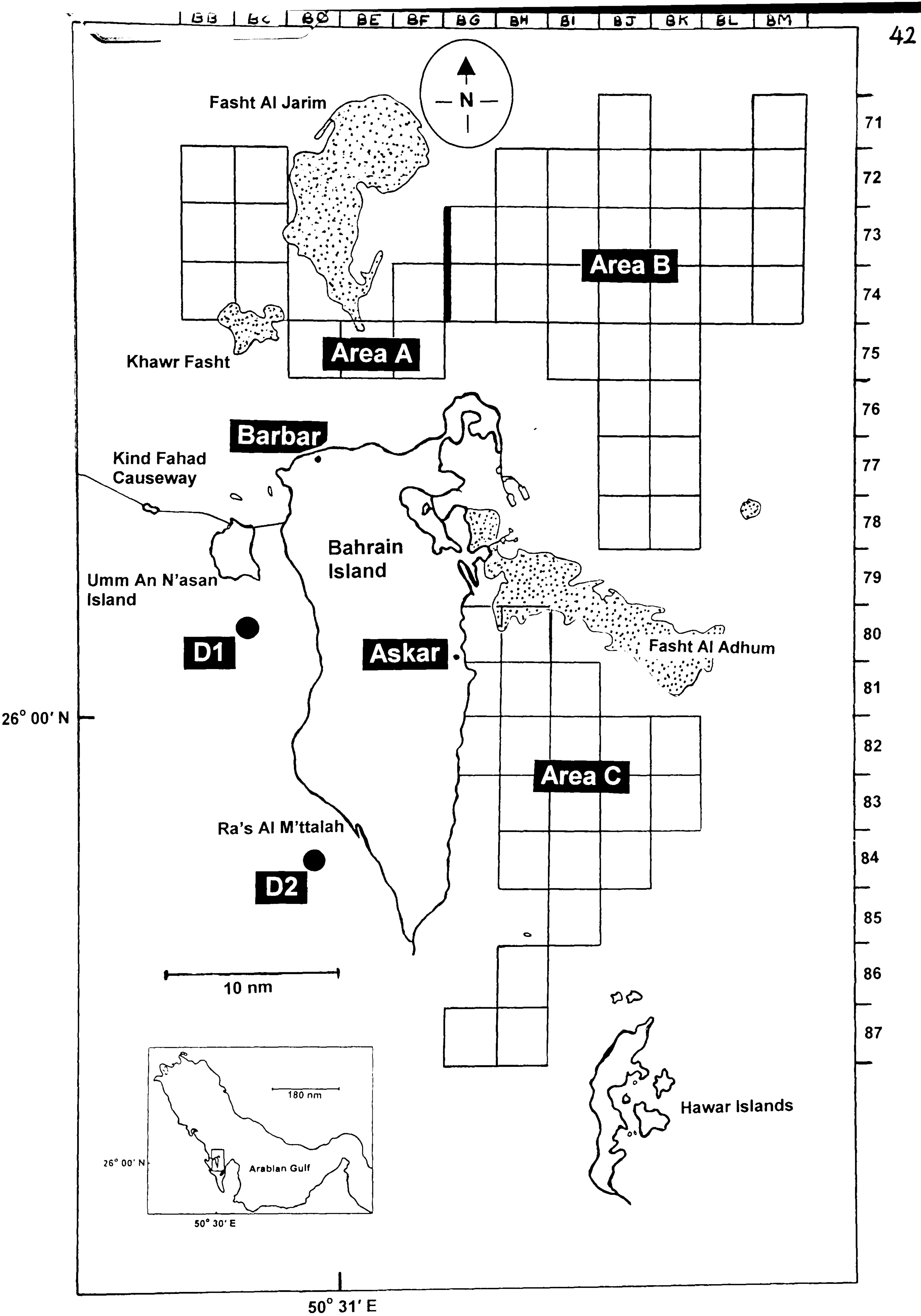


Figure 2.1. Map of the study area in Bahraini waters indicating fishing grounds where the swimming crab, *Portunus pelagicus*, were surveyed.

Area A consists of fishing grounds in the north and is subdivided into only 10 grids (BB to BF). These grids surround **Fasht Al Jarim** (**Fasht** indicates a rocky or reef shallow sea-area) and **Khawr Fasht** to the south-west. The seabed is mainly sandy with isolated patches of coral reef, although in those grids closer to the fasht areas the bottom becomes more rocky with coral. Water depth ranges from 5-14 metres.

Area B is the largest sampling area with 31 grids covering a total area of almost 960 square kilometres. A navigation channel passes through the area giving it a wide depth range from 4-21 metres. Substrata vary from sandy to coral fragments in the shallow areas and from sand to mud in the deeper areas.

Area C is the second largest sampling area with 21 grids extending from **Fasht Al Adhum** in the north all the way south to the Hawar Islands and from coastal areas in the west (around 3 metres) to deeper water towards BK grids in the east (around 18 metres). Situated to the north of this area, **Fasht Al Adhum** forms a natural barrier separating area C from area B. The area in general, particularly south of grids 84 is known for the richness of its seagrass beds (*Halodule uninervis*, *Halophila stipulacea* and *Halophila ovalis*). *H. uninervis* is by far the most abundant species (Price *et al.*, 1984; Sims and Zainal, 2000) interposed with the brown alga, *Sargassum* sp.. Nevertheless, habitats around the study area in general and area C in particular, are affected by seasonal changes wherein during late spring the alga dies back and is removed from the coral by wave action caused by the **Shamal** (northerly) wind events during this period, as indicated by the satellite images shown in Figures 2.2 and 2.3, representing the habitats during autumn 1989 and spring 1999 (Sims and Zainal, 2000). Unlike the salinity in areas A and B which ranges from 39-45‰, the salinity in area C varies to a very great extent from 41‰ in the north up to 53‰ in its southern region.

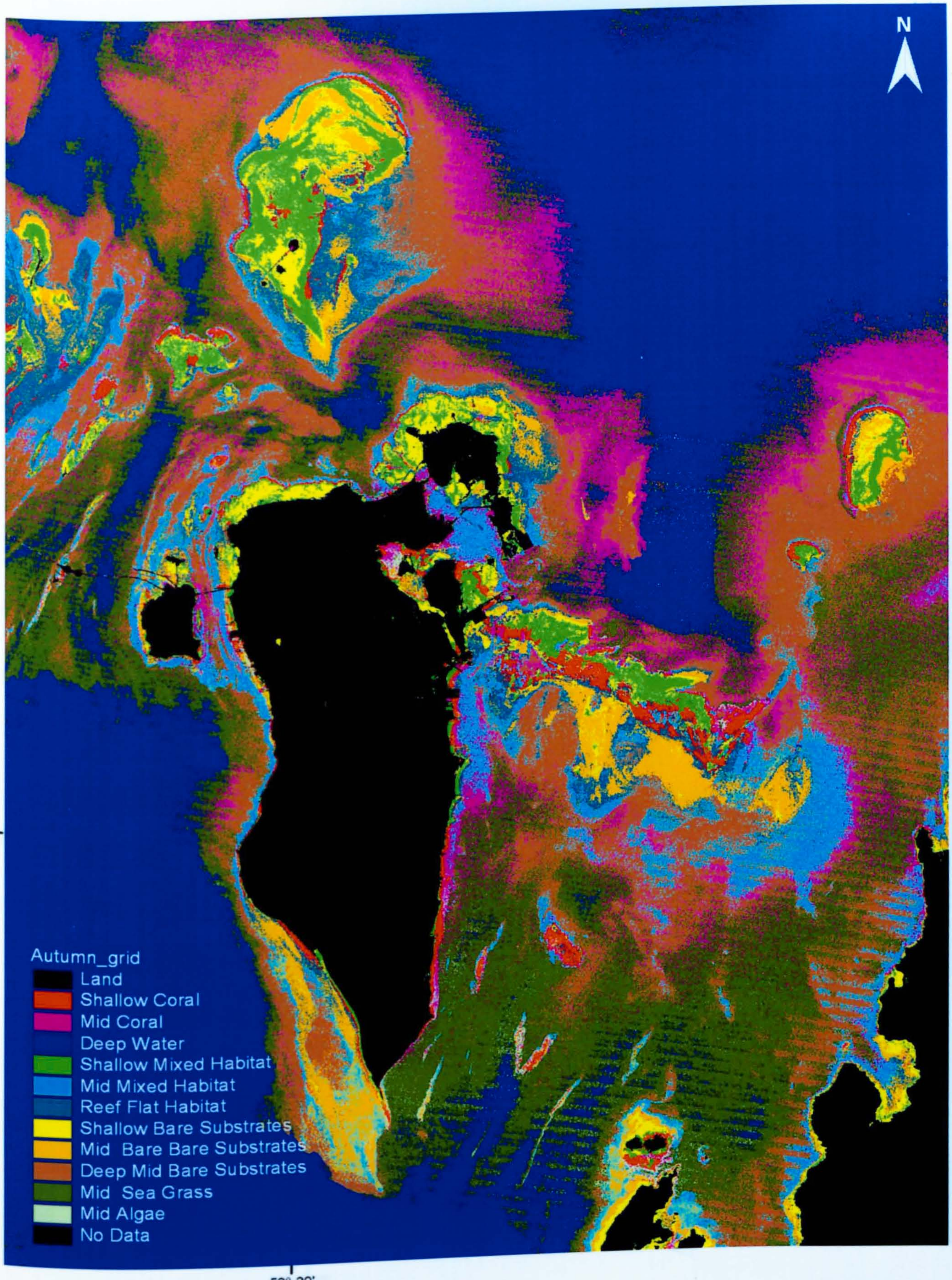


Figure 2.2. Classified Landsat TM image depicting the submerged marine habitats of Bahrain during autumn transition period. Acquisition date: 3 November 1998. Image was obtained from the Saudi Remote Sensing receiving station in Riyadh (Saudi Arabia) and processed by the Remote Sensing and Geographical systems Department, Bahrain Centre for Studies and Research. After Sims and Zainal (2000).

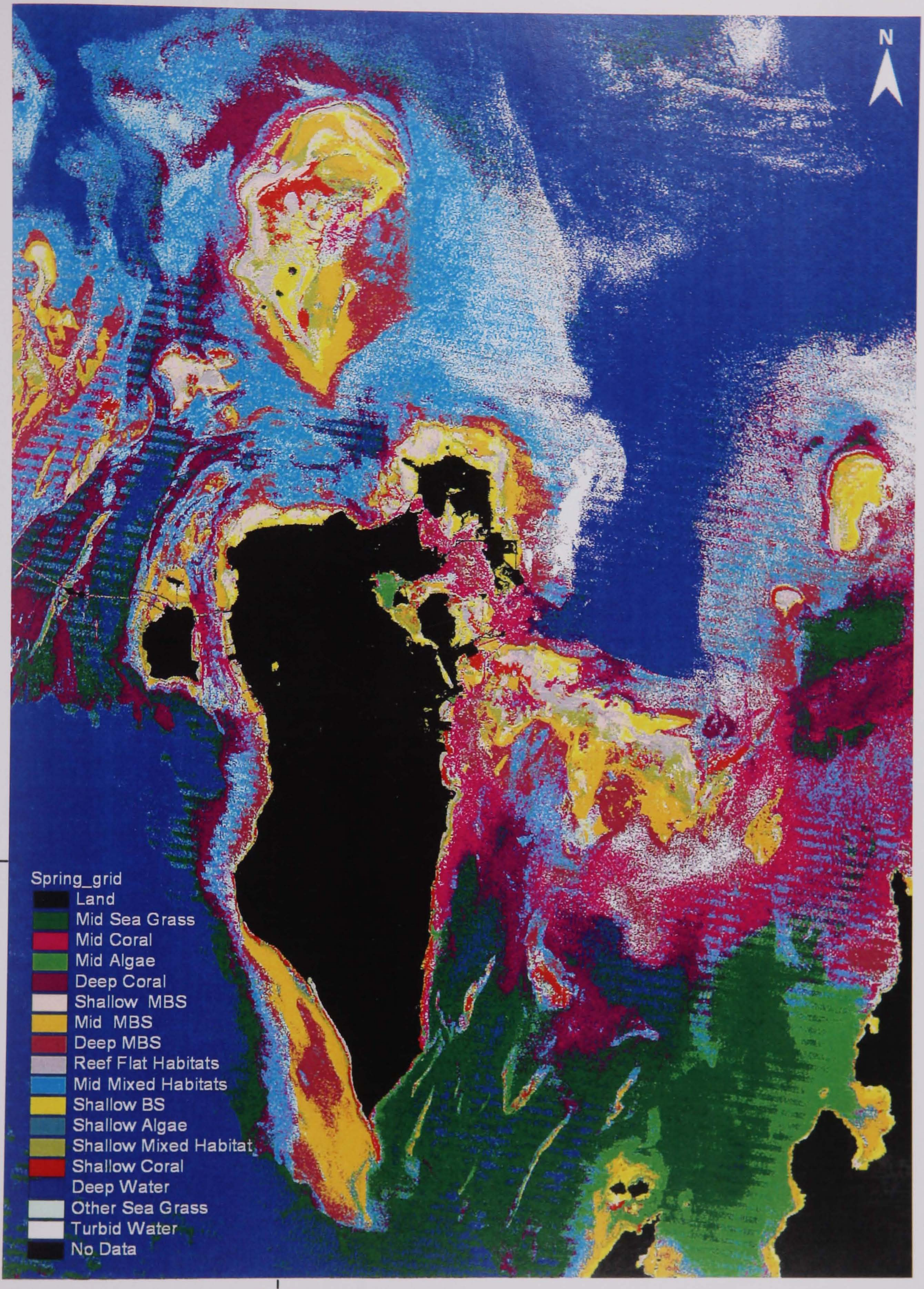


Figure 2.3. Classified Landsat TM image depicting the submerged marine habitats of Bahrain during spring transition per Acquisition date: 28 April 1999. Image was obtained from the Saudi Remote Sensing receiving station in Riyadh (Saudi A and processed by the Remote Sensing and Geographical systems Departments, Bahrain Centre for Studies and Researcl After Sims and Zainal (2000).

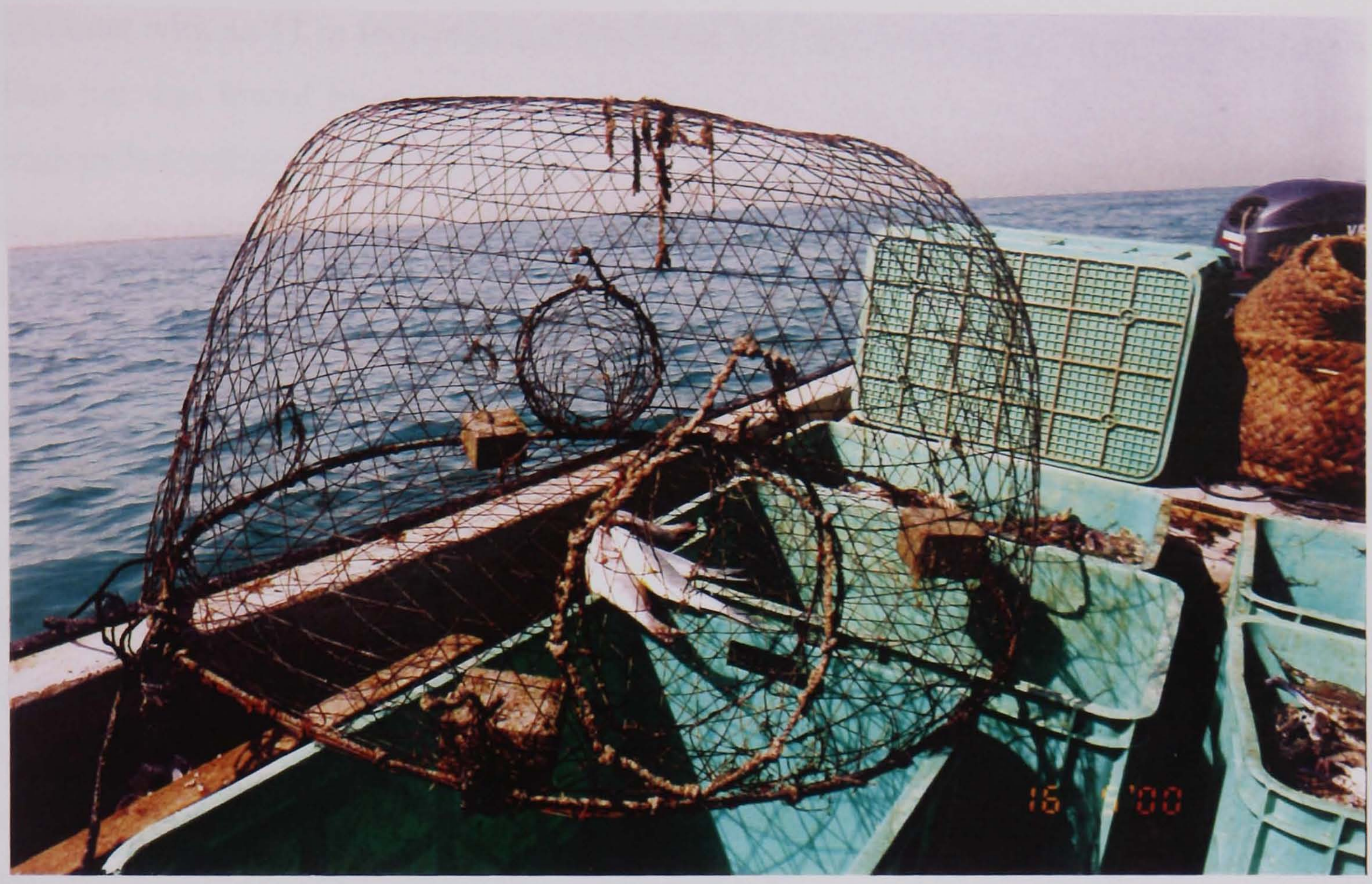
In **Area D** station D1 was 3-3.5 kilometres south of Umm An N'asan Island, in water depth of 8-10 metres. Station D2 was located 6.5-7.5 kilometres off the coast of Ras al M'ttalah, where the depth ranges from 6-8 metres. The seabed at both stations is sandy with isolated patches of scattered corals. However, the substratum of D2 proved too rocky for trawling so was omitted from the sampling scheme. Salinity within area D ranges from 53-57‰.

2.1.2 Inshore fishing grounds

Two sites were selected on the Askar and Barbar coastlines, which are located within the intertidal zone. The Barbar intertidal zone is wide with a low tide water mark extending 1.5-2 kms off the coastline, with substrata consisting mainly of flat seaweed - covered rocks; isolated sandy patches are also found. The low water mark off the Askar zone is around 500 metres. This area has a mixed sandy and rocky seabed with both green and brown algae. Crabs and other marine life in these zones are caught by means of barrier traps and wire traps, locally named **Gargoor** (Photograph 2.1), similar to crab and lobster pots in other countries. The water level during high tide inside a barrier trap is as high as two metres, decreasing to around 0.4 metres during low tide. Many isolated pools are formed during low tide in depression areas, where crabs as small as 1 to 3 cms carapace width are found, especially in summer. The surface water temperature fluctuates widely between winter and summer, ranging from 12-36 °C. Salinity is relatively stable at 42-45‰ through the year.

2.2 FISHING GEAR

The *P. pelagicus* were collected by two types of fishing gear, depending on the fishing ground. In the offshore fishing ground (areas A, B, and C, see Fig. 2.1) a Gulf of Mexico flat otter board trawl with a 29 metre foot-rope and a 3.8 cms mesh size in the belly and codend was used, as is commonly operated by Bahraini shrimp trawlers (Photograph 2.2). The codend twine is thicker than that of the trawl belly at 4.5 and 3 mm respectively. The trawl was operated from a fibreglass dhow of length 21 metres with a 270 horse power engine, owned by a professional shrimp fisherman. A smaller



Photograph 2.1. Hemispherical galvanised wire trap "Gargoor" used by local fishermen for catching *Portunus pelagicus* from Bahraini coastal waters. Mesh size 5 cms.

Photograph 2.2. A 29 metre foot-rope Gulf of Mexico flat otter board trawl, in operation during the present study. The two metre otter boards are shown.

trawl net with an 11 m foot-rope and mesh size 3.8 cms, was used to catch crabs in area D. This net was towed by a ten metre fibreglass boat with 2 x 200 horse power outboard engines belonging to the Bahrain Centre for Studies and Research. Crabs from the coastal areas, were also obtained by means of a barrier trap, locally known as "**Hadhrah**", which is one of the main types of gear operated by artisanal fishermen. The barrier trap (Fig. 2.4) is constructed in the intertidal zone. It is large and has an arrowhead shape pointing seawards (Al-Baharna, 1986). However, its size varies according to the financial constraint of the fisherman, as well as the density of traps in the surrounding locale. It is made of galvanized chicken wire of 1.9 cms mesh size, fastened to and supported by wooden posts 1.5-2 metres apart and fixed vertically on the sea floor by 6 mm nylon guy ropes. The fish and other marine animals move towards the shore during high tide searching for food. As the tide turns, animals are directed towards the mouth of the trap along the central landward running wall (see Fig. 2.4). Once through the trap mouth they are caught and harvested twice a day during low tide.

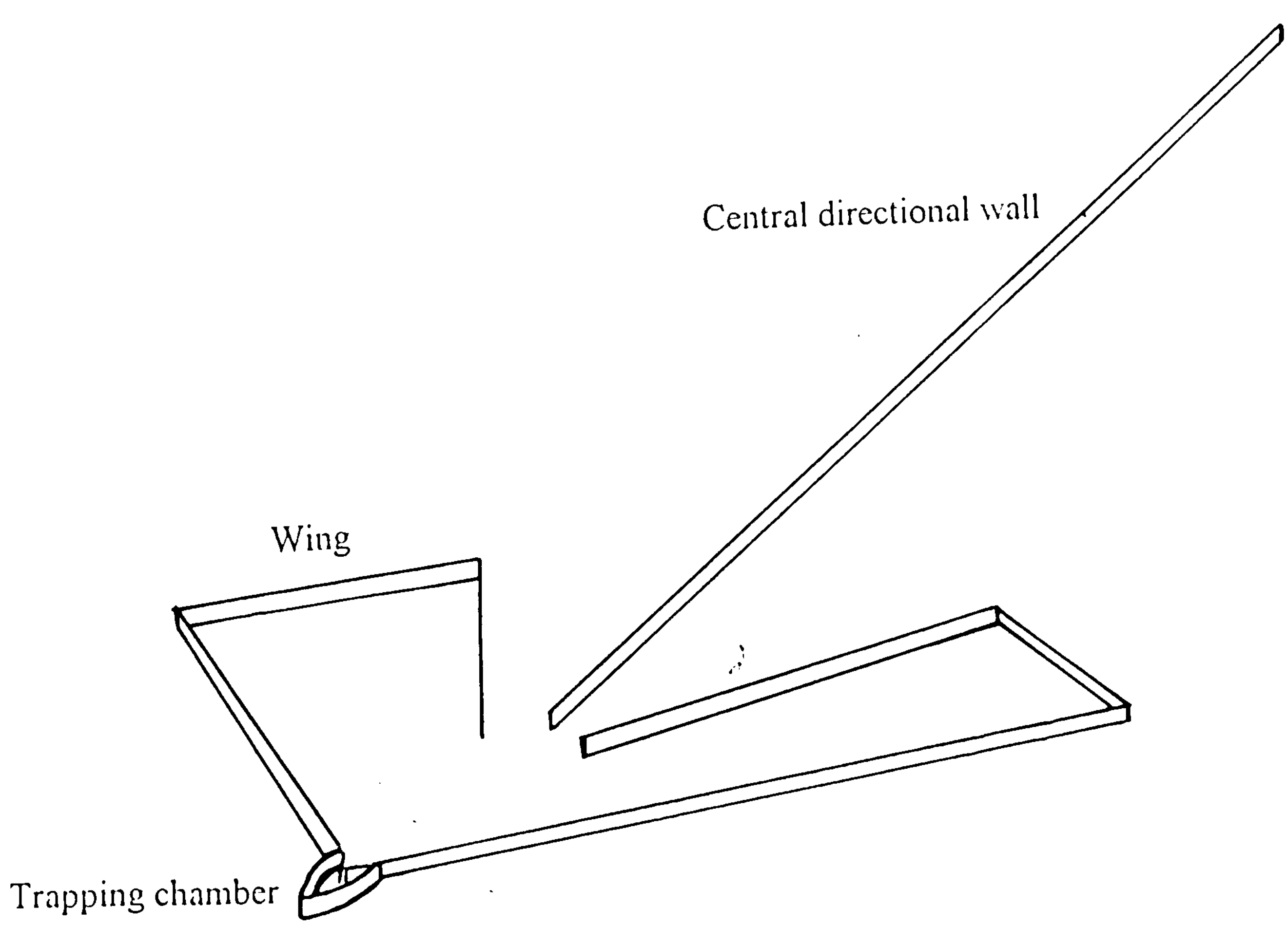


Figure 2.4. Diagram of the barrier trap "**Hadhrah**" for catching fish and crabs in the intertidal zone around Bahrain.

2.3 Field sampling

2.3.1 Offshore fishing grounds

The *P. pelagicus* used in the present study are taken from catches collected during a major survey of shrimp resources (*P. pelagicus* is a by-catch of the shrimp landings (Abdulqader, 2001), see Appendix 1) and so the present study's sampling programme was restricted to that of the shrimp project, in terms of sampling frequency. However, a number of extra trawls were taken from the three areas at certain times in order to fulfil the requirements of the present study.

Catches of *P. pelagicus* were taken at monthly intervals between March 1999 and April 2000. A stratified random sampling approach was applied during this work for the three main areas; hence, out of the total grids, only 60% from each area were chosen randomly and surveyed. On average, four, fifteen and nine grids were surveyed in areas A, B, and C respectively every month. Each trawl, of ca. 30 minutes at a speed of 2.5 knots into the prevailing currents was considered a replicate within an area. All the trawling was done at night, starting soon after sunset and finishing by dawn. The sampling work started on the first Saturday of every Gregorian month for three consecutive nights. Grids within area A and a few in area B were surveyed during the first night and work was resumed the following night to complete the grids of area B. The sampling work was concluded within area C on the third night. However, the programme was flexible enough to incorporate changes when necessary, namely when the sea state was rough in area B, whereupon sampling activities would be moved to the more sheltered area C. Crabs from area D were collected using the 11 m foot-rope trawl net, for 30 minutes at a boat speed of 2.5 knots.

2.3.1.1 Trawling operations

10, 31 and 21 grids (each has an area of 31 km^2) within the study areas A, B and C respectively were extensively surveyed to investigate the *P. pelagicus* resource within the major fishing grounds in Bahraini waters. During the 14 months of sampling activity, 356 trawls took place with 49%, 34% and 17% of the trawls being taken in areas B, C and A respectively (Table 2.1). These percentages reflect the relative areas of the fishing grounds sampled. Only 20 trawls were conducted within area D.

A number of changes and modifications to the study area in terms of the grids available for trawling were applied when necessary as work progressed. In area A, trawling in grids BF74 and BF75 was terminated in February 2000 as the seabed became unsuitable for trawling due to dredging operations. Likewise, grids BJ71, BK77, BK78, BL73, BL74, BM71, BM73 and BM74 of area B were omitted from the survey soon after the March 1999 sampling, as they were not suitable for trawling due to the presence of coral reefs. On the other hand, a number of grids were included in area C, i.e. BG80, BG81 and BG82, from July 1999. Also, grids BG87, BH86 and BH87 were included in the survey's plan, effective from September 1999.

The longitude and latitude coordinates at the start and finish for each trawl were recorded by Global Positioning System using a Furono GPS Navigator Model GP-35 (± 10 m). These were processed to obtain the distance travelled (km) for each trawl. The trawl path lines for March 1999 samples are shown in Fig. 2.5a. Similar charts for samples from April 1999 to April 2000 (Figs. 2.5b to 2.5n) are given in Appendix 2. A navigational error occurred to the GPS system on board the fishing dhow in April 2000 while trawling in area B. Hauls carried out in grids BI73 and BK73 were actually done within BJ73 and thus are included as replicates of BJ73.

Table 2.1. Months when trawling was carried out in the designated grids where *Portunus pelagicus* was sampled from March 1999 to April 2000.

		1999										2000			
Area	Grid	M	A	M	J	J	A	S	O	N	D	J	F	M	A
	BB72		*			*			*	*		*		*	*
	BB73				*	*									
	BB74			*											
	BC72			*			*	*	*			*	*		
	BC73									*			*	*	
	BC74	*	*		*		*				*				*
A	BD75		*	*	*		*		*		*		*		*
	BE75			*	*	*	*	*		*		*	*	*	
	BE76					*									
	BF74	*			*	*			*			*			
	BF74			*				*			*	*		*	
	BF75	*	*		*		*	*		*					
	BG74	*		*	*	*	*	*		*	*	*	*		*
	BH72							*			*		*		*
	BH73			*		*	*			*		*			
	BH74	*		*	*	*			*	*	*	*	*	*	*
	BI72		*	*	*	*	*		*	*	*	*	*	*	*
	BI73						*		*	*	*	*			
	BI74	*	*	*			*		*	*	*	*	*		*
	BI75			*	*		*	*	*			*	*	*	*
B	BJ72	*	*	*				*	*	*	*	*	*		*
	BJ73	*	*		*	*	*	*	*	*	*	*	*	*	*
	BJ74		*	*		*	*	*	*		*	*	*	*	*
	BJ75	*	*			*	*	*	*	*		*			
	BJ76	*	*	*	*	*		*	*	*	*	*	*		*
	BJ77		*			*									
	BJ78				*		*	*	*	*	*		*		*
	BK72		*	*	*	*	*		*	*	*		*	*	
	BK73	*				*		*	*	*		*	*		

Table 2.1. Continued

Area	Grid	1999										2000			
		M	A	M	J	J	A	S	O	N	D	J	F	M	A
	BK74			*	*		*		*	*	*			*	*
	BK75			*		*		*	*	*	*	*	*		*
B	BK76		*	*		*		*							
	BL72			*							*	*	*		*
	BM72	*													
	BG80					*	*	*		*		*	*		
	BG81						*			*	*			*	*
	BG82							*		*		*			
	BG87													*	
	BH80					*	*		*	*	*	*			
	BH81		*			*			*		*		*		
	BH82	*		*		*					*			*	*
	BH83		*	*	*					*	*				
	BH84				*	*		*			*	*	*	*	*
	BH86							*	*			*	*		
C	BH87												*	*	*
	BI81	*			*	*									
	BI82	*	*			*	*	*	*	*			*		*
	BI83	*	*	*	*	*		*	*	*				*	*
	BI84		*	*	*		*	*	*	*	*	*	*	*	*
	BI85	*						*	*				*	*	
	BJ82	*	*	*	*		*				*	*		*	*
	BJ83	*	*		*		*		*						*
	BJ84			*		*			*			*			
	BK82		*	*	*		*					*	*		
	BK83			*	*		*	*		*	*				

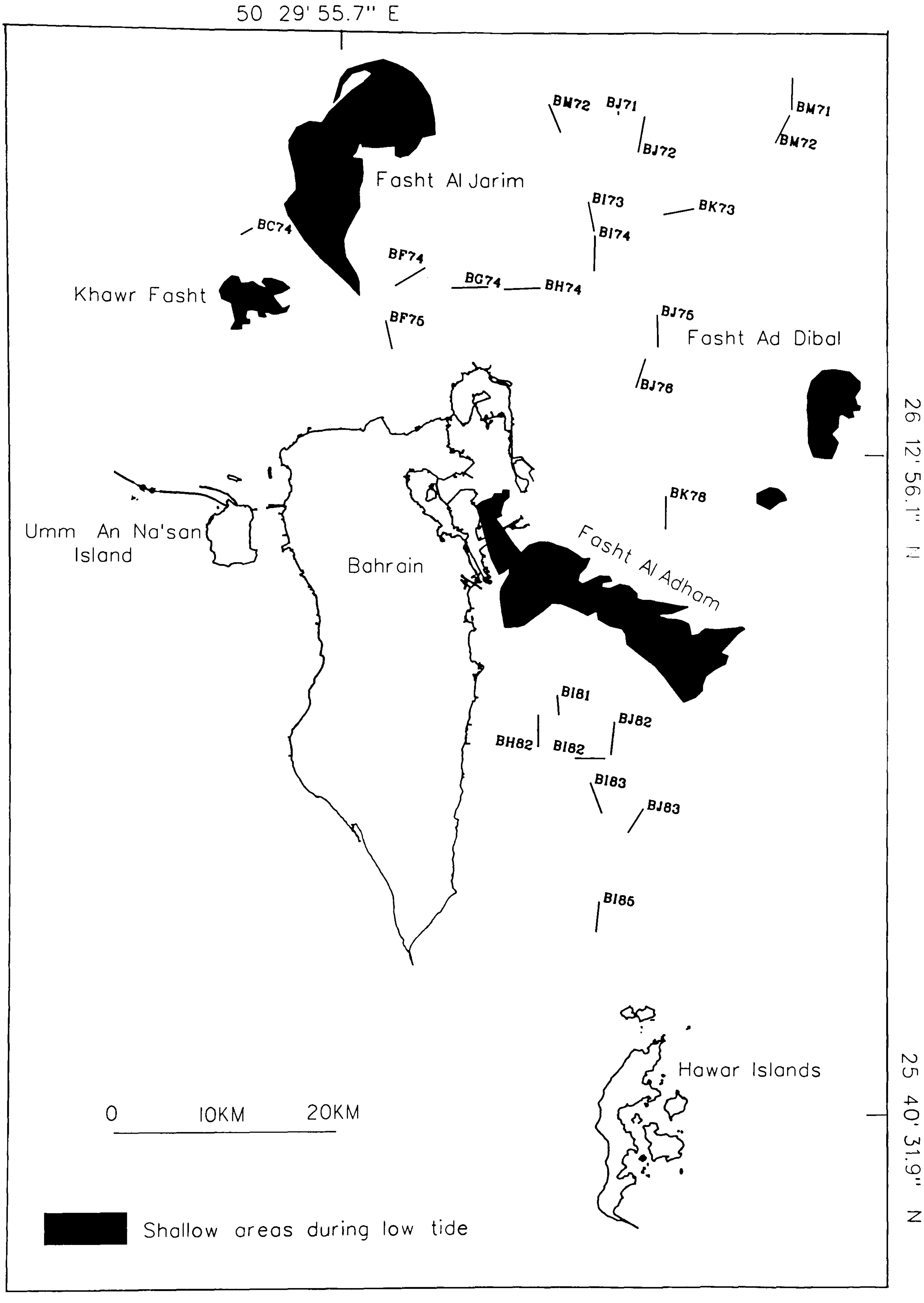


Figure 2.5a. Chart of the study area illustrating the distance and direction of each trawl carried out in March 1999 for sampling *Portunus pelagicus*. Figs. 2.5b-2.5n illustrating trawling paths that were carried out from April 1999 to April 2000 are given in appendix 2.

2.3.1.2 Handling of trawl catches

2.3.1.2.1 Crab sampling

When the trawl net was emptied on deck, *P. pelagicus* were removed from the catch and separated by sex. The difference in abdominal shape between males and females is very easy to distinguish, even in juvenile crabs. The male abdomen is a narrow and inverted T shape, while in females, it is triangular in juveniles and semicircular in adults (Abd El-Hamid, 1988; Sukumaran and Neelakantan, 1997b) (see Photographs 2.3 and 2.4). The total numbers of males, females and ovigerous females in each trawl were recorded. From every study area a target of at least 300 specimens across as full a size range of each sex as was possible was considered sufficient to represent the crab populations in the respective area. Crabs were taken from selected grids on a monthly basis throughout the investigation in order to provide data for population structure, rate of growth, mortality rates, biometric relationships and sex-ratio studies, as well as population density mapping. Crabs of each sex from every trawl were placed in plastic bags within 20-30 minutes of collection with a tag showing the area, grid code, sex and date of collection. All the crabs were kept in cool storage in order to keep them in a fresh condition. On arrival in port, all samples were transferred immediately to the Bahrain Centre for Studies and Research complex, where they were placed in a freezer (-15 °C) until measured at a later date.

2.3.1.2.2 Biometric relationships

2.3.1.2.2.1 Carapace length-width relationship

A set of samples across the full size range was collected at intervals from grids around the study area. Selected trawls, in particular those with big catches and different sizes of crabs, were taken in order to establish the carapace length-width relationship for males and females. Sampling was carried out during October-December 1999, as well as in February 2000 (Fig. 2.6). The criteria used for selecting samples were: (1) large catches containing all possible class sizes and (2) crabs from grids from all shallow water and offshore sites, representing the population of crabs throughout the whole study area.

Photograph 2.3. Ventral view of immature female *Portunus pelagicus* showing the triangular shape of the abdomen. Scale bar equals 2 cms.

Photograph 2.4. Ventral view of mature female *Portunus pelagicus* showing the semicircular shape of the abdomen. Scale bar equals 10 cms.

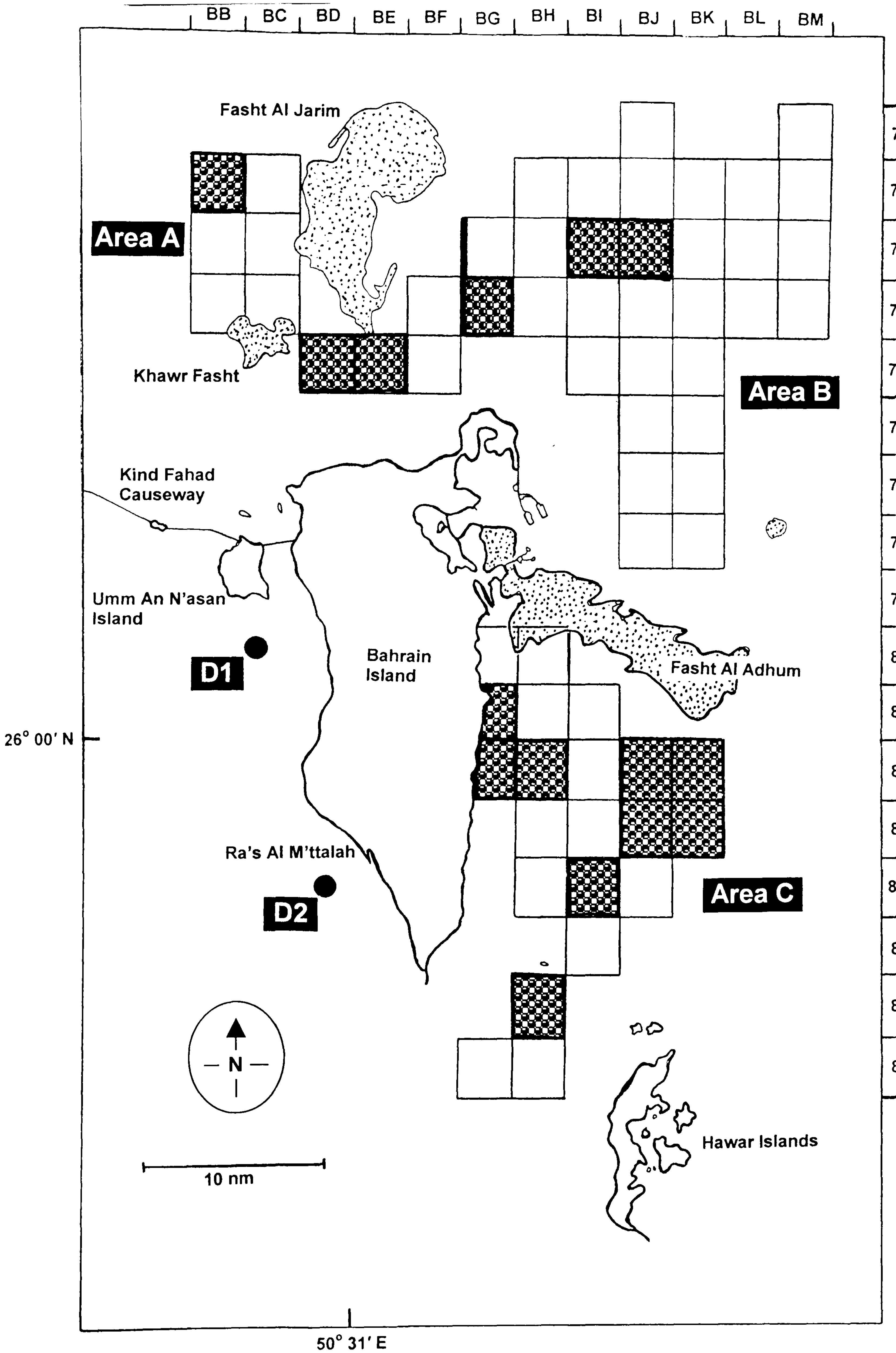


Figure 2.6. Map of the study area illustrating the grids where crabs for carapace length-width relationship were obtained during October-November 1999.

2.3.1.2.2.2 Carapace width-weight relationship

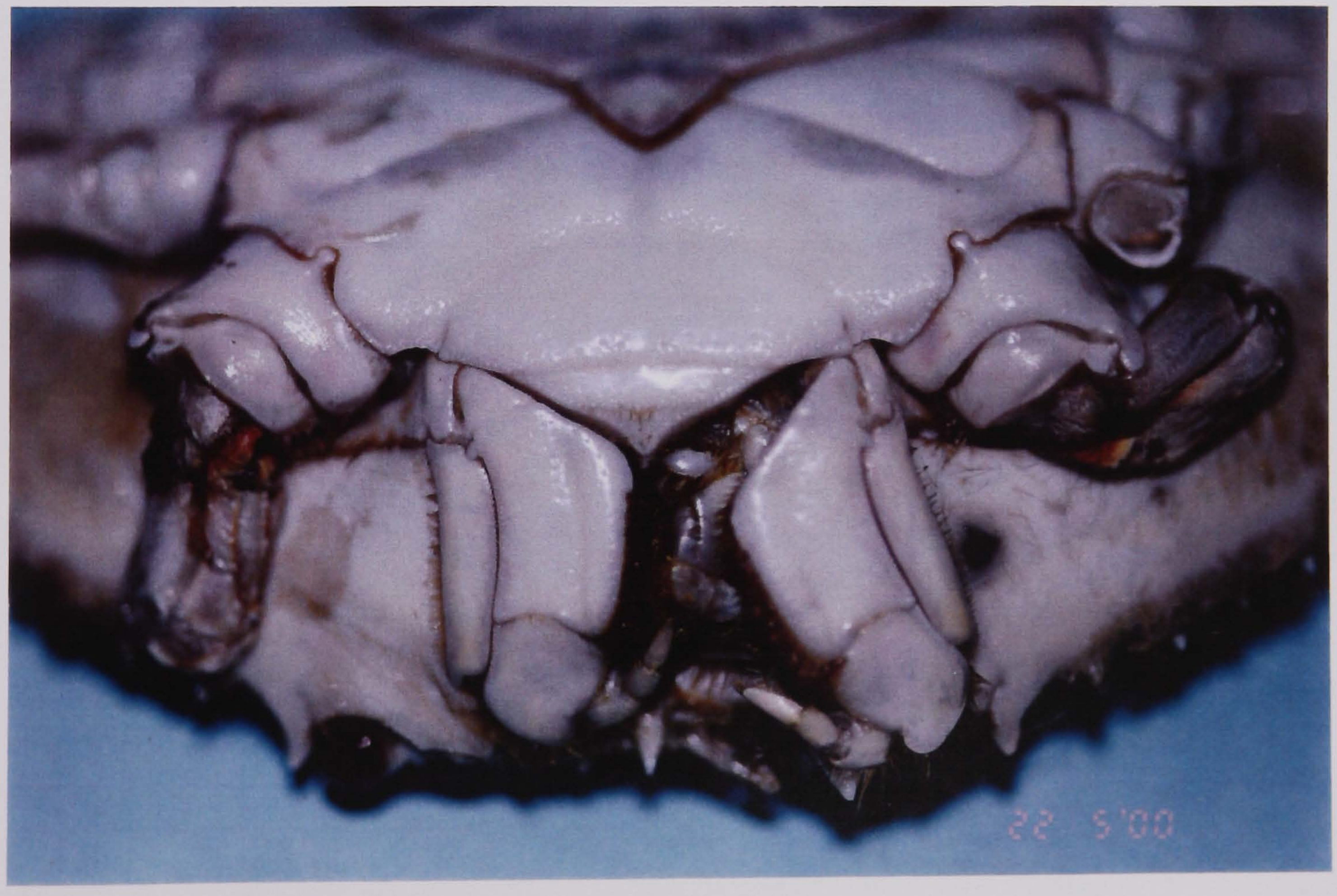
For the length-weight relationship investigations, 4-8 healthy hard-shelled male and female crabs with all appendages intact were taken from each trawl. The sampling strategy ensured that every sample should include specimens across the full size range from each trawl (Photograph 2.5). A sample of 25 crabs per area was found sufficient for comparison between areas, as analysing data of March-April 1999 showed increasing sample size much above 25 did not improve precision in exponent estimation and that relationships were consistent within areas. Ovigerous females and crabs with autotomised or regenerating appendages (Photograph 2.6), broken carapaces, or with epizoic organisms (Photograph 2.7) were not considered, as such features would result in a marked variation in weight (Sukumaran and Neelakantan, 1997c). Samples were placed in plastic bags soon after they were selected and were kept in cold storage, marked with labels indicating: area, grid code, sex and date of collection.

2.3.1.2.3 Reproductive biology

2.3.1.2.3.1 Ovigerous females

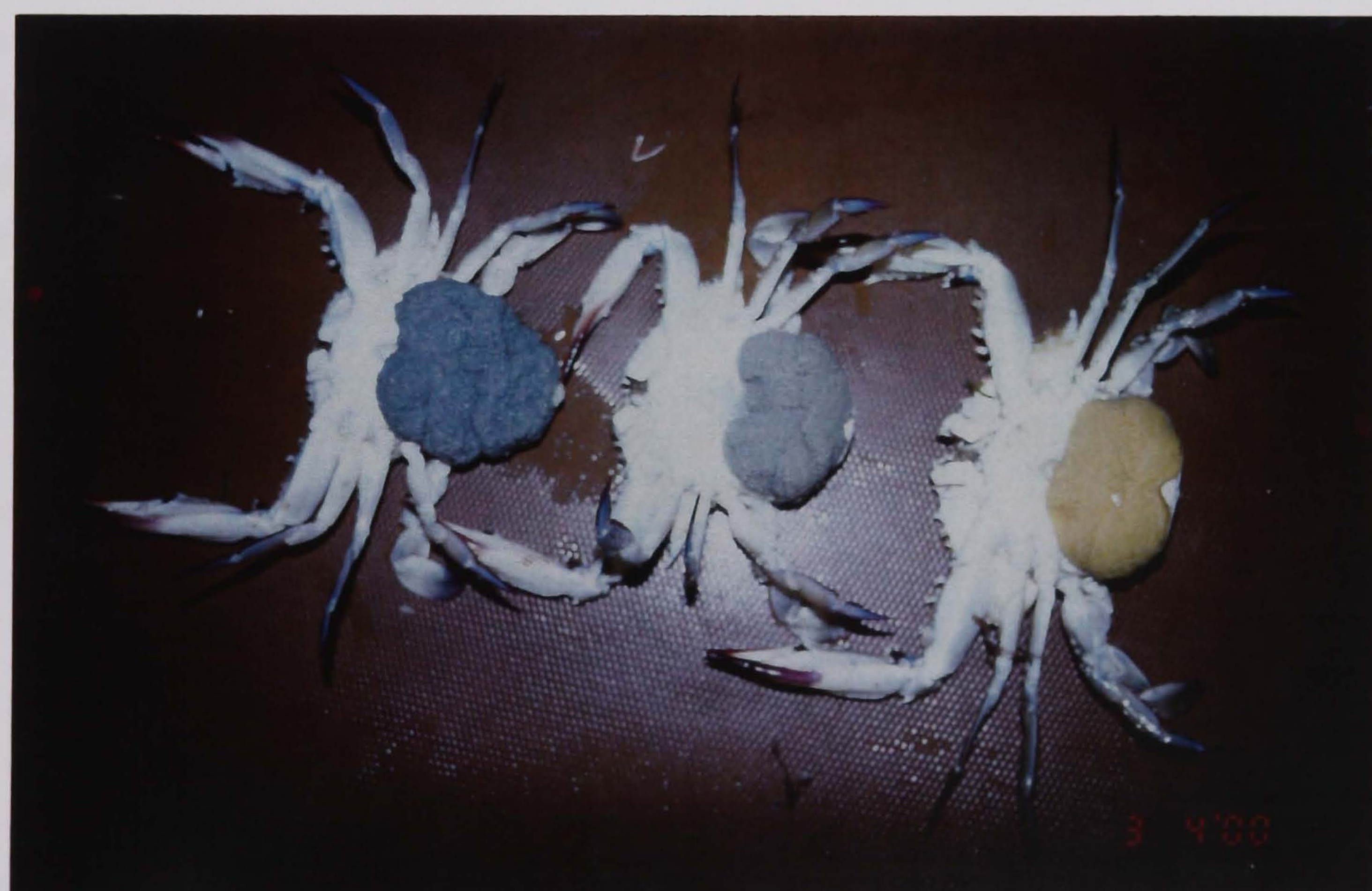
Ovigerous females were collected immediately onboard the dhow for egg diameter, fecundity (egg number) and egg mass weight-carapace width relationship studies. A sample of at least five ovigerous females of various sizes and different egg mass colours; i.e. yellow, grey, and black (Photograph 2.8), were selected from each grid when found. For egg count and egg diameter samples, crabs with black egg masses were not considered, as those masses proved to be hatched zoea still attached to the pleopods. Therefore, for the egg diameter investigation in particular, egg masses of yellow, yellow-greyish, grey-yellowish,

Photograph 2.5. Female *Portunus pelagicus* with all appendages intact, illustrating the different sizes selected from each trawl for the carapace width-weight relationship studies.



Photograph 2.6. *Portunus pelagicus* with regenerating chelipeds. Such specimens were not considered for the carapace width-weight relationship studies.

Photograph 2.7. The barnacle, *Chelonibia patula* (Ranzani), growing on the carapace of *Portunus pelagicus*. Such crabs were not considered for the carapace width-weight relationship studies.



Photograph 2.8. Ovigerous females of *Portunus pelagicus* illustrating different egg mass colours: yellow, grey, and black.

and grey colour only were selected. It was important to classify the egg masses based on these four colours in order to follow egg development. These samples were kept in a fresh condition and were placed in a plastic bag with a label indicating the grid code and date of collection. The ovigerous females were purposefully kept separated from the other crab samples in order to avoid damage to the egg masses.

2.3.1.2.3.2 Plankton collection

The presence of *P. pelagicus* larvae in the water column was examined by taking three replicate vertical hauls from selected grids, by means of a plankton net with an opening diameter of 50 cms and a 250 μm mesh size. Due to time constraints, larval collection was carried out once every 3 trawls. A set of heavy weights was fixed to the opening ring in order to sink the net down to the seabed. At the time of sampling, the net was allowed to sink to the seabed and once it settled on the bottom it was hauled up at a fast steady speed in order to maintain a vertical path to the sea surface. The plankton samples were transferred from the net to a plastic container and preserved immediately. In order to avoid shrinkage by the larvae due to a direct fixative, a few crystals of menthol were first introduced, depending on density of plankton sample, in order for the larvae to relax. Within ten minutes of collection, a sufficient amount of 10% Borax Formalin solution was added to the sample. The Borax Formalin solution was prepared following Omari and Ikeda (1984). Once the plankton samples were preserved, a label was placed inside the container, indicating date of collection, area, grid code and water depth.

The total volume (V) of seawater filtered through the net was estimated by applying the cylinder volume equation, which is modified as follows:

$$\mathbf{V = \pi\, r^2\, d\, h}$$

where r = plankton net radius; i.e. 0.25 metre,

d = depth of water column in metres,

h = no. of hauls; i.e. 3.

2.3.1.3 Hydrology

A number of environmental features were recorded throughout the fieldwork. The salinity to the nearest ppt (‰) and the temperature to the nearest 0.1 °C were measured for surface and bottom water in a grid by means of a digital conductivity meter (Orion, Model 135). These measurements were recorded at the end of each trawl. Depth (m) determinations were also made before and after each trawl by means of an echo sounder "Probe, Interphase". Both readings were averaged to gain the mean depth of each trawl path.

2.3.1.4 Processing of trawl coordinates

The longitude and latitude coordinates were recorded at the start and finish positions of each trawl, using a Furono GPS Navigator Model GP-35. The availability of such information provided essential data to calculate the distance travelled for all 353 trawls made in the course of this investigation, as well as enabling the plotting of trawl paths on charts.

In order to calculate the distance travelled for a trawl and to plot the trawl track on charts the coordinates were entered into an Excel 97 spreadsheet, wherein decimal minutes were converted to minutes and seconds. The data were then rearranged as longitude-latitude, where finishing coordinates were stacked below their starting counterparts. The data were then transferred as "comma delimited text file" format (i.e. month.csv) to MGR Projection Manager (Intergraph) where they were converted to easting/northing coordinates. The data were further saved as "month.bas" and run by a microstation basic macro, which was used to process the easting/northing coordinates for calculating the distance travelled and track plotting for each trawl. This work was completed in conjunction with the Geographical Information Systems and Remote Sensing Department, BCSR, Bahrain, which handled the data from the MGR Projection Manager stage .

2.3.2 Inshore fishing grounds

Crabs from the coastal areas were collected from barrier traps located on the Askar and Barbar coastal areas. Sampling was conducted during daylight at low tide once a month. All the crabs found in the barrier trap at the time of sampling were caught using the traditional method for this purpose (Photograph 2.9). Environmental parameters i.e. salinity and temperature of seawater, were also recorded at the time of sampling by means of a digital conductivity meter (Orion, Model 135). The crabs were placed in plastic bags identified by a label showing: area, sex and date of collection. Specimens were brought to the laboratory in fresh condition and examined 1 to 2 hours after sampling.

Photograph 2.9. Local traditional method of harvesting marine animals caught by barrier trap "**Hadhrah**".

2.4 Laboratory work

2.4.1 Population structure and composition

All the samples brought to the laboratory were measured for length frequency distributions. Prior to measurement all the crabs were allowed to fully thaw. For population size structure, the entire crab catch collected during March 1999 and a few samples for April 1999 were measured for total carapace width (TCW), which is defined as the distance between the tips of the two large lateral spines (Fig. 2.7, dimension 1). However, in May 1999 this dimension was replaced with the short carapace width (SCW), or carapace width (CW), which is defined as the distance across the carapace from the notches between the 8th and 9th antero-lateral spines (Fig. 2.7; dimension 2, and Photograph 2.10). This dimension proved to be quicker and more precise than TCW, as the tips of lateral spines are fragile and occasionally broken, as also reported by Sather (1969) and Quinn and Kojis (1987). All dimensions were measured to the nearest 0.01 cm by means of a vernier calliper. Specimens displaying obvious cephalothoracic damage or malformations (see Photograph 2.11) were not measured. However, these animals were taken into account for the total catch and sex-ratio studies. A calibration equation for converting TCW to CW was also obtained.

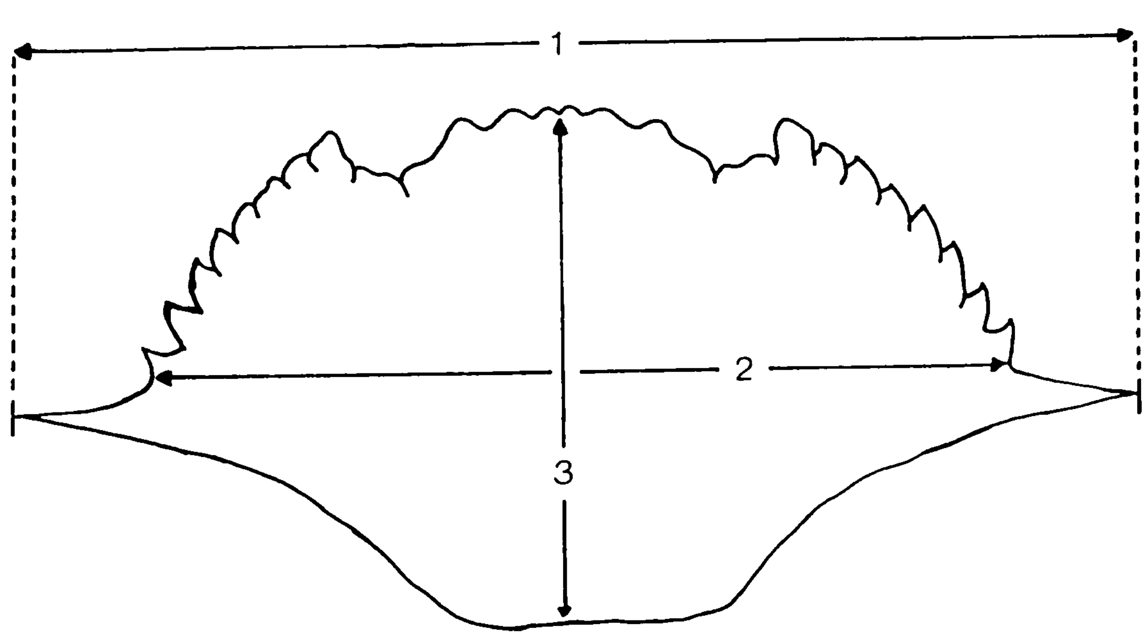


Figure 2.7. Measurement sizes of carapace, (1) total carapace width[TCW]; (2) short carapace width or [CW]; and (3) carapace length [CL]. After Yatsuzuka and Meruane (1987).

2.4.2 Biometric relationships

2.4.2.1 Carapace length-width relationship

The crabs designated for this particular part of the investigation were measured for CW and carapace length (CL). CL is defined as the distance from the centre of the frontal margin to the centre of the posterior margin (Fig. 2.7, dimension 3). Both dimensions were measured to the nearest 0.01 cm by means of a vernier calliper.

2.4.2.2 Carapace width-weight relationship

The crabs for the length-weight relationship were brought to the laboratory in fresh condition and were examined soon after their arrival from the field. The adhering water on the overall surface, including the appendages was completely wiped off using a towel and the total wet weight of each crab free of debris and epizoic forms and with all appendages intact, was weighed to the nearest 0.1 g using a digital balance (Sartorius, Model L310). The carapace width of the crabs was also measured (see above).

It is important to emphasize here that wet weight of crabs collected during March 1999 and a few from April 1999, was not recorded in fresh condition. These crab samples were kept in the freezer for a few days and then were allowed to thaw when their individual wet weight was recorded. A calibration for converting frozen wet weight to fresh weight was obtained.

Photograph 2.10. The carapace width (CW) measurement being taken from the notch between the 8^{th} and 9^{th} antero-lateral spines.

Photograph 2.11. Carapace of *Portunus pelagicus* with abnormal 8^{th} and 9^{th} spines. Such specimens were not considered for population size structure studies.

2.4.2.3 Carapace width-4th abdominal segment relationship

Crabs of both sexes collected from March to May 1999 were measured for CW to determine population size structure and their 4th abdominal segment (defined as the distance between the side edges of the segment (Fig. 2.8)) was also measured. These measurements allowed the minimum size for sexual maturity to be gauged for each gender. The reason the width of 4th abdominal segment is deemed a key measurement is that it is the largest segment on the abdominal flap and it also has the potential to be increased in size due to parasitism (Day, 1935). Both dimensions were measured to the nearest 0.01 cm by means of a vernier calliper.

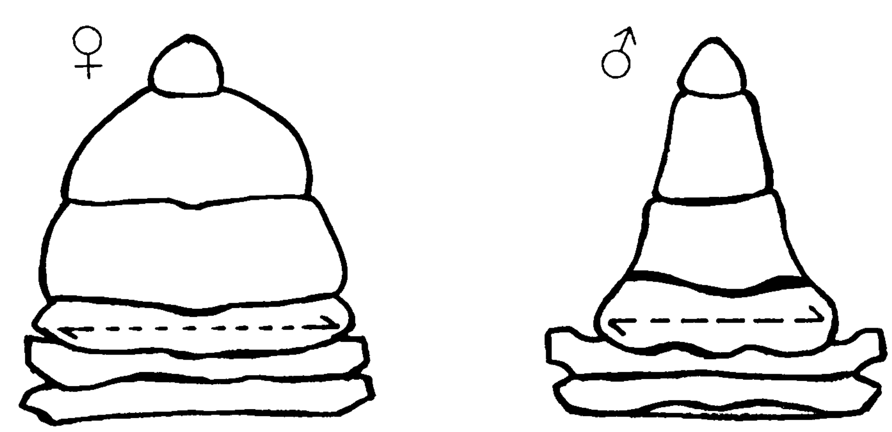


Figure 2.8. Drawing of the abdominal flap of the swimming crab *Portunus pelagicus* (adult), showing the 4th abdominal segment measurement size for both genders.

2.4.3 Reproductive biology

2.4.3.1 Ovigerous females

The incidence of ovigerous females was recorded throughout the course of the investigation. In all cases, the abdomen of females was lifted and examined for the presence of eggs, since in the case of a partly spawned crab, the eggs are completely hidden beneath the broad abdomen (Pillai and Nair, 1973). Ovigerous females were graded by colour of the egg mass (also called "sponge" or "berry") into 3 categories: yellow, grey, and black. The significance of these categories is considered important in understanding the various aspects of the seasonal reproductive biology of *P. pelagicus* in Bahrain waters.

2.4.3.2 Egg diameter measurement

Egg diameter of *P. pelagicus* was investigated during the present study to collect basic reproductive information on this species to compare with studies elsewhere. The egg diameter was determined by pooling all the selected ovigerous females from each night's catch (see 2.3.1.2.3.1) and handling them as one group. This was important in order to investigate egg diameter in relation to the stage of development and crab size (CW). The egg masses were sorted according to colour. A sub-sample was taken from each egg mass and kept in fresh condition in a small vial filled with fresh seawater. No preservatives were needed because the sub-samples were routinely measured 2-3 hours after their arrival from the field and it avoided any shrinkage that invariably occurs to preserved eggs (see Shams, 1998).

The diameter (µm) of 30-35 eggs from each sub-sample was measured using a Nikon Profile Projector, Model V-12, connected to a Nikon Readout Meter, Model SC-112. The correlations between egg diameter and environmental parameters, i.e. temperature, salinity and water depth, were also investigated. The measurements of egg diameter took place at the National Mariculture Station, Bahrain.

2.4.3.3 Fecundity of ovigerous females

Five to eight egg masses across the full size range of crabs available were selected from each study area. The fecundity of ovigerous females was estimated by counting eggs that had been sub-sampled from an egg mass. Egg mass sub-samples were taken as follows. Firstly, the whole egg mass was cut from the abdominal flap, wherein ensuring that as much of the pleopod structures as possible was removed from the mass. Eggs on individual pleopods were teased clear with forceps. Some fine setae inevitably remained, but they were considered negligible in the total egg mass weight. Excess water was removed with a paper towel and the egg masses were weighed to the nearest 0.1 g. by means of a digital balance (Sartorius Model L310). The second step was to remove sub-samples of eggs ranging from 0.1-0.3 g. from the mass, place them in vials and preserve them in neutrally-buffered formalin solution (5%) (Bucke, 1972) (see Table 2.2). The total number of eggs carried by an individual crab was determined by placing the sub-sample on a covered counting chamber (Sedgwick-Rafter 50 x 20 x 1 mm microscope slide) and counting the eggs under a dissecting microscope (Zeiss Model Carl/Zeiss 46 70 85). The total number of eggs in the egg mass was estimated by multiplying the number of eggs in the sub-sample by the weight ratio; i.e. the total weight of egg mass/sub-sample weight.

Table 2.2. Composition of the neutrally-buffered formalin solution (Bucke, 1972).

Chemical	Quantity
Formaldehyde (40% w/v)	50 ml
Distilled water	450 ml
Sodium dihydrogen phosphate (monohydrated)	2 g
Disodium hydrogen phosphate (anhydrous)	3.25 g

2.4.3.4 Egg mass wet weight-carapace width relationship

Once sub-samples for egg diameter measurements and egg counts were taken (see 2.4.3.2 and 2.4.3.3), the egg mass of every ovigerous female was cut off from the abdomen and wet weight obtained to the nearest 0.1 g using a digital balance (Sartorius Model L310). The CW of each female was also recorded.

2.4.3.5 Plankton samples

A quantitative approach was followed in investigating the larval stages of *P. pelagicus* in the water column. Samples were placed in a petri dish and examined under a microscope (Zeiss STMMI DV4). The larval stages; i.e. four zoea and I megalopa (Yatsuzuka, 1962 and Shinkarenko, 1979) were easily recognised, removed and placed in separate vials. The total number of larvae was noted, indicating the abundance of larvae in a given grid for a given time, hence, the spawning season could be identified.

2.4.4 Parasites

All individual specimens were inspected for the rhizocephalan parasite *Sacculina granifera* (as judged by the presence of externae and/or feminisation of males (Day, 1935)), gill parasites and epizoic fauna in order to estimate levels of parasite/epizoite infection/infestation.

Chapter 3

Hydrology

3. HYDROLOGY

3.1 Introduction

Environmental parameters such as temperature are known to be crucial factors influencing marine invertebrate biology (Pillai and Ono, 1978). That water temperature and salinity influence brachyuran biogeography is well known (Fransozo and Negreiros-Fransozo, 1996). A number of studies have been carried out on the effect of salinity and temperature, both separately and in combination, on the larvae of several crab species under controlled conditions in the laboratory, e.g. *Callinectes sapidus* (Sandoz and Rogers, 1944; Costlow, 1967), *Panopeus herbsti* (Costlow *et al.*, 1962), *Rhithropanopeus harrisii* (Costlow *et al.*, 1966), *Sesarma cinereum* (Costlow *et al.*, 1971).

Information on the interaction of such environmental parameters on the blue swimming crab, *Portunus pelagicus* (Linnaeus, 1758), in the wild is lacking. However, a number of laboratory investigations on this species have been carried out. Investigations from India, Australia and the Philippines on temperature have shown that the adults are eurythermal, able to withstand considerable variations in temperature (Dhawan *et al.*, 1976; Neverauskas and Butler, 1982; Batoy *et al.*, 1987). Dhawan *et al.* (1976) noted a tolerance range of 25-40 °C. The biology of *P. pelagicus* is highly temperature dependent (Anon, 1970), where moulting, spawning, embrynic development, breeding cycle and attaining maturity are largely controlled by temperature. Sumpton *et al.* (1989) have shown that foraging activity by *P. pelagicus* is inversely related to water temperature in a similar manner to that shown for the mud crab, *Scylla serrata* by Hill (1980), noting feeding activity at 25 °C but virtually none at 12 °C. Subsequently, Sumpton and Smith (1990) confirmed *P. pelagicus* to be most active at temperatures of 25 °C and above.

The current investigation reports on temperature and salinity found at the sampling areas in Bahraini waters over a 14 months period.

3.2 Salinity

Each month, seawater salinity (recorded at 1 metre depth) varied little between sampling areas. However, over the whole sampling period, salinity in area A ranged from 42 to 49‰ and showed a similar pattern to that in the adjacent area B, which varied from a minimum of 39‰ far offshore to 48‰ in shallower waters, but was generally lower than that in area A. A wider variation was found in area C where the salinity ranged from 41‰ in the north to 54‰ in its southern region. In the three study areas, salinity over the 14 months sampling period fluctuated, as expected. However, large seasonal variations anticipated, due to shortage of rainfall and lack of freshwater inflow from the land, were not observed. The annual means for areas A, B and C, were 45.3 ± 1.6‰, 43.8 ± 1.6‰, 45.3 ± 2.3‰ respectively. Fig. 3.1 shows that in October 1999 salinity in all three areas decreased due to very high rainfall in that month. Similarly, May 1999 shows a large decrease in areas A and B (but not C) again due to particularly high rainfall in the north of the region. Salinity in area D was found to be the highest, reaching 57‰.

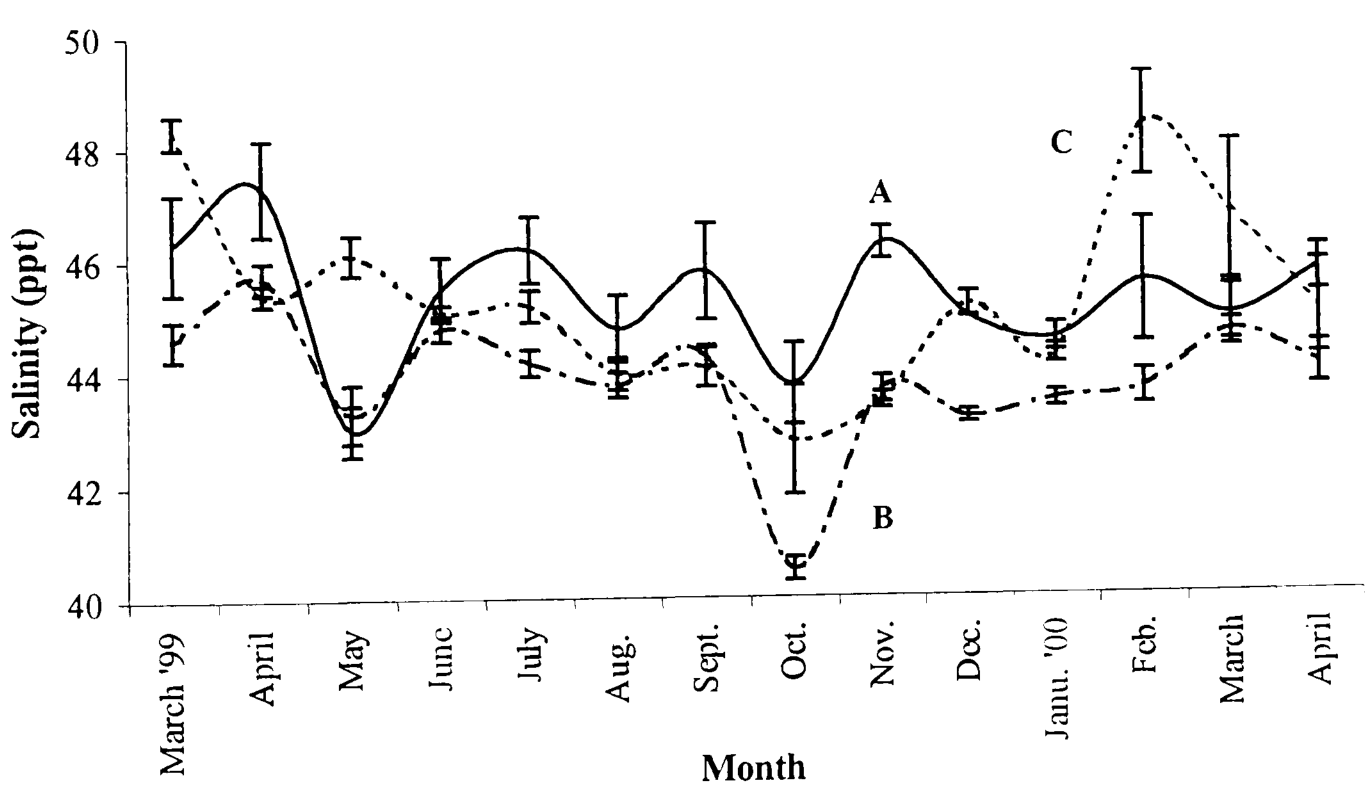


Figure 3.1. Monthly average surface salinity (‰) recorded at 1 metre depth in areas A (——), B (-.-.-) and C (------) from March 1999 to April 2000. Standard error of the means are also given.

3.3 Temperature

The seawater temperature (recorded at 1 metre depth) ranged from as high as 35 °C in September to as low as 16 °C in December. The surface and bottom water temperatures were always very similar in all three areas. The water column was well-mixed due to the shallow water. As with the salinity, seawater temperature around the study area varied temporally from one month to another, but did not vary between areas in a given month (Fig. 3.2). It is most likely that temperature recorded at area C, April 2000 (27 °C), was incorrect in comparison with area A (21 °C) and area B (22 °C) and can only be attributed to calibration error in the thermometer. Fig. 3.3 shows the annual temperature and salinity cycles in Bahraini waters, which reinforce the fact that *P. pelagicus* life history stages must be able to tolerate these considerable seasonal variations.

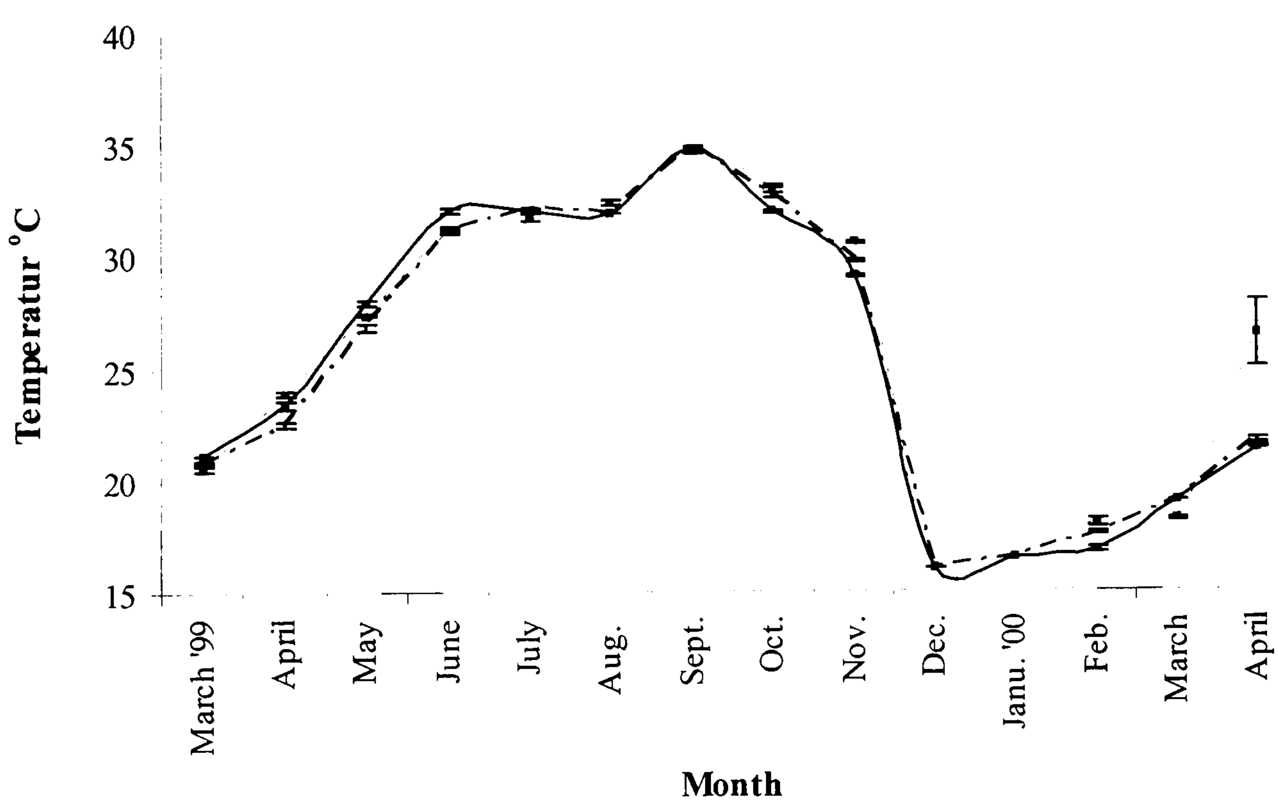


Figure 3.2. Monthly average surface temperatures (°C) recorded at 1 metre depth in areas A (——), B (-.-.-) and C (------) from March 1999 to April 2000. Standard error of the means are also given.

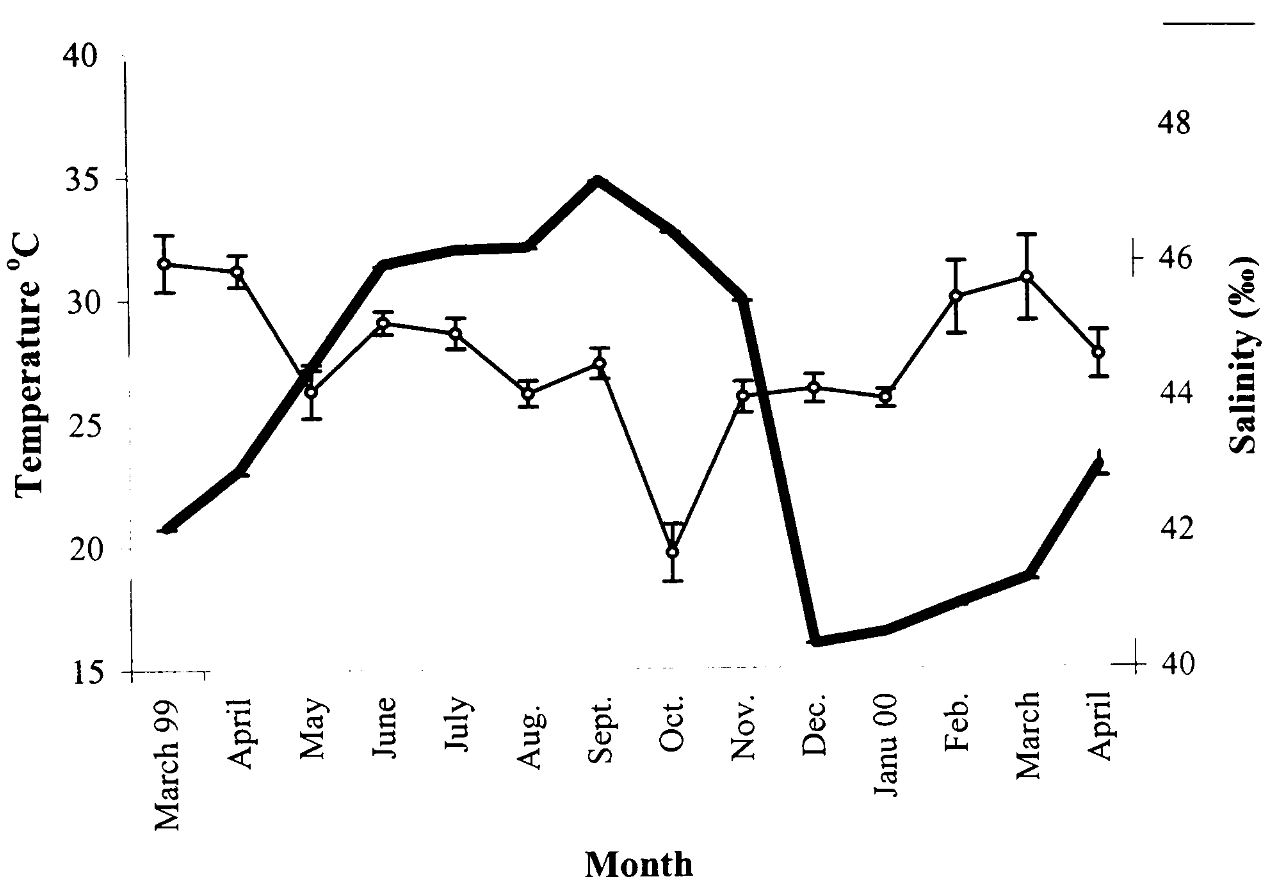


Figure 3.3. Monthly average (areas A, B and C) surface temperature (▬▬) and salinity (——) recorded at 1 metre depth, for the overall study area from March 1999 to April 2000. Standard error of the means are also given. The low salinity figure for October 1999 corresponds to a period of heavy rainfall.

Chapter 4

Reproductive biology

4. REPRODUCTIVE BIOLOGY

4.1 Introduction

Fisheries and reproductive biology of the swimming crab, *Portunus pelagicus*, have been studied extensively along the coasts of Japan, India, Philippines, Egypt (Mediterranean coast) and Australia where fishery management is well established. Data gathered by Pillai and Nair (1971a & 1971b), Pillai and Nair (1973), Ameer Hamsa (1978b), Manohara Ram and Chandra Mohan (1978), Potter *et al.* (1983), Devi (1985), Campbell and Fielder (1986 & 1988), Abdel Razek (1987 & 1988), Batoy *et al.* (1987), Abd El-Hamid (1988), Sumpton *et al.* (1989 and 1994b), Jacob and Kusuma (1990), Reeby *et al.* (1990) and Weng (1992) over the last three decades have furnished the necessary information to understand the biology of this species across its geographical range. The works of Meagher (1971) and Dhawan *et al.* (1976) have provided information on the ecology of *P. pelagicus* in Australia and India respectively. Despite its growing commercial importance, studies on larval occurrence of this species in the wild are lacking, however, larval development has been investigated extensively based on laboratory rearing experiments (Prasad and Tampi, 1953; Yatsuzuka, 1962; Meagher, 1971; Kurata and Midorikawa, 1975; Shinkarenko, 1979; Yatsuzuka and Meruane, 1987; Ingles and Braum, 1989; Jose *et al.*, 1996). Unlike related species viz. *Callinectes sapidus* and *Carcinus maenas*, work on the effect of temperature and salinity on larval development of *P. pelagicus* is not available, however, an investigation on temperature tolerance of adult *P. pelagicus* was carried out by Neverauskas and Butler (1982).

Despite its biological and economic importance, and apart from the previous study on *P. pelagicus* by Al-Rumaidh (1995) that documented the general biology of this species in coastal waters of Bahrain, large gaps persist in our knowledge of its population biology, not only locally, but also from waters around the entire Arabian Gulf. Therefore, the aim of the current work was to understand the reproductive cycle of *P. pelagicus* in terms of size at first sexual maturity, breeding season, fecundity, egg size and development, as well as larval distribution and development. In Bahrain at present, there are no management regulations for the *P. pelagicus* fishery whatsoever, hence, the aforementioned biological aspects should serve as an important tool in formulating regulatory measures appropriate for the proper management of the *P. pelagicus* stock around Bahrain.

4.2 Methods

4.2.1 Size at maturity

Size at maturity in male and female *P. pelagicus* in the course of this study was investigated by observing the inter-related increase in dimensions of the 4^{th} abdominal segment and carapace width (CW) from specimens captured between March and April 1999.

4.2.2 Breeding activity

Occurrence of ovigerous females is presented here in two ways. First, by calculating the percentage of ovigerous females in each month's overall female population and plotting these percentages over time (March 1999 to April 2000), so obtaining the annual breeding cycle. Second, the number of ovigerous females for a given month was broken down further into three broad categories based on their egg mass colour, viz. yellow, grey and black. The percentage of each colour category was calculated and all categories were plotted against the same above-mentioned time period, showing the differences in egg development stage between areas. Data are also presented by area in relation to the annual temperature cycle.

4.2.3 Egg mass colour in relation to crab size

Egg mass colour in relation to female crab size was obtained by from all the ovigerous females collected and numbers of crabs in each egg mass colour category were counted month by month and area by area. All data were then combined to establish the overall female crab size range for each egg mass colour category.

4.2.4 Egg diameter

Mean egg diameter of 33-35 eggs was used to represent the egg size produced by a crab of known CW. Sizes and colours of developing eggs, viz. yellow, yellow-greyish, grey-yellowish, and grey, were plotted against CW in order to investigate whether correlations existed. One-way ANOVA was applied to investigate whether mean diameter differs between eggs of different colours. Egg size (diameter) in relation to crab size (CW) and environmental parameters, viz. temperature, salinity and water depth, were also examined.

4.2.5 Larval abundance and distribution

Distribution of *P. pelagicus* larvae in waters around Bahrain is presented by plotting the occurrence of larvae per month per grid. As the larvae numbers per m^3 are very small, the results are expressed 100 m^{-3} giving more convenient figures to handle. The number of larvae (T) was estimated for a unit volume of seawater (100 m^3), as follows, assuming 100% filtration efficiency during the plankton haul.

$$\mathbf{T = (l / v) \times V}$$

where l = Number of larvae collected $area^{-1}$

v = Total volume of seawater filtered through the plankton net (m^3)

V = Unit volume of seawater (100 m^3)

The abundance of larvae in relation to temperature, salinity and water depth, was described by combining the data for the 11 months of sampling (April 1999-April 2000), thus allowing statistical analysis. Principal component analysis (PCA) was also used to help visualize patterns in larval abundance, which relate to these environmental parameters.

4.3 Results

4.3.1 Size at sexual maturity

The relationship of 4th abdominal segment against CW of male crabs using $\log_{10}$ transformed data is illustrated in Fig. 4.1. Both dimensions are found to be highly correlated ($r = 0.965$; $df = 849$; $p < 0.001$). The exponent of the power function was found not to be significantly different from 1 ($t = 0.514$; $df = 846$; $p = 0.304$), indicative of isometric growth. Therefore, there is clear evidence that the 4th abdominal segment in male *P. pelagicus* does not dramatically change at the pubertal moult.

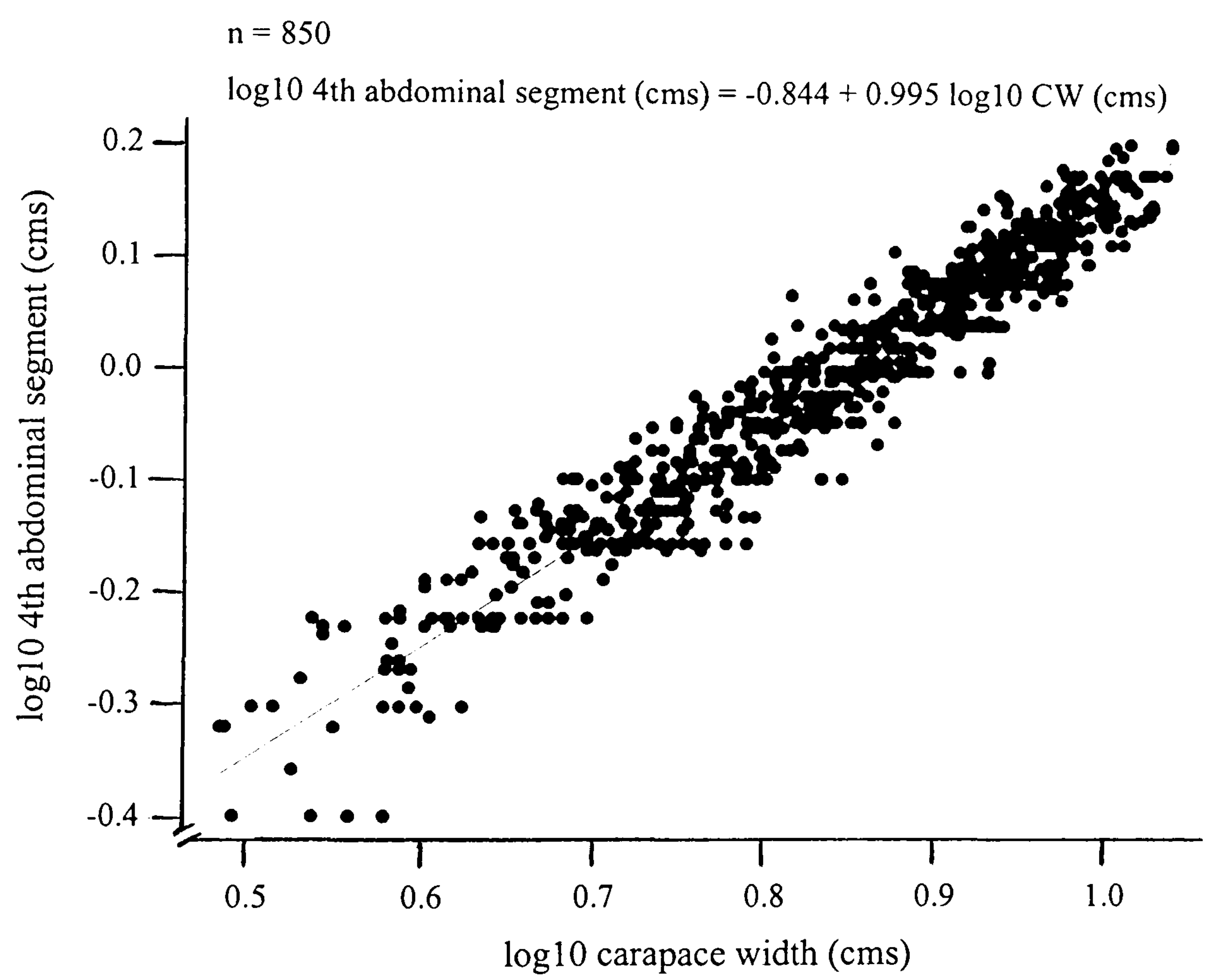


Figure 4.1. Scatterplot to illustrate 4th abdominal segment-carapace width relationship of male *Portunus pelagicus*, collected from the study area (March-April 1999).

Plotting the 4th abdominal segment against CW of female crabs of $\log_{10}$ transformed data indicated a separation (Fig. 4.2). A further investigation on the log/log data in plotting the residuals from a single fitted regression clearly identified two groups of data points – the mature and immature females (Fig. 4.3). Fig. 4.3 further illustrates the sharp transition which occurs to the 4th abdominal segment at about $\log_{10}$ 0.85 (≡ 7 cms actual CW), when the abdomen alters dimension and shape from triangular to semi-circular at the pubertal moult. Such a novel finding provides the evidence that the mean CW when female *P. pelagicus* first become sexually mature in Bahraini waters is 7 cms. Slopes of both groups at 1.2 and the sharp transition at about 7 cms CW, show that this sudden increase in the abdomen dimension is a single event in the life history.

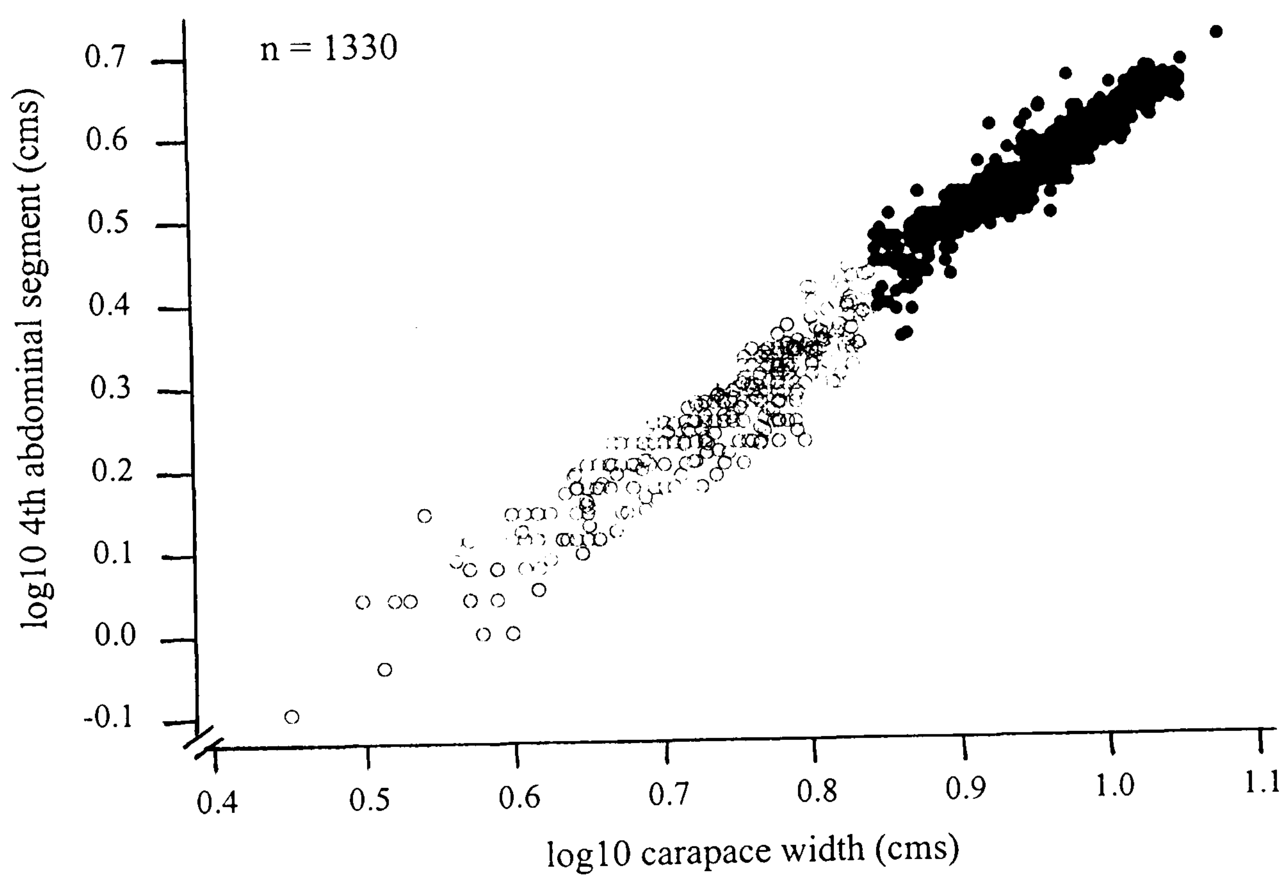


Figure 4.2. Scatterplot to illustrate 4th abdominal segment-carapace width relationship of female *Portunus pelagicus*, collected from the study area (March-April 1999). Immature (o) and mature (•).

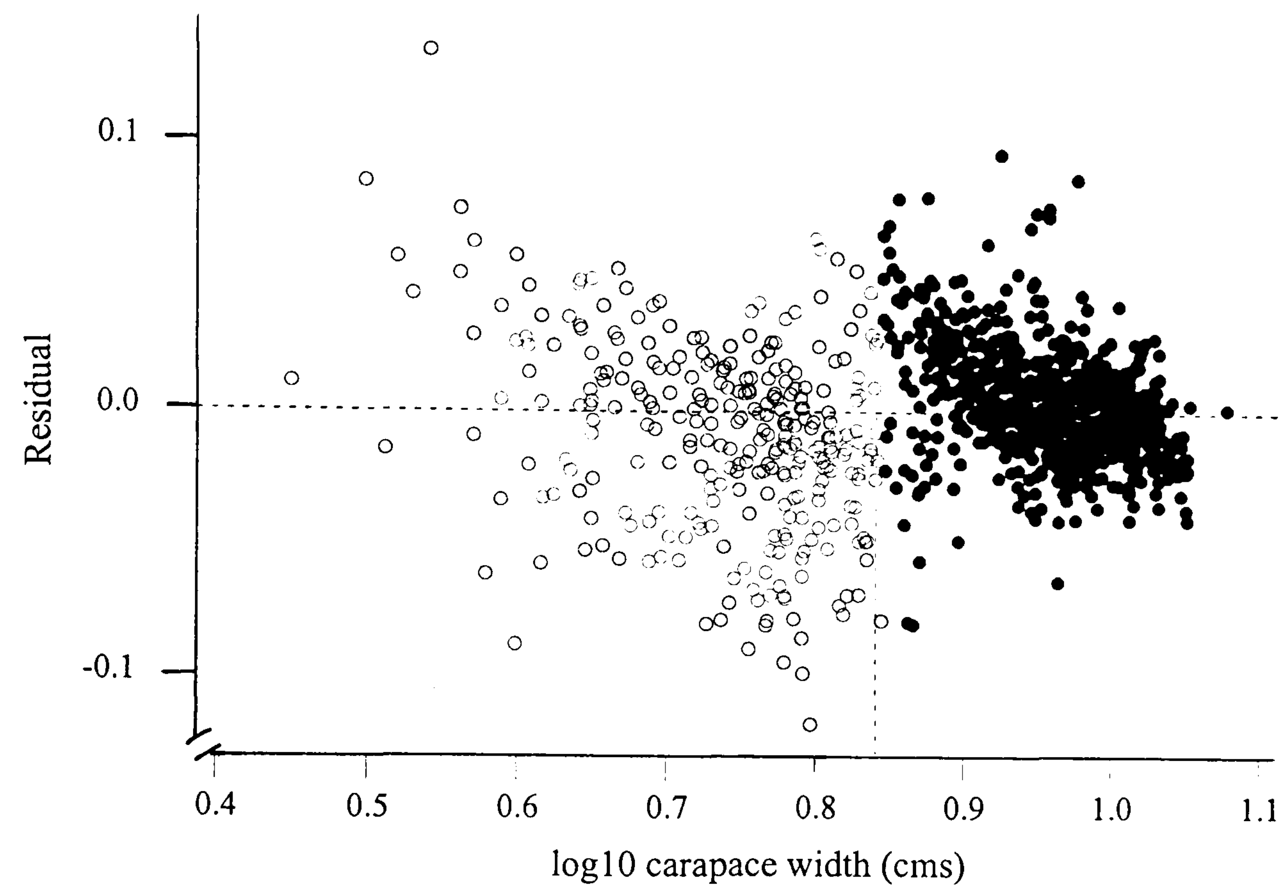


Figure 4.3. Residual plot for 4th abdominal segment and carapace width of female *Portunus pelagicus*, illustrating the sharp transition when becoming mature. Immature (o) and mature (•).

Regression analysis for the 4th abdominal segment against CW of both female groups, juveniles < 7 cms CW and adults > 7 cms CW, has indicated allometric growth. The exponents of the power functions for both groups were found to be significantly more than 1 (female crabs < 7 cms CW, $t = 6.996$; $df = 366$; $p < 0.001$) and (> 7 cms CW, $t = 11.518$; $df = 960$; $p < 0.001$). Regression parameters for both genders are presented in Table 4.1.

Table 4.1. Regression parameters for 4th abdominal segment-carapace width of male and female *P. pelagicus*. Log_{10} 4th abdominal segment (cms) = $a + b \log_{10}$ CW (cms).

Gender	Sample size (n)	Crab size (CW)	$b \pm$ SE	$a \pm$ SE	r	df	p
Male	850	Full range	1 ± 0.01	-0.844 ± 0.01	0.965	848	< 0.001
Female	368	< 7 cms CW	1.16 ± 0.023	-0.593 ± 0.017	0.936	366	< 0.001
	962	> 7 cms CW	1.15 ± 0.013	-0.535 ± 0.012	0.945	960	< 0.001

4.3.2 Breeding and spawning seasons

2,538 ovigerous females were taken from the major fishing grounds - areas A (n = 305, 12%), B (n = 1849, 25%) and C (n = 384, 7.2%), over the 14 month sampling period. The percentage figures above indicate the proportion of spawning females in the overall mature female population in each fishing ground. Out of the ovigerous population, only 7 crabs (0.3%) were found measuring less than 7 cms CW (7 cms is the median size at first maturity, as found by the present study). Sizes of female crabs (CW) found in the ovigerous condition are illustrated in Fig. 4.4, with the smallest being 6.1 cms and the largest 12.6 cms CW; both crabs were captured in area B.

Ovigerous females in area D were rare, with only three crabs (1.2%) found over the entire sampling period. Also, in the coastal fishing grounds of Askar and Barbar, only five (5%) and one (0.14%) were found respectively. Percentages given here are of total mature females captured. Such low figures indicate that area D and the coastal areas are not major breeding grounds for *P. pelagicus*. Details description of these crabs are presented in Table 4.2.

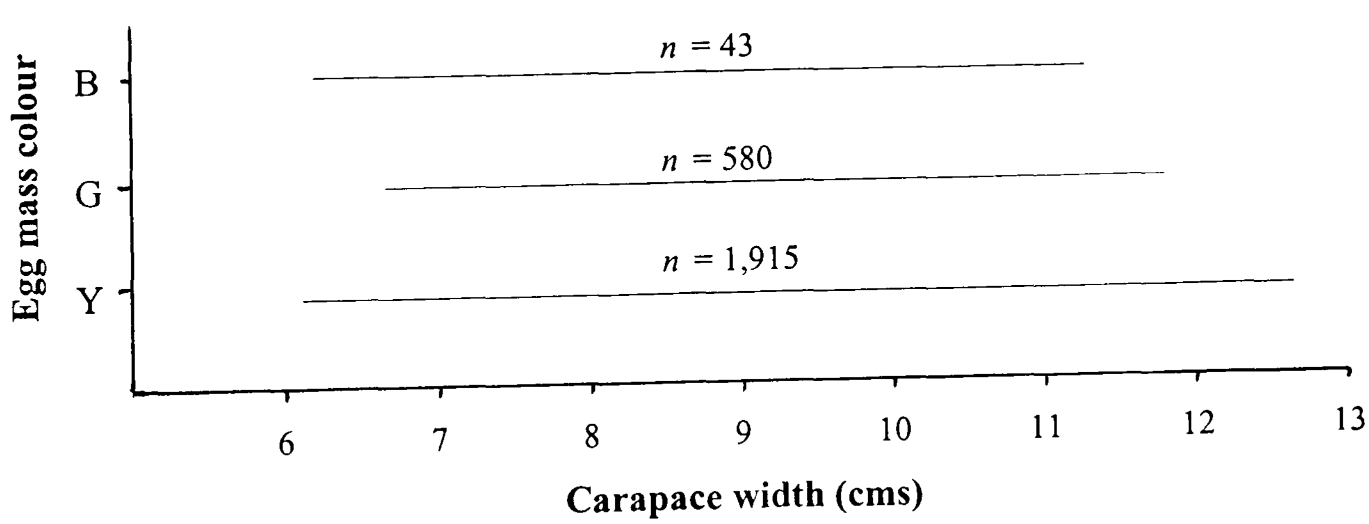


Figure 4.4. Sizes of ovigerous female *Portunus pelagicus* and the colours of the egg masses being carried - yellow (Y), grey (G) and black (B). The crabs were collected between March 1999 and April 2000.

Table 4.2. Ovigerous females and egg mass colour collected from area D and coastal fishing grounds.

Capture month	Location					
	Area D		Askar		Barbar	
	CW	EMC	CW	EMC	CW	EMC
April 1999	8.6	Yellow	10.3	Black		
	8.7	Yellow	9.6	Black		
	9.4	Grey	7.7	Yellow		
			9.3	Grey		
May 1999			8	Yellow	7.4	Yellow

CW = carapace width (cms) of female,
EMC = egg mass colour.

The size frequency distributions (SFDs) of ovigerous females for areas A, B and C, together with those of non-ovigerous females are given in Fig. 4.5. SFDs of ovigerous females from areas B and C were found to be approximately normally distributed (Anderson-Darling $A^2 = 0.286$, $p = 0.624$ and $A^2 = 0.698$, $p = 0.068$ respectively), whereas those in area A and all other non-ovigerous females were not. Size of ovigerous females was found to be similar in the three offshore areas, ranging from 7-11.5 cms CW. Female crabs in areas A and C have distinctly different frequency distributions between non-ovigerous (modes 7-8 cms) and ovigerous (modes 8-9 cms) (Fig. 4.5). With the exception of non-ovigerous females in area B (showing a bell-shaped distribution to a great extent) non-ovigerous females from the other two areas were less abundant as the crabs increase in size. Fig. 4.5 further illustrates that in area B frequency distributions for ovigerous and non-ovigerous populations were the same with modes at 9-10 cms. The findings indicate that fishing grounds within areas A and C represent growing-on areas for female crabs, while study area B represents a spawning area. Also, it is seen that the medium-sized female crabs, 7.5-10 cms CW, represent the most active spawners as evidenced by the greater percentage of ovigerous females within the size range.

Ovigerous females occurred in the crab population from March to November 1999, and from March to April 2000 when sampling ceased. No ovigerous females were found in the study area from December 1999 to February 2000 and they were also absent from area B through March 2000. The incidence of ovigerous females (percentage of the total mature females in each area) around the study area is shown in Fig. 4.6, defining the spatial and temporal variation in breeding and spawning of *P. pelagicus* in this part of the world.

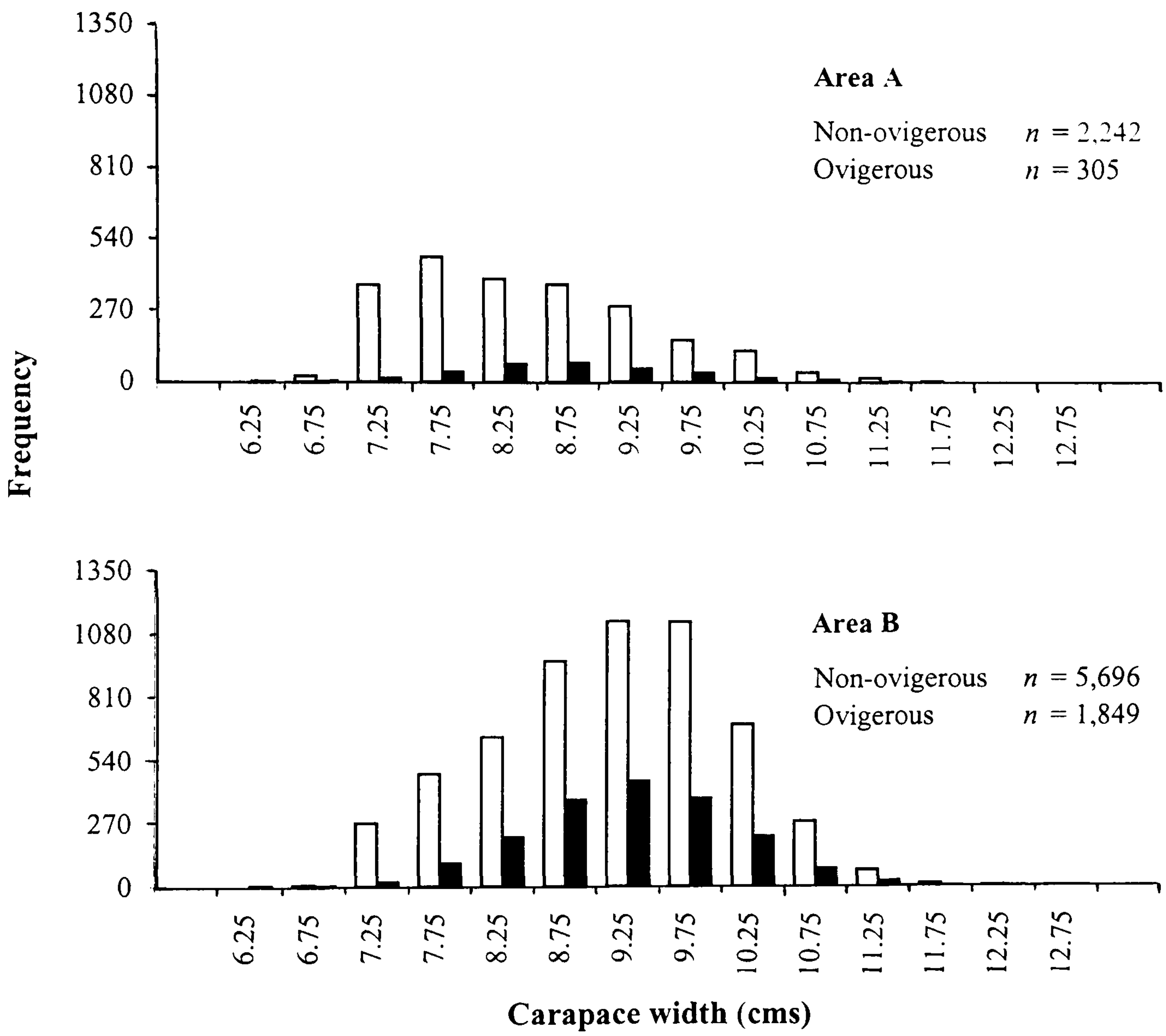


Figure 4.5. Continued

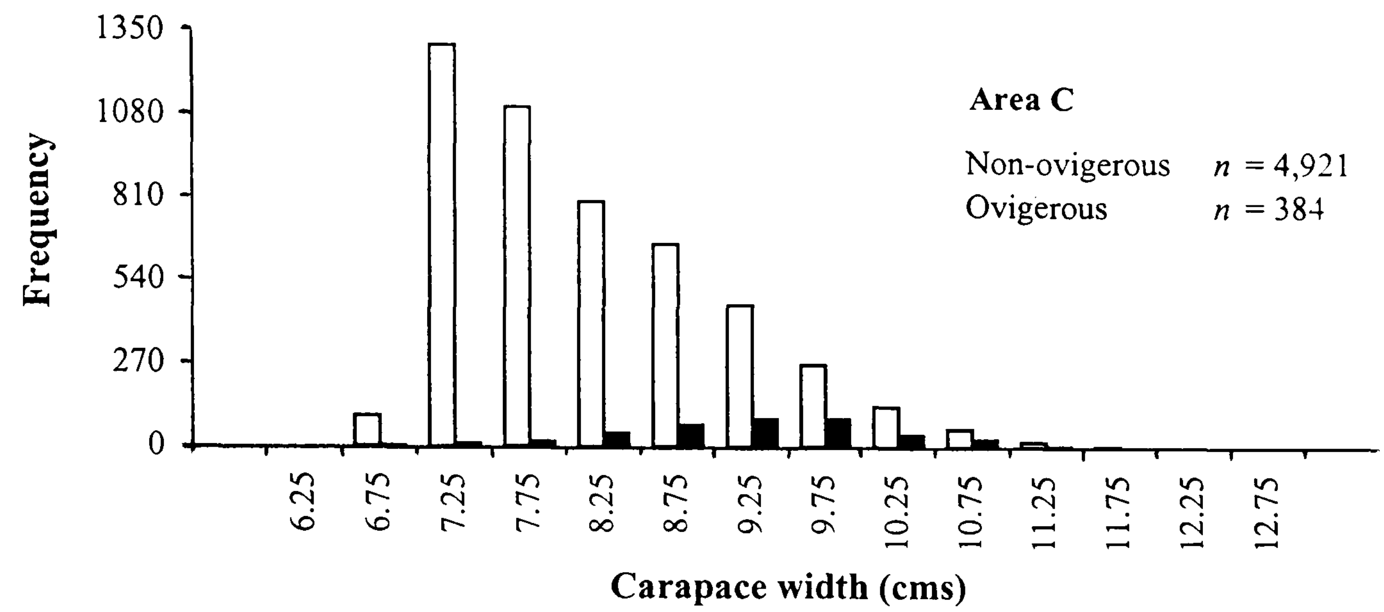


Figure 4.5. Size frequency distributions of ovigerous female (black bars) and non-ovigerous female (open bars) *Portunus pelagicus* collected from areas A, B and C from March 1999 to April 2000.

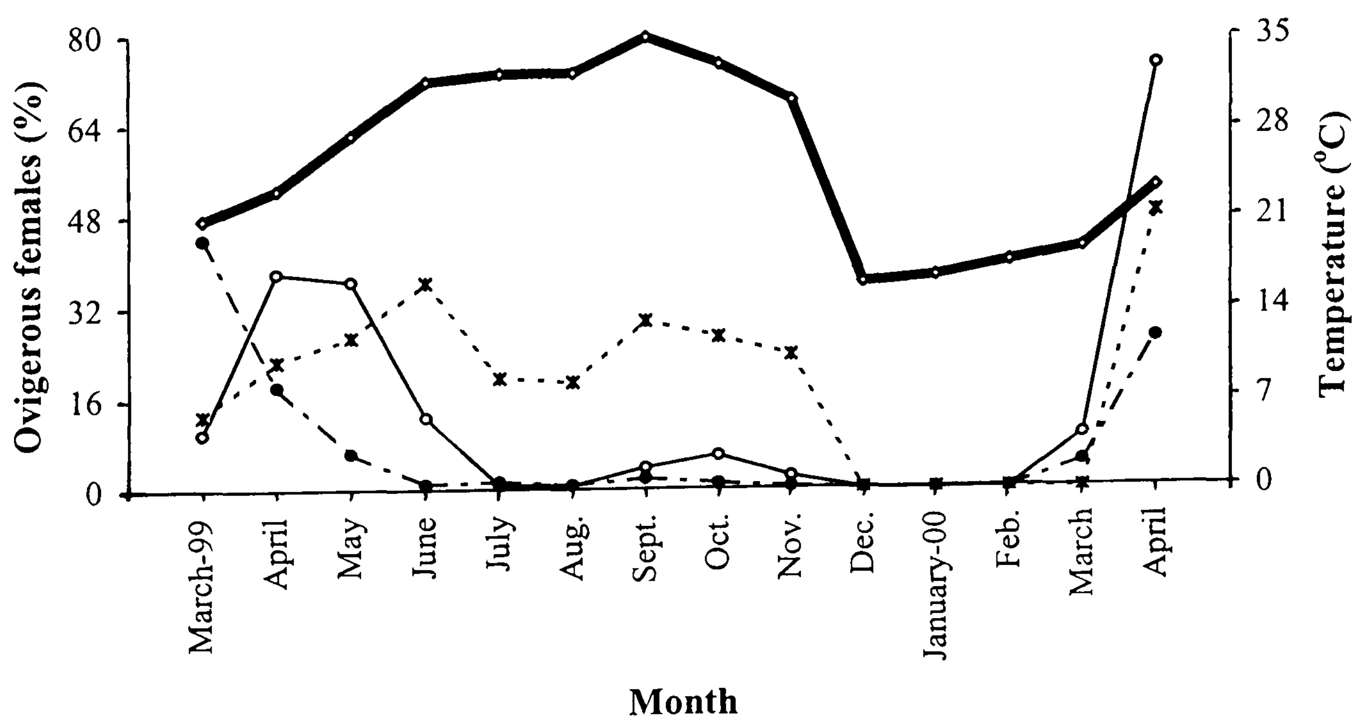


Figure 4.6. The percentage of mature female *Portunus pelagicus* carrying eggs in each area, from March 1999 to April 2000. Area A (—o—), area B (--*--) and area C (--•--). Annual temperature cycle (▬▬ ◊▬▬) is also plotted.

Fig. 4.6 further illustrates the influence of temperature on breeding activity. Only the ovigerous female incidence for area B followed the pattern of temperature change throughout the study period. The absence of ovigerous females in the crab population during December-February was associated with low water temperature, i.e. 16-18 °C indicating that breeding stops when the water temperature falls below 20 °C.

Although ovigerous females were present for most of the duration of the study, their incidence varied within the areas throughout the sampling period; they remained most prolific in area B. The highest incidence of ovigerous females was in March 1999, recorded in area C at 44%, which then progressively declined to 0.9% in June and remained at this low rate until November. Ovigerous females re-occurred in the population in March 2000 at a 5% incidence rate, which increased in the following month up to 26%. The incidence of ovigerous females in area A was low at almost 10% in March 1999. It increased to 38% and 36% in April and May 1999, declining progressively to 0.7% in August. Ovigerous females were rare in areas A and C thereafter. For three consecutive months from December 1999, ovigerous females were absent until March 2000 when the incidence was about 10% followed by a dramatic increase in the following month to 75%. The data suggest that breeding in area A is more active during April-May 1999 and April 2000, and by supposition that spawning in this region also takes place during these months.

In area B, ovigerous females were abundant from June to November, however, egg carrying was greatest during June and September. They then exhibited a gradual decline and were absent in the December catch. Thereafter, ovigerous females were not encountered in the population until April 2000 when 49% (n = 45) of the mature females captured were berried. The incidence of ovigerous females reported in areas A and C during April 2000 as low as 12 and 27 crabs respectively, suggest that younger crabs were growing in these areas then moving to area B. The overall breeding status given in Fig. 4.6 indicates that *P. pelagicus* exhibits a reproductive season over a period of eight months with definite peaks during April, June and September representing the main spawning seasons for this species in Bahraini waters.

Some interesting features of ovigerous female occurrence were noted: (1) despite the highest incidence noted in area C at the start, it was the lowest by the end of the sampling period and (2) although Fig. 4.6 illustrates a higher percentage of ovigerous females in the three areas during March and April 2000, the actual numbers (abundance) were far lower than during the same period of the previous year (Table 4.3). Ovigerous females with late egg stages, i.e. grey and black, were found in highest abundance in area B (see Fig. 4.7).

Table 4.3. Grand total of non-ovigerous and ovigerous females collected from the study areas during March-April 1999, and March-April 2000, to show the decline in the overall female population in 2000.

	Study area					
	A		B		C	
Time	Non-ovigerous	Ovigerous	Non-ovigerous	Ovigerous	Non-ovigerous	Ovigerous
March-April 1999	320	122	801	199	612	294
March-April 2000	23	14	52	45	157	31

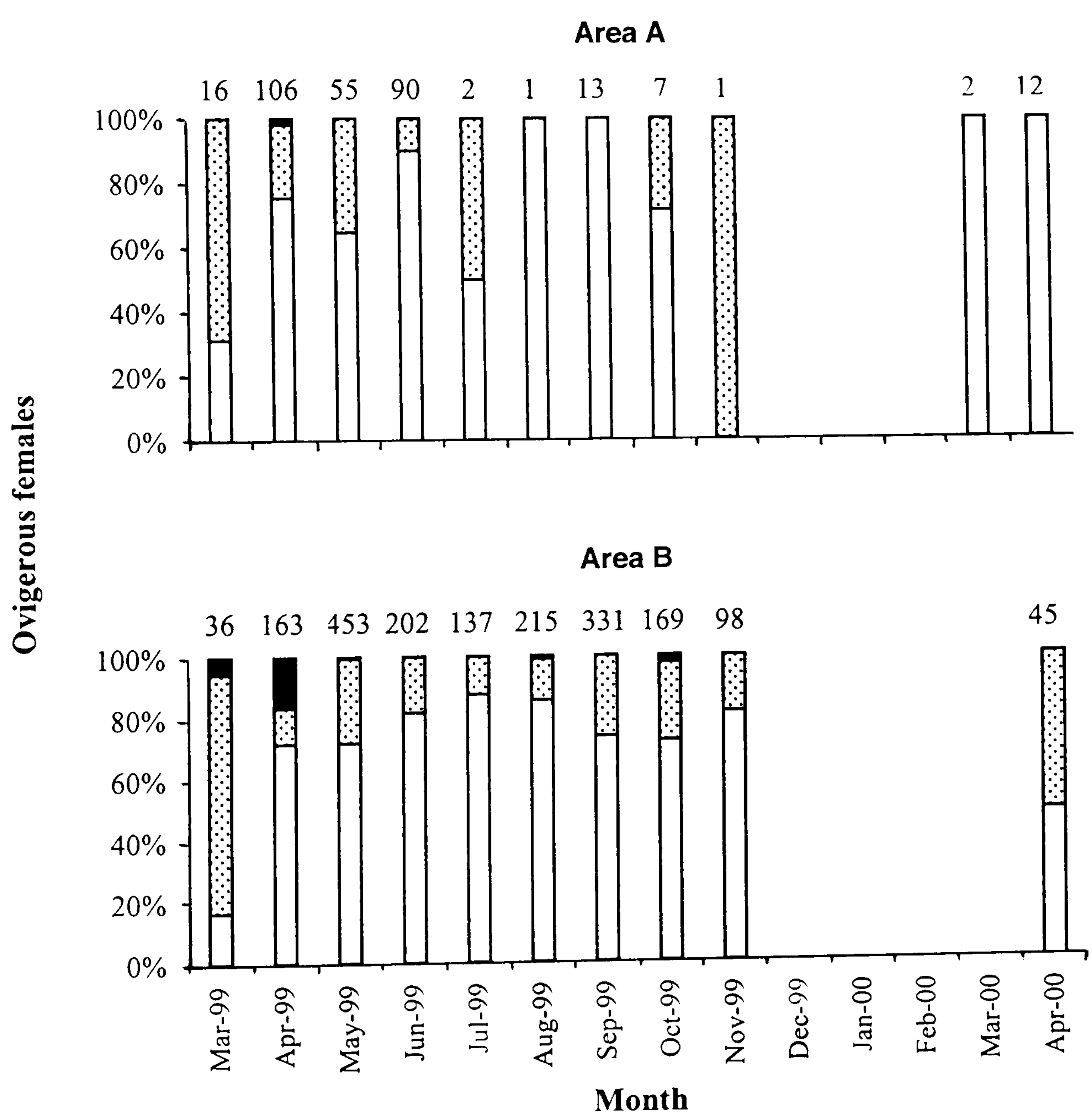


Figure 4.7. Continued

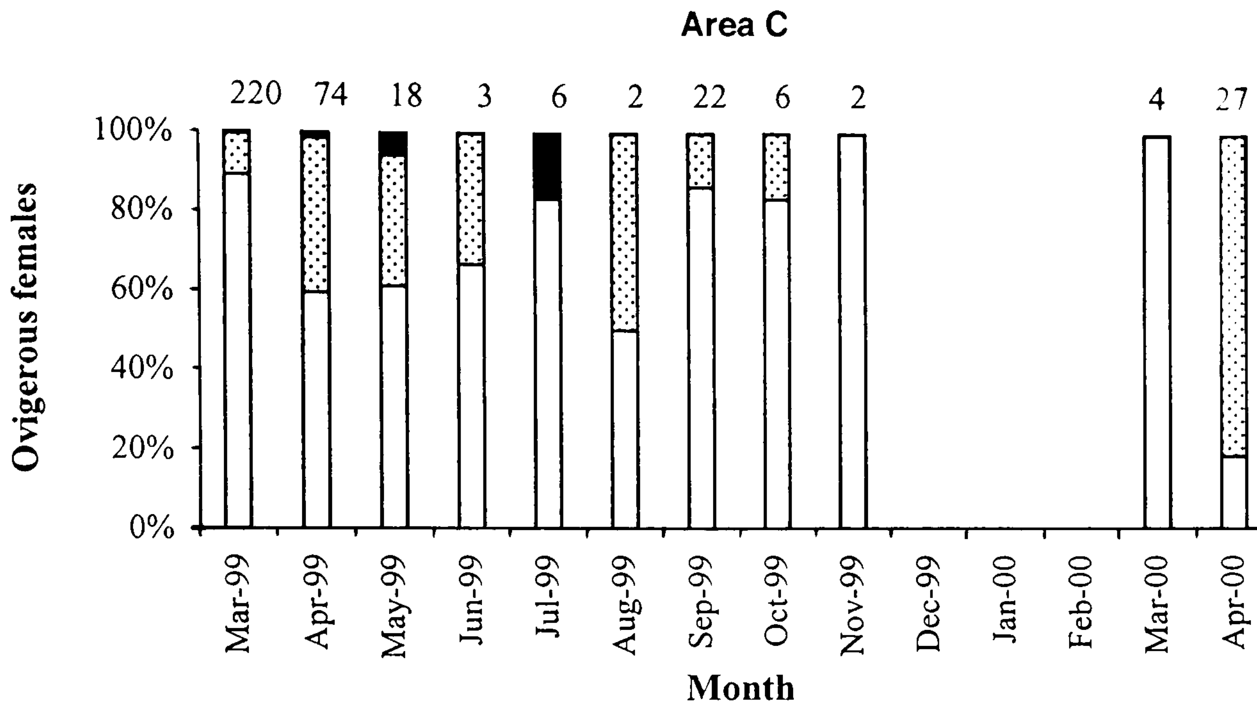


Figure 4.7. Egg masses in the monthly samples (March 1999-April 2000) showing the proportions (expressed as percentages) in terms of colour - yellow egg masses (open bar), grey egg masses (dotted bar), and black egg masses (black bar). Actual numbers of ovigerous females are shown above each bar.

4.3.3 Fecundity

The fecundity of *P. pelagicus* female is defined as number of eggs per brood. Is was measured by the total wet weight of egg mass and a calibration to gain the number of eggs per egg mass.

4.3.3.1 Egg mass wet weight

A total of 85 and 58 egg masses representing yellow and yellowish-grey (early eggs); greyish-yellow and grey (late eggs) respectively, were used to calculate the average wet weight of the egg mass. The smallest and biggest egg masses, examined during this particular study, weighing 9 g (yellow) and 58 g (grey), were found on crabs measuring 8 and 12 cms CW respectively. Egg mass wet weight in both groups increased exponentially with increasing CW (Figs. 4.8a and 4.8b). Slopes varied from 3.69 ± 2 for yellow eggs to 3.55 ± 2 for grey eggs. However, egg mass wet weight in both colour categories is found to be similar at all crab sizes, as tested by the General Linear Model analysis ($F_{1,139} = 3.43$; $p = 0.066$). Findings obtained from this study, give clear evidence of no definite crab size

(CW) for a specific egg stage, so female crabs produce and carry eggs once maturity is attained.

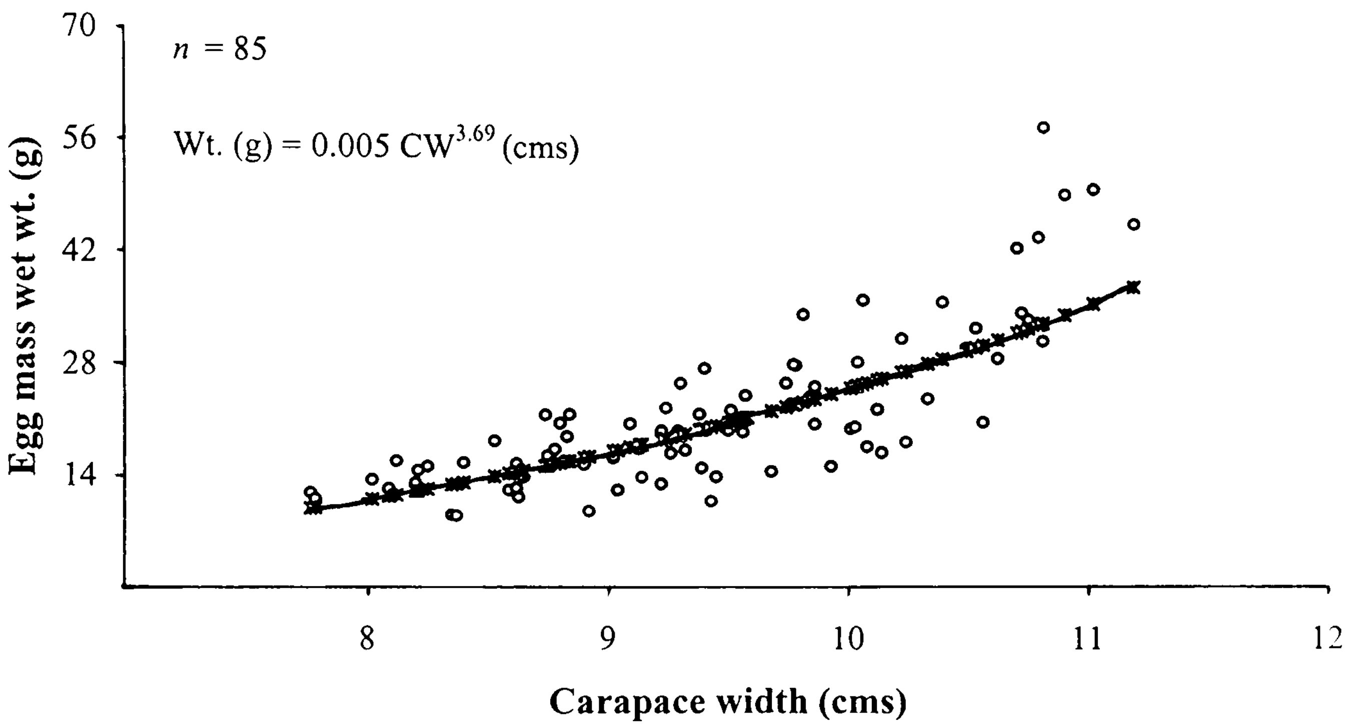


Figure 4.8a. Scatterplot to illustrate the relationship between yellow egg mass weight (early eggs) and carapace width of female *Portunus pelagicus* collected from the study area during September and November 1999, April and May 2000. Curve fitted by least squares regression.

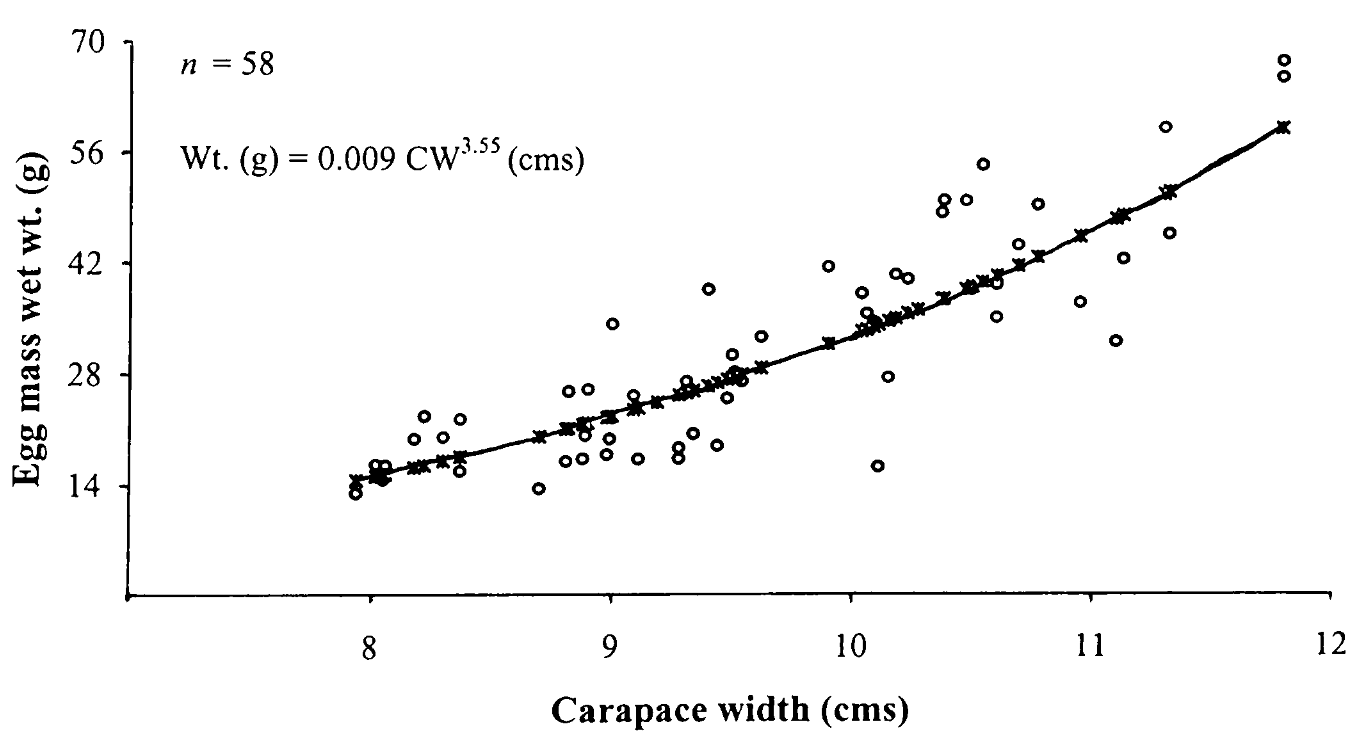


Figure 4.8b. Scatterplot to illustrate the relationship between grey egg mass weight (late eggs) and carapace width of female *Portunus pelagicus* collected from the study area during September and November 1999, April and May 2000. Curve fitted by least squares regression.

4.3.3.2 Number of eggs

A total of 43 ovigerous females ranging from 7 to 12 cms CW, collected during August, October and November 1999 and April 2000, were used to determine the number of eggs per egg mass of a given weight. The mean CW of all examined crabs was 9.2 ± 0.18 cms. Egg mass colour and estimated number of eggs in each egg mass category are presented in Table 4.4 for 24 egg masses only.

The number of eggs produced per ovulation is very large and varies with the size of the crab and even between females of the same size. The number of eggs ranged from 0.302 to 1.54 million eggs, the lowest and highest number of eggs being obtained from females measuring 8.4 and 11.8 cms CW respectively. The mean number of eggs in all the berried crabs examined was found to be 0.82 ± 0.05 million eggs. Some smaller crabs were often found carrying more eggs than bigger crabs, e.g. a female measuring 10.8 cms CW was found to have approximately 0.65 million eggs, while another one measuring only 7.2 cms CW carried approximately 0.882 million eggs. Equally, some crabs carried considerably fewer eggs than others, although the crabs were the same size (Fig. 4.9).

Table 4.4. Approximate number and colour of eggs in specimens of female *Portunus pelagicus* collected from the study area during October 1999 and April 2000.

Carapace width (cms)	Number of crabs	Colour of egg mass	Approximate number of eggs (million) per egg mass
7.2-10.8	16	Yellow	0.4-1.5
7.3-10.8	5	Greyish-yellow	0.3-0.7
7.5-11.8	3	Grey	0.3-1.5

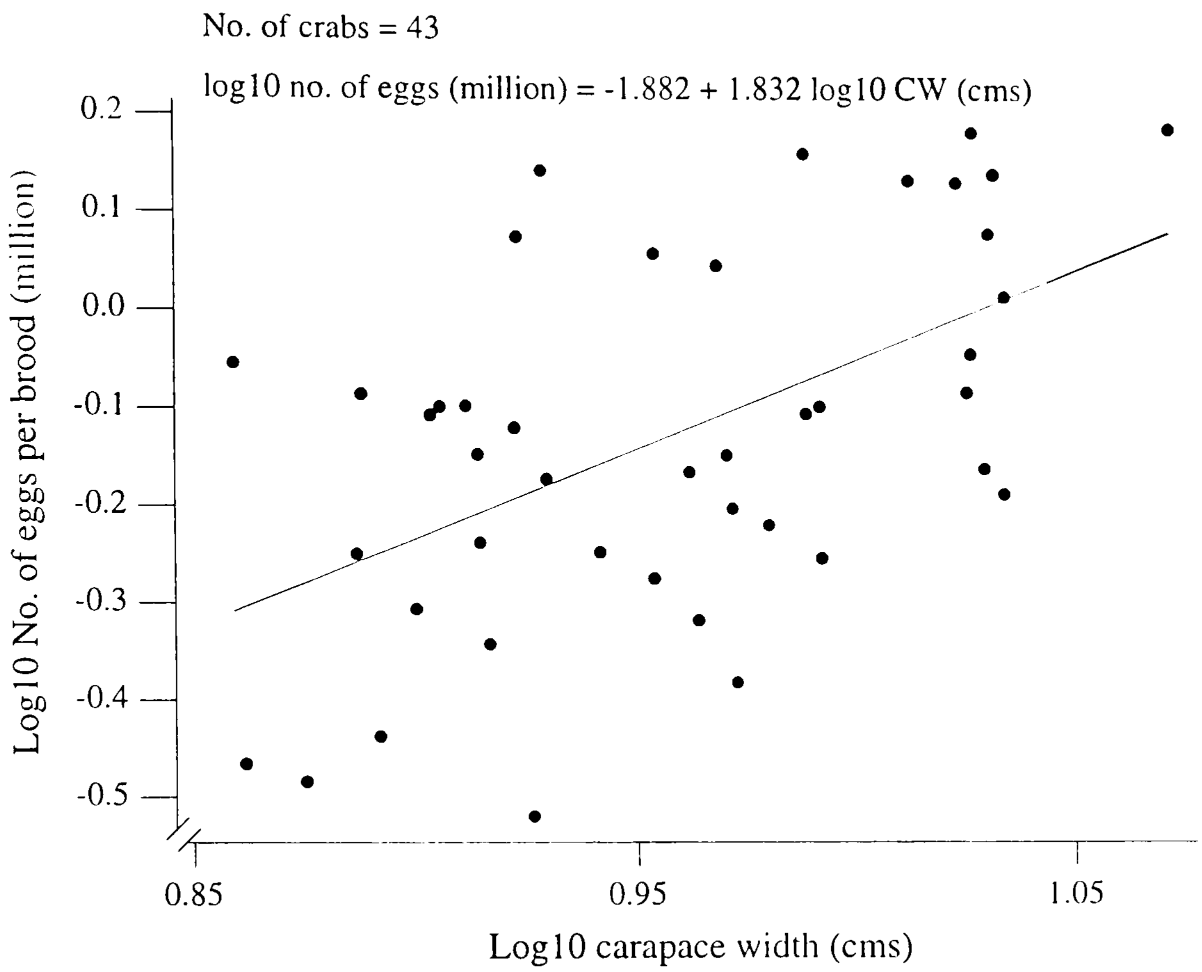


Figure 4.9. Scatterplot (log/log) to illustrate the relationship between number of eggs (million) and size of female *Portunus pelagicus* collected from the study area during August, October and November 1999 and April 2000.

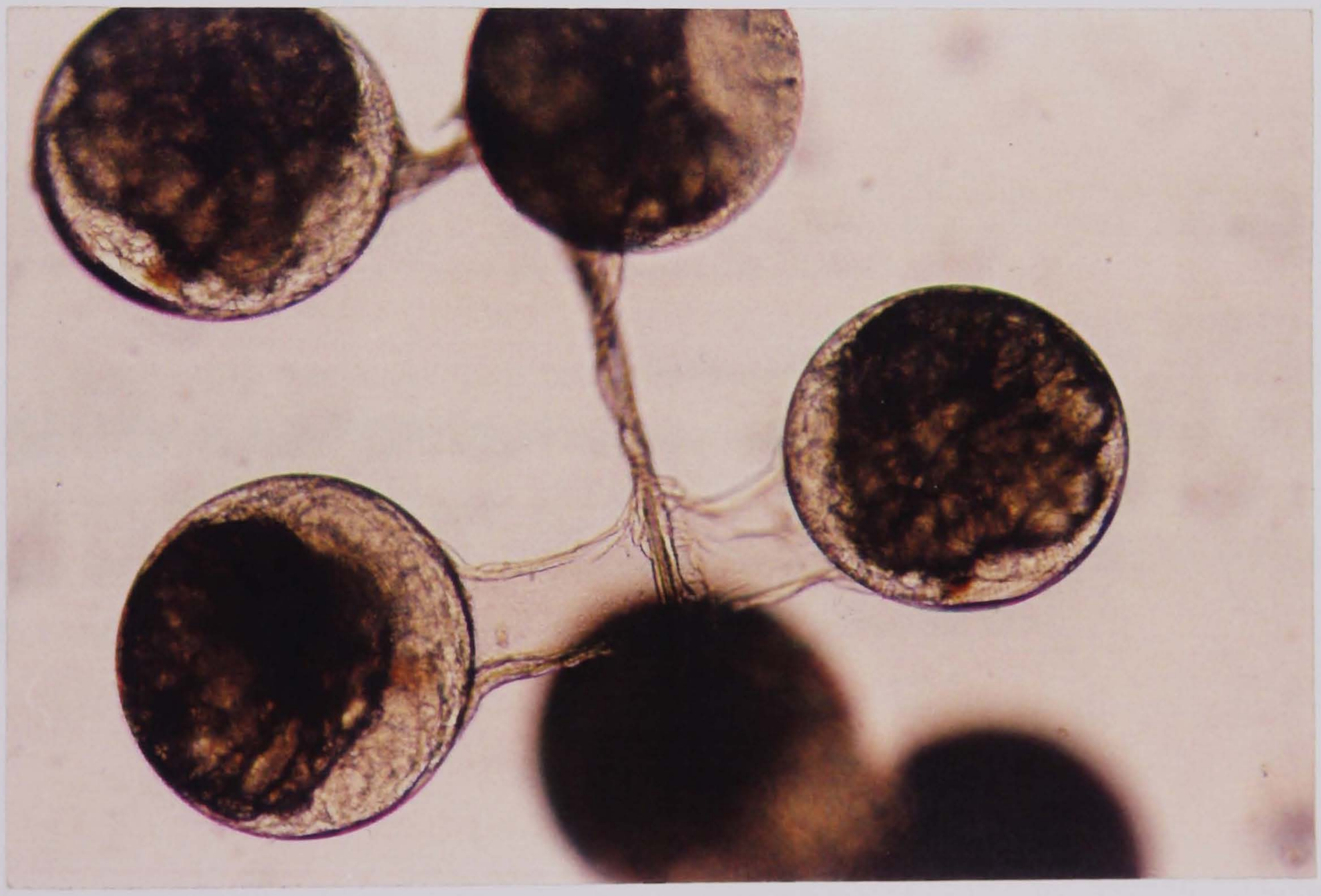
Regression analysis has indicated that egg number increases exponentially as female crabs increase in CW ($\log_{10}$ number of eggs [million] = -1.882 + 1.832 $\log_{10}$ CW [cms]), where exponent of the power function (1.832 ± 0.453) was found to be significantly more than 1 (t = 1.839; df = 41; p = 0.037). As stated earlier, there was a wide range in the number of eggs carried by crabs of the same size; the greatest range was in crabs of mid-size classes 7.25 and 8.75 cms CW, where females in these categories exhibited a range of 0.328-0.882 million eggs and 0.531-1.143 million eggs respectively. The exact cause of this variation in egg number is unknown.

4.3.4 Egg diameter

Eggs of *P. pelagicus* examined in the course of the present investigation are spherical and are surrounded by an inner and an outer membrane (Photograph 4.1). Both of these membranes are transparent and embryo development could be observed through them.

The yolk is visible in the egg as yellow granules. Photograph 4.1 further illustrates that the eggs are attached to the endopoditic setae of the abdominal appendages-the pleopods.

A total of 1,794 eggs from 54 ovigerous females ranging from 7.8 to 11.8 cms CW were measured. Eggs were also classified into four categories depending on their colour, viz. yellow (n = 897), yellowish-grey (n = 167), greyish-yellow (n = 366), and grey (n = 364). Eggs in black masses were not measured as they proved to be hatched zoea still attached to the pleopods. The measured egg diameters ranged from 242 to 531 µm. Yellowish-grey eggs and greyish-yellow eggs were almost same diameter, i.e. 396 ± 2.6 µm and 394 ± 1.3 µm respectively. Hence, both categories were combined and termed "greyish-yellow", as the latter category was numerically larger. The average diameter ± SE for yellow, greyish-yellow and grey eggs was 365 ± 1.1, 394 ± 1.2 and 422 ± 2.1 µm respectively (Table 4.5). Mean egg diameter increased markedly through embryo development ($F_{2,1791} = 411.97$, $p < 0.05$) (Fig. 4.10).



Photograph 4.1. Cluster of spherical eggs of the swimming crab *Portunus pelagicus* attached to a seta of a pleopod. Scale bar ———————— 350 µm.

Table 4.5. Egg diameter range and colour in specimens of female *Portunus pelagicus* collected from the study area from March to May 2000.

Carapace width Size class (cms)	Number of crabs	Colour of egg mass	Egg diameter range (μm)
7.8-11.2	27	Yellow	242-490
7.9-11.3	16	Greyish-yellow	302-491
8.0-11.8	11	Grey	304-531

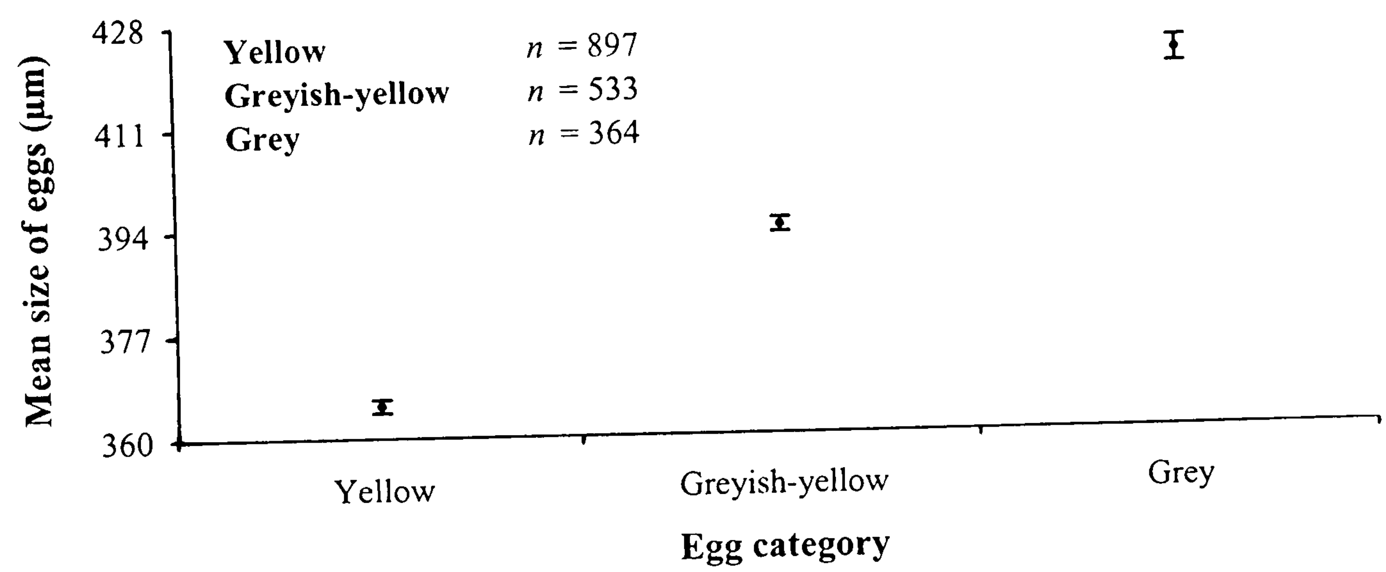


Figure 4.10. Graph showing the average egg diameter of the three colour categories: yellow, greyish-yellow, and grey, of *Portunus pelagicus* from Bahraini waters, March-May 2000. Standard error of the means are given for each category.

Egg diameter was found not to be related to crab size (r = 0.247, df = 52, p = 0.072) (Fig. 4.11). The finding that the three egg colour categories are present for egg masses of crabs over a carapace width range of 7.8-11.8 cms (Table 4.5) suggests that female *P. pelagicus* in Bahrain likely spawn at least twice during their life time, the first being soon after maturity, and the other(s) later in the year or in the subsequent year(s).

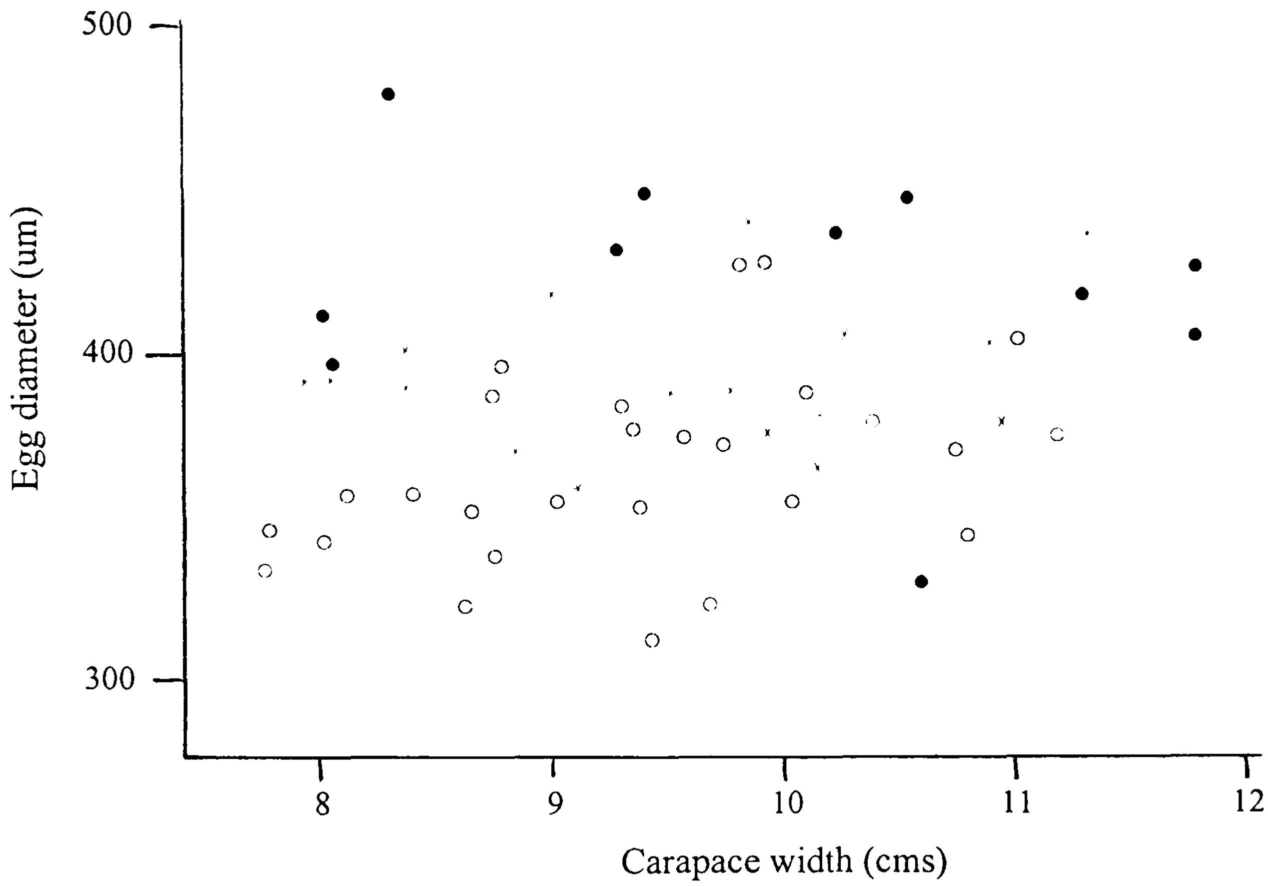


Figure 4.11. Scatterplot of egg diameter of the three egg colour categories against carapace width of *Portunus pelagicus* collected from the study area from March to May 2000. Yellow (o), Greyish-yellow (*) and Grey (•).

As far as the egg diameter in relation to environmental parameters is concerned the findings indicated there was no relationship between egg diameter and either salinity or water depth. The plot of the overall regression model "Egg diameter (μm) = 499 – 4.49 Temperature (°C)" (r = -0.416, $F_{1,45}$ = 9.44, P = 0.004) is illustrated in Fig. 4.12. The inverse relationship alerts to the fact that increasing temperature likely has a stress effect on egg size, through development.

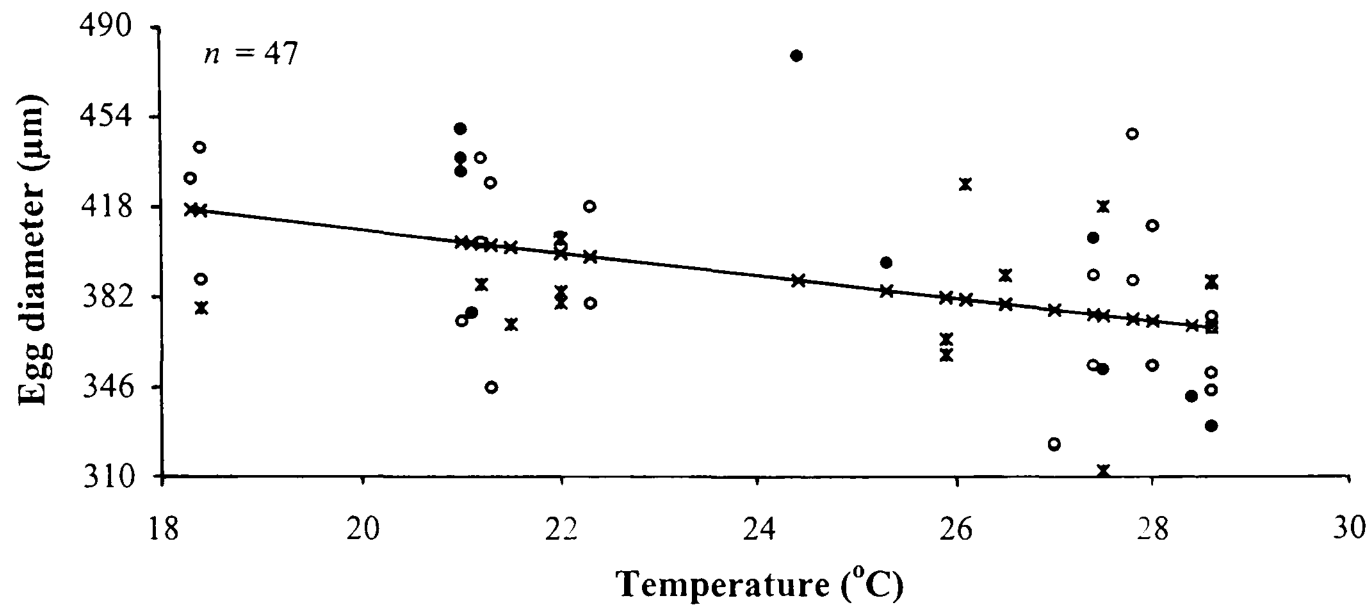


Figure 4.12. Scatterplot of egg diameter of the three egg colour categories of *Portunus pelagicus* against temperature. Data collected from the study areas from March to May 2000. Regression model for combined data is plotted. [Egg diameter (µm) = *a* + *b* Temperature (°C)]. Yellow (o), Greyish-yellow (*) and grey (•).

4.3.5 Larval Biology

4.3.5.1 Larval incidence and distribution

The seasonal fluctuations in the incidence of *P. pelagicus* larvae and their distribution in Bahraini waters were investigated in order to understand the early stages in the life-cycle of this species.

A total of 179 zoea larvae (zoea stages I-IV) and seven megalopae were collected in the course of plankton sampling, carried out at the same time as the trawling operations from April 1999 to April 2000. Larvae of *P. pelagicus* were found dispersed all over the fishing grounds, ranging from the coastal waters to as far as 18 nautical miles off the northern shorelines of Bahrain and the Al Muharraq Islands (Fig. 4.13). Although the conclusion is that spawning of *P. pelagicus* may take place throughout Bahraini waters, it does not necessarily mean that it occurs in all grounds at the same time. However, the presence of larvae was not consistent all year round. They were recorded from almost all grids within areas A and B, whereas in area C they were restricted to the northern and central regions. The absence of larvae at the southern region of area C, i.e. latitudinal grids 85-87, where the salinity levels are above 50‰, indicates that larvae of *P. pelagicus* are

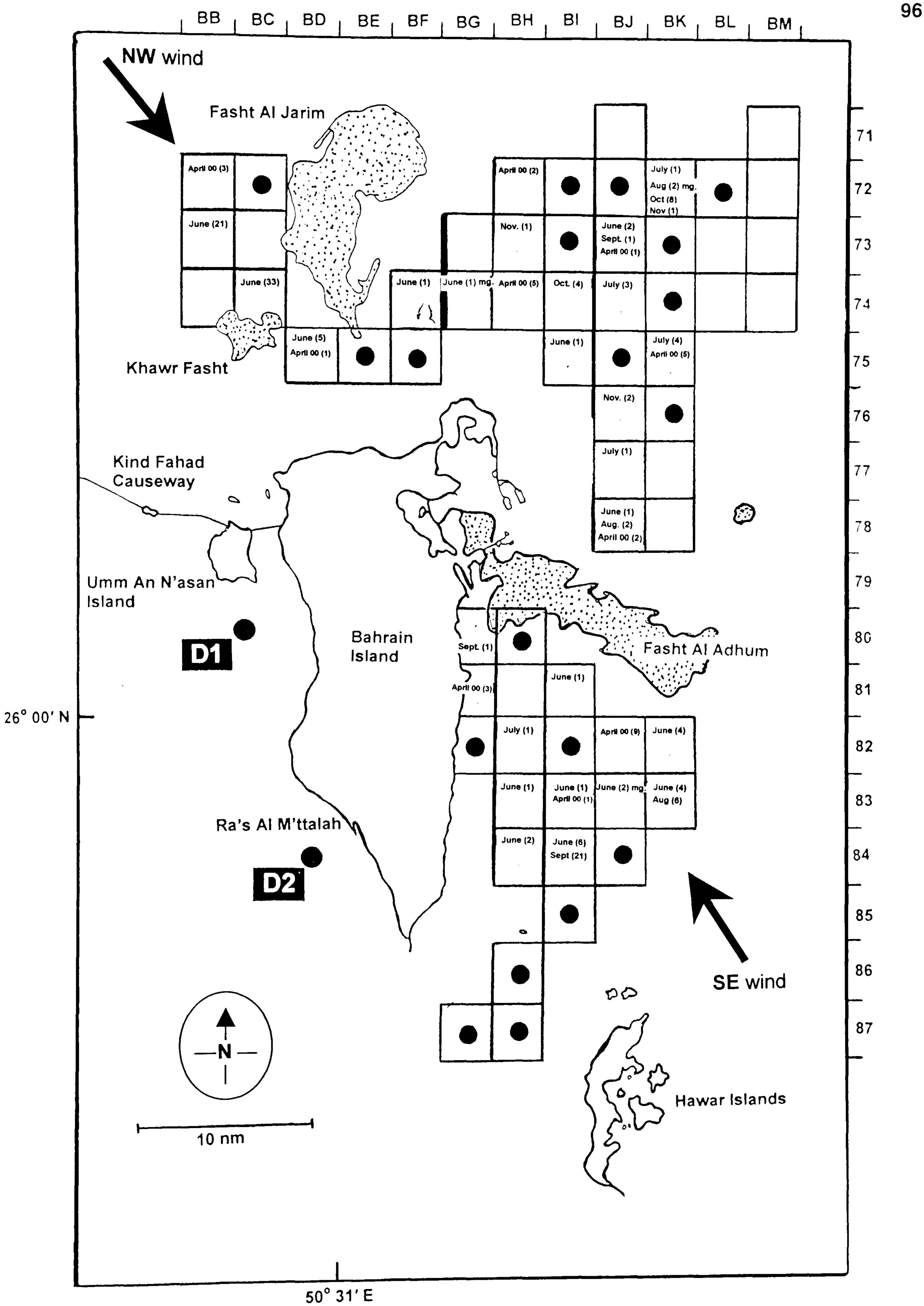


Figure 4.13. Map to illustrate the occurrence of *Portunus pelagicus* larvae and megalopae (mg.) and their numbers in the plankton samples, which were collected across the study region from April 1999 to April 2000. The prevailing north-westerly wind, and south-easterly wind, are indicated. Dark circles in blank grids denote for absence of larvae at the ~~time of sampling~~.

probably unable to tolerate high salinities. The seven megalopae were collected mainly during June 1999 from four of the offshore grids; their abundance, timing, and locations are given in Table 4.6. The presence of megalopae in the water column provides evidence that this instar exhibits a pelagic phase prior to the metamorphosis to first crab.

Table 4.6. Abundance, timing and locations of megalopae of *Portunus pelagicus* found in the plankton samples collected from the study areas, Bahraini waters, from April 1999 to April 2000.

Month	Area	Grid No.	Number of megalopae
June 1999	A	BC74	4
	B	BG74	1
	C	BJ83	1
August 1999	B	BK72	1

Larvae were first reported in April 1999 plankton hauls where they were present in areas A, B and station D2 off the south-western coast of Bahrain Island. No larvae were reported from area C at that time, although 39% of the ovigerous females caught from this area were carrying late stage egg masses. The seasonal variations in the incidence of larvae are given in Table 4.7 and Fig. 4.14. Plankton sampling was not carried out during May 1999 due to the lack of a plankton net.

The larvae in area A were first recorded in April 1999 with relative abundance high in June 1999 with a total of 56 zoeae and 4 megalopae. Larvae in area C were recorded from June to September 1999, with relative high abundance during June (21 larvae) and September (22 larvae). However, the larvae in area B were less abundant compared with those in the other areas and they were present over a period of eight months from April to November 1999. With the exception of just a single larva reported from station D2 , larvae of *P. pelagicus* were not found to the west of Bahrain Island over a period of 11 months. This finding, as well as the absence of ovigerous females in the area, clearly shows that this region is not a spawning area for this species. Area D has high salinity up to 57‰, so is similar to the southern part of area C in that both these areas are influenced by the same environmental stress in terms of lack of water circulation around the southern region of Bahrain Island.

Table 4.7. Total number of larvae (zoea I-IV and megalopae) of *Portunus pelagicus* recorded in the areas A-D from June 1999 to April 2000. The calculated numbers of larvae ± SE in a unit volume of seawater (100 m^{-3}) are also presented.

Month	Areas							
	A		B		C		D	
	No.	No. $100m^{-3}$	No.	No. $100m^{-3}$	No.	No. $100m^{-3}$	No.	No. $100m^{-3}$
April 99	2♀	32 ± 0.0	6♀	20 ± 6	-♀	-	1	68 ± 0.0
May 99		N/A		N/A		N/A		N/A
June 99	60♀	158 ± 82.6	5♀	9 ± 3.4	21♀	53 ± 18.3	-	-
July 99	-♀	-	9♀	20 ± 8.6	1♀	5 ± 5	-	-
Aug. 99	-♀	-	4♀	9 ± 5.5	6♀	25 ± 24.7	-	-
Sept. 99	-♀	-	1♀	2.17 ± 2.2	22♀	123 ± 114	-	-
Oct. 99	-♀	-	12♀	31 ± 21.0	-♀	-	-	-
Nov. 99	-♀	-	4♀	11 ± 4.8	-♀	-	-	-
Dec. 99	-	-	-	-	-	-	-	-
Jan. 00	-	-	-	-	-	-	N/A	-
Feb. 00	-	-	-	-	-	-	-	-
Mar. 00	-♀	-	-	-	-♀	-	-	-
Apr. 00	4♀	36 ± 13.0	15♀	35 ± 14.4	13♀	47 ± 26.0	N/A	-

♀ Denotes the presence of ovigerous female crabs in the respective monthly trawls.

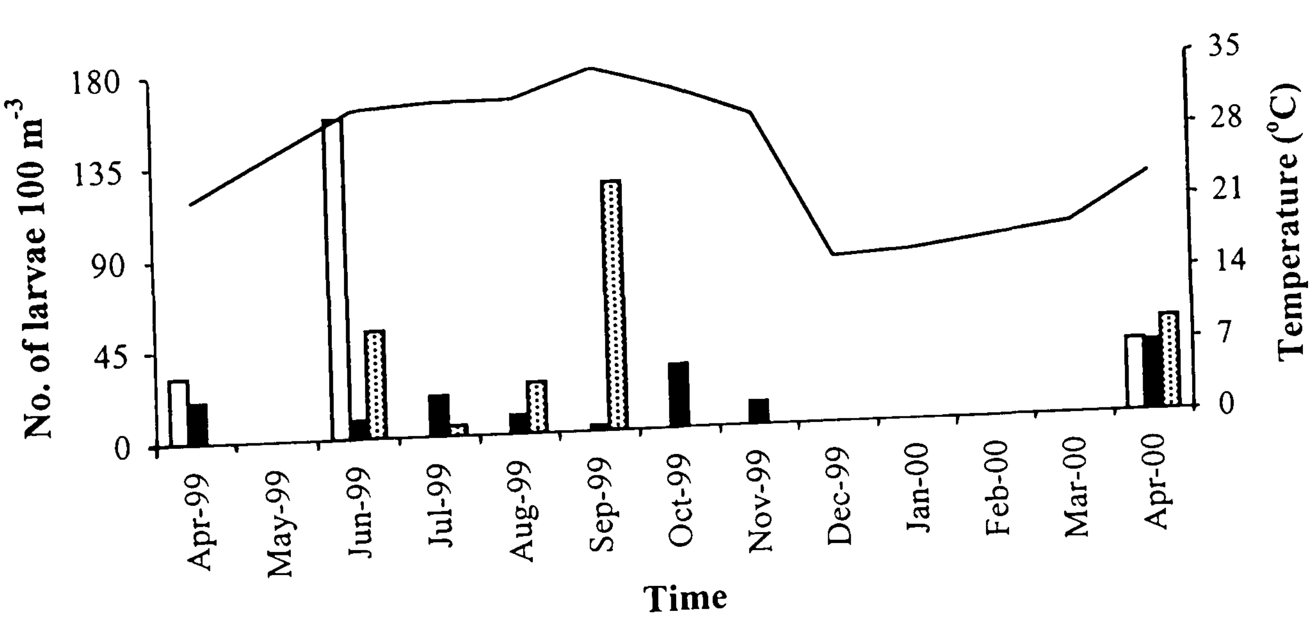


Figure 4.14. The incidence of larvae of *Portunus pelagicus* in the areas A (open), B (black), C (dotted), Bahraini waters, April 1999-April 2000, based on the total calculated number of larvae ± SE in a unit volume of seawater ($100m^3$). Annual temperature cycle (———) is also illustrated.

4.3.5.2 Larval incidence in relation to environmental parameters

As far as the occurrence of larvae in relation to environmental parameters, viz. temperature, salinity and depth, is concerned, it was found that the absence of the larvae is significantly correlated with temperature (n = 143, r = 0.192, p = 0.022). A high number of larvae occurred across the study areas where water temperature ranged from 30 to 35 °C (April-December), whereas at temperatures between 23-29 °C larvae occurred only in area C (Fig. 4.15). In contrast, their occurrence was not significantly related to salinity (n = 143, r = -0.089, p = 0.288) nor to water depth (n = 143, r = -0.008, p = 0.927).

The results from principal component analysis (PCA) on relative abundance of larvae in relation to temperature, salinity and water depth, are given in Table 4.8 and Fig. 4.16. Two sets of data are plotted in Fig. 4.16, the axes PCI and PCII representing salinity and temperature respectively. However the correlation between abundance of larvae and the environmental parameters was not high; the PCA plot (Fig. 4.16) indicated that relative high abundance of larvae was associated with higher temperatures (30-35 °C) and moderate salinity levels ranging from 40 to 48‰.

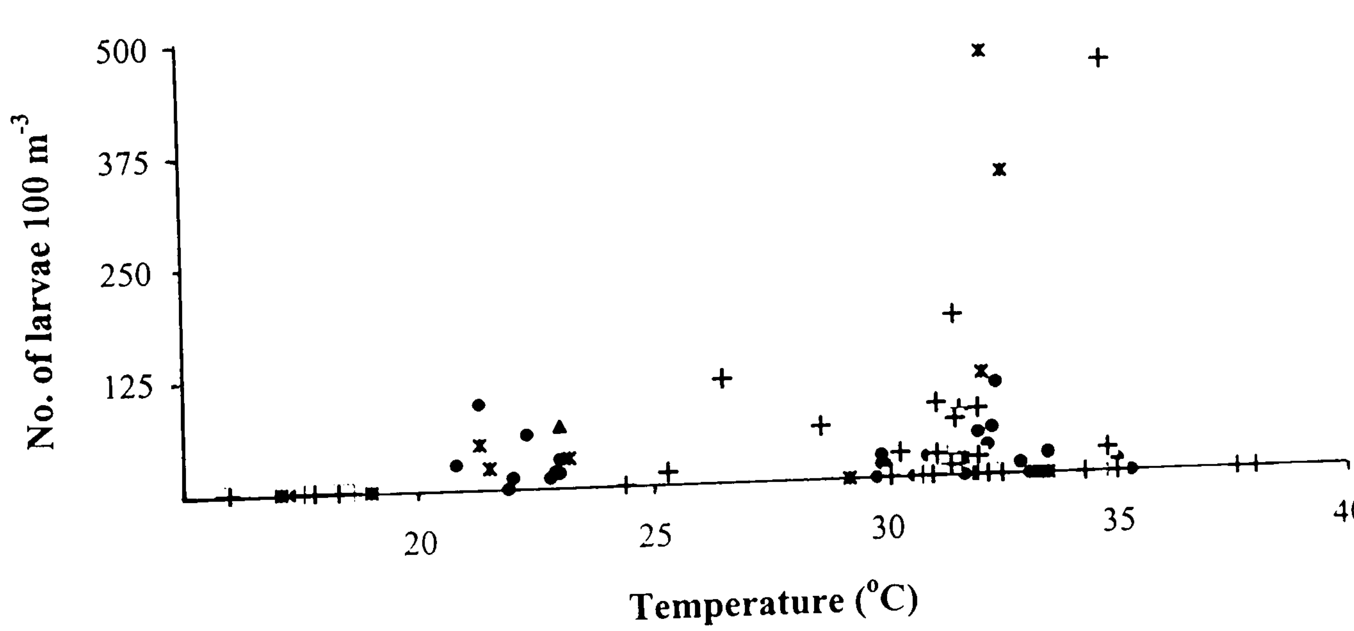


Figure 4.15. Incidence of larvae of *Portunus pelagicus* collected from areas - A (*), B ( ), C (+) and D (▲) in relation to temperature. June 1999-April 2000.

Table 4.8. Correlations between relative abundance of larvae of *Portunus pelagicus* and environmental parameters, viz. temperature, salinity and depth, obtained by the principal component analysis. April 1999-April 2000.

Variables	PCI	PCII	PCIII
Number of larvae	0.338	0.630	0.686
Temperature	0.418	0.536	-0.722
Salinity	-0.645	0.254	-0.057
Depth	0.544	-0.501	0.060

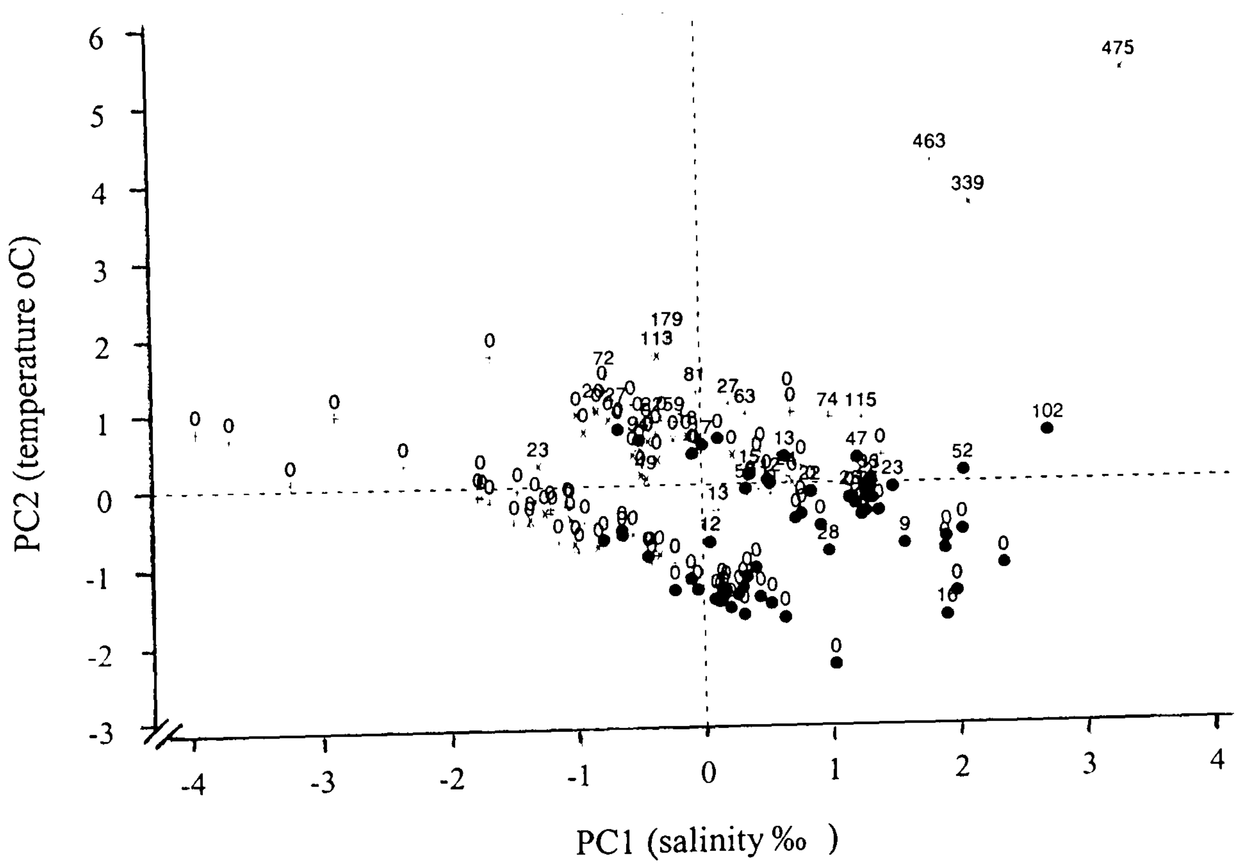


Figure 4.16. Plot for principal component analysis of relative abundance of larvae of *Portunus pelagicus* in relation to environmental parameters, viz. temperature, salinity and depth. Bahrain, April 1999-April 2000. Number of larvae in $100m^{-3}$ is given for each observation. Area A (*), area B () and area C (+).

4.4 Discussion

There has been considerable variation in the results obtained by various workers who have studied the different aspects of reproductive biology such as sexual maturity, breeding season, fecundity, eggs and larval development, of portunid crabs in general and *P. pelagicus* in particular, across its geographical range.

4.4.1 Size at sexual maturity

Determination of size at sexual maturity is not only of scientific interest but also of practical value as it serves as an important tool in studies of population dynamics and management of commercially exploited resources (Prasad and Tampi, 1954; Campbell and Fielder, 1986; Abdel Razek, 1988; Abd EL-Hamid, 1988; Jacob *et al.*, 1990 and Reeby *et al.*, 1990). Size at sexual maturity is accompanied by a series of morphological changes considered to be secondary sexual characters - dimensions of the chelae, width of abdomen and setae on the pleopods, often accompany the pubertal moult in brachyuran crabs. For *Portunus pelagicus*, it is the shape of the abdominal flap and increase in length of the setae on the pleopods (Fielder and Eales, 1972), for the burrowing crab *Corystes cassivelaunus*, the chelae, abdomen, and pleopods (Hartnoll, 1974) and for *P. pelagicus* and *P. sanguinolentus*, the chelae (Reeby *et al.*, 1990). Also, several other studies have indicated the changes which occur to shape and dimension of the abdomen in female crabs, where it is reported as triangular in shape in the juvenile, becoming semi-circular in the mature female *Callinectes sapidus* (Tagatz, 1967 and Archambault *et al.*, 1990) and *P. pelagicus* (Batoy *et al.*, 1987; Weng, 1987; Abd El-Hamid, 1988; Abdel Razek, 1988) (see Fig. 2.8). However, these abdominal changes are only morphologically significant in female crabs. In the present study, a change in the chela colour after maturity was also observed. In males, it changes from light bluish to dark prominent blue, whereas in adult females they are dark brown.

Sexual maturity in the present study was investigated based on external morphology alone, i.e. the relationship between 4^{th} abdominal segment width and CW. González-Gurriarán and Freire (1994) reported a high correlation between physiological processes and morphological changes associated with sexual maturity in the velvet swimming crab, *Necora puber*. Very similar sizes for the onset of maturity were obtained by both methods.

In the species studied here, the morphometric measurements – width of the 4th abdominal segment and CW have indicated that males and females have different maturity growth patterns as far as width of the 4th abdominal segment and CW are concerned. These dimensions exhibited isometric growth in male crabs, whereas the abdominal segment in females more than 7 cms CW does increase allometrically as mature females grow. Similar results on this species were observed in Egyptian waters (Mediterranean) by Abd El-Hamid (1988), however, the relationship between the width of the 5th abdominal segment and CW was not given in the original paper. Also, Prasad and Neelakantan (1989) investigated *Scylla serrata* in a similar way and reported on allometric growth as follows:

Immature female [Abdominal width (mm) = -29.717 + 0.735 CW (mm)],
Mature female [Abdominal width (mm) = -18.678 + 0.687 CW (mm)].

However they did not define the body dimension of the crab, whether it was total CW or short CW. Also, the abdomen segment (segment number) that they used in their investigation was not specified. Findings of the present study in terms of female crabs is in agreement with the observation of Hartnoll (1974) who concluded that slight allometric growth of the abdomen of both immature and mature female crabs was common. Hartnoll (1974) reported "growth of the male abdomen is more or less isometric, with only a minor increase in size at puberty, whereas that of the female shows strong positive allometry before puberty, a marked size increase at puberty, but a reduced positive allometry thereafter".

Size at first maturity for male *P. pelagicus* in Bahraini waters was reported by Al-Rumaidh (1995) at 5.5 cms in total CW (distance between the tips of lateral spines) (or ~ 4 cms in short CW) from noting the abdomen change from tightly sealed to the ventral surface of immature male crabs to loose and flexible in larger mature males. The linear relationship obtained in the current study for the 4th-abdominal segment and CW of male

P. pelagicus (Fig. 4.1) has shown that the 4th abdominal segment does not alter shape after the pubertal moult, which agrees with reports on males of this species from Egypt's Mediterranean waters by Abdel Razek (1988) and the related species, *Callinectes sapidus*, from Chesapeake Bay (Van Engel, 1958) and South Carolina, USA (Archambault *et al.*, 1990). Data collected in the course of the present investigation (see Chapter 6, Fig. 6.4) show that 50% of mature males are 8 cms CW. As far as female crabs are concerned, this research has provided evidence that a morphological change into the mature state occurs at 7 cms CW, when a significant increment in abdomen width takes place to serve as the impending incubation chamber for the eggs. Also, the present research has shown that 50% of mature females are 9 cms CW (see Chapter 6, Fig. 6.4).

The earlier finding by Al-Rumaidh (1995) that some males were mature at 5.5 cms CW and the present one on females attaining sexual maturity at 7 cms CW suggest that male crabs mature at a smaller size than females. This size differential at first sexual maturity of *P. pelagicus* in Bahrain waters agrees with the findings by other workers in other parts of the world, where males attain maturity at a smaller CW than females. However, variations in CW at first maturity are found in different regions (Table 4.9) most likely due to a combination of factors including differences in environmental parameters, as well as diet composition which has an important role in influencing gonad maturation in both wild and captive crustacean broodstock (Harrison, 1990). Findings of this study as well as those from Egypt, India and Philippines, which are presented in Table 4.9, do not agree with Dhawan *et al.* (1976) who reported that females mature at a smaller size than males. However, the basis of this conclusion was not clearly stated and was presumably discerned from length-frequency distribution. It is reported that both genders in Australia attain maturity at the same size (Shields and Wood, 1993; see Table 4.9).

Yatsuzuka and Meruane (1987) reported that *P. pelagicus* in Japan takes almost 4 months to attain maturity. They also found that crabs in the wild attain maturity earlier than those reared in the laboratory, due to better conditions in the natural environment. Abd EL-Hamid (1988) reported that male *P. pelagicus* attain sexual maturity after 18-19 moults following the first crab stage, comparable to the related species, *Callinectes sapidus*, where males also reach maturity in about 18 or 19 moults and females become sexually mature after 18-20 moults from first crab stage (Van Engel, 1958). Recently, Kangas (2000) noted that *P. pelagicus* females reach maturity at about a year old.

Table 4.9. Size (total carapace width [cms]) at first sexual maturity of male and female *Portunus pelagicus* in different regions around the world.

	Wild		Reared		
Region	Male	Female	Male	Female	Source
India	-	9	-	-	Prasad and Tampi (1953)
India	-	6	-	-	Devi (1985)
Philippines	3.7*	4*	-	-	Batoy *et al.* (1987)
Japan	5	6	5	6	Yatsuzuka and Meruane (1987)
Egypt	-	8	-	-	Abdel Razek (1988)
Egypt	5	-	-	-	Abd EL-Hamid (1988)
Philippines	-	-	8	8	Ingles and Braum (1989)
India	7	-	-	-	Reeby *et al.* (1990)
Gulf of Carpentaria, Australia	6	6	-	--	Weng (1992)
Moreton Bay, Autralia	6	6	-	-	Weng (1992)
Australia	8	8	-	-	Shields and Wood (1993)

* Denotes for carapace length, third dimension (see Chapter 2, Fig. 2.7),

The male and female reproductive cycles of *P. pelagicus* are not concurrent. The peak of the reproductive cycle of males occurs slightly earlier in the breeding season than that of females, where mature males moult some weeks before maturing females (Pillai and Nair, 1973; Al-Rumaidh, 1995). Kangas (2000) noted that adult crabs of *P. pelagicus* moult only once a year, which indicates that females mate once a year. This has been observed for females of the related species, *Callinectes sapidus* Rathbun, which are reported to mate only once during their entire life (Van Engel, 1958; Gleeson, 1980). Furthermore, Van Engel (1958) found that spermatophores delivered into female *C. sapidus* can remain viable for at least 12 months to fertilize the two or more broods which occur during their lifetime. Brood biology of *P. pelagicus* is very similar to that of *C. sapidus*, where females can produce more than one batch of fertilized eggs from one mating (Abd El-Hamid, 1988) and can spawn at least twice a year during winter and spring

(Abdel Razek, 1988). In a rearing experiment on *P. pelagicus* Ingles and Braum (1989) reported that oviposition occurred 13 days after copulation. The finding that the three egg colour categories were found on animals within the carapace width size range 6-12.5 cms (see Fig. 4.4) suggested that female *P. pelagicus* in Bahrain spawn at least twice during their life time.

4.4.2 Spawning and breeding activity

The reproductive cycles of marine invertebrates are influenced by environmental factors. Temperature and photoperiod are considered the major environmental parameters controlling breeding (Pillai and Ono (1978) as cited by Quinn and Kojis, 1987). It is well documented in the literature that *P. pelagicus* is able to withstand considerable variations in temperature (Batoy *et al.*, 1987). For the species, Dhawan *et al.* (1976) reported a tolerance range of 25-40 °C in India. Furthermore Pillay and Nair (1971) indicated although temperature affects breeding of marine animals, it is not the sole influencing factor. Moreover, they reported that medium and high salinity conditions during the post-monsoon and pre-monsoon periods respectively, with an abundance of planktonic food for the larvae, seem to be most favourable for breeding activity. In Moreton Bay, Australia, Smith (1982) and Potter *et al.* (1983) reported peaks in the proportion of ovigerous females occurring two or three months earlier than in more temperate Australian populations, suggesting temperature is a crucial reproductive controlling factor.

In crustaceans, the usual methods to determine the breeding season are by plotting (a) the percentage of ovigerous females or (b) some measure of gonad ripeness (gonad index). However, although the former method is widely employed, Ryan (1967c), Pillai and Nair (1971) as well as Prasad and Neelakantan (1989) cautioned against using the percentage of ovigerous females method as the sole criterion for predicting spawning periods. They suggested that this percentage method does not provide a complete picture of the sequence of events during the long and often drawn-out breeding season in tropical habitats. According to Pillai and Nair (1971) the advantages of the gonad index method are: (1) it provides information of the breeding condition of the individual animal, (2) shows the sequence of events in the gonad between spawning seasons. They concluded that the gonad index represents a measure of the reproductive condition of the population. Nevertheless, Pillai and Nair's (1971b) findings furnished supplementary evidence to that obtained from a study of the incidence of ovigerous females (Pillai and Nair, 1973). Nevertheless, the present study emphasizes the importance of ovigerous females in reproductive studies, as it provides clear evidence to breeding season and when larvae are being released.

A reliable insight to the reproductive cycle of *P. pelagicus* has been obtained during the present research by using the incidence and proportion of ovigerous females, giving a clear indication of the breeding cycle in Bahraini waters. The breeding season was found to be discontinuous, lasting from March to November (21-30°C) with enhanced activity during June and September (32-35°C). Ovigerous females were absent in areas A and C from December to February and from area B from December to March, which are the coldest months of the year. Breeding activity was not evident at temperatures lower than 20 °C, i.e. at temperatures that may not be favourable for egg development or larval survival, which is in agreement with Sumpton *et al.* (1989). In the laboratory, Smith and Sumpton (1989) have shown that crab activity declines when water temperature falls below 20 °C. Comparable data on the reproductive biology of *P. pelagicus* from the Arabian Gulf are lacking, as no previous studies have investigated the reproductive biology of the crabs in the region. Therefore, results of this research are compared with data obtained elsewhere across the geographical range of this species. The breeding cycle of *P. pelagicus* is found to be highly variable. In India, Rahman (1967) concluded that *P. pelagicus* is a continuous breeder with three periods of maximal gonad development - November, January and June, but with greatest activity during November-January. Also, in the Kakinada region, India, berried females were found throughout the year, abundant from September to March, with peaks during September-December and February (Devi, 1985). A similar reproductive pattern was also observed in the Philippines, where breeding was found to be continuous throughout the year with peak numbers of ovigerous females during the first and last quarters of the year (Batoy *et al.*, 1987). However, from the south-west coast of India, breeding of *P. pelagicus* was not continuous, but extended from August to April only with distinct peaks in ovigerous female numbers observed in January and December (Pillai and Nair, 1973). They attributed the apparent differences in the breeding season on the east and west coasts, to the different hydrological conditions prevailing in the inshore waters of the west coast of India. The aforementioned continuous breeding patterns might be due to a more consistent year-round temperature, being tropical. Ryan (1967c) has reported that the Hawaiian population of *Portunus sanguinolentus* has the potential for continuous breeding, but it is restricted by water temperature. In Australia, Penn (1977) found summer spawning peaks for *P. pelagicus* at Cockburn Sound, western Australia, whilst in south Australia, Smith (1982) reported ovigerous females from October to April, with highest numbers in November. In south-east Queensland, a major ovigerous female abundance peak was recorded in September (Campbell and Fielder, 1986) but also found that the abundance of ovigerous females was negatively associated with water temperature, as was the case for *P. pelagicus* in the present study. Some early work in Moreton Bay, Australia, by Stead (1988) recorded August to November as the major spawning period, while Weng (1992) found the highest incidence of ovigerous females in Moreton Bay during August and September. From the literature therefore, it is evident that *P. pelagicus* has an extended breeding period with distinct peaks in breeding activity throughout its geographical range. Also, it emphasises the effect of temperature on the occurrence of spawning, as well as the egg incubation period. Other examples of breeding seasons of *P. pelagicus* are presented in Table 4.10, where variation in breeding activity is most likely to be due to differences in temperature (Potter *et al.*, 1983; Campbell and Fielder, 1986). In their review on mating and spawning in the mud crab, *Scylla serrata*, Haesman e*t al.* (1985) have concluded that the length of the spawning period increases with decreasing latitude.

In the present investigation the lack of ovigerous females at certain times of the year has been observed for *P. pelagicus* elsewhere, although the timing and duration differs. In India, there was practically no breeding activity during May, June and July, in either *P. pelagicus* or its related species *P. sanguinolentus* (Pillai and Nair, 1973). In Peel-Harvey Estuary, Australia, Potter *et al.* (1983) did not find ovigerous females in June and July. Furthermore, in south-east Queensland, Australia, Campbell and Fielder (1986) found no ovigerous females during August and *P. sanguinolentus* were not caught during the coldest months, i.e. May-July. Nevertheless, in a later investigation the same scientists (Campbell and Fielder, 1988) reported "ovigerous females were not captured during winter months when water temperatures were not suitable for maturation of eggs". Pinheiro *et al.* (1994), working on the swimming crab, *Arenaeus cribratius* (Lamarck, 1818), in Brazil, found no ovigerous females in the population from July to September.

Table 4.10. Breeding seasons for *Portunus pelagicus* in the Indo-Pacific and east Mediterranean regions.

Hemisphere	Region	Spawning season	Reference
Northern	Egypt	May and September	Bawab and El-Sherief (1987)
	Egypt	Winter-summer (peak in April)	Abdel Razek (1988)
	Cochin, India	January-April and August-December	Pillai & Nair (1973)
	India	January-March	Ameer Hamsa (1978)
	India	September-December and February	Devi (1985)
	Japan	May-July	Yatsuzuka and Meruane (1987)
	Philippines	January, April, July and October	Botay *et al.* (1987)
Southern	Peel-Harvey, Australia	December-March	Potter *et al.* (1983)

The results in the present study for March-April 1999 and March-April 2000, suggest annual variation in breeding activity (Table 4.3). The lower incidence of ovigerous females in areas A, B and C in March 2000, compared with March 1999 (9.5, 0 and 5% vs. 10, 13, 44% respectively) suggest that breeding had occurred earlier in 1998/1999. This hypothesis is further supported by the higher incidence of ovigerous females in the three areas in April 2000 compared with the previous year (75, 49 and 27% vs. 38, 23 and 18% respectively). Differences in ovigerous female occurrence from one year to another could be attributed to fluctuations in environmental parameters, nutrition availability, fishing pressure on the stock and/or migration of crabs.

4.4.3 Fecundity

The fecundity of *P. pelagicus* (defined as the number of eggs per brood) varies throughout its geographical range. In Bahrain, fecundity was found to range from 0.302 to 1.54 million eggs (0.82 ± 0.05 million eggs per brood), higher than fecundity of the species in India of 0.18 to 0.46 million eggs (Pillai and Nair, 1973), and 0.056 to 1.07 million eggs (Sukummaran and Neelakantan, 1997b). In the Mediterranean waters of Egypt, fecundity ranged between 0.08 and 0.8 million eggs for females of 11.1 and 13.6 cms CW respectively (Abdel Razek, 1988). In Australia female *P. pelagicus* carried up to 2.3 million eggs each (Campbell and Fielder, 1988; Kangas, 2000) and ranged between 0.14 and 1.13 million eggs in Ragay Bay, Philippines (Ingles and Braum, 1989). Data on fecundity of *P. pelagicus* obtained throughout show that number of eggs produced increases exponentially with increasing CW. As stated earlier the number of eggs produced per ovulation is very large, varies with the size of the crab and shows considerable variability even between females of the same size.

4.4.4 Incubation, egg diameter and development

The period of egg incubation is controlled by temperature. Laboratory observations by the author on the incubation of eggs of *P. pelagicus* carried out in Bahrain suggested an incubation period between 17 and 21 days at 25 °C, which is slightly longer than their counterparts of western Australia where they hatch after about 15 days although at 24 °C (Kangas, 2000) and much longer than those in eastern Australia with 8 days at 25 °C (Smith, 1982). Also, this latter worker has reported an incubation period of 18 days at 20 °C. These findings from various places across the geographical range of *P. pelagicus* clearly indicate the influence of temperature on the duration of egg incubation. Furthermore, in S.E. Queensland, Australia, Campbell and Fielder (1988) observed an inverse relationship between temperature and mean incubation period of *P. pelagicus*, i.e. 27, 15, 12 and 12 days at 21, 24, 27 and 30 °C respectively. Their findings show that incubation periods were reduced by half with a temperature rise of only 6 °C. The incubation period of this species in Bahrain is contrary to the short incubation period of *P. pelagicus* in Ragay Bay, Philippines, of 5-6 days at 29.5 °C (Ingles and Braum, 1989).

However, it is close to that reported from Japan, where Yatsuzuka (1962) observed an incubation time of about 20 days at 18.5 °C, despite the wide range in temperatures, which are reported here between Bahrain and Japan. In India, Jose *et al.* (1996) found that the total incubation period varied between 10-12 days at 28 °C. Also, these findings on *P. pelagicus* are contrary to its related species *Scylla serrata* where the spawning period increased with decreasing latitude as concluded by Prasad and Neelakantan (1989). The considerable variation in incubation period from one geographical region to another indicates again the influence of water temperature in regulating this process, the fact being that the egg incubation period of tropical crabs is comparatively shorter owing to the higher temperatures (Yatsuzuka, 1962; Pillai and Nair, 1973). Campbell (1984) studied the rate of development of *P. pelagicus* eggs in the laboratory and noted that although egg extrusion (egg mass formation) occurred at 18 °C, none of the eggs matured after 68 days incubation at that temperature. Working on *P. pelagicus* in Moreton Bay, Sumpton *et al.* (1994b) reported that egg extrusion was limited during the winter months, without specifying the water temperature range. However, this is in agreement with findings of the present research where no ovigerous females were caught at temperatures below 20 °C. Although egg extrusion ceases, female gonad maturation would continue through the winter until rising water temperatures initiate extrusion of eggs during early spring.

During the incubation period, egg colour and size change progressively. The freshly spawned eggs are bright yellow in colour becoming darker gradually as the embryos develop to yellowish-grey and further to greyish-yellow due to embryo eye development. This process continues until eggs become grey to black two days prior to hatching. In the present study egg diameter ranged from 242 to 531 µm. Pillai and Nair (1973) quoted egg size of *P. pelagicus* as 343 µm in India, and Ingles and Braum (1989) reported the diameter range from 275 up to 366 µm immediately prior to hatching in Philippine *P. pelagicus*. Thus, the egg diameter of *P. pelagicus* in Bahraini waters has a wider range. This variation in egg size of *P. pelagicus* between the areas around Bahrain may be correlated with the habitat and/or the quantity (number of eggs produced female^{-1}) and quality (amount of yolk present).

It was observed that the larger females had an increased egg-carrying capacity with respect to egg mass wet weight. There was an exponential relationship between egg mass weight and CW, i.e. Egg mass weight (g) = 0.01 $CW^{3.77}$ cms, which agrees with Sukumaran and Neelakantan (1997b) who reported "the egg mass weight and CW are better indices for the estimation of the reproductive potential than the weight of the crab". Several factors such as salinity, temperature, photoperiod, abundance of food and intrinsic state of the animal have been attributed to interspecific variability in fecundity (Giese and Pearse, 1974).

4.4.5 Larval development and distribution

Identification of planktonic crab larvae is of prime importance in order to study the early life history in nature (Kurata and Midorikawa, 1975). Studies on natural larval development of *P. pelagicus* are lacking, however, larval development has been extensively investigated under laboratory conditions. The larval forms (zoeae and megalopa) were collected in the present study over the sampling period. Nevertheless, the amount of data collected was not adequate enough to provide detailed information for larval density and distributions over the fishing grounds, as the larval sampling strategy was restricted to 7-10 vertical plankton net hauls (three replicates each) each month across the whole study area.

As far as *P. pelagicus* is concerned, a number of studies have demonstrated the larval development stages of this species from rearing experiments. Such studies have taken place in Australia (Shinkarenko, 1979; Campbell and Fielder, 1988), Japan (Yatsuzuka, 1962; Kurata and Midorikawa, 1975; Yatsuzuka and Sakai, 1980; Yatsuzuka and Meruane, 1987) and Philippines (Motoh *et al.*, 1978; Ingles and Braum, 1989). All of these workers conclude that the larval stages of *P. pelagicus* consist of four zoeae stages and one megalopa stage before changing into the first crab. However, Prasad and Tampi (1953) from India have reported that it is the 3rd zoea stage which directly metamorphoses into the megalopa. It is most likely that those workers (Prasad and Tampi, 1953) were working on another species, as the larvae of many marine animals are very similar in their early stages, which can lead to confused identification (Anon, 1970). Also, Jose *et al.* (1996) reported five zoeal stages and one megalopa for this species. Nevertheless, the 4 zoeal stages of *P. pelagicus* can clearly be distinguished from each other by the number of abdominal somites (Yatsuzuka, 1962). Due to their planktonic life, crab larvae may be transported long distances by the prevailing currents. The potential for larval dispersal is also in part dependent on water temperature, which determines the length of larval life. In laboratory studies, *P. pelagicus* larvae were found to have a larval life of about 21 days at 20 °C and 39 days at 25 °C (Bryars (1997) as cited by Kangas, 2000).

Temperature, salinity and nutrition are the main factors that control planktotrophic larval development in crustacean species. In laboratory conditions, *P. pelagicus* larvae survived well when reared on a diet of *Artemia* nauplii at temperatures between 20 and 25 °C, and salinities between 30 and 40‰. Larval development was completed in 2 to 3 weeks under these conditions (Meagher, 1970; Motoh *et al.*, 1978). Anon (1970) found that each zoeal stage lasts approximately 3-4 days and the megalopa lasts around 7-8 days, followed by a series of crab stages each of which lasted some 8-14 days. Jose *et al.* (1996) had reported that the five zoea stages of *P. pelagicus* took 12-13 days before metamorphosing into the megalopa, with each zoea stage taking a minimum period of 2-3 days before moulting to the next stage. Furthermore, they noted that megalopae were less active than zoeae, and took 6-7 days to reach the first crab stage.

The present study has provided evidence of a correlation between occurrence of larvae and temperature, where relative high abundance of larvae at 158 $100m^{-3}$ was associated with temperatures ranging from 30 to 35 °C. Despite this correlation, the incidence of larvae across a wide range of temperature, i.e. 21-35 °C, provided strong evidence of the protracted spawning season of *P. pelagicus* in Bahraini waters. On the other hand, abundance of larvae was very low in areas with high salinity levels (> 45‰), viz. the southern region of area C and area D. Discussing the high salinity levels within these two water masses, Vousden (1986) reported that the clockwise circulation around Bahrain (Sugden, 1963) is due to the shallower water in the strait between Bahrain and Qatar as well as phase differences within the tides in The Gulf. Vousden (1986) suggested that this water circulation is of great importance to the salinity patterns and the location of salinity fronts around the island, creating considerably higher salinity to the south of

Bahrain and into Dahwat Salwah than is found anywhere else in the RSA". RSA is defined as the Regional Organisation for the Protection of the Marine Environment, Sea Area.

The occurrence of larvae and the incidence of ovigerous females in area B were always associated (see Table 4.7). However, in areas A and C although ovigerous females were present from July to November in the former and from October to November in the latter, no larvae were caught. Fig. 4.14 shows that during December 1999 to March 2000, larvae were absent in the plankton samples, but were present again in April 2000 in the major fishing grounds. These results show that March to November is the spawning and breeding season of *P. pelagicus* in Bahraini waters.

4.4.6 Water circulation and its role in larval dispersion

The larvae of *P. pelagicus* are planktonic, thus, they are mixed and distributed by the prevailing currents. Hence, understanding the direction and velocity of the currents is necessary to predict larval dispersal. Water circulation in the Arabian Gulf has been studied over the last two decades. In general, most studies agree that the driving forces of the circulation in the Arabian Gulf are mainly density, wind and turbulent vertical mixing processes. Although Hughes and Hunter (1979) reported that wind is the major contributor to the Arabian Gulf circulation, Hunter (1982) suggested that the observed circulation did not show Ekman-type flow, which implied that wind-forcing is not dominant. Basson *et al.* (1981) and Abdelrahman and Ahmad (1995) reported that the water currents in the Arabian Gulf follow a so-called 'Mediterranean circulation pattern', by which heavy, salty Gulf water flows out of the Strait of Hormuz as a bottom current, while a compensatory quantity of lighter and less saline Indian Ocean water flows inward at the surface. Recently, Proctor *et al.* (1994) reported that tides constitute an important component of water movement in the Gulf with velocities exceeding 0.5 m s^{-1} and concord with Hunter (1982) that water movements show a mixed diurnal and semi-diurnal tidal response.

The net water circulation around Bahrain is clockwise (Sugden, 1963), the island experiencing semi-diurnal tides (Vousden, 1995). Lardner *et al.* (1988) found that residual currents around the east coast of Saudi Arabia and adjacent sea areas (Bahrain is located 25 km off the east coast of Saudi Arabia) are dominated by wind-forcing, which also agrees with Proctor *et al.* (1994) who estimated the surface current speed to be 2-3% of the wind speed. The winds around Bahrain are predominantly northerly and north-westerly for most of the year although a south-easterly wind exists for some time during the summer (Sims and Zainal, 2000). From April through to June wind speeds can reach 35-40 knots, locally known as the "**Albareh**". The northerly winds principally influence the marine environment by virtue of the wave action created. Wind-induced waves from the open Gulf break on, or disturb, shallow coastal areas facing north, northwest or northeast creating a relatively high-energy environment (Vousden, 1995).

When investigating the occurrence of larvae with the presence of ovigerous females in the catch, it was found that larvae were not caught in the water column in the respective grids where ovigerous females occurred. There are two possible explanations. Firstly, that the sampling frequency of one sample (three replicates) per grid per month is not adequate to match real larval abundance. Secondly (and this may be an alternative theory or in addition to the first explanation), that the larvae are not found in the same areas as those in which they were spawned because of rapid dispersion. Taking this into account as well as reports by Lardner *et al.* (1988) and Sims and Zainal (2000), the author suggests that the absence of larvae in area A from July 1999 to November 1999 was likely due to their dispersion away into area B where they continued to be caught in the vertical hauls until November 1999. Larvae of area C are more likely to remain in this area due to: (1) clockwise circulation of northerly and north-westerly winds, and (2) **Fasht al Adhum** which forms a natural barrier separating area C from the offshore northern waters (area B).

Chapter 5

Biometric relationships

5. BIOMETRIC RELATIONSHIPS

5.1 Introduction

The study of biometric relationships identifies changes in shape (length-length) or condition (length-weight), which often accompany the growth of an organism and also to illuminate relative growth differences that are often driven environmentally. The length-weight relationship (l-wt.) assumes an added importance in fisheries biology in converting easily measured length to stock biomass. Several studies on l-wt. relationships have been carried out on portunid crabs across their geographical range, e.g. *P. pelagicus* from: Australia (Weng, 1992), Philippines (Batoy *et al.*, 1988), India (Dhawan *et al.*, 1976; Prasad *et al.*, 1989; Sukumaran and Neelakantan, 1997) and Egypt (Abdel Razek, 1987). The l-wt. relationships for related species, i.e. *P. sanguinolentus* from India (Sukumaran and Neelakantan, 1997) and *Callinectes sapidus* from America (Pullen and Trent, 1970) have also been described. The scale of scientific effort indicates the importance of this type of fisheries data, which are useful to determine relative condition and to estimate size at sexual maturity (Pullen and Trent, 1970). Furthermore, the derived relationships are as predictive as they are descriptive and readily permit comparisons of populations from different localities. Length-weight relationships are also used as indicators of physical condition, breeding state and possibly even food availability (Prasad *et al.*, 1989).

Morphometric information for *P. pelagicus* in the Arabian Gulf region is lacking. Thus the current morphometric study was undertaken to establish a precise mathematical model to use as a reliable tool for monitoring *P. pelagicus* populations around Bahrain.

5.2 Methods

5.2.1 Carapace length-width relationship

All carapace length and width measurements for male and female crabs from areas A, B and C (see Fig. 2.6) were considered for analysis. The relationship was analysed by the method of least squares using simple linear regression of $\log_{10}$ transformed observations. Transformation was used with the implicit assumption that a single power function (Pauly, 1983; Sparre and Venema, 1992) would adequately represent the relationship, even if no data was gathered for organisms < 2.5 cms CW.

5.2.2 Carapace width-weight relationship

Carapace width-weight relationships for *P. pelagicus* were determined separately for males and females from each area. Again the method of least squares, using simple linear regression on $\log_{10}$ transformed observations of carapace width (CW, cms) and wet weight (Wt., g) was used to compare crab condition over time (month to month) and between the three sampling areas. The CW-Wt. relationships were compared between the three areas over the whole 13 month sampling period. March 2000 data were excluded from the analysis, due to a lack of crabs in area B. The major aim was to determine whether the exponents differed between gender, month and locality ~ to indicate potential differences in condition.

5.2.3 Fresh weight-frozen weight conversion

A conversion factor for converting a crab's frozen wet weight to an estimate of the original fresh wet weight was needed in order to be able to compare those crabs collected between March-April 1999 (frozen on collection) to those collected between May 1999 and April 2000 (weighed fresh). A total of 26 males and 44 females, fresh wet weight ranging from 20-174 g and 15-192 g respectively, were weighed prior to freezing. After 10 days in the freezer they were allowed to thaw and then re-weighed. The log/log relationship of fresh wet weight vs. frozen wet weight resulted in the following conversion formula:

$$\text{Fresh wet weight (g)} = 1.017\ \text{frozen wet weight}^{0.986}\ \text{(g)}$$

5.3 Results

5.3.1 Carapace length-width relationship

The range of CL and CW of *P. pelagicus* used to establish the CL-CW relationship is presented in Table 5.1. Despite there being ~ 62% more female crabs than male crabs in the sample, the ranges in both CL and CW were very similar (Table 5.1). The average CW was ~ 7 cms and no crabs smaller than 2.9 cms or greater than 11.7 cms were used in the analysis. Fig. 5.1 shows the relationship between CL and CW for male and female crabs. From the log/log plot in Fig. 5.1, there is considerable overlap between the results for male and female crabs such that it is difficult to distinguish one group from the other. Log_{10} CW and log_{10} CL for both genders were highly correlated (males: $r = 0.997$, $df = 761$, $p < 0.001$) and (females: $r = 0.997$, $df = 1238$, $p < 0.001$).

Table 5.1. Summary of the carapace widths and lengths for male and female *Portunus pelagicus* collected for morphometric analysis from the study areas around Bahrain (October to November 1999).

		Carapace width		Carapace length	
Gender	No. of crabs	Range (cms)	Mean ± SE	Range (cms)	Mean ± SE
Male	763	2.9-11.7	7.2 ± 0.07	1.7-6.7	4.1 ± 0.04
Female	1240	3.2-11.4	7.3 ± 0.05	1.8-6.4	4.1 ± 0.03

Log_{10} relationships were analysed by analysis of variance using CW as covariate. Table 5.2 indicates that slopes do not differ between genders ($F_{1,1979} = 1.26$; $p = 0.262$). Similarly, there was no significant differences in slopes between times of collection ($F_{1,1979} = 1.63$; $p = 0.202$). The analysis of variance (Table 5.2) shows that most of the variability is associated with the relationship between CW and CL ($F_{1,1979} = 12.000$; $p < 0.001$). The only other significant slope terms relate to differences between average slopes from different areas ($F_{1,1979} = 3.16$; $p = 0.043$).

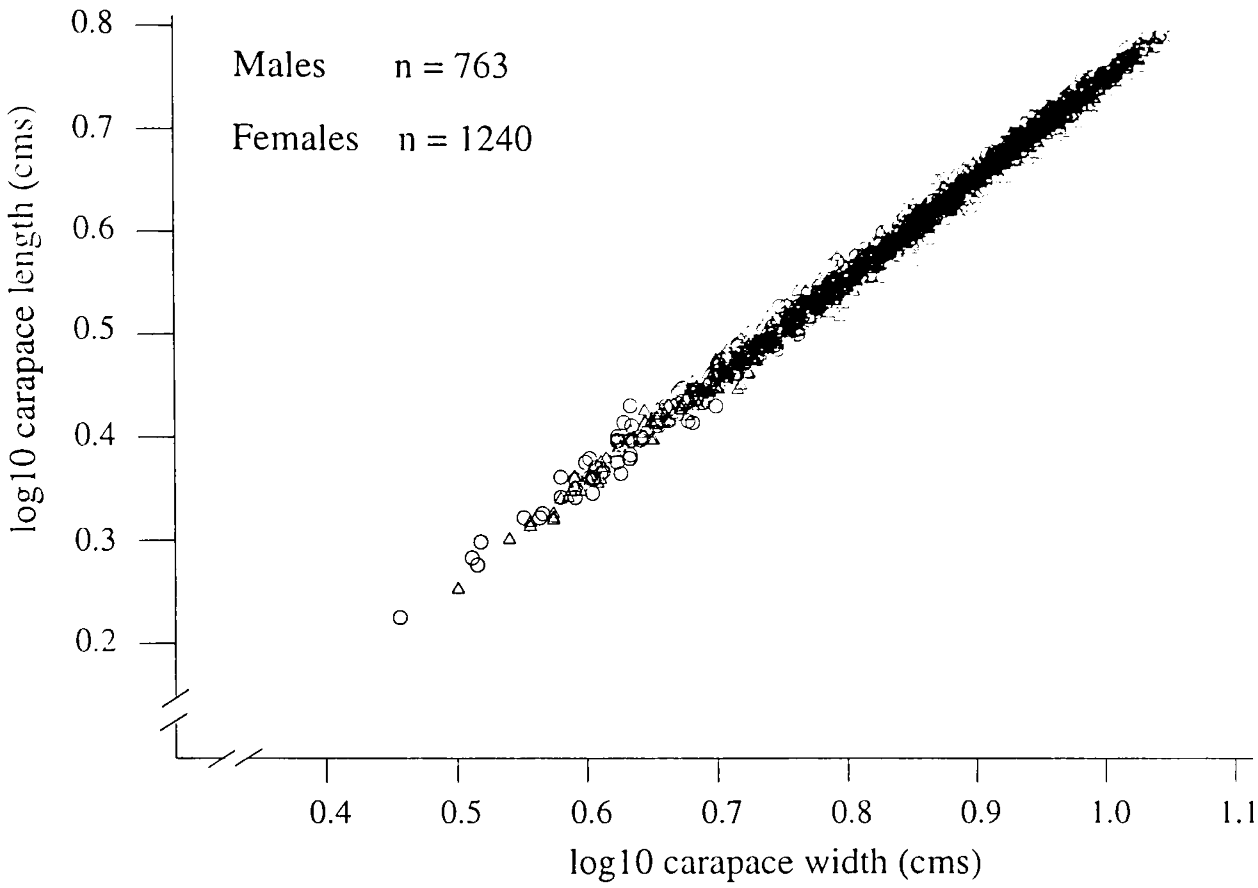


Figure 5.1. Plot of the carapace length against carapace width, $\log_{10}$ transformed data, for male (○) and female (Δ) *Portunus pelagicus* collected from the study areas during October-November 1999.

Table 5.2. ANOVA table for the carapace length and carapace width (covariate) relationship in relation to gender, area and month, for *Portunus pelagicus* collected from Bahraini waters, October and November 1999. Data linearised as $\log_{10}$ transformed.

Source	*df*	Seq. SS	Adj SS	Adj MS	*F*	*p*
CW	1	21.59101	7.233	7.23285	1.2^{+05}	< 0.001
Month	1	0.00134	0.00011	0.00011	1.79	0.181
Area	2	0.00265	0.00159	0.00030	4.84	0.008
Gender	1	0.00055	0.00004	0.00004	0.70	0.403
CW*month	1	0.00069	0.00010	0.00010	1.63	0.202
CW*area	2	0.00033	0.00039	0.00019	3.16	0.043
CW*gender	1	0.00013	0.00008	0.00008	1.26	0.262
Month*area	2	0.00009	0.00003	0.00001	0.22	0.803
Month*gender	1	0.00010	0.00005	0.00005	0.78	0.379
Area*gender	2	0.00045	0.00012	0.00006	0.98	0.376
CW*month*area	2	0.00003	0.00003	0.00001	0.23	0.794
CW*month*gender	1	0.00013	0.00006	0.00006	0.99	0.319

Table 5.2. Continued

Source	*df*	Seq. SS	Adj SS	Adj MS	*F*	*p*
CW*Area*gender	2	0.00013	0.00014	0.00007	1.11	0.329
Month*area*gender	2	0.00004	0.00012	0.00006	0.95	0.386
CW*month*area*gender	2	0.00011	0.00011	0.00605	0.86	0.424
Error	1979	0.12127	0.12127	0.00006		
Total	2002	21.71904				
Average intercept	-0.234 ± 0.003					
Average slope	0.988 ± 0.003					

The slopes varied from as high as 0.994 ± 0.007 in area A to as low as 0.981 ± 0.006 in area C (Table 5.3). The average slopes and intercepts for all three areas are presented in Table 5.3. They are all quite similar yet the slope for area C proved to be significantly less than 1 (t = 3.2, df = 1979; $p < 0.001$) indicating allometric growth with CL getting relatively shorter in bigger crabs. Crabs in areas A and B, however, give an exponent which does not differ significantly from 1 (area A - t = 0.857; df = 1979; p = 0.196, area B - t = 1.375; df = 1979; p = 0.085, hence, CW remains proportional to CL (~1.7 greater). The difference in exponents between area A and area C is a mere 0.013, hence not noticeable as a distinct trend in Fig. 5.1. Given the very large number of observations used in the analysis, standard errors become very small relative to standard deviations.

Table 5.3. Average slopes and intercepts (log10 [CL cms])for carapace length-carapace width relationships of *Portunus pelagicus* in areas A, B and C.

Area	Slope ± SE	Intercept ± SE
A	0.994 ± 0.007	-0.229 ± 0.006
B	0.989 ± 0.008	-0.232 ± 0.008
C	0.981 ± 0.006	-0.241 ± 0.006

5.3.2 Carapace width-weight relationship

A total of 2,070 male (CW ranging from 2.4 to 11.9 cms, wet Wt. ranging from 2.2 to 286.9 g) and 3,005 female (CW ranging from 2.41 to 12.56 cms, wet Wt. ranging from 2 to 263.7 g) *P. pelagicus* from 82 samples collected from areas A, B and C over a period of 14 months were used to investigate the CW-Wt. relationship of this species in Bahraini waters.

The $\log_{10}$ CW-Wt. linear regression models for all 82 samples were found to be highly significant, with correlation coefficient (r) values ranging from 0.936 to 0.983 ($p <$ 0.001). The overall regression models for males and females are shown in Fig. 5.2.

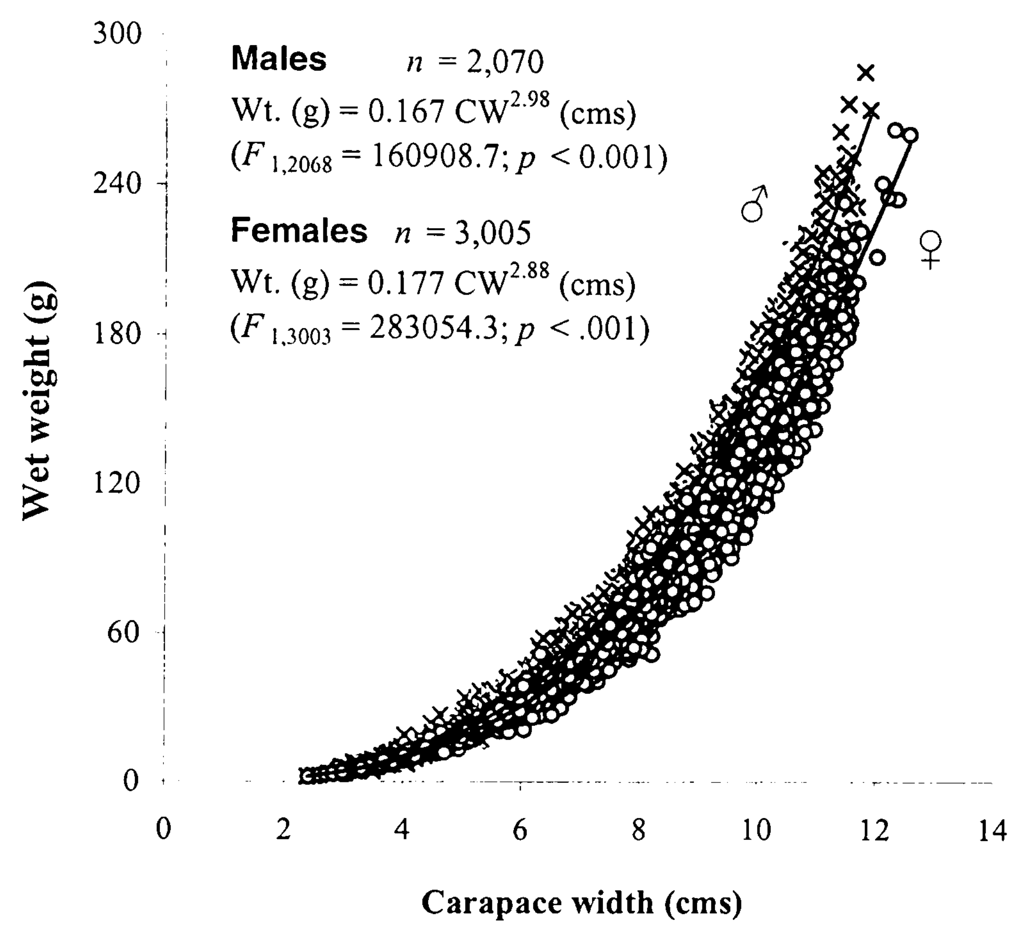


Figure 5.2. Carapace width-weight relationship for male and female *Portunus pelagicus* collected from the three areas around Bahrain from March 1999 to April 2000. Curves are fitted by least squares regression of log10 transformed data. Males (x) and females (○).

Fig. 5.2 clearly shows that male crabs were relatively heavier than females throughout the size range (CW). The difference in relative weight is obviously accentuated as the crabs grow. Indeed the models predict a 1 cm CW female to be 6% heavier than a 1 cm CW male, but this prediction lies beyond the bounds of the current data set. Since there such an obvious difference between male and female crabs (Fig. 5.2), the differences between areas and seasonal differences were analysed for males separately from females. The results of ANOVA with CW as a covariate for male and female *P. pelagicus* are presented in Tables 5.4 and 5.5 respectively. For males (Table 5.4) there was a significant three-way interaction indicating that significant differences in exponent between areas were not generally consistent over time.

Table 5.4. ANOVA table for the carapace width (covariate)-weight relationship for male *Portunus pelagicus* collected from Bahraini waters, March 1999-April 2000, in relation to month and areas. Data linearised as $\log_{10}$ transformed.

Source	*df*	Seq. SS	Adj SS	Adj MS	*F*	*p*
CW	1	371.5394	184.8968	184.8968	1.5^{+05}	< 0.001
Month	12	1.4747	0.5176	0.0431	35.07	< 0.001
Areas	2	0.0415	0.0148	0.0074	6.01	0.002
CW*month	12	0.5623	0.3805	0.0317	25.78	< 0.001
CW*areas	2	0.0725	0.0148	0.0074	6.02	0.002
Month*areas	24	0.1047	0.0666	0.0028	2.26	< 0.001
CW*month*areas	24	0.0690	0.060	0.0029	2.34	< 0.001
Error	1992	2.4503	2.4503	0.0012		
Total	2069	376.3144				
Average intercept	-0.855 ± 0.007					
Average Slope	3.053 ± 0.008					

Fig. 5.3 shows the exponents for male crabs in each area and month. The major contribution to the significant three-way interaction appears to come from area B, where in April 1999 and February 2000 unusually low exponents (2.74 and 2.84 respectively) were found. The general trend in all three areas shows a steady increase in exponent from around 2.8 in March 1999 to 3.1-3.2 in the summer followed by a small but consistent decline in exponent towards winter (see Fig. 5.3). Differences between areas are indicated as significant ($F_{2,1992} = 6.02$; $p < 0.001$, Table 5.4) and seem largely to reflect lower exponents in area C than in either areas A or B throughout the summer to winter decline. Apart from the negative allometric exponents found in all areas in spring 1999 most months and areas show slightly positive allometry throughout the year (see Fig. 5.3).

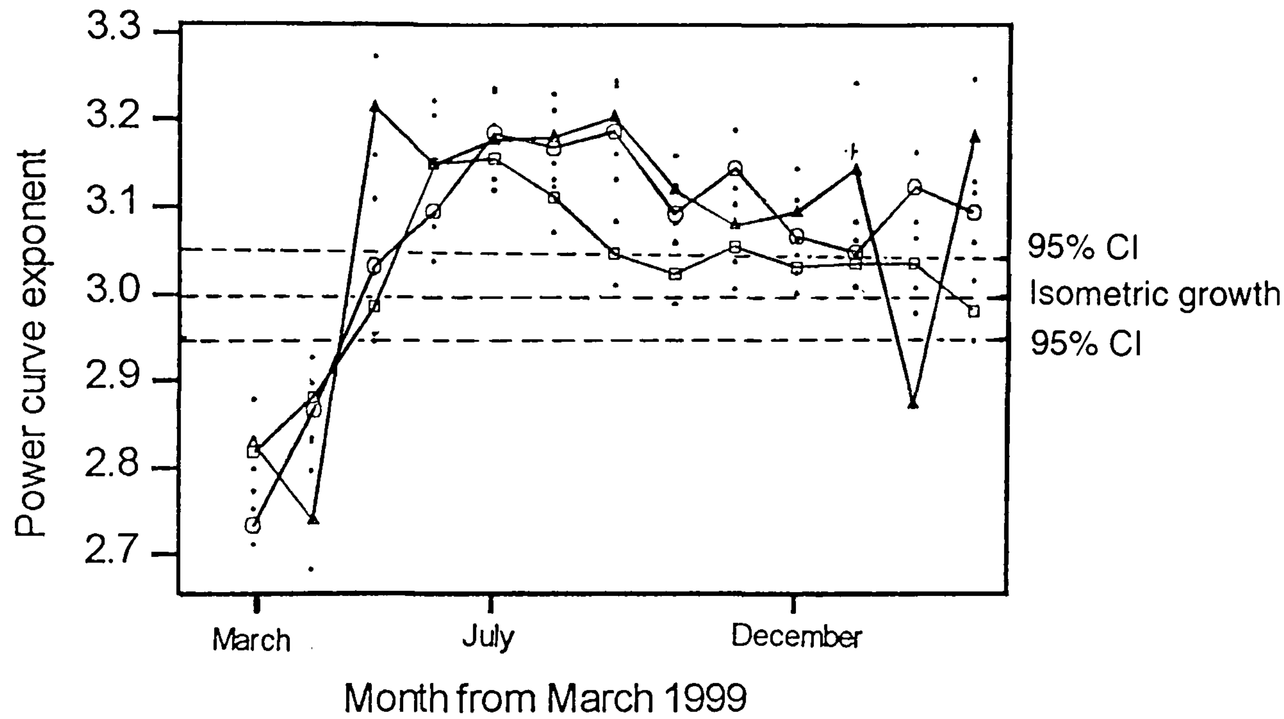


Figure 5.3. Plot of power curve exponents for the carapace width-weight relationship of male *Portunus pelagicus* collected from the study areas from March 1999 to April 2000. Exponents for March 2000 are not available. Area A (—o—), area B (—Δ—) and area C (—□—). Dots indicate the spread of SE. Isometric growth (± 95% confidence intervals) is represented as the horizontal dashed line.

For female crabs (see Table 5.5), the three-way interaction was not significant ($F_{24,2927} = 1.04$; $p = 0.406$) and no significant difference between areas was evident ($F_{2,2927} = 1.06$; $p = 0.348$). However, exponents varied significantly over time ($F_{12,2927} = 7.8$; $p < 0.001$). Fig. 5.4 shows the variability between exponent for female crabs for each area in each month. As with males, area B shows the greatest variability with a particularly low exponent in June 1999. The differences between areas are not significant (Table 5.5) and all exponents show a general negative allometric relationship between weight and CW. Lowest exponents (around 2.8) are seen in early 1999 rising steadily till early summer (as with the male relationship, see Fig. 5.3). The exponents stay fairly constant and just below 3 for the remainder of the study period.

Thus both for male and female *P. pelagicus* lack of condition at the beginning of the study period in 1999 was overcome by the summer of 1999. Condition remained fairly constant through to April 2000 with males being relatively heavier than females throughout.

Table 5.5. ANOVA table for the carapace width (covariate)-weight relationship for female *Portunus pelagicus* collected from Bahraini waters (March 1999-April 2000) in relation to month and areas. Data linearised as $\log_{10}$ transformed.

Source	*df*	Seq. SS	Adj SS	Adj MS	*F*	*p*
CW	1	428.7778	176.4376	176.4376	1.3^{+05}	< 0.001
Month	12	0.1322	0.1102	0.0092	6.74	< 0.001
Areas	2	0.0642	0.0037	0.0018	1.34	0.262
CW*month	12	0.2218	0.1275	0.0106	7.80	< 0.001
CW*areas	2	0.0108	0.0029	0.0014	1.06	0.348
Month*areas	24	0.0986	0.0269	0.0011	0.82	0.711
CW*month*areas	24	0.0341	0.0341	0.0014	1.04	0.406
Error	2927	3.9874	3.9874	0.0014		
Total	3004	433.3268				
Constant	-0.772 ± 0.007					
CW	2.910 ± 0.008					

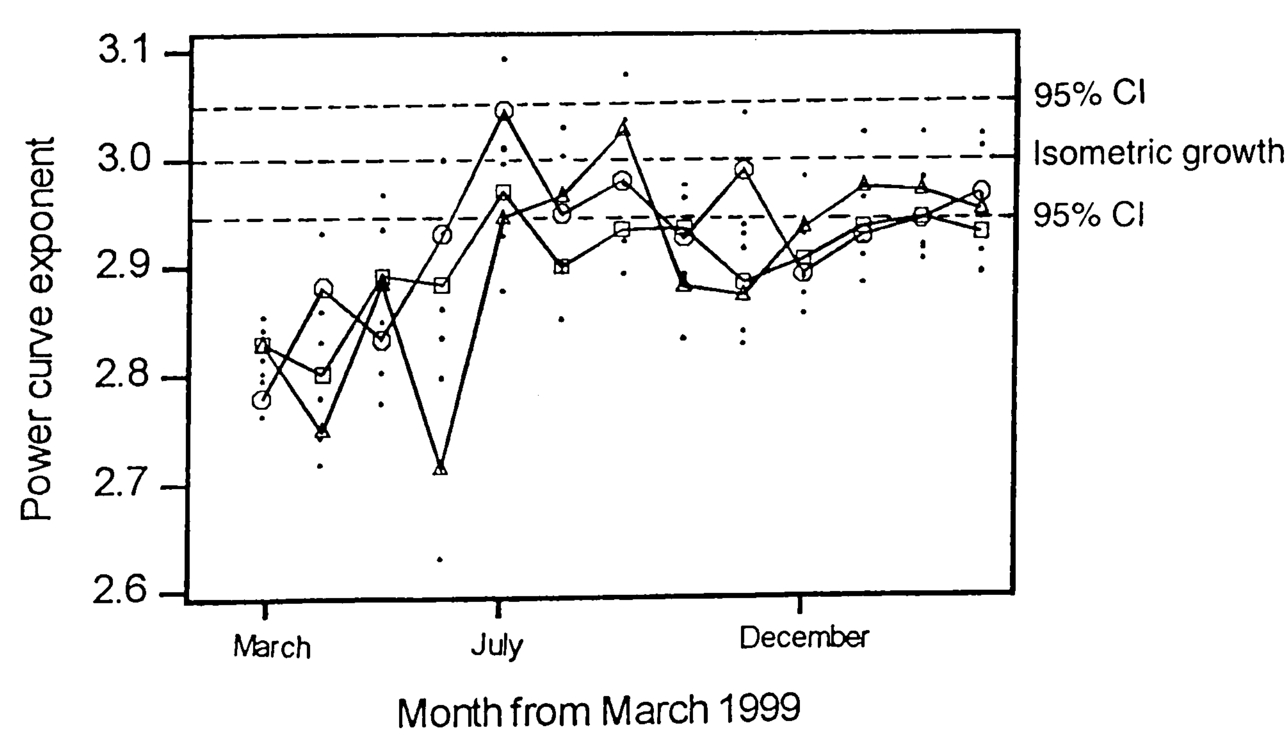


Figure 5.4. Plot of power curve exponents for the carapace width-weight relationship of female *Portunus pelagicus* collected from the study areas from March 1999 to April 2000. Exponents for March 2000 are not available. Area A (—o—), area B (—Δ—) and area C (—□—). Dots indicate the spread of SE. Isometric growth (± 95% confidence intervals) is represented as the horizontal dashed line.

5.4 Discussion

5.4.1 Carapace length-width relationship

Relative growth, as measured by CL and CW, in crabs is usually isometric (Warner, 1977, as cited by Batoy *et al.*, 1988). The present study has revealed a slightly negative allometric relationship between CL and CW on average, from a very large data set. Indeed the negative relationship was only significant in one out of the three areas. Weng (1992) found that CL-CW in *P. pelagicus* from the Gulf of Carpentaria (Australia) exhibited isometric growth, but in Moreton Bay (Australia) CL-CW tends to be negatively allometric (except in the larger females, see Table 5.6). Nevertheless, the present findings concur with these of Prasad and Tampi (1954), who investigated the growth of *Neptunus* (= *Portunus*) *pelagicus* and found that the majority of body part dimensions exhibited allometric growth, where length of carapace relative to width showed a slight decrease in the very small crabs with a slight but significant increase in the largest individuals.

The present study has found that for both genders, CW is ~ 1.7 times CL. Earlier studies have reported that total carapace width (TCW), defined as the distance between the tips of the two large lateral spines (see Fig. 2.7), in both sexes was 2.3 times CL (Stephenson and Campbell, 1959; Al-Rumaidh, 1995; Apel and Spiridonov, 1998). In Philippines, TCW was reported about twice CL (Motoh (1980) as cited by Batoy *et al.*, 1988). The present study recommends CW (cms), i.e. the distance across the carapace from the notch between the 8th and 9th antero-lateral spines, to be a key dimension for measurement, as it proved to be quicker and more precise than TCW, as the tips of the lateral spines are fragile and occasionally broken.

Table 5.6. Carapace length-width relationships for *Portunus pelagicus* recorded at different sites across its geographical range. Relationships obtained by Devi (1985) and Weng (1992) are expressed as TCW (cms) = *a* + *b* CL (cms), and Al-Rumaidh (1995) as CL (cms) = *a* + *b* TCW (cms). Total carapace width (TCW) and carapace length (CL).

	Gender						
	Male			**Female**			
Region	Size range	*a*	*b*	Size range	*a*	*b*	Reference
Kakinada region, India	3-9 cms CL	1.139	1.54	3-9 cms CL	0.5	1.64	Devi (1985)
Gulf of Carpentaria, Australia.	N/A	0.338	2.12	N/A	-0.012	2.22	Weng (1992)
Moreton Bay, Australia.	< 15 cms TCW	0.463	2.06	< 15 cms TCW	0.371	2.09	
Moreton Bay, Australia.	> 15 cms TCW	5.453	1.37	> 15 cms TCW	5.102	1.44	
Bahrain	5-15 cms TCW	0.044	0.463	5-16 cms TCW	0.0437	0.445	Al-Rumaidh (1995)

5.4.2 Carapace width-weight relationship

The present study has shown *P. pelagicus* males to be relatively heavier than females, especially above 6 cms CW. Work on *P. pelagicus* across its geographical range, i.e. Egypt (Abdel Razek, 1987), Australia (Weng, 1992), Bahrain (Al-Rumaidh, 1995) and India (Prasad *et al.*, 1989; Sukumaran and Neelakantan, 1997c) show similar results (see Table 5.7). The finding appears general in swimming crabs e.g. *Callinectes sapidus* (Pullen and Trent, 1970) and *Scylla serrata* and *Portunus sanguinolentus* (Prasad *et al.*, 1989; Sumpton *et al.*, 1989; Sukumaran and Neelakantan, 1997c). In contrast, Dhawan *et al.* (1976) and Batoy *et al.* (1988) working on *P. pelagicus* using TCW and CL respectively showed that females were relatively heavier than males (Table 5.7). The exponent given by Dhawan *et al.* (1976) for female crabs as high as 4.969 may well be a typographical error as it is far higher than the cubic relationship expected. Batoy *et al.* (1988) related the relatively heavier weight of females to environmental conditions, which

Table 5.7. Average slopes (b) and intercepts (a) for carapace length-weight relationships of *Portunus pelagicus* recorded at different locations across its geographical range. Relationships are expressed as wt. (g) = a TCW^b (cms). TCW = total carapace width.

	Gender				
	Male		Female		
Region	*a*	*b*	*a*	*b*	Reference
Zuari Estuary, India Size range: N/A	0.000000275	3.636	0.000000000423	4.969	Dhawan *et al.* (1976)
Abu-Kir, Egypt Size range: 3.5-1.9 cms	0.0085	2.913	0.0057	3.032	Adel Razeq (1987)
Leyte and Vicinity, Philippines, Size range: N/A	.0008	2.406	0.00046	2.515	Batoy *et al.* (1988)
Goa, India Size range: N/A	**Juveniles** 0.000046 **Adults** 0.0000345	2.506 3.104	**Adults** 0.0000048	3.018	Prasar et al. (1989)
Gulf of Carpentaria, Australia. Size range: N/A	0.00000568	3.023	0.0000806	2.943	
Moreton Bay, Australia. Size range: N/A	Crabs < 15 cms TCW 0.0000021	3.284	Crabs < 15 cms TCW 0.0000023	3.25	Weng (1992)
Moreton Bay, Australia. Size range: N/A	Crabs > 15 cms TCW 0.00000855	3.466	Crabs > 15 cms TCW 0.00000931	2.984	
Bahrain	Crabs 5-15 cms TCW 0.00050199	3.293	Crabs 5-16 cms TCW 0.00000691	3.001	Al-Rumaidh (1995)

Table 5.7. Continued

	Gender				
	Male		**Female**		
Region	*a*	*b*	*a*	*b*	Reference
	Juveniles				
Karnataka coast, India Size range: N/A	0.000009	2.873			Sukumaran and Neelakantan (1997c)
	Adults		**Adults**		
	0.00000032	3.617	0.00000163	3.23	

differ between temperate and tropical regions. However, findings from Bahrain (~ 26° N) and Egypt (~ 22-32° N) representing temperate environments, and from the tropical waters of Australia (~ 11-45° S), where in both regions male *P. pelagicus* were found to be heavier, indicate that environmental conditions are not responsible directly for the difference in gender weight. As to the present study, the heavier weight exhibited by male crabs over time indicates the continued good conditions across the study area, particularly during the summer months (i.e. May-September) when moulting and breeding occur. The higher exponents for males in areas A and B almost throughout, suggest a ready food supply available in both these areas compared with area C. The present study has shown that further investigations are now needed on size and weight of chelae, as well as the weight of the whole exoskeleton of both genders of similar sizes (CW). Such information should allow a better understanding as to why the male *P. pelagicus* is the heavier sex.

Chapter 6

Population dynamics

6. POPULATION DYNAMICS

6.1 Introduction

Information on the population dynamics of the edible swimming crab, *Portunus pelagicus*, is contained within a limited literature. Studies dealing with size structure, distribution, abundance, sex ratio and growth were carried out mostly in Australia (Anon. 1970; Potter *et al*, 1983; Sumpton *et al.*, 1989; Gray *et al.*, 1990; Weng, 1992; Sumpton *et al.*, 1994b), Egypt (Abdel Razek, 1987; Abd El-Hamid, 1988) and India (Dhawan *et al.*, 1976; Chatterji *et al.*, 1994). Knowledge of *P. pelagicus* recruitment and nursery grounds in Bahrain are lacking, despite their importance for any commercial fishery management plan.

In Bahrain, *P. pelagicus* is considered as one of the major living marine resources. However, the crab fishery has no management controls whatsoever. Since *P. pelagicus* is essentially a by-catch of the shrimp fishery, it gains some indirect protection in the offshore fishing grounds through the annual closed season for shrimp (~ April-July). The growing importance (Adbulqader, 2001) of this *P. pelagicus* fishery demands that there be a management policy that should be based on its own needs rather than relying on those of the shrimp fishery.

The aims of the present investigation were to describe the size composition, abundance, nursery areas, recruitment, sex ratio and growth rate of the *P. pelagicus* resource. Such information should form the necessary biological database needed to understand the population dynamics of the species. Such understanding will allow for rational exploitation and management of the *P. pelagicus* fishery in Bahraini waters.

6.2 Methods

6.2.1 Population size structure

Size (defined as carapace width, CW) structure for the *P. pelagicus* populations were investigated for each study area over the sampling period. Crab CW data collected from all grids within each area were combined to represent the monthly size structure for male and female crabs. These size data were grouped into size classes of 0.5 cm increments, thus, size frequency distributions (SFDs) were obtained for each gender over time across the study region.

6.2.2 Nursery areas

The ratio of juvenile crabs (defined as males < 5.5 cms CW, females < 7 cms CW) to mature crabs was adopted in the present research as a means to identifying the nursery grounds of *P. pelagicus*. For this analysis, each area was divided into sub-areas. Area A consisted of sub-areas A1 and A2, area B of B1, B2 and B3, area C of C1, C2, C3 and C4, and area D in its entirety (see Fig. 6.1). Sub-areas were grouped under the following criteria: (1) similarity in water depth, (2) distance from the Bahrain coast, (3) nature of the bottom habitat and (4) representative samples available (at least one replicate each month). Grouping grids BG87, BH86 and BH87 (see Fig. 6.1), viz. sub-area C4, did not fully fulfil these criteria because of months when sampling was missed. However, C4 was still considered a distinctive sub-area since salinity rose to levels higher than 50‰.

6.2.3 Recruitment

Index of Recent Recruit (IRR = $\log_e$ [number of juveniles as a proportion of the number of adults]) was used as a measure of recruitment of *P. pelagicus* into the areas. IRR was calculated for both genders in each area over the sampling period. Juveniles up to 5 cms carapace width were considered "recruits" and their relative distribution used to identify where and when recruitment occurred (Morgan *et al.*, 2000). To obtain IRR, numbers of juveniles (size class mid-points from 0.25 to 4.75 cms CW) were divided by total number of adult crabs (classes larger than 5 cms CW). Crabs < 5 cms CW were considered "recent recruits" because most of the juvenile crab peak numbers were associated with size classes 3.5-5 cms CW.

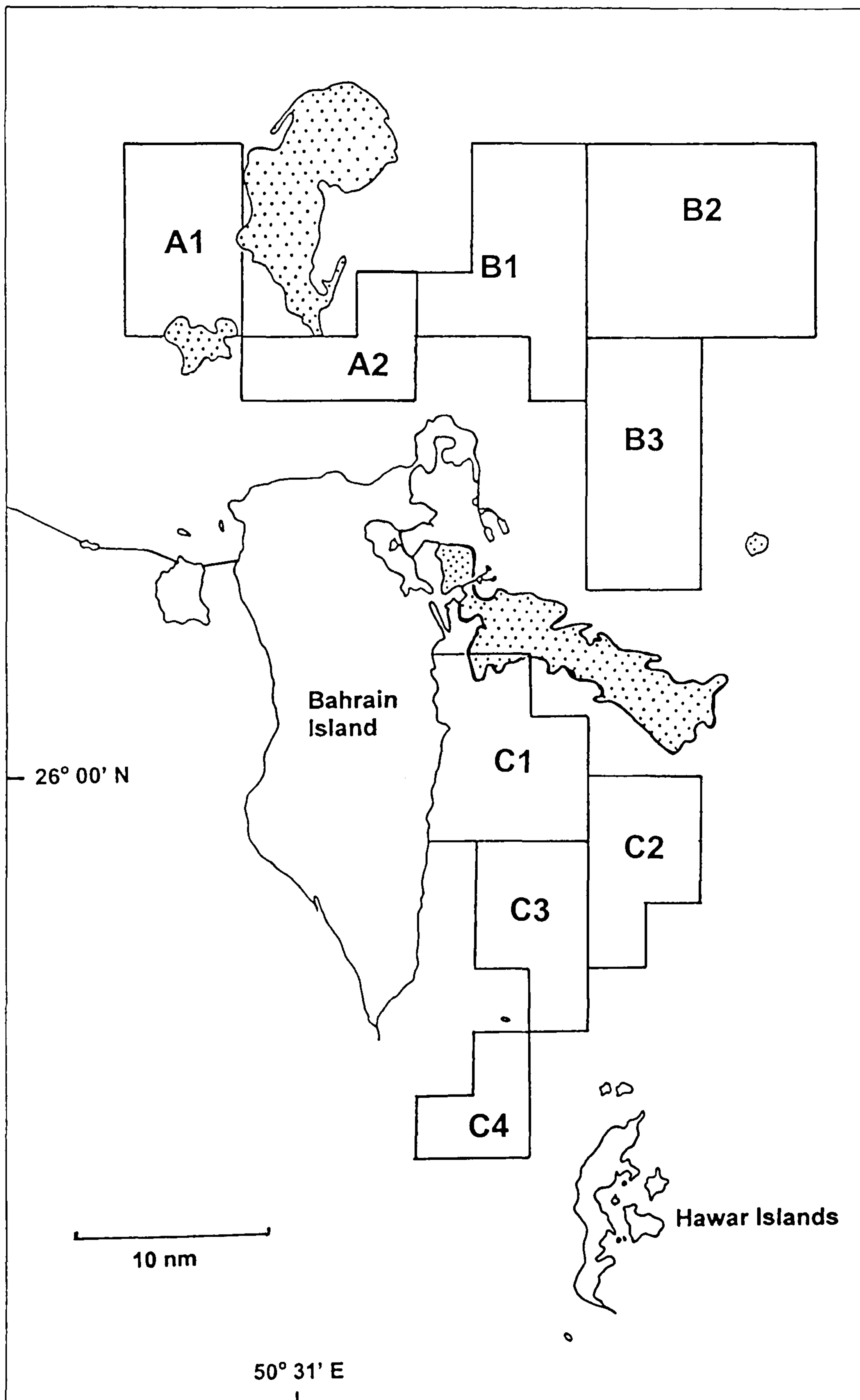


Figure 6.1. Chart to illustrate the sub-areas used for identifying the nursery grounds of *Portunus pelagicus* in Bahraini waters.

6.2.4 Relative abundance

Relative abundance (RA) of *P. pelagicus* in the present study was expressed as the number of crabs caught per kilometre trawled, i.e. catch per unit of effort (CPUE). The distance trawled was accurately determined (± 10 m, see Chapter 2, trawling operations) by GPS, which was regularly calibrated. Since the same trawl net and warp length were used for each trawl the measure of CPUE is comparable between trawls, although the actual swept width of the net was not precisely measured for the shrimp survey. Crabs were classified into four groups on the basis of their gender and maturity status - juvenile males (JM), mature males (MM), juvenile females (JF) and mature females (MF) in order to investigate how the relative abundance of each group varied from one study area to another. Variation in relative abundance was also investigated in relation to certain environmental parameters - temperature, salinity and water depth using principal component analysis.

6.2.5 Sex ratio

Two approaches were followed for investigating sex ratio. The first was the traditional method, that of ascertaining the number of males and females in monthly samples. Every single specimen collected in the course of the survey work, even specimens that were not measured for carapace width due to carapace damage, were included. Data from all grids of a given study area were combined to provide comparisons between the populations from the different areas.

The sex ratio differences between size classes of crabs were also investigated. CW data of the two sexes from the monthly catches in an area were sorted into discrete size classes. For offshore crabs, data were classified into three categories: (1) crabs < 3 cms CW, (2) 3-10 cms CW grouped in 1 cm class intervals and (3) crabs > 11 cms CW. A slight modification to this grouping was used for coastal crabs due to their low numbers in the small and large size classes, thus: (1) crabs < 6 cms CW, (2) 7-9 cms CW grouped in 1 cm CW class intervals and (3) crabs > 10 cms CW. Chi-square (χ^2) goodness of fit tests were assuming departure from a 1:1 sex ratio.

6.2.6 Estimation of growth parameters and rate of growth

As crustaceans do not have bony structures such as scales or otoliths which would allow age to be gauged directly (Garcia and Le Reste, 1981), alternative methods were applied during the present study to estimate the growth of *P. pelagicus* based on size (CW) frequency analysis (Sparre and Venema, 1992). Methods that were applied here are - 1) modal progression analysis, the traditional method of tracing observed modes of cohorts and (2) Ford-Walford plots to determine growth parameters (K and L_∞) having obtained samples over equal time intervals (King, 1995). The Ford-Walford plot was applied to the major modal groups, defined as cohorts that were traced for a minimum period of 4 months. The Von Bertalanffy growth equation (VBGE) was assumed to be an appropriate model and was used to investigate growth parameters for the crabs in each study area. The size frequency distributions (SFDs) for male and female crabs in the monthly samples were composed of 0.5 cm CW size classes intervals. The SFDs were analysed and broken down into their component normal distributions using Bhattacharya's method that assumes cohort dimensions are normally distributed and that they fit the VBGE model. Bhattacharya's method is incorporated into a new suite of fisheries tools called the FAO-ICLARM Stock Assessment Tools (FiSAT) (Gayanilo Jr. *et al.*, 1996). Each major component of the SFDs was considered to constitute a cohort and the progression in time of the mean size used to fit the VBGE asymptotic curve:

$$\mathbf{L_t = L_\infty [\ 1\text{-}e^{-k(t-to)}]}$$

Where $\mathbf{L_t}$ = Length at time,

K = is the growth coefficient,

$\mathbf{L_\infty}$ = the asymptotic maximum length in a population,

$\mathbf{t_0}$ = the time when the animal theoretically has zero length.

6.3 Results

6.3.1 Nursery grounds

The percentage of juvenile crabs in the various study areas over the year are presented in Table 6.1. With the exception of sub-area C4, where juvenile male crabs outnumbered mature males, mature males were significantly more numerous than juvenile males in the other sub-areas.

Table 6.1. Percentages of juvenile crabs of male and female *Portunus pelagicus* in the sub-areas, obtained for crabs collected from March 1999 to April 2000. Juvenile males < 5.5 cms CW, juvenile females < 7.1 cms CW.

	Gender			
	Males		**Females**	
Sub-area	Total number of crabs	Juvenile crabs (%)	Total number of crabs	Juvenile crabs (%)
A1	1280	21	1590	37
A2	3565	32	3142	59
B1	1937	4	3567	13
B2	1249	1	2745	4
B3	607	1	1637	6
C1	3978	27	4774	57
C2	3564	41	3697	74
C3	4989	37	4590	74
C4	509	86	387	94
D	732	28	587	59

For female crabs, juveniles in sub-areas A2, C1-C4 and area D significantly outnumbered mature females. Table 6.1 clearly indicates that the occurrence of juvenile male and female crabs in area B was negligible. The high preponderance of juvenile males and females in sub-area C4, where salinity reached as high as 54‰ in grid BG87, suggests that very young crabs have a high salinity tolerance. Table 6.1 further indicates that percentages of juvenile crabs of both genders in area C increased towards the more southern sub-areas, where there are extensive algae and seagrass beds. Study areas A, C and D, appear to be the major nursery grounds for *P. pelagicus* in Bahraini waters (see Fig. 6.1), all characterised by algal and seagrass beds in shallow water.

6.3.2 Recruitment

6.3.2.1 Recent recruits

Recent recruits are defined as juvenile crabs entering the fishable stocks. All carapace width (CW) frequency distributions for each gender from the study areas showed variation from one month to another, where smaller size classes within the range 1-5 cms CW, representing recent recruits, produced distinct spatial and temporal patterns (see Figs. 6.16-6.18, 6.21 and 6.23-6.24).

The annual Index of Recent Recruitment (IRR) in each area, computed from the total number of crabs caught over the year, indicated that recruitment was higher in areas A, C and D (Fig. 6.2). The temporal variations in recruitment are illustrated in Fig. 6.3, enabling the identification of recruitment seasons.

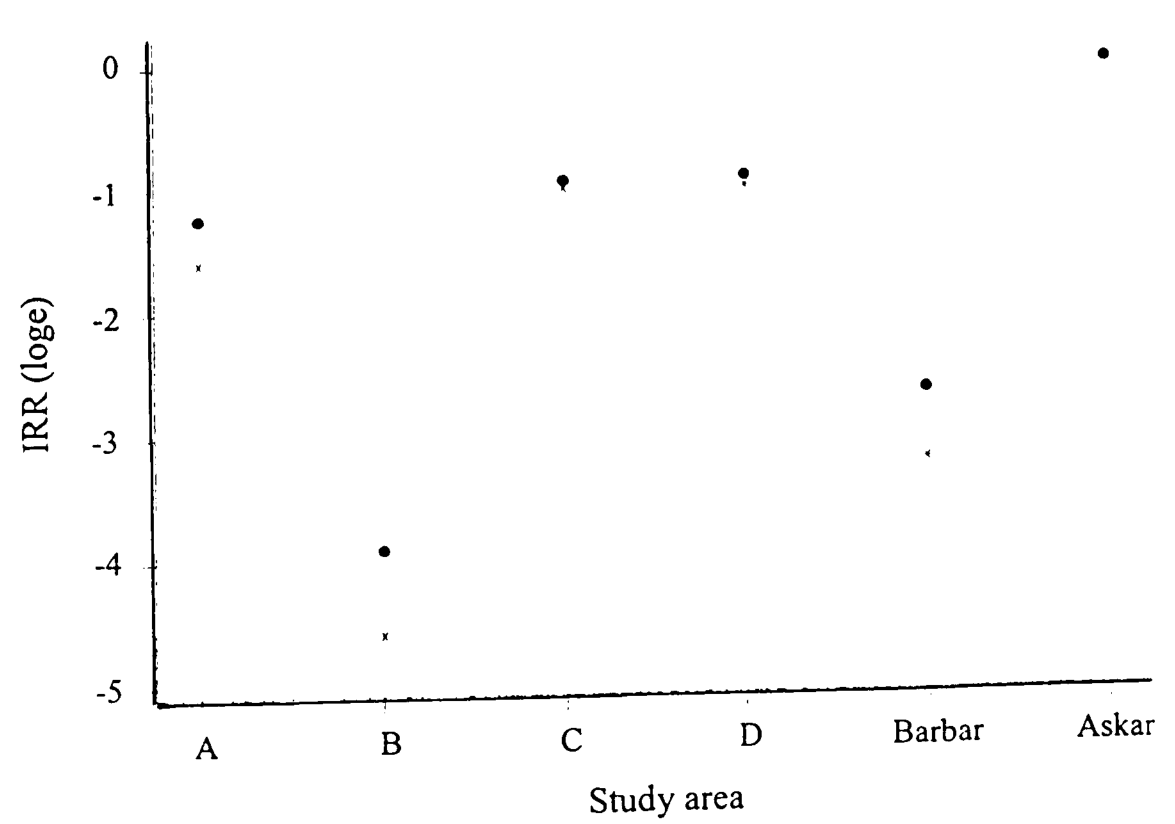


Figure 6.2. Indices of recent recruitment (IRR) for male and female *Portunus pelagicus* illustrate the spatial variation in recruitment in the study areas around Bahraini waters. Males (•), females (*). IRR are presented on $\log_e$ scale.

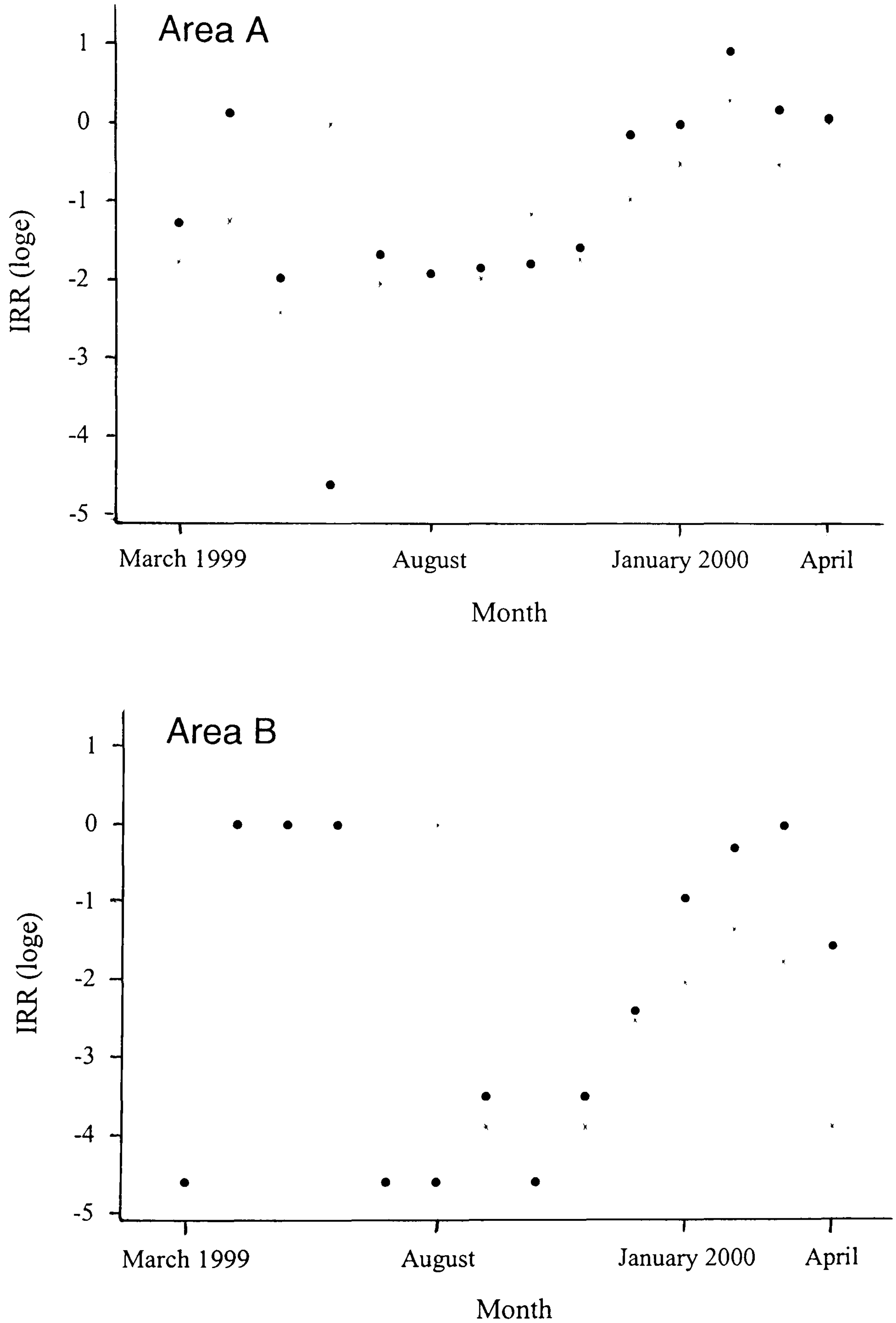


Figure 6.3. Continued

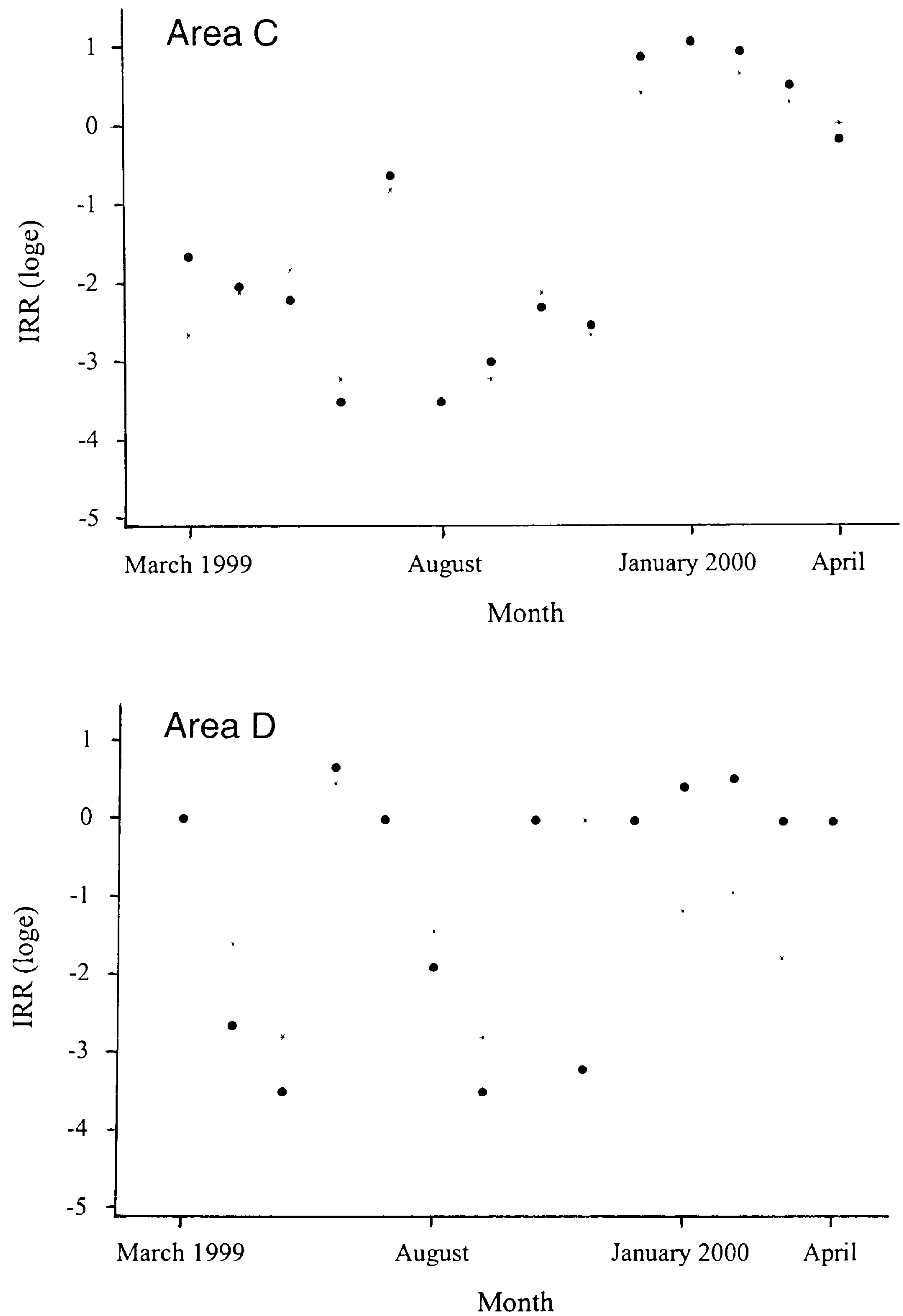


Figure 6.3. Indices of recent recruitment (IRR) for male and female *Portunus pelagicus* illustrate the temporal variation in recruitment within each study area from March 1999 to April 2000. Males (•), females (*).

In area A, reasonable recruitment of males (IRR = 0.2) but lower for females (IRR = -1.2) were first recorded in April 1999. Recruits (i.e. < 5 cms CW) were negligible in May and June 1999. Recruitment gradually increased thenceforth until December 1999, remaining high through to April 2000 reaching 1 for males and 0.3 for females in February. Recruits from December 1999 to April 2000 were predominantly male crabs. The occurrence of male recruits (IRR = 0.2) and females (IRR = 0.3) in March 2000 was almost four-fold higher than that recorded in March 1999. The recruitment of males in April 2000 corresponded with that recorded in April 1999 (IRR = 0.2), however, recruitment of females in April 2000 was twice that recorded in April 1999. The first noticeable recruitment to area C did not occur until July 1999 with the IRR approaching 0.5. During the next four months (August-November 1999), recruitment was very poor. From November to December the IRR for male and female crabs increased 31 and 22-fold respectively, peaking in January 2000 with the IRR as high as 1.1 for both. The IRR then declined over the next three months, although recruitment in March-April 2000 was far higher than that recorded during the same period in 1999. In area B, recruitment was negligible with the exception in January, February and April 2000, with the highest IRR in February at –0.2 for males and –1.2 for females. Recruitment in area D was similar to that for area C with a peak IRR in June 1999, 0.7 for males and 0.5 for females. IRR for male crabs had overtaken that of females during January and March by 5 and 4-fold respectively. The recruitment situation in this area during March 1999 and December 1999 and April 2000 is not known, as no sampling was carried out during these months.

Table 6.2 clearly indicates that areas A, C and D are the major recruitment grounds. Two major recruitment periods for *P. pelagicus* in Bahraini waters are generally indicated: (1) a short period during late spring-summer which varied in timing between areas, and (2) a prolonged period lasting up to four consecutive winter months, i.e. December-April. This latter major recruitment period coincided with the absence of ovigerous females in all study areas from December to February.

Table 6.2. Percentages of recent recruits (i.e. crabs < 5 cms CW) of the total male and female *Portunus pelagicus* populations collected from the study region from March 1999 to April 2000.

Study area	Males	Females
A	29	20
B	2	1
C	39	35
D *	40	38
Barbar **	7	4

* Sampling duration: April-Nov. 1999 and Janu.-March 2000,
** Sampling duration: April 1999-April 2000

6.3.2.2 Recruitment of commercial crabs

Combined CW data of crabs that were collected from the study region over the sampling period, indicated that 50% of all mature males and females caught by the trawl were smaller than 7.5 and 8.5 cms CW respectively (Fig. 6.4).

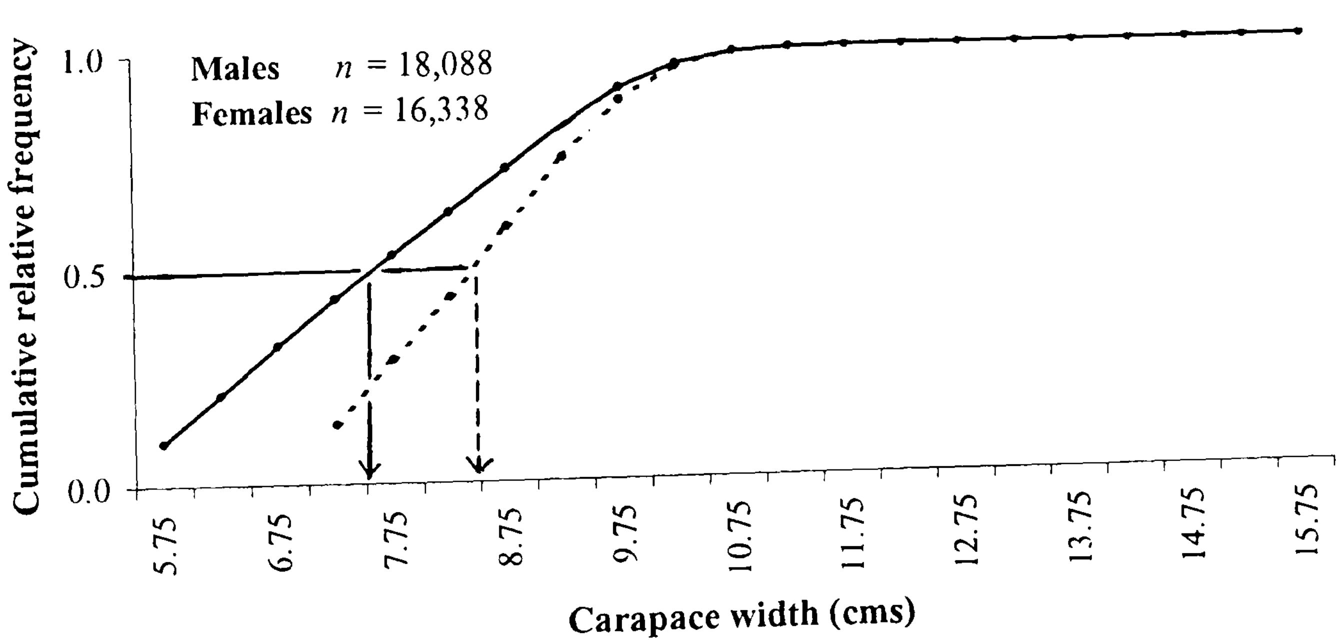


Figure 6.4. Cumulative relative frequency of combined data for mature males (> 5.5 cms CW) and mature females (> 7 cms CW) *Portunus pelagicus* showing the sizes (CW cms) of crabs caught by the trawls. Males (——) and females (----).

6.3.3 Distribution and relative abundance

6.3.3.1 Sexual composition of trawl catch

The composition of the trawl crab catches, classified into juvenile males, mature males, juvenile females and mature females, expressed as percentages of the total crab catch, is illustrated in Fig. 6.5. The crab composition fluctuated in areas A and C from March to December 1999, however, juvenile crabs dominated throughout to April 2000. In area B, mature females predominated at around 60% of the catches over the whole sampling period.

6.3.3.2 Relative abundance

Index of relative abundance dispersion (IRAD = variance/mean) obtained for the four crab groups in the offshore areas across the sampling period, indicated that the crab distribution varied from evenly spaced (IRAD < 1) to aggregated (IRAD > 1). The overall IRAD ranged from 0.1 to 135 (Table 6.3, Table 6.4, Table 6.5). Juvenile males in area A were aggregated more often than mature males during April-May 1999, July-August and November 1999-April 2000, whereas juvenile females exhibited greater aggregation during March-May 1999, July, October-November and January-April 2000 (Table 6.3). In contrast, in area B, mature males were more aggregated than juvenile males from March to November 1999 and April 2000, whereas juvenile males were aggregated from December to March 2000 (Table 6.4). Juveniles and mature females were found to be more aggregated than male crabs across the sampling time series. In area C, IRADs were similar to those recorded in area A in terms of interchange between aggregation of juvenile and mature crabs of both genders (Table 6.5). In general, the temporal fluctuations in IRAD between the three areas suggest movements of crabs within fishing grounds, as well as recruitment by juvenile crabs into the nursery grounds around the study areas.

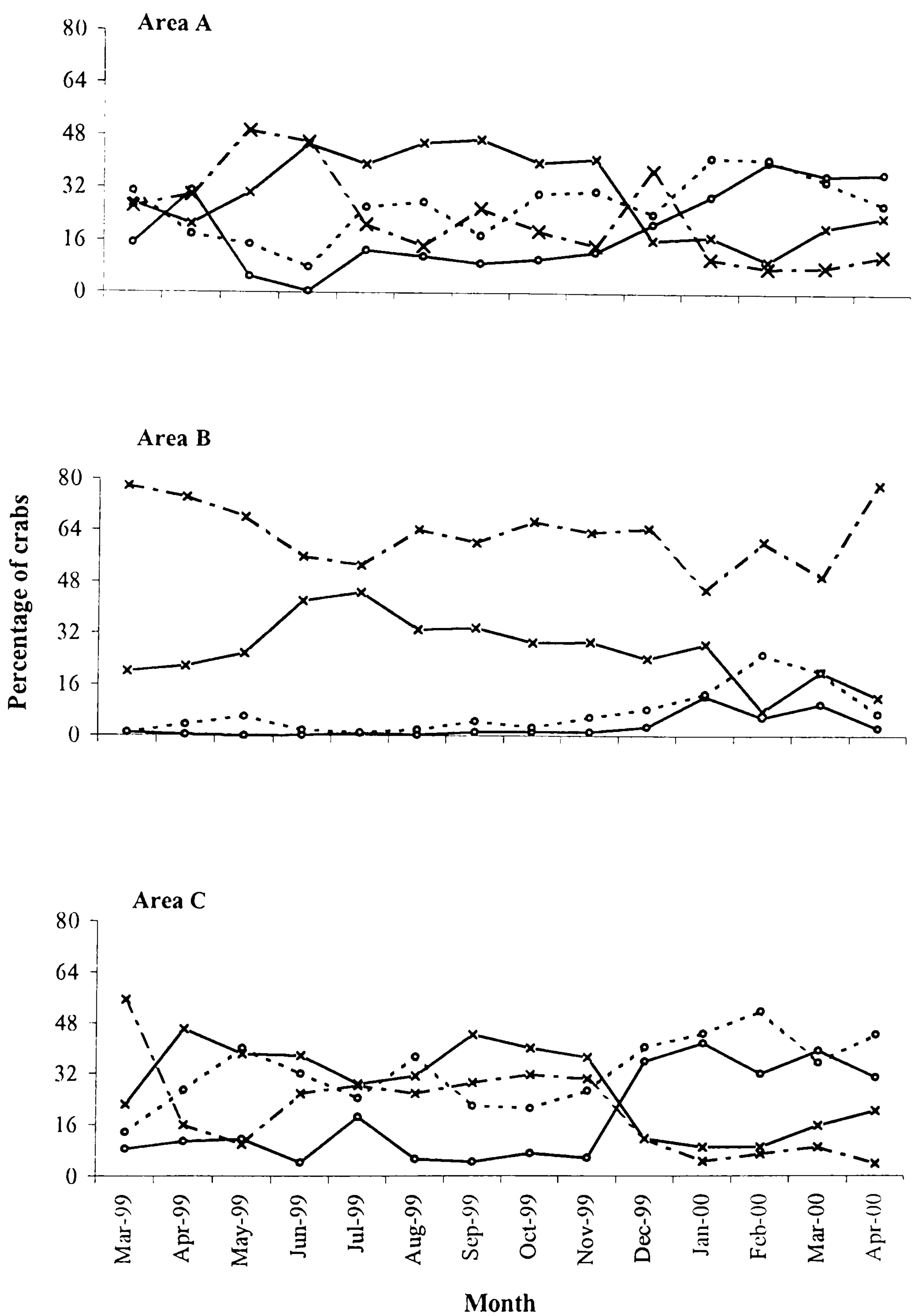


Figure 6.5. Seasonal changes in sexual composition (expressed as percentages of total catch) of juvenile male (—o—), mature male (—x—), juvenile female (---o---) and mature female (-.-x-.-) *Portunus pelagicus* in study areas A, B and C from March 1999 to April 2000.

Table 6.3. Index of relative abundance dispersion for *Portunus pelagicus* sampled in area A from March 1999 to April 2000.

	Males		Females	
Time	Juvenile	Mature	Juvenile	Mature
Mar-99	42	53	61	39
Apr-99	57	2	18	7
May-99	2	0.1	4	2
Jun-99	1	17	16	58
Jul-99	13	12	48	9
Aug-99	13	14	5	7
Sep-99	8	10	6	14
Oct-99	3	3	10	3
Nov-99	2	1	6	1
Dec-99	23	9	13	58
Jan-00	8	6	16	1
Feb-00	1	1	2	0.4
Mar-00	8	5	8	1
Apr-00	6	2	2	3

Table 6.4. Index of relative abundance dispersion for *Portunus pelagicus* sampled in area B from March 1999 to April 2000.

	Males		Females	
Time	Juvenile	Mature	Juvenile	Mature
Mar-99	0.2	2	4	7
Apr-99	1	45	13	135
May-99	0.4	30	42	87
Jun-99	0.3	7	2	12
Jul-99	1	10	1	11
Aug-99	1	5	6	11
Sep-99	2	12	5	6
Oct-99	0.4	3	1	11
Nov-99	0.4	2	1	3
Dec-99	1	1	4	12

Table 6.4 Continued

	Males		Females	
Time	Juvenile	Mature	Juvenile	Mature
Jan-00	5	3	4	4
Feb-00	1	1	2	3
Mar-00	0.3	0.3	0.3	1
Apr-00	0.4	1	6	2

Table 6.5. Index of relative abundance dispersion for *Portunus pelagicus* sampled in area C from March 1999 to April 2000.

	Males		Females	
Time	Juvenile	Mature	Juvenile	Mature
Mar-99	15	6	7	17
Apr-99	4	4	8	3
May-99	4	11	22	2
Jun-99	12	11	49	< 0.1
Jul-99	15	5	14	5
Aug-99	2	< 0.1	0.2	2
Sep-99	6	90	39	89
Oct-99	31	64	63	72
Nov-99	6	2	12	5
Dec-99	61	1	68	5
Jan-00	29	14	33	4
Feb-00	21	9	16	8
Mar-00	18	5	11	2
Apr-00	36	26	55	2

The monthly relative abundances of *P. pelagicus* in study areas A, B and C varied seasonally. In area A (Fig. 6.6), the abundance of juvenile male crabs (JM) was the lowest ranging from 1 to 24 crabs km^{-1}, with the high abundances recorded in March 1999 (21 crabs km^{-1}), April 1999 (24 crabs km^{-1}), and July (21 crabs km^{-1}). The abundance of mature males (MM) was high in March 1999 at 35 crabs km^{-1}, and then declined sharply in the following two months to 8 crabs km^{-1} in May. The highest abundances of MM were recorded from June to September at 62 ± 2 crabs km^{-1}. Abundance declined sharply in October to 20 km^{-1} and continued to decline to as low as 2 crabs km^{-1} (February 2000). MM abundance remained low through March and April 2000 at ~ 4 crabs km^{-1}. Juvenile females (JF) exhibited a similar trend in abundance to that of their male counterparts, although their abundance was generally higher than JM. The highest abundances of JF were recorded in March 1999 (41 crabs km^{-1}), July (47 crabs km^{-1}) and August (39 crabs km^{-1}). The abundance of mature females (MF) fluctuated markedly with three peaks in June (63 crabs km^{-1}), September (30 crabs km^{-1}) and December (29 crabs km^{-1}). Abundance of MF stayed low from January to April 2000 at ~ 2 crabs km^{-1}, far lower than that recorded during March-April of the previous year (30-23 crabs km^{-1} respectively).

In area B, abundances of JM and JF were found to be negligible throughout the study period, so abundances for all four crab groups needed to be expressed on a log_e scale for comparison (see Fig. 6.7). For a ready reference, the actual data are still given in the following text in parenthesis. Abundance of JM as low as –3.1 (0.05 crab km^{-1}) and JF – 2.38 (0.1 crab km^{-1}) were far lower than those of mature crabs, however, JF were more abundant than JM from March to November 1999 and February 2000, ranging between – 0.1-1.9 (1-7 crabs km^{-1}). Abundance of MM increased from 0.7 (2 crabs km^{-1}) in March 1999 to 2.9 (19 crabs km^{-1}) in May, and further increased to 3.1 (22 crabs km^{-1}) in June 1999. Highest abundances occurred from May to September at about 2.9 ± 0.1 (18 ± 1 crabs km^{-1}). After September, abundance declined very sharply from 1.8 (6 crabs km^{-1}) to 0 (1 crab km^{-1}) during February-April 2000. As far as females are concerned, abundance of both juvenile and mature crabs remained high over seven consecutive months (March-September 1999). The highest abundance of JF occurred in May 1.9 (7 crabs km^{-1}) and September 1.1 (3 crabs km^{-1}), and the lowest between December 1999 and April 2000. Similarly, abundance of MF was high from April to September 1999, with two peaks in May at 3.9 (48 crabs km^{-1}) and August at 3.6 (35 crabs km^{-1}). However, abundance was very low at about 2 ± 1 crabs km^{-1} from December 1999 to April 2000.

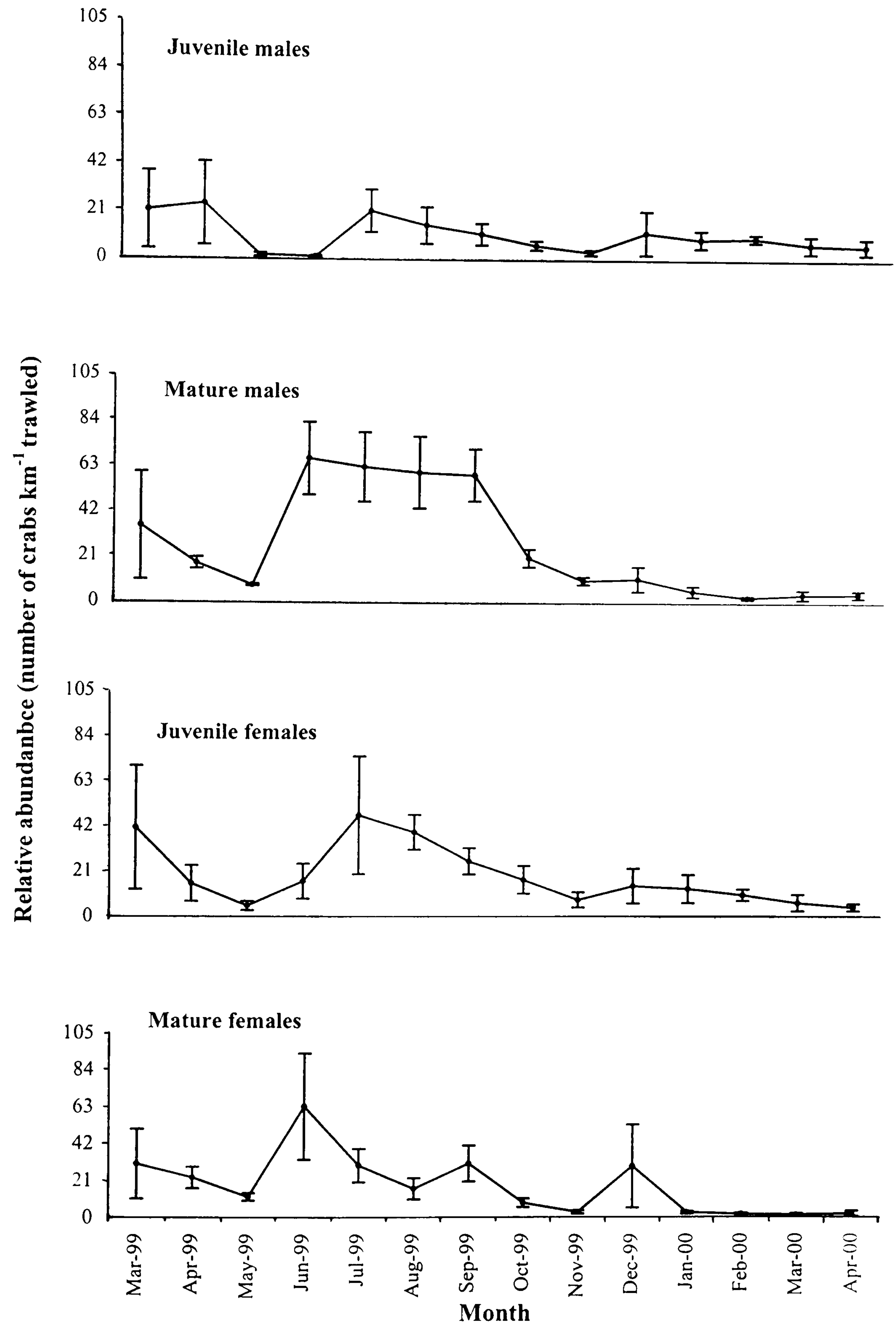
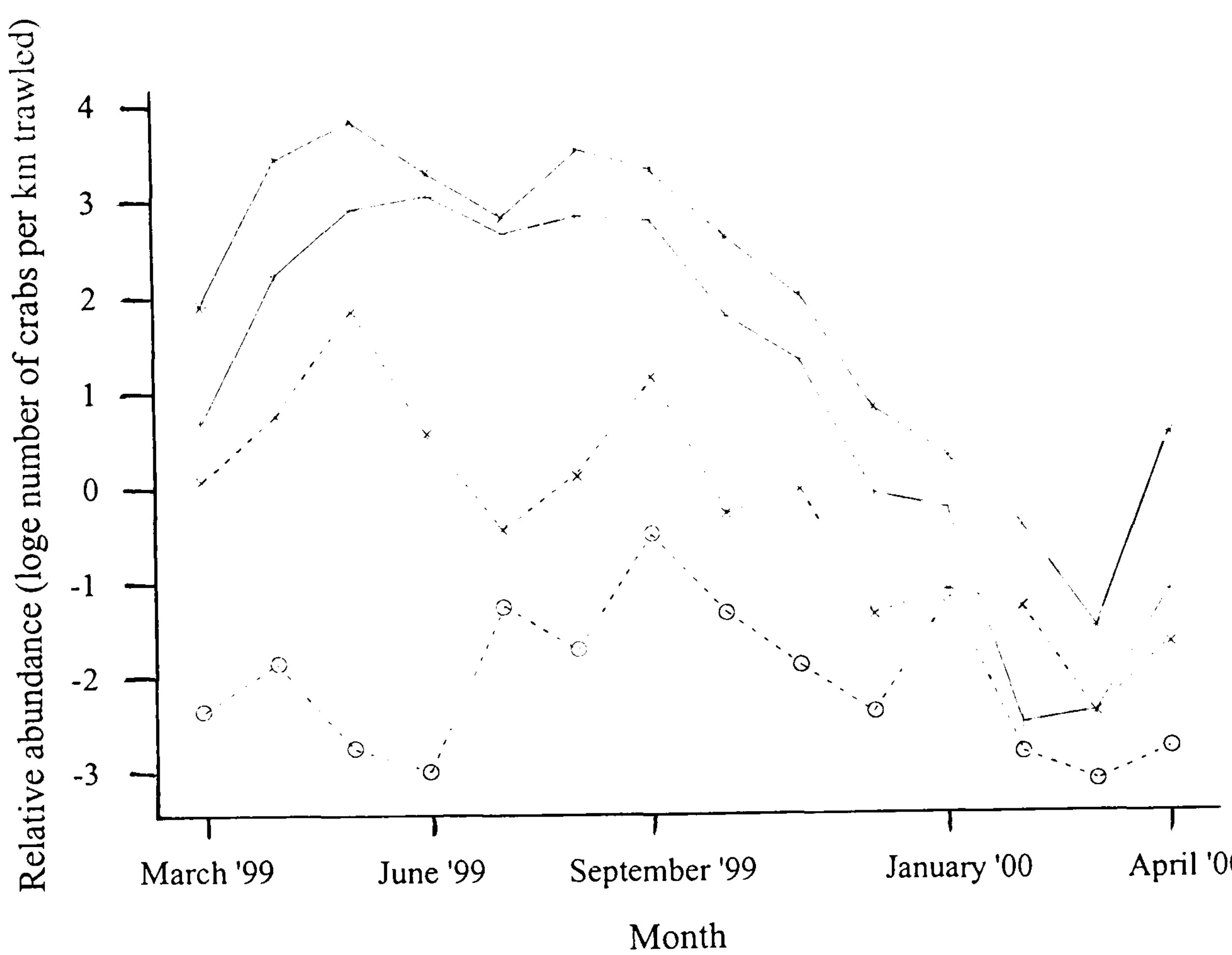


Figure 6.6. Seasonal trend of mean relative abundance (number of crabs ± SE km^{-1}) for juvenile male, mature male, juvenile female and mature female of *Portunus pelagicus* collected from study area A from March 1999 to April 2000.



Fgure 6.7. Seasonal trend of mean relative abundance (number of crabs ± SE km^{-1}) for juvenile male, mature male, juvenile female and mature female of *Portunus pelagicus* collected from study area B from March 1999 to April 2000. Abundance is given on log_e scale. Juvenile males (o), mature males (+), juvenile females (x) and mature females (*).

In area C, the abundance of juvenile crabs of either gender was far higher than that of their counterparts in area B, but within the same range as juvenile crabs in area A (Fig. 6.8). In 1999, abundance of JM was comparatively high in May (17 crabs km^{-1}) and July (11 crabs km^{-1}) but the highest abundances occurred from December 1999 onwards with 2 peaks in January and April 2000 at 28 and 33 crabs km^{-1} respectively. MM exhibited high abundance in April and May 1999 at 50 and 57 crabs km^{-1} respectively, with the highest abundance in September at 98 crabs km^{-1}. Abundance from November 1999 to April 2000 was reduced to 13 ± 4 crabs km^{-1}. Abundance of JF fluctuated markedly from March 1999 at 6 crabs km^{-1} to 50 crabs km^{-1} in April 2000, with the highest abundances in May (65 crabs km^{-1}) and September (68 crabs km^{-1}). Abundances of MF varied from 1-20 crabs km^{-1} for most of the study period, with the exception of peak abundances of 47 crab km^{-1} in September and 30 crabs km^{-1} in October 1999.

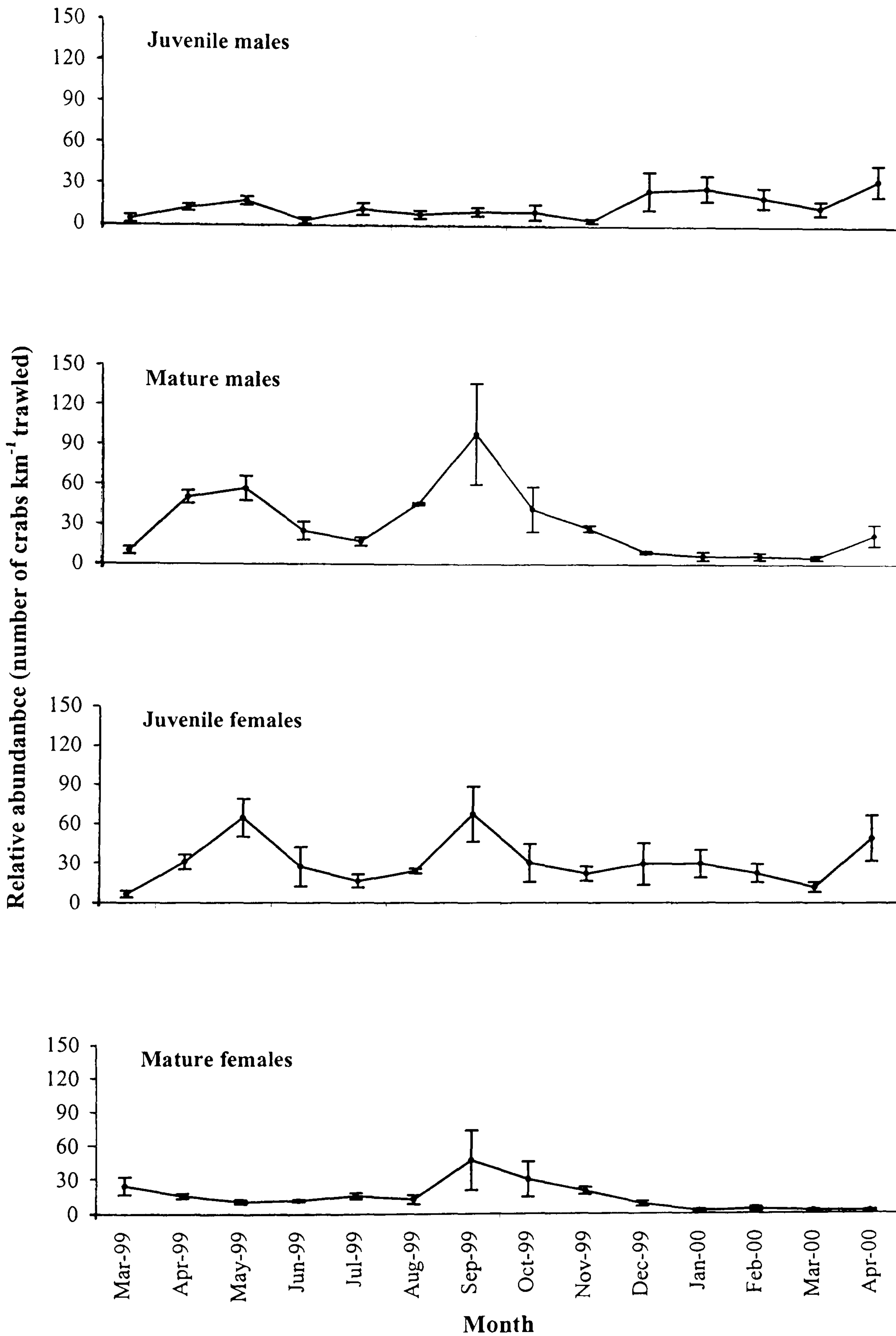


Figure 6.8. Seasonal trend of mean relative abundance (number of crabs ± SE km^{-1}) for juvenile male, mature male, juvenile female and mature female of *Portunus pelagicus* collected from study area C from March 1999 to April 2000.

6.3.3.3 Principal component analysis

Results from principal component analysis (PCA) carried out on abundance data of juvenile males, mature males, juvenile females and mature females, and environmental parameters, viz. temperature (^{o}C), salinity (‰) and water depth (m) are presented in Table 6.6 and illustrated in Fig. 6.9. The percentages of the total variability explained by PC1, PC2 and PC3 were found to be 37%, 24% and 13% respectively. Plotting PC1 vs. PC2 thus represents 61% of the total variability.

Table 6.6. Principal component multipliers (PC1-3) for *Portunus pelagicus* abundance [juvenile males (JM), mature males (MM), juvenile females (JF) and mature females (MF)], temperature, salinity and water depth, carried out for data collected from the study areas A, B and C, from March 1999 to April 2000.

Variables	PC1	PC2	PC3
JM	-0.419	0.365	0.463
MM	-0.522	-0.249	-0.151
JF	-0.564	0.127	0.264
MF	-0.326	-0.435	-0.305
Temp.	-0.199	-0.504	-0.109
Salinity	-0.095	0.459	-0.719
Water depth	0.281	-0.367	0.267

Table 6.6 indicates that negative scores of PC1 relate to high relative abundance (of any crab category) coupled with higher temperatures, salinity has small negative influence on the axis and water depth has a positive influence on the score. PC2 appears to divide juvenile crabs (positive influence) from mature crabs (negative influence) with high temperature and deep water contributing negatively. Positive influence is provided by high salinity. PC3 appears similar to PC2 with a reversal in the role of salinity and water depth in determining score.

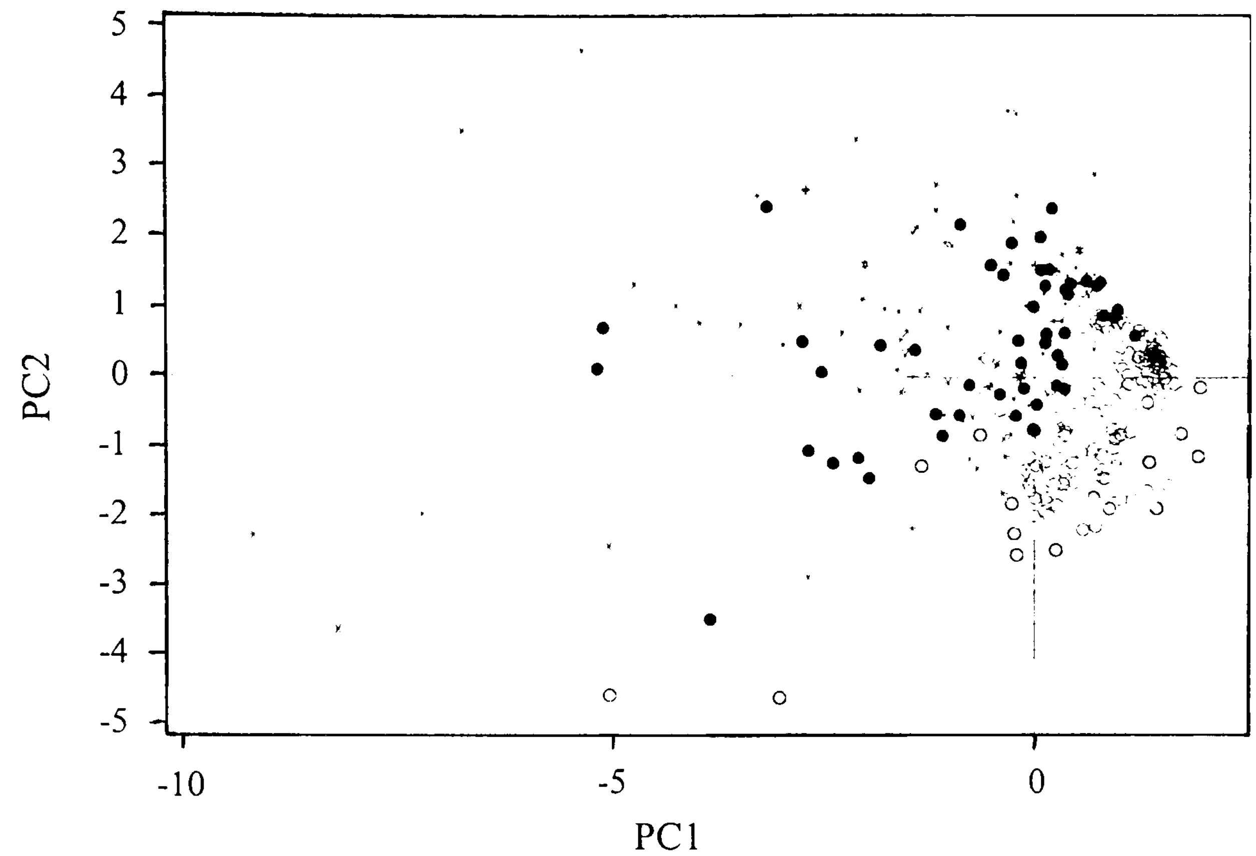


Figure 6.9. Principal component analysis on abundance variables for juvenile male, mature male, juvenile female and mature female *Portunus pelagicus* and environmental parameters, obtained from correlations given in Table 6.6. Area A (•), area B (o) and area C (*).

Fig. 6.9 shows that data points of area B are clustered on the PC1 axis in the low abundance region, indicating low abundance to be associated with deeper waters, with the exception of two points where higher abundance of mature crabs were recorded during April and May 1999 in BK77 and BI74. Crabs in areas A and C occupied almost the same habitat and environment, hence their abundances were scattered together in the same region of Fig. 6.9. High abundance of juvenile crabs was associated with high salinity, shallower water and lower temperatures, whereas high abundance of mature crabs was associated with low salinity, high temperatures and deeper water.

6.3.3.5 Influence of environmental parameters on crab relative abundance

The influence of temperature, salinity and water depth on the abundance distribution of *P. pelagicus* in each area is shown in Figs. 6.10a and 6.10d. Combining data obtained from study areas A, B and C for each crab group has indicated that male and female juveniles occurred more in shallower waters ranging from 4 to 14 metres (JM $r = -0.329$, $p < 0.05$; JF $r = -0.350$, $p < 0.05$), and higher abundance of juvenile males occurred at salinities ranging from 39 to 47‰ ($r = 0.161$, $p < 0.05$). Also, the abundances of mature males and females were higher as the temperature increased (MM $r = 0.396$, $p < 0.05$; MF $r = 0.300$, $p < 0.05$) with the higher abundances of mature males found in shallower waters (4-13 m) ($r = 0.213$, $p < 0.05$). Salinity did not correlate with mature crab abundances (MM $r = 0.033$, $p < 0.05$; MF $r = -0.061$, $p < 0.05$).

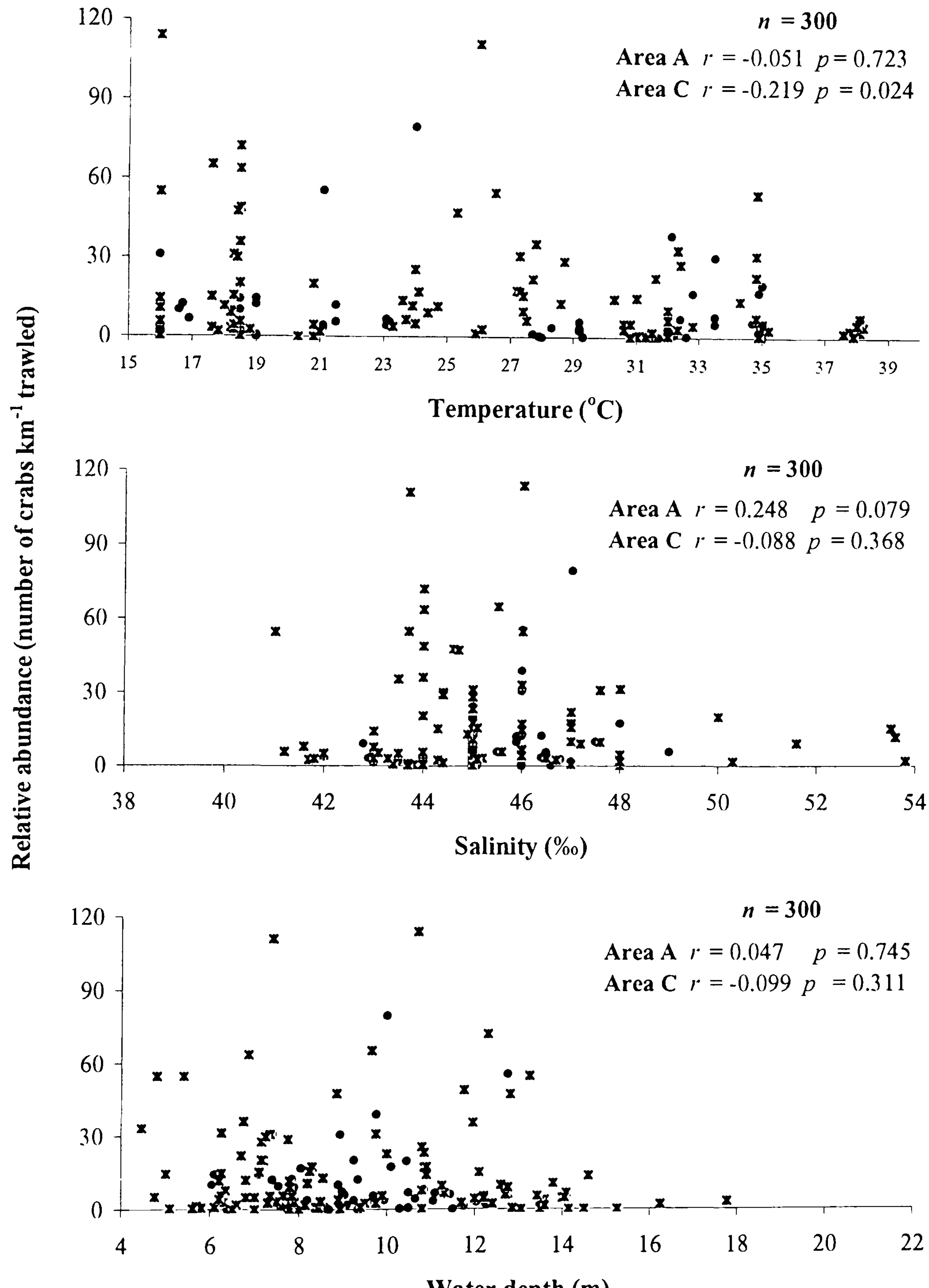


Figure 6.10a. Scatterplot of relative abundance of juvenile male *Portunus pelagicus* collected from study areas A, B and C from March 1999 to April 2000, in relation to temperature, salinity and water depth. Area A (•) and area C (*). Data obtained from area B are not included due to negligible abundances.

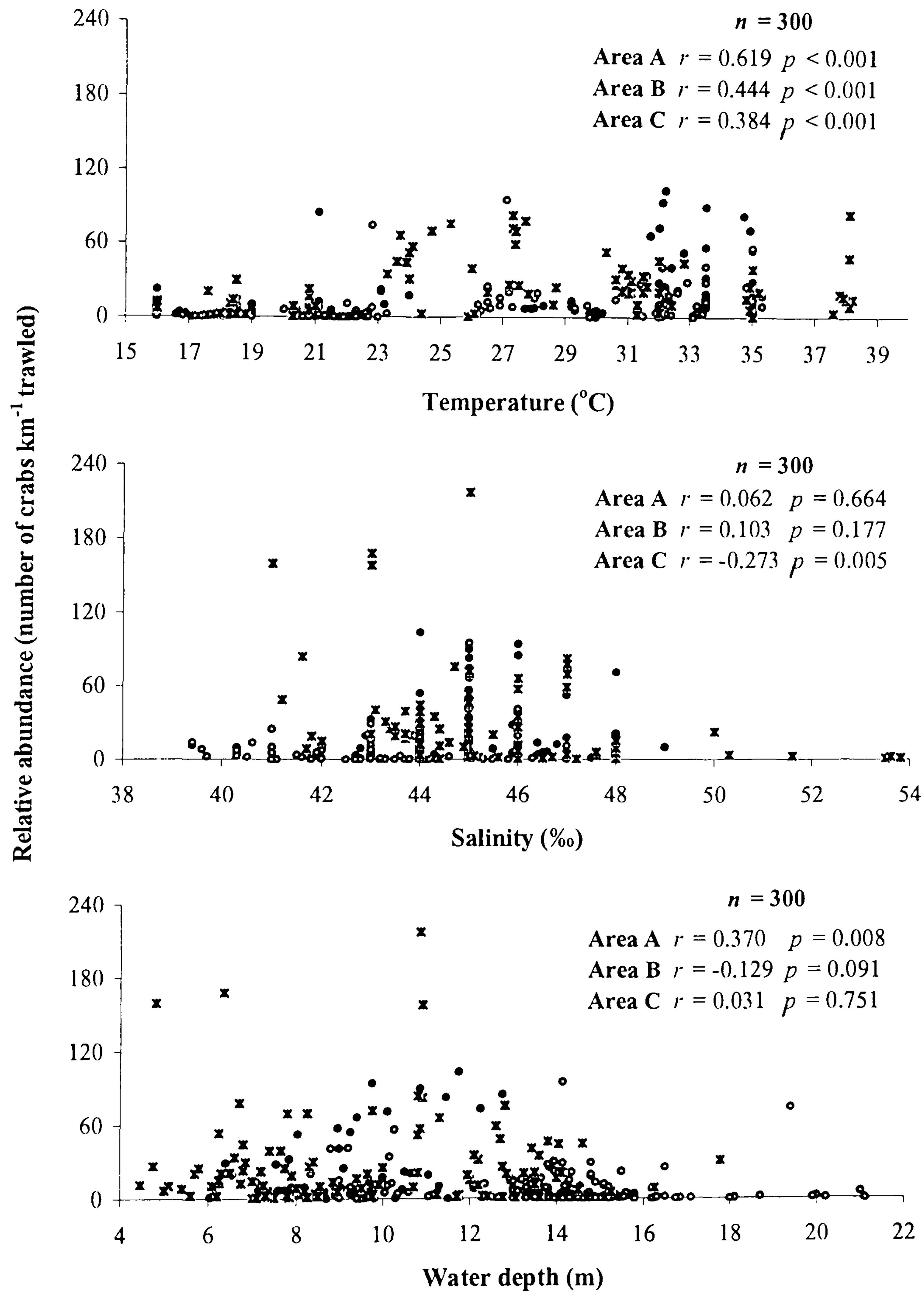


Figure 6.10b. Scatterplot of relative abundance of mature male *Portunus pelagicus* collected from study areas A, B and C from March 1999 to April 2000, in relation to temperature, salinity and water depth. Area A (•), area B (o) and area C (*).

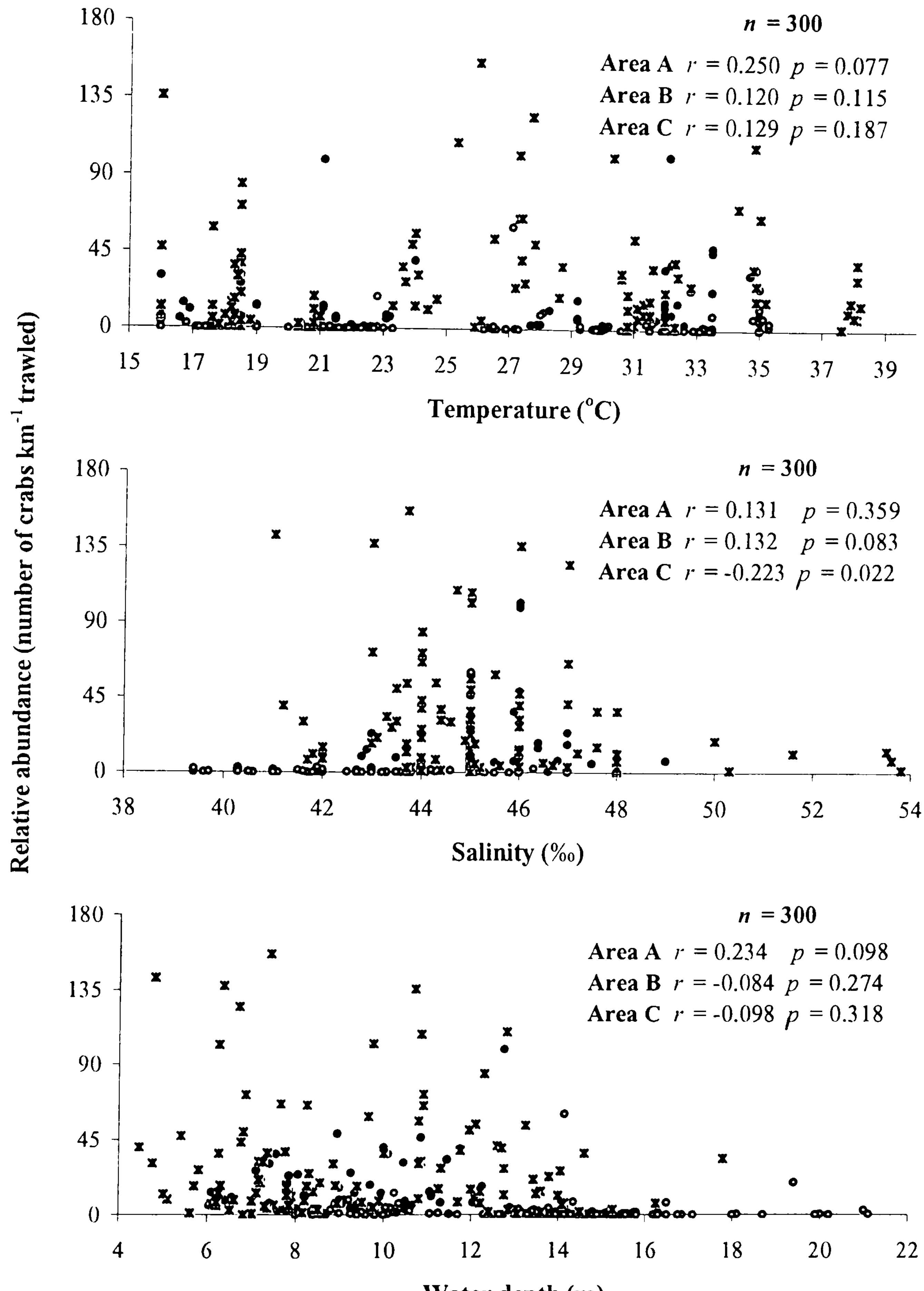


Figure 6.10c. Scatterplot of relative abundance of juvenile female *Portunus pelagicus* collected from study areas A, B and C from March 1999 to April 2000, in relation to temperature, salinity and water depth. Area A (•), area B (o) and area C (*).

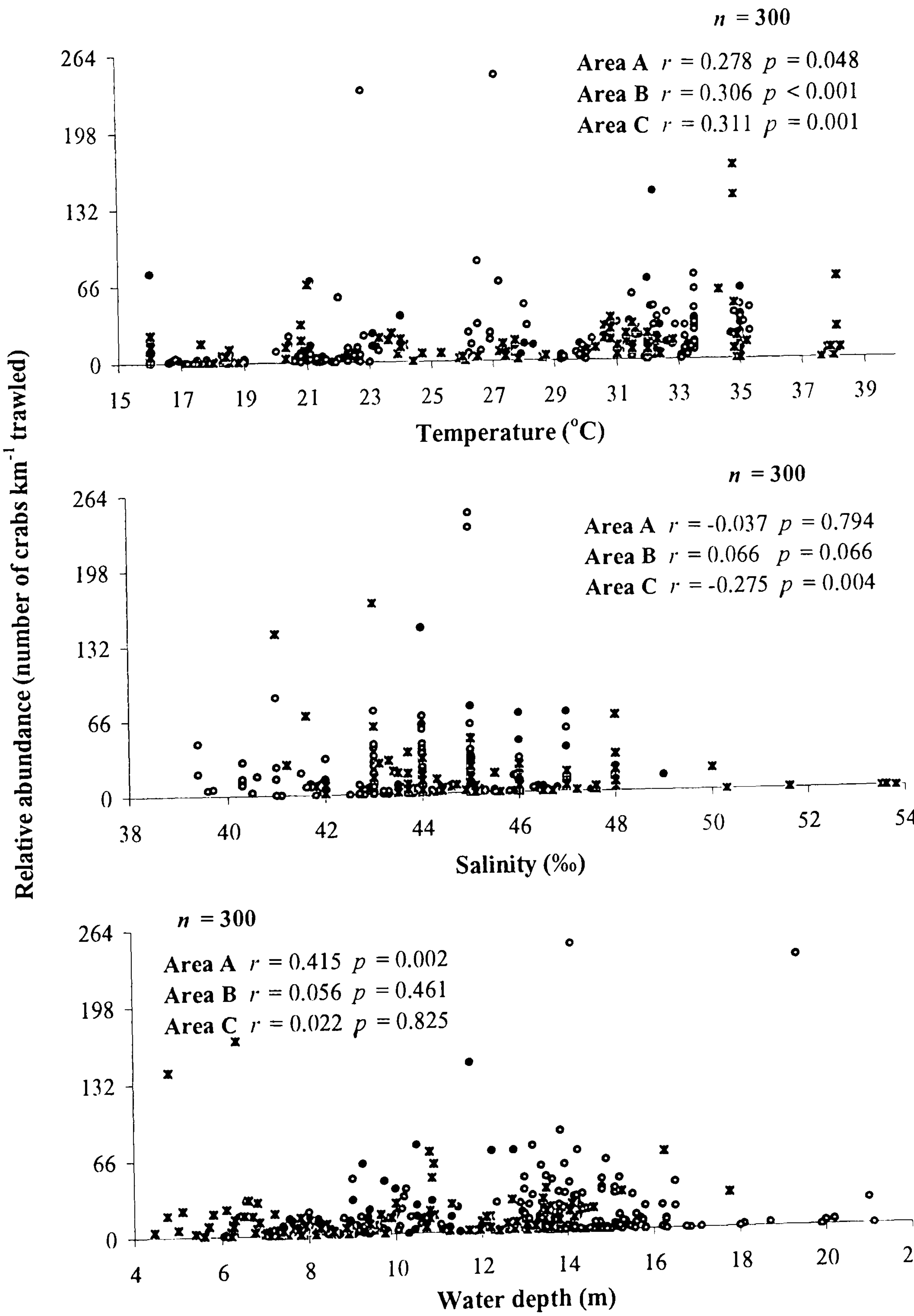


Figure 6.10d. Scatterplot of relative abundance of mature female *Portunus pelagicus* collected from study areas A, B and C from March 1999 to April 2000, in relation to temperature, salinity and water depth. Area A (•), area B (o) and area C (*).

6.3.4 Sex ratio

6.3.4.1 Number of individuals

6.3.4.1.1 Offshore fishing grounds

A total of 58,529 crabs (27,370 males and 31,159 females) was collected from the study areas from which the sex ratio was investigated. Of all the crabs caught, 62% of the males and 54% of the females were taken from area C.

The male:female ratios for the combined monthly samples of the northern fishing grounds were found to be significantly different from a population having a 1:1 sex ratio. In area A, males prevailed at 1.1:1 (goodness of fit $\chi^2 = 11.6$, $df = 1$, $p < 0.001$), whereas there was a preponderance of females in area B at 0.5:1 (goodness of fit $\chi^2 = 1407.7$, $df = 1$, $p < 0.001$). In contrast, the sex ratio of the southern fishing grounds (i.e. area C) was very close to parity (goodness of fit $\chi^2 = 0.04$, $df = 1$, $p = 0.842$). The monthly samples indicated that both genders were present in all fishing grounds throughout the year; however, seasonal, spatial and temporal variations in the sex ratio were detected (Table 6.7). For a better comparison between areas, the male:female sex ratios (M:F) are presented in Table 6.7 and are plotted as $\log_e$ ratio values over time in Fig. 6.11.

In area A, the sex ratio fluctuated between 0.5-1.6:1 (M:F). The May and December 1999 catches had more female crabs than males (0.54-0.61:1 M:F), whereas males predominated in July to September 1999 and March-April 2000. During the rest of the year the ratio remained very close to parity. In the deep waters of area B, there was a preponderance of females throughout the year (see Table 6.7). They dominated for ten consecutive months from March to December 1999 and also in February and April 2000. In area C, the pattern was similar to that recorded in area A. Males dominated in April 1999, August 1999 and March 2000, at 1.3:1, 1.2:1 and 1.3:1 (M:F) respectively, but female crabs predominated in March 1999, June-July 1999 and October-November 1999, which coincided with periods with high numbers of ovigerous females.

Table 6.7. Sex ratio (M:F) of *Portunus pelagicus* for catches in each monthly sample collected from the offshore fishing grounds from March 1999 to April 2000. Values of the χ^2 goodness of fit test to 1:1 ratio ($df = 1$) are given.

	Area A			Area B			Area C		
Month	n	M:F	χ^2	N	M:F	χ^2	n	M:F	χ^2
Mar-99	824	0.9	1.1	440	0.3	**148.9**	992	0.5	**95.6**
Apr-99	939	1.1	2.8	1020	0.3	**292.3**	2569	1.3	**52.4**
May-99	316	0.5	**28.0**	2501	0.4	**546.4**	3036	0.9	3.6
Jun-99	2063	0.9	1.8	1534	0.8	**18**	1683	0.9	**7.3**
Jul-99	1576	1.1	**6.1**	1335	0.9	**7.6**	1604	0.9	**4.2**
Aug-99	2596	1.2	**19.7**	1772	0.5	**182.1**	6001	1.2	**50.2**
Sep-99	1352	1.3	**26.7**	1841	0.5	**164.9**	5260	1.0	2.7
Oct-99	626	1.1	0.6	947	0.4	**145.3**	1938	0.9	**8.5**
Nov-99	293	1.2	2.1	649	0.4	**98.6**	1825	0.8	**33.4**
Dec-99	364	0.6	**21.3**	185	0.4	**39.1**	1851	0.9	**4.5**
Jan-00	529	0.9	1.8	130	0.7	3.7	1857	1.0	1.1
Feb-00	230	1.0	0.0	55	0.3	**13.3**	1706	1.1	3.4
Mar-00	245	1.3	**5.0**	10	0.4	1.6	980	1.3	**14.2**
Apr-00	139	1.6	**7.8**	118	0.2	**57.0**	2598	1.1	2.1

Bold χ^2 values indicate significant departure from the 1:1 ratio.

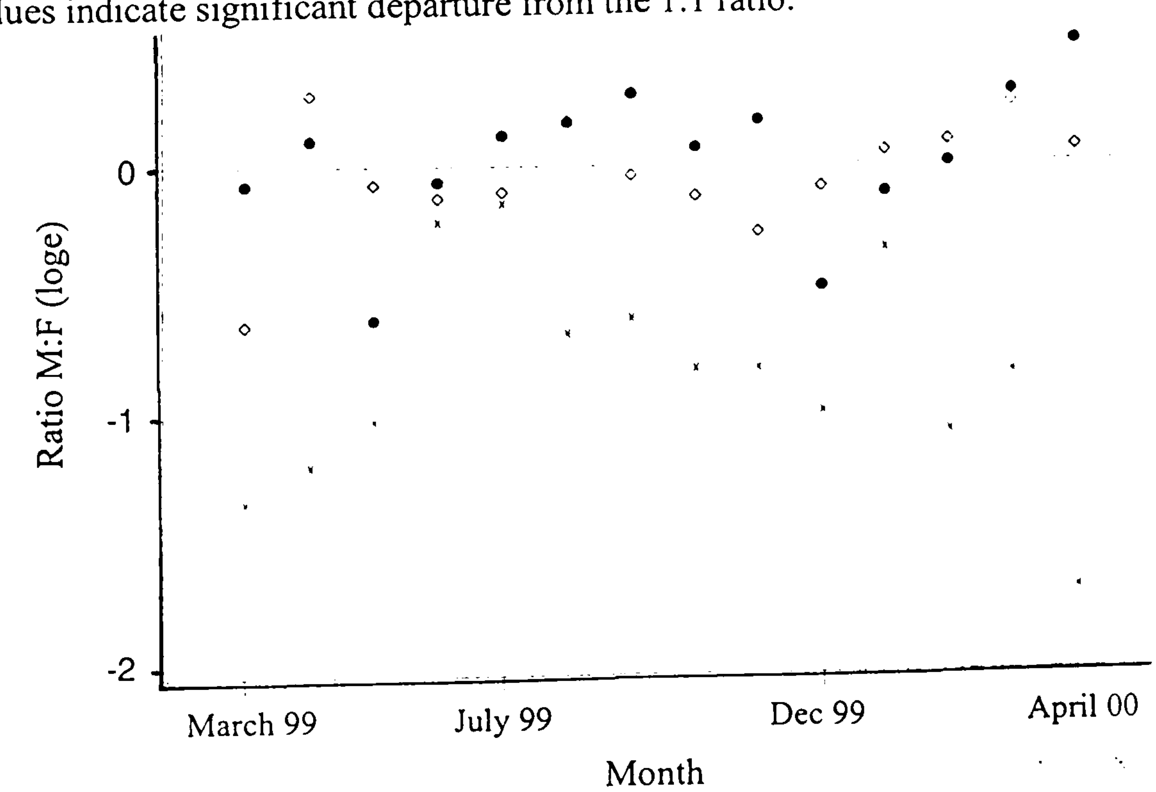


Figure 6.11. Monthly changes in the sex ratio (male:female) of *Portunus pelagicus* collected from the offshore fishing grounds from March 1999 to April 2000. Area A (•), area B (*) and area C (◊). Zero on $\log_e$ scale = 1:1 ratio.

6.3.4.1.2 Coastal fishing grounds

The population structure of crabs inhabiting coastal waters was likewise investigated in order to obtain a better understanding of the population dynamics of *P. pelagicus* of both offshore and inshore waters. A total of 2,957 male and 2,218 female crabs were caught inshore (Table 6.8).

Table 6.8. Total number of male and female *Portunus pelagicus* collected from the coastal fishing grounds from April 1999 to April 2000.

Fishing ground	Males	Females
Area D	742	587
Askar	519	128
Barbar	1,696	1,503

The overall sex ratio (M:F) was significantly dominated by male crabs at the three locations: area D at 1.3:1 (goodness of fit $\chi^2 = 18.1$, $df = 1$, $p < 0.001$), the Askar fishing grounds at 4.1:1 (goodness of fit $\chi^2 = 236.3$, $df = 1$, $p < 0.001$) and the Barbar fishing ground at 1.1:1 (goodness of fit $\chi^2 = 11.6$, $df = 1$, $p < 0.001$). For a clearer comparison between areas, sex ratios (M:F) that are presented in Table 6.9 are plotted in Fig. 6.12 as $\log_e$ (ratio) over time.

In area D off the western coast of Bahrain Island, and in the Askar fishing ground on the eastern coastline of Bahrain Island, significant departures from the 1:1 sex ratio were always due to the preponderance of males. At Askar, the number of males was greater than females in all available samples. In the Barbar fishing ground on the northern coastline of Bahrain Island, males dominated during April 1999, October-November 1999 and April 2000, whereas females dominated during January and February 2000.

Table 6.9. Sex ratio (M:F) of *Portunus pelagicus* for catches in each monthly sample collected from the coastal fishing grounds from April 1999 to April 2000. Values of the χ^2 goodness of fit test to 1:1 ratio ($df = 1$) are given.

Month	Area D			Askar fishing ground			Barbar fishing ground		
	n	M:F	χ^2	N	M:F	χ^2	*n*	M:F	χ^2
Apr-99	53	1.2	0.5	112	2.5	**20.6**	53	1.9	**5.5**
May-99	250	0.9	0.8	129	3.2	**34.8**	237	1.0	0.0
Jun-99	350	1.0	0.2	N/A	-	-	207	0.8	1.7
Jul-99	10	0.7	0.4	41	4.9	**17.8**	495	1.1	2.2
Aug-99	170	2.0	**19.8**	73	3.9	**25.3**	366	1.1	1.6
Sep-99	178	2.1	**23.0**	92	2.5	**17.4**	226	1.3	3.5
Oct-99	40	1.9	3.6	110	6.9	**61.1**	112	3.0	**28.0**
Nov-99	63	1.5	2.7	90	29.0	**78.4**	313	1.5	**14.3**
Dec-99	N/A	-	-	N/A	-	-	131	0.9	0.4
Jan-00	142	1.4	**4.1**	N/A	-	-	236	0.6	**11.5**
Feb-00	58	1.1	0.1	N/A	-	-	229	0.7	**6.0**
Mar-00	15	1.1	0.1	N/A	-	-	397	1.2	2.7
Apr-00	N/A	-	-	N/A	-	-	197	1.7	**14.3**

Bold χ^2 values indicate significant departure from the 1:1 ratio.

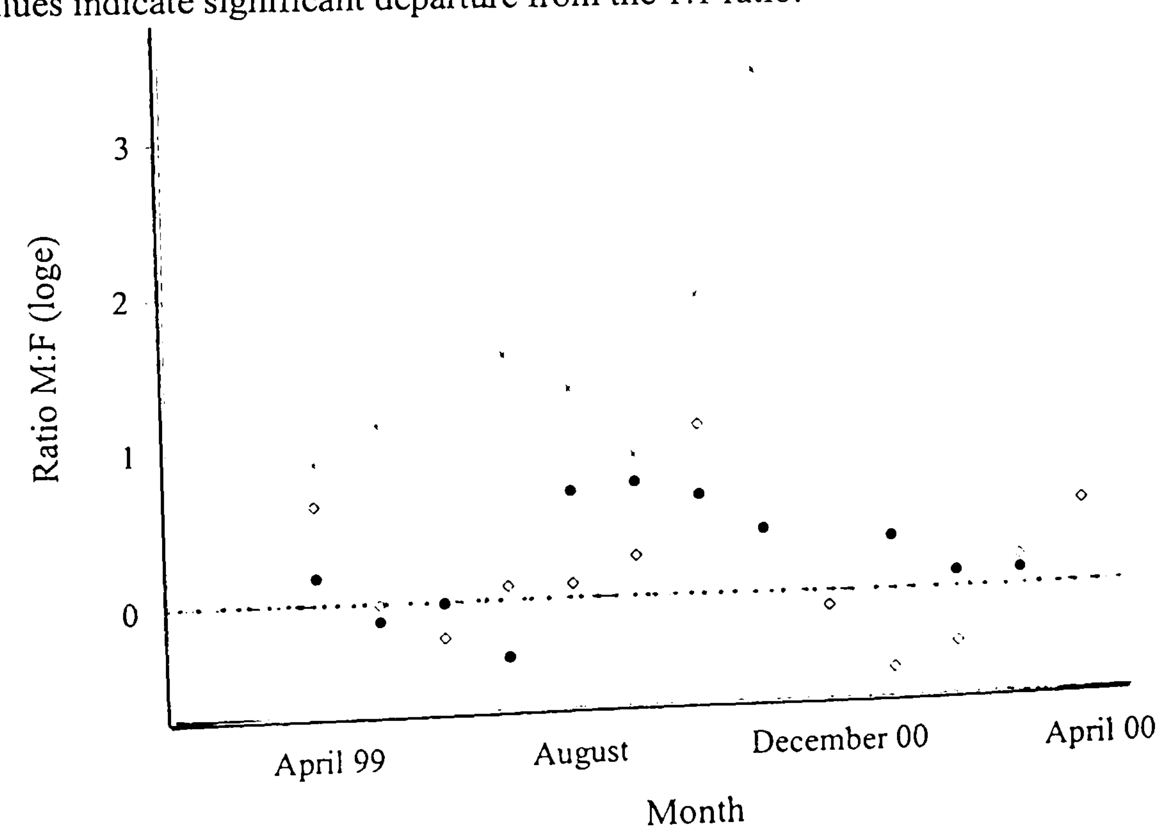


Figure 6.12. Monthly changes in the sex ratio (male:female) of *Portunus pelagicus* collected from the coastal fishing grounds from March 1999 to April 2000. Area D (•), Askar (*) and Barbar (◊). Zero on $\log_e$ scale = 1:1 ratio.

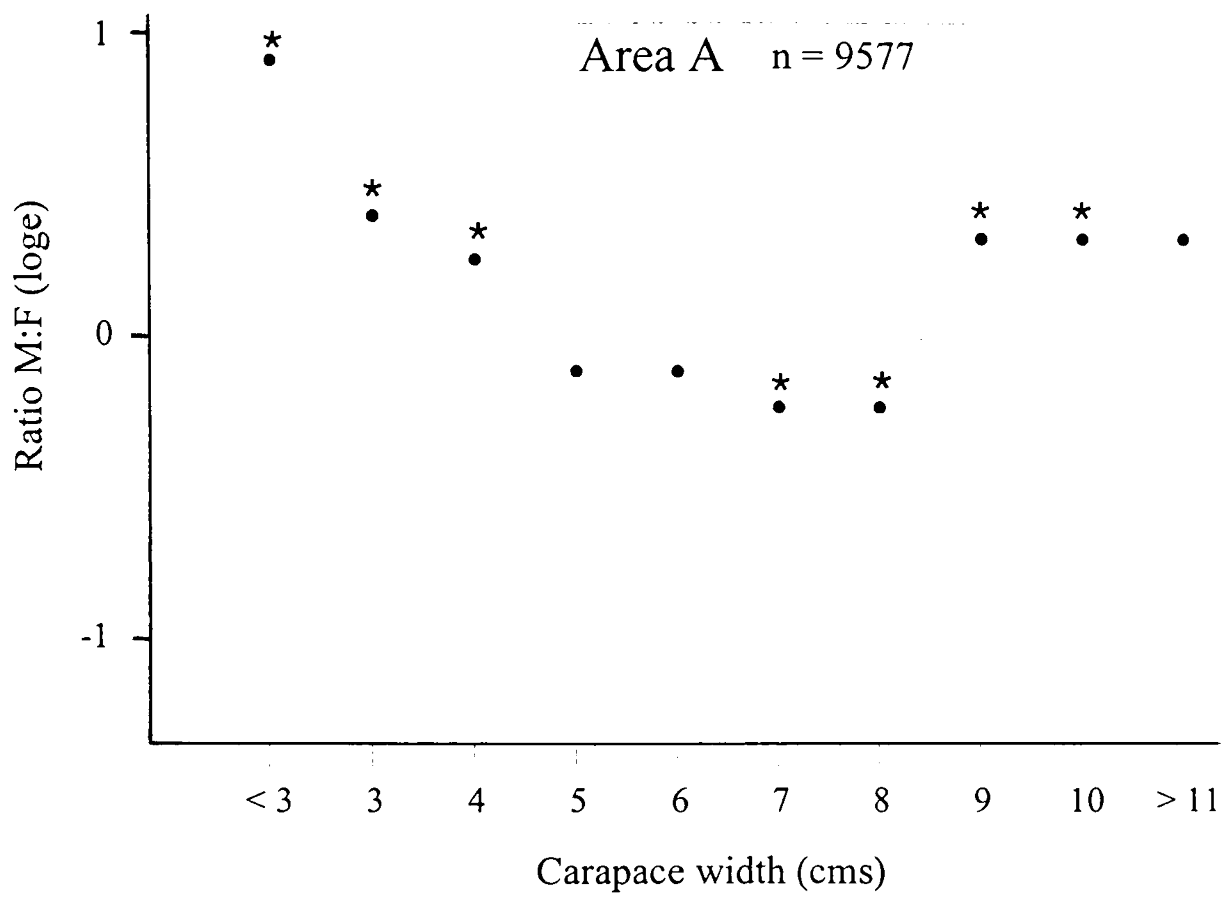
The inferred migration of female crabs from inshore to offshore waters leads to females being relatively more abundant in areas A and B than the Barbar coastal area. This migration pattern is clearer in the southern fishing grounds between Askar and area C where at times of high M:F ratio at Askar (e.g. July-November 1999) the ratio in area C was generally low. However, variability in the sex ratio was much greater for the inshore areas (see Fig. 6.12) where very few large, mature crabs of either gender were captured.

6.3.4.2 Size class analysis

6.3.4.2.1 Offshore fishing grounds

The analysis of the sex ratios for different size classes (combined annual data) indicated that sex ratios varied greatly between size classes in all fishing grounds. Sex ratio values presented hereafter are expressed as $\log_e$ values for comparison.

In area A (Fig. 6.13), the ratio fluctuated across the size classes. Males dominated size classes less than 5 cms CW with sex ratios from 0.26-0.92:0 (M:F), while female crabs dominated the small size classes (7-8 cms CW) at a –0.22:0 (M:F) ratio. Males predominated in the larger size classes, 9-10 cms CW, where the ratio was 0.34:0 (M:F). In area B (Fig. 6.13), female crabs outnumbered males in almost all size classes from 6 to10 cms CW at ratios between –0.92:0 to –0.22:0 (M:F). The preponderance of females over males in the deep water is reflected in the very high incidence of ovigerous females in the area. In area C (Fig. 6.13), the sex ratios across the CW size ranges were generally close to parity. However, males dominated at < 3 cms CW with a sex ratio at 0.59:0 (M:F) and in size class 7 cms CW females dominated with a sex ratio of –0.22:0 (M:F).



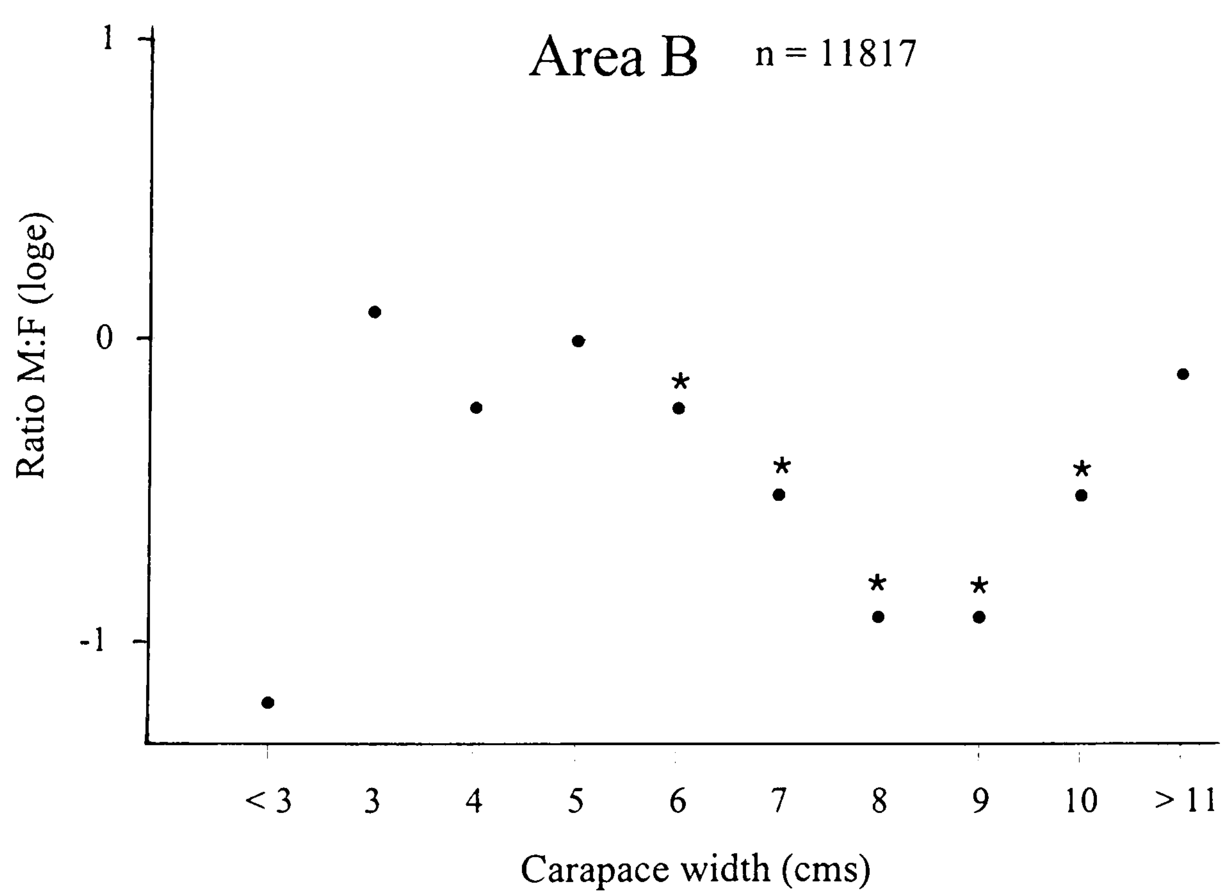


Figure 6.13. Continued

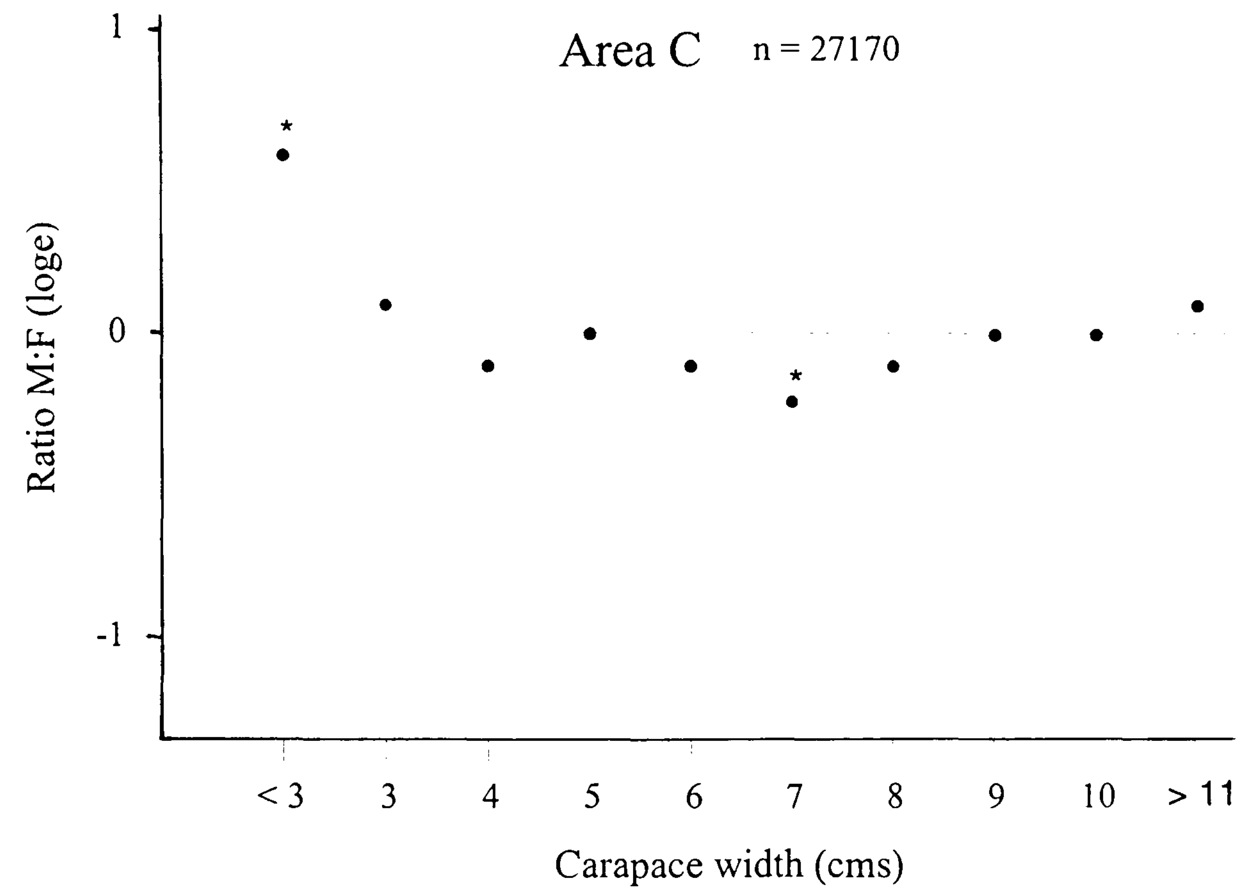


Figure 6.13. Variation in sex ratio with size classes of *Portunus pelagicus* collected from the offshore fishing grounds from March 1999 to April 2000. Ratios are plotted as $\log_e$ for clearer comparison between areas. Total numbers of males and females are given for each area. * denotes a significant difference from the 1:1 ratio.

6.3.4.2.2 Coastal fishing grounds

The preponderance of male crabs in the coastal fishing areas was very obvious, since in all size groups where sex ratios departed significantly from parity, male crabs outnumbered females. In area D (Fig. 6.14), males dominated in the < 7 cms CW size classes and in size classes 8-9 cms CW. Crabs in the 7 cms CW size class were close to parity. In Askar coastal area (Fig. 6.14), males dominated size classes > 7 cms CW and Fig. 6.12 confirms that males mainly inhabit this coastal area. However, data obtained are not adequate to be confident of the population dynamics at this coastal area. In the Barbar coastal area (Fig. 6.14), male crabs predominated size classes 8-9 cms CW, while in all other size classes the sex ratio was close to parity.

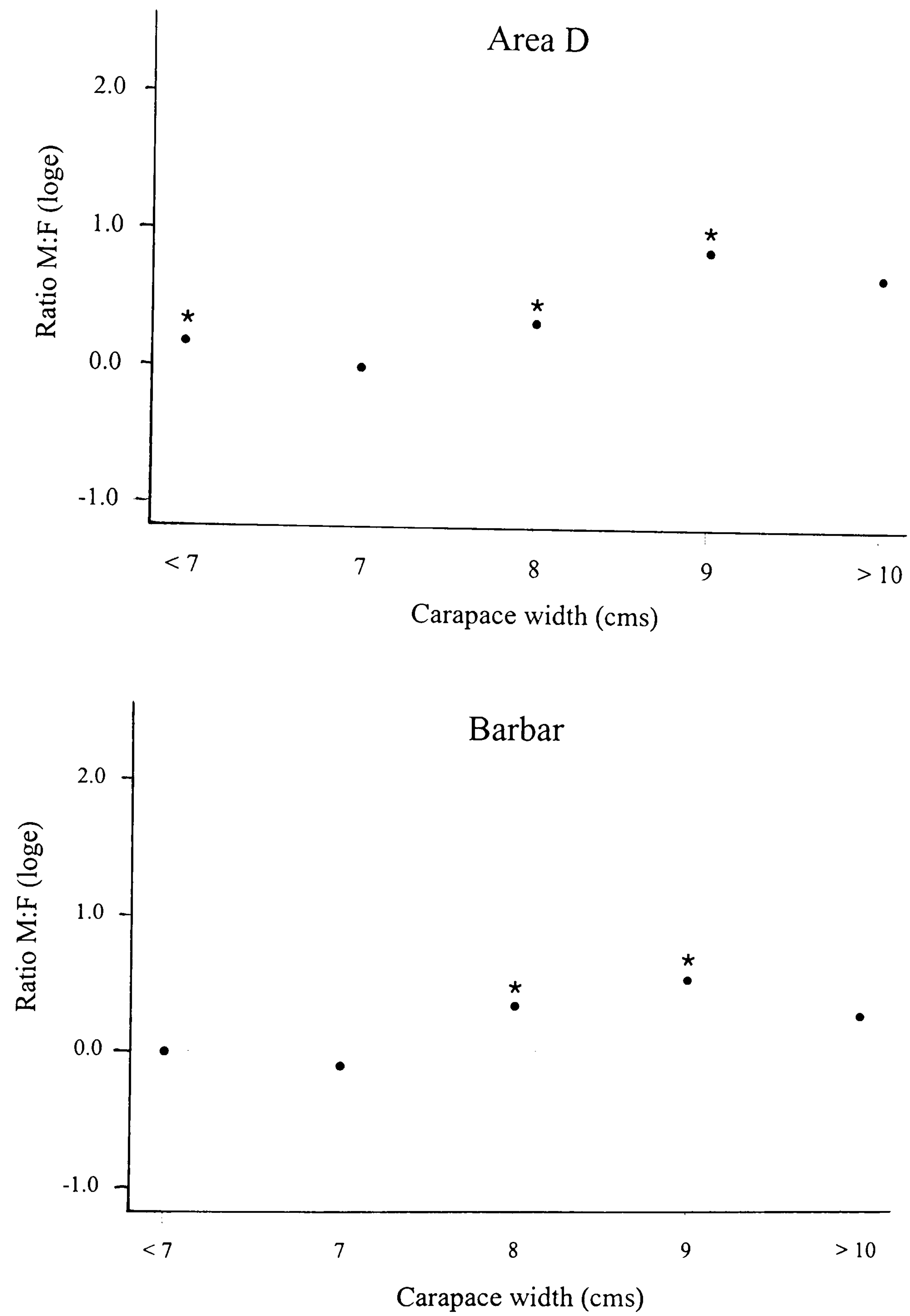


Figure 6.14. Continued

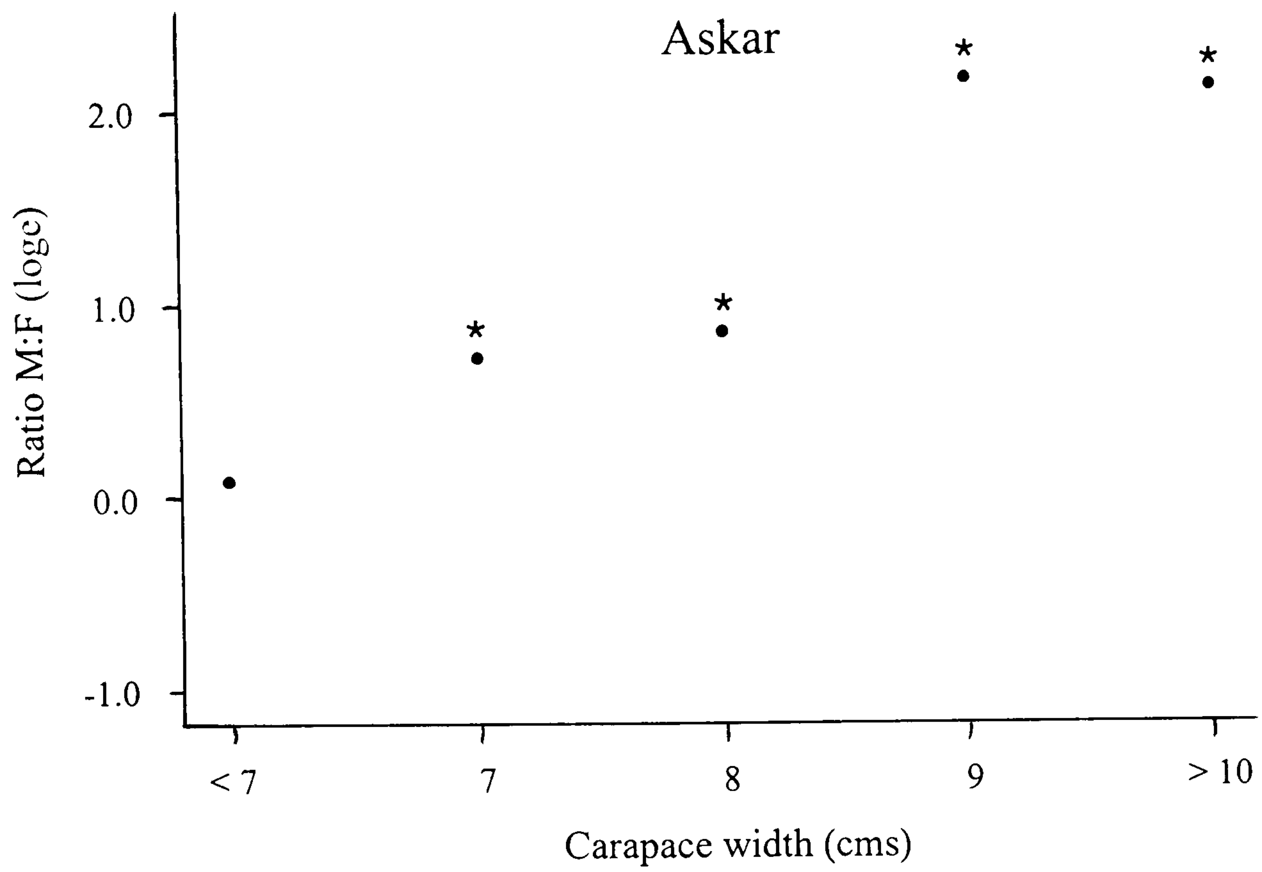


Figure 6.14. Variation in sex ratio with size classes of *Portunus pelagicus* collected from the coastal fishing grounds from March 1999 to April 2000. Ratios are plotted as $\log_e$ for clearer comparison between areas. Total numbers of males and females are given for each area. * denotes a significant difference from the 1:1 sex ratio.

6.3.5 Population size structure

24,975 male and 28,750 female *P. pelagicus* were collected from the study areas (offshore, and inshore fishing grounds). The male crabs ranged from 1.8 to 14.5 cms CW, and females ranged from 1.1 to 15.8 cms CW. For both genders, CW was greatest for the offshore crabs (see Table 6.10). However the shrimp trawl net is likely not to be 100% efficient for catching crabs with their swimming ability allowing some to escape from the path of the trawl. However, the presence of crabs less than 3.8 cms CW in the catch (mesh size of belly and codend of the trawl net was 3.8 cms) indicates that once they were within the confines of the trawl, the fishing gear retained even small crabs with CW as low as 1.1 cms.

Table 6.10. Total number, size range and mean carapace width of male and female *Portunus pelagicus* collected from the study area from March 1999 to April 2000.

Fishing ground	Males			Females		
	n	Size range (cms)	Mean ± SD	*n*	Size range (cms)	Mean ± SD
Area A	4,844	2.3-11.8	7.0 ± 2.1	4,733	1.9-11.7	7.1 ± 1.9
Area B	3,808	3.0-12.4	8.9 ± 1.4	8,009	1.1-15.8	9.0 ± 1.2
Area C	13,380	1.8-14.5	6.2 ± 1.9	13,790	1.3-11.7	6.4 ± 1.9
Area D	732	2.2-11.5	6.4 ± 2.2	587	2.2-10.9	6.3 ± 2.0
Barbar	1,692	3.3-11.5	7.3 ± 1.5	1,503	2.3-11.4	7.1 ± 1.4
Askar	519	3.6-11.6	9.2 ± 1.2	128	4.8-10.5	8.4 ± 1.2

6.3.5.1 Offshore fishing grounds

Size frequency distributions (SFDs) of CW for both genders that were collected from the offshore fishing grounds at regular monthly intervals from March 1999 through to April 2000, are illustrated in Figs. 6.16 (area A), 6.17 (area B) and 6.18 (area C). Such presented data immediately revealed the existence of spatial and temporal variability in the population structure of *P. pelagicus* around Bahrain. The shape of the frequency histograms for males and females in all the study areas were generally identical, differing only in relative numbers of either gender. It is important to note that *P. pelagicus* was under no fishing pressure from April to July 1999, since the annual closed season for the shrimp fishery in the territorial waters of Bahrain was in effect. Thus, changes in abundance from one month to another during this period are due to a combination of movements of crabs in and out of the fishing grounds and mortality.

6.3.5.1.1 Growth

6.3.5.1.1.1 Modal progression analysis

Cohort means obtained by the Bhattacharya's method for each SFD from the offshore fishing grounds were plotted on their relevant SFDs and linked as they progressed in time, which has provided modal groups (MGs) for each data set. A MG is defined in the present study as an identifiable size group that can be coherently followed as its members increase in size over 4 consecutive months or more. MGs illustrated in Figs. 6.16, 6.17 and 6.18 will also represent the growth rates of *P. pelagicus*.

6.3.5.1.1.1.1 Area A

The crabs from area A showed both males and females to cover a wide size range, 2-12 cms CW with no dominant size intervals (Fig. 6.15, area A). In area A (Fig. 6.16), thirteen MGs were observed for male crabs, out of which MG numbers 1, 7, 8, and 10 could be traced for 4-6 consecutive months (Fig. 6.16, males). March 1999 samples consisted of 3 modes at 4.6 ± 0.7, 6.6 ± 0.7 and 8.5 ± 0.5 cms CW, i.e. MGs 1, 2 and 3 respectively. Mean size of cohort MG 1 at 4.6 ± 0.7 cms CW in March 1999 had moved to 5.9 ± 1.0 cms CW in the following month, and continued increasing until the crabs achieved a CW of 9.6 ± 0.6 cms in August, equivalent to a growth rate of 1 ± 0.5 cms CW month^{-1} at 28 ± 2 °C. MG 7 was first observed in July at 6.8 ± 0.5 cms CW and in the following months the cohort grew rapidly and reached 11 ± 0.5 cms CW by November, equivalent to a growth rate of 1.1 ± 0.4 cms CW month^{-1} at 32 ± 0.8 °C. The 8th MG was first recorded at 4.0 ± 0.4 cms CW in August, after which the crabs exhibited rapid growth reaching 10.9 ± 0.5 cms CW by January 2000 equivalent to a growth rate of 1.4 ± 0.5 cms CW month^{-1} at 27 ± 3.4 °C. Similarly, MG 10 was first observed at 4.0 ± 0.6 cms CW in October, reaching 10.2 ± 0.5 cms CW over the following six months equivalent to a growth rate of 1 ± 0.4 cms CW month^{-1} at 22 ± 2.5 °C. MGs that were traced for less than four months are presented in Table 6.11.

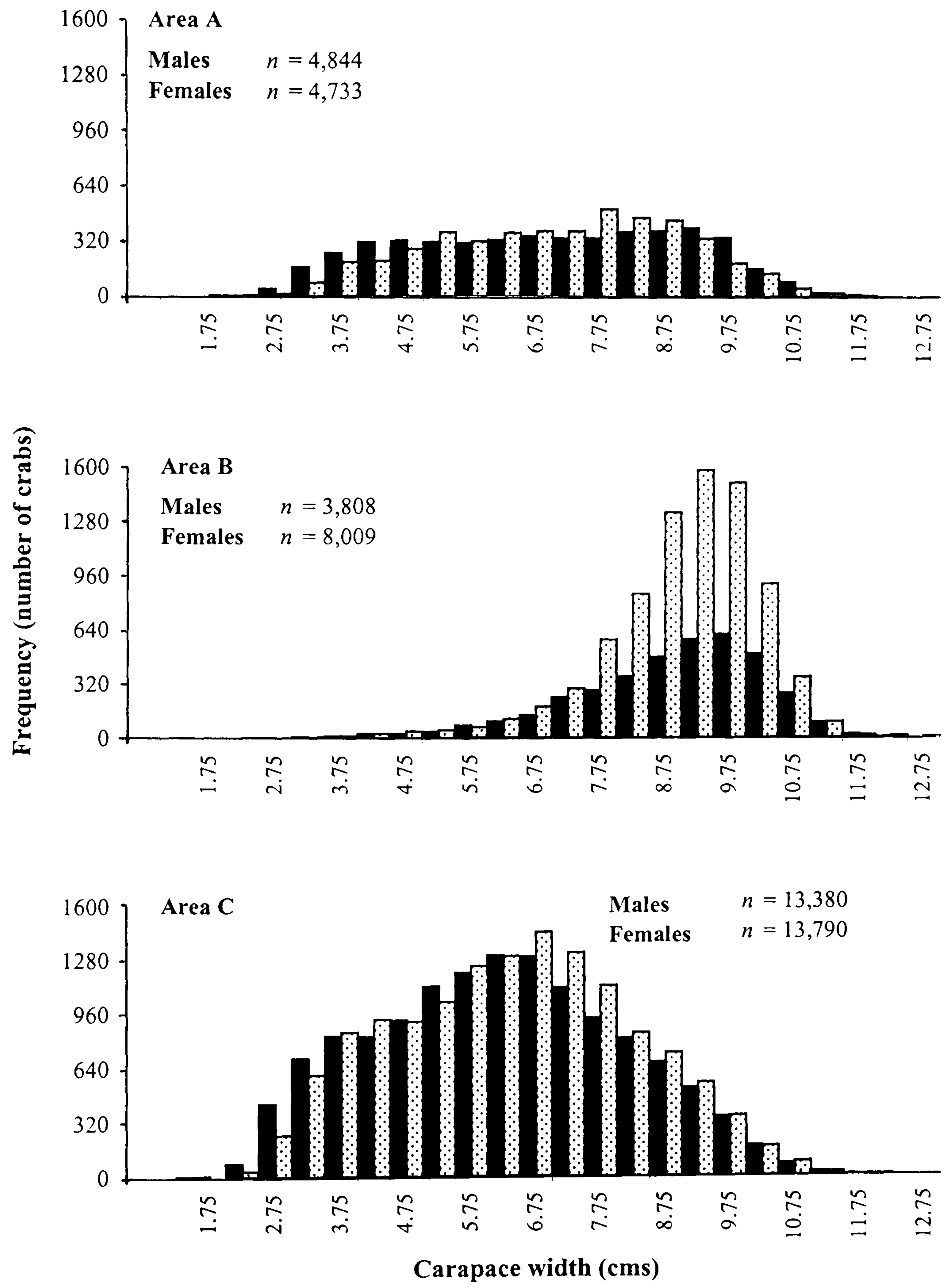


Figure 6.15. Size frequency distributions for all the *Portunus pelagicus* collected from offshore fishing grounds off Bahrain from March 1999 to April 2000. Males (dark bars), females (dotted bars).

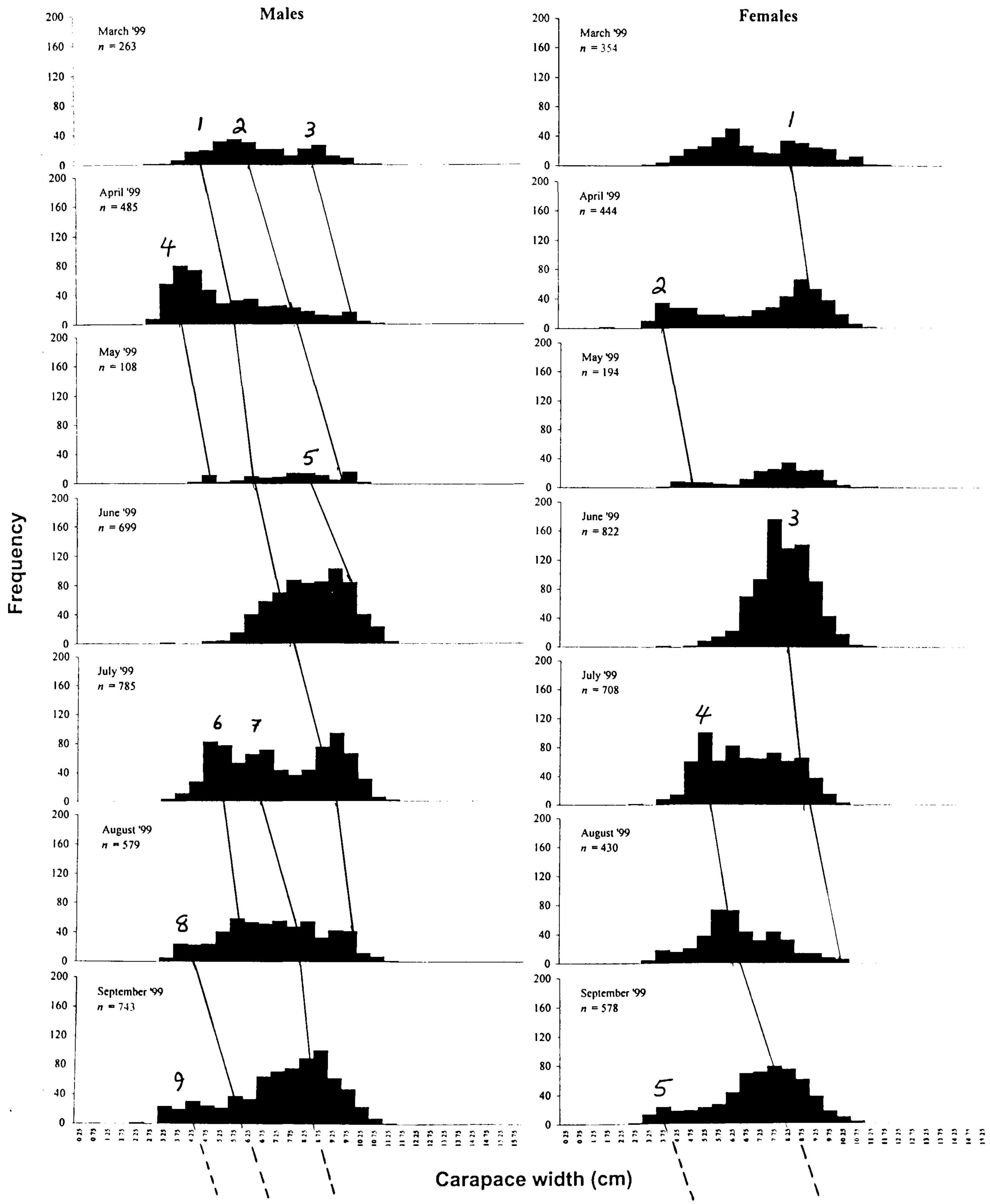


Figure 6.16. Continued

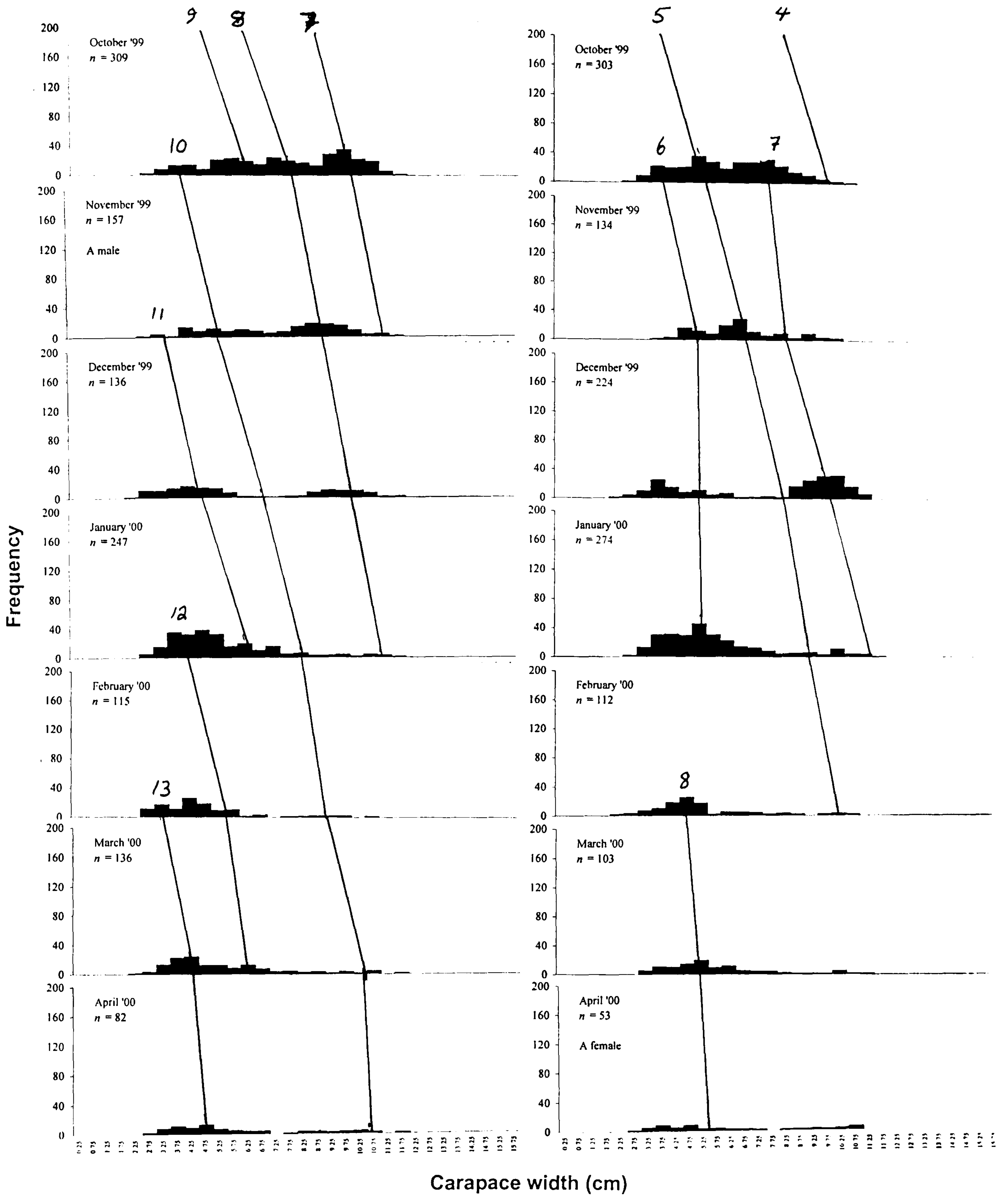


Figure 6.16. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from area A from March 1999 to April 2000. Numbers of crabs caught each month are also given. Growth curves were plotted using cohorts obtained by Battacharya's method.

Table 6.11. Modal groups of male and female *Portunus pelagicus* (see Fig. 6.16) that were traced for less than four months in area A and their equivalent growth rates.

Gender	Carapace width range (cms)	Modal group	Months	Rate of growth month^{-1} Mean ± SE (cms)	Temperature Mean ± SE °C
Males	8.5-9.7	1	Mar-Apr 99	1.2	22 ± 1
	6.6-9.5	2	Mar-May 99	1.5 ± 0.1	24 ± 1.8
	3.9-4.8	4	Apr-May 99	0.9	25 ± 2
	8.2-9.6	5	May-June 99	1.4	30 ± 2.5
	5.2-5.9	6	July-Aug 99	0.7	32 ± 0
	4.3-5.8	9	Sept-Oct 99	1.5	34 ± 1
	3.3-6.2	11	Nov 99-Jan 00	1.4 ± 0.4	21 ± 4.5
	4-6.2	12	Jan-Mar 00	1.1 ± 0.4	18 ± 0.6
	3.3-4	13	Feb-Mar 00	1.3	19 ± 0.5
Females	8.3-9	1	Mar-Apr 99	0.7	22 ± 1
	3.9-4.5	2	Apr-May 99	0.6	25 ± 2
	7.9-9.7	3	June-Aug 99	0.9 ± 0.3	32 ± 0
	4.7-5.5	8	Feb-Apr 00	0.4 ± 0	20 ± 1

Female *P. pelagicus* in area A also exhibited a similar growth pattern, however, cohorts that were observed in March 1999 could not be traced after May 1999 (Fig. 6.16, females). It is obvious that MGs 4-7 progressed from summer to winter (July 1999-February 2000) with a high mean growth rate of 1.3-2.7 cms CW month^{-1}. The highest growth rate for females in area A was found to be 1.6 ± 0.1 cms CW month^{-1} as exhibited by MG 4 which coincided with the ambient temperature of 34 ± 0.1 °C. MG 4 started at 5.3 ± 0.51 cms CW in July and had shifted to 6 ± 0.6 cms CW in August with a growth increment of 1.3 cms CW at 32 °C. In the following 2 months growth was at 1.7 cms CW month^{-1} with the rise in temperature to 33 °C. The average rate of growth for the female cohorts was found to be 1.6 ± 0.1 cms month^{-1} at 34 ± 1 °C. MG 5 was first recorded at 3.8 ± 0.4 cms CW in September. This cohort had moved to 5.4 ± 0.5 cms CW in October, to 6.6 ± 0.5 cms CW in November and then increased rapidly reaching 10.3 ± 0.5 cms CW in February 2000, with a mean growth rate of 1.3 ± 0.1 cms CW month^{-1} at 25 ± 3.6 °C. The cohort of MG 6 grew from 7.6 ± 0.73 cms CW in October to 11.0 ± 0.42 cms CW in January 2000, with growth increments of 0.6, 1.6 and 1.2 cms CW in each moult respectively, equivalent to a mean growth rate of 1.1 ± 0.5 cms CW month^{-1} at 24 ± 4.4 °C. MG 6 at 3.9 ± 0.5 cms CW in October shifted to 4.9 cms CW in the following month (a growth increment of 1 cm at 32 ± 1.5 °C). Nevertheless, during the following months (December 1999-January 2000) growth was restrained to a 0.1 cm CW increment that coincided with low ambient temperatures of 17 ± 0.5 °C, giving an overall growth rate of 0.5 ± 0.3 cm CW month^{-1} at 24 ± 4.4 °C. Growth increments exhibited by crabs smaller than 6 cms CW (MG 6) were lower than those achieved by crabs bigger than 7 cms CW (MG 7), as well as MG 5 that occurred a month earlier, although all three experienced the same temperature range (35-17 °C). Influence of temperature on the growth of the crabs was apparent, where increments declined from 1.0 cm CW (October-November 32 ± 1.5 °C) to 0.3 cm CW (November-December 23 ± 7 °C) and further to 0.1 cm CW (December-January 17 ± 0.5 °C). Data for MGs 1-3 and 8 are presented in Table 6.11.

The high number of male and female crabs in June 1999 as opposed to the previous month when very few were captured, signifies migration into this area. Similarly, male crabs at the mid-point of cohorts 3.75 and 4.75 cms CW that occurred in April and July 1999, female crabs at the mid-point of size class 5.25 cms CW in July 1999, as well as female crabs of cohort at mid-point 3.75 cms CW in December 1999, clearly show migration in. Growth curves for both genders, the major MGs in particular, are found to be similar showing that crabs in all cohorts grow at equivalent rates.

6.3.5.1.1.1.2 Area B

In contrast to the *P. pelagicus* populations in area A crabs in area B demonstrated a skewed size distribution. Overall, crabs ranged from 1.0 to 12.5 cms CW with only one female at the mid-point size class 15.75 cms CW and only one mode for males and females at the mid-point size classes 9.75 and 9.25 cms CW respectively (Fig. 6.15, area B).

In contrast to crabs in area A, data obtained suggest that male and female *P. pelagicus* in area B did not exhibit much growth, where only one major MG was traced for either gender (Fig. 6.18). MG 1 for male crabs was traced from March 1999 through to October. It was first recorded at 5.8 ± 0.3 cms CW and exhibited growth during the following two months with a mean rate of 1.4 ± 0.1 cms CW $month^{-1}$ at 24 ± 1.8 °C. However, after May through to October, growth decreased to only 0.3 ± 0.1 cms CW $month^{-1}$ even at the ambient temperature of 31 ± 1.1 °C. The overall mean growth for this MG was found to be 0.6 ± 0.2 cms CW $month^{-1}$ at 29 ± 1.8 °C. The discontinuity of young crab MGs suggests that these crabs occur in area B for just a short period (Table 6.12).

Table 6.12. Modal groups of male and female *Portunus pelagicus* (see Fig. 6.17) that were traced for less than four months in area B, from March 1999 to April 2000.

Gender	Carapace width range (cms)	Modal group	Months	Growth rate $month^{-1}$ Mean ± SE (cms)	Temperature Mean ± SE °C
Males	7.3-8.6	2	Mar-Apr 99	1.3	22 ± 1
	9.2-10.5	3	Mar-Apr 99	1.3	22 ± 1

For female crabs, the single major MG which was traced over a period of 10 consecutive months (March-September 1999) remained at the mid-point of cohort 9.5 cms CW throughout (Fig. 6.17, females), which indicated that female *P. pelagicus* of this size do not grow in area B.

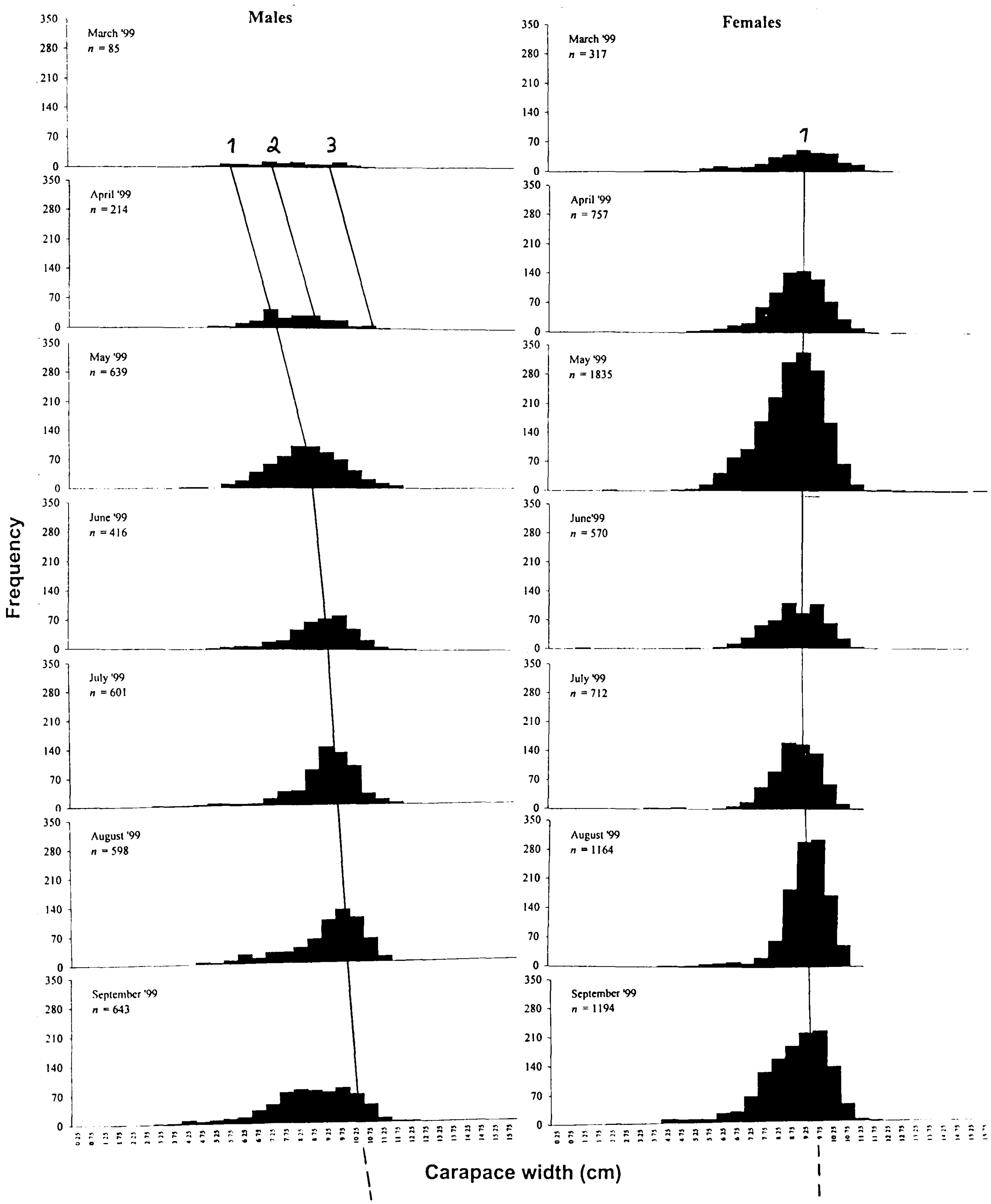


Figure 6.17. Continued

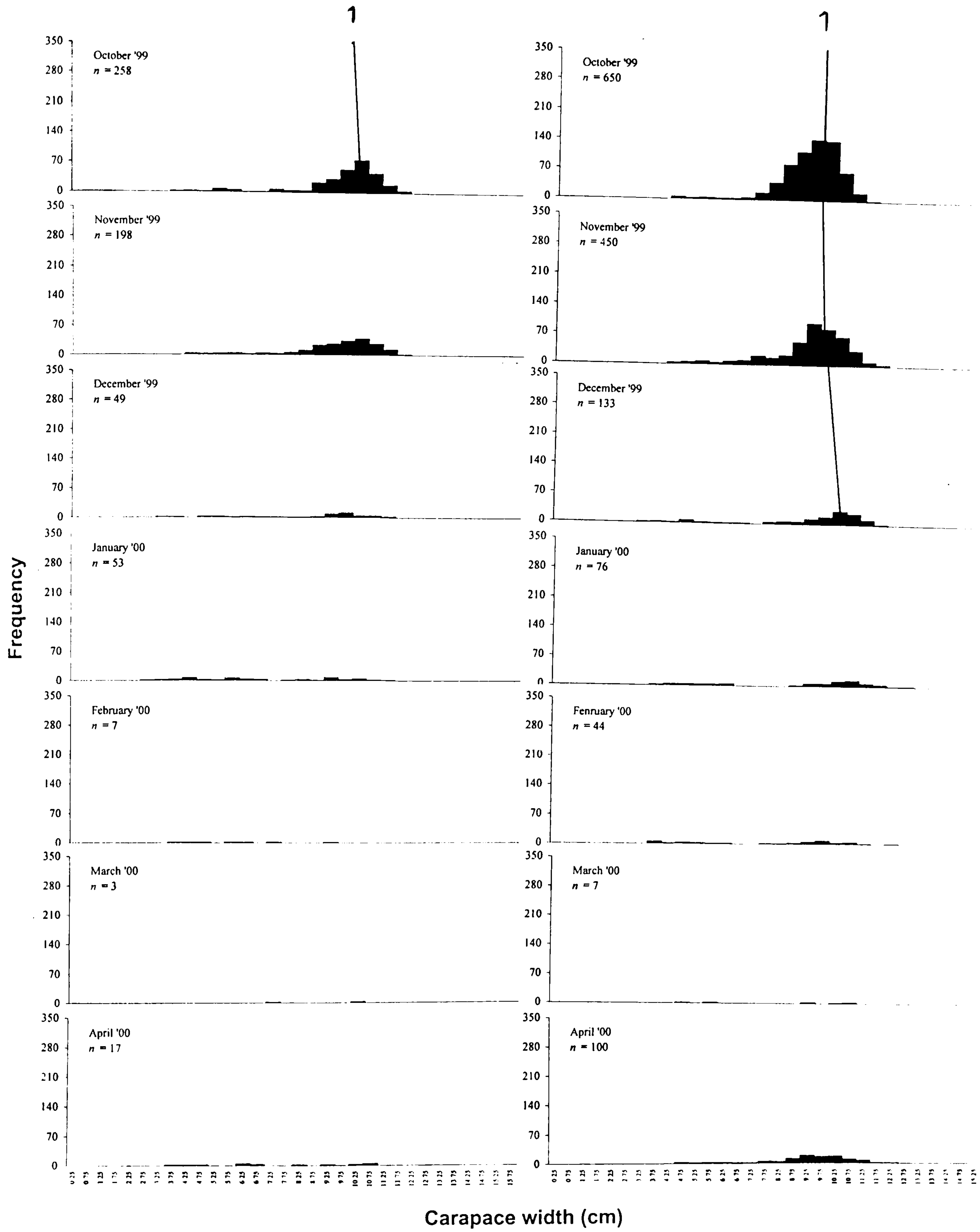


Figure 6.17. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from area B from March 1999 to April 2000. Numbers of crabs caught each month are also given. Growth curves were plotted using cohorts obtained by Battacharya's method.

6.3.5.1.1.1.3 Area C

SFDs for male and female crabs in area C (Fig. 9.19) are very similar to those seen in area A, in terms of temporal variation in crab size classes, although the cohorts in area C were more distinct throughout (compare Fig. 6.16 with Fig. 6.18).

A total of seven MGs were identified for male crabs, however, MG 1 was the only one that could be traced over a period of 7 consecutive months (March-September 1999) (Fig. 6.18, males). MGs 3 and 5 could only be traced for 3 months. MG 1 was first observed at 5.2 ± 0.4 cms CW in March 1999, grew steadily during the following months until September when the crabs had reached 9.4 ± 0.8 cms CW giving a mean growth rate of 0.7 ± 0.4 cms CW month^{-1} at 29 ± 2 °C. MG 3 occurred in July at 3.7 ± 0.4 cms CW and had grown to 6.2 ± 0.5 cms CW in August and to 7.2 ± 1.0 cms CW in September, an overall growth rate of 1.8 ± 1.1 cms CW month^{-1} at 33 ± 1 °C. MG 5 was first recorded in November at 5.8 ± 0.6 cms CW. The crabs grew very quickly to 8.4 ± 0.8 cms CW by December and reached 9.8 ± 0.4 cms CW by January 2000, giving a mean growth rate of 2.0 ± 0.9 cms CW month^{-1} at 21 ± 5 °C. Details of MGs 2-7 are presented in Table 6.13.

Table 6.13. Modal groups of male and female *Portunus pelagicus* (see Fig. 6.18) that were traced for less than four months in area C, from March 1999 to April 2000.

Gender	Carapace width range (cms)	Modal group	Months	Growth rate month^{-1} Mean ± SE (cms)	Temperature Mean ± SE °C
Males	8.8-9.8	2	March-April 99	0.7	22 ± 1
	3.7-7.2	3	July-Sept 99	1.8 ± 0.6	33 ± 0.8
	7.2-8.5	4	Oct-Nov 99	1.3	32 ± 1.5
	5.8-9.8	5	Nov 99-Janu 00	2 ± 0.6	20 ± 3.5
	3.2-4.1	6	Jan-Feb 00	0.9	18 ± 0.5
	3.75-5.25	7	Mar-Apr 00	1.5	21 ± 2
Females	4.2-4.9	5	Dec 99-Jan 00	0.7	17 ± 0.5
	3.4-4.2	6	Jan-Feb 00	0.8	18 ± 0.5
	4-5.4	7	Mar-Apr 00	1.4	21 ± 2

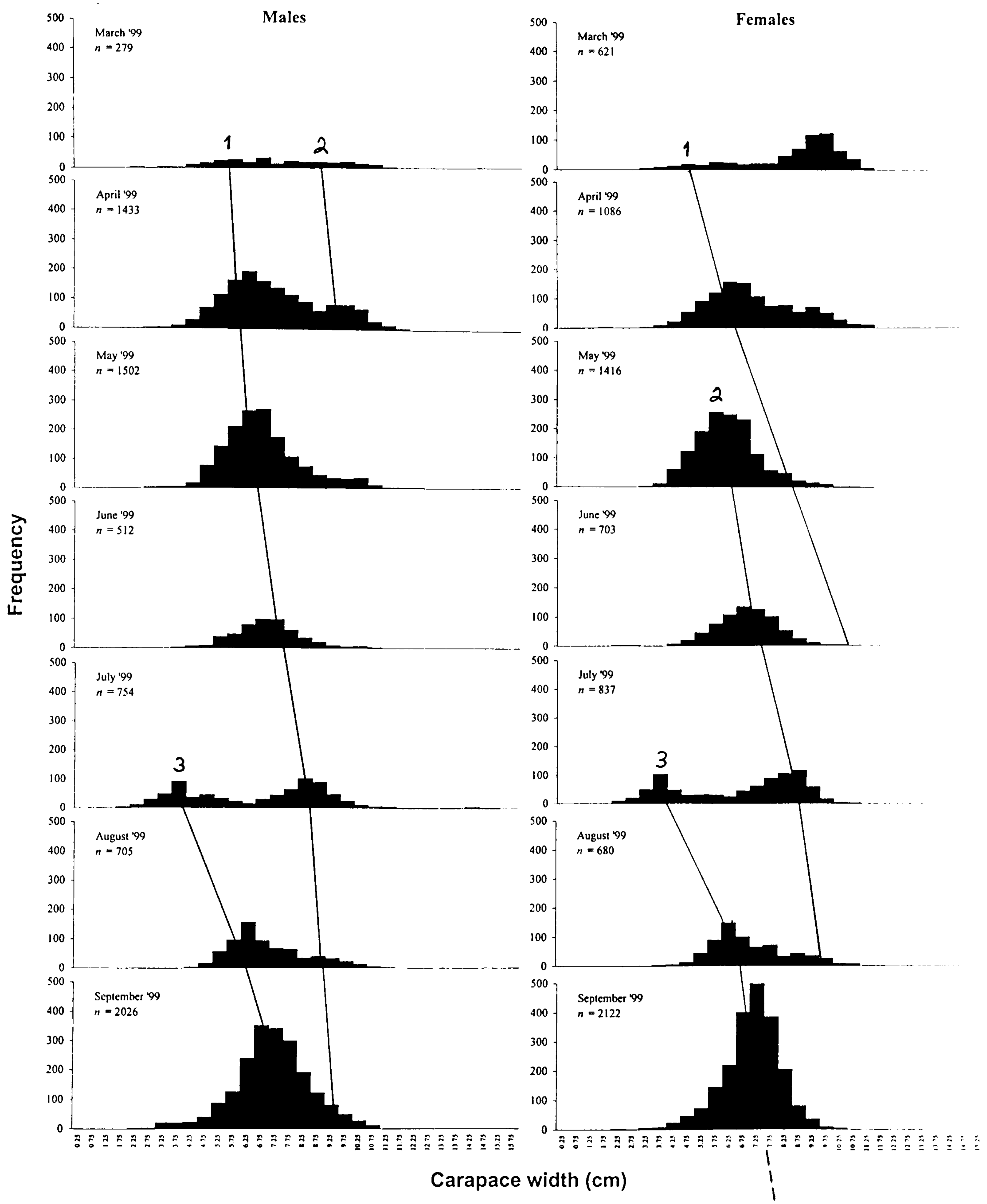


Figure 6.18. Continued

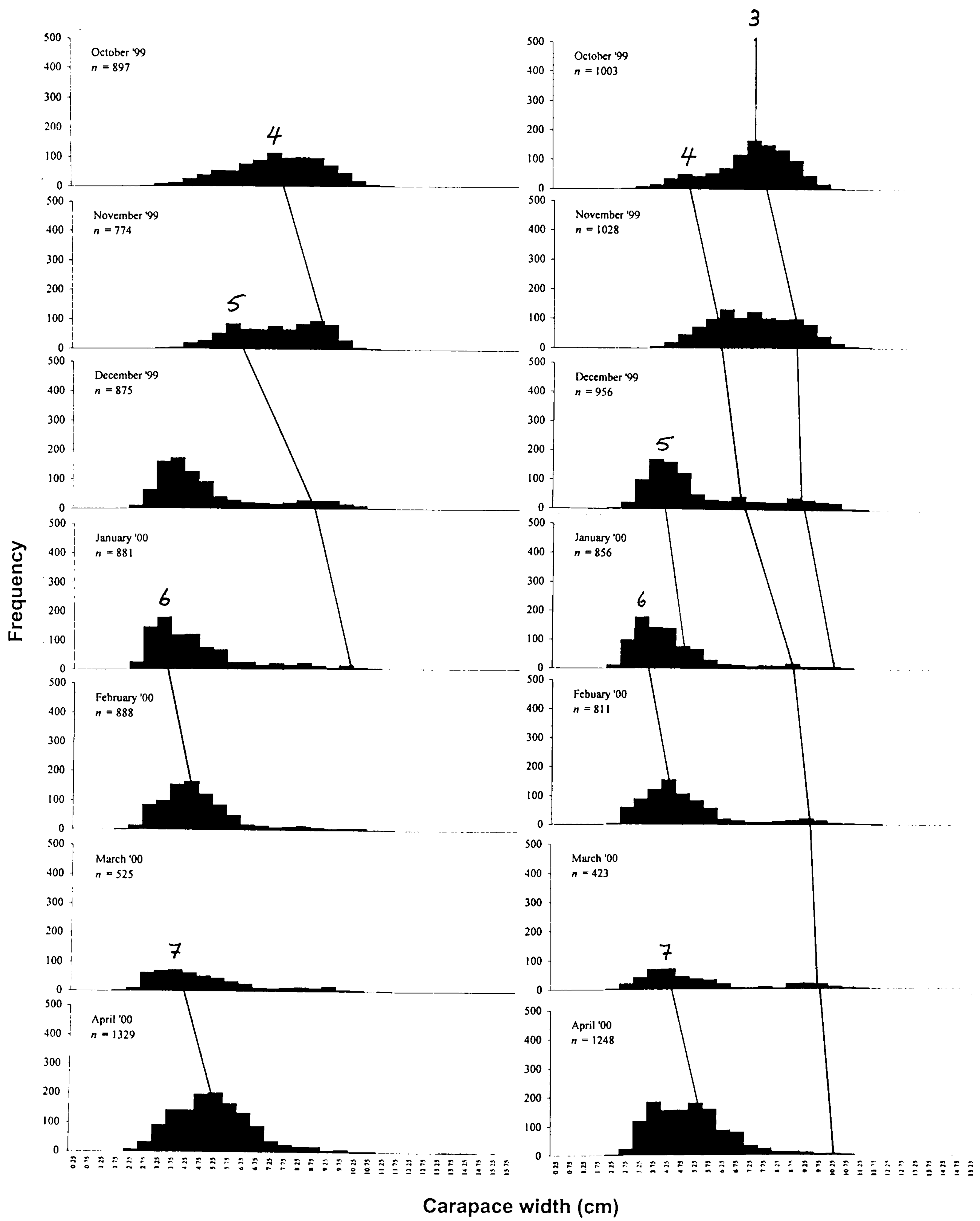


Figure 6.18. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from area C from March 1999 to April 2000. Numbers of crabs caught each month are also given. Growth curves were plotted using cohorts obtained by Battacharya's method.

For female crabs seven MGs could be identified, out of which MGs 1, 2, 3 and 4, were traced for 4, 4, 7 and 7 months respectively. Crabs Sampled in March 1999 consisted of two cohorts at mid-points of 4.8 ± 0.7 cms and 9.5 ± 0.7 cms CW. The 4.8 ± 0.7 cms CW cohort reached 10.4 ± 0.2 cms CW in June, with an average growth rate of 1.9 ± 0.4 cms CW month^{-1} at 26 ± 2.4 °C. MG 2 was traced from May to August as crabs grew from 6.0 ± 1.0 to 9.3 ± 0.5 cms CW respectively, a growth rate of 1.1 ± 0.4 cms CW month^{-1} at 31 ± 2.5 °C. The 3rd MG, traced for 7 consecutive months was observed initially at 5.5 ± 1.1 cms CW in July reaching 10.1 ± 0.51 cms CW in January 2000, a mean growth rate of 0.8 ± 0.2 cms CW month^{-1} at 28 ± 3 °C. Growth increments for crabs belonging to MG 4 fluctuated over time. The first cohort occurred at 4.9 ± 0.7 cms CW in October, grew to 6.3 ± 0.7 cms CW in November, with growth increment of 1.4 cms CW month^{-1} at 32 ± 1.5 °C. However, the growth increment declined in the following month to as low as 0.5 cm CW coincident with a drop in ambient temperature down to 17 ± 0.5 °C. Female *P. pelagicus* exhibited rapid growth in January, as high as 8.7 cms CW, with growth increment of 1.9 cms CW from the previous month, despite low temperature (17 °C). Females grew slightly to 9.2 cms CW in February 2000 where their cohort remained at this size through to March 2000 (19 ± 0.5 °C). Furthermore, females were active again growing to 10.1 cms CW in April, i.e. increment of 0.9 cm. The overall growth rate for the 5th MG was 0.9 ± 0.3 cms month^{-1} at 22 ± 2.5 °C. Details for MGs 2 and 5-7 are presented in Table 6.13.

The female *P. pelagicus* cohort that occurred in March 1999 at mid-point of 9.75 cms CW, was not traced in the following month. Conversely, female crabs at 5.75 cms CW (May 1999), 3.75 cms CW (July 1999) and 3.75 cms CW (December 1999), and male crabs at 3.75 cms CW in July and December 1999, suddenly appeared in the catches, which is likely to be crabs moving in form other areas and/or recruits joining the stock. Male and female *P. pelagicus* abundances were at their highest in September 1999, at mid-point of size class 7.25 cms CW. However, crabs of both genders belonging to this cohort exhibited a rapid decline in number in the following three months and remained so from December 1999 through to April 2000. Such an absence of adult crabs over a fairly long period clearly highlights migration by these crabs from this area.

Plotting all estimates of growth derived from Figs. 6.16-6.18 against temperature, clearly indicates that growth can occur over a wide range of temperature, i.e. 16-34 °C (Fig. 6.19). However, growth of both genders is found to be similar ($F_{1,82}$ = 0.01; p = 0.911) in response to temperature. Various values for increase in CW are reported at each temperature, which gives clear evidence that increase in CW continues over a fairly long period of time. Highest monthly rates of increase in CW were found during the summer months, e.g. 2.4 and 2.6 cms CW at 25 and 32 °C respectively.

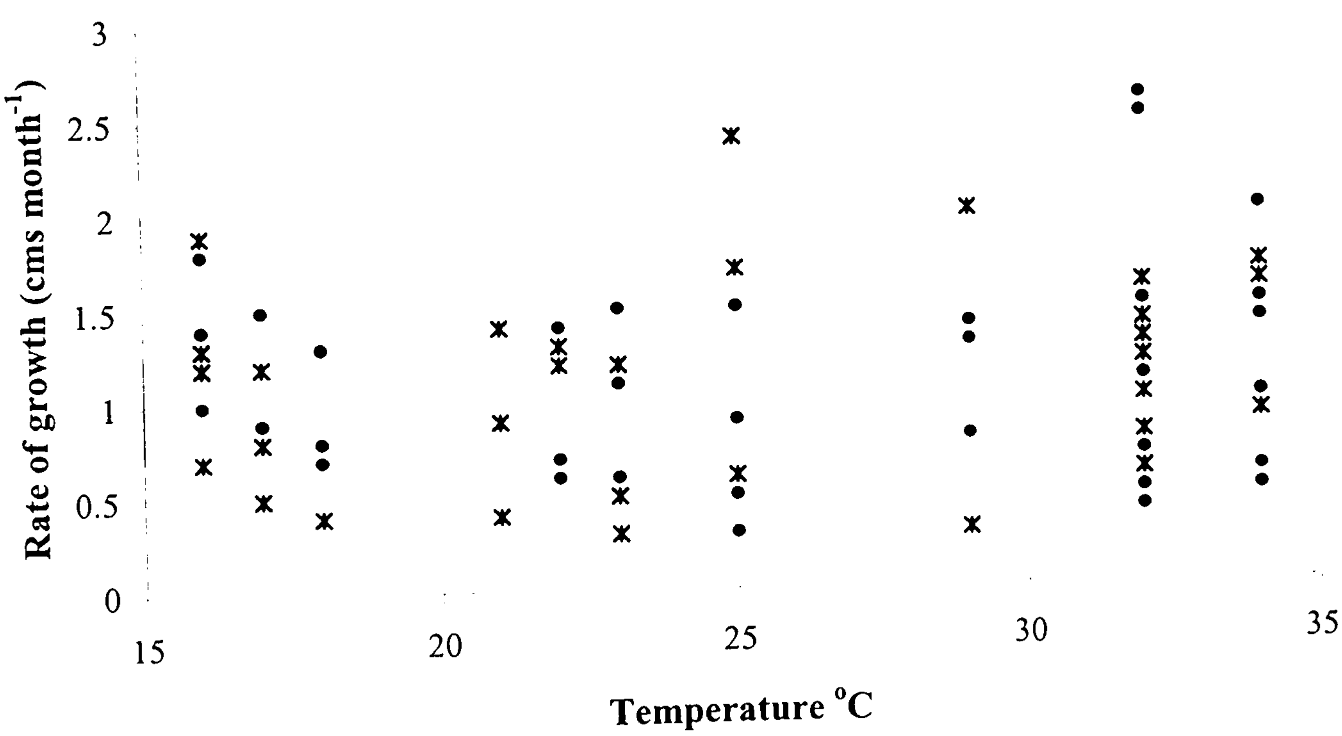


Figure 6.19. Illustration for estimates of increase in carapace width in relation to temperature. Males (•), females (*).

6.3.5.1.1.2 Mathematical models

6.3.5.1.1.2.1 Ford-Walford plot

Sampling *P. pelagicus* at equal intervals (monthly samples), provided the opportunity to estimate the growth parameters (GPs): K (year^{-1}) and L_∞ (cms CW) of the Von Bertalanffy growth equation by means of a Ford-Walford plot. GPs were estimated for the modal groups separately (see Figs. 6.16-6.18) and are presented in Table 6.14.

Table 6.14. Growth parameters obtained by Ford-Walford plot for the major modal groups of male and female *Portunus pelagicus* sampled in areas A, B and C from March 1999 to April 2000.

Area	Gender	Modal group (GP)	Tracing period	Growth parameters		Remark
				K year^{-1}	L_∞ cms CW	
A	Males	1	Mar-Aug 99	1.2	17.3	see Fig. 6.16
		7	July-Nov 99	-1.2	-3.7	
		8	Aug 99-Jan 00	2.4	14.9	
		10	Oct 99-Apr 00	2.4	13.5	
	Females	4	Jul-Oct 99	-3.6	2.3	
		5	Sept 99-Feb 00	1.2	29.3	
		6	Oct 99-Jan 00	-1.8	1.7	
		7	Oct 99-Jan 00	14.4	5.3	
B	Males	1	Mar-Oct 99	4.8	10.4	see Fig. 6.17
	Females	1	March-Dec 99	*	*	
C	Males	1	Mar-Sept 99	0.12	77	see Fig. 6.18
	Females	1	Mar-Jun 99	-2.4	-4.71	
		2	May-Aug 99	1.2	18.8	
		3	Jul 99-Jan 00	0.02	770	
		4	Oct 99-Apr 00	3	11.4	

* No growth detected.

Table 6.14 indicates a wide variation in GPs, not only between study areas but also between genders. Some cohorts exhibited rapid growth with time (see Figs. 6.16-6.18), yet their K and L_∞ values were negative, which cannot be true. Thus, it is concluded that mathematical models, e.g. Ford-Walford plot, are not reliable for measuring *P. pelagicus* growth.

6.3.5.2 Coastal fishing grounds

6.3.5.2.1 Area D

In area D male and female crabs occurred over a wide size range from 2 to 12 cms CW, with a trimodal distribution for males at size classes mid-points 3.25, 6.75 and 8.25 cms CW (Fig. 6.20) suggesting three age classes. The bimodal distribution for females, which were mainly immature were observed at size classes of mid-points 3.25 and 7.25 cms CW. As 80% of the female crabs caught were immature, which coupled with the fact that ovigerous females were rare, suggests that this fishing ground is a nursery area rather than spawning ground. Monthly SFDs are illustrated in Fig. 6.21.

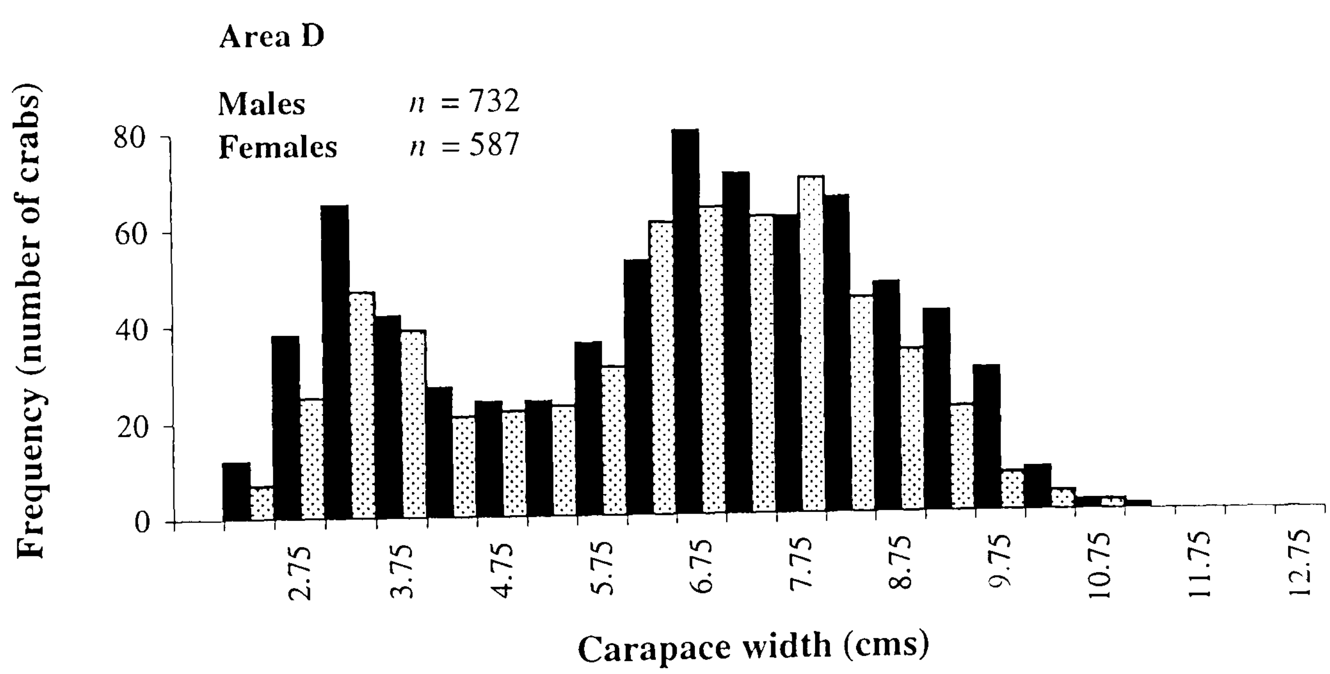


Figure 6.20. Size frequency distributions for all the *Portunus pelagicus* collected from area D off the western coast of Bahrain Island from March 1999 to April 2000. Males (dark bars), females (dotted bars).

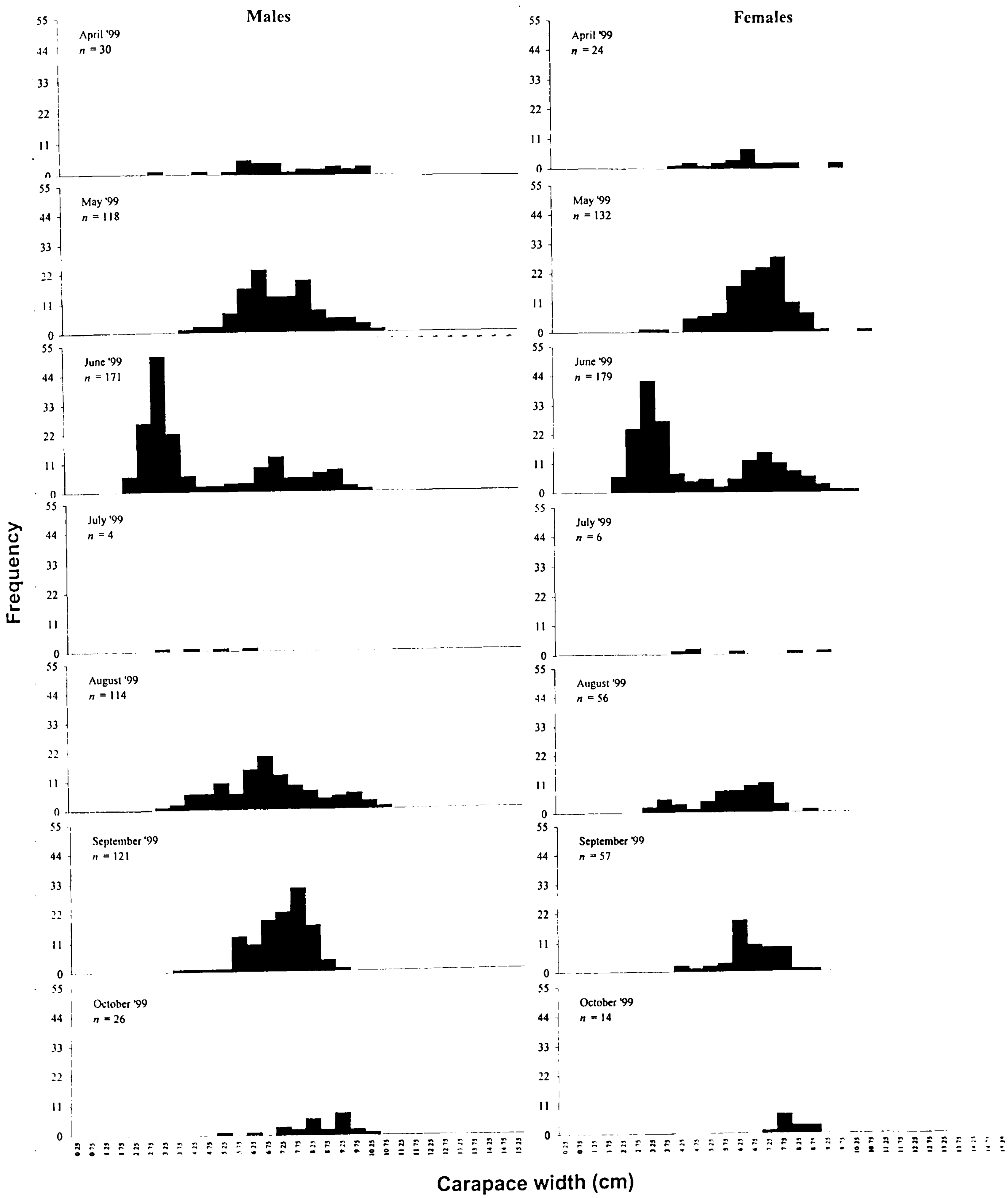


Figure 6.21. Continued

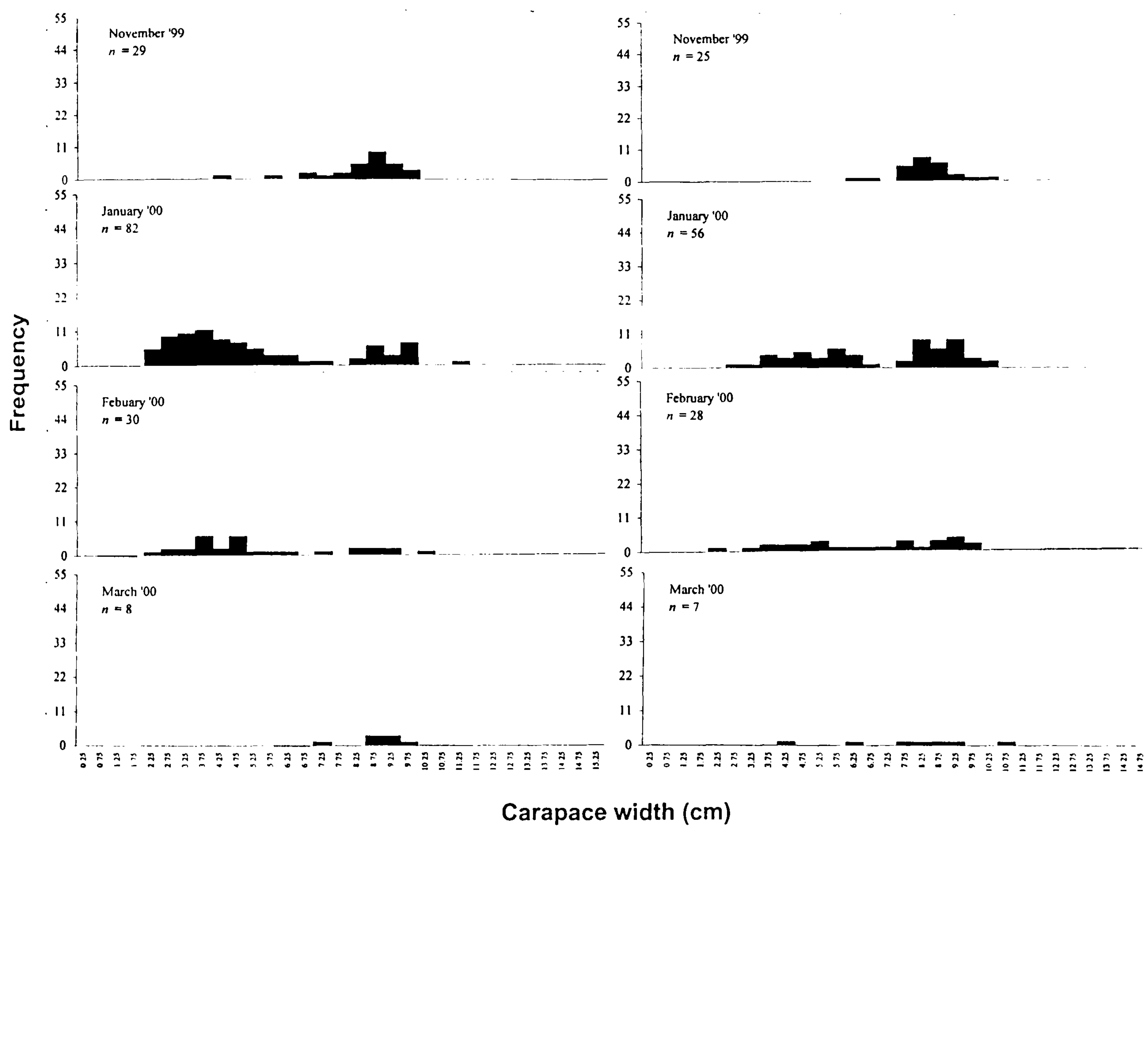


Figure 6.21. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from area D from April 1999 to March 2000, with the exception of December 1999, when sampling was not carried out. Numbers of crabs caught each month are also given.

6.3.5.2.2 Barbar & Askar coastal areas

In the Barbar coastal area on the northern coastline of Bahrain Island, annual combined trap data showed the crabs ranged from 2.0 to 11.5 cms CW (Fig. 6.22, Barbar). The male population exhibited two modes at mid-points 6.25 cms and 8.75 cms CW, while females consisted mainly of one age class with the mode at mid-point 6.75 cms CW.

On the eastern coastline of Bahrain Island where crabs of the Askar fishing ground were taken, their size ranged from 3.5 to 11.6 cms CW (Fig. 6.22, Askar). Males and females exhibited a skewed size distribution: 57% of males and 94% of females ranged from 9 to 10.5 cms and 6.5 to 10.5 cms CW respectively. Male and female crabs both had a unimodal peak at 9.25 cms and 8.75 cms CW respectively. The monthly size distribution of the *P. pelagicus* populations from Barbar (Fig. 6.23) and Askar (Fig. 6.24) also highlighted differences which occur from one coastal ground to another.

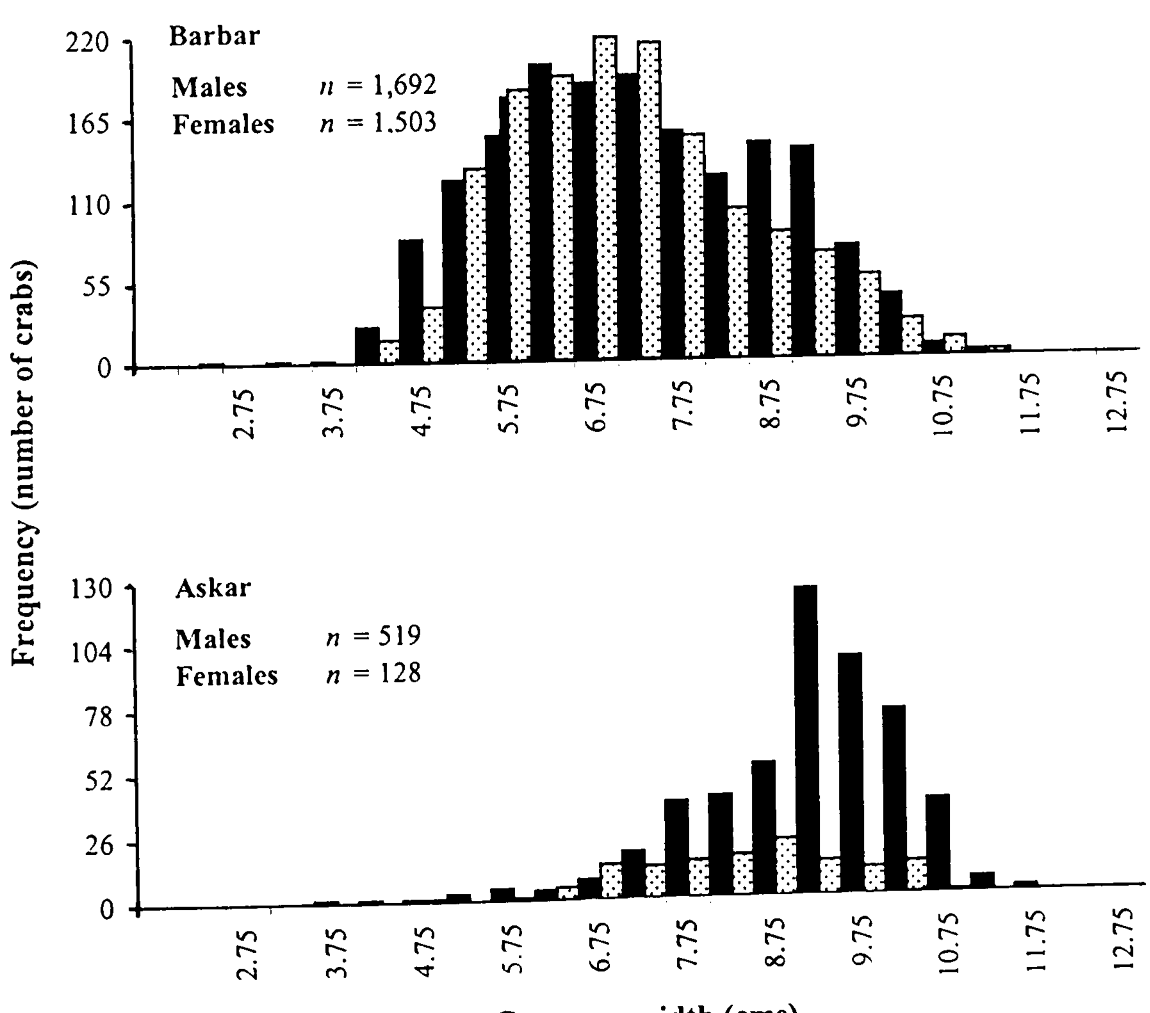


Figure 6.22. Size frequency distributions for *Portunus pelagicus* collected from the inshore fishing grounds, viz. Barbar and Askar, from March 1999 to April 2000. Males (dark bars), females (dotted bars).

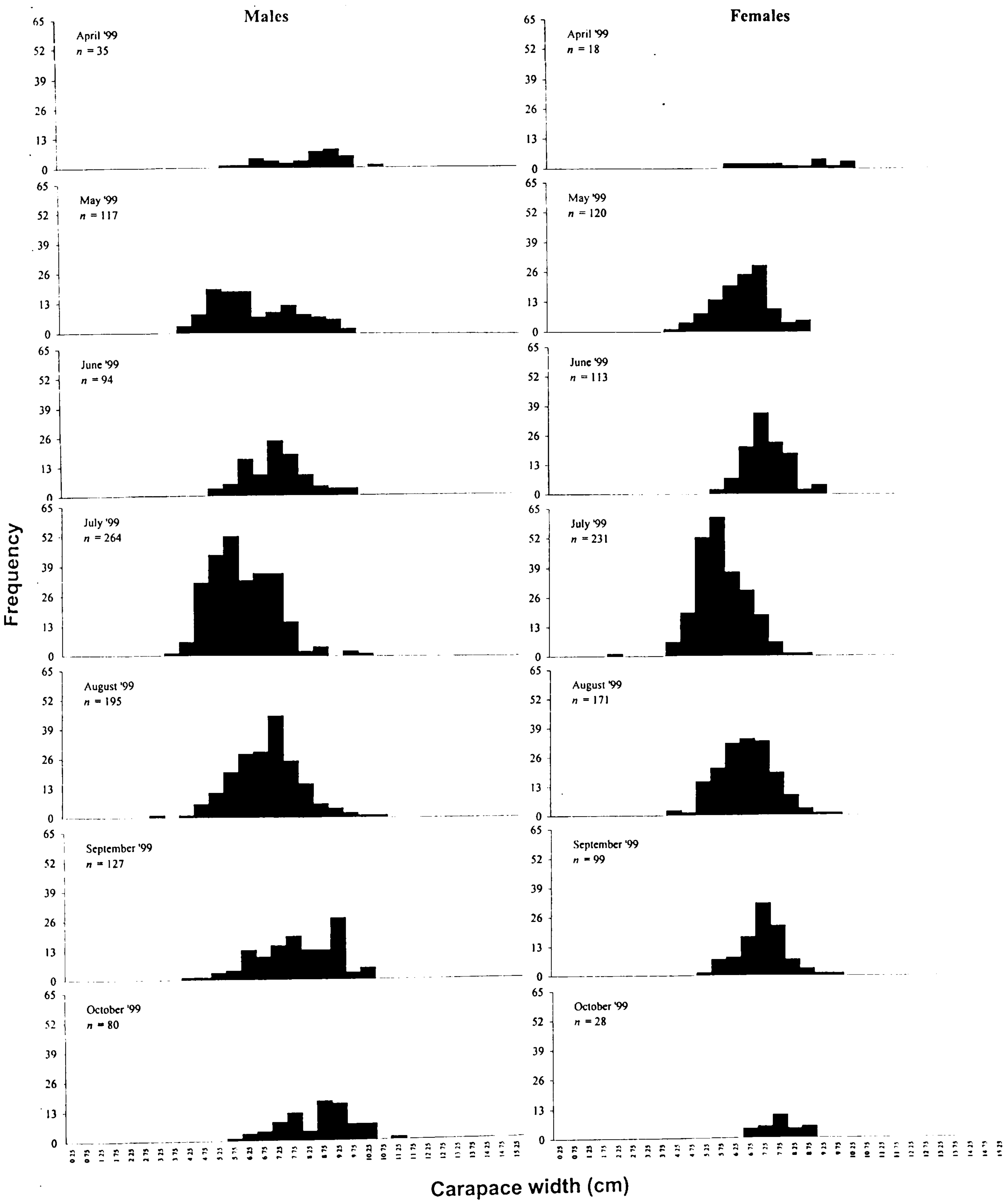


Figure 6.23. Continued

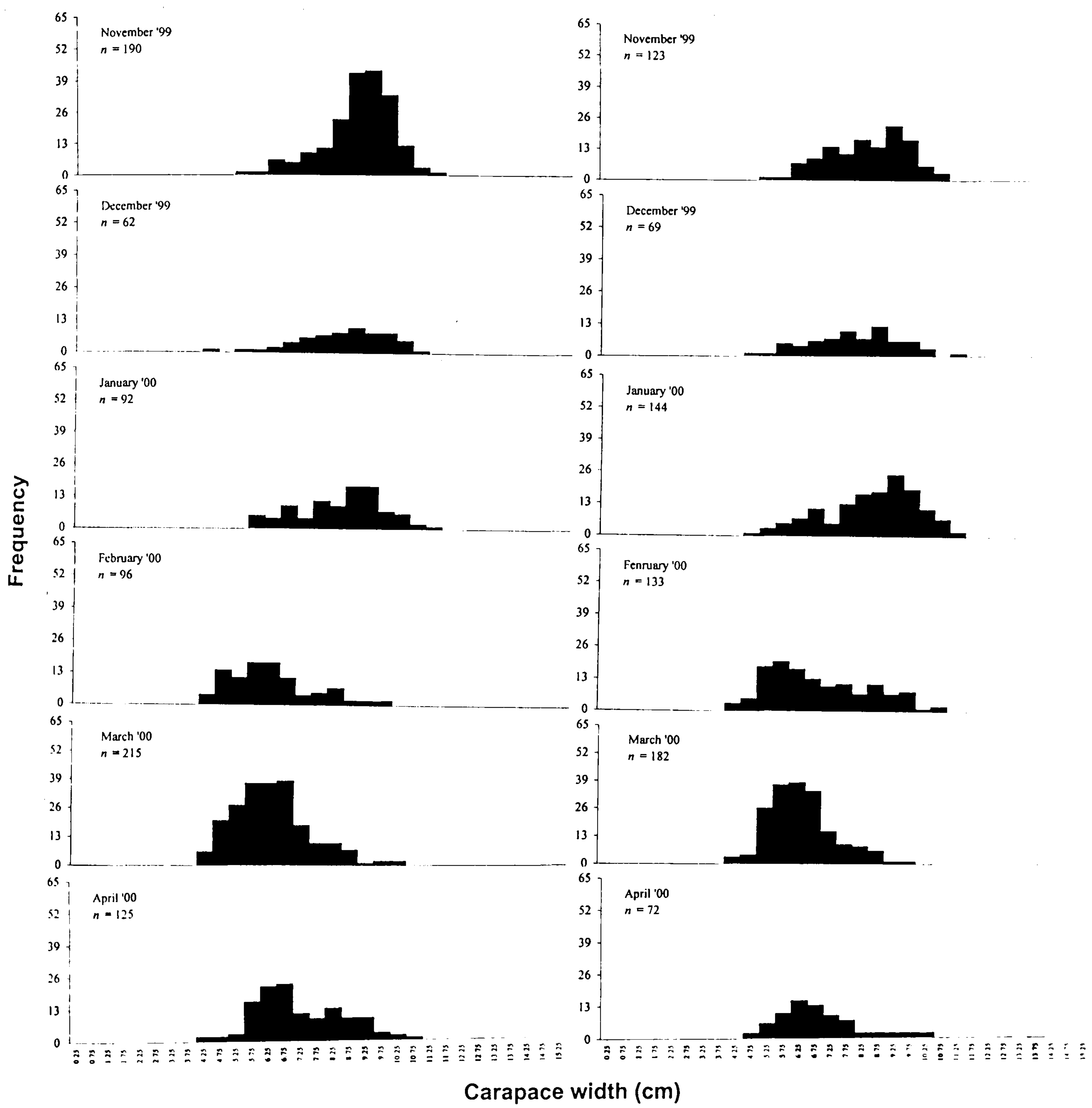


Figure 6.23. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from Barbar coastal area from April 1999 to April 2000. Numbers of crabs caught each month are also given.

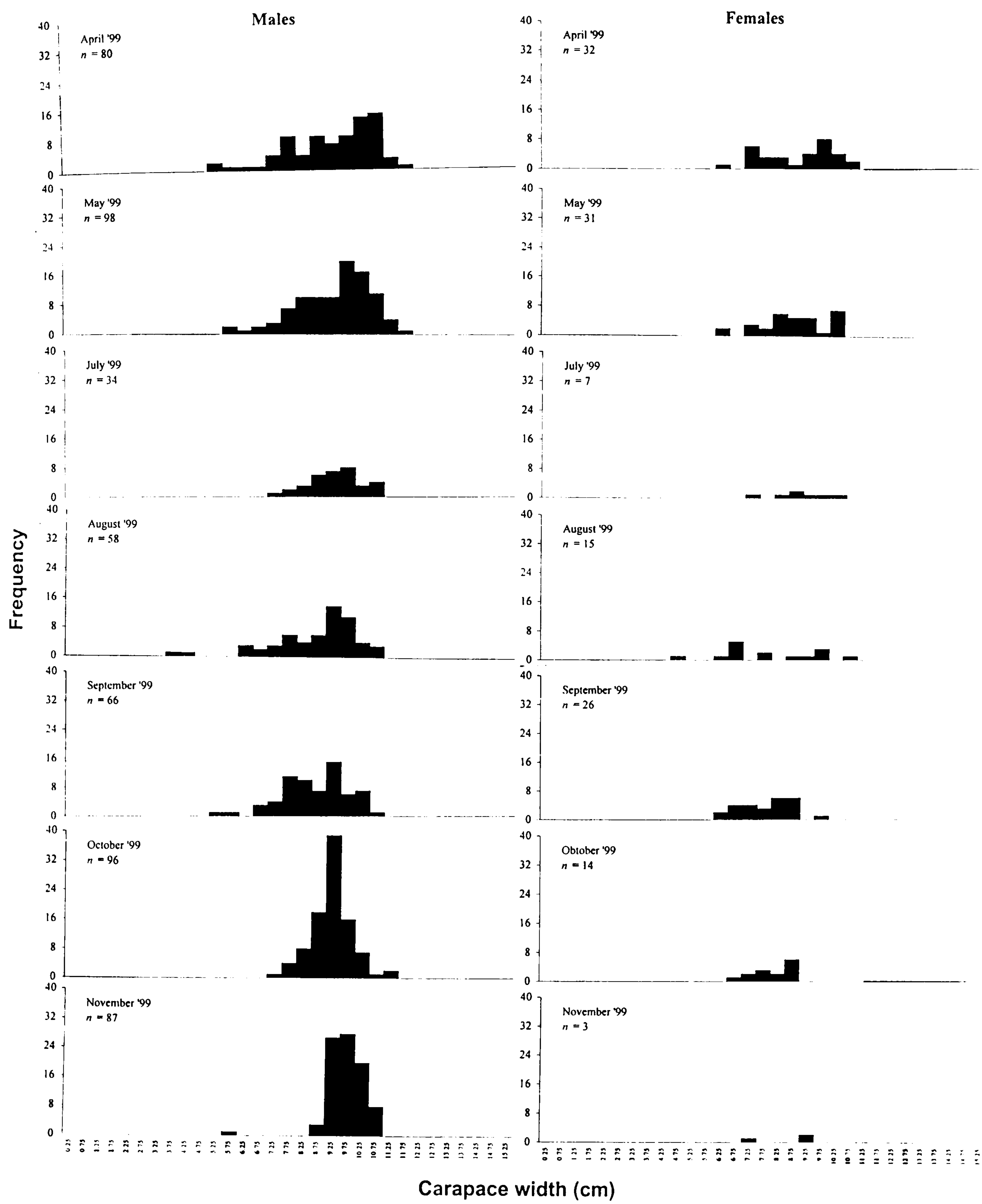


Figure 6.24. Monthly carapace width frequency distributions for male and female *Portunus pelagicus* sampled from Askar from April to November 1999, with the exception of June 1999, where sampling was not carried out. Numbers of crabs caught each month are also given.

6.3.6 Parasitic and symbiotic fauna

Investigating the parasitic and symbiont fauna of *P. pelagicus* in the course of the present study, revealed important information about these organisms and their level of occurrence of this crab species. Fauna to investigate were the rhizocephalan barnacle parasite *Sacculina granifera* Boschma, 1973, the causal organism of Pink Spot Shell Disease (PSSD) and the barnacle *Chelonibia patula*.

6.3.6.1 *Sacculina granifera*

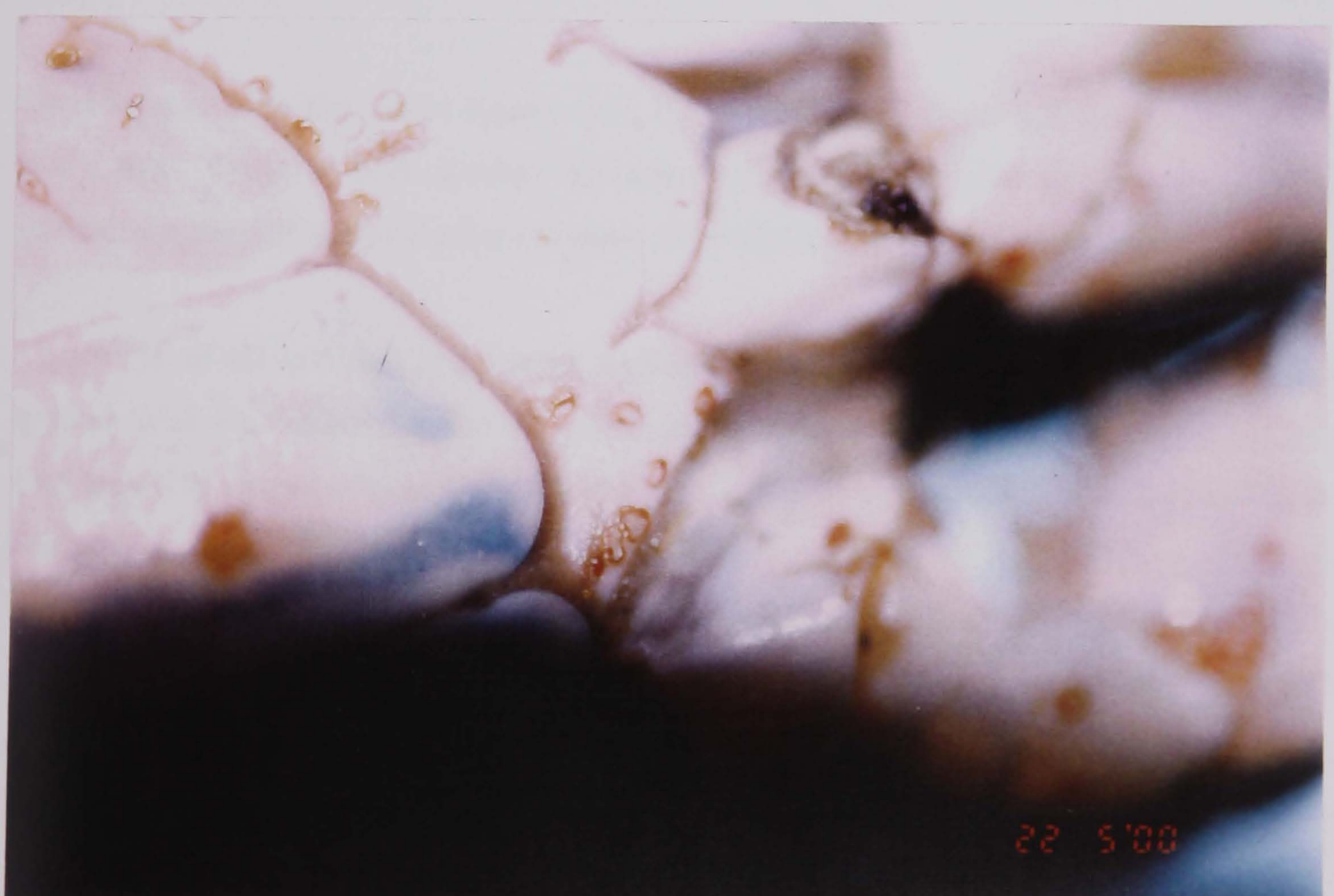
Not a single crab of *P. pelagicus* collected over the 14 month sampling period was found infected with the rhizocephalan barnacle *S. granifera*.

6.3.6.2 Pink Spot Shell Disease

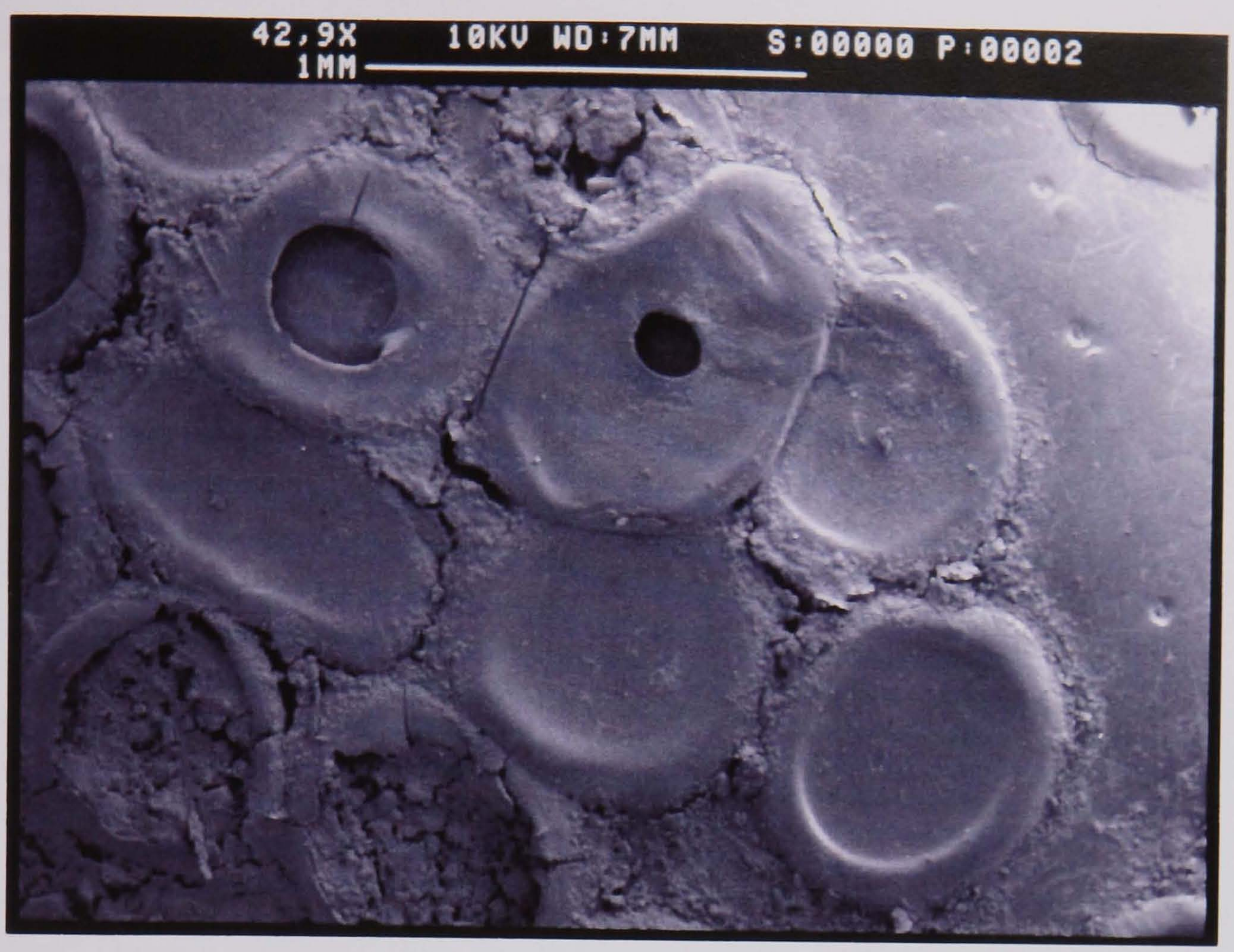
Pigmented spots were noted on the appendages and ventral surfaces of female *P. pelagicus*. It is believed that a bacterium belonging to the genus *Vibrio* causes this exoskeleton disease. In the fresh condition the pigmented spots are pinkish-red in colour and are of irregular shape. The spots are dark pink on the edges and whitish in the central region (see Photographs 6.1 and 6.2). PSSD is caused by a dense bacterial biofilm on the cuticle, as revealed by scanning electron microscopy (see Photograph 6.3).

A total of 552 non-ovigerous mature female *P. pelagicus* collected from the study areas A (n = 50), B (n = 500) and area C (n = 2) and two ovigerous females from area B, from April 1999 to April 2000, were found to be infected by PSSD. The CW size distribution for infested female crabs had a range from 7.12 to 11.52 cms in both area A and B. The distributions were approximately normally distributed (A^2 = 0.437; p = 0.283) and (A^2 = 0.349; p = 0.485) respectively, indicative that crabs of all sizes are present. Combining specimens from the three areas indicated that 80% of the infected crabs ranged from 8.5-10.5 cms CW (Fig. 6.25). Immature females in all regions were found to be free of PSSD, most likely due to their short intermoult period that does not allow the *Vibrio* to accumulate on the cuticle so preventing the exoskeleton from being invaded. Also, it is

Photograph 6.1. Pink Spot Shell Disease infecting the appendages and ventral surfaces of female *Portunus pelagicus* in Bahraini waters.



Photograph 6.2. Higher magnification showing the pigments of Pink Spot Shell Disease, which is illustrated in Photograph 6.1.



Photograph 6.3. Scanning electron micrograph to illustrate the dense bacterial biofilm on the cuticle that causes the Pink Spot Shell Disease for *Portunus pelagicus* in Bahraini waters.

interesting to note that not a single male *P. pelagicus* was found infested throughout the study area. Crabs of both genders harvested from area D as well as the inshore fishing grounds on the Askar and Barbar coastline were also found to be free of PSSD.

91% of all infected crabs were reported at the deep northeastern offshore fishing ground (area B), where also the only two infected ovigerous females, measuring 10.3 and 10.5 cms CW, were collected in May 1999. Infection rate in area A was as low as 9% and negligable in area C. Findings of the present study indicate that the incidence of infected female crabs follows a seasonal pattern. Taking area B as a model, PSSD occurred during the summer months (April-July 1999) with the highest infection peak recorded in May 1999 as high as 19% of the total female catch. All crabs collected from August to November 1999 were free of infection; however, PSSD reoccurred in female crabs in December 1999 and January 2000, but at lower rates, i.e. 2% and 5% respectively. It then disappeared and re-occurred in April 2000 when 8% of females were infected. This rate was fairly close to that recorded during the same period of the previous year. The occurrence of PSSD in the overall study area is illustrated in Table 6.15. In general, PSSD infection in Bahraini waters is found to be associated with mature, non-ovigerous female crabs occurring in deep waters at temperatures of 23 to 32 °C and salinity ~ 49‰.

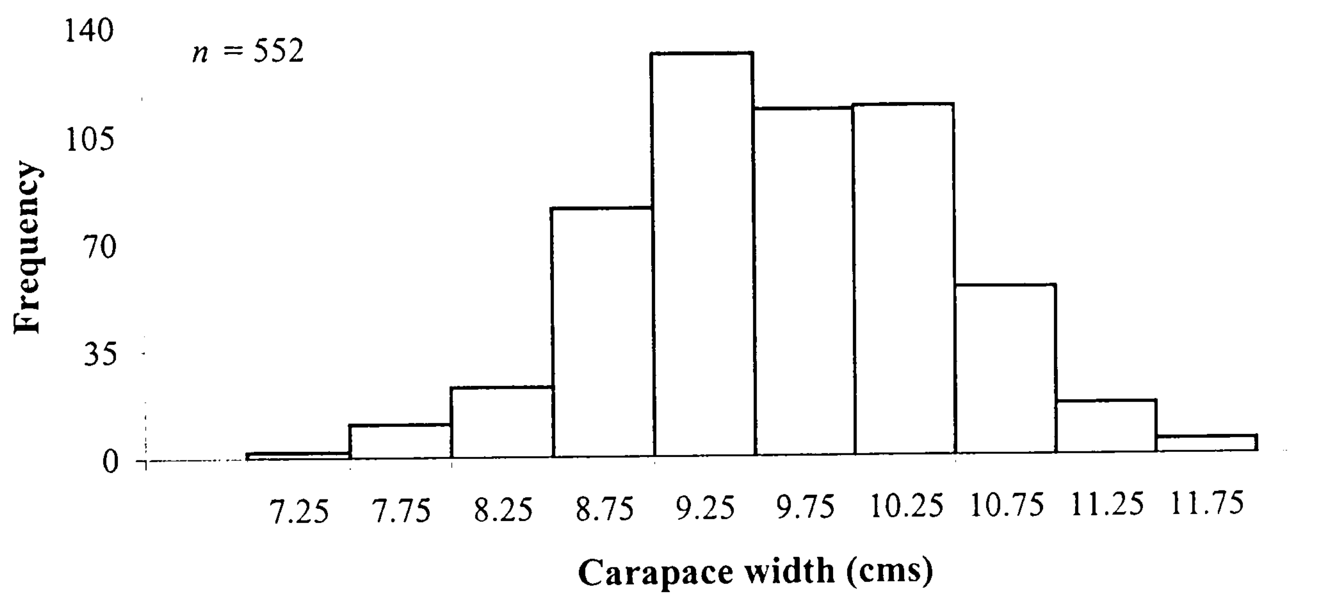


Figure 6.25. Size frequency distribution for female *Portunus pelagicus* infected by Pink Spot Shell Disease, collected from the study region from April 1999 to April 2000.

Table 6.15. Incidence and abundance of Pink Spot Shell Disease infecting the non-ovigerous female *Portunus pelagicus* around the offshore and coastal fishing grounds. Bahrain, April 1999-April 2000.

Area	Total number of females	Percentage of infected females	Time of occurrence
A	145	5	April 1999
	822	3	June 1999
B	261	6	April 1999
	799	19	May 1999
	562	11	June 1999
	358	4	July 1999
	91	2	December 1999
	24	5	January 2000
	47	8	April 2000

Table 6.15. Continued

Area	Total number of females	Percentage of infected females	Time of occurrence
C	158	0.1	April 1999
	58	0.14	June 1999
D	-	-	-
Askar	-	-	-
Barbar	-	-	-

- Denotes free of PSSD.

6.3.6.3 Barnacle, *Chelonibia patula* (Ranzani)

The barnacle, *Chelonibia patula* (Ranzani) is found attached to the thoracic appendages and dorsal surface of *P. pelagicus* (Pilsbry, 1916). The presence of *C. patula* is indicative of long intermoult periods, hence it is basically associated with the larger crabs (moult infrequently) (Fig. 6.26), thus, offering an uninterrupted surface for the larval settlement and subsequent fast growth. Fig. 6.26 further illustrates that in crabs below 9.5 cms CW, *C. patula* was more likely to grow on male crabs, whereas females above 9 cms CW were more likely to carry this barnacle species.

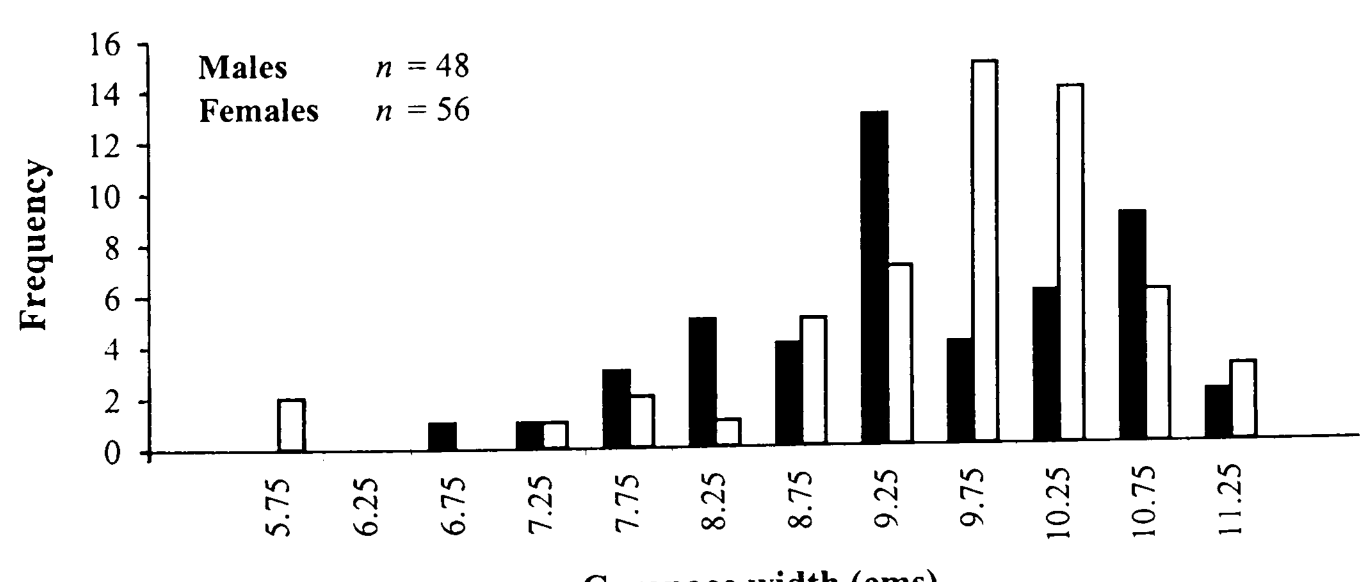


Figure 6.26. Carapace width frequency distribution for male and female *Portunus pelagicus* with the barnacle, *Chelonibia patula*, growing on the carapace. Data for males (dark bars) and females (open bars) were obtained from samples collected from the study region from March through to May 1999.

6.4 Discussion

6.4.1 Mating

Mating in *P. pelagicus* can only occur between a hard shelled male and soft female immediately after she moults (Hartnoll, 1969; Fielder and Ealse, 1972; Abd EL-Hamid, 1988; Weng, 1992 and Shields and Wood, 1993). Surprisingly, during the present investigation, not a single crab of either gender was ever found in the soft-shelled condition, even though the sampling covered a vast area within the fishing grounds. Thus, it was not possible to provide evidence for a particular season or location where mating likely takes place. The absence of recently moulted crabs in the catch is probably due to behaviour whereby soft shelled crabs bury themselves in the sediment and thus escape capture in the trawl.

6.4.2 Nursery areas

Crab nursery areas were found within the shrimp fishing grounds. The high abundances of juvenile male and female *P. pelagicus* in size classes of < 5 cms CW in areas A and C provide clear evidence of the importance of both sea-areas as nursery grounds. Both the areas have substantial rich algal and seagrass communities in generally shallow water. However, area C proved to be the major nursery ground since juveniles of both genders occurred in far higher abundances compared with area A. The negligible number of crabs < 5 cms CW in the trapped catches from the Barbar and Askar fishing grounds show that the barrier traps simply do not retain juvenile crabs.

6.4.3 Recruitment

Since ovigerous females were absent from December 1999 to February 2000, recruitment that occurred in area A during March and April 1999 (spring) must have resulted from individuals spawned the previous autumn (October-November 1998). Thus, assuming about 5 months from hatch to recruitment at average CW of 4.25 cms CW, the rate of growth for male and female juveniles was found to be 0.8 cms CW month^{-1} during the winter. Similarly, the recruitment observed in area C during June/July 1999 was likely to have emanated from larvae spawned in March 1999. Thus, 4 months from larval hatch to recruit and a rate of growth reaching at least 1 cm CW month^{-1}. The high level of recruitment observed in areas A and C throughout the winter and spring (December 1999-April 2000) was a consequence of the prolonged breeding season from spring to autumn (March to November 1999). The virtual absence of recruit-sized crabs in area B, which has a very high incidence of ovigerous females throughout the spawning season, suggests that all larvae spawned in area B are dispersed by the currents (range 0.6-2.5 knots, MHME, 1997). The dispersal must carry them to the nursery areas in the southern fishing grounds around area C, northern fishing grounds around area A and further southwest to area D. Winds may also be indirectly responsible for dispersing the larvae to their settlement areas within the fishing grounds by influencing current directions.

6.4.4 Relative abundance and biomass

Studies on fishing technology in the Arabian Gulf region are lacking, with the exception of one major investigation that was carried out in Bahrain on reducing the by-catch caught by shrimp trawl nets by means of a grid reduction device (Abdulqader, 2000). In Bahrain, trawling is presently the only method by which shrimps are caught commercially; several marine resources such as crabs (*P. pelagicus*) and finfish are harvested as by-catch of this shrimp fishing (Abdulqader, 2001; see appendix 1). Despite the importance of the shrimp fishery to the total marine resources landed in Bahrain, information on the shrimp trawling in terms of – catch efficiency (i.e. the number of organism(s) caught in the nets divided by the total number of such organisms in the trawl path before fishing), catch mortality (i.e. the number of dead animals in the catch divided by the total number of such animals in the catch), non-catch mortality (i.e. the number of dead animals in the trawl path divided by the total number of such animals in the trawl path after fishing), have not been investigated. It is well documented that trawl and/or catch efficiency is required for any reliable estimates of density and biomass of benthic communities (Edwards and Steele, 1968; Lideboom and Groot, 1998; Somerton and Otto, 1999). Also, it is most likely that the fast swimming exhibited by *P. pelagicus* with a maximum speed of 23 m min^{-1} (Gribble and Thorne, 1998) enables particularly the larger individuals in the trawl path to escape, which would bias the population structure, where reliance on true representative samples are fundamental for reliable density and biomass estimates (Edwards and Steele, 1968; Kaiser *et al.*, 1994). Dimensions of the trawl net, dimensions and weight of otter boards, bridles, length of footrope and its composition, net mesh size, speed of vessel, substrata, as well as current velocity and direction are all crucial parameters, which control collectively the wing spread and hence trawl net gape whilst in operation (Edwards and Steele, 1968). Edwards and Steele (1968) noted trawls can have a catch efficiency as low as 30%. In the eastern Bering Sea, USA, snow crab *Chionectes opilio* and Tanner crab, *C. baridi*, are fished commercially by means of an 83-112 eastern bottom trawl with 34.1 m footrope and average wing spread of 17 m, i.e. 50% of the footrope length (Somerton and Otto, 1999).

In the course of the present study, distance travelled (kms) by the trawl has been determined for all trawling hauls that were carried out. However, catch efficiency of the shrimp trawl net used to capture crabs was not measured. Also, the other parameter not measured was the swept width (i.e. the distance across the gape of the net) of the trawl in operation, which is fundamental for calculating the swept area (km^2). To give some indication of crab density and area standing crop as biomass, two estimates of sweep area were derived, providing two levels within which the realistic population level will lie. Hence, the density and biomass of *P. pelagicus* in this study was based on two assumptions – 1) trawl having 100% footrope length and 100% catch efficiency, i.e. all crabs in the path of the trawl were captured (hereafter 100% efficiency) and 2) trawl having 50% footrope length [swept width] and 50% catch efficiency, i.e. half of the crabs were able to escape capture (hereafter 50% efficiency). Density and biomass values using these assumptions represent an underestimate and an overestimate respectively. These values for male and female *P. pelagicus* in the offshore fishing grounds are presented in Table 6.16.

Catch data obtained during the present study revealed spatial and temporal variations in the biomass of male and female *P. pelagicus* in all fishing grounds. The maximum biomass recorded for male crabs in area A (July 1999) was 90 / 362 mt, i.e. using 100% / 50% efficiency assumptions respectively. In area C, the maximum biomass for male and female crabs occurred in September 1999, with that for male *P. pelagicus*

Table 6.16. Maximum and minimum mean estimates for density (number of crabs km^{-2} ± SE) and biomass (weight of crabs [metric tons] $area^{-1}$) of mature male (> 5.5 cms CW) and mature female (> 7 cms CW) *Portunus pelagicus* calculated from catches collected around Bahrain from March 1999 to April 2000. The density and biomass figures are estimates using the 100% and 50% efficiency assumptions (for explanation of these assumptions see text).

		Density (crabs km^{-2})				**Biomass (metric tons $area^{-1}$)**			
		100% efficiency		50% efficiency		100% efficiency		50% efficiency	
Gender	Area	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Male	A	85 ± 24	2262 ± 572	340 ± 96	9048 ± 2288	2.3	90.3	9.3	361.4
	B	3 ± 2	737 ± 166	11 ± 9	2948 ± 664	0.2	73.7	0.6	294.8
	C	171 ± 58	3352 ± 1308	682 ± 234	13408 ± 5232	6.4	200.7	25.7	802.7
Female	A	50 ± 23	2151 ± 1034	200 ± 92	8604 ± 4136	1.4	60.4	5.6	241.6
	B	8 ± 5	1629 ± 609	32 ± 21	6516 ± 2436	0.7	100.5	2.9	402.1
	C	95 ± 29	1607 ± 901	378 ± 114	6428 ± 3604	5	73.1	20.1	292

exceeding that of females by a factor of 2.7. In contrast, biomass of female crabs in area B exceeded that of males throughout most of the study period, with a maximum in May 1999 of 100.5 / 402.1 mt (100% / 50% efficiency assumption respectively) a 2.6 fold increase over that of male crabs. Male crabs in area B only exhibited a greater biomass on one occasion ~ 73.7 / 294.8 mt (July 1999), a 1.7 fold increase over that of females. Maximum biomass figures in Table 6.16 are for crabs captured during the summer months, i.e. May-September (28-35 °C), whereas the lowest figures were obtained for crabs captured in the winter and spring months, i.e. February-April (17-23 °C), reinforcing that high *P. pelagicus* biomass is a summer phenomenon. Also, the biomass estimates obtained for both genders in all fishing grounds were far lower during March and April 2000 than those for the same period in the previous year, with the exception of male crabs from area C (see Table 6.17), although temperatures recorded for March and April in 1999 and 2000 were similar (19-23 °C).

Table 6.17. Percentage difference in biomass of *Portunus pelagicus* between March-April 2000 and March-April 1999.

	Males		Females	
Area	March 2000	April 2000	March 2000	April 2000
A	- 56 %	- 25 %	- 95 %	- 88 %
B	- 77 %	- 89 %	- 96 %	- 93 %
C	+ 38 %	- 20 %	- 90 %	- 83 %

6.4.5 Sex ratio

Deviation from the 1:1 sex ratio is common among marine crustaceans. Also, the ratio varies with size for several crustaceans and many reasons have been proposed for such findings (see review by Wenner, 1972).

The current investigation revealed that the overall male:female ratios in area A at 1.1:1, area D at 1.3:1 and Barbar fishing ground at 1.1:1, agrees closely with the sex ratios found previously in Barbar (1.2:1, Al-Rumaidh, 1995), India (1.3:1, Devi, 1985) and in the Gulf of Carpentaria and Moreton Bay, Australia (1.1:1, Weng, 1992). On the other hand, the male:female ratio of 0.5:1 recorded in area B is similar to that found by Shields and Wood (1993) for Moreton Bay, indicating both regions are the likely spawning grounds for *P. pelagicus*. Thomson (1951) and Phillips (1978) have suggested that complete sexual segregation may occur for *P. pelagicus*. During the present study, however, both genders were present in all fishing grounds throughout the year, albeit with twice as many females as males in area B.

The sex ratios for *P. pelagicus* from the offshore and inshore fishing grounds around Bahrain showed considerable variation with season and locality. The preponderance of males in area A during July-September and March-April 2000 was associated with the high relative abundance of females in area B during the same period. It appears that females move from the shallower water in area A to the deeper waters of area B twice a year. The significant preponderance of ovigerous females in area B indicates that the northern fishing grounds are the major spawning area and that the spawning season is prolonged. Juvenile crabs were relatively more abundant in areas A and C (see Figs. 6.10a-6.10c). Male crabs dominate in the coastal grounds at the same time as females tend to dominate in the offshore fishing grounds (areas B and C in particular). There is clear evidence for the migration of females to these deeper water areas to spawn. In general, temporal and spatial differences in sex ratio suggest that migration occurs more from area A to B than from C to B. A similar, but less marked inverse relationship in sex ratio between areas C and B also occurs. However, the **Fasht Al Adhum** forms a natural barrier between both regions that probably limits any crab migration northwards. Furthermore, area C is influenced strongly by inshore tidal currents (Atkins and Partners, 1985) that may also mitigate against crab migration to the deeper northern waters. There appears to be no net movement crabs in or out of area C.

Class size analysis for combined data (carapace width) with mature females in area B (deep waters) dominating the population of crabs larger than 6 cms CW, whilst mature males dominate the inshore population (see Figs. 6.13 and 6.14) again provides strong evidence of female migration to deeper waters. Furthermore, the proportion of mature females dropped in area A (July-September 1999 and March-April 2000) and area C (April and August 1999, March 2000), which coincided with the preponderance of females in area B for ten consecutive months (March-December 1999).

6.4.6 Growth

Many organisms continue to grow throughout their life span, although often at a decreasing rate with age as more energy is channelled into reproduction. Consequently such organisms exhibit no final or definitive size. Earlier studies of *Callinectes sapidus* indicated continued rapid growth at all life stages and sizes (Gray and Newcombe (1938) as cited by Sather, 1965), which is unusual given that relative growth in crustacean usually decreases with age (Hartnoll, 1974).

The maximum crab size for male and female *P. pelagicus* obtained during the present research at 15 and 16 cms CW (~ 17 and 18 cms TCW) respectively, is smaller than the maximum CW size recorded for the species at 20 cms TCW (Thomson, 1951; Pillay *et al.*, 1971b; Penn, 1977; Smith, 1982; Potter *et al.*, 1983 and Potter *et al.*, 1991). This difference in CW between *P. pelagicus* in Bahraini waters and elsewhere could be attributed to its heavy exploitation in Bahrain in both coastal and offshore fishing grounds. Fishing pressure is lessened during the period from April to July (closed season for shrimp fishery) in the offshore grounds. Presumably the pressure is such that most crabs are caught before they have the opportunity to reach maximal size. Alternatively, the high salinity of Bahraini waters (42-57‰) might also have a role in preventing crabs from attaining the recorded maximum size. Several workers studying *Callinectes* have observed a negative correlation between the size of crabs and salinity where they occur. They assume that crabs in low salinities absorb more water when they moult and, thus, increase in size faster than crabs in water of higher salinity (Cargo, 1958; Van Engel 1958; Fischler, 1959; Tagatz, 1965). This phenomenon has been noted for *P. pelagicus* from Alexandria, Egypt (Abdel Razek, 1987) and Bahrain (Al-Rumaidh, 1995), where the rate of growth in Bahrain was the lower due to the high salinity whereas off Alexandria (Mediterranean) the salinity was much lower due to the proximity of the Nile delta.

Despite the commercial importance of *P. pelagicus* throughout its geographical range, there are few studies of growth or mortality rates (Potter *et al.*, 1983: Devi. 1985; Abdel Razek, 1987; Sumpton *et al.*, 1994b). Modal progression analysis for crabs in Bahrain indicated that growth rate by male and female crabs in study areas A and C ranged from 0.6 ± 0.2 to 2 ± 0.9 cms CW month^{-1} (equivalent to 34-1200 mg month^{-1}). Growth in area B was virtually undetectable for mature females (made more difficult to determine due to much immigration) and extremely limited for mature males.

The average growth rate estimated during the present investigation for both genders was 1.3 cms CW month^{-1} (equivalent to 335 mg month^{-1}), very close to that for crabs in India at 1.2 cms month^{-1} estimated by Ameer Hamsa (1982). Devi (1985) reported growth rates of 0.7 cms month^{-1} for males and 0.6 cms month^{-1} for female *P. pelagicus*, also in India. It would be expected that crab growth rates around Bahrain would be similar to that recorded in India as the Arabian Gulf is linked directly to the Indian Ocean and similar climatic and hydrographic conditions exist in both regions. Abdel Razek (1987) noted that the rate of growth of Egyptian *P. pelagicus* in the Mediterranean varied from 0.5 cms at about 10 °C to 1.7 cms CW month^{-1} at about 30 °C ($Q_{10} \sim 1.8$), with an average rate of 1.2 cms CW month^{-1} under culture conditions. Devi (1985) found that males and females in India attain 7.7 cms and 8.2 cms CW, respectively, at one year old. Having a growth rate of ~ 1.3 cms CW month^{-1}, crabs from Bahrain might expected to grow to 15.6 cms CW in one year. However, CW frequency analysis indicated three mature size classes for *P. pelagicus* during the present study, suggesting a lifespan of 3 years. *P. pelagicus* in Australia also have a lifespan of up to 3 years (Smith and Sumpton, 1987; Kailola *et al.* (1993) as cited by Bryars and Adams, 1999). Using length frequency analysis, Sukumaran and Neelakantan (1997d) determined the longevity of *P. pelagicus* for south-western India to be 2.5 years. Thus, many of the Bahraini crabs reach a size suitable for exploitation by the commercial fishery when 6-7 months old. The longevity of *Callinectes sapidus* was thought to be 3 years, based on crabs held in captivity (Van Engel. 1958). More recent tagging studies, however, indicate that *C. sapidus* has lifespan of 8 years (Rugolo *et al.*, 1998).

Previous estimates of the growth parameters of an asymptotic growth curve (K, L_∞ and t_0) for *P. pelagicus* are restricted to two regions, Arabian Gulf (Bahrain) and Australia (Moreton Bay). In Bahrain, male growth parameters were found to be: $K = 1.3$ year^{-1}, L_∞ = 15.6 cms TCW and t_o = -0.477 (Al-Rumaidh, 1995), whereas in Moreton Bay they were reported for males as K = 1.597 year^{-1}, L_∞ = 17.5 cms TCW and t_o = -0.203, and for females as K = 1.613 year^{-1}, L_∞ = 17 cms TCW and t_o = -0.189 (Sumpton *et al.*, 1994). These figures show that male *P. pelagicus* in Moreton Bay are predicted to a have greater maximum carapace width than females, however their relatively growth coefficients were similar. Also, these two investigations indicate faster growth in Moreton Bay in comparison to Bahrain, due probably to more favourable environmental conditions in the former.

In the present study, mathematical models that were applied to carapace width data did not provide reliable estimates of growth parameters for male and female crabs. Monthly CW frequency distributions indicated a seasonal growth pattern for both genders. Thus, it was not possible to describe growth parameters for the Von Bertalanffy growth equation (VBGE) using the three methods available in the Length Frequency Distribution Analysis (LFDA) software package (Holden *et al.*, 1995) as these methods are all based on a non-seasonal VBGE.

On the other hand, the lack of reliable descriptors of the growth parameters for *P. pelagicus* may well be attributed to the stepwise increase in carapace width, which occurs at each month. The mathematical models may not be able to handle such discontinuous growth, but are more effective with organisms that increase in size continuously. Working on the life history of the blue crab *Callinectes sapidus*, Darnell (1959) summarised three factors responsible for difficultly in following growth in this crustacean, as follows: (1) increase in CW is stepwise, where techniques employed in the analysis of continuously growing animals may not be directly applicable, (2) successive waves of different instars that appear in estuaries coupled with the migration of adult animals seaward, and (3) different stages in the life history occupy different habitats. All these difficulties were probably operating during the present research. Estimates of *P. pelagicus* mortality rates were not attempted due to the lack of reliable growth parameters.

In general, modal group (MG) analysis for male crabs indicated that growth continued year-round. The continued presence of MGs for the smaller sized males (< 5 cms CW) in area A over most of the year again confirms the prolonged spawning season for *P. pelagicus* around Bahrain. The lack of large males from January to April 2000 in areas A and C associated with a small number of large male crabs in area B, raises several possible scenarios for their absence – they may have been taken by the fishery, migrated away to an area not sampled, e.g. adjacent Saudi fishing grounds, selectively predated or even died naturally.

Temperature and photoperiod are considered two major environmental factors determining biology in marine invertebrates (Pillai and Ono, 1978). The biology of *P. pelagicus* is highly temperature dependent (Anon, 1970), the crabs needing warm temperatures over extended periods (Anon, 1978). The water temperature influence on brachyuran geographical distribution is well known (Fransozo and Negreiros-Fransozo, 1996), as evidenced by the limits of *P. pelagicus* in the cooler waters off Victoria and Tasmania, Australia (Todd, 1995). Batoy (1987) noted that *P. pelagicus* was eurythermal and Dhawan *et al.* (1976) gave a tolerance range of 25-40 °C for the species. When temperatures fall below 20 °C all activity ceases including the search for food and the crabs remain buried in the sand (Kinne, 1963; Anon, 1970). Activity increases at 25 °C and above (Sumpton and Smith, 1990), however, 39.5 °C is the upper incipient lethal temperature (Neverauskas and Butlet, 1982).

Sather (1969) reported that temperature influences the moulting frequency in crabs and Hill (1975) stated that *Scylla serrata* CW increase is mainly a summer phenomenon. In Bahrain, seasonal changes in water temperature are well documented, ranging from 16 to as high as 35 °C. Growth rate was found to be as high as 1.5 cms CW month^{-1} at temperatures above 30 °C (summer) and < 1 cm month^{-1} at < 20°C in the winter. Influence of higher temperatures is more apparent on the smaller crabs, which frequently moult and least apparent for large crabs which have prolonged intermoult periods.

6.4.7 Parasitic and symbiotic fauna

Findings of the present study indicate that parasitic and epibiotic fauna are not causing impact on the *P. pelagicus* fishery in Bahrain. The absence of the barnacle parasite *Sacculina granifera* over the 14 month period provides strong evidence that *S. granifera* does not occur in this part of the world.

Chapter 7

General discussion

7. GENERAL DISCUSSION

The present study is the first attempt to investigate the life history and population dynamics of the blue swimming crab, *Portunus pelagicus*, in Bahraini waters and the Arabian Gulf region. The information obtained provides the base-line for management protocols, which will facilitate the rational exploitation of *P. pelagicus* around Bahrain and near-shore environments of adjacent countries.

7.1 Crab fishery

Unlike other local, living marine resources, which are maintained by legislative measures protecting them from overexploitation, the blue swimming crab fishery in the Kingdom of Bahrain is presently neither organised nor regulated by management protocols, (Directorate of Fisheries [DOF], year is not determined). Despite the lack of legislation, the crab fishery contributes considerably to the total marine resource landings for human consumption and is of further importance as bait for the considerable local Gargoor fishery. *P. pelagicus* landings in Bahrain (Fig. 7.1) nearly doubled from 518 metric tons (mt) (6.7% of total marine resource landings) in 1985 to 914 mt (11.4%) in 1992 and had more than doubled again to 2,380 mt (20.3%) by 2000. The catch in 2000 was worth BD. 308,000/- (equivalent to £ 574,000) representing 3.3% of the total marine catch revenue (DOF, 2001). The steadily increasing crab catch is attributable basically to increased fishing effort, viz. fleet size, more efficient fishing gear and number of fishermen in response to a growing awareness of the importance of *P. pelagicus* as a local food resource (see appendix 3) and increasing demand for the export market.

In 2000, the crabs were caught by various fishing methods, where 26.8%, 9.3% and 0.2% of the total landings were caught by Hadhrah, Gargoor and Gillnet respectively with the major proportion, 64%, harvested as a by-catch of the shrimp fishery (see appendix 1). The green tiger shrimp *Penaeus semisulcatus* De Haan, 1844, is considered one of the major living marine resources in Bahrain. In 2000, its contribution was 2,104 mt (i.e. 18% of total marine resource landings) with a value of 2.9 million Bahraini Dinnar (BD.) (equivalent to £ 5.3 million) (DOF, 2001). The shrimp landings have exhibited fluctuations over the last 16 years or so (1985-2000) with three major peaks of 1843 mt

(1987), 1514 mt (1989) and 2127 mt (1993). The highest shrimp landing was 3565 mt (1996), while the lowest were in 1991 and 1992 at 812 and 754 mt respectively, the result of low fishing effort due to restrictions imposed during the Gulf war (Abdulqader, 2001). *P. pelagicus* landings have shown a rapid increase since 1985 and exceeded those of the shrimp in 1999 and 2000 by 34% and 13% respectively (Fig. 7.1). The more recent decline in the shrimp landings and concomitant significant increase in crab landings cannot yet be explained.

In recent years, *P. pelagicus* has become a source of income to many fishermen where they have specifically targeted this species. This specific fishery takes place within the coastal fishing grounds, particularly along the northern region of **Fasht Al Adhum** off the eastern coast of the Bahrain Island, as well as grounds along the north coastline of Bahrain Island and around Al Muharraq Island. The fishery is based on **Gargoor** with 5 cms mesh size. The number of fishermen involved and the extent of the catch is not known since no systematic means of data collection have been established.

In the Arabian Gulf generally, berried females fetch high market prices (Carpenters *et al.*, 1997). Bahrain is no exception with the average retail price for male crabs is BD. 0.4 kg^{-1}, but that for females is BD. 1.0 kg^{-1} (equivalent to £ 0.75 and £ 1.90 respectively). A large proportion of the Bahrain *P. pelagicus* catch is exported. From 1997-1999 the export trade increased from 800 mt to 1225 mt, corresponding to values of BD. 214,000 (£ 400,000), and 401,000 (£ 750,000) respectively (DOF, 1998, 2000).

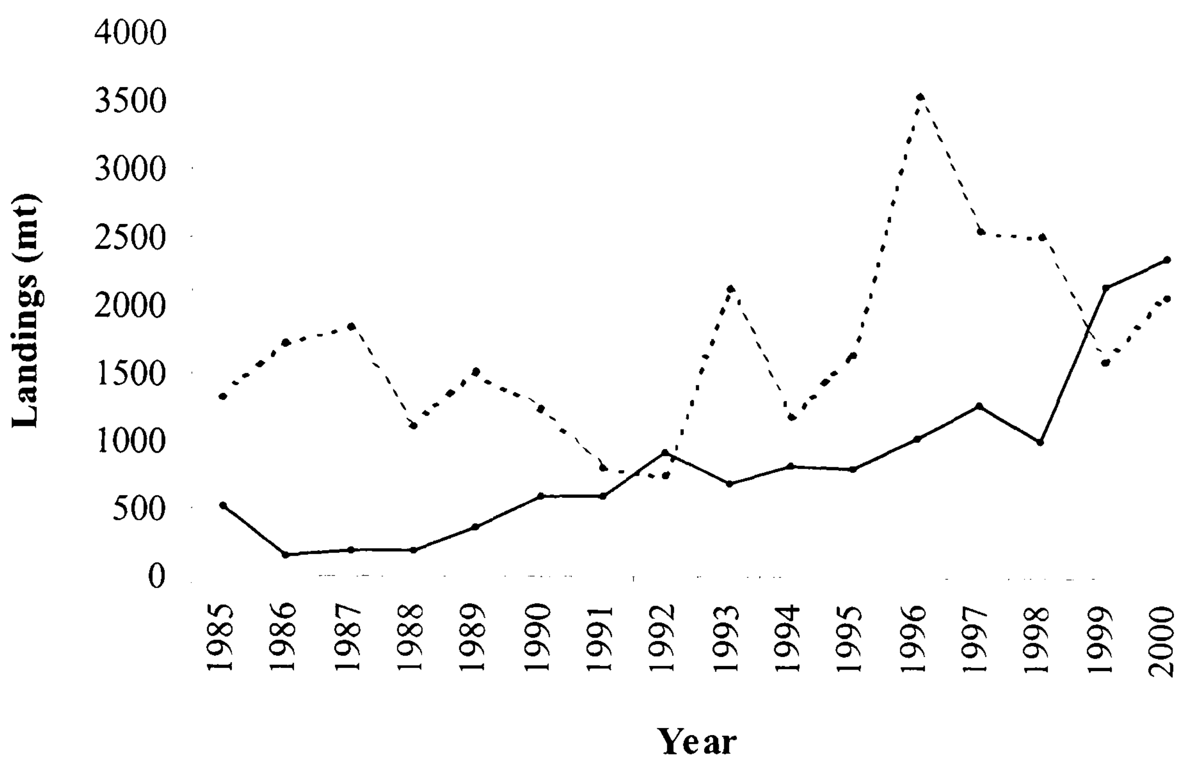


Figure 7.1. Landings (metric tons, mt) of the swimming crab, *Portunus pelagicus* (——) and the green tiger shrimp *Penaeus semisulcatus* (------) from the Bahraini fishing grounds, over the period from 1985 to 2000. Data are taken from Directorate of Fisheries (2001).

7.2 *Portunus pelagicus* fishing grounds

The findings of the present study have revealed that *P. pelagicus* occurs across an extensive area within Bahrain's traditional fishing grounds. According to their geographical locations, the fishing grounds were categorised into three major areas as follows: 1) area A represents the northern fishing grounds that are located between the western region of **Fasht Al Jarim** all the way to the Bahrain-Saudi boundary on the west, with a total area of 309 km^2, 2) area B represents the north and north-eastern grounds, extending over an area of 678 km^2 from the eastern region of **Fasht Al Jarim** in the west nearly to the Bahrain-Qatari boundary in the east, and 3) area C off the eastern coast of Bahrain Island, which is the second largest fishing ground with an overall area of 648 km^2, ranging from **Fasht Al Adhum** in the north all the way south to Hawar Islands. *P. pelagicus* is also found in most the coastal areas around Bahrain.

7.3 Environmental characteristics

P. pelagicus was found from shallow (1 metre [m]) to 20 m water depth as previously reported by Stephenson (1972). The crabs were most abundant in waters of 10 to 15 m depth. In areas A, B and C the water depth ranges are 5-14, 4-21 and 3-18 metres respectively. The substratum in area A is mainly sand with isolated patches of coral reef, whereas in area B it ranges from coral fragments in shallow water to sand and mud in deeper areas. The seabed in area C was a sandy-mud substratum with high faunal and floral diversity. The area particularly from grid 84 southwards, is known for the richness of its seagrass beds (Price *et al.*, 1984; Sims and Zainal, 1999) interspersed with *Sargassum* sp, a brown alga. Salinity in areas A and B ranged from 39-45‰, but in area C it was always higher and varied over a wide range from 41‰ in the north up to 53‰ in the south. Seawater temperature was similar in all areas, but varied seasonally from 16 to 35 °C.

7.4 Life history

Not a single soft-shelled (recently moulted) crab was found in the course of the study. This possibly indicates that moulting crabs bury in the seabed to protect themselves during this vulnerable stage. Such behaviour means they are likely not to be captured in the trawls.

The present study revealed that the breeding season of *P. pelagicus* is protracted, extending from March to November, when seawater temperatures range between 27-30 °C. *P. pelagicus* breeding activity ceases at temperatures below 20 °C, an observation previously noted by Smith and Sumpton (1989) and Sumpton *et al.* (1989). The highest numbers of ovigerous females were found in area B, where the overall proportion of ovigerous females was 25% of the total mature females in the area itself equivalent to 73% of all ovigerous females throughout the overall study region. Such a concentration of ovigerous females is an important finding for future fishery management. The larval sampling strategy that was carried out in the present study did not provide a detailed picture for the larval density and distribution over the fishing grounds due to the restricted number of samples and hence small water volumes filtered in each area every month. Nevertheless, the samples collected did indicate the presence of *P. pelagicus* larvae over all the fishing grounds, ranging from the coastal waters to 18 nautical miles off the northern shorelines of Bahrain and Al Muharraq Islands, especially during the summer months (viz. June-September). Larvae in area B were always associated with the presence of higher numbers of ovigerous females in the trawls. The absence of larvae in the southern region of study areas C and D is attributed to the high salinity levels (50-57‰). The larvae are probably unable to tolerate high salinities, unlike the juvenile crabs which were found in relatively high abundance in these areas. Seawater temperatures of 30-35 °C and moderate salinities (40-48‰) were most associated with the presence of *P. pelagicus* larvae.

The absence of larvae and ovigerous females between December 1999 and March 2000 (except for some ovigerous females in areas A and C in March 2000) provides strong evidence of short egg incubation period and larval development from hatching to first crab stage, otherwise larvae should have been found in December from being spawned in November. The observed short egg incubation period, i.e. 17-21 days at 25 °C is very close to that obtained by workers from Australia (Campbell and Fielder, 1988), Philippines (Ingles and Braum, 1989), Japan (Yatsuzuka, 1962) and India (Jose *et al.*, 1996), where the incubation period for eggs of *P. pelagicus* under laboratory conditions lasted from 5 to 27 days, the variation depending on seawater temperature and geographical region. Campbell and Fielder (1988) observed an inverse relationship between seawater temperature and egg incubation period, where duration becomes shorter as temperature increases. Jose *et al.* (1996) reported that each zoeal stage of *P. pelagicus* takes a minimum period of 2-3 days before moulting to the next stage with megalopae existing for 6-7 days. Considering the findings on larval development from India (Jose *et al.*, 1996) as the basis to predict larval development duration in Bahraini waters (both regions share similar environmental conditions), it will take about 19 days for larvae to develop through to the first crab stage.

7.5 Recruitment and nursery grounds

Sampling *P. pelagicus* during a major survey of shrimps in Bahraini waters provided the opportunity to identify the recruitment season, areas and nurseries for the crab. The present study indicates that areas A, C and D are the major recruitment grounds, where recruitment occurs at two seasons: 1) a short season from late spring to summer, which varied in timing between areas and 2) a prolonged season lasting up to four months (i.e.

December-April). Juvenile crabs were found to recruit to these areas at about 2 cms CW and 50% of the crabs of both genders were found to be < 3.75 cms CW. Indications that area A receives recruits from the adjacent Saudi fishing grounds needs further joint investigation between the fisheries agencies in both countries. Such liaison would help in managing any shared stock(s).

Similarly, the southern region of area A, northern of area C and whole of area D have been identified as major nursery grounds. These areas have rich algae and seagrass habitats in common as well as shallow waters, mostly less than 10 metres deep. Juvenile male and female crabs remain in these areas until they attain maturity at ~ 5.5 and 7 cms CW respectively.

7.6 Migration

The negligible number of juvenile crabs in area B as opposed to the high numbers of juveniles in other areas, clearly indicates that small-sized crabs do move to shallower areas, e.g. areas A, C and D, where they grow and attain maturity. Analysis of sex ratios, as well as crab size (CW) differences between adjacent areas (i.e. A-B and B-C), clearly indicate a pattern of mature female crab migration from areas A and C to the deeper water within area B. The high incidence of ovigerous females found in area B provides strong evidence that such females migrate to this area to spawn. This pattern of female migration has implications for management of the *P. pelagicus* stock. It is suggested that a tagging programme would prove useful in understanding more fully the *P. pelagicus* migration patterns within the Bahraini fishing grounds.

7.7 Growth

The results of the present study show that CW of crabs in areas A and B exhibits isometric relative growth with carapace length (CL), where CW remains proportional to CL (~ 1.7 greater). In area C, however, both dimensions indicated allometric growth with CL getting relatively shorter in the larger crabs. Male crabs are relatively heavier than females at > 2 cms CW, the differential becoming more pronounced with increasing size.

The higher exponents of male crabs over time as expressed by the carapace width-weight relationship, indicate the continued good conditions across the study area, particularly during the summer months, i.e. May-September.

In general, the time series of monthly CW frequency distributions indicate a clear seasonal pattern, with growth fastest in the summer. The mean growth rate for both genders was ~ 1.3 cms CW month^{-1}. The seasonal trend indicated the influence of temperature with growth ranging from 0.6 cms CW month^{-1} in winter (17 °C) to 1.5 cms CW month^{-1} in summer (35 °C). This high rate in summer is supported by the mathematical methods that expressed the growth coefficient "*K*" as 1.1-1.6 year^{-1}, confirming the fast growth exhibited by *P. pelagicus*. At an annual average of 1.05 cms CW month^{-1} it would be expected that a crab would attain a CW of 12-14 cms within year from initial post-larval settlement. Very few crabs sampled in the present study approached these dimensions which would suggest a lifespan of just over a year. Bryars and Adams (1999) have suggested a lifespan of three years for *P. pelagicus* in Australia. It is reported that *P. pelagicus* can grow to as large as 20 cms TCW (~ 17 cms CW) (Thomson, 1951; Pillai *et al.*, 1971b; Penn, 1977; Smith, 1982; Potter *et al.*, 1983 and Potter *et al.*, 1991), a size probably only reached by crabs in an unexploited stock.

Fluctuations in mean relative abundance of juvenile and mature *P. pelagicus* over all the study areas were found to be highly seasonal. Juvenile crabs were most often associated with high salinity, shallower waters and lower temperatures, whereas mature crabs were most often associated with low salinities, high temperatures and deeper waters. Occurrence of males and females also varied spatially and temporally, with more males occurring in study areas A and C and more females in area B.

7.8 Dual fishery concerns

Given that the trawling survey was specifically undertaken to sample the shrimp population, it is abundantly clear that *P. pelagicus* shares the same offshore fishing grounds with the commercial shrimp species, *Penaeus semisulcatus* De Haan, 1844 (Abdulqader, 1995). Hence, fishing pressure affects both resources simultaneously. The problem of managing the fishery for these two living marine resources revolves around differences in species biology and their relative commercial values of the separate fisheries. The resolution of the problem may require separate fisheries measures and regulations ensuring that both resources are conserved properly. Differences in species shape and migratory patterns, however, may mean that different, specific measures may be required but would be difficult to implement when the same habitats are occupied by both species. In Bahrain, shrimp fisheries are well established, where a number of ministerial decrees have been issued since 1980 in order to exploit the resource in an appropriate manner. Regulations that are already implemented in the shrimp management include: 1) control of the fleet size through registration and licensing, 2) a shrimp fishing closed season, 3) control of fishing effort per boat (Abdulqader, 1995). In the light of no regulations for the *P. pelagicus* fishery, any proposed management protocols for crabs will be inextricably linked to those operating for the shrimp fishery.

7.9 Suggestions for crab fishery management

7.9.1 Size limit

In Australia, one of the Queensland fishing regulations to protect the *P. pelagicus* stock is a complete ban on the capture of females and a size limit for males. Male crabs < 15 cms TCW (~ 12.5 cms CW) are not permitted to be taken (Sumpton *et al.*, 1989). In Bahrain consumers prefer female crabs. Thus, this study recommends prohibiting the taking of male crabs < 6 cms CW (~ 8 cms TCW) and females < 7 cms CW (~ 9 cms TCW) as they are immature. Such prohibition will enhance the fishery by allowing females below the proposed size limit to mature allowing the opportunity to spawn on at least one occasion, and for sufficient males to mature to fulfil their propagation role.

7.9.2 Ovigerous female prohibition

The high incidence of ovigerous females in area B as a consequence of their migration from areas A, C and the coastal grounds, suggest that it would be most appropriate to prohibit the taking of ovigerous females from within area B. All ovigerous crabs caught should be returned to the sea immediately. Also, this prohibition scheme needs to be implemented for ovigerous females in fishing grounds within areas A and C. Provided that proper enforcement is applied, such a regulation will be of enormous benefit in the management of the fishery.

7.9.3 Closed fishing grounds

The finding obtained by the present study that extensive regions of the study areas A, C and D are nursery grounds for *P. pelagicus*, is crucial in formulating fishery management protocols. Fig. 6.1 and Table 6.1 (see Chapter 6) clearly show sub-areas A2, C1 and the whole of area D as major nurseries (see Fig. 6.1). Price *et al.* (1984) and Abdulqader (1995) have classified the coastal area along the east coast of Bahrain Island (i.e. longitudinal grid BG) and the region to the south of **Fasht Al Adhum** (i.e. latitudinal grids 80-81), both situated within sub-area C1 of the present study, as nursery grounds for the shrimp, *P. semisulcatus*. The importance of these sub-areas (i.e. A2, C1 and D) provides strong evidence of the significance of these habitats for the crab and shrimp resources, as well as to other marine organisms. It is therefore proposed that trawling in these nursery grounds be banned. The use of small-scale artisanal fishing, using Gargoors, should be allowed provided the traps do not retain males < 6 cms CW and females < 7 cms CW. Such measures will protect the juveniles allowing them to reach adulthood, as well as protecting the seabed in the nursery grounds from unnecessary trawl damage.

7.9.4 Fishing gear

7.9.4.1 Offshore fishing grounds

Trawling is the only major fishing method to harvest shrimps and crabs in the offshore fishing grounds around Bahrain. Although trawling activity in Bahrain has been ongoing on a large scale over the last 35 years (FAO, 1978), studies on the ecological effect of the shrimp and finfish trawl nets on the marine environment have not been carried out [finfish trawling was banned completely in 1998 (DOF, year not determined)]. Also, studies on trawl net efficiency (i.e. the proportion of the animals in the trawl path that are actually captured by the net) and the gape of the trawl when in operation in Bahrain are lacking. Literature cited, such as Edwards and Steele (1968), Kaiser *et al.* (1994) and Somerton and Otto (1998), emphasises the need for trawl efficiency values as they are crucial for reliable estimates of density and hence biomass of benthos. The present study has highlighted the need to establish a research programme to investigate the trawl net gape and the catch efficiency of the shrimp trawls being used by Bahraini fishermen. Such a programme would allow more accurate estimates of the density and biomass of both the shrimp and crab resources.

Despite the importance of trawling for the offshore fisheries, there is however an environmental cost. Such ongoing activity may well have a significant impact on the benthic communities and may have disturbed or altered the marine habitat ecosystem significantly already (see Werner *et al.*, 1990; Kaiser, 1998; Lindeboom and Groot, 1998; Coggan and Atkinson, 2000). Therefore, the present study suggests a research programme be initiated for assessing the short and long-term effects of trawling and by-catch discards on the benthic ecology. This programme should be carried out in parallel with the aforementioned research on trawl and catch efficiencies.

7.9.4.2 Inshore fishing grounds

Concerning the fishing gear that is presently operated in coastal fishing grounds, i.e. Gargoor and Hadhrah, the present study recommends investigating the possibility of modifying such gear in order to increase fishing efficiency. As Gargoor fishing for *P. pelagicus* has been introduced as a new technique, where over recent years many fishermen have used this gear to harvest *P. pelagicus* as a target species, it is likely that the currently used Gargoor will experience significant advances in gear technology. Such advances could take the form of changes to Gargoor design [including shape, mesh size, number and shape of entrance(s)], bait type or its positioning within the Gargoor, boat size or design. Should managers plan to retain the Gargoor fishery, then the impact of such advances on crab stocks needs to be carefully considered in the future. In particular, there is a need to standardise on a particular Gargoor size and design, so that future catch and fishing effort statistics will be comparable. As for Hadhrah, the present study suggests a need for modification by increasing the mesh size to allow juvenile crabs to escape. Such implementation would also have a role in enhancing the fish stocks, as even very small fishes are presently caught in the trapping chamber of the Hadhrah.

7.10 Regional Cooperation in *P. pelagicus* studies

The hypothesised recruitment from the Kingdom of Saudi Arabia nursery(ies) to area A and quite likely from nursery(ies) off the western coast of the State of Qatar to area C, suggests that interaction between these crab stocks warrants investigation. It would therefore seem appropriate to establish exchange corporation programmes between the Bahraini-Saudi and Bahraini-Qatari fisheries agencies in order to develop an integrated survey for the region, which will mutually aid crab fishery management.

7.11 Proposed regulation summary and enforcement

Enforcement of the proposed fishery regulations is crucial to the success of any crab fishery management process. A set of ministerial decrees will need to be issued by the Bahrain government, which will cover the main recommendations of the present study, as follows:

- Prohibition of the taking of ovigerous females,
- Implementation of size limit. Only male and non-ovigerous female crabs larger than 6 and 7 cms CW (~ 8 and 9 cms TCW) respectively can be retained.
- Ban trawl fishing within sub-areas A2, C1 and the whole of area D.
- Monitoring fishermen involved in the fishery through limited licensing, boat registration schemes and careful collection of landing statistics.

Furthermore, the current study has highlighted the need for collecting catch per unit of effort (CPUE) data by the Fisheries Statistics Section of the Directorate of Fisheries on a regular basis. The data should then be used for estimating the maximum sustainable yield and routinely updated to provide predictions on the future state of the fishery. Advanced warning of fisheries problems obtained through realistic and reliable predictive models allows legislative authorities and enforcement agencies to be pro-active in maintaining the long term health of a valuable fishery.

These proposed regulations need to be supported and enforced by the Coast Guard authorities across the fishing grounds to safeguard the fishery. It is hoped that adoption of these recommendations by the authorities concerned will ensure the rational long-term exploitation of the *P. pelagicus* resource in Bahraini waters.

References

REFERENCES

Abd EL-Hamid, N.F. (1988). Size composition, sex ratio, size at maturity, mating and egg-laying in the crab *Portunus pelagicus* (Linnaeus). *Folia Morph.*, **36** (2): 200-210.

Abdulqader, E.A.A. (1995). Fisheries and aspects of the biology of Penaeid shrimps of Bahrain. Ph.D Thesis. University of Wales - Bangor, UK. 195 pp.

Abdulqader, E.A.A. & Naylor, E. (1995). Bionomics and migration patterns of the green tiger *Penaeus semisulcatus* De Haan, in Bahrain waters. *Fish. Res.* **21**: 395-407.

Abdulqader, E.A.A. (2000). Bycatch reduction device (BRD) experiments in Bahrain waters, February 1999 to January 2000. Biological and Environmental Research Program, Bahrain Centre for Studies and Research, 77.pp.

Abdulqader, E. A. A. (2001). Bahrain shrimp fishery and marine environment. in FAO, Tropical shrimp fisheries and their impact on living resources. Shrimp fisheries in Asia: Bangladesh, Indonesia, and the Philippines; in the Near East: Bahrain and Iran; in Africa: Cameroon, Nigeria, and the United Republic of Tanzania; in Latin America: Colombia, Costa Rica, Cuba, Trinidad and Tobago, and Venezuela. FAO Fisheries Circular No. 974, pp. 96-137.

Abdelrahman S.M. & Ahmad, F. (1995). A note on the residual currents in the Arabian Gulf. *Cont. Shelf Res.*, **15** (8): 1015-1022.

Abdel Razek, F.A. (1987). Crab fishery of the Egyptian waters with notes on the bionomics of *Portunus pelagicus* (L.). *Acta Adriat.*, **28** (1-2): 143-154.

Abdel Razek, F.A. (1988). Some biological studies on the Egyptian crab *Portunus pelagicus* (Linnaeus, 1766). *Acta Adriat.*, **29** (1-2): 133-143.

Aboul Naga, W.M. (1996). Comparative study of trace metals accumulated in the muscle tissues of the most common and marketable sea food in Alexandria waters. *Int. J. Environ Health Res.*, **6** (4): 289-300.

Addison, J.T. & Bannister R.C.A. (1994). Re-stocking and enhancement of clawed lobster stocks: a review. *Crustaceana*, **67** (2): 131-155.

AL-Baharna, W. S. (1986). Fishes of Bahrain. Ministry of Commerce and Agriculture, Bahrain, Directorate of Fisheries. 294 pp.

Alvarez, F., Hines, A.H. & Beaka-Kudla, M.L. (1995). The effects of parasitism by the barnacle *Loxothylacus panopaei* (Gissler) (Cirripedia : Rhizocephala) on growth and survival of the host crab *Rhithropanopeus harrisii* (Gould) (Brachyura : Xanthidae). *J. Exp. Mar. Biol. Ecol.*, **192**: 221-232.

Al-Rumaidh, M.J. (1995). Investigations on the biology and population dynamics of the edible swimming crab *Portunus pelagicus* (Linnaeus, 1758) in Bahrain waters. M.Sc. Dissertation. University of Wales - Bangor, UK. 79 pp.

Ameer Hamsa, K.M.S. (1973). Abnormality in the right chela of the portunid crab *Portunus pelagicus* Linnaeus. *Indian J. Fish.*, **20** (1): 231-232.

Ameer Hamsa, K.M.S. (1978a). On the meat content of *Portunus pelagicus* with some observation on lunar periodicity in relation to abundance, weight and moulting. *Indian J. Fish.*, **25** (1-2): 165-170.

Ameer Hamsa, K.M.S. (1978b). Fishery of the swimming crab *Portunus pelagicus* Linnaeus from Palk Bay and Gulf of Mannar. *Indian J. Fish.*, **25** (1-2): 229-233.

Ameer Hamsa, K.M.S. (1979). On the moulting of *Portunus pelagicus* Linnaeus. *Indian J. Fish.*, **26** (1-2): 247-249.

Ameer Hamsa, K.M.S. (1982). Observations on moulting of crab *Portunus pelagicus* Linnaeus reared in the laboratory. *J. mar. biol. Ass. India*, **24** (1-2): 69-71.

Ang, S.G. & Chong, P.S. (1998). Purification of metallothionein proteins from the crab, *Portunus pelagicus*-selectivity of hydrophobic interaction chromatography. *Talanta*, **45**: 693-701.

Anon, (1970). Crab research programme Leschenault Inlet Bunbury. *Nature Walkabout*, **3** (1): 18-27.

Anon, (1978). Blue manna crabs. *Nature Walkabout*, **14** (2): 66-69. October.

Apel, M. & Spiridonov, V.A. (1998). Taxonomy and zoogeography of the portunid crabs (Crustacea: Decapoda: Brachyura: Portunidae) of the Arabian Gulf and adjacent waters. *Fauna of Arabia*, **17**: 159-331

Archambault, J.A., Wenner, E.L. & Whitaker, J.D. (1990). Life history and abuandance of blue crab *Callinectes sapidus* Rathbun, at Charleston Harbor, South Carolina. *Bull. Mar. Sci.*, **46** (1): 145-158.

Atkins, W.S. & Partners (1985). Fashat Al-Adhom, environmental studies. Phase I. Report to Ministry of Housing, Bahrain.

Batoy, C. B., Sarmago, J. F. & Pilapil, B. C. (1987). Breeding season, sexual maturity and fecundity of the blue crab *Portunus pelagicus* (L.) in selected coastal waters in Leyte and Vicinity, Philippines. *Ann. Trop. Res.*, **9:** 157-177.

Batoy, C. B., Pilapil, B. C. & Sarmago, J. F. (1988). Size composition, distribution, length weight relationship and natural food of the blue crab *Portunus pelagicus* (L.) in selected coastal waters in Leyte and Vicinity, Philippines. *Ann. Trop. Res.*, **10** 3-4: 127-142.

Badawi, H.K. (1971). On the chemical composition of the red crab *Portunus pelagicus*. *Mar.Biol.*, **11** (3): 198-200.

Basson, P.W., Burchard, J. E., Hardy, J. T. & Price, A. R. (1981). Biotopes of the western Arabian Gulf, 2nd ed. Dept Loss Prevention and Environmental Affairs, Dhahran, Saudi Arabia. 284 pp.

Bawab, F.M. & El-Sherief, S.S. (1987). Cyclic changes in the histological structure of the ovaries of *Portunus pelagicus* (L.) (Crustacea-Brachyura). *Egypt. J. Histol.*, **10** (2): 297-307.

Beckley, L.E., Van der Elst, R.P., Chater, S.A. & Birnie, S.L. (1995). Fish trapping during the operation of the Durban Harbour Graving Dock, South Africa. *Sth. Afr. Aquat. Sci.*, **21** (1-2): 78-87.

Beyers, C.J.De B. (1994). Population size and density of the deep-sea red crab *Chaceon maritae* (Manning and Holthuis) off Namibia determined from tag-recapture. *S. Afr. J. mar. Sci.*, **14**:1-9.

Beverton, R.J.H. (1963). In: North Atlantic Fish Marking Symposium, Woods Hole, Mass., May 1961. *ICNAF Special Publication* No. 4, pp. 5-6.

Bishop, R.K. & Cannon, L.R.G. (1979). Morbid behaviour of the commercial sand crab *Portunus pelagicus* (L.), parasited by *Sacculina granifera* Boschma, 1973 (Cirripedia: Rhizocephalan). *J. Fish Dis.*, **2** (2): 131-144.

Bocquet-Vedrine, J. (1972). Les rhizocephales. *Cah. Biol. Mar.*, **13**:615-626.

Bookhout, C.G. & Costlow, J.D. Jnr. (1974). Larval development of *Portunus spinicarpus* reared in the laboratory. *Bull. Mar. Sci.*, **24** (1): 20-51.

Bookhout, C.G. & Costlow, J.D. Jnr. (1977). Larval development of *Callinectes similes* reared in the laboratory. *Bull. Mar. Sci.*, **27** (4): 704-728.

Boschma, H. (1955). The described species of the family Sacculindae, *Zool. Verh.*, No. 27:1-76.

Boschma, H. (1973). *Sacculina granifera* nov. sp., a rhizocephalan parasite of the crab *Potunus* (*Portunus*) *Pelagicus* (Linnaeus) from the coast of Queensland. *Proc. K. Ned. Akad. Wet.*, **76**: 313-318.

Broekhuysen, G.J. (1936). On development, growth and distribution of *Carcinides maenas* (L.). *Arch. Néerl. Zool.* **2**: 257-399.

Brown, D. & Rothery, P. (1993). Models in Biology, Mathematics, statistics and computing. Chichester: John Wiley and Sons. 688 pp.

Bryars, S.R. (1997). Larval dispersal of the blue swimmer crab *Portunus pelagicus* Linnaeus (Crustacea : Decapoda : Portunidae), in South Australia. Flinders University, Australia. Unpublished PhD thesis, 256 pp.

Bryars, S.R. & Adams, M. (1999). An allozyme study of the blue swimmer crab *Portunus pelagicus* (Crustacea : Portunidae), in Australia : stock delineation in southern Australia and evidence for a cryptic species in northern waters. *Mar. Freshwater Res.*, **50**: 15-26.

Bucke, D. (1972). Some histological techniques applicable to fish tissues. *Symp. Zool.Soc. Lond.* **30**: 153-189.

Campbell, B.M. & Stephenson, W. (1970). The sublittoral Brachyura (Crustacea : Decapoda) of Moreton Bay. *Memoirs of the Queensland Museum.* **15:** 271-272.

Campbell, G.R. (1984). A comparative study of adult sexual behaiveour and larval ecology of three commercially important portunid crabs from the Moreton Bay region of Queensland, Australia. Unpublished Thesis, University of Queensland, Australia.

Campbell, G.R. & Fielder, D.R. (1986). Size at sexual maturity and occurrence of ovigerous females in three species of commercially exploited portunid crabs in S. E. Queensland. *Proc. R. Soc., Qd.* **97:** 79-87.

Campbell, G.R. & Fielder, D.R. (1988). Egg extrusion and egg development in three species of commercially important portunid crabs from S.E. Queensland. *Proc. R. Soc. Qd.*, **99**: 93-100.

Campbell, A. (1994). Seashores and shallow seas of Britain and Europe. Hamlyn Limited (London). 320 pp.

Cargo, D.G. (1958). Sizes of crabs compared. **Md.** *Tidewater news.* **13** (3): 1-4.

Carpenter, K.E., Krupp, F., Jones, D.A., & Zajonz, U (1997). Living marine resources of Kuwait, Eastern Saudi Arabia, Bahrain, Qatar, and the United Arab Emirates. FAO/UN. Rome. 293 pp.

Chatterji, A., Ansari, Z.A., Ingole, B.S., Sreepada, R.A., Kanti, A. & Parulekar, A.H. (1994). Effect of lunar periodicity on the abundance of the crabs from the Goa coast. *Indian J. Mar. Sci.*, **23**: 180-181.

Cheung, T. S. (1966). An observation of copulation in the shore crab *Carcinus maenas* (L.). *Crustaceana.* **11:** 107-108.

Chhapgar, B.F. (1957). On the marine crabs (Decapoda : Brachyura) of Bombay State. *J. Bombay Nat. Hist. Soc.*, **54** (1): 399-439.

Chittleborough, R.G. (1975). Environmental factors affecting growth and survival of juvenile western rock lobsters *Panulirus longipes* (Milne Edwards). *Aust. J. Mar. Freshwater Res.* **26**: 177 pp.

Chopra, B. (1939). Some food prawns and crabs of India and their fisheries. *J. Bombay Nat.Hist. Soc.*, **4** (2): 221-234.

Churchil, E.P. (1919). Life history of the blue crab. *Bull. U.S. Bur. Fisher.*, **36**: 95-128.

Coggan, R. & Atkinson, J (2000). Scampi trawling – measuring impact and effort. In. 30th Annual Report. University Marine Biological Station Millport. Isle of Cumbrae, Scotland. pp. 12-14.

Costlow, J. D. Jr. & Bookout, C.G. (1959). Larval development of *Callinectes sapidus* Rathbun reared in the laboratory. *Biol. Bull.* **116:** 373-396.

Costlow, J.D. Jr., Bookhout C.G. & Rees G.H. (1959). Preliminary note on the complete larval development of *Callinectes sapidus* Rathbun under Laboratory conditions. *Limnol. Oceanogr.*, **4**: 222-223.

Costlow, J.D. Jr., Bookhout C.G. & Monroe R. (1962). Salinity-temperature effects on the larval development of the crab *Panopeus herbsti* Milne Edwards, reared in the laboratory. *Physiol. Zool*, **35**: 79-93.

Costlow, J.D. Jr., Bookhout, C.G. & Monroe, R. (1966). Studies on the larval development of the crab *Rhithropanopeus harrisii* (Gould), I. The effect of salinity and temperature on larval development. *Physiol. Zool*, **39** (2): 81-100

Costlow, J.D Jr. (1967). The effect of salinity and temperature on survival and metamorphosis of megalopa of the blue crab *Callinectes sapidus*. *J. Helgol, Wiss. Meeresunters.*, **15**: 84-97.

Costlow, J.D., Bookhout, C.G. & Monroe, R. (1971). The effect of salinity and temperature on larval development of *Sesarma cinereum* (BOSC) reared in the laboratory. *Biol. Bull. Mar. Biol. Lab.* (Wood Hole), 118: 183-202.

Darnell, R.M. (1959). Studies of the life history of the blue crab (*Callinectes sapidus* Rathbun) in Louisiana waters. *Trans. Amer. Fish. Soc.*, **88**: 294:304

Daugherty, S.J. (1969). Aspects of ecology, life history, and host-parasite relationship of *Loxothylacus panopaei* (Sacculinidae) in Chesapeake Bay. M.A. Thesis, College of William and Mary, Williamsburg, Virginia. 68 pp.

Davidson, R. J. (1986). Mussel selection by the paddle crab *Ovalipes catharus* (White): evidence of flexible foraging behaviour. *J. Exp. Mar. Biol. Ecol.* **102:** 281-299.

Dionysius, D.A.; Hoek, K.S.; Milne, J.M. & Slattery, S.L. (1993). Trypsin-like enzyme from sand crab *Portunus pelagicus*: purification and characterization. *J. Food Sci.*, **58** (4): 780-792.

Day, J.H. (1935). The life-history of *Sacculina*. *Quart. J. Micros. Sci.*, **77**: 549-583.

Delage, Y. (1884). Évolution de la *Sacculine*. *Arch. Zool. Exp. gén*, tom. ii, sér. 2.

Devi, S. L. (1985). The fishery biology of the crabs of Kakinada region (India). *Indian J. Fish.*, **32** (1): 18-32.

Dhawan, R.M., Dwivedi, S.N. & Rajamanickam, G.V. (1976). Ecology of the blue crab *Portunus pelagicus* (Linnaeus) and its potential fishery in Zuzri Estuary. *Indian J. Fish.*, **23** (1-2): 57-64.

Diehl, W.J. & Biesiot, P.M. (1994). Relationships between multilocus heterozygosity and morphometric indices in a population of the deep-sea red crab *Chaceon quinquedens* (Smith). *J. Exp. Mar.Biol. Ecol.*, **182**: 237-250.

Dionysius, D.A., Hoek, K.S., Milne, J.M., & Slattery, S.L. (1993). Trypsin-like enzyme from sand crab *Portunus pelagicus*: purification and characterization. *J. Food Sci.*, **58** (4): 780-792.

DOF (year is not determined). Exploitation and conservation legislations of fisheries resources. Ministry of Works and Agriculture, Directorate of Fisheries, Bahrain. 38 pp.

DOF (1998). Annual statistical report 1997, Ministry of Works and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 70. 90 pp.

DOF (1999). Annual statistical report 1998, Ministry of Works and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 75. 85 pp.

DOF (2000). Annual statistical report 1999, Ministry of Housing and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 78. 84 pp.

DOF (2001). Annual statistical report 2000, Ministry of Housing and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 81. 85 pp.

Du Pereez, H.H. (1984). Molluscan predation by *Ovalipes punctatus* (De Haan) (Crustacea : Brachyura : Portunidae). *J. Exp. Mar. Biol. Ecol.* **84**: 55-71.

Eales, A. J. (1974). Sex pheromone in the shore crab *Carcinus maenas*. and the site of its release from females. *Mar. Behav. Physiol.* **2**: 345-355.

Edgar, G.J. (1990). Predator-prey interactions in seagrass beds. II. Distribution and diet of the blue manna crab *Portunus pelagicus* Linnaeus at Cliff Head, western Australia. *J. Exp. Mar. Biol. Ecol.*, **139** (1-2): 23-32.

Edwards, R.L. (1958). Movements of individual members in a population of the shore crab *Carcinus maenas* L. in the littoral zone. *J. Animal Ecol.*, **27**: 37-45.

El-Faer, Z.M.; Rawdah, T.N. Attar, K.M. & Arab M. (1992). Mineral and proximate composition of some commercially important fish of the Arabian Gulf. *Food Chemistry*, **45**: 95-98.

Elner, R.W. (1978). The mechanics of predation by the shore crab *Carcinus maenas* (L.), on the edible mussel *Mytilus edulis* L. *Oecologica.* **36**: 333-344.

Estrella, B.T. & Morrissey T.O. (1997). Seasonal movement of offshore american lobster *Homarus americanus* tagged along the eastern shore of Cape Cod, Massachusetts. *Fish. Bull.*, **95** (3): 466-476.

Evans, C.R. & Lockwood, A.P.M. (1994). Population field studies of the Guinea Chick lobster (*Panulirus guttatus* Latreille) at Bermuda: abundance, catchability, and behavior. *J. of Shellfish Research.*, **13** (2): 393-415.

Evian, C.I. (1971). The dentition of the Brachyura. *J. Dental Association of South Africa.*, **26** (6): 216-218.

FAO, (1985). Fishery Statistics, "Catches and Landings". FAO Yearbook. **60:** 463p. (Italy).

FAO, (1992). Fishery Statistics, "Catches and Landings". FAO Yearbook. **74:** 680p. (Italy).

Fielder, D.R. & Greenwood, J.G. (1979). Larval development of the swimming crab *Thalamita danae* Stimpson, 1858 (Decapoda, Portunidae), reared in the laboratory. *Proc. R. Soc. Qd.*, **90**: 13-20.

Fielder, D.R. & Eales, A.J. (1972). Observation on courtship, mating and sexual maturity in *Portunus pelagicus* (Linnaeus, 1766) (Crustacea : Portunidae). *J. Nat. Hist.*, **6**: 273-277.

Fischler, K. J. (1959). Occurrence of extremely small ovigerous crabs (*Callinectes* sp.) in coastal North Carolina. *Ecology.* 40: 720.

Foxon, G.E.H. (1940). Notes on the life history of *Sacculina carcini* Thompson. *J. of the Mar. Biological Association, UK.*, **24** (1): 253-264.

Garcia, S. & Le Reste, L. (1981). Life cycles, dynamics, exploitation and assessment of coastal Penaeid shrimp stocks. FAO Fisheries Technical Papers. **203**: 215p. (Italy).

Garrod, D.J. (1963). The application of a method for the estimation of growth parameters from tagging data at unequal time intervals. In: North Atlantic Fish Marking Symposium, Woods Hole, Mass., May 1961. *ICNAF Special Publication* No. 4, pp. 258-261.

Garth, J. S. and Stephenson, W. (1966). Brachyura of the pacific coast of America, Brachyura : Portunidae. *Allan Hancock Monog. Mar. Biol.*, 1, 154 pp.

Gayanilo Jr, F.C., Sparre, P. & Pauly, D. (1996). *FAO-ICLARM stock assessment tools, User Manual.* Rome: International Centre for Living Aquatic Resources Management (LCLARM), 126 pp.

Gleeson, R. A. (1980). Pheromone communication in the reproductive behaviour of the blue crab *Callinectes sapidus. Mar. Behav. Physiol.* **7:** 119-134.

George, M.J. (1949). Early stages in the development of *Sacculina* sp. parasitic on *Neptunus sanguinolentus* from Madras. *Proc. Indian Acad. Sci.*, **B30**: 207-214.

George, M.J. (1963). The anatomy of the crab *Neptunus sanguinolentus* Herbest. 4. Reproductive system and embryological studies. *Journ. Madras. Univ.*, (B) **33**: 289-304.

Giard, A. (1887). Parasitic castration and its influence upon the external characters of the male sex in the Decapoda Crustacea. *Ann. & Mag. N. Hist.*, Ser. 5, **19** (113): 325-345.

Giese, A.C. & Pearse, J.S. (1974). in Reproduction of marine invertebrates by Giese, A.C. & Pierse, J.S. (Academic Press, New York), 1.

Gnanamuthu, C.P. (1954). *Choniosphaera indica*, a copepod parasitic on the crab *Neptunus* sp. *Parasitilogy*, **44**: 371-378.

Gomes, V. (1991). First results of tagging experiments on the crab *Carcinus maenas* (L.) in the Ria de Aveiro Lagoon-Portugal. *Cienc. Biol. Ecol. Syst.* (Portugal), **11** (1-2): 21-29.

González-Gurriarán, E & Freire, J. (1994). Sexual maturity in the velvet swimming crab *Necora puber* (Brachyura, Portunidae): morphometric and reproductive analysis. *J. mar. Sci.* **51**: 133-145.

Gray, E.H. & Newcombe, C.I. (1938). Studies in the moulting in *Callinectes sapidus* Rathbun. *Growth*, **2**: 285.

Gray, C.A., McDonall, V.C. & Reid, D.D. (1990). By-catch from prawn trawling in the Hawkesbury River, New South Wales: species composition, distribution and abundance. *Aust. J. Mar. Freshwater Res.*, **41**: 13-26.

Greenwood, J.G. & Fielder, D.R. (1979). The zoeal stages and megalopa of *Portunus rubromarginatus* (Lanchester) (Decapoda : Portunidae), reared in the laboratory. *J. Plankton Res.*, **1** (2): 191-205.

Gribble, N.A. & Thorne M.T. (1998). Locomotor activity, track and pattern of movement over 24 hours of the crab *Portunus pelagicus* (Linnaeus) in a sub-tropical tidal passage. *Proc. R. Soc. Qd.*., **107**: 35-43.

Haefner, P.A. & Shuster, C.N. (1964). Length increments during terminal molt of the female blue crab *Callinectes sapidus* in different salinity environments. *Chesapeake Sci.*, **5** (3): 114-118.

Haley, S.R. (1973). On the use of morphometric data as a guide to reproductive maturity in the ghost crab *Ocypoda ceratopthalmes* (Pallas) (Brachyura, Ocypodidae). *Pac. Sci.*, **27**: 350-362.

Harrison, K.E. (1990). The role of nutrition in maturation, reproduction and embryonic development of decapod crustaceans: A review. *J. Shellfish Res.* **9** (1): 1-28.

Hartnoll, R.G. (1967). The effects of sacculinid parasite on two Jamaican crabs. *J. Linn. Soc. (Zool.)*, **46**: 275-295.

Hartnoll, R.G. (1969). Mating in Brachyura. *Crustaceana.*, **16:** 161-181.

Hartnoll, R.G. (1974). Variation in growth pattern between some secondary sexual characters in crabs (Decapoda : Brachyura). *Crustaceana.*, **27** (2): 131-136.

Hasselblad, V. (1966). Estimation of parameters for a mixture of normal distributions. *Technometrics*, **8**: 431-444.

Haesman, M.P., Fielder, D.R. & Shepard, R.K. (1985). Mating and spawning in the mud crab, *Scylla serrata* (Forskal) (Decapoda, Portunidae). *Aust. J. Mar. Freshwater Res.* **36**: 773-783.

Hayes, M.L. (1963). King crab tagging methods in Alaska. In: North Atlantic Fish Marking Symposium, Woods Hole, Mass., May 1961. *ICNAF Special Publication* No. 4, pp. 262-265.

Hilbish, T.J. (1996). Population genetics of marine species: the interaction of natural selection and historically differentiated populations. *J. Exp. Mar. Biol. Ecol.*, **200**: 67-83.

Hill, B.J. (1975). Abundance, breeding and growth of the crab *Scylla serrata* in two South African estuaries. *Mar. Biol.*, **32**: 119-126.

Hill, B.J. (1976). Natural food, foregut clearance-rate and activity of the crab *Scylla serrata*. *Mar. Biol.*, **34**: 109-116.

Hill, B.J. (1980). Effects of temperature on feeding and activity in the crab *Scylla serrata*. *Mar.Biol.*, **59**: 189-192.

Hilmy, A.M., Abdul-Hamid, N.F. & Ghazaly, K.S. (1985). Toxic effects of both zinc and copper in size and sex of *Portunus pelagicus* (L) (Crustacea : Decapoda). *Bull. Inst. Oceanogr. & Fish. ARE.*, **11**: 207-215.

Hilmy, A.M., Abd El-Hamid, N.F. & Adham, KH. G. (1986). Glycogen content of some organs in two marine crustaceans. *Bull. Inst. Oceanogr. & Fish. ARE.*, **12**: 215-229.

Hilmy, A.M.; Abd El-Hamid, N.F. & Adham, KH. (1988a). Changes in lipid and cholesterol composition in relation to sex and the moult cycle in the crab *Portunus pelagicus* (L.) and the prawn *Penaeus kerathurus* (L.). *Folia Morph.*, **36** (2): 141-159.

Hilmy, A.M., Abdul-Hamid, N.F. & Ghazaly, K.S. (1988b). Observations on intraspecific variation of total protein, amino acid and total nonprotein compound levels and their fractions in the muscles, heptopancreas and gonads of two crustaceans, *Portunus pelagicus* (L.) and *Penaeus kerathurus* (L.), in relation to maturation. I. Total protein and amino acids. *Folia Morph.*, **36** (2): 188-199.

Høeg, J.T. (1995). Functional and evolutionary aspects of the sexual in the Rhizocephala (Crustacea: Cirripedia: Rhizocephala). In, Crustacean sexual biology, edited by R. Bauer and J. Martin, Columbia University, New York, pp. 208-227.

Høeg, J.T. & Lützen, J. (1995). Life cycle and reproduction in the Cirripedia Rhizocephala. *Oceanogr. Mar. Biol.*: An annual review, **33**: 427-485.

Holden, S., Kirkwood, G.P. & Bravington, M.V. (1995). *LFDA, version 4.01 User Manual*. London: MRAG Ltd, 43 pp.

Hudson, D.A. & Shields, J.D. (1994). *Hematodinium australis* n. sp., a parasite dinoflagellate of the sand crab *Portunus pelagicus* from Moreton Bay, Australia. *Dis. aquat. Org.*, **19** (2): 109-119.

Hudson, D.A. & Adlard, R.D. (1994). PCR techniques applied to *Hematodinium* spp. and *Hematodinium*-like dinoflagellates in decapod crustaceans. *Dis. aquat. Org.*, **20** (3): 203-206.

Hughes, P.& Hunter, J.R. (1979). Physical oceanography and numerical modelling of the Kuwait Action Plan region. UNESCO, Division of Marine Sciences, report MARINE/27.

Hughes, R.N. & Seed, R. (1981). Size selection of mussels by the blue crab *Callinectes sapidus*: energy maximizer or time minimizer? *Mar. Ecol. Porg. Ser.*, **6**: 83-89.

Hunter, J.R. (1982). The physical oceanography of the Arabian Gulf: A review and theoretical interpretation of previous observations. Presented at the first Conference on Environment and Pollution. Kuwait, 7-9 February 1982.

Hyland, S.J., Hill, B.J. & Lee, C.P. (1984). Movement within and between different habitats by the portunid crab *Scylla serrata*. *Mar. Biol.*, **80** (1):57-61.

Hyslop, E.J. (1980). Stomach contents analysis-a review of methods and their application. *J. Fish Biol.*, **17**: 411-429.

Ingle, R. (1992). Larval stages of Northeastern Atlantic crabs "An Illustrated Key". 363p. Natural History Museum Publication. Chapman and Hall. (London).

Ingles, J.A. & Braum, E. (1989). Reproduction and larval ecology of the blue swimming crab *Portunus pelagicus* in Ragay Gulf, Philippines. *Int. Revue. ges. Hydrobiol.*, **74** (5): 471-490.

Jacob, R., Prasad, P. N. & Kusuma, M. S. (1990). Maturity and dimensional studies in female crabs of *Portunus sanguinolentus* and *P. pelagicus* (Decapoda : Portunidae). *Indian J. Mar. Sci.*, **19** (3): 221-223.

James, P.S.B.R. (1966). On an anomaly in the cheliped of the portunid crab *Portunus pelagicus* (Linnaeus). *J. Mar. Biol. Assoc. India.*, **8** (1-2): 218-220.

James, I.R. (1991). Estimation of von Bertalanffy growth curve parameters from recapture data. *Biometrics*, **47**: 1519-1530.

Jesperson, A. & Lützen, J. (1992). *Thompsonia dofleini*, a colonial akentrogonid rhizocephalan with dimorphic, ova- or sperm-producing, externae (Crustacea : Cirripedia). *Zoomorphology*, **112** (2): 105-116.

Joel, D.R. & Sanjeeva, Raj P.J. (1981). Epizoic fauna of some portunid crabs of the Pulicat Lake. *Biol. Ass. India*, **23** (1-2): 173-180.

Jones, D. A. (1986). A field guide to the sea shores of Kuwait and the Arabian Gulf. University of Kuwait. U. K. 192 pp.

Jose, J., Arputharaj, M.R. & Viramani, A. (1996). Larval rearing of the crab *Portunus pelagicus* (Crustacea, Protunidae) in hatchery at Mandapam Regional Centre of CMFRI. Marine Fisheries Information Service Technical Extension Series of CMFRI. **143**: 23-24.

Judy, M.H. & Dudley, D.L. (1970). Movements of tagged blue crabs in north Carolina waters. *Commerc. Fish. Rev.*, **32**: 29-35.

Kabata, Z. (1963). Parasites as biological tags. In: North Atlantic Fish Marking Symposium, Woods Hole, Mass., May 1961. *ICNAF Special Publication* No. 4. pp. 31-37.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. & Grieve, C. (1993). Australian Fisheries resources. Bureau of Resources Sciences and the Fisheries Research and Development Corporation: Canberra, Australia. 422 pp.

Kaiser, M.J., Rogers, S.I. & McCandless, D.T. (1994). Improving quantitative surveys of epibenthic communities using a modified 2 m beam trawl. *Mar. Ecol. Prog. Ser.* **106:** 131-138.

Kaiser, M.J. (1998). Significance of Bottom-Fishing Disturbance. *Conserv. Biol.*, **12** (6): 1230-1235.

Kangas, M.I (2000). Synopsis of the biology and exploitation of the blue swimmer crab, *Portunus pelagicus* Linnaeus, in Western Australia. *Fish. Res. Rep. Fish. West. Aust*, **121**, 22 pp.

Kawamura, G., Matsuoka, T., Tajiri, T., Nishida, M. & Hayashi M. (1995). Effectiveness of a sugarcane-fish combination as bait in trapping swimming crabs. *Fish. Res.*, **22** (1-2): 155-160.

Kelly, G.F. & Barker, A.M. (1963). Estimation of population size and mortality rates from tagged redfish *Sebastes marinus* L. at Eastport Maine. In: North Atlantic Fish Marking Symposium, Woods Hole, Mass., May 1961. *ICNAF Special Publication* No. 4, pp. 204-209.

Kimball, D.C. & Helm, W.T. (1971). A methods of estimating fish stomach capacity. *Trans. Amer. Fish. Soc.*, **100** (3): 572-575.

King, M. (1995). Fisheries biology assessment and management. Oxford: Fishing News Books, Blackwell Science, 341 pp.

Kinne, O. (1963). The effect of temperature and salinity on marine and brackishwater animals. I. Temperature. *Oceanogr. Mar. Biol.*; An annual review. **1**: 301-340.

Kittredge, J.S. & Takahashi, F.T. (1971). Sex pheromone activity of the moulting hormone, crustecdysone, on male crabs (*Pachygrapsus crassipes*, *Cancer antennarius*, and *C. anthonyi*). *Fishery Bull. Fish Wildl. U.S.* **69**: 337-343.

Krishnan, T. & Kannupandi, T. (1990). Laboratory cultured zoeae, megalopa and first crab of the estuarine crab *Thalamita crenata* (Latr.) A. Milne Edwards 1861 (Brachyura : Portunidea). *Mahasagar*, **23** (2): 139-152.

Kurata, H. & Midorikawa, T. (1975). The larval stages of the swimming crabs *Portunus pelagicus* and *Portunus sanguinolentus* reared in the laboratory. *Bull. Nasei Reg. Fisg. Res. Lab.*, **8:** 29-38.

Kuris, A.M. & Lafferty, K.D. (1992). Modelling crustacean fisheries: effects of parasites on management strategies. *Can. J. Fish. Aquat. Sci.*, **49**: 327-336.

Lardner, R.W., Lehr, W.J., Fraga, R.J., & Sarhan, M.A. (1988). A model of residual currents and pollutant in the Arabian Gulf. *Appl. Math. Modelling,* **12**: August 379-390.

Le Cren, E.D. (1965). A note on the history of mark-recapture population estimates. *J. of Animal Ecology*, **34**: 453-454.

Lee, S.Y. (1996). Distribution pattern and interaction of two infaunal bivalves. *Tapes philippinarum* (Adams and Reeve) and *Anomalocardia squamosa* (Linnaeus) (Bivalvia: Veneridae). *J. Exp. Mar. Biol. Ecol.* **201**: 253-273.

Lester, R.J.G. (1978). Marine parasite costly for fishermen. *Aust. Fish.*, **39** (10): 32-33.

Lester, R.J.G. (1980). Marine parasitology research aiding industry. *Aust. Fish.*, **39** (10): 13-15.

Lewis, C.T. and Short, C. (1879). A Latin Dictionary. (Oxford University Press: London).

Li, G., Shen, Q. and Xu, Z. (1993). Morphometric and biochemical genetic variation of the mitten crab *Eriocheir*, in southern China. *Aquaculture*, **111**: 103-115.

Lindeboom, H.J & Groot, S.J. (1998). The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems (Impact-II). NIOZ-REPORT 1998 – 1, RIVO-DLO REPORT C003/98. Nethellands Institute for sea research, 404 pp.

Lo, Chu-Fang, Ho, Ching-Hui, Peng Shao-En, Chau-Huei, Hsu Hui-Chen, Chiu Ya-Lin, Chang Chen-Fang, Liu Kuan-Fu, Su Mao-Sen, Wang Chung-Hsiung, & Kou Guang-Hsiung (1996). White spot syndrome baculovirus (WSBV) detected in cultured and captured shrimp, crabs and other arthropods. *Dis. Aquat. Org.*, **27** (3): 215-225.

Maclean, S.A. & Ruddell, C.L. (1978). Three new crustacean hosts for the parasitic dinoflagellate *Hematodinium perezi* (Dinoflagellata : Syndinidae). *J. Parasitol*, **64** (1): 158-160.

Manohara Ram, B.H. & Chandra Mohan, K. (1978). Some preliminary observations on the trend in commercial crab fishery of Mangalor. *Seafood Export. J.*, **10** (5): 25-27.

Marichamy, R. & Rajapackiam, S. (1984). Culture of larvae of *Scylla serrata*. Marine Fisheries Information Service. Technical and Extension Series, No. 85, pp. 13-15. Central Marine Fisheries Research Institute, Cochin, India.

McMillen-Jackson, A.L., Bert, T.M. & Steele, P. (1994). Population genetics of the blue crab *Callinectes sapidus*: modest population structuring in a background of high gene flow. *Mar. Biol.*, **118**: 53-65.

Meagher, T.D. (1971). The larval ecology of the blue swimming crab *Portunus pelagicus* in south western Australia. *Aust. Mar. Sci. Bull.*, **32**: 10-16.

Melville-Smith, R. (1987). Movements of deep-sea red crab *Geryon maritae* off south west Africa/Namibia. *S. Afr. J. Zool.*, **22** (2): 143-152.

Melville-Smith, R. & Chubb, C.F. (1997). Comparison of dorsal and ventral tag retention in western rock lobsters, *Panulirus Cygnus* (George). *Mar. Freshwater Res.*, **48**: 577-580.

Melville-Smith, R, Cliff, M. and Anderton, S.M. (1999). Catch, effort and the conversion from gill nets to traps in the Peel-Harvey and Cockburn Sound blue swimmer crab (*Portunus pelagicus*) fisheries. *Fish. Res. Rep. Fish. West. Aust*, **113**, 24 pp.

Meyer, R.M. (1974). Marking fishes and invertebrates. IV. A nonpermanent tag for King Crabs *Paralithodes camtschatica* and Tanner Crabs *Chionoecetes bairdi. Marine Fisheries Review*, **36** (7): 14-16.

Meyers, T.R., Koeneman, T.M., Botelho, C. & Short, S. (1987). Bitter crab disease: a fatal dinoglagellate infection and marketing problem for Alaskan Tanner *Chionoecetes bairdi. Dis. Aquat.Org.* **3**: 195-216.

Meyers, T.R. (1990). Diseases caused by protistans and metazoans. In: Kinne, O. (ed.) Diseases of marine Animals. Vol. III. Biologische Anstalt Helgoland, Hamburg, p. 350-400.

MHME (1997). Tidal stream atlas. Published by the Survey Directorate (Hydrographic Section), Ministry of Housing, Municipality and Environment, State of Bahrain. 18 pp.

Morgan, L.E., Wing, S.R., Botsford, L.W., Lundquist, C.J. & Diehl, J.M. (2000). Spatial variability in red sea urchin (*Strongylocentrotus franciscanus*) recruitment in northern California. *Fish. Oceanogr*, **9**: 83-98.

Moriyasu, M., Landsburg, L. & Conan, G.Y. (1995). Sphyrion tag shedding and tag induced mortality of the American lobster *Homarus americanus* H. Milne Edwards, 1837 (Decapoda : Portunidae). *Crustaceana*, **68** (2): 184-192.

Mortimer, M.R. & Miller, G.J. (1994). Susceptibility of larval and juvenile instars of the sand crab *Portunus pelagicus* (L.) to sea water contaminated by chromium, nickel and copper. *Aust. J. Mar. Freshwater Res.*, **45** (7): 1107-1121.

Mortimer, M.R. & Connell, D.W. (1995). Effect of exposure to chlorobenzenes on growth rates of the crab *Portunus pelagicus* (L). *Environ. Sci. Technol.*, **29** (8):1881-1886.

Motoh, H., de la Pena, D., Dimaano, M. & Tampos, E. (1978). Preliminary report on the first production of the crab stages of Alimasag *Portunus pelagicus* (Linnaeus). *Quarterly Res. Rep.*, **2** (3): 16-21.

Motoh, H. (1980). Field guide of the edible Crustacea of the Philippines. SEAFDEC Aquaculture Dept., Iloilo, Phil. pp 72-73.

Munch-Peterson, S., Sparre, P. & Hoffmann, E. (1982). Abundance of the shore crab *Carcinus maenas* from mark-recapture experiments. *Dana*, **2**: 97-121.

Nagaraj, M. (1993). Combined effects of temperature and salinity on the zoeal development of the green crab *Carcinus maenas* (Linnaeus, 1758) (Decapoda : Portunidae). *Scientia Marina*, **57** (1): 1-8.

Neverauskas, V.P. & Butler, A.J. (1982). Tolerance of blue crab *Portunus pelagicus* (L.) to high temperature. *Transactions. Royal Society of South Australia*, **106** (3-4): 215-216.

Newman, M.W. & Johnson, C.A. (1975). A disease of blue crab *Callinectes sapidus* caused by a parasitic dinoflagellate *Hematodinium* sp. *J. Parasitol*, **63** (3): 554-557.

Newman, W.A. & Ross A. (1976). Revision of the balanomorph barnacles; including a catalog of the spoecies. Menoir 9, San Diego Society of Natural History. 108 pp.

Norse, E.A. (1978). An experimental gradient analysis : hyposalinity as an "upstress" distributional determinant for Caribbean portunid crabs. *Biol. Bull.*, **155**:586-598.

Omari, M. & Akeda, T. (1984). Fixation and preservation of samples. In: Methods in marine zooplankton ecology. A Wiley-Interscience Publication, 33 pp.

Ong Kah Sin, (1964). The early developmental stages of *Scylla serrata* Forskal (Crustacea Portunidae), reared I the laboratory. *Proc. Indo-Pacific Fish. Coun.*, **11**: 135-146.

Oshima, S. (1938). Biological and fishery research in Japanese blue crab (*Portunus trituberculatus*) (Miers). *Journ. imp. Fish. exp.* Sta., **9**: 208-212.

Overstreet, R.M. (1983). Metazoan symbionts of crustaceans. In, *The biology of the Crustacea, Vol.* **6**, edited by A.J. Provenzano, Academic Press Inc., pp. 156-251.

Patel, N.M., Chhaya, N.D. & Bhaskaran, M. (1979). Stomach contents of *Portunus pelagicus* (Linn.) from AD net catches. *Indian J. Mar. Sci.*, **8** (1): 48-49.

Paula, J. (1988). The larval and post-larval development of Pennant's swimming crab, *Portumnus latipes* (Pannant) (BRACHTUEA : PORTUNIDAE), reared in the laboratory. *Crustaceana*. **55** (2): 202-216.

Pauly, D. (1983). Some simple methods for the assessment of tropical fish stocks. FAO Fisheries technical paper no. 234. Food and Agriculture Organisation of the United Nations, Rome. 52 pp.

Penn, J.W. (1977). Trawl caught fish and crustaceans from Cockburn Sound. Report, Department of Fishery and Wildlife, Western Australian **20**: 1-24.

Peterson, C.H. (1991). Intertidal zonation of marine invertebrates in sand and mud. *Amer. Sci.*, **79**: 236-249.

Phillips, B.F. Palmer, M.J. Cruz, R. & Trendall, J.T. (1992). Estimating growth of the spiny lobsters *Panulirus cygnus*, *P. argus* and *P. ornatus*. *Aust. J. Mar. Freshwater Res.*, **43**: 1177-1188.

Phillips, W.J. (1978). Some parasitic barnacles (Rhizocephala : Sacculinidae) from portunid crabs in Moreton Bay, Queensland. *Mem. Qd. Mus.*, **18** (2): 255-263.

Phillips, W.J. & Cannon, L.R.G. (1978). Ecological observations on the commercial sand crab *Portunus pelagicus* (L.) and its parasite *Sacculina granifera* Boschma 1973 (Cirripedia : Rhizocephala). *J. fish Dis.*, **1** (2):137-149.

Pillai, K.K. & Nair, N.B. (1971a). The annual reproductive cycles of *Uca annulipes*, *Portunus pelagicus* and *Metapenaeus affinis* (Decapoda : Crustacea) from the south-west coast of India. *Mar. Biol.*, **11**: 152-166.

Pillai, K.K. & Nair, N.B. (1971b). The reproductive cycle of three decapod crustaceans from the south-west coast of India. *Current Sci.* **40** (7): 161-162.

Pillai, K.K. & Nair, N.B. (1973). Observation on the breeding biology of some crabs from the southwest coast of India. *J. mar. boil. Ass. India*, **15** (2): 754-770.

Pillai, K.K. & Ono, Y. (1978). The breeding cycles of two species of grapsid crabs (Crustacea : Decapoda) from the north coast of Kyushu, Japan. *Mar. Biol.*, **45**: 237-248.

Pilsbry, H.A. (1916). The sessile barnacles (Cirripedia) contained in the collections of the U.S. National Museum, including a monograph of the American species. Washington Government Printing Office. Bulletin 93. 336 pp.

Pinheiro, M.A.A., Fransozo, A. & Negreiros-Fransozo, M.L. (1996). Distribution pattern of *Aernaeus cribrarius* (Lamarck, 1818) (Crustacea, Portunidea) in Fortaleza Bay, Ubatuba (SP), Brazil. *Rev. Brasil. Biol.*, **56** (4): 705-716.

Pitcher, T.J. & MacDonald, P.D.M. (1973). Two models for seasonal growth in fishes. *J. Appl. Ecol.*, **10**: 599-606.

Potter, I. C., Chrystal, P. J. & Loneragan, N. R. (1983). The biology of the manna crab *Portunus pelagicus* in an Australian Estuary. *Mar. Biol.*, **78** (1): 75-85.

Potter, M., Sumpton, W. & Smith, G. (1987). Queensland sand crab study highlights a need for changes in management. *Aust. Fish.* June, **46** (6): 22-26.

Potter, M.A., Sumpton, W.D. & Smith, G.S. (1991). Movement, fishing sector impact, and factors affecting the recapture rate of tagged sand crabs *Portunus pelagicus* (L.) in Moreton Bay, Queensland. *Aust. J. Mar. Freshwater. Res.*, **42** (6): 751-760.

Potts, F.A. (1909). Observations on the changes in the common shore crab caused by *Sacculina*. *Proc. Camb. Philos. Soc.*, **25**: 96-100.

Prasad, R.R. & Tampi, P.R. (1951). An account of the fishery and fishing methods for *Neptunus pelagicus* (Linnaeus) near Mandapam. *J. Zool. Soc. India*, **3**: 335-339.

Prasad, R. P. & Tampi, P.R.S. (1953). A contribution to the biology of the swimming crab *Neptunus pelagicus* (Linnaeus) with note on the zoea of *Thalamita crenata* Labreille). *J. Bombay nat. Hist. Soc.*, **51** (3): 674-689.

Prasad, R.P. & Tampi, P.R.S. (1954). Some aspects of relative growth in the blue swimming crab *Neptunus pelagicus* (Linnaeus). *Proc. Natn. Inst. Sci., (India).* **20** (2): 218-234.

Prasad, P.N. & Neelakantan, B. (1989). Maturity and breeding of the mud crab *Scylla serrata* (Forskal) (Decapoda : Brachyura : Portunidea). *Pros. Indian Acad. Sci. (Anim. Sci.)*, **98** (5): 341-349.

Prasad, P.N., Reeby, J, Kusuma, N. & Neelakantan, B. (1989). Width-weight and length-weight relationships in three portunid crab species. *Uttar Pradesh J. Zool.*, **9** (1): 116-120.

Premkumar, V.K. & Danial, A. (1971). Crustaceans of economic value of Great Nicobar Island, 2. Decapoda : Brachyura : Portunidae. *J. Zool. Soc. India*, **23** (2): 109-112.

Price, A.R.G., Vousden, D.H.P. & Ormond, R.F.G. (1984). An ecological study of sites on the coast of Bahrain with special reference to the shrimp fishery and possible impact from the Saudi-Bahrain causeway under construction (Draft). Report of IUCN to UNEP Regional Seas Programme, Geneva. Ministry of Health, Directorate of Environmental Affairs, Bahrain. 70 pp.

Proctor, R., Flather, R.A. & Elliott, A.J. (1994). Modelling tides and surface drift in the Arabian Gulf – application to the Gulf oil spill. *Cont. Shelf Res.*, **14** (5): 531-545.

Pullen, E.J. & Trent, W.L. (1970). Carapace width-total weight relationship of the blue crabs from Galveston Bay, Texas. *Trans. Amer. Fish. Soc.*, **4**: 795-798.

Quinn, N.J. & Kojis, B.L. (1987). Reproductive biology of *Scylla* spp. (Crustacea : Portunidae) from the Labu Estuary in Papua New Guinea. *Bull. mar. Sci.*, **41** (2): 234-241.

Radhakrishnan, C.K. & Samuel, C.T. (1980). Prospects of fishery, utilisation and culture of crabs in India. *Fish. Technol.*, **17** (2): 67-69.

Rahman, A.A. (1967). Reproductive and nutritional cycle of the crab, *Portunus pelagicus* (Linnaeus) (Decapoda : Brachyura) of the Madras Coast. *Proc. Indian Acad. Sci.* (B) **65**: 76-82.

Rasmussen, E. (1959). Behaviour of sacculinized shore crabs (*Carcinus maenas* Pennant). *Nature*, **183** (4653): 479-480.

Reeby, J., Prasad, P. N. & Kusuma, M. S. (1990). Size at maturity in the in the male crabs of *Portunus sanguinolentus* and *P. pelagicus*. *Fish Technol.*, **27** (2): 115-119.

Reid, D. G., Abello, P., Warman, C. G. & Naylor, E. (1994). Size-related mating success in the shore crab *Carcinus maenas* (CRUSTACEA : BRACHYURA). *J. Zool. Lond.* **232:** 397-407.

Reinhard, E.G. (1950). An analysis of the effects of a sacculinid parasite on the external morphology of *Callinectes sapidus* Rathbun. *Biol. Bull.*, **98** (3): 277-288.

Rice, A.L. (1979). A remarkable benthic catch of portunid crab zoeae (Decapoda : Brachyura). *Crustaceana, Suppl.*, **5**: 17-21.

Richmond, C.E. & Woodin, S.A. (1996). Short-term fluctuations in salinity: effects on planktonic invertebrate larvae. *Mar. Ecol. Prog. Ser.*, **133**: 167-177.

Robichaud, D.A. & Campbell, A. (1995). Movement, reproduction and growth of ovigerous lobster *Homarus americanus* from Newfoundland released off Grand Manan, Bay of Fundy. *J. of Shellfish Research.*, **14** (1): 199-204.

Rugolo, L.J, Knotts, K.S., Lange, A.M. and Crecco, V.A. (1998). Stock assessment of Chesapeake Bay blue crab (*Callinectes sapidus* Rathbun). *J. Shellfish Res.*, **17**: 493-517.

Ruzzante, D.E. (1998). A comparison of several measures of genetic distance and population structure with microsatellite data: bias and sampling variance. *Can. J. Fish. Aquat.Sci.*, **55**: 1-14.

Ryan, E. P. (1966). Pheromone: evidence in a Decapoda Crustacea. *Science.* **151** (3708): 340-341.

Ryan, E. P. (1967a). Structure and function of the reproductive system of the crab *Portunus sanguinolentus* (Herbst) (BRACHYURA : PORTUNIDAE). I. The male system. *Mar. biol. Ass. India Symposium Ser.* **2** (2): 506-521.

Ryan, E. P. (1967b). Structure and function of the reproductive system of the crab *Portunus sanguinolentus* (Herbst) (BRACHYURA : PORTUNIDAE). II. The female system. *Mar. biol. Ass. India Symposium Ser.* **2** (2): 522-544.

Ryan, E. P. (1967c). The morphometry of sexual mature instars of the crab *Portunus sanguinolentus* (Herbst) (BRACHYURA : PORTUNIDAE). *Proc. Biol. Ass. Ind.* Part **II**: 715-723.

Sandoz, M. & Rogers, R. (1944). The effect of environmental factors on hatching, moulting and survival of zoae larvae of the blue crab *Callinectes sapidus* Rathbun. *Ecology*, **25** (2): 216-228.

Sather, B.T. (1969). Observation on the moult cycle and growth of the crab *Podophthalmus vigil* (Fabricius) (Decapoda, Portunidae). *Crustaceana.*, **11:** 185-197.

Scarratt, D.J. & Elson, P.F. (1965). Preliminary trials of a tag for salmon and lobsters. *J. Fish. Res. Bd. Canada*, **22** (2): 421-423.

Scarratt, D.J. (1970). Laboratory and field tests of modified Sphyrion tags on lobsters *Homarus americanus*. *J. Fish. Res. Bd. Canada*, **27**: 257-264.

Shams, A.J. (1998). Environmental and endocrine control of reproduction and its manipulation in the rabbitfish *Siganus canaliculatus* (Park, 1797). Ph.D. Thesis. University of Wales - Bangor, UK. 162 pp.

Shaup, J.B. (1968).). Shell opening of crabs of genus Calappa. *Science*, **160**: p. 887.

Shields, J.D. (1992). Parasites and symbionts of the crab *Portunus pelagicus* from Moreton Bay, eastern Australia. *J. of Crustacean Biology.*, **12** (1): 94-100.

Shields, J.D. (1993). The infestation and dispersion patterns of *Carcinonemertes* spp. (Nemertea). *Hydrobiologia*, **266** (1-3): 45-56.

Shields, J.D. & Wood, F.E.I. (1993). Impact of parasites on the reproduction and fecundity of the blue sand crab *Portunus pelagicus* from Moreton Bay, Australia. *Mar. Ecol. Prog. Ser.*, **92** (1-2): 159-170.

Shinkarenko, L. (1979). Development of the larval stages of the blue swimming crab *Portunus pelagicus* L. (Portunidae : Decapoda : Crustacea). *Aust. J. Mar. Freshwater Res.*, **30** (4): 485-504.

Siddiquie, P.J.A., Akbar, Z. and Qasim, R. (1987). Biochemical composition and calorific values values of the three edible species of portunid crabs from Karachi. *Pak. J. Sci. Ind. Res.*, **30** (2): 119-121.

Sims, R. & Zainal, A.M. (2000). Marine environmental geographical information system (MARGIS) phase 1, final report. Bahrain Centre for Studies and Research, State of Bahrain. 54 pp.

Slattery, S.L., Dionysius, D.A., Smith, R.A.D. & Deeth H.C. (1989). Mushiness in the blue swimming crab *Portunus pelagicus* (L.). *Food Australia*, (April), **41** (4): 698-709.

Smith, H. (1982). Blue crabs in south Australian-their status, potential and biology. *SAFIC (*Adelaide, Australia), **6** (5): 6-9.

Smith, G.S. & Sumpton, W.D. (1987). Sand crabs a valuable fisher in southeast Queensland. *Queensland Fisherman*, **5**: 13-15.

Smith, G.S. & Sumpton, W.D. (1989). Behaviour of the commercial sandcrab *Portunus pelagicus* (L.) at trap entrances. *Asian.Fish. Sci.*, **3** :103-113.

Soltanpour-Gargari, A., Engelmann, R. & Wellershaus (1989). Development and rearing of zoea larvae in Brachyura (CRUSTACEA : DECAPODA). *Crustaceana Suppl.* **14:** 18-27.

Somerton, D.A. & Otto, R.S. (1999). Net efficiency of a survey trawl for snow crab, *Chionectes opilio*, and Tanner crab, *C. baridi*. *Fish. Bull.* **97:** 617-625.

Sparre, P. & Venema, S. (1992). Introduction to tropical fish stock assessment. FAO Fisheries technical paper no. 306/1, Rev.1. Food and Agriculture Organisation of the United Nations, Rome. 376 pp.

Srinivasagam, S. (1979). On the nutritive values of the meat of portunid crabs. *J. Inland Fish. Soc. India*, **11** (2): 128-131.

Stead, D.G. (1988). Contributions to knowledge of the Australian fauna. No. 1. Observations on the genus *Nuptunus*. *Proc. Linn. Soc. N. S. W.*, **23**: 746-758.

Stephenson, W. (1972). An annotated check list and key to the Indo-West-Pacific swimming crabs (Crustacea : Decapoda : Portunidae). *Bull. R. Soc., N. Z.* **10,** 64 pp.

Stephenson, W. & Campbell, B. (1959). The Australian portunids (Crustacea : Portunidae). III. The genus *Portunus*. *Aust. J. Mar. Freshwater. Res.*, **10** (1): 84-124.

Stephenson, W., Chant, D.C. & Cook, S.D. (1982). Trawled catches in northern Moreton Bay I. Effects of sampling variables. *Mem. Qd. Mus.*, **20** (3): 375-386.

Sumpton, W.D.; Potter, M.A. & Smith, G.S. (1989). The commercial pot and trawl fisheries for sand crab *Portunus pelagicus* (L.) in Moreton Bay, Queensland. *Proc. R. Soc. Qd.*, **100** (1): 89-100.

Sukumaran, K.K. & Neelakantan, B. (1997a). Food and feeding of *Portunus* (*Portunus*) *sanguinolentus* (Herbst) and *Portunus* (*Portunus*) *pelagicus* (Linnaeus) (Brachyura: Portunidae) along Karnataka coast. *Indian J. Mar. Sci.*, **26** (1): 35-38.

Sukumaran, K.K. & Neelakantan, B. (1997b). Sex ratio, fecundity and reproductive potential in two marine portunid crabs, *Portunus* (*Portunus*) *sanguinolentus* (Herbst) and *Portunus* (*Portunus*) *pelagicus* (Linnaeus) along the Karnataka coast. *Indian J. Mar. Sci.*, **26** (1): 43-48.

Sukumaran, K.K. & Neelakantan, B. (1997c). Length-weight relationship in two marine portunid crabs, *Portunus* (*Portunus*) *sanguinolentus* (Herbst) and *Portunus* (*Portunus*) *pelagicus* (Linnaeus) along the Karnataka coast. *Indian J. Mar. Sci.*, **27** (1): 39-42.

Sukumaran, K.K. & Neelakantan, B. (1997d). Age and growth in two marine portunid crabs (*Portunus*) *sanguinolentus* (Herbst) and *Portunus* (*Portunus*) *pelagicus* (Linnaeus) along the Karnataka coast. *Indian J. Fish.*, **44**: 111-131.

Sugden, W. (1963). The hydrology of the Persian Gulf and its significance in respect to evaporite deposition. *Am. J. Sci*, **261**:741-751.

Sumpton, W.D., Potter, M.A. & Smith, G.S. (1989). The commercial pot and trawl fisheries for sand crab *Portunus pelagicus* (L.) in Moreton Bay, Queensland. *Proc. R. Soc. Qd.*, **100** (1): 89-100.

Sumpton, W.D. & Smith, G.S. (1990). Effect of temperature on the emergence, activity and feeding of male and female sand crabs (*Portunus pelagicus*). *Aust. J. Mar. Freshwater Res.*, **41** (4): 545-550.

Sumpton, W.D. (1994). Infection of sand crab *Portunus pelagicus* by the microsporidian *Ameson* sp. in Moreton Bay. *Proc. R. Soc. Qd.*, **104**: 85-87.

Sumpton, W.D., Potter, M.A. & Smith, G.S. (1994a). Parasitism of the commercial sand crab *Portunus pelagicus* (L.), by the Rhizocephalan *Sacculina granifera* Boschma, 1973 in Moreton Bay, Queensland, Australia. *Aust. J. Mar. Freshwater Res.*, **45** (2): 169-175.

Sumpton, W.D., Potter, M.A. & Smith, G.S. (1994b). Reproduction and growth of the commercial sand crab, *Portunus pelagicus* (L.) in Moreton Bay, Queensland. *Asian.Fish. Sci.*, **7** :103-113.

Supamattaya, K., Hoffmann, R.W., Boonyaratpalin, S. & Kanchanaphum, P. (1998). Experimental transmission of white spot syndrome virus (WSSV) from black tiger shrimp *Penaeus monodon* to the sand crab *Portunus pelagicus*, mud crab *Scylla serrata* and krill *Acetes* sp.. *Dis. aquat. Org.*, **32** (2): 79-85.

Tagatz, M. E. (1965). The fishery of blue crabs in the St. Johns River, Florida, with special reference to fluctuation in yield between 1961 and 1962. *U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish.*, 501: iii+11 pp.

Tagatz, M. E. (1967). Growth of juvenile blue crabs, *Callinectes sapidus* Rathbun, in the St. Jones River, Florida. *Fishery bull.*, **67** (2): 281-288.

Tagatz, M. E. (1968). Biology of the blue crab, *Callinectes sapidus* Rathbun, in the St. Johns River, Florida. *Fish. Bull.* **67** (1): 17-33.

Tattersall, W.M. (1920). *Sacculina* and its effects on the host species. *Reports Transections Manchester Microscopical Society*, pp. 29-41.

Thomson, J. M. (1951). Catches composition of the sand crab in Moreton Bay. *Aust. J. Mar. Freshwater Res.*, **2:** 237-244.

Titgen, R.H. (1982). The systematics and ecology of the Decapods of Dubai, and their zoogeographic relationships to the Arabian Gulf and the Western Indian Ocean. D. Phil. Thesis. Texas A&P. pelagicus University. 292 pp.

Todd, J. (1995). So you want to go crabbing. *Southern Fisheries*. **3** (2): 29.

Trainor, N. (1990). Review of the east coast otter trawl fishery. *Queensland Fishermen* (September), appendix II pp. 1-4.

Truitt, R. V. (1939). The blue crab. In: Our water resources and their conservation. Chesapeake. *Biol. Lab Contrib.* **27:** 10-38.

Uglem, I., Noess, H., Farestveit, E. & Jorstad, K.E. (1996). Tagging of juvenile lobsters *Homarus gammarus* (L.) with visible implant Fluorescent Elastomer Tags. Aquacultural Engineering, **15** (6): 499-501.

Van Engle, W.A. (1958). The blue crab and its fishery in Chesapeake Bay. Part I. Reproduction, early development, growth and migration. *Commer. Fish. Rev.*, **20** (6): 6-17.

Vousden, D.P. (1986). The Bahrain Marine Habitat Survey. Project Report, Vol. **1**, 1986, Environmental Protection Committee, State of Bahrain.

Vousden, D.H.P. (1995). Bahrain marine habitat and some environmental effects on seagrass beds. Ph.D. Thesis, University of Wales - Bangor, UK. 261 pp.

Wardly, W.J. & Tirpak, A.J. (1991). Occurrence and distribution of an infection of *Loxothylacus texanus* (Rhizophela) in blue crabs in Galveston Bay, Texas, with special reference to size and coloration of the parasite's external reproductive structures. *J. Crust. Biol.* **11**: 553-560.

Warner, G. F. (1977). The biology of crabs. Unwin Bro. Ltd. The Gresha, London. pp. 119-194.

Wassenberg, T.J. & Hill, B.J. (1987). Feeding by the sand crab *Portunus pelagicus* on material discarded from prawn trawlers in Moreton Bay, Aust. Mar. Biol., **95** (3): 387-393.

Watson, J. (1970). Maturity, mating and egg laying in the spider crab *Chinocoetes opilio*. *J. Fish. Res. Board Can.* **27**: 1607-1616.

Weis, J.S., Cristini, A. & Rao, K.R. (1992). Effects of pollutants on molting and regeneration in crustacea. Amer. Zool., 32: 495-500.

Weng, H.T. (1987). The parasitic barnacle *Sacculina granifera* Boschma, affecting the commercial sand crab *Portunus pelagicus* (L.) in populations from two different environments in Queensland. J. Fish Dis., **10** (3): 221-227.

Weng, H. T. (1992). The sand crab (*Portunus pelagicus* (Linnaeus)) populations of two different environments in Queensland. *Fish. Res.*, **13** (4): 407-422.

Wenner, A.M. (1972). Sex ratio as a function of size in marine crustacea. *Amer. Nat.*, **106** (949): 321-350.

Werner, F., Hoffmann, G., Bernhard, M., Milkert, D & Vikgren, K. (1990). Sedimentological effects of trawl fishery in Kiel Bay (western Baltic). *Meynaiana*. **42**: 123-151.

White, A. Q. & Spirito, C. P. (1973). Anatomy and physiology of the swimming leg musculature in the blue crab *Callinectes sapidus*. *Mar. Behav. Physiol.*, **2:** 141-153.

Williams, M.J. (1981). Methods for analysis of natural diet in portunid crabs (CRUSTACEA : DECAPODA : PORTUNIDAE). *J. Exp. Mar. Biol. Ecol.* **52** (1): 103-113.

Williams, M. J. (1982). Natural food and feeding in the commercial sand crabs *Portunus pelagicus* Linnaeus, 1766 (Crustacea : Decapoda : Portunidae) in Moreton Bay, Queensland. *J. Exp. Mar. Biol. Ecol.*, **59** (2-3): 165-176.

Williams, M.J. & Hill, B.J. (1982). Factors influencing pot catches and population estimates of the portunid crab *Scylla serrata*. **71**: 187-192.

Williams, M.J. (1986). Evaluation of anchor tags for marking the commercial sand crab *Portunus pelagicus* (L.) (Portunidae : Decapoda). *Aust. J. Mar. Freshwater Res.*, **37** (6): 707-712.

Wolcott, T.G. & Hines, A.H. (1996). Advances in ultrasonic biotelemetry for animal movement and behaviour: the blue crab case study. In: Methods and techniques of underwater research. Proceedings of the American Academy of Underwater Sciences, 1996, Scientific Diving Symposium Smithsonia Institution, Washington, pp. 229-236.

Yatsuzuka, K. (1962). Studies on the artificial rearing of the larval Brachyura, especially of the larval blue-crab, *Neptunus pelagicus* Linnaeus. *Rep. Usa Mar. Biol. Sta.*, **9** (1): 1-4.

Yatsuzuka, K. & Sakai, K. (1980). The larval juvenile crabs of Japanese Portunidae (Crustacea : Brachyura). *Rep. USA. Mar. Biol. Inst.*, **2**: 25-42.

Yatsuzuka, K. & Meruane, J. (1987). Growth and development, especially on external sexual characters of *Portunus pelagicus* (Linne) (Crustacea : Brachyura). *Rep. Usa. Mar. Biol. Inst.*, **9**: 1-37.

Yoodee, K. (1984). Study on bottom gill net and trap for catching blue swimming crab *Portunus pelagicus*. Current Technical Papers Series no. 26. Southeast Asian Fisheries Development Centre, Thiland. 21 pp.

Appendix 1

Bahrain shrimp fishery

1. BAHRAIN SHRIMP FISHERY

1.1 The Fishery History

Traditionally, the tidal barrier trap (local name: Hadhrah) was the main gear used for shrimp fishing in Bahrain. These traps are usually placed to face the direction of shrimp migrations. The importance of these traps was reduced after the introduction of trawling in 1967 (FAO, 1978). At present, trawl nets are responsible for most shrimp landings in the kingdom.

The Bahrain Fishing Company (BFC) was the first established company to commercially exploit shrimp resources. It had started its fishing operations in March 1967 (FAO, 1978) with American and Japanese markets the main purchasers of the shrimp catches, most of which were exported as headless shrimp (Boreama and Job 1968). In the first two years of its operation BFC operated eight trawlers. Eight more trawlers were added in 1968 and a further two more boats in 1973 (FAO, 1978). In 1976, some of these trawlers were replaced and the total number was reduced to 15 boats (FAO, 1978). All trawlers were double rigged, using Gulf of Mexico trawl nets. Their head rope length ranged from 14 m for small boats, to 17 m for large boats. Mesh sizes of the nets ranged from 45 to 50mm. All boats were steel hulled and their overall length ranged from 15 to 23 m. BFC was the only company allowed to fish in Bahraini waters. The fishing season of this company usually started in the Maniffa grounds off the eastern coast of Saudi Arabia during the period July- February and both Saudi and Bahraini grounds were fished (FAO, 1978). Total landings of this sector included the catches from both Bahrain and Saudi waters (Boerema and Job, 1968; Boerema, 1969; FAO, 1973 and FAO, 1978). After a sharp decline in catches in both the 1978/79 and 1979/80 seasons, shrimp trawling became uneconomical and the BFC ceased fishing in August 1979 (Abdulqader, 1983). Shrimp landings from its start in 1967 until its collapse in 1979 are plotted in Fig. 1. In 1980/81 another industrial fleet started operating with 4 double rigged trawlers. These trawlers were previously trawling for finfish since 1975.

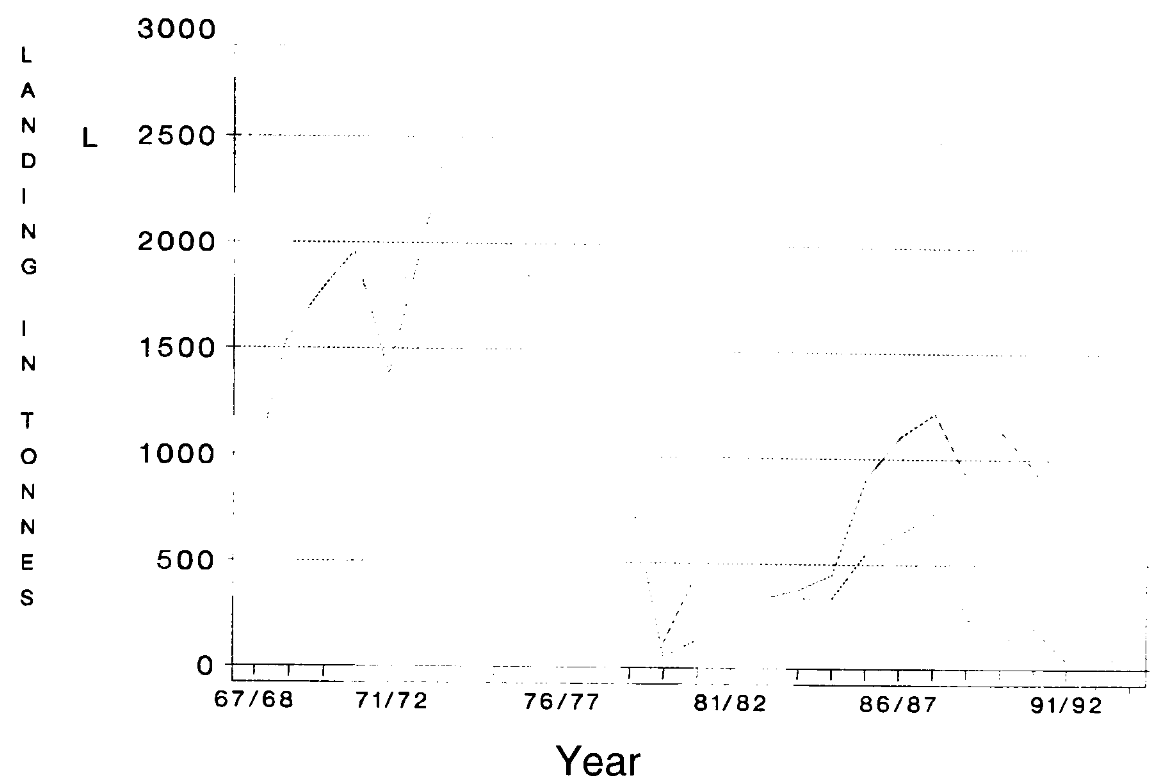


Figure 1. Shrimp landings from artisanal (solid line) and industrial sectors from 1967/68 to 1993/94 fishing seasons. (Source: FAO 1978, and Fisheries Statistical Services, various years). (After Abdulqader, 2001).

The artisanal trawl fishery started in 1971 (Abdulqader, 1983) by fishermen previously involved in the barrier trap fishing. In 1976, there were 26 full-time shrimp trawlers, increasing to 68 in 1983 after the implementation of the registration and licensing regulations. Since then, the number of shrimp fishing boats has increased dramatically with 394 boats licensed for the 2001/02 shrimping season.

1.2 The Shrimp Fishery

1.2.1 Shrimp resources

Seven penaeid species are found in Bahraini waters (Muthu and Al-Rumaidh, 1998; Abdulqader, 1999). Commercial shrimp landings are mainly made up by a single species, the Green Tiger shrimp *Penaeus semisulcatus* De Haan, 1844. The six remaining species make up about 5% of the annual shrimp landings. Two species *Penaeus latisulcatus* Kishinouye 1896 and *Metapenaeus kutchensis* George and Rao, 1963 grow to large sizes but the remaining four species *Metapenaeus stebbingi* Nobili, 1909, *Trachypenaeus curvirostris*, *Metapenaeopsis stridulans* (Alcock, 1905), and *Metapenaeus mogiensis* (Rathbun, 1902) are smaller and are usually partially or entirely discarded.

1.2.2 Shrimp fishing grounds

Shrimp fishing grounds around Bahrain extend from water depths of 2 to 20 metres. These are categorized into three major shrimping regions: northern, western, and southern areas. Fishermen had identified fifty shrimp fishing grounds by their local names with the total shrimping area estimated at about 871 km^2 (Abdulqader, 2001) (see Fig. 2).

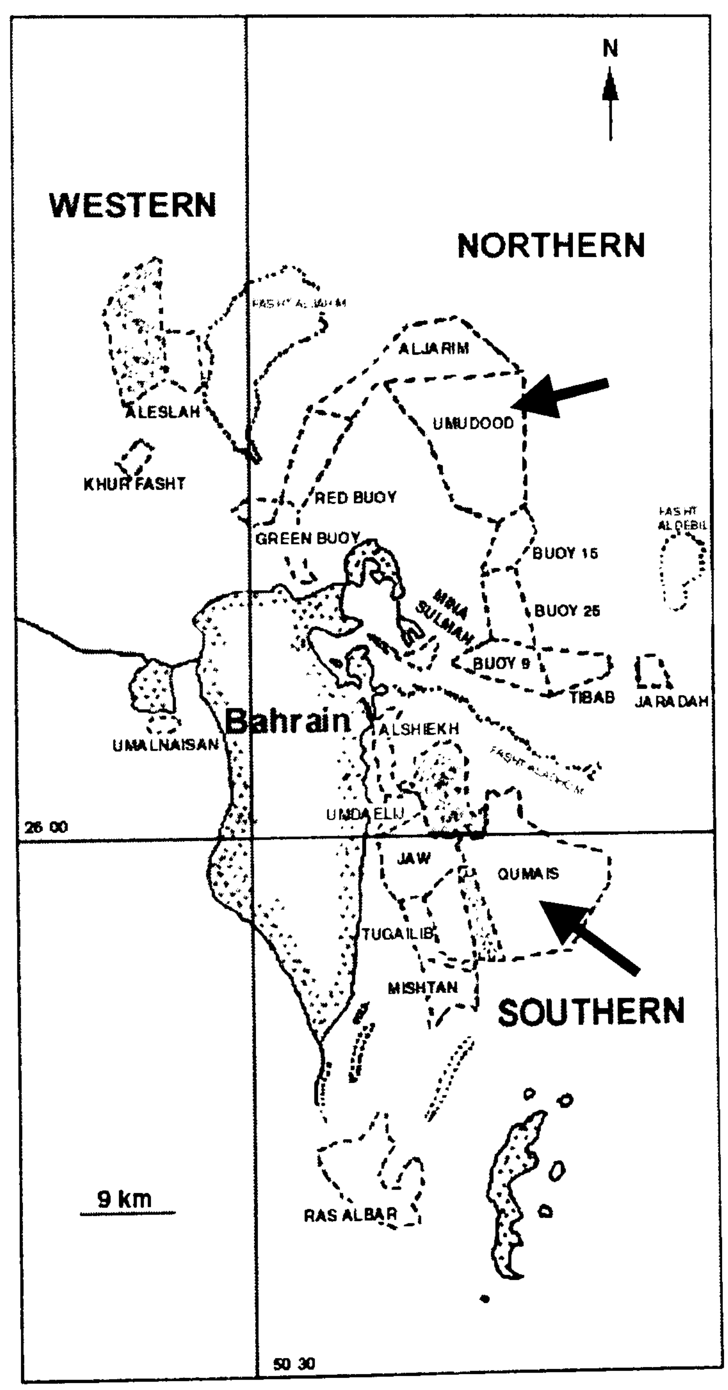


Figure 2. Bahrain shrimp grounds categorized into three main areas; western, northern, and southern. Major coral reefs (Fasht Al Jarim, Fasht AlAdhom, and Fasht AlDebil) are outlined by dotted line. After (Abdulqader, 2001).

1.2.3 Fishing Fleet and Gear

The Bahrain shrimp fishing fleet includes a wide range of boat sizes. Wood is the traditional material used in boat building; recently the number of fibreglass boats has increased. Low maintenance costs and lighter weights are the advantages of the use of fibreglass boats. Regardless of the building material used all large and medium-sized boats are built following the traditional boat design. This design is well known in the Arabian Gulf area and adjacent seas and **Banoush** is the common local name used to identify these boats. All large and medium boats are equipped with a winch but most of the small boats retrieve their nets manually. The majority of winch-equipped boat use second hand car engines or diesel engines to power their winches.

1.2.4 Fishing Nets

Shrimp trawlers in Bahrain use a single net per fishing boat. By law, the shrimp trawl should follow the Gulf of Mexico flat shrimp trawl net design, with the following specification: 1) length of the net should not exceed 28m, 2) mesh size at the codend should not be smaller than 38 mm, 3) use of one line of chains at the foot-rope and thickness of chain should not exceed 8mm, 4) leg-line between otter boards and the net should not exceed 2m. The law also determined the upper specification of the doors to be used; their dimensions should not exceed 80 x 200 x 8 cms and weigh less than 100 kgs.

1.2.5 Shrimp Landings

Shrimp total annual landing was 2,104 metric tons (mt) in 2000, 18.0 % of Bahrain total landings, with a value of 2.9 million Bahraini Dinnar (BD.) (equivalent to £ 5.3 million) (Directorate of Fisheries [DOF], 2001). During the period from 1980 to 2000, the maximum annual landing was 3,565 mt in 1996, while the lowest was 754 mt in 1992, which coincided with the second Gulf war. In addition to shrimp several fish groups are landed; total fish landings for the year 2000 was 11.718 mt with a value of BD. 9.4 million (equivalent to £ 17.1 million).

1.2.6 Fisheries management

The Bahrain fishing law was declared in 1981. There have been no major changes to the law since then. However, based on this law, a number of ministerial decrees were issued, many of them concerning the shrimp fishery. At present, the Directorate of Fisheries and Marine Resources, Bahrain, adopts 3 pillars in managing the Bahrain shrimp fishery. These are: 1) controlling the number and size of fishing boat through registration and licensing scheme, 2) protection of shrimp recruits by enforcing a fishing ban period (mid of March-mid of June, or 1^{st} April-31^{st} July, depending on the spawning season) and 3) improving fishing gear specification to lessen its impact on the shrimp stock and biodiversity of the marine habitat.

Recently, Abdulqader (2001) has suggested an immediate adoption of management regulations for the Bahrain shrimp fishery, as follows: 1) protecting the nursery areas for juveniles by banning the fishing operation in these shallow waters, 2) protecting the recruits by extending the shrimp ban period from 4 to 6 months (March-August), 1^{st} September is suggested to be an ideal date for the start of the starting fishing season, where low catch rates and high percentage of small shrimp are observed in August, 3) reducing the number of shrimp fishing licenses, 4) Fixing an upper and lower size limit for shrimp fishing boats, where they should range only from 12 to 23 m in overall boat length and 5) implementing the by-catch reduction device in the shrimp trawl, which is also beneficial to other marine resources, e.g. turtle and dugong, as well as the marine environment.

1.2.7 Shrimp by-catch

Several different animal groups are found in the shrimp landings as by-catch, e.g. fin-fish, turtles, crabs and other crustaceans.

1.2.7.1 Crabs

The blue swimming crab, *Portunus pelagicus* (Linnaeus, 1758) is a common species in shrimp by-catch, where most crabs caught by the fishery are landed. Crab landings have exhibited a rapid increasing trend from 518 mt in 1985 to 2380 mt in 2000 (DOF, 2001). The increase in crab landings is the result of the growing demand for this product, mainly for the export market. Crab landings exceeded shrimp landings in 1999 and 2000 by 34% and 13% respectively. In recent years, a direct trap fishery was developed for specifically catching this crab species, with crab landings from the traps of 221 mt in 2000 (DOF, 2001).

1.2.7.2 Finfish

A recent sampling survey by the Bahrain Center for Studies and Research on the finfish component of the shrimp by-catch, was carried out on a bi-weekly basis from February 1999 to January 2000 (Abdulqader, 2000). Preliminary results indicated the presence of 92 fin-fish species as shrimp by-catch throughout the study period. Blackfin Mojarra *Gerres argyreus* was found to be the most dominant by-catch finfish species.

1.2.7.3 Marine Turtles

In Bahrain waters, turtles are accidentally caught in shrimp trawls. The magnitude of these incidences is difficult to assess especially since turtles are not landed for human consumption. However, collection of the turtle incidence data started from the 1997/98 shrimping season. Results of this first season showed that 1,229 turtles were caught in 54,831 fishing days (Abdulqader, 2000). Turtles were found in 12 out of the 20 shrimp fishing grounds. The highest turtle incidences were found in "Qumais" fishing ground in the southern region, which had the second highest fishing effort, whereas "Umudood" fishing ground in the northern region which received most of the fishing effort was the second highest in turtle number. Qumais and Umudood fishing grounds are indicated with bold arrows in Fig. 2.

1.2.7.4 Other fauna

The shovelnose lobster, *Thynus orientalis*, is also common in the shrimp by-catch. This species was found in trawls in good quantities during October to January.

Almost 200 mt of shovelnose were landed in 1997 (DOF, 1998). The mantis shrimp, *Squilla sp.,* is another crustacean found in the shrimp by-catch. This species is not consumed locally. Towards the end of the shrimp season cuttlefish, *Sepia sp.*, are usually caught in good quantities. Such quantities may exceed the shrimp catch during this period.

References

Abdulqader, E. A. A. (1983). Review of the statistical system adopted by the Directorate of Fisheries (Bahrain), Directorate of Fisheries, Ministry of Commerce and Agriculture, Technical Circular No. 16, pp.

Abdulqader, E. A. A. (1999). The role of shallow waters in the life cycle of the Bahrain penaeid shrimps. Estuarine, Coastal and Shelf Sciences, 49 (Supplement A) pp. 115-121.

Abdulqader, E. A. A. (2000). Turtle incidences in shrimp trawl nets during the 1997/98 shrimp season in Bahrain waters. *Asian.Fish. Sci.*, **13**: 287-296.

Abdulqader, E. A. A. (2001). Bahrain shrimp fishery and marine environment. in FAO, Tropical shrimp fisheries and their impact on living resources. Shrimp fisheries in Asia: Bangladesh, Indonesia, and the Philippines; in the Near East: Bahrain and Iran; in Africa: Cameroon, Nigeria, and the United Republic of Tanzania; in Latin America: Colombia, Costa Rica, Cuba, Trinidad and Tobago, and Venezuela. FAO Fisheries Circular No. 974, pp. 96-137.

Boerema, L. K. & Job, T. J. (1968). The state of shrimp and fish resources in the gulf between Iran and the Arabian peninsula. IOFC, first session, Italy, 16-12 September 1968, IOFC/68/INF.11, pp.16.

Boerema, L. K. (1969). The shrimp resources in the gulf between Iran and the Arabian Peninsula. FAO Fisheries Circular No. 310, pp. 29.

DOF (1998). Annual statistical report 1997, Ministry of Housing and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 70. 90 pp.

DOF (2001). Annual statistical report 2000, Ministry of Housing and Agriculture, Directorate of Fisheries, Bahrain, Technical circular no. 81. 85 pp.

FAO (1973). Report of the first session of the Indian Ocean Fishery Commission-special working party on stock assessment of shrimp in the Indian Ocean area. FAO Fisheries Reports No. 138, pp. 40.

FAO (1978). Fisheries biologist - shrimp - Bahrain - project findings and recommendations. FI:DP/BAH/74/017, pp. 58.

Muthu, M.S. & Al-Rumaidh, M.J. (1998). Taxonomy of the penaeoid shrimp of the Arabian Gulf. Bahrain Centre for Studies and Research, Scientific Studies and Research Series no. 23. 49 pp.

Appendix 2

Trawl path lines

April 1999-April 2000

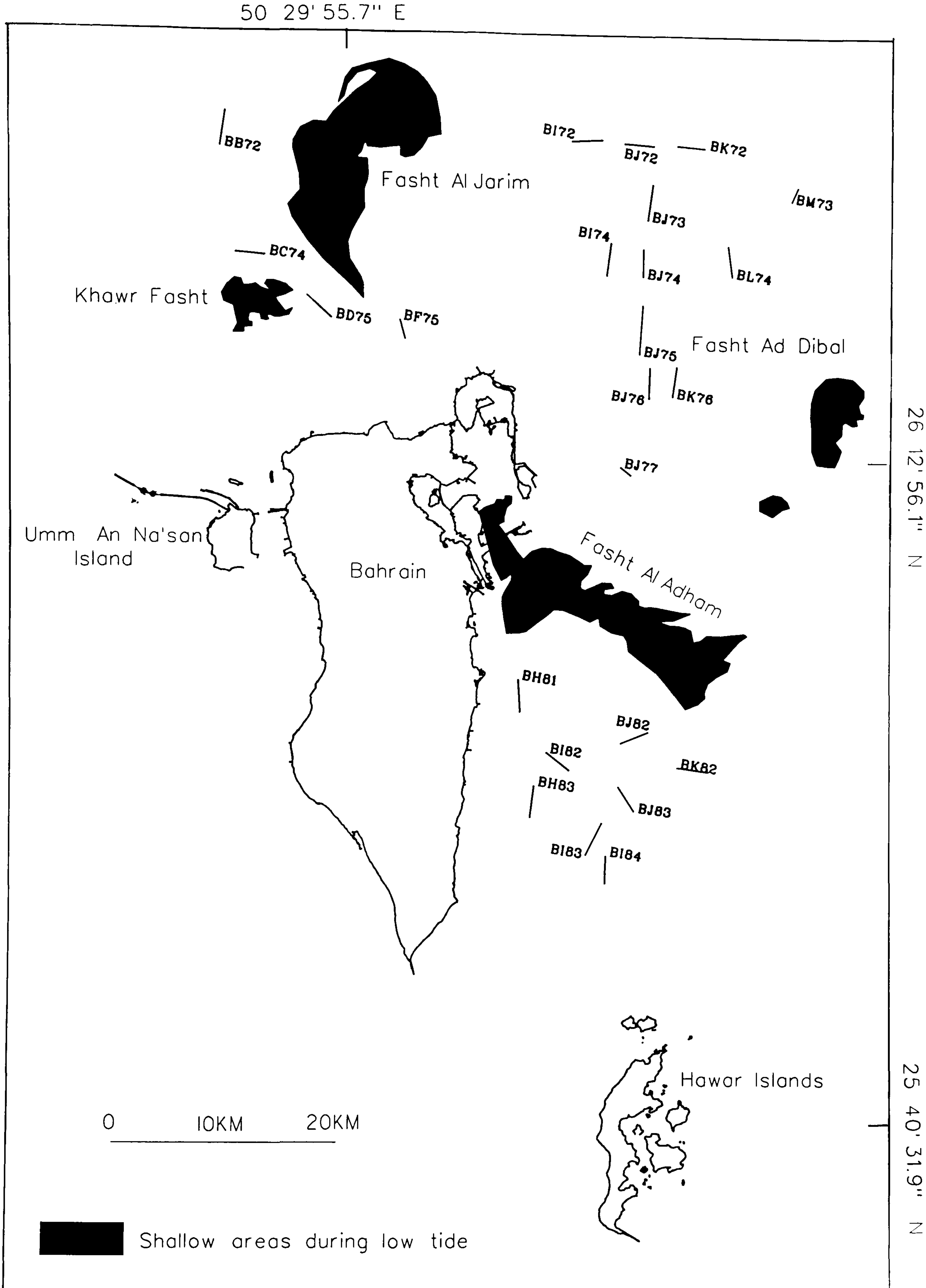


Figure 2.5b. Chart of the study area illustrating the distance and direction of each trawl carried out in April 1999 for sampling *Portunus pelagicus*.

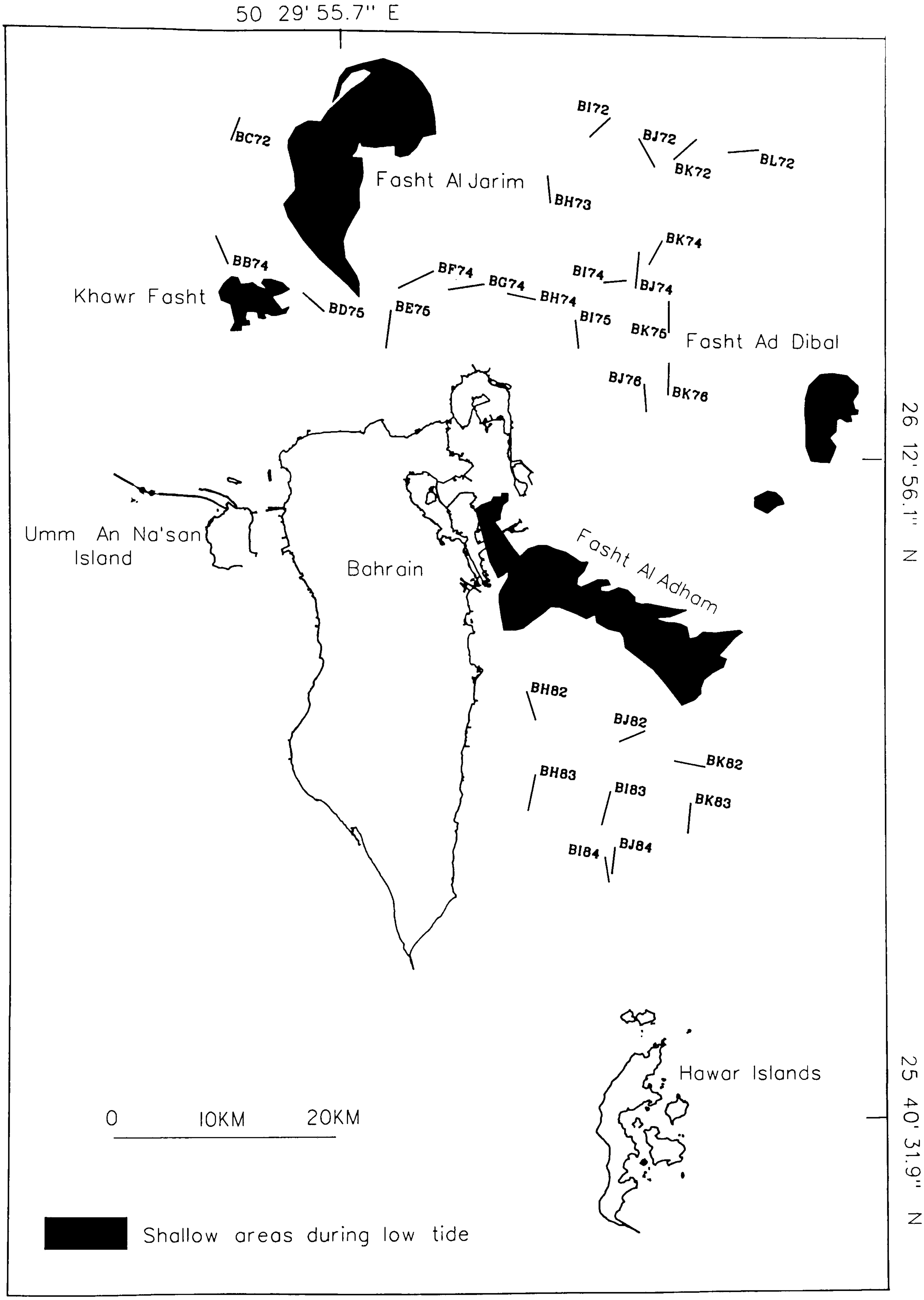


Figure 2.5c. Chart of the study area illustrating the distance and direction of each trawl carried out in May 1999 for sampling *Portunus pelagicus*.

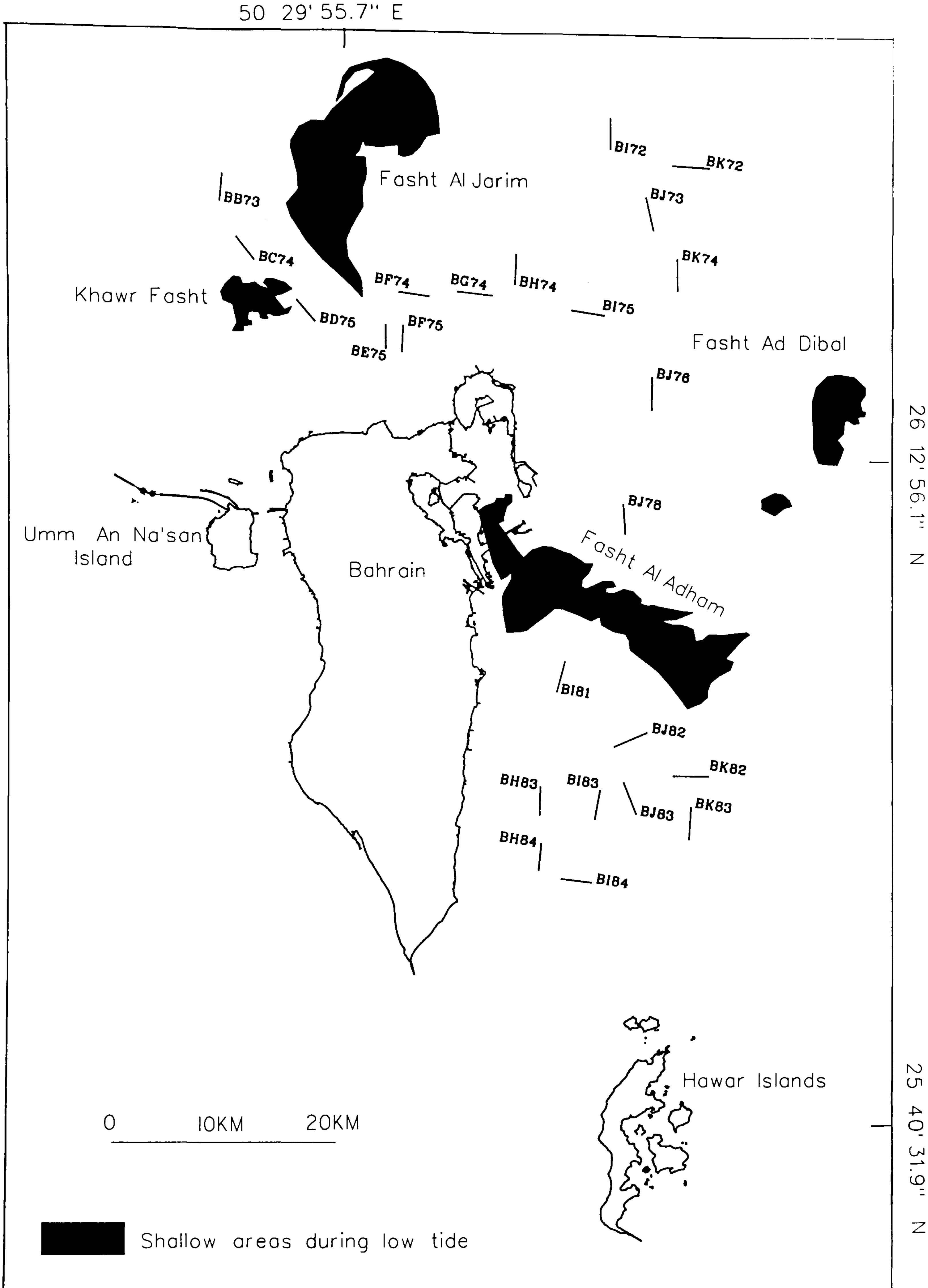


Figure 2.5d. Chart of the study area illustrating the distance and direction of each trawl carried out in June 1999 for sampling *Portunus pelagicus*.

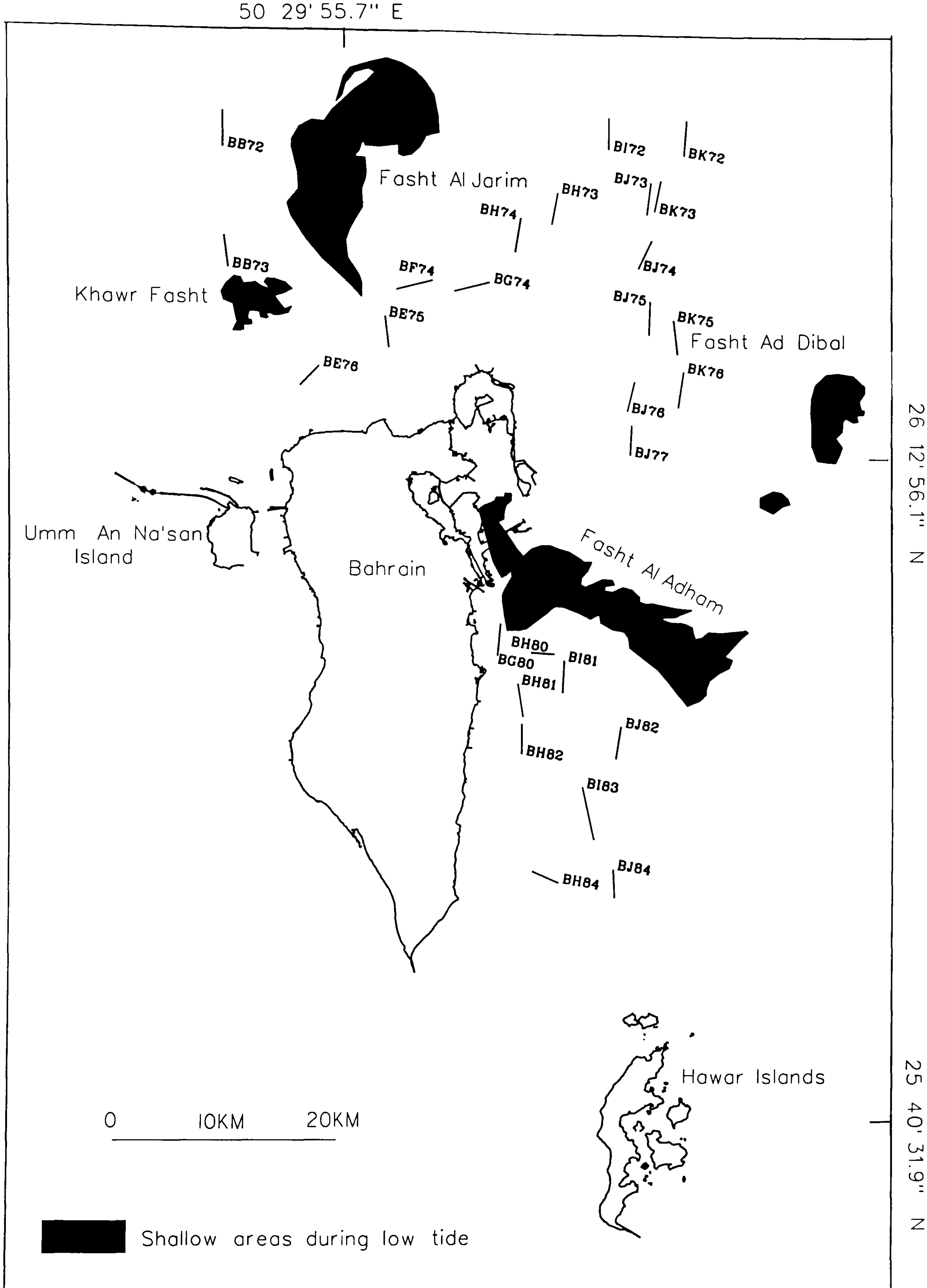


Figure 2.5e. Chart of the study area illustrating the distance and direction of each trawl carried out in July 1999 for sampling *Portunus pelagicus*.

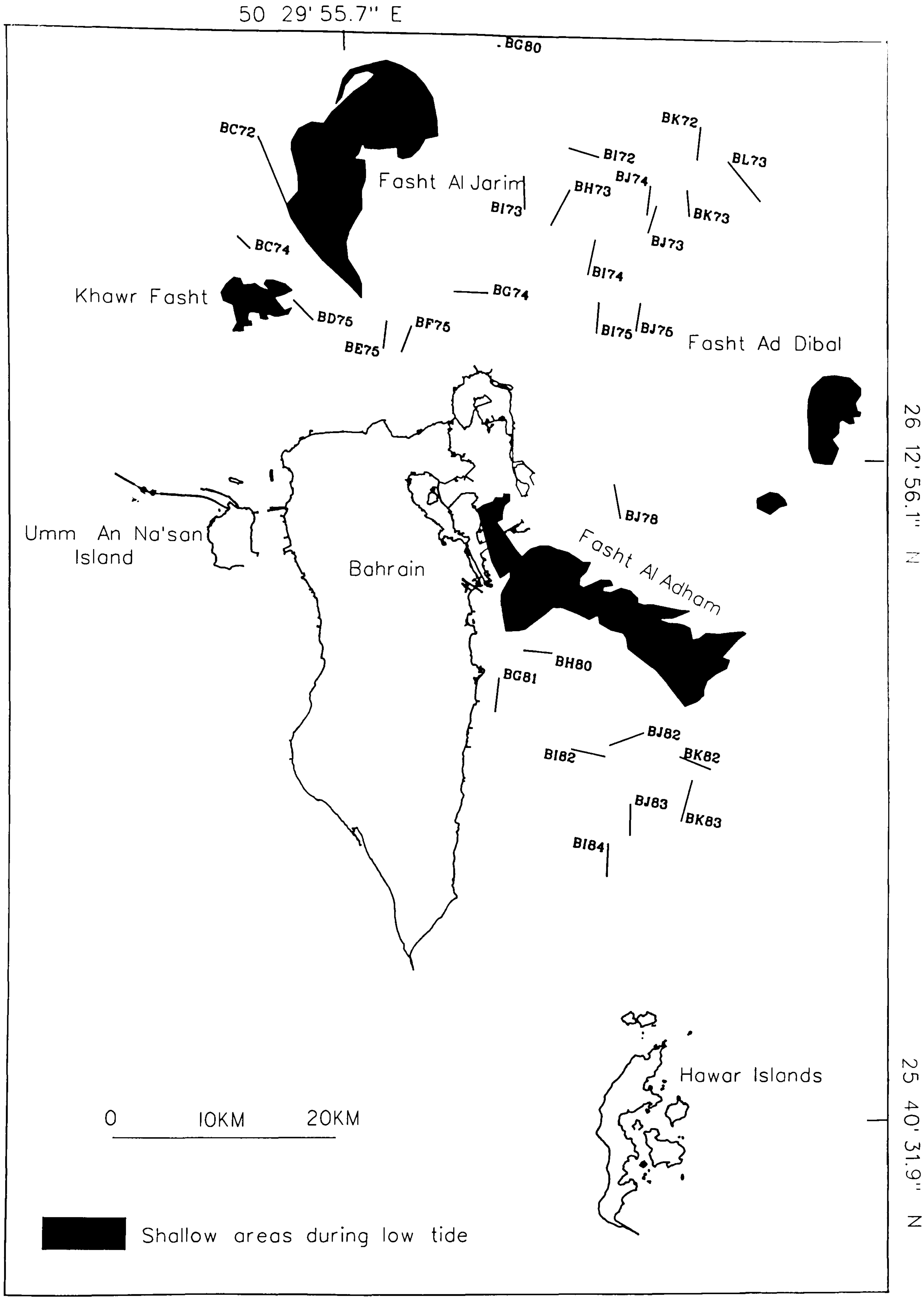


Figure 2.5f. Chart of the study area illustrating the distance and direction of each trawl carried out in August 1999 for sampling *Portunus pelagicus*.

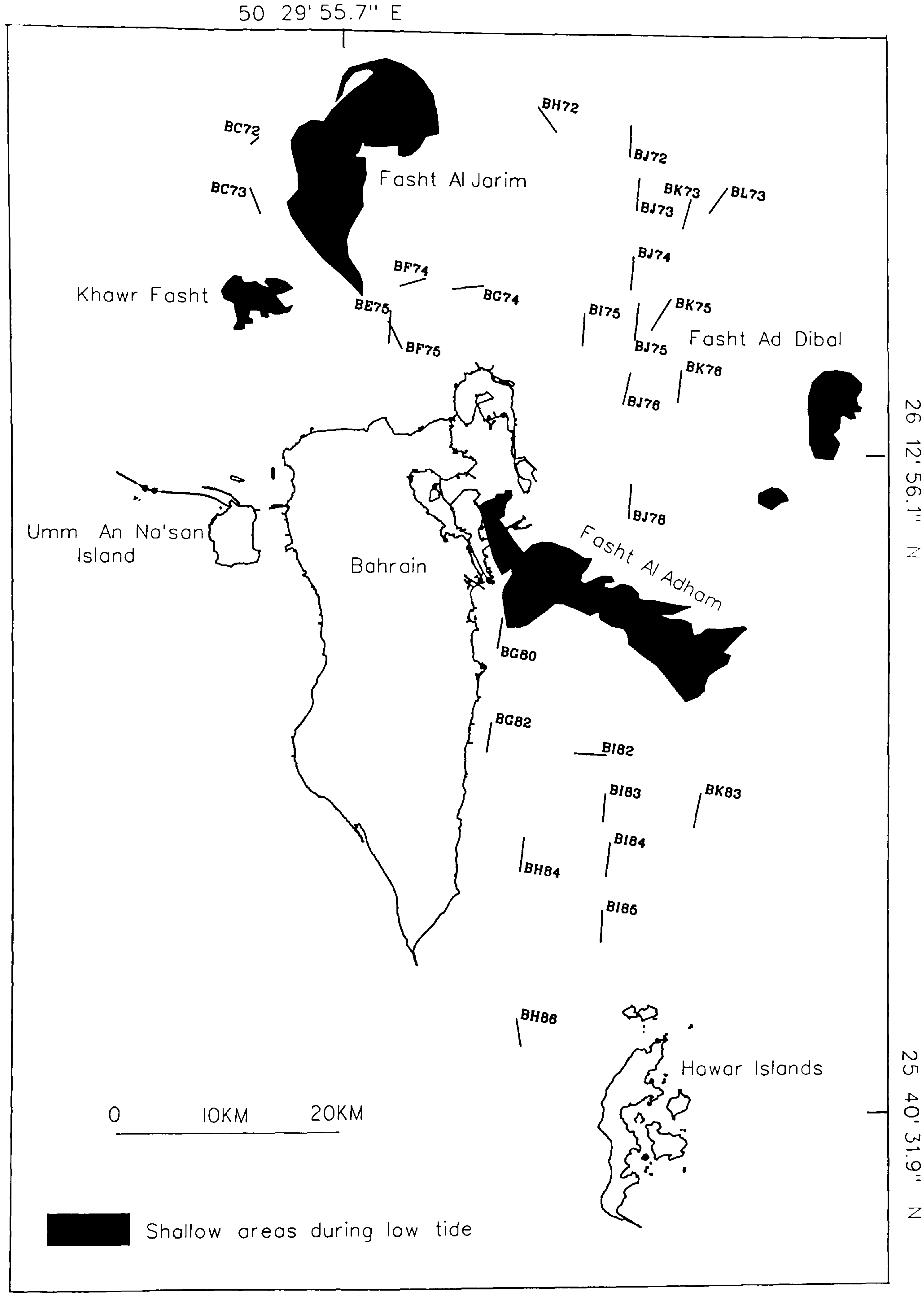


Figure 2.5g. Chart of the study area illustrating the distance and direction of each trawl carried out in September 1999 for sampling *Portunus pelagicus*.

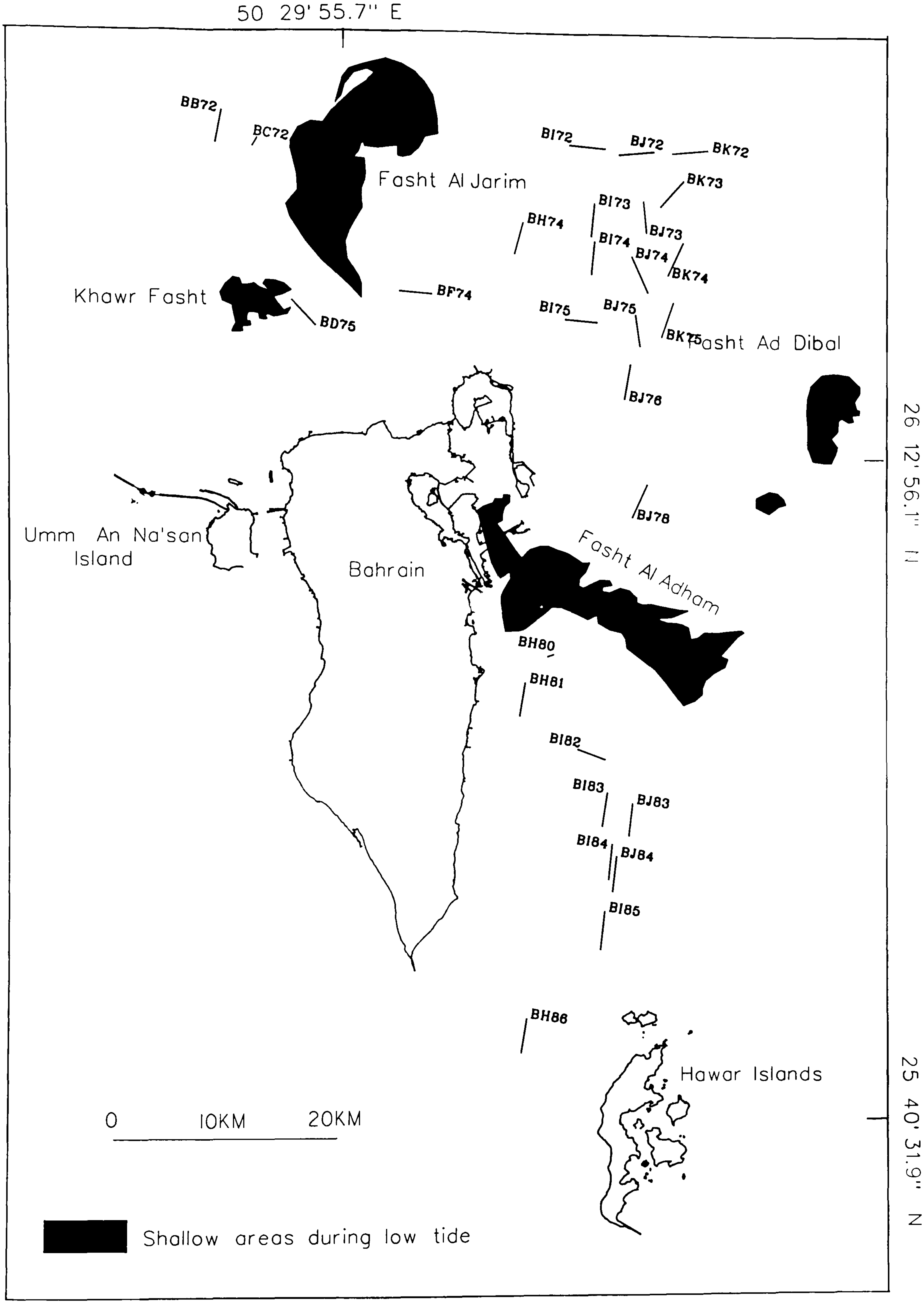


Figure 2.5h. Chart of the study area illustrating the distance and direction of each trawl carried out in October 1999 for sampling *Portunus pelagicus*.

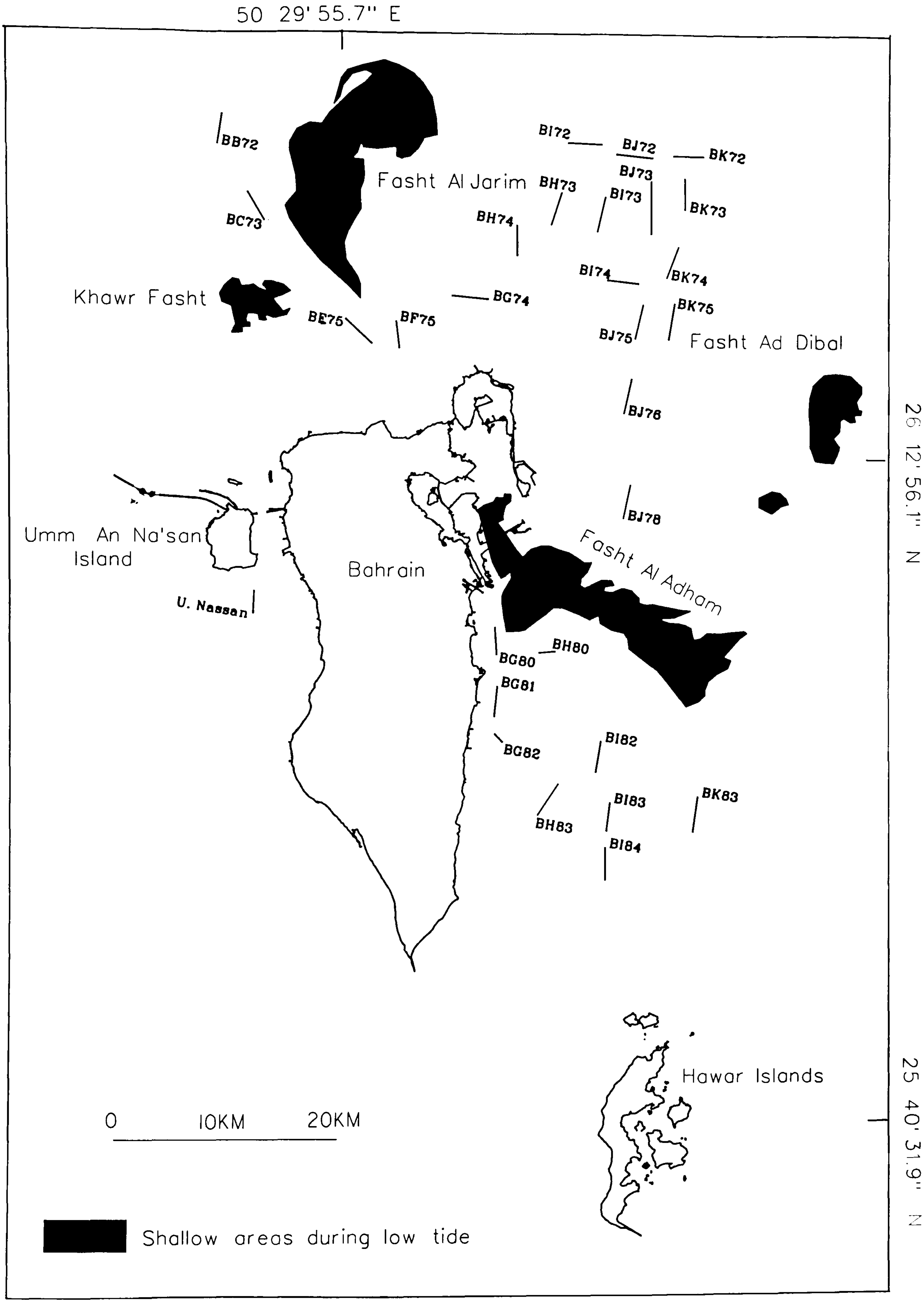


Figure 2.5i. Chart of the study area illustrating the distance and direction of each trawl carried out in November 1999 for sampling *Portunus pelagicus*.

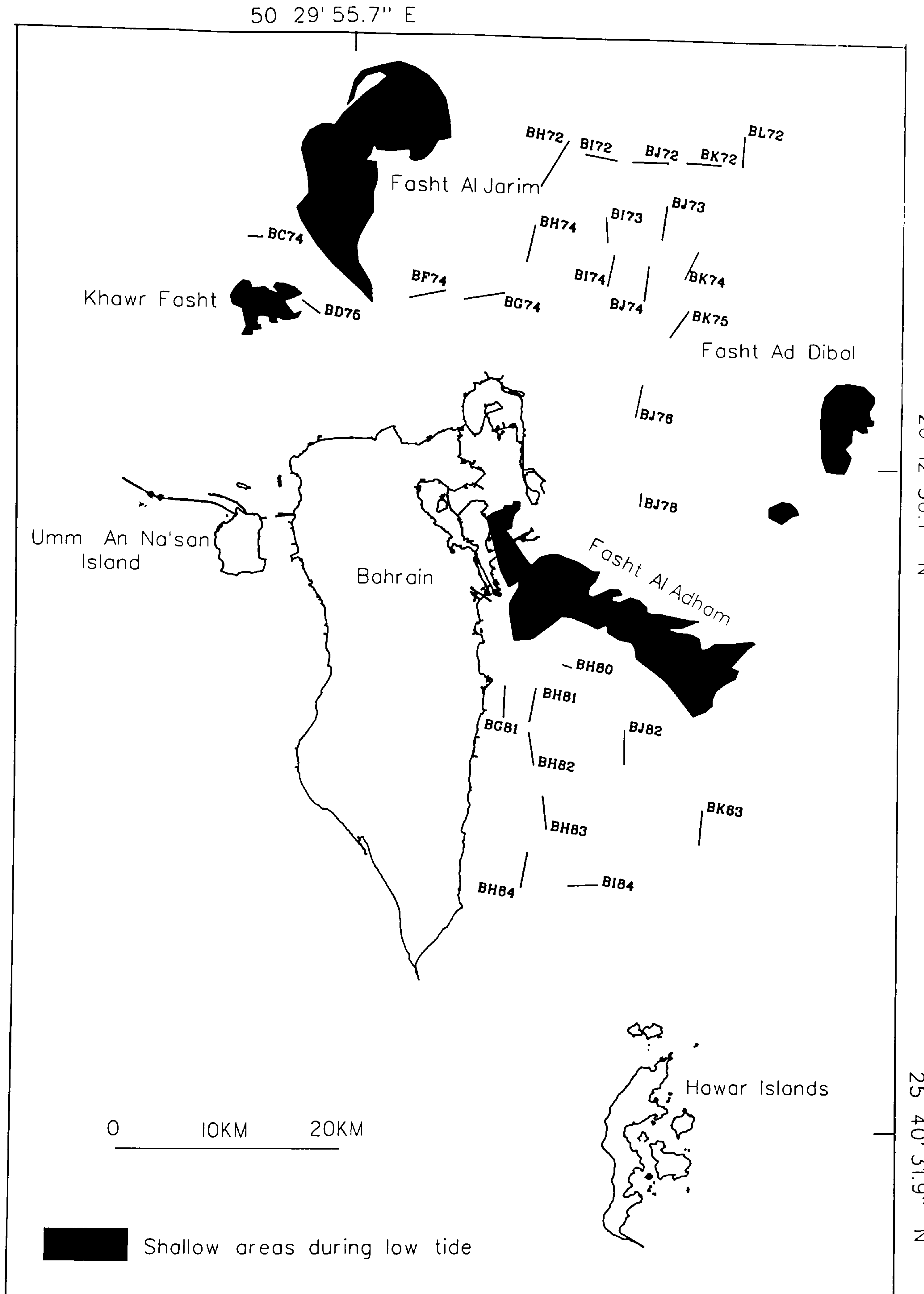


Figure 2.5j. Chart of the study area illustrating the distance and direction of each trawl carried out in December 1999 for sampling *Portunus pelagicus*.

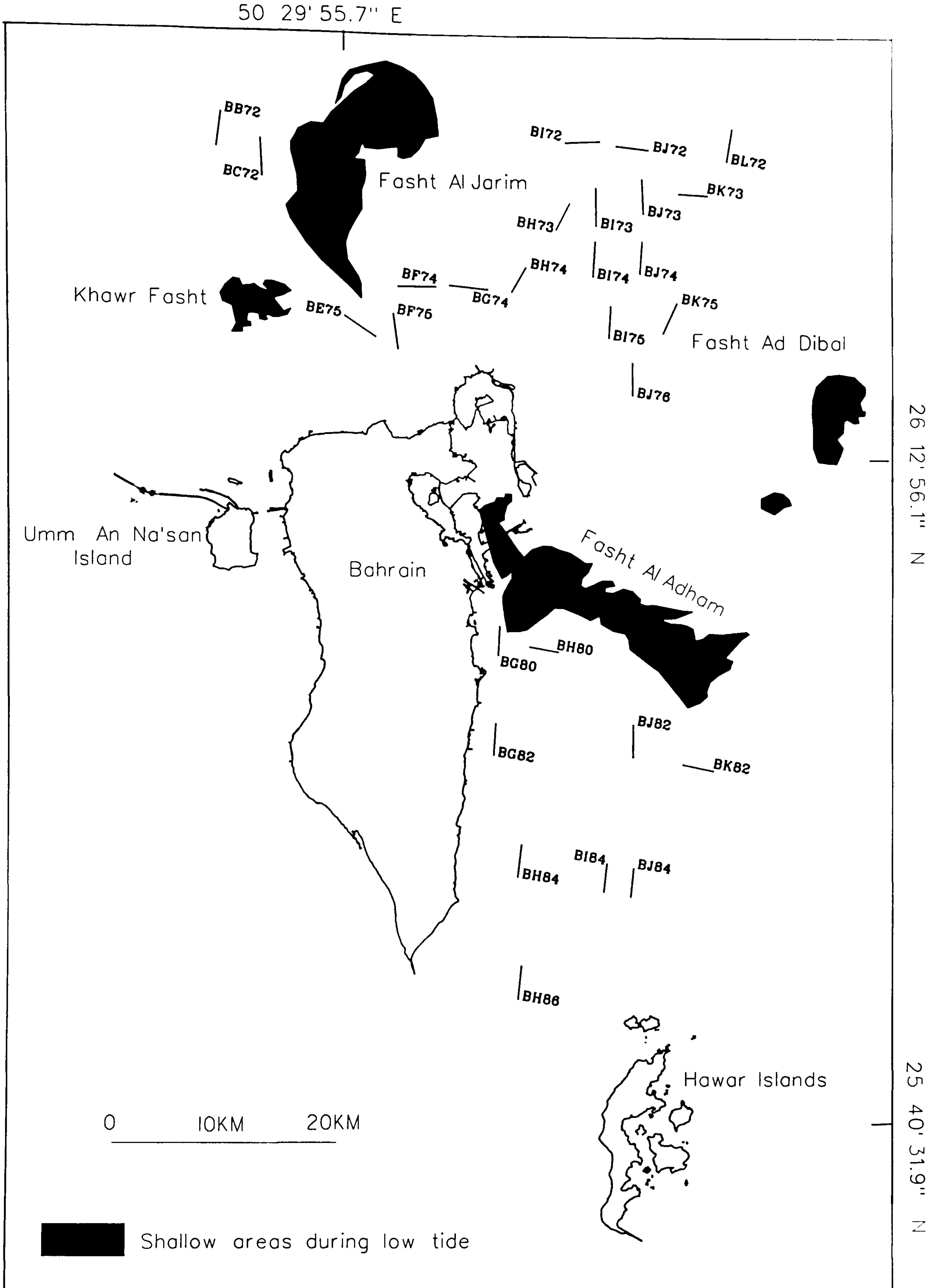


Figure 2.5k. Chart of the study area illustrating the distance and direction of each trawl carried out in January 2000 for sampling *Portunus pelagicus*.

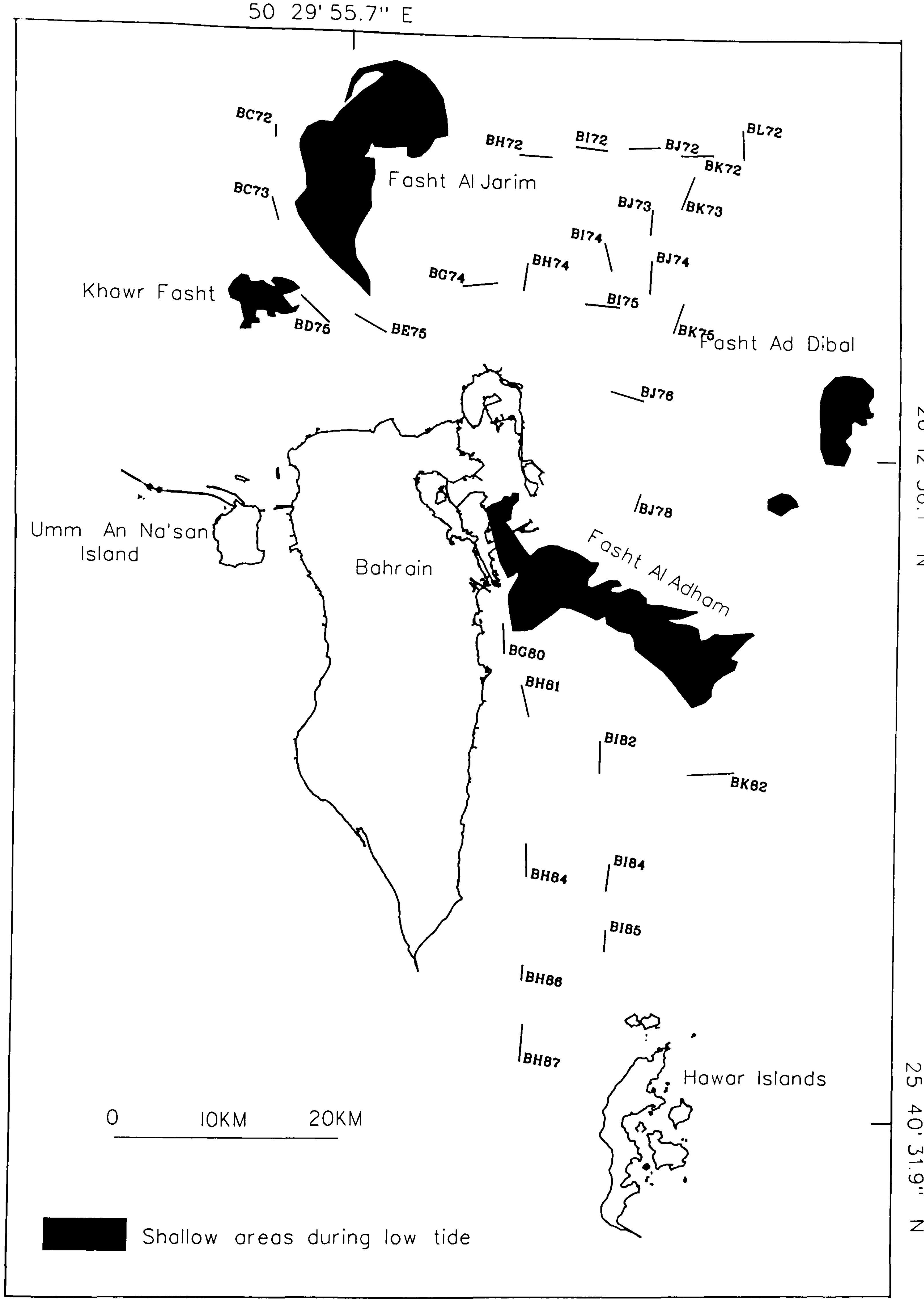


Figure 2.5I. Chart of the study area illustrating the distance and direction of each trawl carried out in February 2000 for sampling *Portunus pelagicus*.

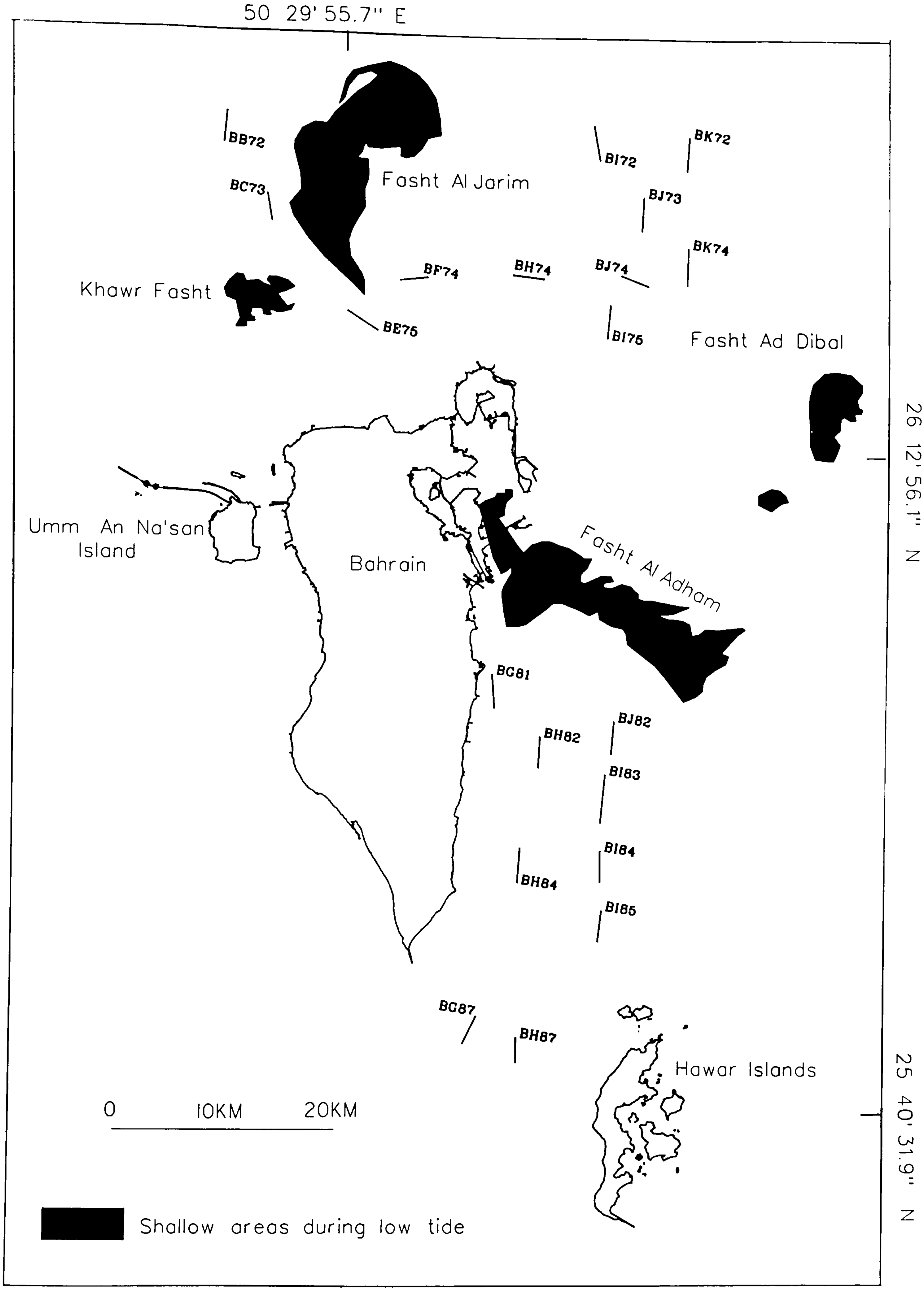


Figure 2.5m. Chart of the study area illustrating the distance and direction of each trawl carried out in March 2000 for sampling *Portunus pelagicus*.

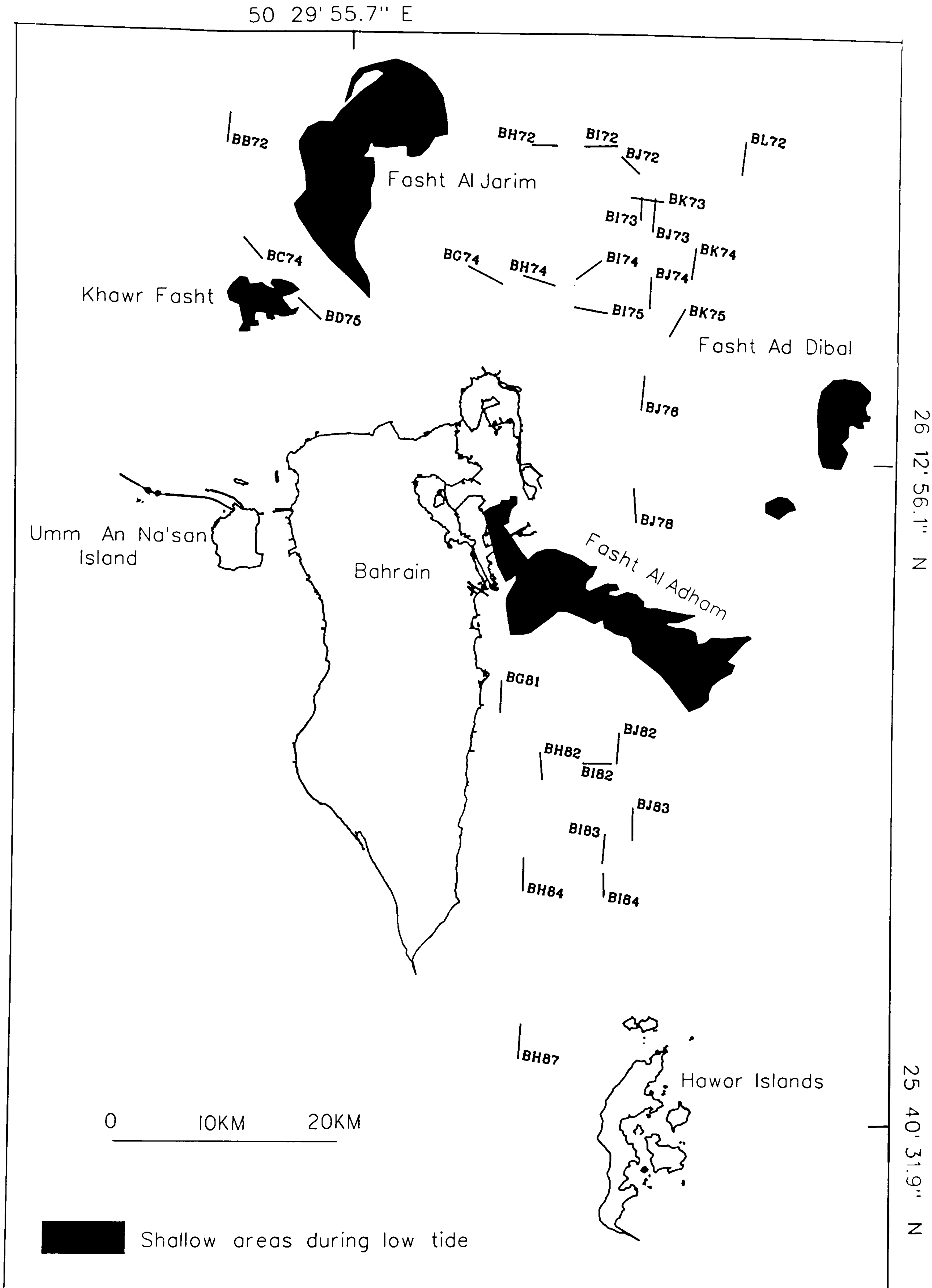


Figure 2.5n. Chart of the study area illustrating the distance and direction of each trawl carried out in April 2000 for sampling *Portunus pelagicus*.

Appendix 3

Biochemical composition of *Portunus pelagicus* around Bahraini waters.

3. Biochemical composition of the blue swimming crab, *Portunus pelagicus* (Linnaeus, 1758), around Bahraini waters.

3.1 Introduction

The blue swimming crab, *Portunus pelagicus* (Linnaeus, 1758), is one of the larger edible species, distributed widely throughout the Indian and Pacific Oceans, ranging from Tanzania and East Africa to Tahiti including Japan, Philippines, Australia, New Zealand, Thailand; and Indonesia (Stephenson, 1972). It is also found in the Red Sea and in the Mediterranean where it has migrated through the Suez Canal (Abdel Razek, 1988; Shields and Wood, 1993).

Although *P. pelagicus* enjoys a wide distribution along the Indo-Pacific region, and eastern Mediterranean, investigations of the nutritive value of this species are meagre. Even in countries where the fishery is of substantial economic importance, such as Australia where it is considered to be one of the tastiest treats available from its waterways (Todd, 1995), little is known of its nutritive value. Only six investigations on this topic have been reported on this species from the Indo-Pacific, viz. India; Pakistan; Australia (Ameer Hamsa, 1978a; Srinivasagam, 1979; Siddiquie *et al.*, 1989; Slattery *et al.*, 1989; Dionysius *et al.*, 1993; Ang and Chong, 1998), and four from Egypt (Badawi, 1971; Hilmy *et al.*, 1986; Hilmy *et al.*, 1988a; Hilmy *et al.*, 1988b). The most extensive studies on chemical composition on *P. pelagicus* are by Srinivasagam (1979) and Siddiquie *et al.* (1987). The latter investigated the carbohydrate, protein, lipid and moisture contents of the meat of *P. pelagicus*, *Portunus sanguinolentus*, *Scylla serrata*, and *Charybdis cruciata*.

In several countries around the world, it is believed that crab meat has valuable medicinal properties, in India for instance, crab curry is a reputed cure for asthma, chronic fevers and is often used after recovery from malaria (Chopra, 1939). Although Thomson (1951) stated that crabs infected with rhizocephalan barnacle *Sacculina granifera* Boschma, 1973, are usually quite edible and palatable, Potter *et. al.* (1983) reported that the parasite makes such crabs unmarketable as the flesh is stained during cooking by discolouration from the hepatopancreas. Also, Sumpton *et al.* (1989) noted that infected crabs do not moult hence often carry a heavy load of epizoic organisms, which makes them aesthetically unacceptable for sale.

It is important to emphasise here that this investigation is the first one of its kind not only in Bahrain, but in the entire Arabian Gulf. The objectives of the present study are: 1) to investigate the proximate and mineral content of *P. pelagicus* crabs, 2) to compare the in chemical compositien of male and female crabs, 3) to identify the effect of cooking on the nutritive value of the crabs, and 4) to discovre whether there are any differences in chemical composition between crabs fished from offshore and inshore waters.

3.2 Materials and methods

3.2.1 Sample preparation

Fresh male and female *P. pelagicus* were collected in December 1999. Two stations, viz. **Ghomais** (located within area C) and **Hidd** coastal area, representing the major offshore and inshore fishing grounds around Bahrain were selected in order to investigate the biochemical composition of the crabs in relation to the different habitats (see Chapter 2, Fig. 2.1). Crabs from the offshore and inshore fishing grounds were collected by means of an otter board trawl and barrier trap respectively. Details of the crabs used for the present investigation are given in Table 1.

Table 1. Details of male and female of *Portunus pelagiicus* collected from Ghomais fishing ground (within area C) and Hidd coastal area, that were collected in December 1999.

Sampling site	Gender	No. of crabs	Mean carapace width (cms)	Muscle status	Muscle wet weight (g)
Offshore waters, **Ghomais**	Male	58	9.0 ± 0.6	Raw	1,300
	Male	27	9.5 ± 0.9	Cooked	500
	Female	93	8.8 ± 0.9	Raw	700
	Female	45	8.6 ± 0.8	Cooked	540

Table 1. Continued

Sampling site	Gender	No. of crabs	Mean carapace width (cms)	Muscle status	Muscle wet weight (g)
Inshore waters, **Hidd**	Male	32	10.3 ± 0.7	Raw	400
	Male	29	10.0 ± 0.9	Cooked	900
	Female	44	10.7 ± 0.7	Raw	500
	Female	39	10.0 ± 0.7	Cooked	600

Crabs from each station were separated sex wise and each sex sample was then divided into two groups to allow the chemical composition of raw and cooked muscles to be gained. Carapace width (CW) of all individuals was measured to the nearest 0.1 cm by means of avernier calliper (see Chapter 2, Fig. 2.7, dimension 2). Cooked muscle was processed according to the Bahrain tradition recipe for crabs. Crabs were allowed to boil for 2 hours with Turmeric powder and other mixed spices, as well as dates. Carapaces of both raw and cooked specimens were removed, and the two largest muscles connected to the swimming legs were carefully scraped out by scalpel (Fig. 1). These muscle samples were kept in polythene bags separately, each coded with the necessary information. Samples were held in a freezer until time of shipment to Sweden where they were analysed. For shipment specimens were placed in a polystyrene box filled with dry ice, so that they remained in good condition, prior to analysis.

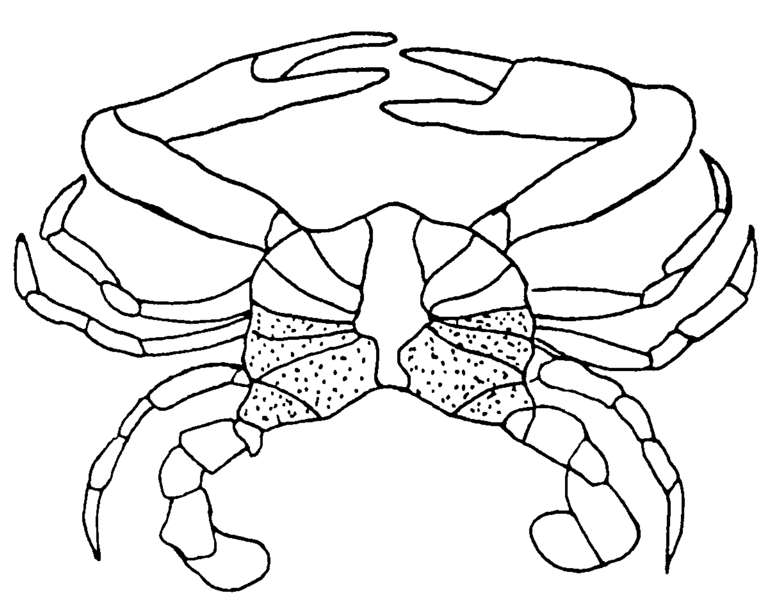


Figure 1. Illustration for *Portunus pelagicus* showing the part of the body (dotted) where the flesh was removed for the biochemical composition studies.

3.2.2 Methods of analysis

3.2.2.1 Moisture Content

Determination of moisture involved drying of the sample at 102-105 °C for 16-18 hours.

3.2.2.2 Nitrogen Determination

The sample was digested with concentrated sulphuric acid, with the addition of potassium sulphate and copper (II) sulphate. The ammonia formed is distilled off with sodium hydroxide solution and collected in boric acid. The nitrogen content of the sample is then determined by titration with hydrochloric acid.

3.2.2.3 Fat Determination

The sample was treated with 8M hydrochloric and after addition of ethanol the liberated fat is extracted with a mixture of diethyl ether and petroleum ether. The solvent is then evaporated and the fat residue weighed.

3.2.2.4 Mineral Composition

The samples were dried (~ 100 °C)and then ashed in muffer furnance at 450 °C, under gradual temperature increase. Hydrochloric acid is then added and the solution obtained evaporated to dryness. The residue is dissolved in 0.1 mol liter^{-1} nitric acid and the metal levels determined by AAS flame and graphite procedures.

3.2.2.5 Fatty Acid Profiles

Fatty acids were separated and quantitatively determined by gas liquid chromatography (GLC) as their methyl esters using the method of AOAC (1990). Only flesh with fat content more than 4% was included in the study. The oil was extracted from

3 g of tissue by a 2/1 chloroform/methanol mixture and methyl esters of fatty acids were then prepared using boron trifluoride as a catalyst. A gas liquid chromatograph (Packard Model 430) equipped with a flame ionization detector and a glass column (2m x 2m i.d.) packed with 10% DEGS was used. The column temperature was programmed to run at 150 °C for 3 min then raised progressively to 200 °C at 5 °C minute^{-1}. Both detector and injector temperatures were kept at 250 °C. Nitrogen was used as the carrier gas at a flow rate of 25 ml/min. The flow rates for hydrogen and air were 25 and 250 ml minute^{-1}, respectively. The various fatty acids were identified and quantified by comparison with known amounts of standard fatty acid methyl esters (Sigma, USA). Fatty acid content was then calculated as mg 100 g^{-1} edible protein.

3.3 Results and discussion

The carbohydrate, protein, fat, ash and water contents of the meat of *P. pelagicus* were determined separately for males and females to note any differences between the raw and cooked meats (Table 2). The water content ranged from 75.6% to 80% while that of protein ranged from 16.8% to 20.8%. Fat level was very low (0.6-1.4%). The protein and fat contents were reduced in both male and female crabs after cooking, whereas the fat concentration increased. Data obtained by the present study indicate that meat composition in both genders is similar.

Table 2. Proximate composition of *Portunus pelagicus* (g 100 g^{-1} wet weight).

Sampling site	Crab/area	Water	Protein	Fat	Ash	CHO	Energy	
							KJ	Kcal
Offshore waters, **Ghomais**	Female, raw	77.8	19.5	0.8	2.1	0.0	361.1	86.3
	Male, raw	80.0	18.7	0.6	2.1	0.5	316.3	75.6
	Female, cooked	78.2	18.8	1.4	2.7	0.9	352.7	84.3
	Male, cooked	75.6	16.8	1.2	3.7	0.8	375.9	89.8

Table 2. Continued

Sampling site	Crab/area	Water	Protein	Fat	Ash	CHO	Energy	
							KJ	Kcal
Inshore waters, **Hidd.**	Female, raw	75.6	20.1	0.8	2.7	0.8	384.9	92.0
	Male, raw	76.3	20.8	0.6	2.5	0.0	375.8	89.8
	Female, cooked	79.2	17.1	1.3	2.2	0.2	342.2	81.8
	Male, cooked	77.9	18.1	1.0	3.4	0.0	344.7	82.4

The mineral levels of *P. pelagicus* are presented in Table 3. The crab meat was low in iron and copper, but had a considerable amount of sodium (Na) , potassium (K), calcium (Ca) and magnesium (Mg).

Table 3. Minerals and heavy metals composition (ppm) of *Portunus pelagicus*. Concentrations are given in mg $100g^{-1}$ wet weight.

Sampling site	Fe	Na	K	Ca	Mg	P	Cu	Zn	Pb	Hg	Cd
Offshore waters, **Ghomais**											
Female, raw	0.3	330	370	64	37	300	0.5	2.1	0.02	0.03	< 0.02
Male, ra	0.4	290	320	130	36	250	0.6	2.3	0.02	0.04	0.02
Female, cooked	0.6	500	210	290	62	230	0.8	3.0	< 0.02	0.03	0.06
Male, cooked	0.6	820	290	250	71	240	0.9	2.6	< 0.02	0.05	0.1
Inshore waters, **Hidd**											
Female, raw	0.4	300	490	160	47	320	0.6	3.0	0.05	< 0.02	< 0.02
Male, raw	0.3	290	440	100	40	320	0.6	2.3	0.06	0.03	< 0.02
Female, cooked	0.6	420	210	180	53	200	1.1	3.6	0.05	< 0.02	0.03
Male, cooked	0.6	620	270	280	66	220	1.1	3.0	0.04	0.03	0.04

Unlike most fishes, crab meat has a high calcium content. Mercury and cadmium were detected in crabs caught from area 1 compared to area 2. However lead (Pb) level was higher in crabs caught in area 2. The presence of heavy metals in crabs may indicate pollution in these areas.

The protein in Bahrain crabs was higher than that reported by Srinivasagam (1979) in India, but fat levels were much lower. Srinivasagam (1979) found that there was a significant difference in fat content between male and female crabs. In Saudi Arabia, El-Faer *et al.* (1992) found similar findings as in our study in relation to protein, fat and moisture content. Our findings were also in good agreement with those from Pakistan in relation to proximate analysis, but with a higher content of protein in the Bahrain crabs. Hilmy *et al.* (1988) showed that mean lipid values in the muscles, hepatopanereas and gonads of two species of crabs were high.

3.4 Conclusions

1. *P. pelagicus*, commonly consumed in Bahrain is a good source of high quality protein.

2. The relatively high levels of calcium, phosphorus, potassium and zinc in the crabs make them a good source of these essential elements. One disadvantage of the cooked crabs is the increased level of sodium by more than 50%. Thus, it is recommended that the method of cooking be modified by reducing the amount of salt added to the crabs during the boiling procces.

3. All heavy metals that were investigated in the present study are below the recommended levels for human consumption. However, the slightly elevated levels of lead and cadimum found in the coastal specimens warrant further investigation as a means to gauge possible environmental contamination along the **Hidd** coastline.

3.5 Declaration

This study is a joint effort carried out by: 1) Dr. Abdulrahman Musaiger, Nutritionist; Director, Environmental and Biological Research Programme, Bahrain Centre for Studies and Research and 2) Mohammed Al-Rumaidh, author of the present thesis.

REFERENCES

Abdel Razek, F.A. (1988). Some biological studies on the Egyptian crab *Portunus pelagicus* (Linnaeus, 1766). *Acta Adriat.*, **29** (1-2): 133-143.

Ameer Hamsa, K.M.S. (1978a). On the meat content of *Portunus pelagicus* with some observation on lunar periodicity in relation to abundance, weight and moulting. *Indian J. Fish.*, **25** (1-2): 165-170.

Ang, S.G. & Chong, P.S. (1998). Purification of metallothionein proteins from the crab, *Portunus pelagicus*-selectivity of hydrophobic interaction chromatography. *Talanta*, **45**: 693-701.

Badawi, H.K. (1971). On the chemical composition of the red crab *Portunus pelagicus*. *Mar.Biol.*, **11** (3): 198-200.

Chopra, B. (1939). Some food prawns and crabs of India and their fisheries. *J. Bombay Nat.Hist. Soc.*, **4** (2): 221-234.

Dionysius, D.A.; Hoek, K.S.; Milne, J.M. & Slattery, S.L. (1993). Trypsin-like enzyme from sand crab *Portunus pelagicus*: purification and characterization. *J. Food Sci.*, **58** (4): 780-792.

El-Faer, Z.M.; Rawdah, T.N. Attar, K.M. & Arab M. (1992). Mineral and proximate composition of some commercially important fish of the Arabian Gulf. *Food Chemistry*, **45**: 95-98.

Hilmy, A.M., Abd El-Hamid, N.F. & Adham, KH. G. (1986). Glycogen content of some organs in two marine crustaceans. *Bull. Inst. Oceanogr. & Fish. ARE.*, **12**: 215-229.

Hilmy, A.M.; Abd El-Hamid, N.F. & Adham, KH. (1988a). Changes in lipid and cholesterol composition in relation to sex and the moult cycle in the crab *Portunus pelagicus* (L.) and the prawn *Penaeus kerathurus* (L.). *Folia Morph.*, **36** (2): 141-159.

Hilmy, A.M., Abdul-Hamid, N.F. & Ghazaly, K.S. (1988b). Observations on intraspecific variation of total protein, amino acid and total nonprotein compound levels and their fractions in the muscles, heptopancreas and gonads of two crustaceans, *Portunus pelagicus* (L.) and *Penaeus kerathurus* (L.), in relation to maturation. I. Total protein and amino acids. *Folia Morph.*, **36** (2): 188-199.

Potter, I. C., Chrystal, P. J. & Loneragan, N. R. (1983). The biology of the manna crab *Portunus pelagicus* in an Australian Estuary. *Mar. Biol.*, **78** (1): 75-85.

Shields, J.D. & Wood, F.E.I. (1993). Impact of parasites on the reproduction and fecundity of the blue sand crab *Portunus pelagicus* from Moreton Bay. Australia. *Mar. Ecol. Prog. Ser.*, **92** (1-2): 159-170.

Siddiquie, P.J.A., Akbar, Z. and Qasim, R. (1987). Biochemical composition and calorific values values of the three edible species of portunid crabs from Karachi. *Pak. J. Sci. Ind. Res.*, **30** (2): 119-121.

Slattery, S.L., Dionysius, D.A., Smith, R.A.D. & Deeth H.C. (1989). Mushiness in the blue swimming crab *Portunus pelagicus* (L.). *Food Australia*, (April). **41** (4): 698-709.

Srinivasagam, S. (1979). On the nutritive values of the meat of portunid crabs. *J. Inland Fish. Soc. India*, **11** (2): 128-131.

Stephenson, W. (1972). An annotated check list and key to the Indo-West-Pacific swimming crabs (Crustacea : Decapoda : Portunidae). *Bull. R. Soc., N. Z.* **10,** 64 pp.

Sumpton, W.D.; Potter, M.A. & Smith, G.S. (1989). The commercial pot and trawl fisheries for sand crab *Portunus pelagicus* (L.) in Moreton Bay, Queensland. *Proc. R. Soc. Qd.*, **100** (1): 89-100.

Thomson, J. M. (1951). Catches composition of the sand crab in Moreton Bay. *Aust. J. Mar. Freshwater Res.*, **2:** 237-244.

Todd, J. (1995). So you want to go crabbing. *Southern Fisheries*. **3** (2): 29.