Postlarval and juvenile western king prawn *Penaeus latisulcatus* Kishinouye studies in Gulf St Vincent, South Australia with reference to the commercial fishery

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ABSTRACT

A seven-year study was undertaken on the spatial and temporal variability of postlarval settlement and juvenile abundance of western king prawn *Penaeus latisulcatus* in nurseries. Key nursery areas within Gulf St Vincent were established and settlement trends in key nurseries were monitored from October 1989 to June 1996. These trends were related to the adult stock and subsequent recruitment to the fishery and commercial catches. During this period, the commercial fishery was closed for two years and this study provides baseline information on the natural variability of settlement between years and allows for a comparison of postlarval settlement rates during varying levels of fishing effort. This could be viewed within the concept of 'adaptive management' whereby responses in postlarval settlement and recruitment levels are sought due to the presence and absence of fishing pressure on the spawning population. No significant difference was observed for postlarval settlement, juvenile abundance or recruitment between the periods, before, during or after closure. Challenges posed when undertaking adaptive experiments are discussed.

The main nursery areas occur north of Port Gawler on the eastern side around to Ardrossan on the western shore. Favoured nursery habitats tend to be shallow and sheltered with a sand-mud sediment and often associated with mangrove areas. The tidal flats throughout these areas can extend from 200m up to one km offshore and major nurseries encompass approximately 150 km^2. Prawn nursery habitats within Gulf St Vincent cover a relatively small area overall, and the likely loss or substantial impact on these areas requires their protection from additional or continuing pollution sources and major coastal developments.

One aim of this study was to determine an acceptable semi-quantitative measure of the number of prawns within a nursery area that will be comparable within and between years as well as between sites. *P. latisulcatus* is nocturnal and buries in the sediment during the day. Knowing this behaviour, led to the development of a daytime sampling device, the jet net. The jet net was shown to be an efficient sampling device minimising catchability effects by sampling prawns during the day when they are buried within the substrate. It is more efficient in capturing the available juvenile prawns than a traditional beam trawl commonly used in juvenile prawn studies.

From a number of trials investigating the small-scale spatial and temporal variability within a nursery site, it was determined that the best sampling technique for *P. latisulcatus* was to use a fully enclosed jet net, towed perpendicular to the shore or covering the width of the available nursery area to incorporate any depth preference for different sized individuals. The diagonal sampling method provides a reliable relative measure from one time to the next and samples from one or a few sites within this extended region is representative of the true relative abundance of prawns at that region.

It was found that variation in postlarval settlement occurs on a seasonal, spatial and annual basis. Variation between years was smaller than observed for months and sites. Site was the most significant effect. Postlarval settlement and juvenile abundance was higher in the northern sites compared to the two southern sites. The postlarval settlement pattern appears to be continuous between mid December and early June. No postlarvae were found in nursery areas during winter. Juvenile prawns are found in nurseries throughout the year with highest numbers occurring in late February to late May. The number of juvenile prawns in nurseries depends on the strength of postlarval settlement and overall prawn production from nurseries is dependent on the survival and growth characteristics within each nursery area. Estimates of

growth and mortality in nursery areas are discussed. The timing of settlement and temperatures experienced while in the nurseries will determine how fast the prawns will grow and when they move out of nurseries. A decline in juvenile prawn abundance in late May and again in late November probably indicates movement out of nurseries. These periods correspond to recruitment peaks in the commercial fishery.

Tidal and wind modelling was undertaken to follow larval movement from main spawning areas within the gulf where aggregations of spawning females were found. The years, 1989/90 and 1990/91 were used for the modelling because wind and tide information was available at regular intervals. The northern spawning areas were more important than southern regions as the larvae were advected to key nursery areas in either the eastern or western side of the gulfs. Differences in settlement patterns between the two years were predicted from the modelling and there was some reflection of these in field sampling. Modelling however, could not predict the timing, specific location or abundance of settling postlarvae precisely. Oceanographic and wind information on a finer spatial scale along with more accurate information on the reproductive biology, timing of spawning, distribution patterns and larval behaviour of *P. latisulcatus* is required to increase the precision or predictive ability of modelling.

The initial numbers of postlarvae in nurseries depend on larval supply. A correlation was observed between postlarval settlement and juvenile abundance. In general it is expected that a pulse of postlarval settlement gives rise to a pulse of early juveniles about four weeks later. Furthermore a correlation was seen between juvenile numbers and recruits to the fishery as well as with recruitment and commercial catch rates. However, the number of data points is small and additional sampling should be undertaken to further validate these relationships. A period of at least ten years would be required to provide stronger evidence of relationships. Knowing these relationships could allow for an earlier assessment of the health of the fishery and the adoption of conservative harvesting strategies to reduce the risk of over-exploitation.

For the Gulf St Vincent prawn fishery, although there was some evidence of a relationship between recruitment and commercial catch rates, it appeared that the level of recruitment did not drive the level of catches during the period of this study. This may be due to other factors being more important in determining catch rates namely, low overall fishing effort, large harvest size and spatial and temporal fishing strategies. With current harvesting practices in place, postlarval settlement indices could not be used to predict the level of catch in the fishery. Sampling in key nursery sites would, however, provide a cost-effective means of maintaining long-term monitoring the health of nurseries and can detect low settlement years.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due acknowledgment is made in the text.

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1. INTRODUCTION

1.1 Importance of inshore stages in marine species and impetus for recruitment studies

Most coastal marine species have life histories consisting of a planktonic egg and/or larval stage and a benthic juvenile and adult stage (Thresher 1991). There is high potential for transport of eggs and larvae over long distances (Scheltema 1971, 1986, Scheltema & Williams 1983) and for high levels of mortality during this period due to predation and starvation. The length of the larval phase will greatly influence survival and transport. The variability in the transport mechanisms and survival of larvae contribute to the spatial and temporal variations seen in marine populations.

For many marine species, inshore, shallow, sheltered areas provide suitable nursery areas for individuals to shelter, feed and grow before entering the adult phase of their life cycle. What happens to individuals in these inshore regions has been an area of investigation for many species, particularly those contributing to commercial or recreational fisheries.

The understanding of recruitment processes and recruitment variability in fisheries is fundamental to their management. Often, initial studies are undertaken to describe this variability and then further investigations are made to determine the processes that cause or influence variability. In fisheries, recruitment can be defined as the addition of individuals to an adult unit stock (King 1995). This can either be by individuals becoming vulnerable to exploitation due to their size or by individuals moving into areas where fishing takes place. This recruitment process comes after the juveniles have spent some time in nurseries. The period spent in nurseries and juvenile survival to the next life-history phase is central to the recruitment process.

1.2 The importance of Penaeidae

The penaeid prawns are economically important throughout the world. Significant commercial penaeid fisheries became established in various countries by the late nineteenth century. A great expansion of offshore trawling for penaeids started about 1950. This stimulated research on the Penaeidae (Dall *et al.* 1990). Penaeidae comprise most of the total world catch of prawns, estimated at around 700, 000 tonne per year (Rothschild & Brunenmeister 1984, Garcia 1988). The *Penaeus* genus contains many species and has the greatest value (Dall *et al.* 1990). *Penaeus* spp. are the basis of many artisanal, recreational and commercial fisheries worldwide and provide local and export products, employment opportunities and recreation. In Australia, substantial fisheries exist for a number of penaeid species in Northern Australia, New South Wales, South Australia (SA) and Western Australia (WA).

1.3 Life-history pattern of Penaeus latisulcatus

Most penaeid prawns inhabit shallow and inshore tropical and sub-tropical waters. The life histories of the common commercial species are well known. Generally for penaeids there are four types of life histories (Dall *et al.* 1990),

1. fully estuarine life cycles,
2. cycles where spawning takes place offshore and planktonic stages migrate inshore towards the end of larval development. For these:
   2.1. postlarvae prefer estuarine-like environments
   2.2. postlarvae prefer salinity at seawater or above, usually in sheltered inshore waters
3. fully oceanic life cycles

Penaeus latisulcatus has a life cycle corresponding to 2.2., with an oceanic adult life and an inshore juvenile stage (Figure 1.1).

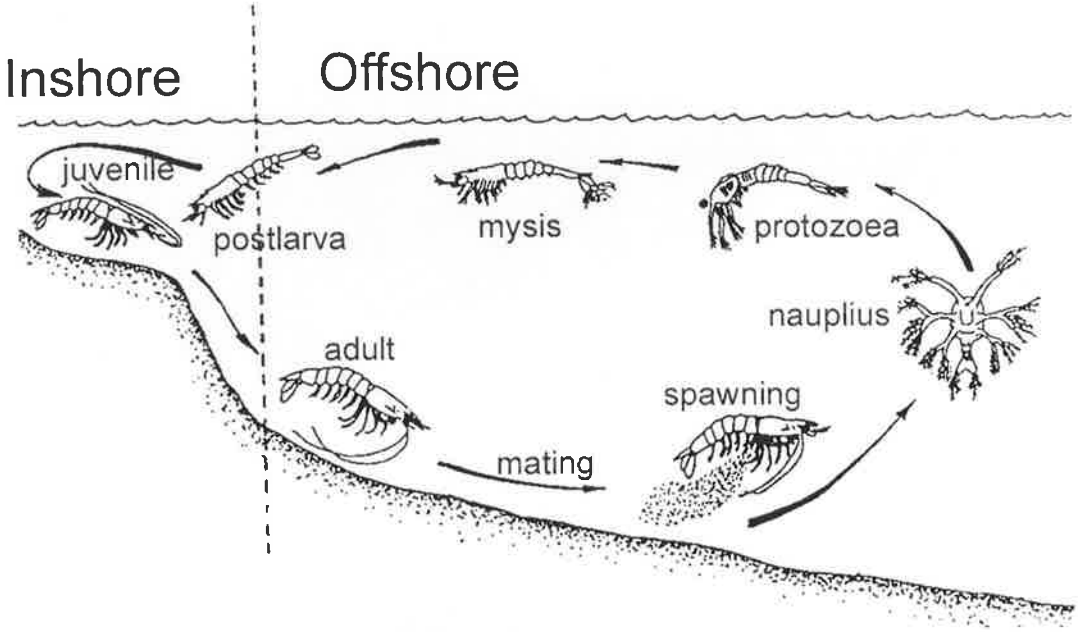


Figure 1.1 Life-history pattern of *Penaeus latisulcatus* in Gulf St Vincent indicating inshore and offshore stages.

* Source - NSW State Fisheries Leaflet No.8 'Biology & life cycles of prawns'

Adult female prawns spawn between October and March (King 1977) and in Spencer Gulf it has been demonstrated that there are two main spawning peaks, one in November-December and one in February-March (Carrick 1996). The general reproductive process in prawns is described in Dall *et al.* (1990) and Penn (1980) and Courtney and Dredge (1988) have studied reproduction of *P. latisulcatus*. The male transfers its sperm capsule (spermatophore) into the female (thelycum) using its petasma. For successful insertion, the female prawn needs to have moulted recently so that the plates of the thelycum are open. When the eggs are mature they are released into the water column; on release, the spermatophore ruptures and the eggs are fertilised (Dall *et al.* 1990).

A study of female prawns from Gulf St Vincent (GSV) indicates that they can release between 80,000 and 600,000 eggs in a single spawning. Female prawns may spawn more than once in a season (Penn 1980). Adult prawns can live three to four years after recruiting onto the fishing grounds. This has been confirmed by tagging studies in GSV (unpublished data) with the longest time at liberty being just over three years for both male and female prawns. Adult prawns can therefore contribute to egg production more than once.

The eggs hatch and the prawns develop through larval stages nauplius, protozoea, zoea, mysis and postlarva (Shokita 1984). At this stage they are ready to settle. Laboratory trials at 29.5°C indicated a larval period of eight days for *P. latisulcatus* (Shokita 1984), while Penn (1975) estimated a larval period of two to four weeks at temperatures between 18° and 25°C. In GSV, observations on postlarval settlement and the timing of spawning suggest that the larval period can be from four to eight weeks. The apparently longer larval stage in GSV may be related to cooler water temperatures.

We know something of the annual cycles of postlarval settlement from previous studies of *Penaeus latisulcatus* in South Australia (King 1977, Wallner 1985, Carrick 1996). The postlarvae settle into shallow sheltered inshore areas where they can spend up to 12 months depending on the time of year they settle. Those postlarvae that settle as a result of early spawning in October-November, arrive in nursery areas in December-January, grow rapidly and may move back out into deeper water or onto the fishing grounds in May-June. These small prawns moving out onto the nursery areas are known as 'direct' recruits. Those postlarvae that result from later spawning in February-March settle in nurseries April-May and grow slowly while remaining in the nursery areas over winter. In January-February the following year they move out into deeper water. These are known as 'overwintered' recruits (Carrick 1996). These alternative life history scenarios are shown in (Figure 1.2).

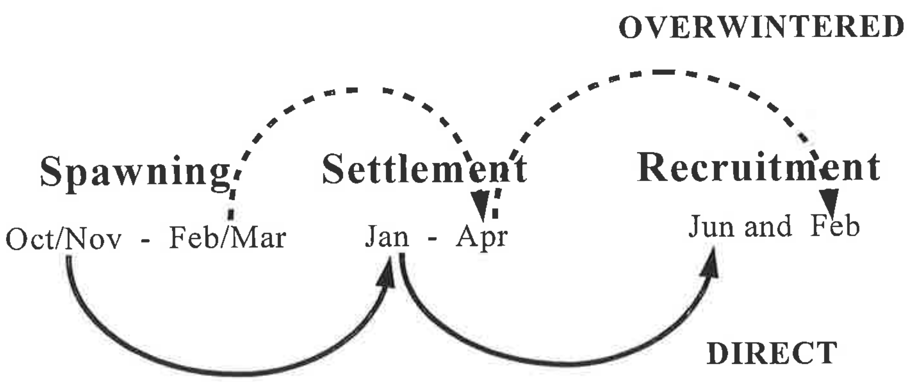


Figure 1.2 Schematic diagram of the life-history of *Penaeus latisulcatus* indicating two possible scenarios in Gulf St Vincent; early spawning, early settlement and direct recruitment and later spawning, later settlement and overwintered recruitment to the fishery.

1.4 Commercial prawn fisheries in South Australia

The western king prawn, *Penaeus latisulcatus* Kishinouye, is distributed throughout the Indo-west Pacific waters (Grey *et al.* 1983). Its distribution in SA is restricted to waters of Spencer Gulf and GSV and along the west coast in Anxious Bay, Venus Bay and Ceduna (Figure 1.3). It forms a basis of three commercial prawn fisheries with a total annual catch of 2500 tonne. Its distribution continues to south-western Australia where it contributes to the commercial and recreational fishery (Potter *et al.* 1991) and to a major commercial fishery in Shark Bay and Exmouth Gulf in Western Australia (Kailola *et al.* 1993). Their distribution then extends along the northern shores of Australia in the Northern Territory and Queensland where it is a minor species in a multi-species prawn fishery.

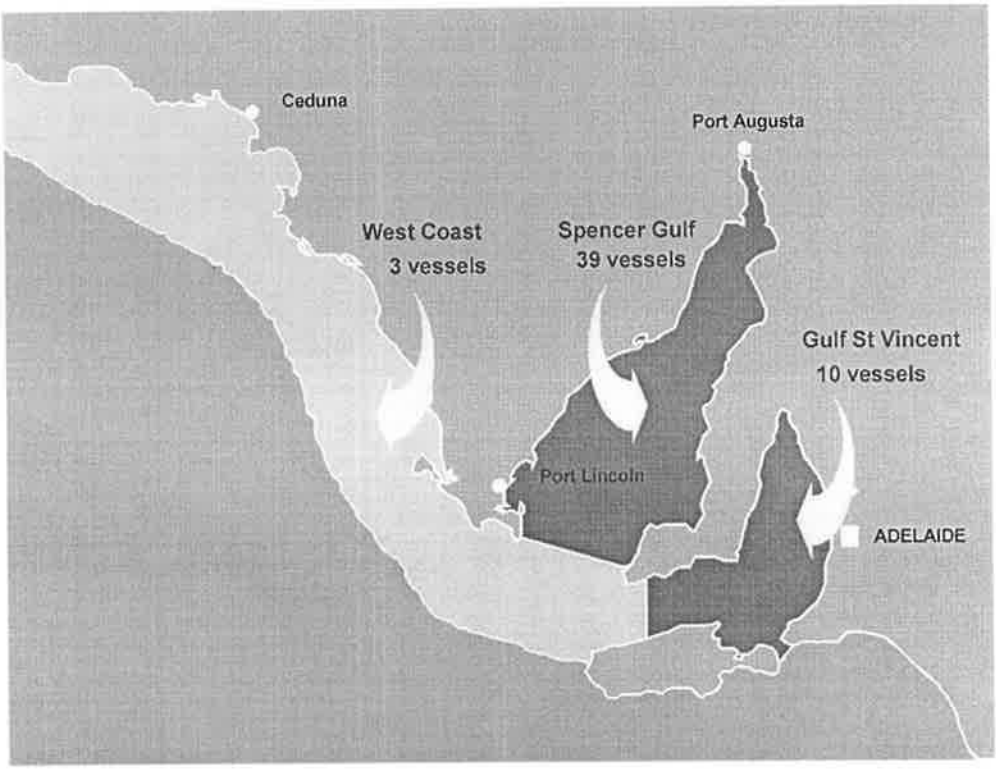


Figure 1.3 Prawn fishing zones in South Australia.
Source* South Australian Research and Development Institute, 1997.

Commercial prawn fishing commenced in South Australia in the late 1960's and is currently valued at around $35 million. The Spencer Gulf prawn fishery is the most productive, harvesting on average 2000 tonne per year. The GSV and West Coast prawn fisheries each presently produce on average around 250 to 350 tonne per year. The GSV prawn fishery currently is valued at around $3 million.

Commercial prawn fishing is undertaken using otter trawls. Twin rig (two nets) is used in Spencer Gulf and the West Coast fisheries while GSV vessels use triple rig gear. Each fishery is limited entry with 10 licence holders in GSV, 39 in Spencer Gulf and three on the West Coast. This limitation is intended to control the overall level of fishing effort in each fishery. Additional methods by which fishing effort is controlled are limits on the vessel size and horsepower, a limit on the headline length (amount of net on the bottom) of the nets, minimum mesh regulations as well as seasonal, lunar cycle and area closures. These closures limit the total number of nights fished and also provide protection to areas of spawning females and smaller prawns allowing them to grow to a larger and more valuable size.

1.5 History of the Gulf St Vincent prawn fishery

The Gulf St Vincent prawn fishery commenced in 1968 and a record of the fishery's statistics is available from its inception (Figure 1.4). The first few years of the fishery were exploratory in nature with up to seven participants. By the early to mid seventies the fishery had 14 participants and the skill and experience level of the fishers was advanced with good catches being recorded. At this time, the fishers were using single rig trawl gear. During this period, there were very few restrictions in the amount of time allowed for fishing or where fishing occurred. However, anecdotal evidence indicates that the fishers tended to target larger prawns during this period. A permanent closure prohibiting trawling in areas less than 20m in depth was put in place during 1972. This ensured that seagrass beds and inshore nursery areas were not fished.

Due to the increased level of catches and apparent high level of stocks in GSV and Investigator Strait (IS), the IS region was opened up as a separate fishery in 1975 with the issue of 5 ministerial permits. This created the separation of the GSV (with 14 licence holders) and IS fisheries (5 licence holders). In addition, those waters outside three kilometres of state shores (outside the gulfs) were assigned as Commonwealth waters and under their jurisdiction. Therefore, additional Commonwealth endorsed vessels (anything up to ten vessels) also fished IS waters. Catch details are not available for these vessels. This ceased in 1977.

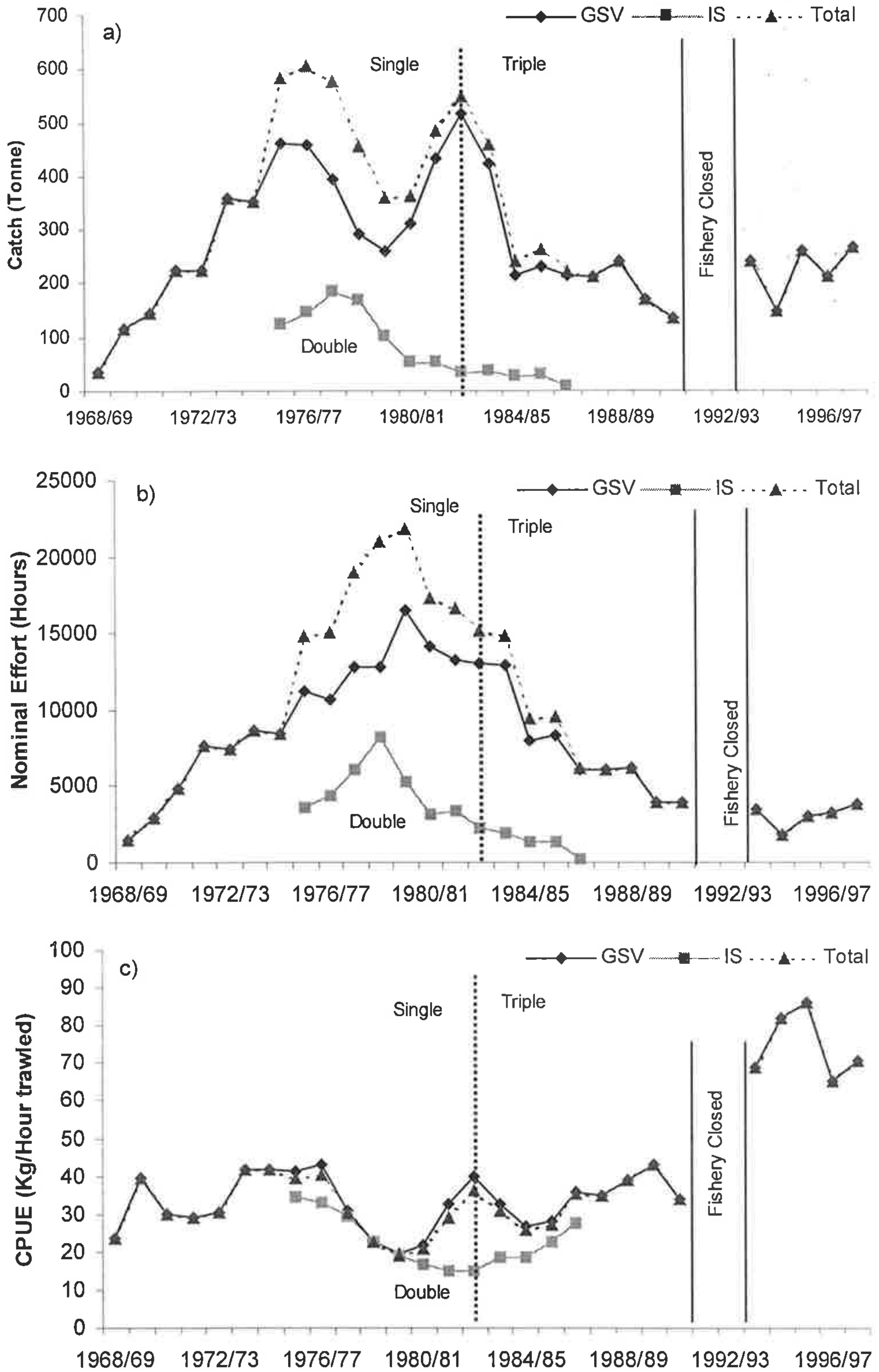


Figure 1.4 Catch and effort history of Gulf St Vincent and Investigator Strait prawn fisheries for financial years. a) Catch in GSV and IS between 1968/69 and 1997/98 showing years of single and triple rig use (dashed line) for GSV (double at all times in IS) and the period of total closure in 1991/92 and 1992/93, b) nominal fishing effort for GSV and IS during 1968/69 to 1997/98, c) CPUE for GSV and IS during 1968/69 and 1997/98.

Significant conflict occurred between the GSV and IS fishers over their perceptions of the impact one group was having on the harvest and harvest rates of the other. Speculation was made as to which regions sustained the fishery, eastern IS or northern Gulf regions, with each group of fishers accusing the other of detrimentally affecting the fishery.

From 1975, the IS fishery showed good catches for several years but this fell in the early eighties to a sustained lower level (Figure 1.4). The catches from the first few years of this fishery were based on the fishing down of relatively unexploited stock (King 1977) and after that the IS fishery may have been based on prawns that moved south from the GSV stock (Carrick, pers. comm.). In GSV, catches and catch rates started to decline in the late seventies and in 1982 the vessels converted from single rig to triple rig. During 1982 and 1983 the catches again increased, due in part to the significant increase in catch efficiency of the vessels as a result of the gear changes. The harvesting patterns also changed during this time with vessels fishing in more northerly areas of GSV and targeting smaller prawns (Carrick, pers. comm.). During this period, heavy fishing of the stocks took place in the northern regions of GSV, particularly during the spawning period. The consequence of heavy fishing prior to spawning is to reduce the amount of female prawns producing eggs.

By the mid eighties low catches suggested that the stock levels were low (Figure 1.4) and remedial action was required to rehabilitate the stocks. The level of effort, the pattern of fishing and prawn target size needed to be reviewed to allow protection to spawners and smaller prawns. A buy-back scheme was introduced in 1987 following an economic review of the fishery by Copes (1986) and five vessels were removed from the fishery, including the remaining two vessels in IS and three from GSV. The two fisheries were combined as the GSV prawn fishery. This removal of vessels reduced the potential effort in the fishery and restrictive fishing practices put in place in the mid eighties were also continued. During the period between 1984 to 1989, improvement in the level of recruitment into the fishery was suggested from results of stock monitoring surveys that were reported to the GSV prawn management advisory committee at the conclusion of each survey. However, these levels of improvement were not translated into higher catches to fishers. A total closure of the fishery was implemented in 1991 for two years following a parliamentary review into the fishery

(Quirke *et al.* 1991). One licence was surrendered during this closure period. Commercial fishing re-commenced in March 1994. The fluctuating catches and changing management practices reflect the ongoing controversy in the GSV prawn fishery.

1.6 Earlier studies of P. latisulcatus in South Australia

Several unpublished biological studies have been undertaken on *Penaeus latisulcatus* in South Australia. Zed (1977) and Wu (1985) carried out physiological studies of the tolerance of *P. latisulcatus* to salinity and temperature fluctuations. Zed (1977) used these studies to describe the distribution of the species in SA whilst Wu (1985) was interested in the aquaculture potential of the species.

King (1977) undertook biological studies of both adult and juvenile *P. latisulcatus* with an emphasis on Spencer Gulf populations. He determined broad distribution patterns and population parameters such as growth and mortality for both adults and juveniles by several methods. King (1977) sampled areas in GSV for potential nursery sites using a beam trawl and undertook monthly sampling in Barker Inlet over 12 months. This provided preliminary information on seasonal variation in juvenile abundance and emigration out of one nursery area in GSV. The mesh size of the beam trawl was 12.7 mm and selectivity trials indicated that prawns < 5mm were under-sampled. Therefore, postlarvae (<3 mm CL) were not sampled in his study.

Wallner (1985) studied the biology of adult, juvenile and larval prawns on the west coast of SA. The main regions of study were Anxious Bay and the Ceduna/Thevenard where most of the commercial fishing takes place in this region. Juvenile studies were conducted between February 1984 and June 1985. He utilised extensive spotlight surveys to determine relative abundance of juveniles at various sites. Regular monthly sampling at Bosanquet Bay was initially made with a roller beam trawl, which due to difficulties of working in shallow water was replaced by a roller pushnet with a 5-mm mesh. Between February and June 1985 he used a jet-net designed by Penn and Stalker (1975) to sample juvenile populations. From size frequency and abundance information over the 12 months, Wallner (1985) made estimates of growth and emigration patterns.

The most recent biological work undertaken on *Penaeus latisulcatus* in SA was that of Carrick (1996). This was based solely on Spencer Gulf prawn populations. The study had two parts. One dealt with fishery dynamics, including harvest models, fishing power and the effects of fishing on dispersal and population fecundity. The other focussed on aspects of the early life-history of the species, including reproductive dynamics of adult prawns, larval distribution, advection and mortality over two years as well as juvenile prawn distribution, temporal and spatial variability in abundance over two years.

The apparent decline in GSV prawn stocks in early 1980's and concerns for recovery and future sustainability provided impetus for additional research in GSV of the dynamics of postlarval and juvenile populations and their variability and the relationship between this variability and the commercial fishery. Several economics and fisheries management documents have been written on the Gulf St Vincent prawn fishery including Sluczanowski (1978), Byrne (1978, 1982), Copes (1986, 1990), Quirke *et al.* (1991), Morgan (1995) and Morison (1996). Changes in the number of vessels, research support provided and management arrangements for the Gulf St Vincent prawn fishery have resulted from recommendations outlined in these documents. These documents would have benefited from additional information on postlarval and juvenile prawn dynamics and recruitment variability in the Gulf St Vincent prawn fishery.

1.7 Objectives of this study

This current study concentrates on the settlement and nursery stages of the life history of *Penaeus latisulcatus* (Figure 1.5) over a seven year period. The objectives of the study were to;

1. Establish key *Penaeus latisulcatus* nurseries in Gulf St Vincent and Investigator Strait,
2. Determine an acceptable semi-quantitative measure of the number of prawns within a nursery area that will be comparable within and between years as well as between sites. This requires gear development and determination of small-scale spatial and temporal variability in prawn size and abundance within a nursery area.
3. Determine spatial, seasonal and yearly postlarval settlement trends in key nurseries. This study provides baseline information on the natural variability of settlement during seven years and allows comparison of settlement rates during varying levels of fishing effort.
4. Utilise mathematical modelling of winds, tides and larval behaviour in Gulf St Vincent to answer biological questions related to settlement patterns during 1990 and 1991. Differences in settlement patterns were observed between these years.
5. Determine production characteristics (growth and mortality) of the juvenile population from field information. Size of growth increments and the length of intermoult period were also observed under laboratory conditions for a period of seven weeks.
6. Establish relationships between postlarval and juvenile abundance and other life-history stages of *P. latisulcatus.* This information could enable the use of postlarval or juvenile indices for predictive purposes and as a tool to aid in the management of the fishery.
7. Consider adaptive management as a tool in management of fisheries by evaluating the effectiveness of a total closure for two years on postlarval settlement, juvenile abundance and recruitment to the fishery.

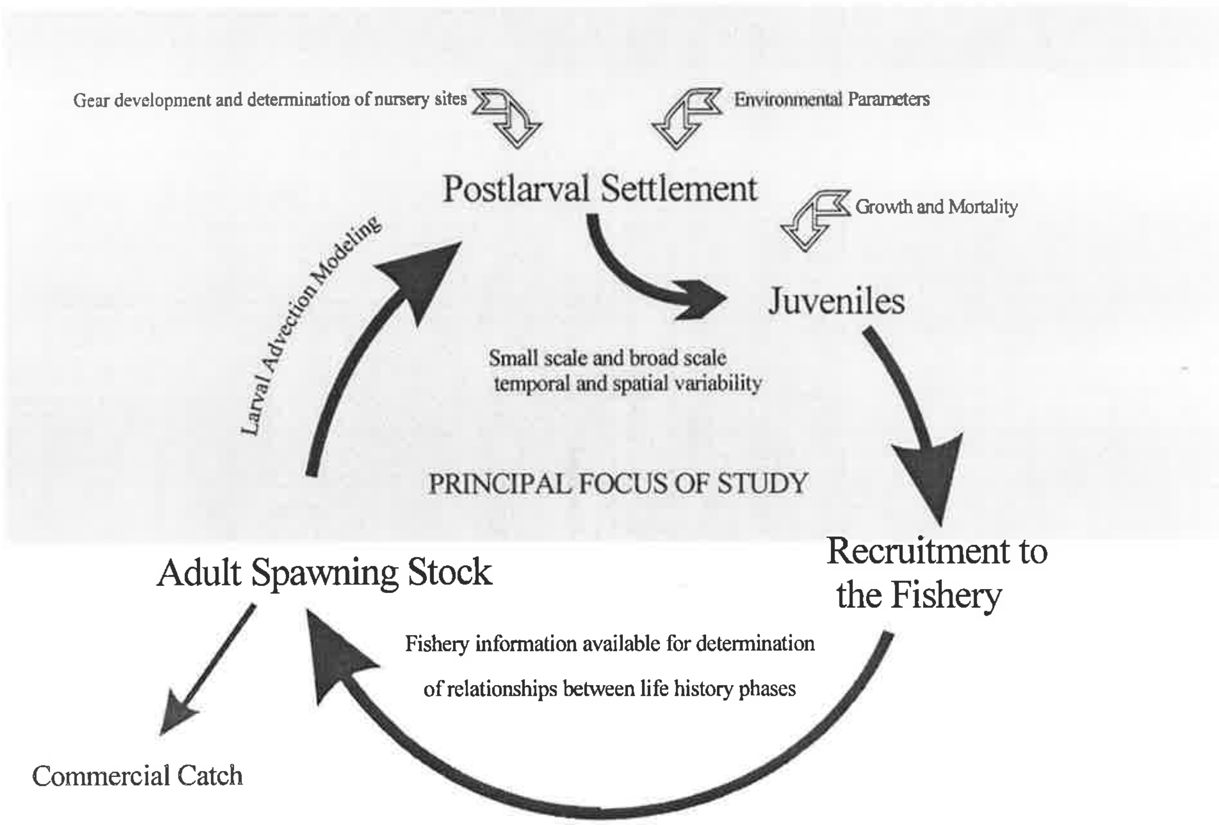


Figure 1.5 Model depicting life-history pattern of *Penaeus latisulcatus* highlighting the principal aims of this study, gear development and determination of nursery sites, small-scale and broad-scale temporal and spatial variability in postlarval settlement and juveniles in nurseries, growth and mortality of postlarvae and juveniles in nurseries and variability in environmental parameters during the study.

2. SURVEY TO ESTABLISH *Penaeus latisulcatus* NURSERY AREAS

2.1 Introduction

For some penaeid species, the life history patterns include juvenile nursery areas in estuarine systems. The situation for *Penaeus latisulcatus* in Gulf St Vincent is different. The waters of GSV do not have any major inflowing rivers and in summer 'inverse estuary' conditions develop in the northern parts of the gulf (Thomas & Edmonds 1956, Bye 1976). Shallow inshore areas have significant seasonal temperature fluctuations and higher salinities during summer months. This is also a characteristic of nurseries for *P. latisulcatus* in Exmouth Gulf and Shark Bay (Penn 1975) and Peel-Harvey Estuary and Serpentine River (Loneragan *et al.* 1986) in Western Australia (WA). *Penaeus latisulcatus* appears well adapted to these conditions. Zed (1977) and Wu (1990) showed that the juvenile stages of *P. latisulcatus* in SA, are highly tolerant of salinity and temperature fluctuations with high survival rates at salinities between 18‰ to 44‰ for temperatures between 17.0°C and 32.0°C.

Historically and to date there has been debate between sectors of industry and scientists on the relative contribution of nursery areas in northern GSV compared to inshore areas in Kangaroo Island (KI) and southern Yorke Peninsula. The regions that constitute the main nurseries needed to be established. This could be done by surveys of suitable habitats in the KI and GSV areas.

The juveniles of many penaeid prawns are found in vegetation such as seagrasses or *Spartina* (Dall *et al.* 1990). The banana prawn, *P. merguiensis* is found associated with mangroves at high tide and creek banks on low tide (Staples 1980a, Staples & Vance 1987, Haywood & Staples 1993, Vance *et al.* 1994) whilst tiger prawns *P. esculentus* and *P.semisulcatus* have been recorded mainly in seagrass and/or algal beds (Young & Carpenter 1977, Turnbull & Mellors 1990, Loneragan *et al.* 1994, O'Brien 1994a, Haywood *et al.* 1995, Vance *et al.* 1996). The eastern king prawn *P. plebejus* and greasyback prawn *Metapenaeus* *bennettae* have been observed both on seagrass and bare substrates but generally show higher numbers in areas with seagrass (Young 1978, Worthington *et al.* 1995).

Juvenile prawn sampling in Spencer Gulf by Carrick (1996) and on the West Coast by Wallner (1985) indicated that juvenile prawns occur mainly in the intertidal zone inside the seagrass line. In WA, Penn *et al.* (1989) states that juvenile *P. latisulcatus* is found on the bare sand areas of shallow sandflats and Potter *et al.* (1991) found juvenile *P. latisulcatus* on sandy substrates in the Peel-Harvey Inlet. In East Africa, Subramanian (1990) found *P. latisulcatus* in sheltered sandy beaches and mangrove areas but also associated with seagrasses. This preference for intertidal sand/mud flats by juvenile *P. latisulcatus* differs to most other Penaeid prawns.

2.2 Methods

2.2.1 Site selection

Potential settlement sites were selected using aerial photographs and ground truthing. Suitable areas were considered to be regions which had; some intertidal flats, reasonable boat access nearby, sufficient tidal height to be able to launch, sample and retrieve the boat during a tidal cycle and each site to be at least 10 km apart. The area covered was from Barker Inlet north on the eastern shore and on the western shore, from Port Arthur in the north to Sturt Bay on the southern tip of Yorke Peninsula. An area on the eastern side of GSV south of Port Wakefield to just north of Port Prime could not be accessed, as it is a military zone. On KI, only the northern sheltered shores of the island were inspected, as generally the southern regions of the island are very exposed with high wave action. Potential settlement sites were selected as those which had; some intertidal flats, reasonable boat access nearby, sufficient tidal height to be able to launch, sample and retrieve the boat during a tidal cycle and each site to be at least 10 kilometres (km) apart. Either walking over the site at low tide and/or motoring over the area undertook ground truthing with the boat at high tide. Approximately one half to two km of shoreline was surveyed by these methods at each potential site.

Areas considered to be unsuitable for sampling were; areas south of Coobowie that consisted of exposed beaches and/or rocky limestone outcrops, Rogues Point and Port Julia on the western side due to rocky limestone outcrops, Thompsons Beach on the eastern shore due to insufficient tide height and north of Bolivar to just south of Port Gawler due to excessive epiphytic algal growth.

The total extent of nursery areas was calculated from results of field sampling. This was extended to the whole of GSV by measuring the length of the coastline where main nursery grounds occur using a chart and aerial photographs. This was converted to an areas by and assuming that the average width of suitable nursery areas (from field sampling in nursery areas) was a width of one kilometre.

2.2.2 Sampling

The sampling gear developed was a modification of a jet net described by Penn and Stalker (1975). Gear development and testing are described in detail in Chapter 3. Sampling was undertaken during April-May 1989 and during February-March 1990 (Table 2.1). On the second sampling, Barker Inlet was omitted because of extreme difficulties in sampling due to presence of epiphytic algae and *Ulva* and Port Gawler was omitted because obstructions such as mangrove roots and branches on tidal flats that had been washed out from Gawler River after rains. However, Coobowie, was added to the sampling in 1990.

Sampling in 1989 was undertaken parallel to the shore, halfway between the seagrass line and high water mark. In 1990, trawls were undertaken perpendicular to the shore because a better representation of overall prawn size composition was achieved by this method. These comparisons are detailed in Chapter 3. At each site, three trawl shots were made, each 100 metres (m) in length. At Stansbury and Coobowie two to three tows were made to equal 100m due to the limited area of clean bottom for trawling. The samples were sorted on shore and prawns were counted and measured in the laboratory. Measurements of carapace length (CL) to the nearest 0.1mm were made using a dissecting microscope with an ocular micrometer.

2.3 *Results*

High numbers were observed in the northern parts of GSV between Port Gawler on the eastern shore to Port Clinton on the western shore (Table 2.1, Figure 2.1). Extensive tidal flats, relatively sheltered conditions and presence of mangroves characterized these areas. Ardrossan, further south on the western side had less, but still reasonable numbers of prawns during 1990 but the site is more exposed and is a sandy beach without mangroves. Juvenile numbers in Coobowie Bay during 1990 were also moderate and this bay has muddy/sandy sediments and is relatively sheltered compared to adjacent coastal areas.

An assessment of the total area available as nursery habitat in GSV using aerial photographs and ground surveys indicate an approximate distance of 150 km of coastline at a maximum of one km width providing a total area of around 150 km^2. Very few prawns were found on KI in either year. American River was sheltered, had clean sandy substrate and no prawns were found at all. Bay of Shoals was a sheltered area with mud/sand substrates and very few prawns were found. Eastern and Western Coves had mud/sand substrates with some wave exposure. Only two prawns were found in Western Cove in 1990 and none in Eastern Cove.

Table 2.1 Mean number of juvenile *Penaeus latisulcatus* m^{-2} for three trawls at sampling sites for April-May 1989 and February-March 1990

Location	1989	1990
Barker Inlet	0.1	not sampled
Port Gawler	1.2	not sampled
Port Wakefield	0.8	1.51
Port Arthur	0.5	3.25
Port Price	1.5	0.52
Port Clinton	0.3	1.56
Ardrossan	0.05	0.53
Port Vincent	0.03	0.07
Stansbury	0.03	0.23
Coobowie	not sampled	0.59
American River, KI	0	0
Bay of Shoals, KI	0.01	0.003
Eastern Cove, KI	0	0
Western Cove, KI	0	0.02

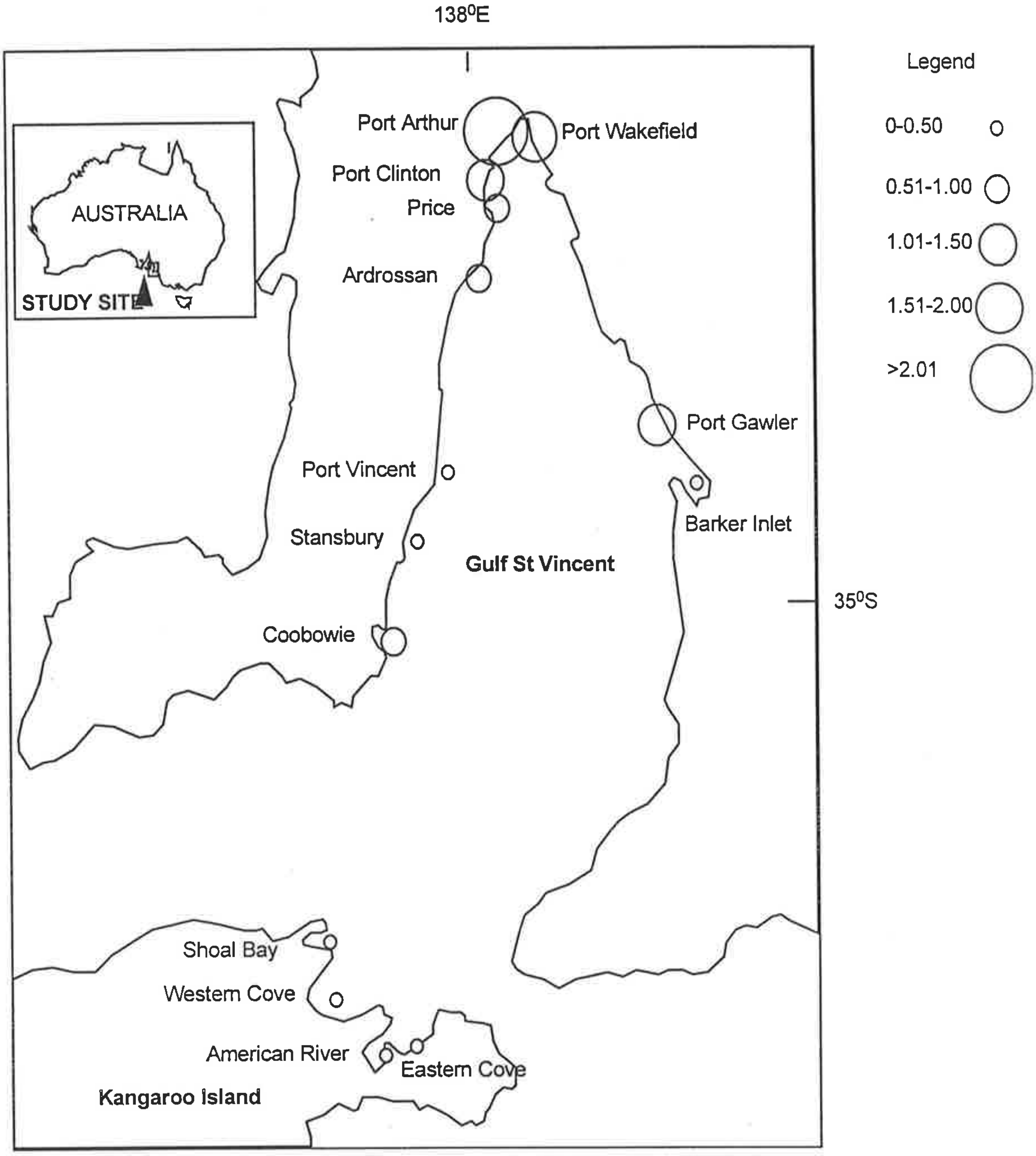


Figure 2.1 Mean number (m^{-2}) of juvenile *Penaeus latisulcatus* sampled for three trawls in inshore areas in Gulf St Vincent and Kangaroo Island in April-May 1989 and February-March 1990.

2.4 Discussion

The results from the two sampling periods show that the nursery areas in northern Gulf St Vincent contain high numbers of postlarval and juvenile prawns during February to May. These areas can be considered to be major nursery areas for prawns. All suitable areas on Kangaroo Island were sampled. The sediment type was similar to sites in Gulf St Vincent and if they were significant nursery areas, prawns would have been collected. Sampling by King (1977) and Carrick (pers. comm.) also showed that the areas sampled on KI contained fewer prawns than those areas in northern GSV. Kangaroo Island is not a major nursery area for *Penaeus latisulcatus.*

In Queensland, researchers have undertaken considerable work in determining and mapping juvenile prawn nursery areas. This has principally involved mapping and sampling seagrass areas in Gulf of Carpentaria (Coles & Lee Long 1985, Poiner *et al.* 1987), Cairns Harbour (Coles *et al.* 1993), Cape York to Hervey Bay (Lee Long *et al.* 1993), and Moreton Bay (Young & Kirkman 1975, Young & Carpenter 1977, Young 1978). Estimates of the extent of seagrass (Long & Poiner 1993) and prawn nursery areas on reef tops (Turnbull & Mellors 1990) have also been made for Torres Straits. Long & Poiner (1993) mapped 18,000 km^2 of seagrasses throughout Torres Strait, Lee Long *et al.* (1993) estimated that 2464 km^2 of seagrass habitat exists in coastal waters between Townsville and Cape Yorke and Poiner *et al.* (1987, 1989) estimated that the total area of seagrass cover in Gulf of Carpentaria to be 880 km^2. However, recent work in the Gulf of Carpentaria on tiger prawns by Loneragan *et al.* (1994) and Haywood *et al.* (1995) indicated that within a seagrass bed, preferred habitat is confined to the intertidal and shallow-subtidal zone. Due to this microhabitat selection within seagrass and algal beds, overall productivity maybe less that calculated for a total seagrass area.

Mapping seagrass areas is not appropriate in determining available nursery areas for *P. latisulcatus* in SA because it occupies the sand/mud substrates of tidal flats, inshore of seagrass beds. Some workers hypothesize that seagrass/algal beds (Coen *et al.* 1981, Zimmerman & Minello 1984, Minello & Zimmerman 1985, Minello *et al.* 1989, Dall *et al.* 1990) or mangrove roots (Primavera 1997) may provide shelter and protection from predators while food and habitat preference are also factors (Bell & Westoby 1986, Loneragan *et al.* 1994, Haywood *et al.* 1995). *Penaeus latisulcatus* is strongly nocturnal (Penn 1984), and buries during the day making it less vulnerable to predators and can therefore it can occupy bare tidal flats. Within GSV, the main nursery areas occur north of Port Gawler on the eastern side around to Ardrossan on the western shore. Favoured nursery habitats tend to be shallow and sheltered with a sand-mud sediment and often associated with mangrove areas. The tidal flats throughout these areas can extend from 200m up to one km offshore and major nurseries encompass approximately 150 km^2. Prawn nursery habitats within Gulf St Vincent cover a relatively small area overall, and the likely loss or substantial impact on these areas requires their protection from additional or continuing pollution sources and major coastal developments.

In the Peel-Harvey Estuary WA, in the 1970's, there was a massive algal bloom of the macroalga *Cladophora montagneana* that formed dense mats on the substratum (Potter *et al.* 1991). This reduced the amount of exposed sandy substratum that was favoured by *P. latisulcatus.* This event coincided with a decline in the commercial catches in this area between 1969 and 1979. Loss of habitat may have attributed to lowered commercial catches. Changes in the relative importance of particular nursery habitats may have also occurred through the history of the GSV fishery. Neverauskas (1987) and Clarke (1987) have documented loss of seagrasses off the metropolitan coast. This loss can be attributed to point sources, including sewage outfalls and industrial discharges, and diffuse sources such as stormwater and river/creek discharges. Two sewage treatment plants may have impacted on Barker Inlet/North Arm increasing the nutrient load into this system. Personal observations during 1990 showed that dense epiphytic alga and *Ulva* extended from Barker Inlet to Port Gawler, where the outfall from the Bolivar treatment works is located. The presence of large quantities of *Ulva* within the Barker Inlet system has been noted since at least the mid seventies and its distribution was mapped during 1985 and 1986 (Connolly 1986). Sampling by King (1977) in Barker Inlet in the early 1970's, indicated that this region was a significant prawn nursery. He collected prawns using a beam trawl at night. My own sampling at night within Barker Inlet-Port River with a beam trawl during 1990 did show that *P. latisulcatus* occurs in this area. However, jet net sampling in the same locations on the following day showed very few prawns. The juvenile prawns appear to come into these areas to feed during the night but do not remain buried in the area during the day. Attempts were made to establish a regular sampling location in this region on several occasions. Due to the presence of large quantities of epiphytic algae and *Ulva* in the Barker Inlet system it was extremely difficult to sample using any sampling device, particularly the jet net due to clogging of nets and jets by the algae. Therefore changes and possible reduction in the overall area of favorable nursery sites since the 1970's are difficult to quantify.

To monitor the variability in postlarval settlement over several years and areas, four sites were chosen. These were areas where significant numbers of prawns had been collected during the 1989 and 1990 surveys. The sites selected were Port Wakefield, Port Arthur, Port Clinton and Ardrossan. In 1993, an additional site on the eastern shore, at Webb Beach, was added to the regular sampling to provide more detail on settlement patterns on the eastern side of GSV (Figure 2.2). Settlement trends at these sites will be discussed in Chapter 4.

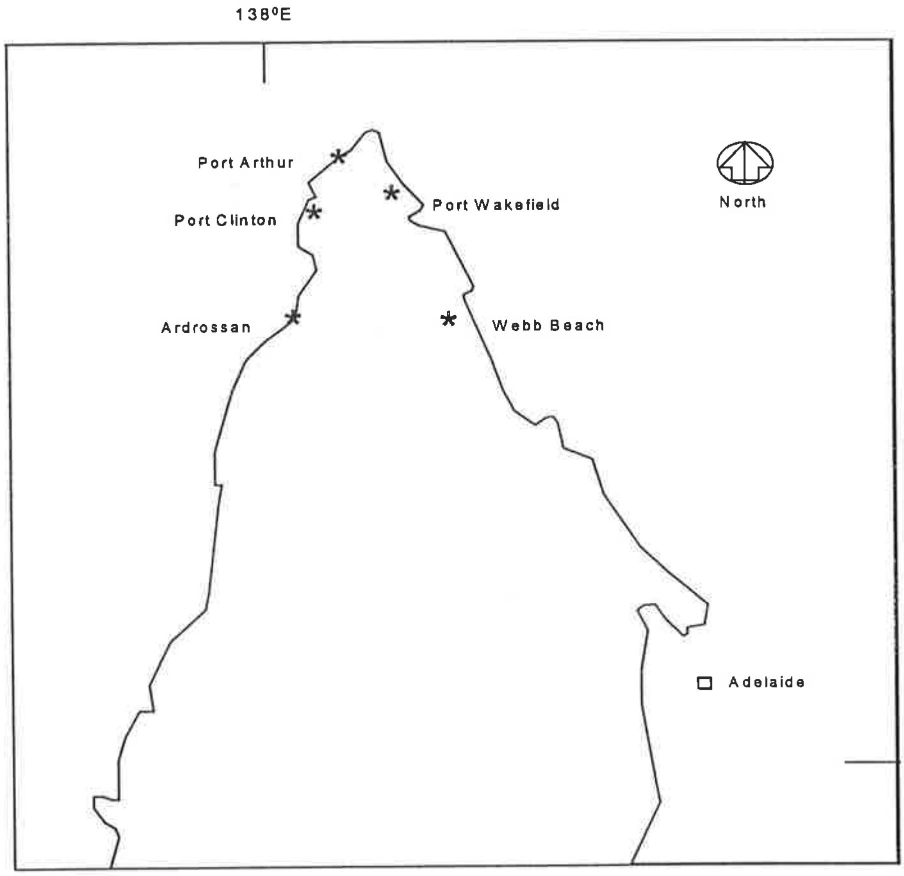


Figure 2.2 Gulf St Vincent indicating the location of five regular sampling sites selected for monitoring variability in seasonal and yearly settlement trends.

3. GEAR DEVELOPMENT AND TESTING, SMALL-SCALE SPATIAL AND TEMPORAL VARIABILITY IN JUVENILE PRAWN ABUNDANCE WITHIN A NURSERY AREA AND NURSERY HABITAT DESCRIPTION AND COMPLEXITY.

3.1 Introduction

Sampling problems are encountered when individuals display changes in behaviour and their vulnerability to the sampling gear is affected by this behaviour. Any method that catches prawns during their active phase will likely vary in its effectiveness. Changes in catchability of prawns have been attributed to day-night cycles (Young 1975, Subrahmanyan 1976, Coles 1979, Vance & Staples 1992, Vance *et al.* 1994), tidal cycles (Hughes 1972, Staples & Vance 1979, Vance & Staples 1992), moonlight (Fuss & Ogren 1966), turbidity (Minello *et al.* 1987), temperature (Aldrich *et al.* 1968) and salinity (Lakshimi *et al.* 1976, Matthews *et al.* 1991). *P.latisulcatus* is active at night and buries during the day (Penn 1984, Wassenberg & Hill 1994) and has been shown to be highly sensitive to light (Wassenberg & Hill 1994) as well as having activity patterns related to temperature (Penn 1976) and tidal influences (Carrick pers comm).

Various methods have been employed to sample juvenile prawns in nursery areas. These include passive box-traps (Herke & Rogers 1984, Rogers *et al.* 1993), scoop nets (Subramaniam 1990), collecting by beam trawl at night (Young & Carpenter 1977, Young 1978, Penn 1986, Staples *et al.*1985, Coles *et al.* 1993, O'Brien 1994a, Haywood *et al.* 1995, Loneragan *et al.* 1995, Mohan & Siddeek 1996, Vance *et al.* 1996), drop traps (Zimmerman *et al.* 1984) and jet nets (Penn & Stalker 1975, Wallner 1985, Turnbull & Watson 1990,1992).

Studies using beam trawls have generally attempted to standardise sampling by sampling over the same moon phase and tidal cycle to minimise catchability effects. Preliminary studies are usually required to determine the times when the catches are at their highest (Staples *et al.* 1985). These characteristics tend to be species specific. However, a regular monitoring program that requires sampling under the highest catch conditions may not be practical as these may be irregular or infrequent.

Beam trawl efficiency may vary between different nets and habitats (McNeill & Bell 1992). McNeill & Bell (1992) compared three types of beam trawls and found differences in the species composition and abundance of vagile fauna in *Posidonia* beds due to selectivity inherent in each design. Loneragan *et al.* (1995) estimated the efficiency of a beam trawl for sampling tiger prawns in different seagrass beds using removal experiments and found that the beam trawl was about 65% efficient for postlarvae and 50% efficient for juvenile tiger prawns in relatively shallow water (< 2m). They were considered less efficient in deeper water. Even with constant sampling conditions, a semi-quantitative measurement of relative abundance is the best that may be obtained using a beam trawl. One reason for the widespread use of beam trawls is that they sample effectively in seagrass beds and cause little damage. *P. latisulcatus* is not associated with seagrasses and so sampling gear more appropriate to sand and mudflats and which may be more quantitative can be developed.

Turnbull and Watson (1992) compared a beam trawl, jet beam trawl and an electric beam trawl both during day and night on reef flats and found that the catch rates were highest for the night-time conventional beam trawl but variable sampling conditions made the catch rates more variable than with the jet net. They found the jet net a more reliable form of sampling for comparative purposes. Jet nets (Penn & Stalker 1975, Turnbull & Watson 1992) disturb and lift the prawns while they are buried in the substrate. Jet nets minimise catchability effects as they sample prawns in their inactive state. *P. latisulcatus* is inactive during the day so this type of gear is particularly suitable for the present study. Under laboratory conditions, *P.latisulcatus* bury only a few centimetres into the substrate (Carrick, unpublished observation) and therefore the jets would disturb the prawns from their shallow resting-place. Thus jet nets would provide a reliable measure of relative abundance between each sampling period. Additional benefits in sampling during the day include the ease of sampling and of sorting of small prawns in daylight.

Understanding the dynamics of juvenile prawn populations requires monitoring of trends in spatial distribution and abundance. Once a suitable method for sampling juvenile prawns is adopted, information should be gathered on the small-scale spatial and temporal variation to determine if the results can be extrapolated to describe more general trends for most or all nursery habitats. Very few studies on the small-scale spatial distribution of juvenile prawns (Staples *et al.*1985, Bishop & Khan 1991) or on short-term or daily variation within a site have been undertaken. Most studies of juvenile prawns have sampled several sites in different habitat types (Young & Carpenter 1977, Coles & Greenwood 1983, Coles & Lee Long 1985, Potter *et al.* 1991, Turnbull & Mellors 1992, Vance & Staples 1992, Loneragan *et al.* 1994, Vance *et al.* 1996) or have sampled at one site over several years (O'Brien 1994a).

The principal aim of this study was to develop a quantitative method of sampling juvenile *P. latisulcatus* in its nursery habitats. A jet net was developed to sample juvenile prawns and comparisons were made between; a jet net deployed with and without an enclosed front on the net and daytime jet net sampling and a traditional beam trawl at night. Three different trials were undertaken to determine the small-scale spatial and short-term temporal variability in juvenile prawn catches at a site. The issues of distribution that were investigated were 1) whether there were spatial differences in size composition and abundance associated with depth across the intertidal-subtidal zone, 2) whether there were horizontal differences in abundance along the shore when samples were taken by perpendicular or by parallel trawls, and 3) whether there was daily variation in abundance or size composition when sampling was repeated over several days 4) the precision of mean abundance when samples were taken within a small distance of each and 250m apart.

3.2 Gear description and sampling methods

3.2.1 Design and operation of the jet net

The jet net used in this study was modified from that described by Penn and Stalker (1975). The water jet principle was similar but the frame and net were significantly larger. The cod-end was tied off instead of using a collecting jar. The frame (Plate 1) is 1.0m x 0.95m, made of steel (galvanised after construction) tubing (25mm) with 100mm X 5mm skis lined with marine ply and rollers at the back of the frame for ease of towing. A central t-bar (Plate 2) had holes (3mm diameter) drilled every 50mm through which water was pumped using a Finsbury centrifugal pump (500l min^{-1}, up to 120 psi) driven by a 5.5 hp Honda engine.

The net covers the entire frame, was made of 2mm-nylon (Nytal) netting and was 2.5m long (Plate 3). The front cover of the net was separate and laced to the frame and could be removed to leave the front open. The original net made was of 1mm mesh but due to coarse sediment at some sites; the mesh size had to be increased to 2mm for ease of retrieval. As a result, prawns less than 2 mm carapace length (CL) can be lost and are under-represented in the samples. The net was towed using a shallow-draft, 6m aluminium net boat (Plate 4) with a counter-weight towed from the other boom. Two nets can be towed at one time but due to space limitations on the boat only one was used. Underwater observations of the net in operation using snorkel showed that the net stayed on the bottom at all the trawl speeds used for sampling (1000 - 1600 rvs/min). A 100m trawl was completed in two to three minutes, depending on tidal flow. The water jets penetrate the substrate by at least 50mm and leave shallow furrows (Plate 5) in the sediment that are mostly obliterated during the following tide cycle.

Plate 1 Jet net design showing the galvanised iron frame, skids and rollers. The dimension of the frame is 1.0 m wide and 0.95 m long with 100mm x 5mm skis lined with marine ply and rubber rollers at the back of the frame for ease of towing. The central vertical bar connects to the water hose.

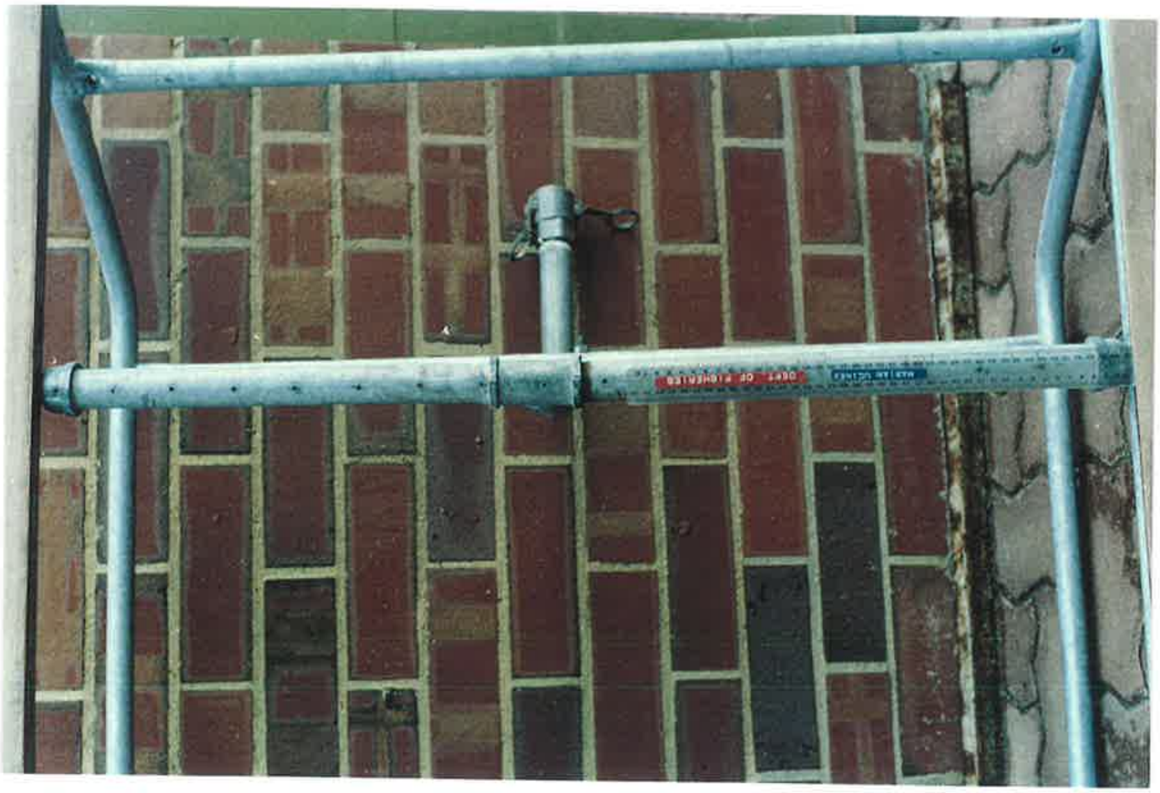


Plate 2 Underside of jet showing central bar with holes 50mm apart. Water is pumped at 500 litres per minute as the net is towed.

Plate 3 Jet net shows a fully closed net in front (2mm mesh), connected water hose and pump with intake hose. The bridle is used to connect to the hauling rope attached to boom on sampling boat.

Plate 4 Boat used for sampling, shallow draft, 6m aluminium net boat with boom attached for towing. The net was towed approximately 5 metres behind boat to avoid prop wash at a speed of 1000 to 1600 rvs per minute depending on tidal movement. A 100 m^2 trawl was completed in two to three minutes.

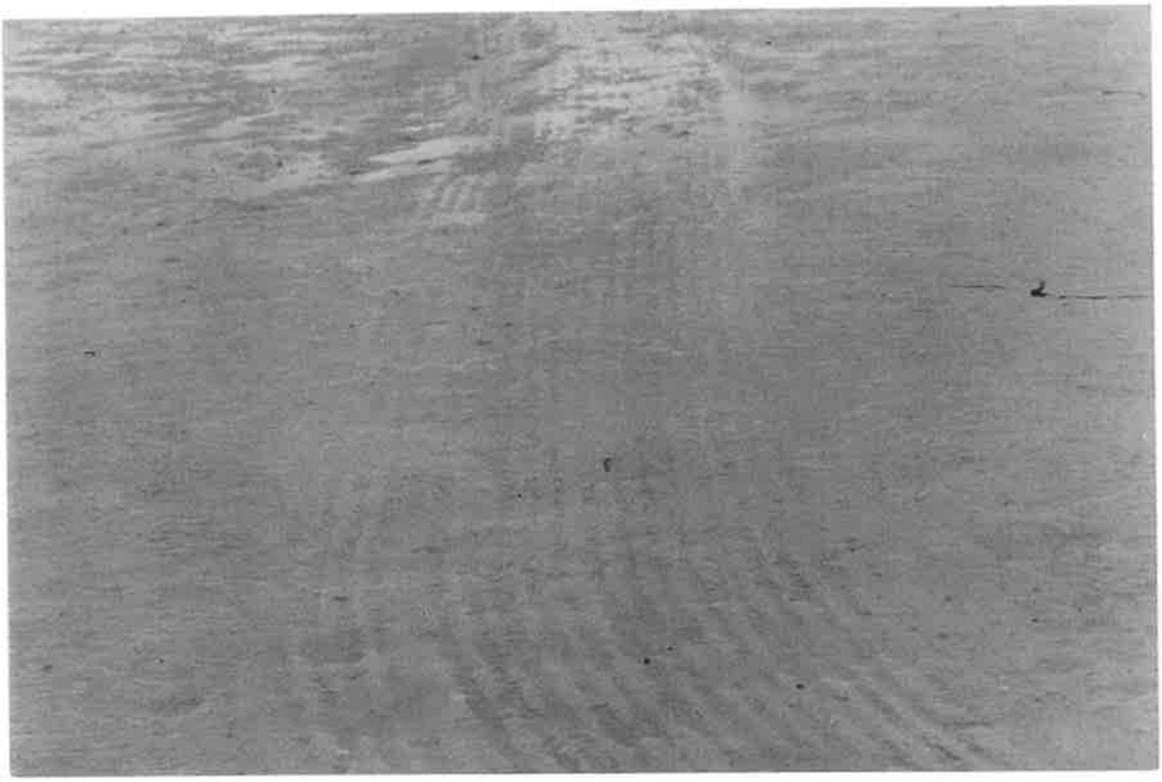


Plate 5 Track of jet net after sampling showing shallow furrows created by the water jets. These are obliterated during the following incoming tide.

3.2.2 Sampling procedure and comparison of sampling methods and small-scale temporal and spatial variability

To test whether prawns disturbed by the jets would pass through the front of the net when open; nets with and without front covers were compared at Port Arthur in October 1989, in deep (2-3 m) and shallower (0.5 -1 m) water (Table 3.1). Sampling was undertaken at high tide, during daylight, in the intertidal zone where the prawns were buried. Trawls were made parallel to the shore and two 100 m^2 trawls were made for each combination. A second series of trials were conducted at Port Arthur during March 1991 to validate the 1989 results and to provide information on prawn size composition using perpendicular trawls. One 100m^2 trawl was made for each combination.

To determine small-scale temporal and spatial variability, open and enclosed nets were used at three sites 250m apart for shallow, deep and perpendicular trawls at Port Arthur on March 1991. Only one 100 m^2 trawl was made for each combination so that all trials could be completed on one day. A second set of trials were undertaken during three periods in March-April 1993 (at 2-week intervals) and conducted over ten sites (250m apart) perpendicular to the shore with one or two 100 m^2 trawls at each site depending on the ease of retrieval of net (Table 3.1). The sediment type along the sites was crudely estimated visually by walking over the track made by the jet net during the next low tide after sampling took place. The following categories were used; fine mud, fine mud/sand, coarse, very coarse, very coarse/shells, intermediate/shell and fine mud and *Zostera* and mapped.

To determine daily variability within one site, three 100 m^2 trawls were made across the same area (110 m x 12 m) over four consecutive days at Port Arthur and Port Wakefield during February 1992 (Table 3.1).

Information from the daily study at Port Wakefield during February 1992, monthly sampling at Port Arthur and Port Wakefield for 12 months in 1990 and ten sites (250m apart) at Port Arthur during March 1993 are utilised to determine the precision of the estimates of mean numbers (m^{-2}) at one site using three or four trawls.

Abundance (number m^{-2}) of juvenile prawns from the 1.0 m wide jet net (2 mm mesh) were compared with those from a 1.5 m wide beam trawl (1 mm mesh) at Port Arthur in March 1990. Sampling was undertaken using the jet net during one day and the beam trawl the following night (three nights after new moon and two hours after high tide) to determine sampling efficiency of the two types of gear. Four 100 m^2 trawls, perpendicular to the shoreline was made using both methods (Table 3.1). Buoys with lights were used to guide the boat at night.

3.2.3 Sample processing

The net was retrieved after the trawl, prawns emptied into a container and later sorted on shore. The samples were then fixed in 5% formalin, identified, counted and measured in the laboratory to the nearest 0.1 mm with an ocular micrometer. Postlarval and juvenile *P. latisulcatus* were easily distinguished from two other prawn species found in nurseries, *Trachypenaeus curvirostris* and *Metapenaeopsis lindae* by characteristics of the telson spines.

3.2.4 Limitations of sampling gear

There are several physical limitations in deploying the jet net. Areas that have very coarse sediment cannot be sampled as the excessive weight of accumulated sediment in the net prevents it being retrieved. In areas where there are obstacles such as rocks or limestone reefs the net becomes caught and may be damaged. Also, the net does not sample efficiently in areas with a high density of floating or drift seagrass or algae (such as *Ulva*) due both to jets being clogged and to a reduction in jet penetration.

For sampling the intertidal area, it is necessary for water to be covering the area and that the water be a sufficient depth to allow the boat to operate without the motor touching the bottom. A high tide of at least two metres is required for sampling. This allows three to four hours of sampling time either side of the high tide. Suitable tide heights occur only for a period of four to five days every fortnight.

3.3 Data analysis

The abundance of prawns was calculated from the total number of prawns caught divided by the distance trawled. Prawns ≥ 3mm carapace length (CL) were used in the analyses because for some species of prawns, the postlarvae (< 3 mm carapace length (CL)) differ markedly in their behaviour and catchability compared with juveniles (≥ 3 mm CL) (Liu & Loneragan 1997). Also, the 2mm mesh used for the jet net will not fully sample prawns < 2mm CL.

A 2 x 3 factorial analysis of variance (ANOVA) was made on the abundance of prawns between site, depth and open and enclosed nets (for samples collected at Port Arthur in March 1991). The data sets were checked for normality using Wilk-Shapiro Rankit plots, homogeneity of variances by the Cochran's test (Winer 1971, Underwood 1981) and for non-additivity using Tukey's 1 Degree of freedom test. The data were used untransformed. Where ANOVA showed significant differences, a LSD(T) test was used to determine which means were significantly different at the 0.05 level of probability.

The mean number of juvenile prawns caught m^{-2} with a daytime jet net and night-time beam trawl and the abundance of prawns between consecutive days at Port Wakefield were compared using a one-way ANOVA.

The precision of an estimate of mean abundance of prawns at a site was assessed by several methods, 1) monthly sampling, from January to December 1990 at Port Wakefield, Port Arthur, Port Clinton and Ardrossan using at each site, four trawls within a small distance from each other 2) three trawls, within a short distance from each other over four consecutive days at Port Wakefield in February 1992 3) ten trawls, 250m apart for a distance of 2.25 km at Port Arthur in March 1993.

The mean CLs of *P. latisulcatus* caught in the deep and shallow samples in Port Arthur, October 1989 was compared with a one-way ANOVA. The CL frequencies of prawns were compared between sites, depth, gear type and consecutive days using non-parametric Kolmogorov-Smirnov tests. Both postlarval (< 3 mm CL) and juvenile (≥ 3 mm CL) prawns were used in these comparisons. Since the Kolmogorov-Smirnov test is sensitive to small differences in size distribution (differences in location, spread and shape of the distribution) the results were considered to be biologically significant only at the $P < 0.01$ level.

The pattern of dispersion for prawns at Port Arthur, over ten sites during March-April 1993 was tested with the Morisita index of dispersion (I_δ, Morisita 1959). This index is in the form of: $I_\delta = k \sum_{i=1}^{k} \frac{n_i(n_i - 1)}{T(T-1)}$ when; k - is the total number of samples taken, n_i - number of individuals in sample i, T - total number of individuals taken. The significance of the departure from randomness is given by the variance ratio: $F = I_\delta(T-1)+k-\frac{T}{T-1}$ for k-1 and ∞ degrees of freedom. If $I_\delta \approx 1$ then the distribution is random. The number of prawns per $100m^2$ was used in this analysis.

Table 3.1. Overview of the number of samples taken for comparisons between methods used in sampling postlarval and juvenile *Penaeus latisulcatus* in Gulf St Vincent.

Comparison	Location	Date	No. of trawls per method	Total no. trawls
Cover: open/enclosed	Port Arthur	October 1989	2	8
Cover: open/enclosed	Port Arthur	March 1991	1	6
Depth 1: deep vs shallow	Port Arthur	October 1989	2	8
Depth 2: shallow vs perpendicular vs deep	Port Arthur	March 1991	1	6
Net type: jet net vs beam trawl	Port Arthur	March 1990	4	8
Daily variation: 4 consecutive days	Port Wakefield	February 1992	3	12
Spatial variation: 10 sites, 250 m apart	Port Arthur	March 1993	1 or 2	36

3.4 *Results*

3.4.1 The effect of an enclosed or open net on prawn capture and the occurrence of prawns in deep and shallow areas of the intertidal region

In October 1989 (Table 3.2), significantly more prawns (m^{-2}, mean ± s.e.m.) were caught when the front of the net was enclosed (0.89 ± 0.15) than when it was open (0.45 ± 0.12). However, the abundance did not differ between shallow (0.53 ± 0.20) and deep water (0.81 ± 0.13).

Table 3.2 Number of juvenile *Penaeus latisulcatus* caught (m^{-2}) using different sampling methods, shallow and deep, and with or without an enclosed front for two $100m^2$ trawls at Port Arthur, October 1989.

Sampling method	Trawl 1	Trawl 2
Shallow Open	0.20	0.32
Shallow Closed	0.51	1.10
Deep Open	0.74	0.53
Deep Closed	0.79	1.18

In March 1991, at Site 1 (regular sampling site) there was no significant difference in the abundance of prawns (no. ≥ 3 mm CL m^{-2}, mean ± s.e.m.) caught between open (0.81 ± 0.30) and enclosed nets (0.67 ± 0.21) (Table 3.3). No difference in prawn abundance between shallow (0.74 ± 0.02), perpendicular (0.82 ± 0.54) or deep (0.67 ± 0.36) samples was evident.

Table 3.3 Number of juvenile *Penaeus latisulcatus* ≥ 3mm CL caught (m^{-2}) using different sampling methods, shallow, deep and perpendicular, and with or without an enclosed front for a $100m^2$ trawl at Site 1, Port Arthur, March 1991. The table summarises the total number caught m^{-2}, number of individuals ≥ 3mm CL (m^{-2}) and the mean size of prawns caught for each sampling method.

Sampling Method	Number of prawns	Number ≥3mm CL	Mean size (mm CL)
Shallow Open	2.53	0.76	3.41
Shallow Enclosed	1.23	0.72	4.65
Deep Open	2.04	0.31	4.00
Deep Enclosed	1.77	1.02	4.46
Perpendicular Open	2.77	1.36	3.46
Perpendicular Enclosed	1.45	0.28	3.82

3.4.2 Comparison of size of prawn with enclosed and open nets in intertidal regions

In October 1989, the size composition of juvenile prawns did not differ between open and enclosed nets (Figure 3.1, Table 3.4). In March 1991, the size range of juvenile prawns caught (all three sampling sites combined) were the same between open and enclosed nets (Figure 2).

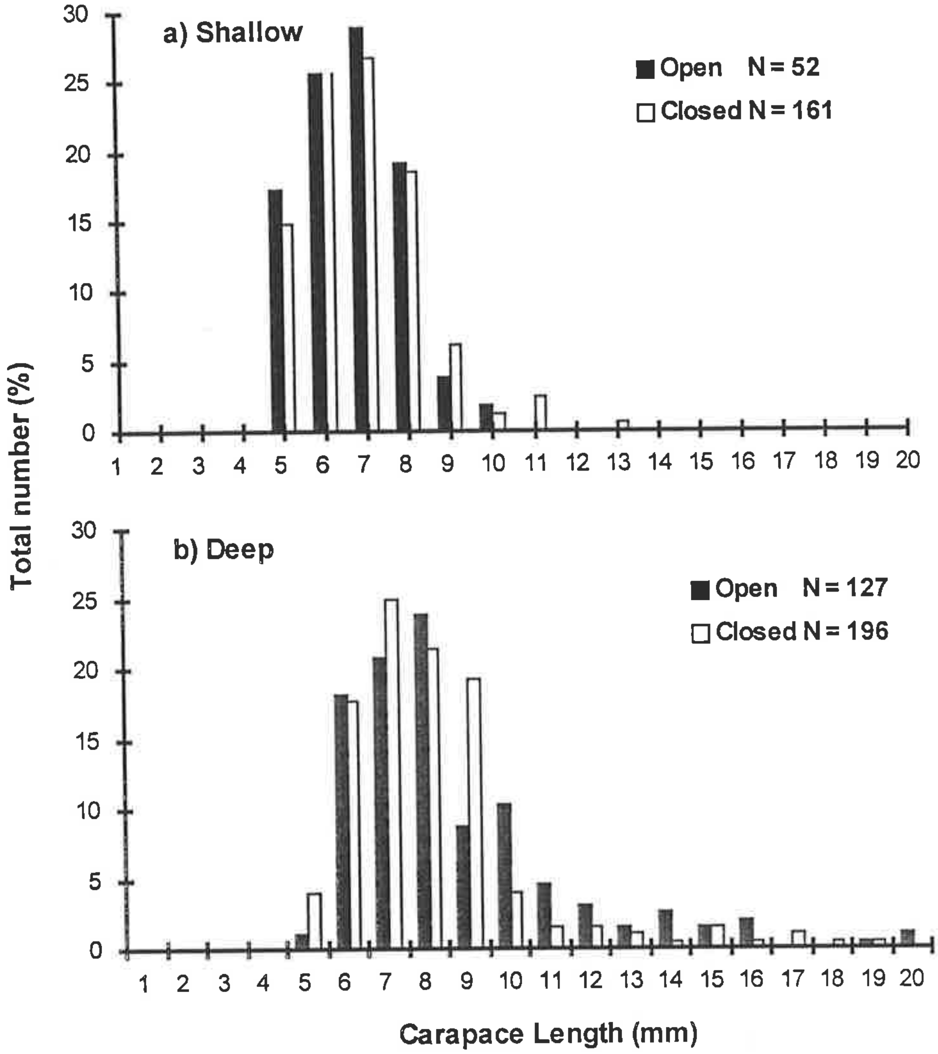


Figure 3.1 Percentage size composition of juvenile *Penaeus latisulcatus* collected at Port Arthur, October 1989. a) jet net sampling in shallow using net with and without enclosed front b) jet net sampling in deep using net with and without enclosed front.

Table 3.4 Kolmogorov-Smirnov tests comparing size distributions of juvenile *Penaeus latisulcatus* for different sampling methods at Port Arthur, October 1989. SO - shallow without enclosed front, SC - shallow with enclosed front, DO - deep without enclosed front, DC - deep with enclosed front, S - shallow both with and without enclosed front, D - deep both with and without enclosed front, O - shallow and deep without enclosed front, C - shallow and deep with enclosed front.

Treatment	P-value (Smirnov's Chi-square approx)
SO vs SC	1.0000
DO vs DC	0.0284
SO vs DO	0.001***
SC vs DC	0.001***
S vs D	0.000***
O vs C	0.0136

*** = $P \leq 0.001$

3.4.3 Comparison of size of prawn with depth across areas of the intertidal region

In October 1989, the size composition of juvenile prawns differed significantly between depth (Figure 3.1. Table 3.4). A One-Way ANOVA (Table 3.5) of mean carapace length showed that significantly ($F = 92.49$, $P = \leq 0.001$) larger prawns were caught in the deep (7.5 mm ± 0.1, mean ± 1 SE, range 4-19 mm) than in the shallow (5.8 mm ± 0.2, range 4-12mm) water. There was a preference for shallower or inshore areas by smaller juvenile prawns.

Table 3.5 ANOVA table for comparison of mean size of juvenile *Penaeus latisulcatus* for shallow and deep samples at Port Arthur, October 1989 using a jet net with an enclosed front and without an enclosed front (combined).

Source	SS	df	MS	F	*P*
Depth	5.4121	1	5.4121	94.4873	7.2334E-05***
Within	0.3511	6	0.0585		
Total	5.7632	7			

*** = $P \leq 0.001$

The differences in size observed in October 1989 between shallow and deep locations were not obvious in March 1991 (Figure 3.2). This was due to high numbers of small prawns in March that were distributed over all the areas sampled and comparatively low numbers of larger prawns. The samples taken perpendicular across the intertidal zone showed size distributions intermediate between shallow and deep samples and so are representative samples for the site.

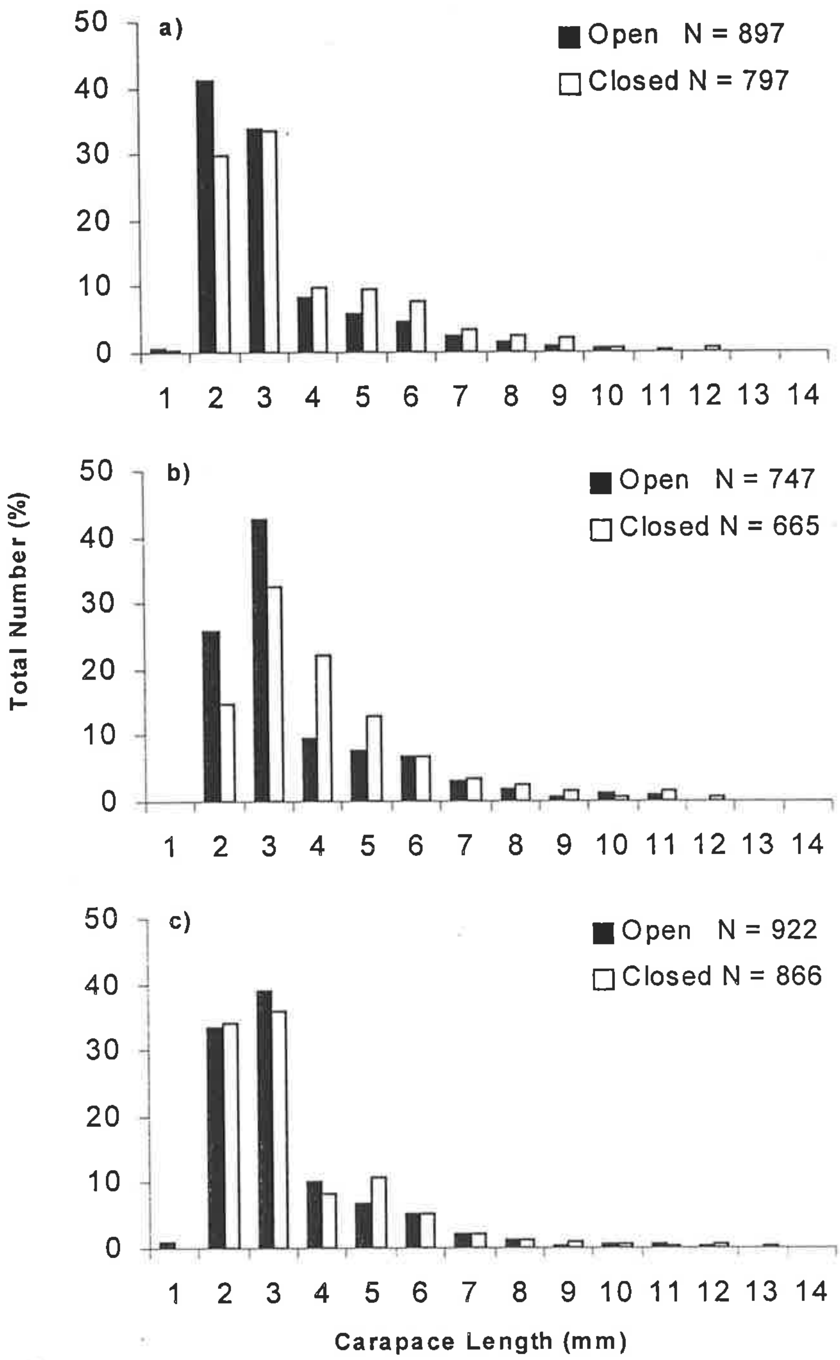


Figure 3.2 Percentage size composition of juvenile *Penaeus latisulcatus* collected at Port Arthur, March 1991 for three sites (250m apart) combined. a) jet net sampling in shallow using net with and without enclosed front b) jet net sampling in deep using net with and without enclosed front c) jet net sampling perpendicular using net with and without enclosed front.

3.4.4 Small-scale spatial variation in prawn abundance and size distribution with depth and along a stretch of the intertidal zone at Port Arthur

In March 1991, the abundance of juvenile prawns (m^{-2}) (Table 3.6) differed significantly between sites but not between depths (shallow, perpendicular, deep) or nets (open, enclosed) (Table 3.7). LSD(T) pairwise comparisons of sites revealed that sites 3 and 1 were different.

Table 3.6 Number of juvenile *Penaeus latisulcatus* caught (number ≥ 3 mm CL m^{-2}) at three sites at Port Arthur, March 1991 in shallow (Sh), perpendicular (Pp) and deep (Dp) trawls of 100 m^2 with a net fully enclosed and one without and enclosed front.

	Site 1			Site 2			Site 3		
	Sh	Pp	Dp	Sh	Pp	Dp	Sh	Pp	Dp
Open	1.49	1.26	2.14	1.05	2.21	1.66	2.30	2.48	1.55
Enclosed	0.81	1.21	1.15	2.69	1.84	1.71	2.17	2.68	2.82

Table 3.7 Three-way ANOVA table for abundance (number m^{-2}) of juvenile *Penaeus latisulcatus* caught at Port Arthur, March 1991, comparing site, depth (shallow, perpendicular, deep) and open or enclosed nets.

Source	df	SS	MS	F	*P*
Site (A)	2	4.08404	2.04202	4.39	0.04*
Depth (B)	2	0.97298	0.48649	1.05	0.39 NS
Open (C)	1	0.32805	0.32805	0.71	0.42 NS
B * C	2	0.49653	0.24827	0.53	0.60 NS
A * B * C	10	4.64656	0.46466		
Total	17	10.5282			

* = $0.01 < P \leq 0.05$, NS – not significant

Due to the numerous combinations required for checking differences between size distributions between samples, only a comparison between sites for each sampling method was made (sites with perpendicular sampling using enclosed nets Figure 3.3). In general, size distributions were similar, with only three significant differences out of a total of 18 comparisons (Table 3.8). The samples taken using a perpendicular trawl and enclosed net method had the same size distribution at all three sites. This method of sampling was adopted for the next study on spatial distribution.

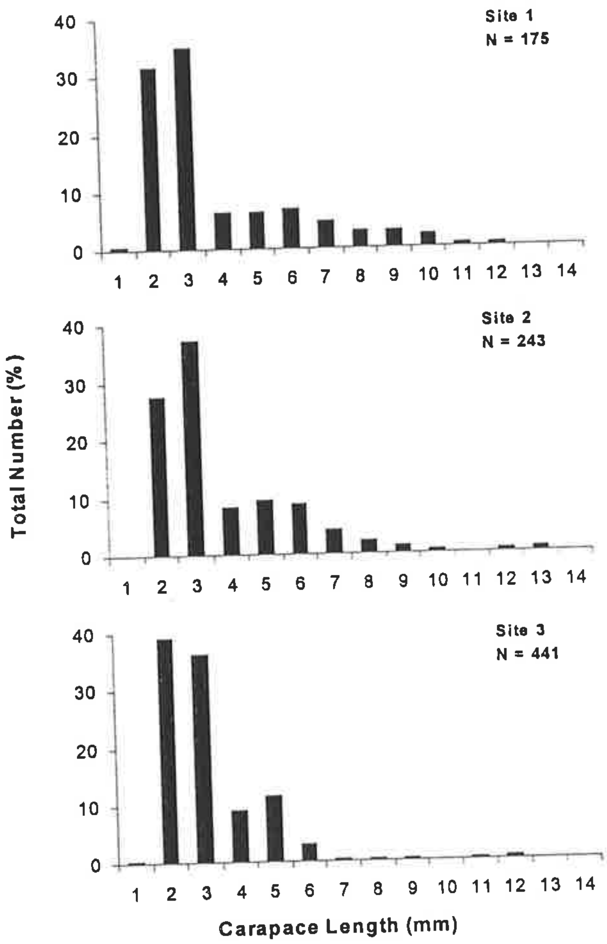


Figure 3.3 Percentage size composition of juvenile *Penaeus latisulcatus* at three sites 250m apart using an enclosed jet net trawled perpendicular to the shoreline, at Port Arthur, March 1991.

Table 3.8 Kolmogorov-Smirnov tests comparing size distributions of juvenile *Penaeus latisulcatus* between three sites (250m apart) for different sampling methods at Port Arthur during March 1991

Treatment	Site 1 vs Site 2	Site 1 vs Site 3	Site 2 vs Site 3
Shallow Closed	1.0	0.3937	0.2675
Shallow Open	0.0690	0.4127	0.0138
Diagonal Closed	0.1298	0.0012**	0.2584
Diagonal Open	0.4463	0.5825	1.0
Deep Closed	0.0006***	0.0002***	0.9094
Deep Open	0.8526	0.7756	1.0

** = $0.001 < P \leq 0.01$, *** = $P \leq 0.001$

In March-April 1993, the catches of juveniles (number ≥ 3 mm CL, Table 3.9) for each period did not show any significant deviation from a random distribution at any site (Figure 3.4). The size composition for the ten sites on the first sampling date (Figure 3.5) was compared by Kolmogorov-Smirnov tests. For most sites there were no significant differences in prawn size distribution - across the 46 comparisons only five were significant and four of these related to the distribution at site 6 (Table 3.10).

Table 3.9 Numbers of juvenile *Penaeus latisulcatus* ≥ 3 mm CL caught for one or two $100m^2$ trawls at 10 sites, 250m apart for a distance of 2.25 km of shoreline, at Port Arthur at two-weekly intervals March to April 1993.

	10 March 1993		25 March 1993		6 April 1993	
Site	Trawl 1	Trawl 2	Trawl 1	Trawl 2	Trawl 1	Trawl 2
1	57		124			
2	125	85	233	77	125	232
3	247		169			
4	300	133	119	102	192	219
5	165		238			
6	367		*		318	
7	443		399			
8	260	207	344	479	466	350
9	279		289			
10	551	326	340	583	299	352

* - Sample spoiled, poorly preserved

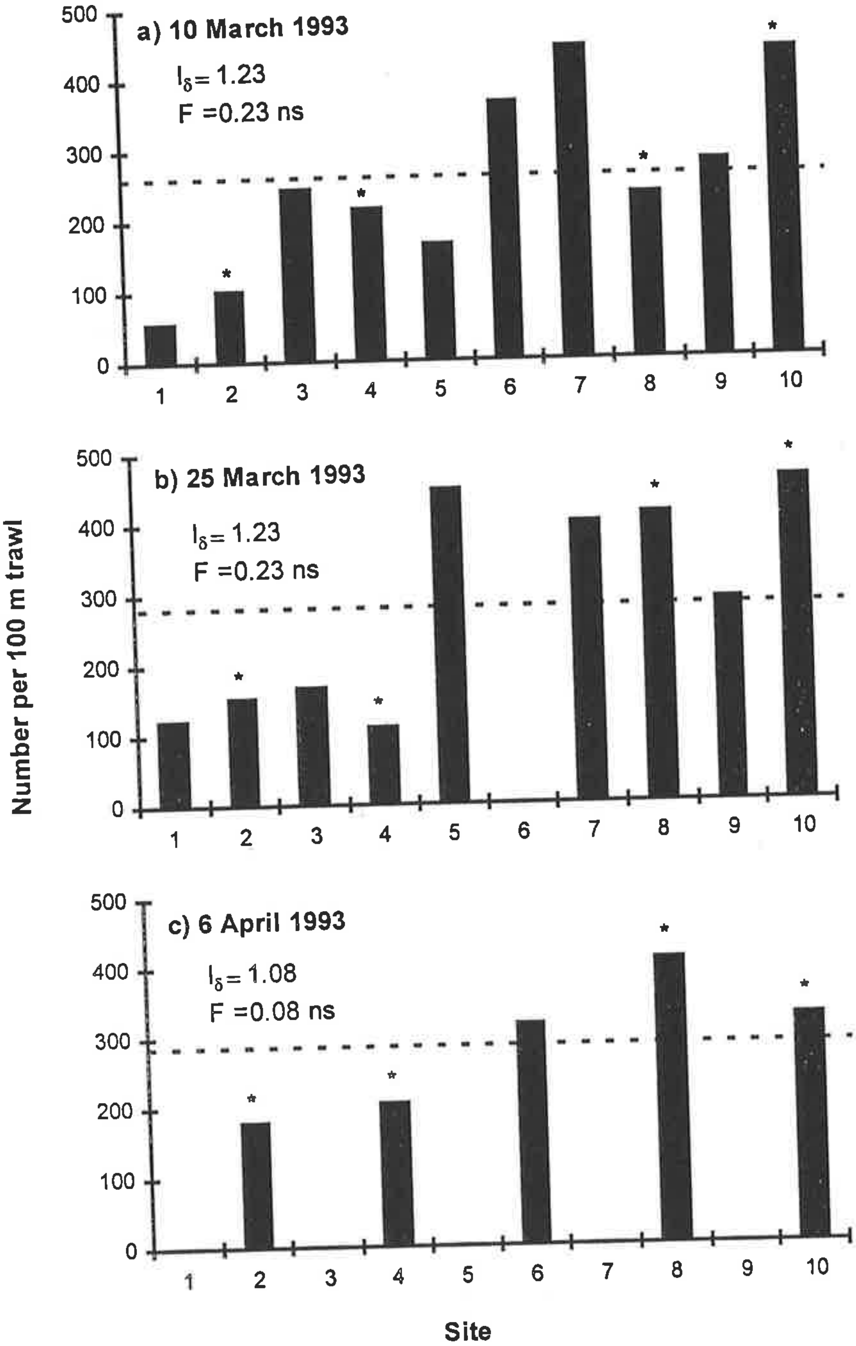


Figure 3.4 Numbers of juvenile *Penaeus latisulcatus* ≥ 3 mm CL caught per 100 m^2 trawl at sites 250m apart for a distance of 2.25 km of shore line at Port Arthur in March to April 1993. Dotted line is mean number overall. * At sites where two trawls were made, the value shown is the mean. I_δ and F are indicated.

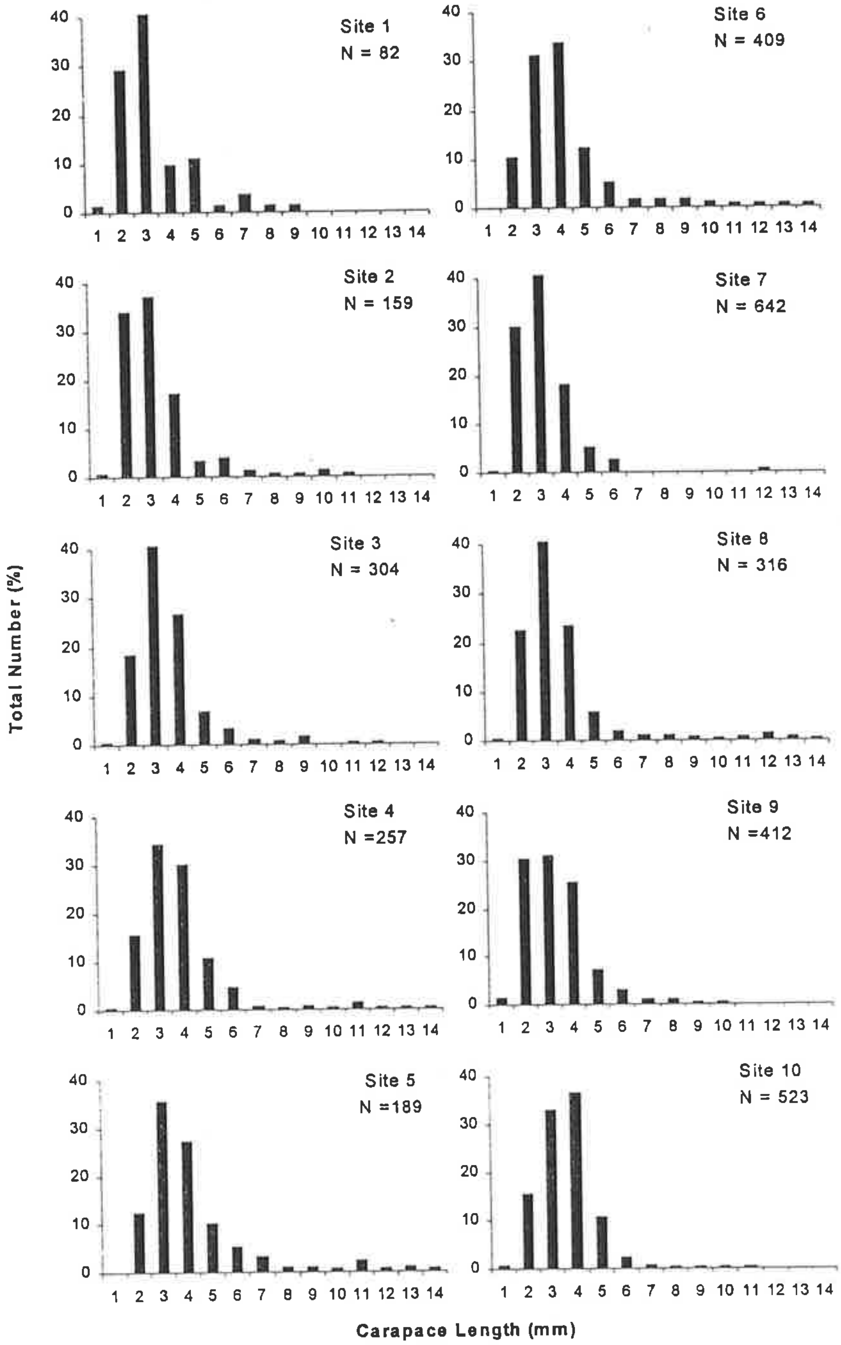


Figure 3.5 Percentage size composition of juvenile *Penaeus latisulcatus* at 10 sites 250m apart, over a distance of 2.25 km of shoreline, at Port Arthur, 10 March 1993.

Table 3.10 Kolmogorov-Smirnov tests for comparison of size distributions for juvenile *Penaeus latisulcatus* for 10 sites, 250m apart for a distance of 2.25 km along the shoreline at Port Arthur during 10 March 1993.

Sites	P	Sites	P	Sites	P	Sites	P	Sites	P	Sites	P	Sites	P	Sites	P	Sites	P
1 vs 2	0.7511																
1 vs 3	0.4713	2 vs 3	0.1530														
1 vs 4	0.0530	2 vs 4	0.0362	3 vs 4	0.8690												
1 vs 5	0.0562	2 vs5	0.0267	3 vs 5	0.7252	4 vs 5	1.000										
1 vs 6	0.0007 *	2 vs 6	0.0004 ***	3 vs 6	0.0791	4 vs 6	0.8517	5 vs 6	1.000								
1 vs 7	0.0384	2 vs 7	1.000	3 vs 7	0.4393	4 vs 7	0.0207	5 vs 7	0.0115	6 vs 7	0.0002 ***						
1 vs 8	0.7205	2 vs 8	1.000	3 vs 8	1.000	4 vs 8	0.1289	5 vs 8	0.0832	6 vs 8	0.0026 **	7 vs 8	1.000				
1 vs 9	0.8776	2 vs 9	1.000	3 vs 9	0.2541	4 vs 9	0.1188	5 vs 9	0.1313	6 vs 9	0.0171	7 vs 9	0.8526	8 vs 9	1.000		
1 v 10	0.0136	2 v 10	0.0116	3 v 10	0.5008	4 v10	1.000	5 v 10	0.8747	6 v 10	1.000	7 v 10	0.0062 **	8 v 10	0.0385	9 v 10	0.027

** = $0.001 < P \leq 0.01$, *** = $P \leq 0.001$

The sediment composition of the area was variable within short distances and even within one transect line (site), and overall prawn abundance is the result of sampling over several sediment types within the 100 m^2 trawl (Table 3.11, Figure 3.6). It may be possible that smaller-scale 'patchiness' occurs but would be difficult to detect. The finer sediments can also be transported over a tidal cycle and during storm events, changing the pattern over time. Juvenile prawn abundance was not correlated with any sediment category (Table 3.12, all $P \geq 0.10$, Figure 3.7).

Table 3.11 Percentage of sediment type along each 100m^2 transect line for each site, 250m apart for a distance of 2.25 km at Port Arthur on 10 March 1993. Proportions were estimated visually by walking along the transect line at low tide after sampling on 10 March 1993 at Port Arthur.

Site	Fine Mud, fine mud and Zostera	Fine mud/sand	Coarse	Very coarse	Very coarse/shells	Intermediate coarse/shells
1	50	50				
2		100				
3		5	95			
4		15	40	35	10	
5		5	25	25	45	
6		10	25		65	
7		40	40	10		10
8		40	35			25
9			65			35
10		20	50	10		20

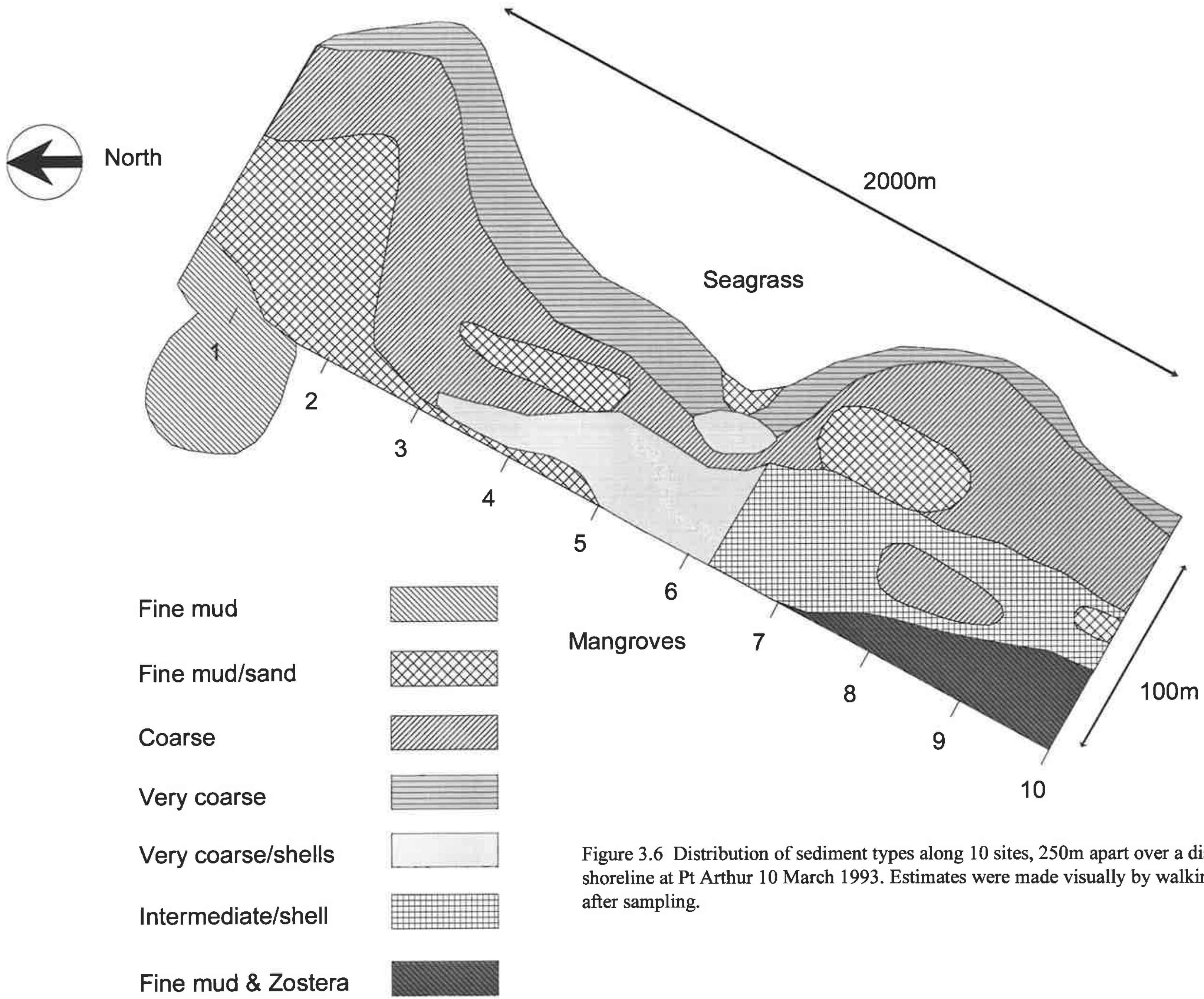


Figure 3.6 Distribution of sediment types along 10 sites, 250m apart over a distance of 2.25km of shoreline at Pt Arthur 10 March 1993. Estimates were made visually by walking over transect lines, after sampling.

Table 3.12 Pearson correlation coefficients for abundance (number m^{-2}) of juvenile *Penaeus latisulcatus* and % composition for three sediment categories, fine, coarse and very coarse with shells for each site (10 sites, 250 m apart) at Port Arthur, March 1993. NS – not significant

Sediment Category	r^2	*P*
Fine/mud	0.4662	0.17 NS
Coarse	-0.5521	0.10 NS
Very coarse with shells	0.2912	0.41 NS

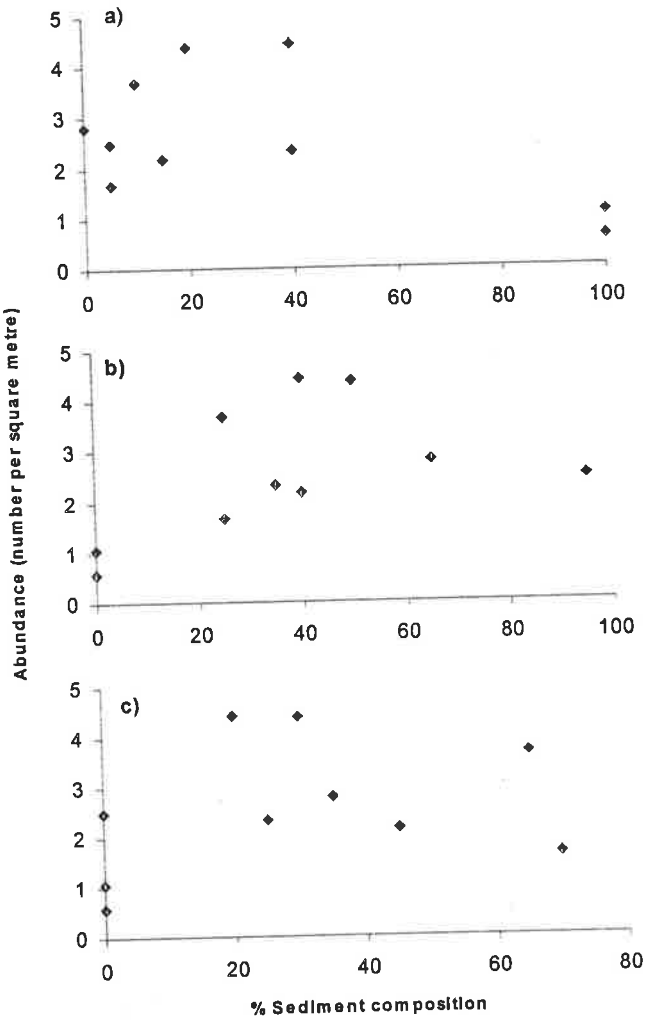


Figure 3.7 Relationship between the abundance (number m^{-2}) of juvenile (≥ 3 mm CL) *Penaeus latisulcatus* sampled per $100m^2$ trawl and the percentage sediment composition occurring along the trawl at Port Arthur on 10 March 1993. a) fine mud ($r^2 = 0.4662$, $P = 0.17$) b) coarse ($r^2 = -0.5521$, $P = 0.10$) c) very coarse with shells ($r^2 = 0.2912$, $P = 0.41$).

3.4.5 Daily variability at two locations

The abundance of juvenile prawns (Table 3.13) did not differ significantly (Table 3.14) over four days at Port Wakefield ($F = 2.06$, $P = 0.18$). The abundance (mean ± 1 s.e.m., 1.83 ± 0.1) m^{-2} over the four days ranged from 1.52 ± 0.23 to 2.16 ± 0.10 m^{-2}. The size composition (Figure 3.8) of prawns over the four days (mean ± 1 s.e.m., 3.98 ± 0.09, size range, 1-15 mm CL) were similar (Table 3.15). Low numbers of juvenile prawns were found in Port Arthur during this time.

Table 3.13 Abundance (number m^{-2}) of juvenile *Penaeus latisulcatus* ≥ 3 mm CL sampled in 100m^2 trawls over consecutive days at Port Arthur and Port Wakefield, during February 1992. ns – no sampling.

	18 Feb 1992			19 Feb 1992			20 Feb 1992			21 Feb 1992		
Trawl	1	2	3	1	2	3	1	2	3	1	2	3
Pt Arthur	0.28	0.28	0.18	ns	ns	ns	0.44	0.25	0.33	ns	ns	ns
Pt Wakefield	1.56	1.10	1.91	2.04	2.37	2.08	1.45	1.76	2.19	2.11	1.63	1.73

Table 3.14 One-way ANOVA of number of juvenile *Penaeus latisulcatus* sampled at Port Wakefield, over consecutive days in February 1992. NS – not significant

Source	df	SS	MS	F	*P*
Days	3	0.6182	0.2061	2.062	0.18 NS
Within	8	0.7994	0.09992		
Total	11	1.4176			

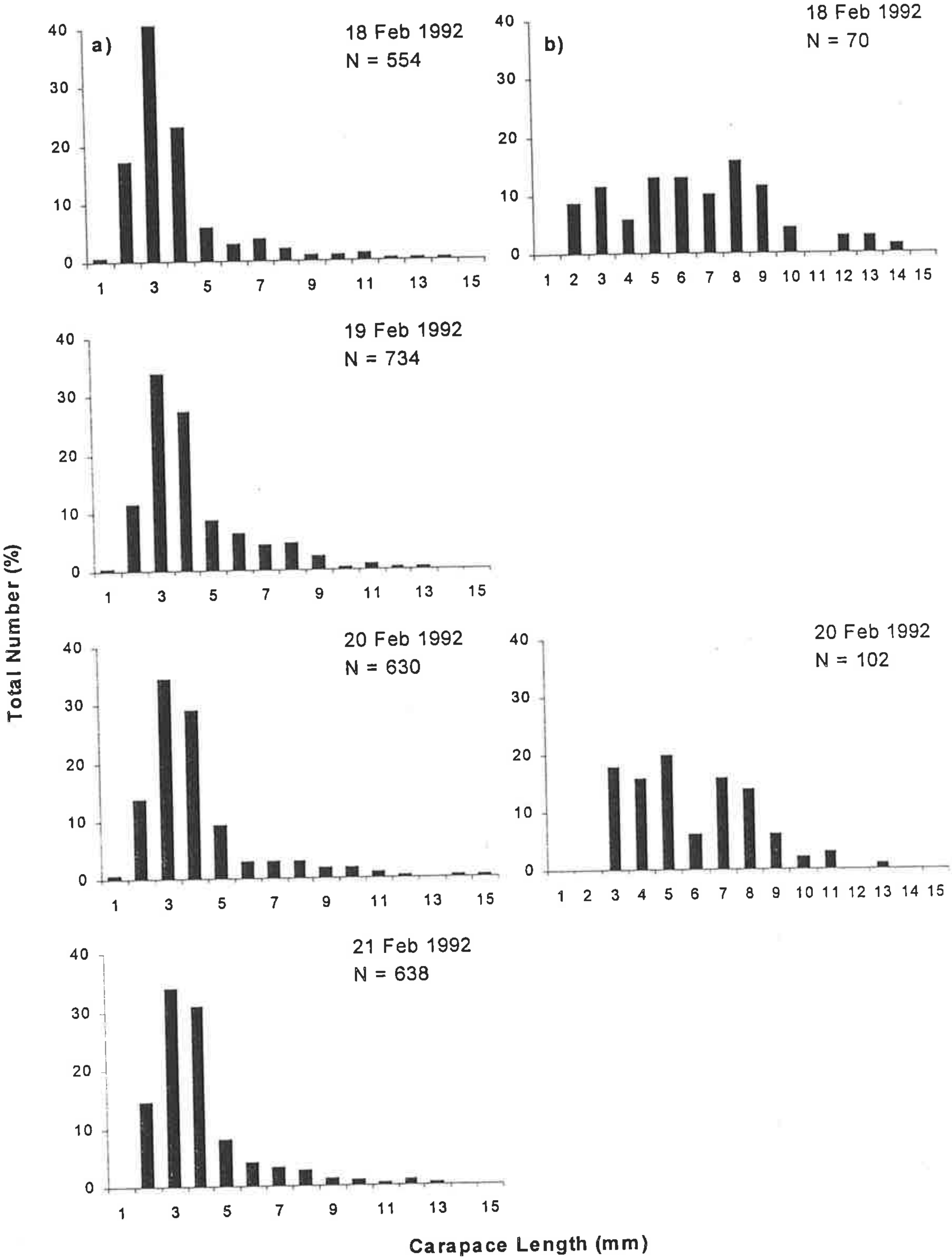


Figure 3.8 Percentage size composition of juvenile *Penaeus latisulcatus* sampled at a) Port Wakefield and b) Port Arthur on consecutive days in February 1992.

Table 3.15 Kolmogorov-Smirnov test on size distribution of juvenile *Penaeus latisulcatus* sampled at Port Wakefield on consecutive days in February 1992. NS – not significant

Comparison	P-value (Smirnov's Chi-square)
Day 1 vs Day 2	0.2135 NS
Day 1 vs Day 3	0.5521 NS
Day 1 vs Day 4	0.5521 NS
Day 2 vs Day 3	1.000 NS
Day 2 vs Day 4	1.000 NS
Day 3 vs Day 4	1.000 NS

3.4.6 Precision of the estimate of mean numbers

The mean number of prawns calculated from three $100m^2$ trawls at one site is considered a good estimate of the abundance of juvenile prawns in the area. During 12 months of sampling at Port Wakefield, Port Arthur, Port Clinton and Ardrossan during 1990 (Table 3.16), there was no significant difference between the number (number m^{-2}) of juvenile prawns sampled between four trawls at any one time period (Table 3.17, F = 0.11, $P = 0.95$). Similarly, during February 1992, over four consecutive days, there was no significant difference (F = 0.67, $P = 0.54$) in the number of prawns sampled between three trawls at Port Wakefield. On a broader scale, the number of prawns sampled over a 2.25 km stretch of the intertidal zone at Port Arthur in March 1993 indicated that the distribution of prawns was close to random over this distance.

Table 3.16 Abundance (number m^{-2}) of juvenile *Penaeus latisulcatus* ≥ 3 mm CL caught by the jet net for four $100m^2$ trawls during monthly sampling at Port Wakefield, Port Arthur, Port Clinton and Ardrossan during 1990.

	Port Wakefield				Port Arthur				Port Clinton				Ardrossan			
Trawl	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Jan90	0.13	0.14	0.17	0.27	0.07	0.03	0.03	0.06	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
Feb90	0.58	1.04	0.50	0.50	0.80	1.42	0.76	0.63	0.11	0.08	0.13	0.12	0.00	0.00	0.00	0.02
Mar90	0.98	2.16	1.30	1.18	2.48	2.12	2.41	2.23	0.49	0.29	0.23	0.54	0.45	0.37	0.47	0.51
Apr90	1.81	1.52	1.28	1.80	2.29	2.62	2.79	1.18	0.45	0.28	0.07	0.43	0.21	0.18	0.31	0.19
May90	0.68	1.39	1.04	0.57	1.80	1.57	1.79	1.76	0.23	0.31	0.68	0.26	0.30	0.26	0.19	0.29
Jun90	0.85	1.03	0.81	1.18	0.71	0.46	0.85	0.56	0.78	0.13	0.34	0.13	0.48	0.15	0.07	0.16
Jul90	0.76	0.50	0.61	0.94	0.84	0.68	0.81	1.20	0.65	0.53	0.33	0.24	0.24	0.22	0.22	0.20
Aug90	0.41	0.50	0.49	0.57	0.32	0.30	0.19	0.26	0.54	0.39	0.20	0.13	0.19	0.21	0.17	0.25
Sep90	0.13	0.43	0.17	0.39	0.42	0.56	0.45	0.48	0.08	0.07	0.17	0.30	0.10	0.21	0.22	0.18
Oct90	0.37	0.24	0.31	0.30	0.11	0.18	0.05	0.03	0.02	0.05	0.10	0.29	0.14	0.12	0.25	0.22
Nov90	0.10	0.03	0.03	0.03	0.01	0.05	0.02	0.01	0.05	0.03	0.04	0.00	0.25	0.24	0.10	0.18
Dec90	0.66	0.53	0.46	0.69	0.06	0.08	0.08	0.05	0.01	0.00	0.00	0.00	0.02	0.04	0.07	0.05

Table 3.17 ANOVA of abundance (number m^{-2}) of juvenile *Penaeus latisulcatus* ≥ 3 mm CL caught for four trawls during January to December 1990 at four nursery sites. NS – not significant

Source	df	SS	MS	F	*P*
Site	3	14.597	4.866	122.67	0.00 ***
Month	11	24.223	2.202	55.52	0.00 ***
Trawl	3	0.067	0.022	0.56	0.64 NS
Site*Month	33	18.595	0.563	14.21	0.00 ***
Site*Trawl	9	0.445	0.049	1.25	0.27 NS
Month*Trawl	33	0.909	0.028	0.69	0.88 NS
Error	99	3.927	0.040		

*** = $P \leq 0.001$

3.4.7 Daytime jet net and night-time beam trawl comparison

More prawns in the 1 mm size category were caught by the beam trawl (1 mm mesh) than by the jet net (2 mm mesh) (Table 3.18, Figure 3.9). Comparisons between catch rates of the sampling methods were therefore made omitting the 1.0-1.9 mm CL size-class. The mean number (m^{-2}) of prawns (± s.e.m.) was significantly higher in the jet net (2.83 ± 0.20) than in the beam trawl (0.90 ± 0.20); F = 35.97, $P = 0.001$) and the size distributions of prawns for all four trawls combined differed between the jet net and beam trawl ($P = 0.002$). The jet net captured many prawns of 2-4 mm CL, whereas the beam trawl captured low numbers over a large size range. Both nets caught prawns ranging from 1 to 14 mm CL.

Table 3.18 Number of juvenile *Penaeus latisulcatus* (m^{-2}) sampled by daytime jet net and night-time beam trawl for four $100 m^2$ trawls at Port Arthur, April 1990 showing the total number caught and the number of prawns ≥2 mm CL.

Trawl	Jet net Total number	Jet net Number ≥ 2mm CL	Beam trawl Total number	Beam trawl Number≥2 mm CL
1	3.28	3.27	0.98	0.94
2	3.06	3.06	0.39	0.26
3	2.56	2.56	1.36	1.16
4	2.43	2.43	1.34	1.23

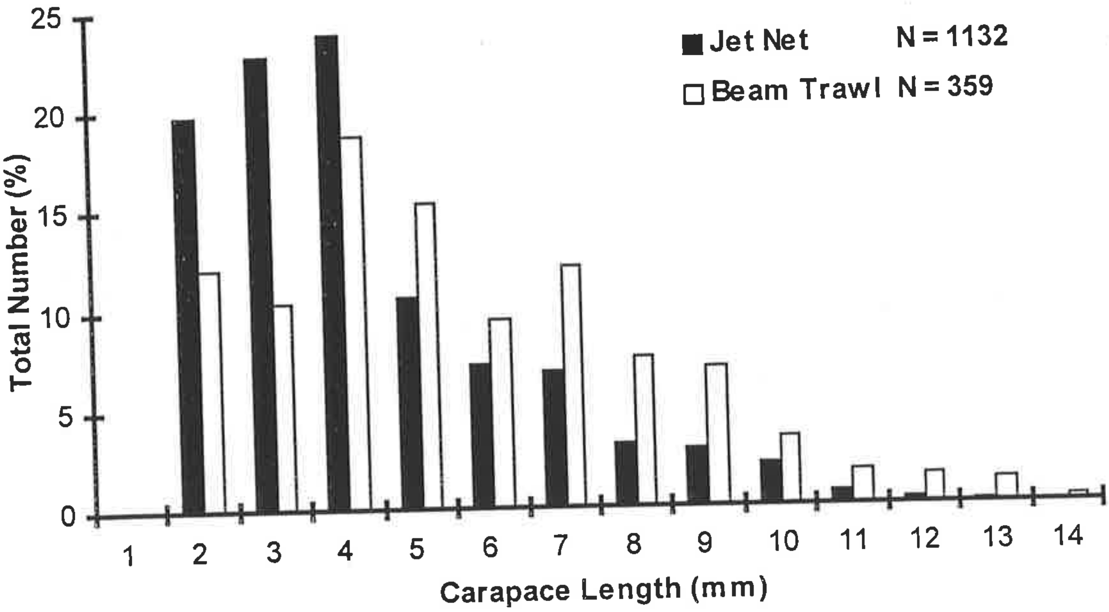


Figure 3.9 Carapace lengths of juvenile *Penaeus latisulcatus* caught with a jet net (2mm mesh) in daylight and beam trawl (1-mm mesh) at night at Port Arthur in March 1990. Only prawns ≥ 2 mm CL are included.

3.5 Discussion

The minimisation of catchability effects and the consequent catch of high numbers of juvenile prawns during the day makes the jet net a good sampling device for juvenile *Penaeus latisulcatus.* Additional benefits from sampling during the day include the ease of sampling and of sorting small prawns in daylight.

The jet net is particularly useful in sand and mudflat areas and its role in juvenile prawn research thus depends on the habitat preference of the particular species being studied. Juveniles of many other prawn species occur amongst seagrass and algal beds (Young 1978, O'Brien 1994a, Loneragan *et al.* 1994, Vance *et al.* 1996) or in salt marsh habitats (Wenner & Beatty 1993) and the jet net would be less effective and could be destructive in these habitats. *P.latisulcatus* is not closely associated with seagrass beds, but prefers intertidal sand- or mudflats (Wallner 1985, Penn *et al.* 1989, Potter *et al.* 1991, Carrick 1996) where this type of sampling gear is ideal.

Loneragan *et al.* (1995) conducted depletion experiments using a beam trawl and found them to be 65% efficient in sampling postlarvae and 35 to 50% efficient in sampling juveniles. Carrick (1996) found the jet net to be 96% efficient in capturing juvenile prawns in Spencer Gulf, SA. Depletion experiments were not conducted in GSV and therefore it is assumed that the efficiency of the jet net in this study falls within 65 to 96%.

No significant differences in size composition of prawns were observed for the fully enclosed and the open net. Higher catch rates were observed with the fully enclosed net when only larger individuals were present in nurseries. During the peak settlement period in March, both net types sampled high numbers of prawns. Since the enclosed net also prevented the collection of drift algae within a sampling site, the enclosed net was the preferred option for regular sampling.

Differences in distribution and abundance patterns in shallow and deep intertidal areas were observed. Smaller individuals were more abundant in the inshore areas while the larger juveniles were found in higher numbers in deeper water. This difference in size distribution was most evident later in the season (October), when overall numbers are lower with a greater proportion of larger individuals. During the peak postlarval settlement period, high numbers of smaller prawns are found throughout the nursery area. When the size distribution of prawns from shallow, perpendicular and deep samples were compared, the perpendicular trawl represented a combination of the sizes found in the shallow and deep trawls.

Penn (1981), Potter *et al.* (1989), Bishop & Khan (1991) and Loneragan *et al.* (1994) have also described depth preference according to size where the smaller individuals were in the shallows. To get a good representation of the abundance and size composition of the juvenile prawns present over the whole area of interest, it is best to sample perpendicular to the shore or to cover the entire width of an area to incorporate any depth preference by individual prawns.

On a time scale of days, there was no difference in the abundance or size composition of prawns within a site. Hence, the relative abundance index on any one day is representative of the numbers of prawns at that site over some time.

At any site, there was no significant difference in the abundance of juvenile prawns caught using four separate trawls. A mean index of abundance calculated from these trawls is considered to be a good estimate of relative abundance in the area sampled. The absence of high variability between trawls allowed for a reduction in the number of trawls at each site from an original regime of four trawls to using three trawls from January 1994 to June 1996. This reduction in trawls enabled two nursery sites to be sampled in one day (one tidal cycle) increasing sampling efficiency and reducing overall sampling costs.

Along-shore differences in distribution patterns were observed at Port Arthur; however, there were few significant differences in these 'micro-geographic' samples. Calculation of Morisita's index of dispersion (Morisita 1959) indicated that the numbers of prawns sampled over these sites were close to random. This pattern was also observed by Staples *et al.* (1985) for *P. merguiensis, M. endeavouri, P. esculentus* and *P. semisulcatus.* Contagious distributions are common in natural populations (Elliott 1977). For *P. latisulcatus* distribution patterns in nurseries may be related to environmental factors associated with larval transport and settlement processes and- or habitat conditions once settled.

Comparison of sediment type at Port Arthur, along sampling transects and along shore for a distance of 2.25 km showed that the proportion of sediment types (visual estimates) may vary along a transect line and forms a 'sediment complex' in the broader region. Over time, the distribution pattern of sediments may change due to tidal influences and storm events and cannot be considered static. No strong relationship was evident between substratum type and prawn abundance, but this finding was confounded by the variability of sediment type within one transect which may result in the inability to detect patterns. Even though there are some microhabitat differences and juvenile prawn patchiness over a wider area, which tend to be most evident early in the settlement season (late December to January) sampling with the jet net provides an adequate index of abundance within a site. The indices are not absolute but relative measures of abundance that can be compared from year to year.

From these studies on gear effectiveness and small-scale temporal and spatial distribution of postlarval and juvenile prawns, I have demonstrated that the enclosed jet net using the diagonal sampling method provides a reliable relative measure and that samples from one or a few 'sites' within an extended 'region' (eg. Port Arthur) and taken on one day are representative of the true relative abundance of prawns at that 'region'.

4. SPATIAL, SEASONAL AND ANNUAL VARIATION IN POSTLARVAL SETTLEMENT AND JUVENILE ABUNDANCE

4.1 Introduction

The management of prawn fisheries requires an understanding and identification of the causes of variability in the harvestable catch. The maintenance of a viable prawn fishery is in part determined by the success of the early life history stages of the prawn. Data needs to be collected for several years to identify seasonal settlement patterns into nurseries and the amount of annual variation in those patterns (Vance *et al.* 1998).

As adults, *Penaeus latisulcatus* occur in deeper water offshore and spawn in October to March (Carrick 1996). The resultant larvae spend time in the water column until they reach a postlarval stage when they settle out of the water column and become epi-benthic, usually in shallow inshore regions. Although prawn larvae have the ability to move up and down within the water column (Penn 1975, Rothlisberg 1982, Rothlisberg *et al.* 1983a, Rogers *et al.* 1993, Staples & Vance 1985, Vance 1992) they cannot move significant distances horizontally and would generally be advected and dispersed from offshore spawning areas by winds, tides and currents that are prevailing during their larval phase.

Once in proximity to inshore nursery areas a combination of passive and active transport is probably responsible for the overall inshore transport of larvae (Barber & Lee 1975, Staples 1980a). Penaeid larvae migrate vertically on a day-night cycle, being higher in the water column at night and lower in the day (Temple & Fisher 1965, Rothlisberg 1982). Although no studies on larval diurnal behaviour of *P. latisulcatus* have been documented, larvae of *P. plebejus*, a species similar to *P. latisulcatus,* have been observed to rise to the surface at night and sink to lower strata during the day (Racek 1959). Penn (1975) assumed a similar larval behavioural response for *P. latisulcatus* in Shark Bay, WA. As postlarvae, they may exhibit a similar nocturnal response offshore, but as they approach near-shore nursery grounds and become epibenthic, they may change their behaviour from nocturnal to tidal activity

(Rothlisberg *et al.* 1995, 1996). This behaviour would facilitate their inshore movement during flooding tides.

Once in the shallow regions, it has been postulated that postlarvae may be able to select whether they remain in an area or seek more favourable conditions (Forbes & Benfield 1986, de Freitas 1986). A reduced abundance of prawns in a particular habitat may also be due to increased predation (Forbes & Benfield 1986, de Freitas 1986, Kenyon *et al.* 1995). Habitat preference with respect to grain size or sediment type has been clearly shown for *Metapenaeus monoceros* (Joshi *et al.* 1979), *M. bennettae* (Aziz & Greenwood 1982), *P. monodon, P. indicus* (Branford 1981, de Freitas 1986, Mohan & Siddeek 1996) and *P. japonicus* (de Freitas 1986), and many prawn species are principally found on seagrasses or algae compared to bare substrates (Giles & Zamora 1973, Young & Carpenter 1977, Zimmerman *et al.* 1984, de Freitas 1986, Coles & Lee Long 1985, Turnbull & Mellors 1990, Loneragan *et al.* 1994, Kenyon *et al.* 1995). Within a nursery complex, microhabitat preferences have been observed (Wenner & Beatty 1993, Loneragan *et al.* 1994) and even if postlarvae do enter shallow intertidal areas, a juvenile population will only result if that system contains the microbiotope preferred by that species (de Freitas 1986). Hence, the final selection of a nursery ground probably depends on a number features of habitat structure such as depth, substratum, types of plant or other cover (Dall 1981).

Several studies have been undertaken in Australia on postlarval settlement trends in nurseries including those on *P. plebejus, P. esculentus, M. bennettae* and *M. macleayi* (Young 1978), *P. esculentus, M. endeavouri, P. latisulcatus* and *M. dalli* (Coles & Lee Long 1985), *P.merguiensis* (Staples 1980a, Staples & Vance 1985,1987, Vance *et al.* 1998), *P. esculentus* (Turnbull & Mellors 1990, O'Brien 1994a), *P. esculentus* and *P. semisulcatus* (Loneragan *et al.* 1994, Haywood *et al.* 1995), *P. semisulcatus* (Vance *et al.* 1994, 1996), *P. plebejus* (Worthington *et al.* 1995) and *P. latisulcatus* (Carrick 1996).

The current study describes the postlarval settlement trends and numbers of juvenile *P. latisulcatus* at five sites in GSV, over a seven-year period. This is one of the longest time-series available for postlarval settlement and juvenile prawn studies. The study was undertaken to establish; 1) the main times of recruitment to inshore habitats, 2) the residence times in the nurseries, 3) the time of emigration and 4) differences between nursery sites and years in these variables.

4.2 Sampling Methods

Monthly sampling using the jet net, deployed diagonally across the intertidal zone, was made at Port Wakefield, Port Arthur, Port Clinton and Ardrossan from October 1989 to June 1996. Monthly sampling at Webb Beach commenced in February 1993 and continued until June 1996. Fortnightly samples were taken during peak settlement times (January to June) at, Port Arthur from January 1990 to April 1994, Port Wakefield from December 1991 to April 1994 and Webb Beach from December 1993 to April 1994. The standard sampling procedure consisted of making four (until January 1994) or three (from January 1994 to June 1996) $100m^2$ trawls at the sampling site, which was identified by buoys or marks from shore.

The net was retrieved after the trawl, prawns emptied into a container and later sorted on shore. The samples were then fixed in 5% formalin, identified, counted and measured in the laboratory to the nearest 0.1 mm with an ocular micrometer. Postlarval and juvenile *P. latisulcatus* were easily distinguished from two other prawn species found in nurseries, *Trachypenaeus curvirostris* and *Metapenaeopsis lindae* by characteristics of the telson spines.

Length-frequency data was stored on a $DBIII^+$ database and information accessed through FOCUS. Water temperature was recorded at the time of sampling and salinity samples were collected at each site. The salinities were later measured using a YEO-KAL inductively coupled salinometer and results entered onto an Excel spreadsheet.

4.3 *Data Analysis*

Abundance of prawns (number m^{-2}) was estimated from the total number caught divided by the distance trawled. Postlarval prawns were defined as prawns < 3mm CL and juveniles were ≥ 3mm CL.

Three-way analyses of variance (ANOVA) was used to determine whether the abundance (number m^{-2}) of postlarvae and juvenile prawns differed amongst sites, months and years. For postlarvae, a four-month period over the peak settlement period (February to May) was used in the analysis and for juvenile prawns, six months January to June was used. Site, Year and Month were treated as fixed factors. Variation between trawls at one site was considered not significant (refer, 3.4.6) and all data sets comprised three trawls. Prior to January 1994, four trawls were taken at each nursery site for each sampling period and, three trawls were randomly selected from these four for the analyses to provide equal replication in the ANOVA. The data sets were checked for normality using Wilk-Shapiro Rankit plots, homogeneity of variances by the Cochran's test (Winer 1971, Underwood 1981) and for non-additivity using Tukey's 1 Degree of freedom test. To take into account the skewness of abundance distributions, ANOVA's were undertaken using log transformed (N +1) data.

Where ANOVA showed significant differences, Bonferroni multiple range tests were used to determine which means were significantly different at the 0.05 level of probability.

Pearson correlation coefficients were calculated for postlarval (<3mm CL) settlement and juvenile (≥ 3 mm CL) abundance (number m^{-2}) between sites over years and for postlarval and juvenile abundance between years at a site. Correlations between environmental variables and postlarval and juvenile abundance were investigated using annual mean temperature and salinity measurements and annual mean postlarval and juvenile abundance. These comparisons overcome difficulties associated with data that exhibits seasonal fluctuations. A possible cyclical trend in postlarval and juvenile prawn abundance over years was related to *El Nino* events. Pearson correlation coefficients were calculated between the mean value of the Southern Oscillation Index (SOI) and mean annual postlarval and juvenile abundance.

To further investigate the relationship between postlarval settlement and juvenile abundance, Pearson correlation coefficients were calculated for postlarval (<3 mm CL) and juvenile (≥3 mm CL) prawn abundance (number m^{-2}) at Port Arthur (1990 to 1994) and Port Wakefield (1992 to 1994) for samples collected at two, four and six-week intervals during February to May. This information will provide the appropriate lag-period for postlarval prawns from one sampling period to grow into the juveniles of the following sampling period.

4.4 Results

4.4.1 Environmental variation

Postlarval and juvenile *Penaeus latisulcatus* experience a wide range of temperatures in nurseries. Water temperatures exhibited a seasonal pattern (Figure 4.1) with lowest temperatures during winter (July to September) and highest temperatures in summer (January to March). All sites showed similar seasonal fluctuations. The surface water temperatures sampled on morning high tides ranged from 9.7°C at Ardrossan in July 1989 to 25.0°C at Port Arthur in February 1996. Afternoon temperatures are not depicted. Higher temperatures were recorded on afternoon high tides during summer, with measurements up by as much as 6°C compared to morning high tides. The highest recorded temperature on an afternoon high tide was 28.5°C in March 1994 at Port Arthur. The temperatures recorded may not encompass the extremes of temperatures that are experienced in nursery sites during a winter's night or during late afternoon in summer. No data loggers were used at any of the nursery sites due to ease of access of public to the locations.

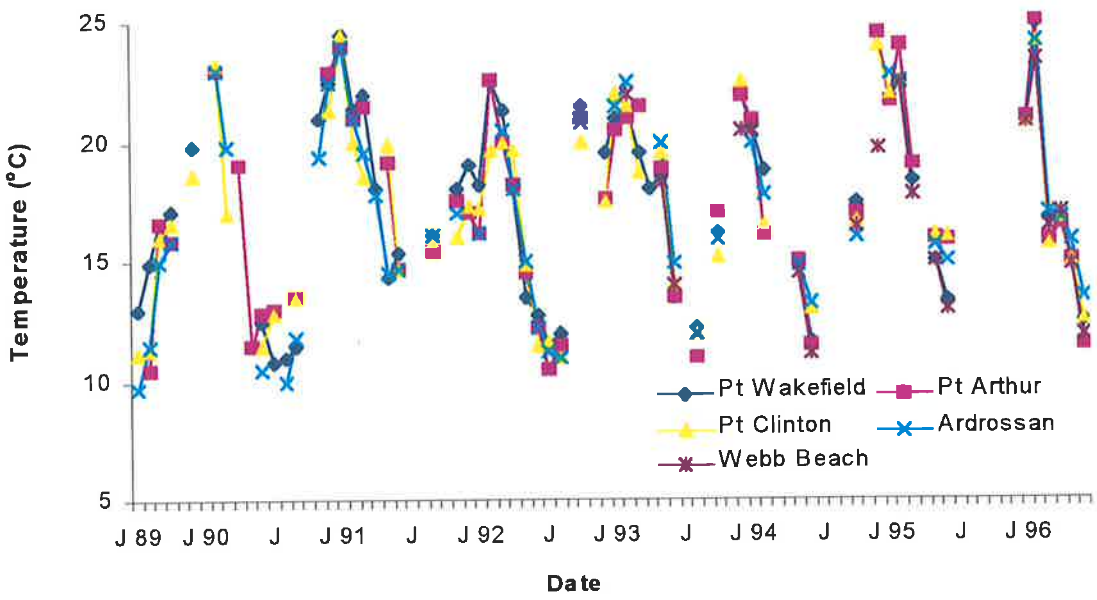


Figure 4.1 Surface water temperatures at nursery sites during morning sampling periods between June 1989 and July 1996.

Salinities also showed seasonal fluctuations (Figure 4.2) with site differences in salinity related to their distance up the gulf. Salinities at Ardrossan, the southern-most site fluctuated with less amplitude and salinities were lower compared to the northern sites. The highest salinity recorded was 42.2‰ at Port Wakefield during March 1991 and the lowest was 36.7‰ at Port Clinton in November 1989.

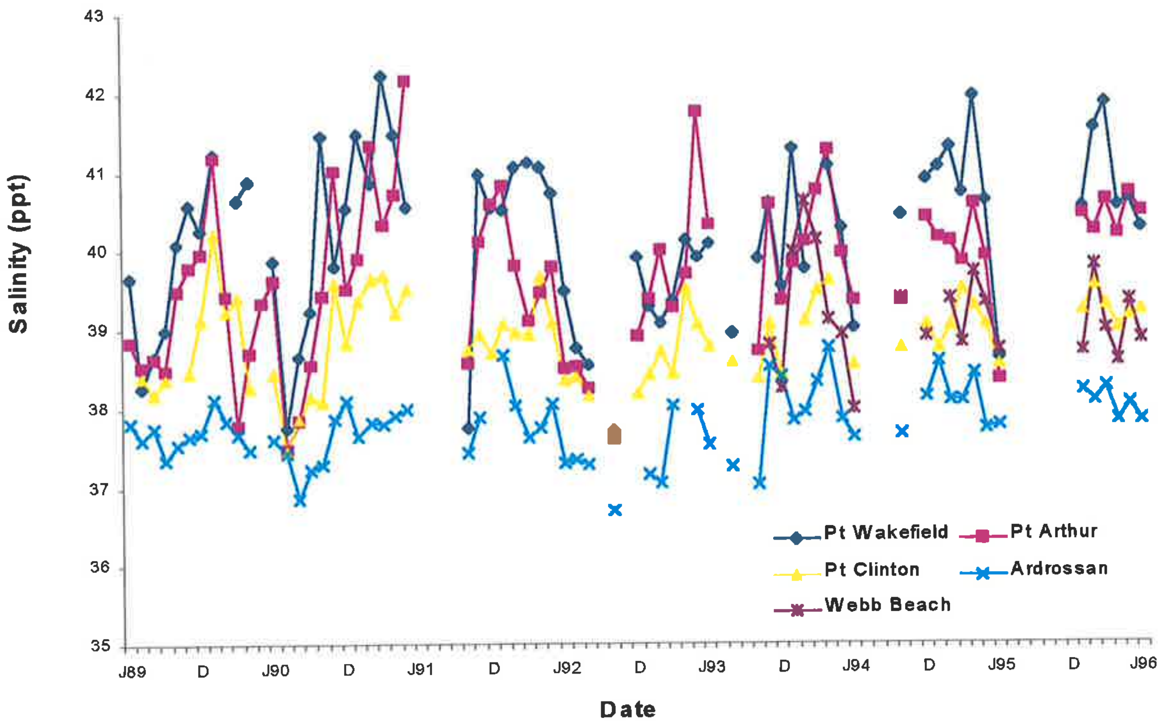


Figure 4.2 Surface water salinity measurements at nursery sites between June 1989 and July 1996.

4.4.2 Seasonal postlarval settlement and juvenile abundance variation

A strong seasonal component is observed with postlarval settlement. Settlement (< 3 mm CL) in nurseries occurs from mid December to early June (Figure 4.3). No settlement is observed during winter and spring (July to November). Settlement patterns are similar between the northern-most sites, Port Wakefield and Port Arthur with high numbers between February and early May. The southern sites show a more variable pattern and in some years, Ardrossan and Webb Beach appear to have an earlier low peak in settlement compared to northern sites as well as settlement continuing into June (Figure 4.4).

Juvenile prawns (≥ 3 mm CL) are found in nurseries throughout the year. Highest numbers are found in late February to late May. Low numbers are found during late November to early January just prior to the commencement of postlarval settlement.

Differences in the timing and abundance of postlarval settlement and the abundance of juvenile *P. latisulcatus* are observed between sites and years (Figure 4.4). Annual patterns are not consistent between sites. The peak in postlarval settlement abundance can occur between January and May in any one year. The juvenile peak is generally observed a month after the postlarval peak. This is in part due to the duration between sampling periods. In 1990, all sites except Port Arthur have lower settlement and juvenile prawn abundance when compared with 1991 to 1993. However, for Port Arthur, the abundance, particularly of juvenile prawns is higher than for any other year sampled. During 1994, lowest settlement and juvenile abundance over the seven years was observed at Port Wakefield, Port Arthur and Port Clinton but at Ardrossan 1995 was the lowest years and at Webb Beach 1996 was the lowest year. Overall, Port Wakefield, Port Arthur and Webb Beach have higher numbers of postlarval and juvenile prawns compared to Port Clinton and Ardrossan.

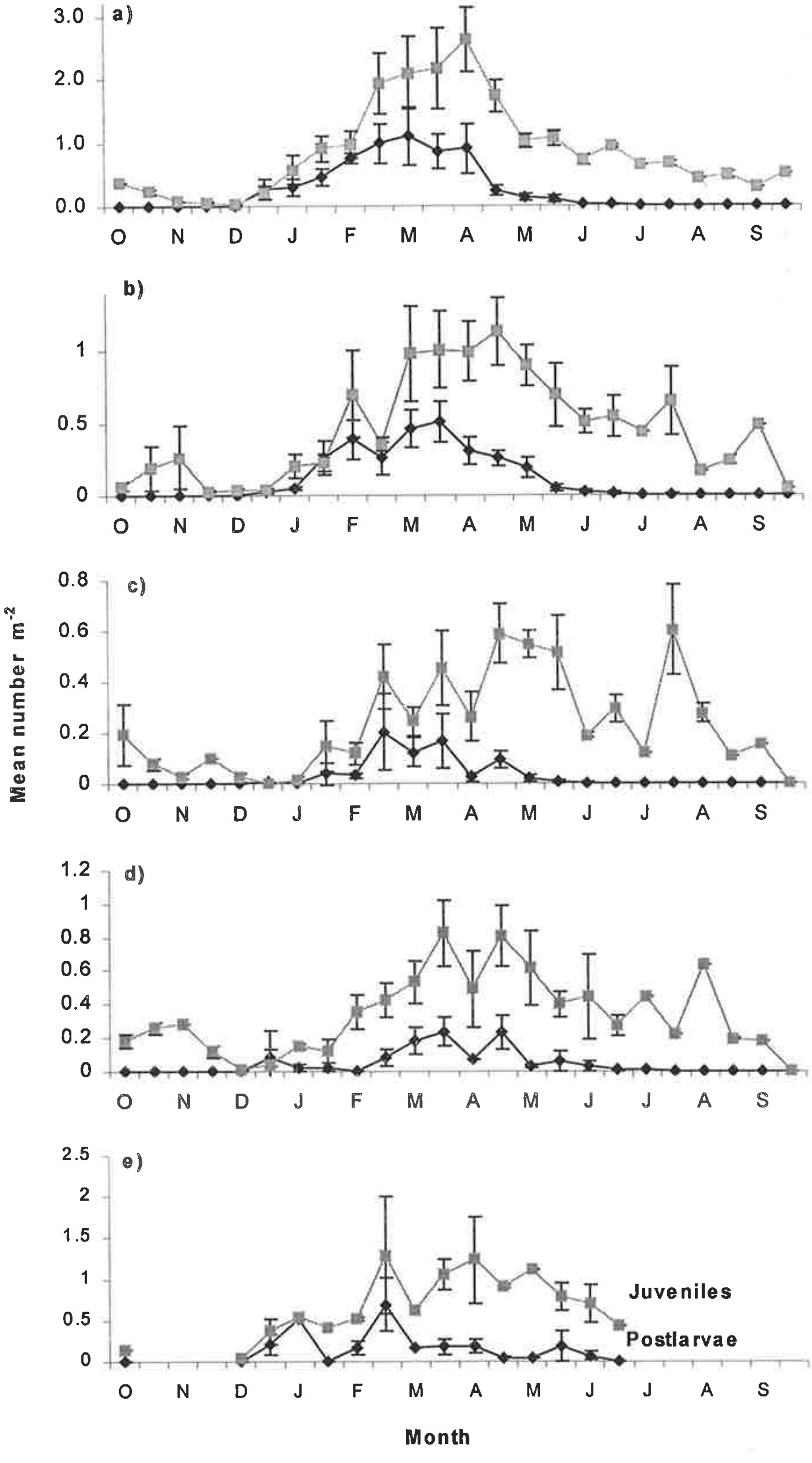


Figure 4.3 Mean fortnightly catches (number $m^{-2} \pm 1$ s.e.m.) of postlarval and juvenile *Penaeus latisulcatus* in nurseries over seven years; a) Port Wakefield, b) Port Arthur, c) Port Clinton, d) Ardrossan and e) Webb Beach (over four years). Note varying Y-scale.

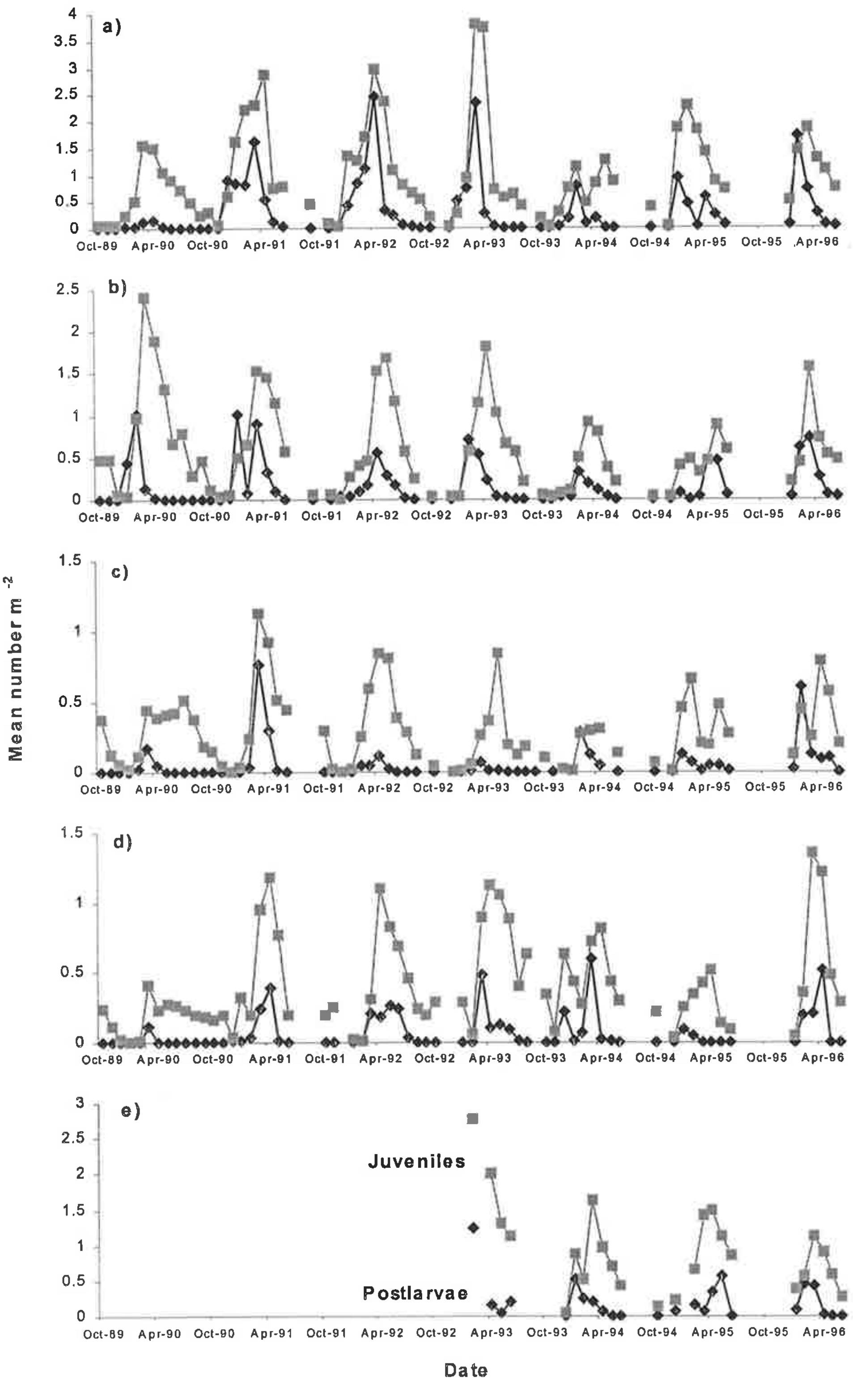


Figure 4.4 Mean number (m^{-2}) of postlarval (< 3mm CL) and juvenile (≥ 3mm CL) *Penaeus latisulcatus* sampled in nursery sites over a seven year period from October 1989 until May 1996. a) Port Wakefield, b) Port Arthur, c) Port Clinton, d) Ardrossan and e) Webb Beach. Note varying Y-scale.

4.4.3 Annual and spatial postlarval settlement and juvenile abundance variation

Variation in annual and spatial postlarval settlement and juvenile abundance is evident in nursery sites in GSV (Figures 4.3 and 4.4). Three-way ANOVAs showed that the mean number (log (N+1)) of postlarval and juvenile prawns differed significantly between Site, Month, Year and all interactions ($P < 0.001$, Table 4.1 and 4.2).

Table 4.1 Three-way ANOVA for abundance (log (N+1)) of postlarval (<3 mm CL) *Penaeus latisulcatus* settling between February to May for years 1990 to 1996 at four nursery sites, Port Wakefield, Port Arthur, Port Clinton and Ardrossan.

Source	df	SS	MS	F	*P*
Site	3	5.176	1.725	163.364	0.000***
Month	3	2.114	0.705	66.723	0.000***
Year	6	1.931	0.322	30.467	0.000***
Site*Month	9	1.709	0.190	17.975	0.000***
Site*Year	18	2.399	0.133	12.616	0.000***
Month*Year	18	3.125	0.174	16.435	0.000***
Site*Month*Year	54	5.640	0.104	9.889	0.000***
Error	224	2.366	0.011		
Total	335	24.460			

*** - $P \leq 0.001$

Table 4.2 Three-way ANOVA for abundance (log (N+1)) of juvenile (≥3 mm CL) *Penaeus latisulcatus* settling between January to June for years 1990 to 1996 at four nursery sites, Port Wakefield, Port Arthur, Port Clinton and Ardrossan.

Source	df	SS	MS	F	*P*
Site	3	19.040	6.347	337.845	0.000***
Month	5	11.132	2.226	118.516	0.000***
Year	6	2.665	0.444	23.641	0.000***
Site*Month	15	2.557	0.170	9.074	0.000***
Site*Year	18	3.517	0.195	10.400	0.000***
Month*Year	30	6.812	0.227	12.088	0.000***
Site*Month*Year	90	7.579	0.084	4.483	0.000***
Error	336	6.312	0.019		
Total	503	59.614			

*** - $P \leq 0.001$

For both postlarval and juvenile abundance, Site had the highest mean squares (Table 4.1 and 4.2), then Month and Year. The interaction terms had lower means squares than any of the main effects.

Investigation of Site indicates that Port Wakefield has highest mean number (± 1 s.e.m.) for both postlarval (0.601 ± 0.076) and juvenile prawns (1.332 ± 0.074) compared to other sites. Port Arthur has higher mean numbers of postlarvae (0.345 ± 0.035) and juveniles (0.801 ± 0.052) compared to Port Clinton and Ardrossan. For postlarvae, Port Clinton (0.110 ± 0.026) and Ardrossan (0.137 ± 0.020) have similar mean numbers but for juvenile prawns Ardrossan (0.502 ± 0.036) is higher than Port Clinton (0.347 ± 0.032).

The Site x Year interaction was significant although much less than the main effect of Site in both analyses. This significance can be explained by the change from highest mean numbers of postlarvae and juveniles at Port Arthur during 1990 to highest numbers at Port Wakefield from 1991 to 1996 (Figure 4.5). No significant correlation was found between sites (all combinations, $P > 0.05$) for postlarval or juvenile abundance over years.

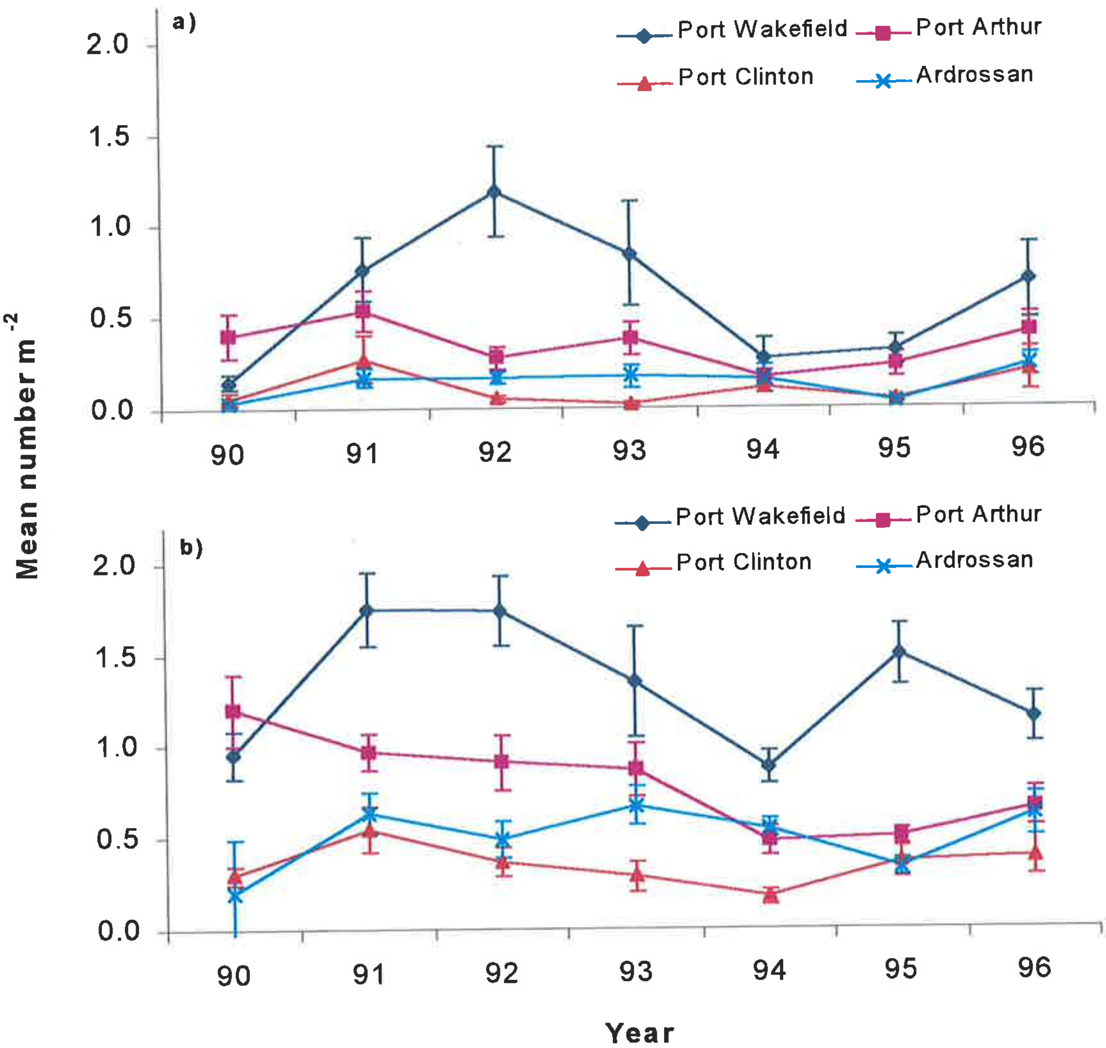


Figure 4.5 Mean number (m^{-2})(± 1 s.e.m) of *Penaeus latisulcatus* caught in nursery sites during February to May (combined) for postlarvae and January to June (combined) for juveniles, between 1990 and 1996. a) postlarvae (< 3 mm CL), b) juveniles (≥ 3 mm CL).

The Site x Month interaction was also significant (Figure 4.6) but more for postlarvae than juveniles. This can be attributed to differences in abundance at Port Clinton and Ardrossan between February and March and changes in abundance at Port Wakefield and Port Arthur between April and May. A significant correlation was observed for monthly (February to May) postlarval abundance between Port Wakefield and Port Clinton ($r = 0.961$, $P = 0.039$) and Port Arthur and Port Clinton ($r = 0.975$, $P = 0.025$). A significant correlation was observed for monthly (January to June) juvenile abundance between Port Arthur and Port Clinton ($r = 0.877$, $P = 0.022$), Port Arthur and Ardrossan (r = 0.944, $P = 0.005$) and Port Clinton and Ardrossan ($r = 0.863$, $P = 0.027$).

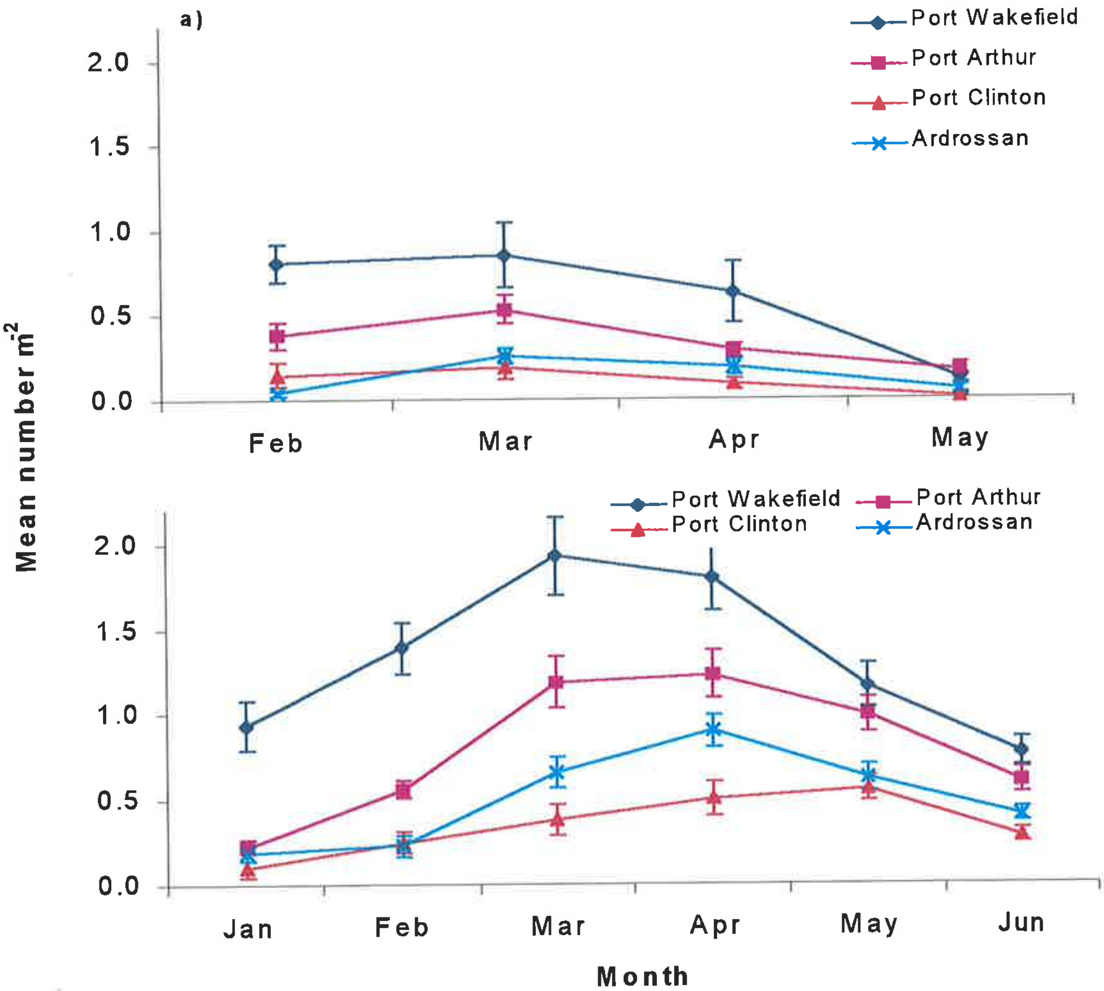


Figure 4.6 Mean number (m^{-2})(± 1 s.e.m) of *Penaeus latisulcatus* caught in nursery sites during February to May (postlarvae) and January to June (juveniles) for years 1990 to 1996 combined. a) postlarvae (< 3 mm CL), b) juveniles (≥ 3 mm CL).

Month was the next most significant effect but much less than Site (Table 4.1 and 4.2). The mean abundance (number $m^{-2} \pm 1$ s.e.m.) of postlarvae caught in May (0.096 ± 0.015) was significantly lower than for months February to April (Figure 4.6 a). February, March and April were all similar to each other. Juveniles of *P. latisulcatus* are found in nurseries all year round but higher numbers are caught between January and June and only these months were included in the ANOVA. For these months, the mean abundance in January (0.363 ± 0.054) was significantly lower than for months February to June. February (0.608 ± 0.067) and June (0.518 ± 0.038) had similar abundance levels. Highest juvenile prawn abundance was observed in March (1.039 ± 0.099) and April (1.108 ± 0.083) (Figure 4.6 b). The Month x Year interaction was also significant (Tables 4.1 and 4.2) but much lower than the main effect and can be explained by differences between the month in which the highest abundance for all sites was observed each year (Figure 4.7). For both postlarval and juvenile *Penaeus latisulcatus*, no consistent pattern was observed over the seven years with highest abundance occurring between the months February to May (Figure 4.7 a and b).

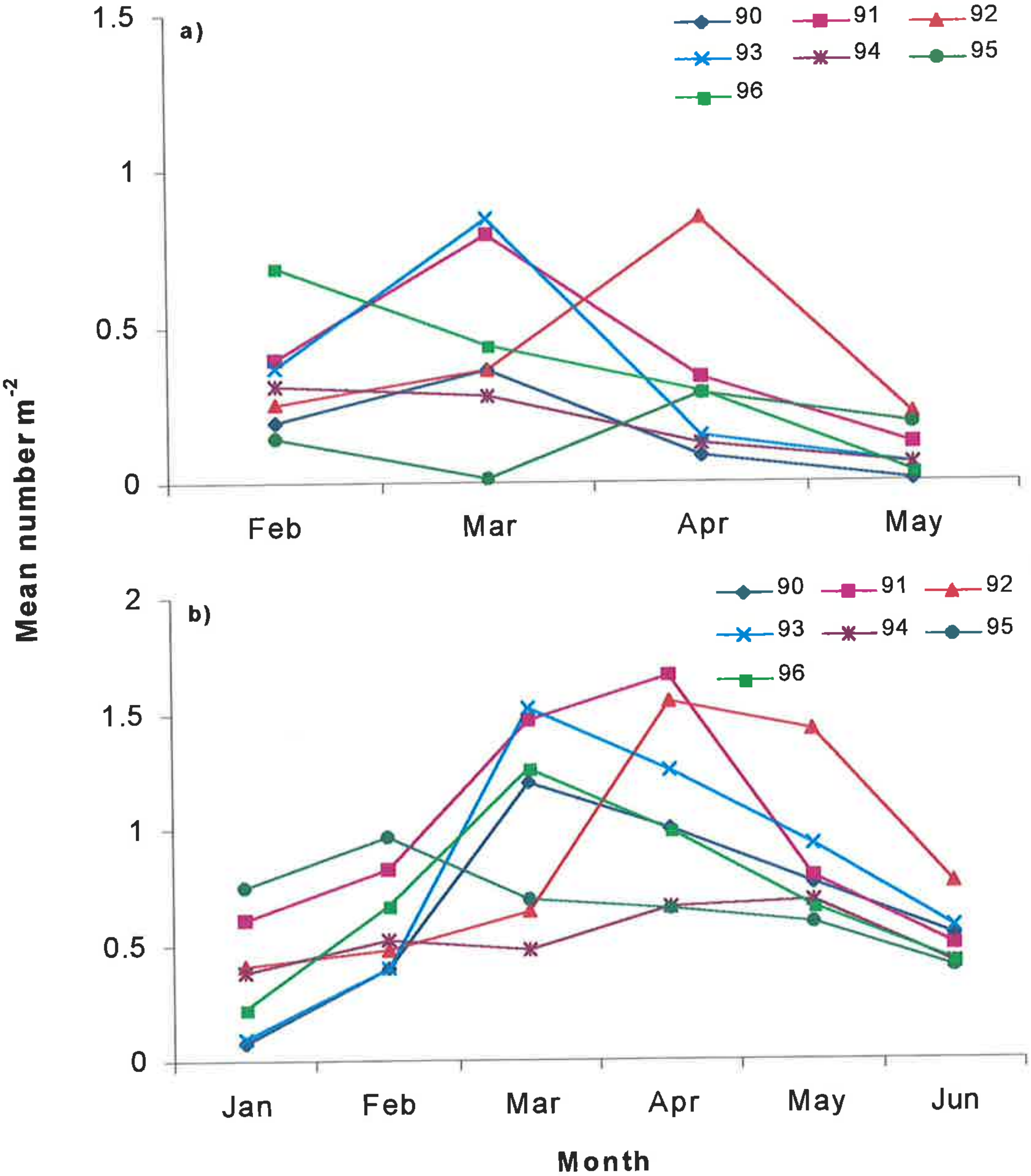


Figure 4.7 Mean abundance (number m^{-2}) of *Penaeus latisulcatus* caught in nursery sites (combined) during February to May for postlarvae (< 3 mm CL) and during January to June for juveniles (≥ 3 mm CL). a) postlarvae, b) juveniles.

Year was also significant (Table 4.1 and 4.2) for both postlarvae and juveniles, but much lower than Site or Month. Investigation of Year (Figure 4.8) indicated that for postlarvae, the highest mean abundance (number $m^{-2} \pm 1$ s.e.m.) is seen in 1992 (0.418 ± 0.091) but this is not significantly different to years 1991, 1993 or 1996. However, 1990 (0.161 ± 0.039), 1994 (0.179 ± 0.036) and 1995 (0.156 ± 0.032) are significantly lower than the other years. For juveniles, highest abundance is observed in 1991 (0.976 ± 0.089) but is not significantly different to 1992 or 1993. Lowest abundances for juveniles were observed in 1990 (0.663 ± 0.079) and 1994 (0.524 ± 0.044).

Overall yearly trends for the seven years suggest some cycling of postlarval and juvenile abundance. However several more years of data would be needed to confirm this. No correlation was observed with the mean annual abundance of postlarvae or juveniles with the mean annual estimate of the Southern Oscillation Index (SOI) (postlarvae: r = -0.125, $P = 0.790$, juveniles: r = -0.193, $P = 0.681$) between 1990 and 1996.

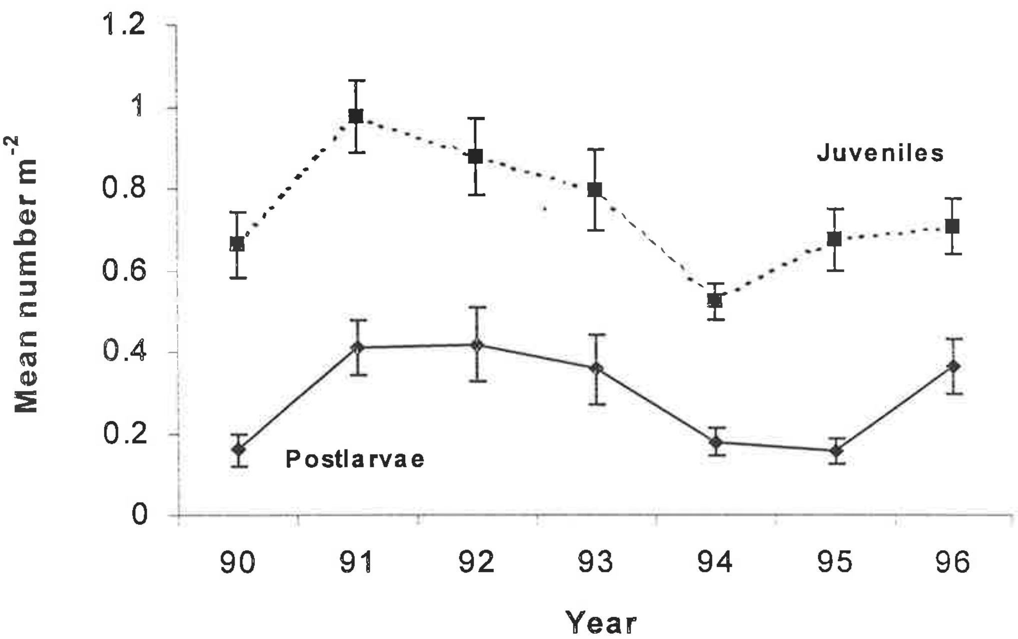


Figure 4.8 Mean abundance (number m^{-2}) of postlarval (February to May) and juvenile (January to June) *Penaeus latisulcatus* caught in nursery sites (combined) for years 1990 to 1996.

4.4.4 Correlation of postlarval settlement with juvenile abundance

Higher numbers of juvenile prawns are caught compared to postlarvae because of the 2-mm mesh used for sampling causing loss of some postlarvae. The annual variation in postlarval and juvenile abundance (number m^{-2}) are significantly correlated (r = 0.826, P = 0.022) (Figure 4.8) and hence the relationship between postlarval and juvenile abundance in nurseries was investigated.

A significant correlation was observed between postlarval and juvenile abundance at Port Wakefield for a two (r = 0.712, P = 0.001) and four week time-lag (r = 0.685, P = 0.002) but not at six weeks (r = 0.225, P = 0.401) (Figure 4.9). At Port Arthur, a significant correlation was observed between postlarval and juvenile abundance at a four (r = 0.371, P = 0.043) and six week time-lag (r = 0.398, P = 0.044) but not at two weeks (r = 0.278, P = 0.136) (Figure 4.10).

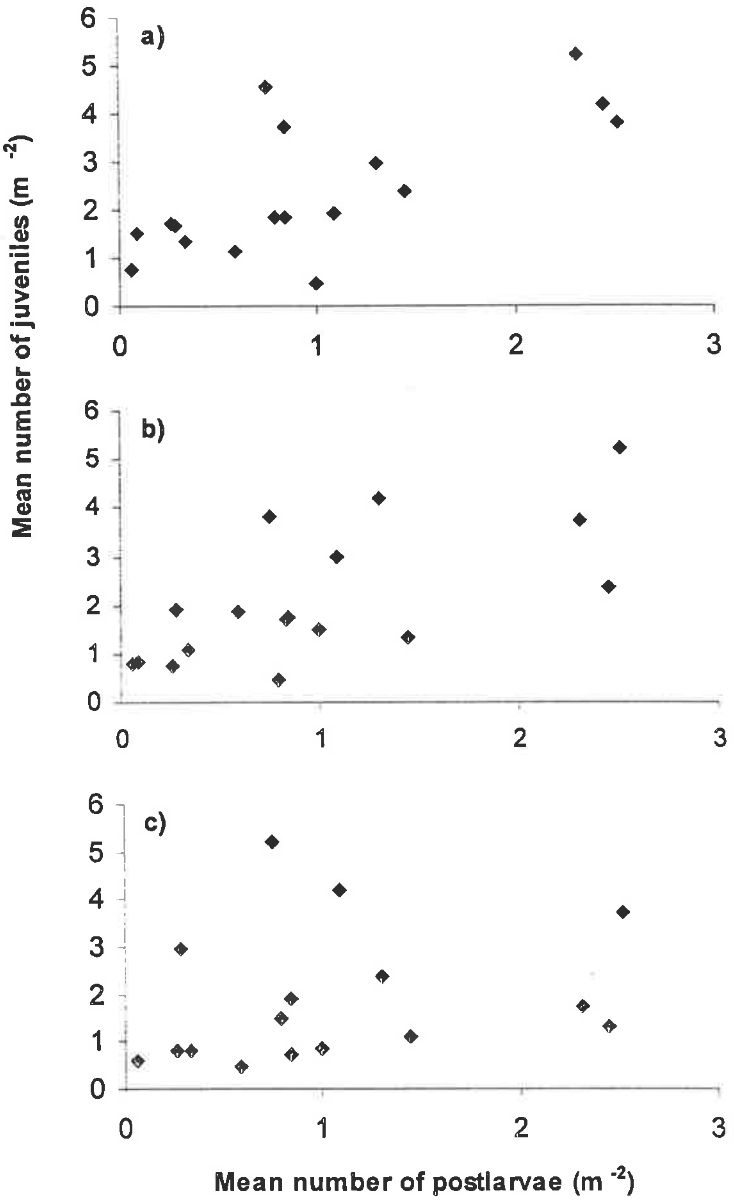


Figure 4.9 Relationship between the mean number (m^{-2}) of postlarval (<3 mm CL) *Penaeus latisulcatus* sampled in Port Wakefield during February to May and the mean number (m^{-2}) of juveniles (≥3 mm CL) sampled in the same area during 1992 to 1994. a) two-week interval ($r = 0.712$, $P = 0.001$), b) four-week interval ($r = 0.685$, $P = 0.002$), and c) six-week interval ($r = 0.225$, $P = 0.402$).

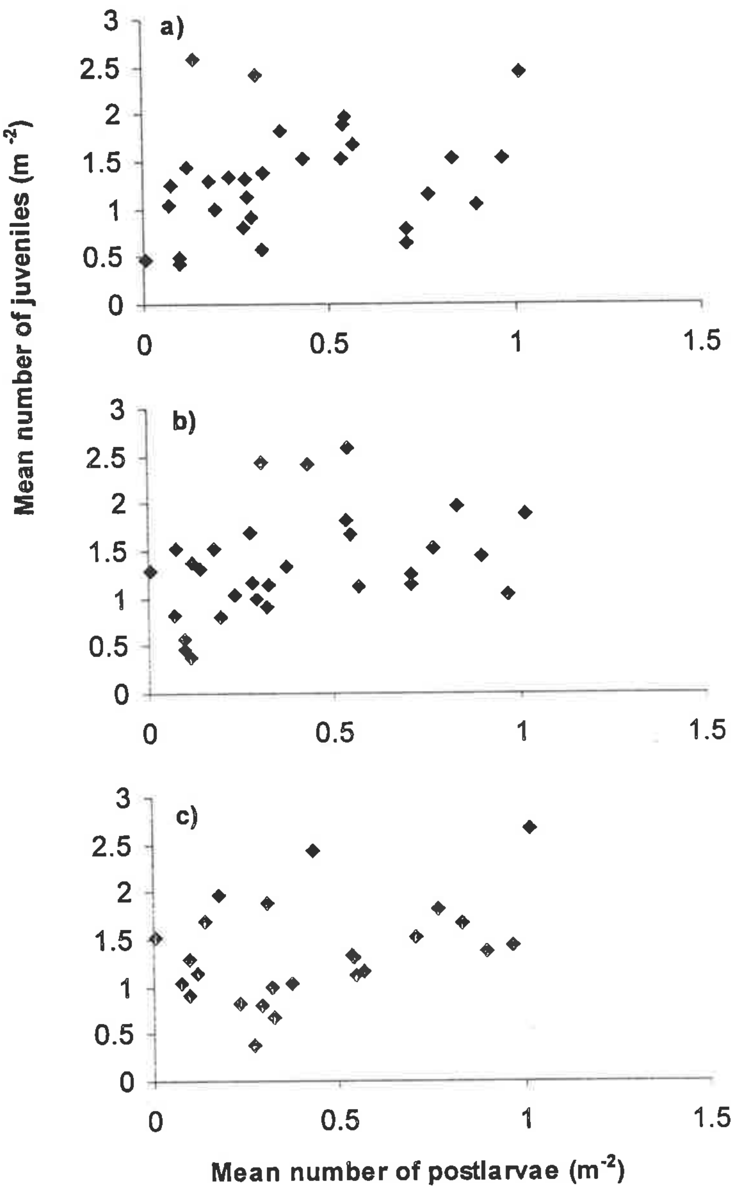


Figure 4.10 Relationship between the mean number (m^{-2}) of postlarval (<3 mm CL) *Penaeus latisulcatus* sampled in Port Arthur during February to May and the mean number (m^{-2}) of juveniles (≥3 mm CL) sampled in the same area during 1990 to 1994. a) two-week interval ($r = 0.278$, $P = 0.136$), b) four-week interval ($r = 0.371$, $P = 0.043$), and c) six-week interval ($r = 0.398$, $P = 0.044$).

4.4.5 Correlation of postlarval settlement and juvenile abundance with environmental variables

For individual sites, comparison of mean annual temperature and salinity (over peak settlement months) and postlarval and juvenile abundance indicated a significant correlation between temperature and postlarval abundance ($r = 0.815$, $P = 0.020$) and juvenile abundance ($r = 0.841$, $P = 0.018$) at Port Wakefield and for temperature and juvenile abundance ($r = 0.798$, $P = 0.032$) at Port Clinton. For all sites combined, a significant correlation was only observed between temperature and juvenile abundance ($r = 0.762$, $P = 0.047$, Figure 4.11).

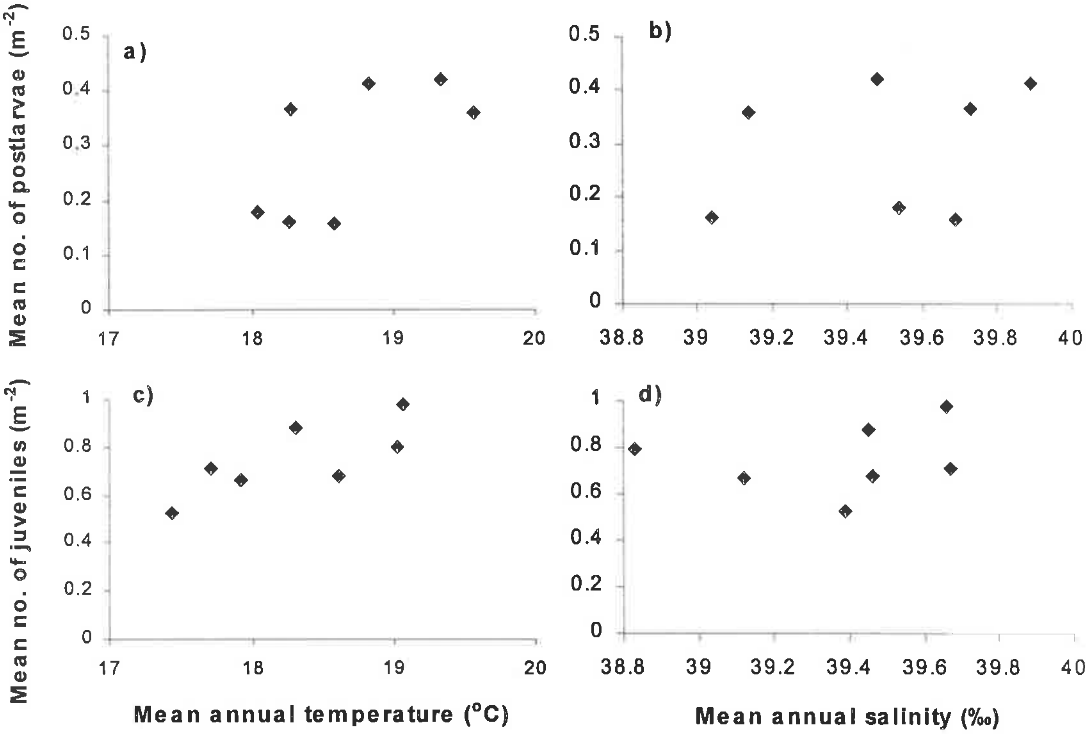


Figure 4.11 Relationship between the mean annual temperature and salinity for all nursery sites combined and the number (m^{-2}) of postlarval (<3 mm CL) *Penaeus latisulcatus* sampled in all sites during February to May and the mean number (m^{-2}) of juveniles (≥3 mm CL) sampled between January to June during 1990 to 1996. a) mean postlarval abundance and annual temperature ($r = 0.644$, $P = 0.119$), b) mean postlarval abundance and annual salinity ($r = 0.284$, $P = 0.537$), c) mean juvenile abundance and annual temperature ($r = 0.762$, $P = 0.047$), and d) mean juvenile abundance and annual salinity ($r = 0.182$, $P = 0.695$).

4.5 Discussion

Variation in postlarval settlement and juvenile prawn abundance occurs on a seasonal, spatial and annual basis. Variation between years was smaller than observed for months and sites. The variation may be caused by factors acting directly on prawns so they enter and settle in the nursery grounds or on an earlier life-history stage outside the nursery grounds (Vance *et al.* 1996).

The reproductive activity of adult prawns directly influence the availability of larvae and in turn postlarvae. In Gulf St Vincent, female *P. latisulcatus* spawn between October to March (Carrick 1996). The spawning period is limited to warmer months because water temperatures during winter are too low for reproductive activity. A time lag of six to eight weeks is observed before postlarvae are found in nursery areas.

The postlarval settlement pattern appears to be continuous between mid December and early June. No postlarvae were found in nursery areas during winter. Juvenile prawns are found in nurseries throughout the year with highest numbers occurring in late February to late May. Relatively low numbers are found in nurseries during late November to early January. Monitoring of the emigration of juvenile prawns from nursery sites was not feasible during this study and precise information on the timing of emigration cannot be deduced from juvenile abundance information. However, the decline in juvenile prawn abundance in late May and further during late November to early January, may indicate movement out of the nurseries during these times. These periods correspond to recruitment peaks in the commercial fishery (7.2.1.6).

Spatial differences in postlarval settlement and juvenile prawn abundance are evident with the northern-most sites having higher abundances compared to southern sites. Port Wakefield and Port Arthur, the two northern sites show similar settlement patterns with highest numbers occurring in February to early May. The southern sites show a more variable pattern with some evidence of an earlier low peak in settlement compared to northern sites as well as settlement continuing to June. These differences may reflect the spatial distribution and abundance of spawning females and larval advection.

The key spawning population is south of all the main nursery areas. Postlarvae that are ready to settle are moved inshore, encounter the southern nursery sites before the northern sites and an earlier settlement peak is observed. As the settlement season progresses the northern sites have higher numbers of postlarvae settling compared to southern sites. This may be due to larvae being moved in a northerly direction up the gulf and to more favourable conditions and higher survival for settling postlarvae. Later in the spawning season (April) resultant larvae may not reach the northern nursery sites and therefore only the southern sites have a late peak in settlement. Modelling the advection of larvae using wind and tidal information will be used in Chapter 5 to determine whether observed differences in the spatial pattern of postlarval settlement is due to advection processes.

Three-way ANOVAs indicated that variation in postlarval settlement and juvenile abundance was significant for sites, months and years. Site was the most significant effect. Port Wakefield had the highest mean numbers of postlarvae and juveniles compared to other sites. Port Arthur was higher than either Port Clinton or Ardrossan. For postlarvae, the two southern sites had similar settlement abundance but for juvenile prawns Ardrossan had higher numbers compared to Port Clinton. The importance (prawn abundance) of one nursery site relative to another was not always consistent from year to year nor were peaks in abundance always seen in the same month. Generally, highest postlarval settlement occurred in February to April and highest juvenile abundance was observed in March and April.

Yearly variability was lower than for site or month. Highest abundance of postlarvae was observed in 1992 but it was not significantly different to 1991, 1993 or 1996. The years 1990, 1994 and 1995 were significantly lower. For juvenile prawn abundance, 1991 had the highest numbers but these were not significantly different to 1992 or 1993. Lower abundance was observed in 1990 and 1994. A possible cyclic trend in postlarval and juvenile prawn abundance was observed over the seven years but several more years data would be required to confirm this. An absence of a consistent negative or positive trend over the years may indicate stability in the population during the study period.

Only a few studies have been undertaken on postlarval settlement, which have been carried out for at least two years. Staples & Vance (1985) studied *P. merguiensis* for four years, Vance *et al.* (1996, 1998) studied *P. semisulcatus* and *P. merguiensis* for six years and Carrick (1996) studied *P. latisulcatus* for two years. They observed high variability in annual abundance of postlarvae and juvenile prawns unlike this study. Subramaniam (1990) also showed similar catches between two years for *P. latisulcatus*. The relative stability observed in GSV will be further investigated in Chapter 7.

In tropical regions, extreme environmental conditions can occur such as cyclone events and high rainfall that can influence settlement and or survival of postlarvae. Staples & Vance (1985) found for *P. merguiensis* that postlarval abundance was correlated with salinity, temperature and nutrient differences as well as with the biomass of adult prawns offshore. They found that advection of postlarvae to estuaries is enhanced by the prevailing currents outside the estuary. If these strong seasonal factors are superimposed on the adult spawning patterns the result is a strong seasonal pattern of juvenile abundance in estuaries.

In Gulf St Vincent, surface water temperatures and salinities show seasonal variation with highest values recorded in summer and lowest in winter. As reproductive activity and subsequent release of eggs and larvae is related to water temperature for *P. latisulcatus* in GSV seasonal variation in postlarval settlement and juvenile is observed. For all sites combined mean annual temperature variation was significantly correlated to mean annual juvenile abundance whereas salinity had no significant correlation which is not surprising because all salinities recorded fall well within the species tolerance range (Wu 1990).

A correlation between postlarval settlement and juvenile numbers was observed for time-lags of two and four weeks at Port Wakefield and four and six weeks at Port Arthur. The application of a four-week time lag between postlarvae and juveniles seems appropriate for nurseries in GSV allowing for differences observed between sites. In general it is expected that a pulse of postlarval settlement gives rise to a pulse of early juveniles about four weeks later. Similar correlations have been shown in other prawn studies (Staples 1980a, Staples & Vance 1985, 1987, Subramaniam 1990, Vance *et al.* 1996, 1998). The variability between sites and apparent correlation with a number of time-lag scenarios in GSV is likely attributed to the differences in time spent in nurseries by postlarvae and juveniles. The group comprising postlarvae (≤ 3 mm CL) belong to a very small 'age class' and are most likely derived from only one or two pulses of immigration into a nursery site. Juvenile prawns comprise a much larger size (and therefore age) range and therefore juvenile abundance is likely due to comprise a number of pulses of postlarvae over a more extended period.

Vance *et al.* (1996, 1998) considered the most important factor determining the abundance of juvenile prawns was the supply and successful settlement of postlarvae. This concept of 'supply side ecology', where variability in abundance is not determined by *in situ* processes but by 'recruit' supply is one that is familiar to benthic ecologists (Gaines & Bertness 1992, Hurlbut 1992). It is also well documented for tropical reef fish communities (Millicich *et al.* 1992, Meekan *et al.* 1993, Doherty *et al.* 1994). Only fairly recently have temperate-zone demersal fish being investigated (Bell & Westoby 1986, Bell *et al.* 1987, 1988, Worthington *et al.* 1992, Hamer & Jenkins 1996) and some evidence has been shown that larval supply to particular seagrass beds influence recruitment to seagrass habitats.

In Gulf St Vincent it appears that the number of juvenile prawns in nurseries depends on the strength of settlement and this in turn on the initial number of larvae available, their survival in the planktonic phase and movement into inshore nursery areas. Larval advection and water movement modelling will be discussed in Chapter 5. The nursery sites in the northern-most parts of Gulf St Vincent are more important in terms of postlarval settlement and juvenile prawn abundance compared to southern sites. Seasonal differences in postlarval settlement and juvenile abundance can be attributed to the reproductive activity patterns and distribution of adult prawns. The influence of parental stock will be further investigated in Chapter 7. Annual variability during the seven-year study was much smaller than variability between sites and months (seasonal). The overall prawn production in nursery grounds is therefore dependent on the survival and growth characteristics within each nursery area and will be discussed Chapter 6.

5. HYDROGRAPHIC MODELLING AND LARVAL SETTLEMENT PREDICTIONS USING ADULT STOCK SURVEYS TO ESTIMATE EGG PRODUCTION

5.1 Introduction

Marine larvae may undergo extensive dispersal that can be controlled by their behaviour, environmental stimuli and local current regimes (Rothlisberg *et al.* 1996). Larval dispersal and subsequent supply to nurseries are influenced by a complex interplay of factors including physical oceanographic characteristics such as currents, tides, wind speed and direction, density structure and pressure systems. Temporal and spatial distribution and abundance of adult prawns determine initial larval numbers. The behaviour of the larvae during the time they are in the water column and the length of the planktonic phase is important to their survival.

The vertical diurnal movement of penaeid larvae during a day-night cycle is well documented (Racek 1959, Temple & Fisher 1965, Penn 1975, Rothlisberg 1982, Rothlisberg *et al.* 1983a, Staples & Vance 1985, Dall *et al.* 1990, Rogers *et al.* 1993, Vance 1992) and clearly this behaviour facilitates larval transport. It also has been shown that the diurnal vertical behaviour of penaeids may change when they approach inshore nursery areas to being active only during flooding tides (Rothlisberg *et al.* 1995, 1996) moving them further inshore into nursery sites.

Field based prawn larval studies are uncommon due to the time and resources required in sampling, sorting and identification of larval samples. Carrick (1996) found that the use of larval sampling as a tool for stock assessment, via estimating effective egg production, has merit but the time and cost required to obtain results are prohibitive. Tracking newly hatched larvae over time and space is generally not a practical or cost effective method in determining larval movement patterns.

Dakin (1938, 1946), Dakin & Colefax (1940), Racek (1959) and Kirkegaard (1972) undertook some early work on larval distribution in Australia. Taxonomic difficulties and the labour intensive nature of these studies have precluded many intensive larval prawn investigations. Research on prawn life-history dynamics including larval distribution and abundance studies has been conducted in the Gulf of Carpentaria, Queensland by Rothlisberg (1982), Rothlisberg *et al.* (1983a,b 1985,1987) and Jackson *et al.* (1989). Studies have been undertaken for other crustaceans in determining the role of environmental factors on recruitment into nurseries (Johnson *et al.* 1984, Johnson 1985, Nixon 1996, Bryars & Adams 1997). Carrick (1996) conducted sampling of larval *Penaeus latisulcatus* in Spencer Gulf, South Australia during 1992 and 1993 and compared spatial and seasonal distribution within the gulf. This work indicated seasonal and yearly differences in larval abundance with peaks in zoeal numbers in December and February and generally higher numbers of larvae in the northern parts of the gulf. Some localised differences in larval abundance were observed suggesting local egg production and advection processes were important in postlarval settlement to nurseries (Carrick 1996).

Adult prawn stock surveys were conducted during the spawning period to determine the distribution, abundance and size of female *P. latisulcatus* throughout GSV. This allowed the estimation of the relative number of eggs that may be released at each station sampled. Research surveys to determine the distribution and abundance of the spawning stock have been utilised extensively in Spencer Gulf and have been used as an alternative to, or to complement, catch and effort information in WA (Penn & Caputi 1985).

Gulf St Vincent is an inverse estuary with only limited exchange with the open ocean via IS and Backstairs Passage. This is due to the location of Kangaroo Island, blocking the mouth of the gulf. Water depth for the gulf and its two connections to the Southern Ocean rarely exceeds 40m. GSV extends approximately 170 km from Port Wakefield (34°S latitude) at the head to Cape Jervis (35°30'S latitude) in the south. Typical width in the southern part is 50 to 60 km, giving it a surface area of about 7.3 x 10^3 km^2 (Grzechnik & Noye 1996).

The wind field over GSV is determined by west to east moving synoptic pressure systems modulated by local effects such as summer sea breezes (Petrusevics 1990). The region is influenced largely by south to southeast winds in the summer and southwest to north winds in the winter.

Tidal charts have been calculated using observed data for GSV (Bowers & Lennon 1989). Lennon (1982) suggests a resonance at 13.4 hours using observed data. The main tidal features are the very rapid progression of the tides in the gulf, taking less than 30 minutes to progress the gulf from west to east, and the increase in amplitude of tides in shallow waters towards the head of the gulf (Grzechnik & Noye 1996). The major solar tide has virtually the same amplitude throughout GSV as the major lunar tide. Since the solar tide has a period of exactly 12 hours and the lunar tide has a period of 12 hours 25 minutes, then every 14.77 days the two tides are in opposition. At this time 'neap' tides are produced, and in this case the semi-diurnal component of the tide is virtually absent. Because of this, the waters of the gulf are relatively stationary for a day or two each fortnight, and in some seasons may become stratified during this time if weather is calm (Lennon 1982). At equinoxes, the diurnal component of tide vanishes also causing the water level to become almost constant for several days. This skipping of the high or low tide is called a dodge tide.

Tidal models for GSV at coarse and finer resolution was developed by Grzechnik & Noye (1996) and for the current study, wind induced currents are incorporated into this model (Grzechnik & Noye 1999). Larvae are considered to be particles in the water column and their movement through the use of a particle tracking procedure is used (Grzechnik & Noye 1998a,b, 1999). This simulates both advection (by a Lagrangian procedure) and diffusion (by a stochastic process) of the larvae from key spawning sites.

This chapter focuses on the modelling of oceanographic characteristics using tidal and wind information and simulating the biology (initial diurnal vertical movement and inshore tidal behaviour) of larval prawns to generate larval trajectories and subsequent postlarval settlement. Field information on adult prawn distribution and abundance is used to estimate initial larval numbers and model prediction of settlement is compared with actual field observations. Several biological questions are posed for 1989/90 and 1990/91 that provide an opportunity to evaluate the usefulness of modelling for describing factors influencing postlarval settlement and abundance in nurseries.

These questions were;

1. Are there different larval movement paths in 1989/90 and 1990/91 that explain observed differences in settlement between the eastern and western sides of the gulf in these years?
2. Does larval advection account for differences in the general settlement patterns between northern and southern nursery sites?
3. What are the most important spawning areas for successful settlement into key nurseries?

5.2 Methods

5.2.1 Field sampling of adult prawn abundance and distribution and estimation of potential egg production

Adult prawn distribution and abundance was determined from fishery independent surveys of the trawl grounds using commercial prawn vessels. The trawl ground were separated into regions (blocks) and within each block were a series of stations (Figure 5.1) which represented inshore, midshore and offshore transects. Sampling took place on or close to the quarter moon phase during October-November, at the start of the spawning period and during February-March towards the end of the spawning period.

Sampling at each station consisted of a 40 minute trawl covering two nautical miles (or distance noted if less than two nautical miles). For each station, a representative sample of 200 to 500 prawns was collected, the prawns were separated into sexes, weighed and their CL measured to the nearest millimetre with vernier calipers. Estimated total catch (kg.), sample weight (kg.) and measurements of males and females for the sample were entered on to a DATAFLEX database and data manipulated in FOCUS. The numbers of prawns for each size in the sample were weighted to estimate total catch. Validation procedures using the length-weight relationship for *P. latisulcatus* (Carrick, unpublished) checked on data accuracy. Potential egg production was calculated from the length-fecundity relationship for

P. latisulcatus in GSV (Kangas & Stewart-Rowe, unpublished) using the total number per nautical mile trawled of females for each mm size category at each station sampled. The female prawns contributing to spawning were all ≥ 30 mm CL. Estimates were also made for larger prawns (≥ 42 mm CL) only. The overall distribution pattern of relative egg production was similar for both estimations and therefore the former was used in the modelling..

Estimates of the time of spawning time were made using field observations of postlarval settlement for the two years. The beginning of spawning was calculated to be four to six weeks before the first time postlarvae were observed in nurseries. Next, a period of highest settlement for the season was selected and the spawning date back-calculated four to six weeks from this day. In 1990/91, the settlement period was longer and two dates were estimated for the 'peak' settlement period. Thirdly, the end of the spawning period was estimated by backdating from the last observation of postlarval settlement in nurseries. For each run of the model, all prawns were simulated to spawn over one week. The starting point of each spawning period was set as, 23 November 1989, 20 December 1989 and 14 January 1990 for the 1989/90 modelling and, 26 October 1990, 27 November 1990, 22 January 1991 and 19 February 1991 for 1990/91 modelling. For the October and November simulations in both years, egg production from the October-November surveys were used. For the December, January and February simulations, both October-November and February-March surveys were combined to determine potential egg production.

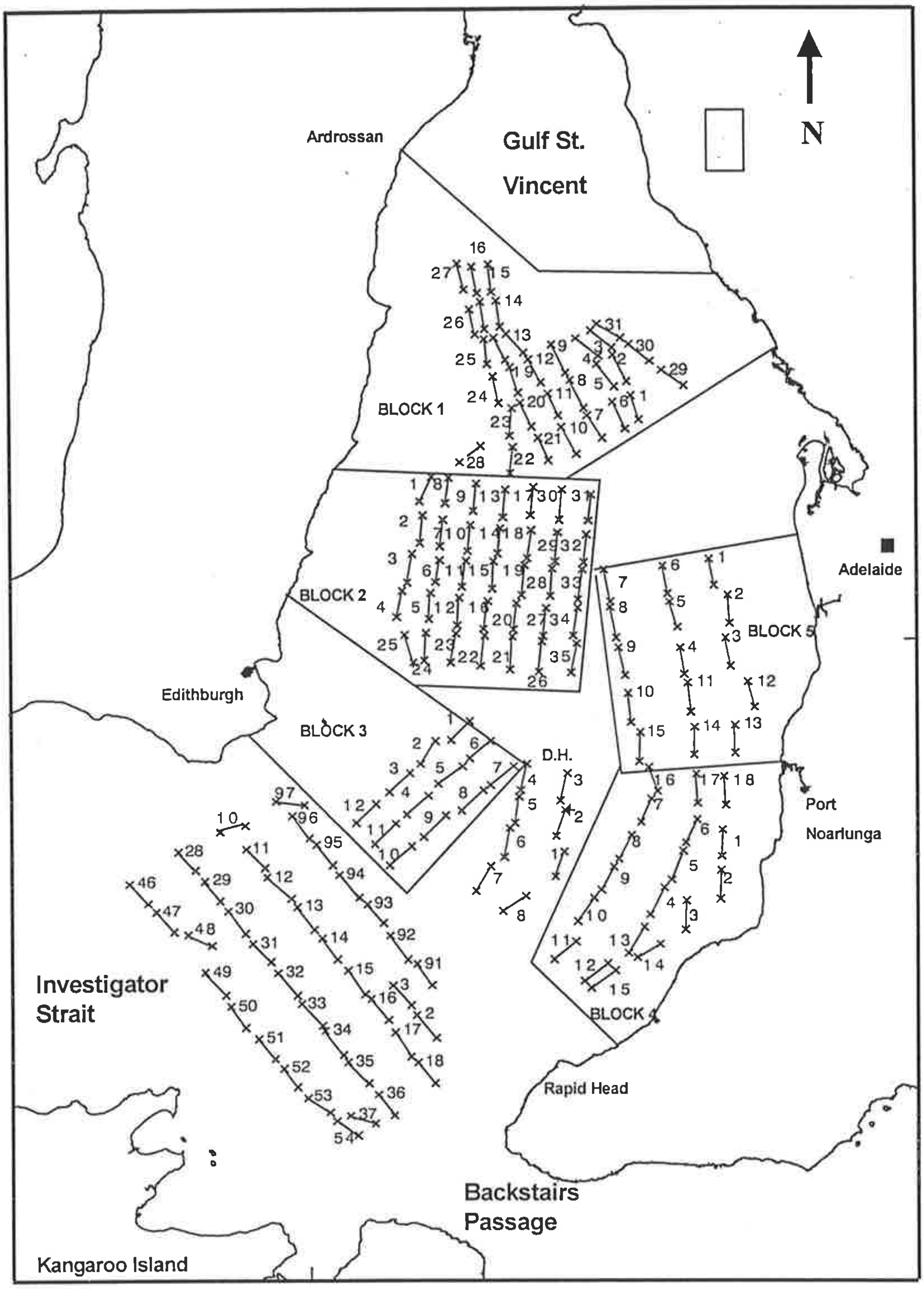


Figure 5.1 Map of Gulf St Vincent showing location of trawl stations (2 nautical miles) situated inshore, midshore and offshore within larger regions (Blocks). Stations were sampled during October-November and February-March to determine the distribution, abundance and size composition of female prawns.

5.2.2 Tidal and wind Model and prediction of larval movement and postlarval settlement

The tidal and wind induced model is detailed in Grzechnik & Noye (1999) and the particle tracking procedure is described in Grzechnik & Noye (1998 a, b). Three locations were used to generate wind patterns. For both 1989/90 and 1990/91 modelling utilised three hourly wind data from Adelaide airport and Cape Borda (western Kangaroo Island), while data from Cape Willoughby (eastern Kangaroo Island) was at six hourly intervals.

Particle tracking was conducted for a total of eight weeks after the spawning date. For the first 20 days, larval behaviour was simulated as diurnal vertical behaviour where larvae were up in the water column at night and moved down during daylight. After 20 days of larval life, a new behaviour was simulated. If the prawn larvae were in water less than 15m depth they changed from a diurnal vertical migration pattern to being active only for the first three hours after the turn of the tide (i.e. the first three hours of the flood tide). This inshore behaviour was one of four scenarios suggested by Rothlisberg *et al.* (1996) for *P. merguiensis* and *P. semisulcatus* based on extensive larval studies of *P. plebejus* (Rothlisberg *et al.* 1995). Since no larval behavioural studies have been conducted on *P. latisulcatus* this behaviour pattern was considered to be feasible. Mortality of prawn larvae, that is depletion of particles with time, was not included in the modelling exercise.

Larval movement is presented as a series of location/density charts at four, six and eight weeks after spawning and as graphs of number of particles found at each nursery sites between 10 and 50 days after spawning. The predicted mean density of particles arriving in nursery sites over a seven day period around an actual field sampling date was used to compare the predicted mean density in nursery sites and actual abundance from field sampling. The mean density was estimated from numerical output of the modelling of particle density at half hourly intervals. Comparisons were made for Port Arthur and Port Wakefield.

5.2.3 Field observations of postlarval settlement and abundance

Postlarvae were collected in nursery sites and sorted, preserved and measured as described in 4.2. Postlarvae were regarded as prawns < 3mm CL.

5.3 Results

5.3.1 Potential egg production during October/November and February/March

Broad areas of spawning aggregations (higher egg production) are apparent (Table 5.1, Figures 5.2 a and 5.4 a). Stations in the northern parts (Block 1 and northern end of Block 2) of GSV consistently have higher numbers of eggs produced compared to southern regions (Blocks 3, 4 and IS). However, the number of eggs produced at any one station within these broad areas can vary between sampling periods. This may be due to changes in the abundance and size structure within a station, movement of prawns between stations, impacts of fishing (removal of prawns) and changes in catchability.

Table 5.1 Number of eggs (billions) produced by female *Penaeus latisulcatus* per nautical mile trawled for all stations sampled in November 1989 and 1990 and February/March 1990 and 1991. The shaded cells indicate stations with highest potential egg abundance during each of the sampling periods.

Blk	Stn	20/11/89	19/2/90	11/11/90	8/3/91	Blk	Stn	20/11/89	19/2/90	11/11/90	8/3/91
1	29	0.048583	0.000825	0.019879	0.001331	2	1	0.026416	0.129837	0.066834	0.054490
1	30	0.643707	0.157128	0.321563	0.039957	2	2	0.013826	0.036614	0.015039	0.031904
1	31	0.251220	0.054442	0.179384	0.066985	2	3	0.007925	0.086646	0.009007	0.045526
1	1	0.000096	0.050328	0.073015	0.116718	2	4	0.004771	0.050537	0.011438	0.069410
1	2	0.045373	0.192417	0.258317	0.106885	2	25	0.010234	0.041307	0.008642	0.052974
1	3	0.133620	0.062819	0.155552	0.051406	2	8	0.052831	0.091825	0.059446	0.073611
1	4	0.200346	0.169405	0.052798	0.146717	2	7	0.027652	0.115253	0.015896	0.094432
1	5	0.113527	0.128007	0.180552	0.074391	2	6	0.016850	0.052975	0.019146	0.077500
1	6	0.001984	0.045168	0.052128	0.113339	2	5	0.015696	0.059675	0.027019	0.036538
1	7	0.004714	0.043194	0.006911	0.075375	2	24	0.007522	0.012999	0.002059	0.075596
1	8	0.074845	0.065100	0.014875	0.216799	2	9	0.074485	0.176428	0.022104	0.033495
1	9	0.062539	0.063308	0.029776	0.125253	2	10	0.046458	0.189071	0.035646	0.063991
1	10	0.014317	0.026225	0.014907	0.064185	2	11	0.040483	0.144189	0.028958	0.079407
1	11	0.249176	0.021788	0.011918	0.113260	2	12	0.041305	0.162186	0.025315	0.162210
1	12	0.274428	0.115985	0.084599	0.109015	2	23	0.025122	0.053647	0.010760	0.040444
1	21	0.188247	0.010474	0.083667	0.006815	2	13	0.064059	0.107594	0.024635	0.098222
1	20	0.314615	0.024013	0.008854	0.016310	2	14	0.038938	0.136362	0.042341	0.093824
1	19	0.137573	0.109988	0.092309	0.080060	2	15	0.040612	0.131328	0.030668	0.157569
1	22	0.149440	0.076986	0.022135	0.014258	2	16	0.076842	0.116100	0.032138	0.159126
1	23	0.175512	0.018950	0.014384	0.009145	2	22	0.049342	0.044402	0.045020	0.107390
1	24	0.163003	0.082857	0.113494	0.056989	2	17	0.113550	0.074023	0.103179	0.027314
1	13	0.016180	0.150555	0.011066	0.023548	2	18	0.079627	0.117988	0.039128	0.036611
1	14	0.029276	0.189375	0.022017	0.273739	2	19	0.071346	0.096022	0.064240	0.040044
1	15	0.076114	0.226522	0.035503	0.087279	2	20	0.021407	0.080275	0.042329	0.081760
1	16	0.080579	0.135239	0.030546	0.012975	2	21	0.066970	0.069718	0.037679	0.077758
1	17	0.034396	0.205519	0.046564	0.052313	2	30	0.186932	0.037843	0.241860	0.023922
1	18	0.137573	0.156039	0.156438	0.069691	2	29	0.122830	0.067263	0.192588	0.033375
1	25	0.163003	0.215947	0.091234	0.049256	2	28	0.056459	0.108945	0.082933	0.055621
1	26	0.133768	0.123166	0.053338	0.029043	2	27	0.045130	0.071593	0.039618	0.053986
1	27	0.062153	0.127480	0.033415	0.030859	2	26	0.059871	0.063416	0.036660	0.089104
1	28	0.023153	0.133577	0.123628	0.092577	2	31	0.236749	0.030330	0.033896	0.055153
						2	32	0.286565	0.032020	0.056168	0.011324
						2	33	0.181174	0.109705	0.040598	0.070690
						2	34	0.069401	0.055815	0.004782	0.033940
						2	35	0.052375	0.085980	0.017699	0.084387

Table 5.1 Number of eggs (billions) produced by female *Penaeus latisulcatus* per nautical mile trawled for all stations sampled in November 1989 and 1990 and February/March 1990 and 1991. The shaded cells indicate stations with highest potential egg abundance during each of the sampling periods.

Blk	Stn	20/11/89	19/2/90	11/11/90	8/3/91	Blk	Stn	20/11/89	19/2/90	11/11/90	8/3/91
5	1	0.009854	0.003244	0.049421	0.006737	IS	52	0.017904	0.043889	0.074151	
5	2	0.003327	0.010111	0.016384	0.000080	IS	53	0.016923	0.018364	0.022299	
5	3	0.000464	0.008110	0.012196	0.005606	IS	54	0.014225	0.021212	0.050666	
5	4	0.002949	0.002244	0.005120	0.011211	IS	37	0.014158	0.023045	0.050890	
5	5	0.066956	0.020221	0.069430	0.130150	IS	91	0.033208	0.046100	0.011531	
5	6	0.004683	0.016220	0.024391	0.033687	IS	36	0.027184	0.019977	0.053378	
5	7	0.095635	0.058162	0.132768	0.026778	IS	35	0.044203	0.031080	0.093070	
5	8	0.154515	0.095742	0.140501	0.077200	IS	34	0.063938	0.037099	0.055704	
5	9	0.034918	0.097036	0.082910	0.056907	IS	18	0.029933	0.005215	0.009197	
5	10	0.033841	0.068326	0.023462	0.012753	IS	17	0.044620	0.028544	0.026211	
5	11	0.025714	0.033942	0.015695	0.014606	IS	16	0.042759	0.099346	0.034418	
5	12	0.045293	0.016784	0.103233	0.034651	IS	2	0.033510	0.063945	0.024814	
5	13	0.000238	0.023608	0.075939	0.023347	IS	3	0.022107	0.031973	0.015264	
5	14	0.038886	0.082879	0.020741	0.074921	IS	51	0.050418	0.039441	0.053869	
5	15	0.022158	0.062474	0.017906	0.010097	IS	50	0.031974	0.044361	0.023195	
3	1	0.052116	0.001441	0.019240	0.098113	IS	49	0.014695	0.013464	0.012364	
3	2	0.021015	0.000540	0.034523	0.045388	IS	92	0.014464	0.015944	0.047155	
3	3	0.015203	0.000001	0.037857	0.025789	IS	93	0.020160	0.012689	0.011418	
3	4	0.068466	0.094665	0.060715	0.052600	IS	94	0.038747	0.011126	0.014385	
3	5	0.032018	0.002565	0.038666	0.075321	IS	33	0.023335	0.014964	0.051469	
3	6	0.026314	0.000000	0.020001	0.156739	IS	32	0.006490	0.010426	0.029544	
3	7	0.014778	0.115094	0.101780	0.160612	IS	31	0.014504	0.017742	0.025398	
3	8	0.025271	0.098810	0.103653	0.099018	IS	15	0.020450	0.044373	0.026828	
3	9	0.091301	0.092113	0.086341	0.010011	IS	14	0.011234	0.015038	0.015197	
3	10	0.091403	0.039103	0.026899	0.027768	IS	13	0.012414	0.010497	0.012705	
3	11	0.127758	0.137784	0.038186	0.026300	IS	48	0.013647	0.011461	0.022021	
3	12	0.031219	0.177680	0.027701	0.012356	IS	47	0.020626	0.029630	0.027000	
4	1	0.019317	0.053565	0.013851		IS	46	0.010515	0.017889	0.017184	
4	2	0.009554	0.012120	0.001567		IS	95	0.019595	0.023987	0.010925	
4	3	0.010567	0.009966	0.015679		IS	96	0.015151	0.012789	0.006239	
4	4	0.008508	0.008096	0.003499		IS	97	0.014141	0.015277	0.000088	
4	5	0.008407	0.035329	0.007897		IS	30	0.022934	0.008802	0.031456	
4	6	0.024573	0.066545	0.017840		IS	29	0.013612	0.012656	0.022057	
4	7	0.011938	0.012431	0.015051		IS	28	0.013501	0.010120	0.010269	
4	8	0.001245	0.045450	0.006597		IS	12	0.009331	0.011603	0.010006	
4	9	0.002356	0.031434	0.005169		IS	11	0.007484	0.012882	0.020625	
4	16	0.022765	0.001673	0.011112	0.028634	IS	10	0.005373	0.033850	0.014395	
4	17	0.024235	0.066951	0.036998	0.030115						
4	18	0.043516	0.034312	0.040950	0.011209						
7	1			0.063865	0.079755						
7	2			0.114908	0.118376						
7	3			0.067345	0.056906						
7	4			0.047971	0.113597						
7	5			0.045603	0.047945						
7	6			0.035929	0.036799						
7	7			0.045099	0.010988						
7	8			0.058008	0.069068						

5.3.2 Overall larval trajectories

Five larval movement simulations are described, two for 1990 and three for 1991. The spawning dates depicted for 1990 settlement are; 20 December 1989 (Figure 5.2 a and b) which represented the middle of the spawning period for the season and the 14 January 1990 (Figure 5.3 a and b) which represented the estimated spawning time which produced peak settlement in 1990. The 22 November 1989 simulation trajectories were very similar to those of December 1989 and are therefore not described.

The December 1989 simulation predicts larval movement to generally be in a northerly direction. Time-series plots of particle settlement from the tenth day after spawning shows daily variability in particle (larval) ingress into the nursery areas (Figure 5.2 b). This was predicted in all simulations. The first nursery site predicted to receive settlement of particles (of those sites regularly monitored) was Port Wakefield, 24 days after spawning (Figure 5.2 b). Settlement levels then rise around 30 days after spawning for Port Wakefield and first settlement is predicted at Port Arthur. At Port Wakefield, settlement occurs in pulses. The pulsing may be as a result of wind and tide effects on settlement. At Port Arthur postlarval settlement builds up over time which may be as a result on onshore movement of larvae in a northerly direction. However, it appears that when a peak in settlement occurs in Port Wakefield, a corresponding trough is observed in Port Arthur. This may indicate that the majority of available larvae are transported to one side of the gulf at any one time rather than simultaneously to both sides. Overall, Port Wakefield received the most particles (larvae) for the duration of the simulation. Lower levels of settlement were predicted to occur at Port Clinton and even lower at Ardrossan in comparison to the northern sites between 26 and 50 days after spawning. A small peak in settlement is predicted for Port Clinton at around 40 days after spawning.

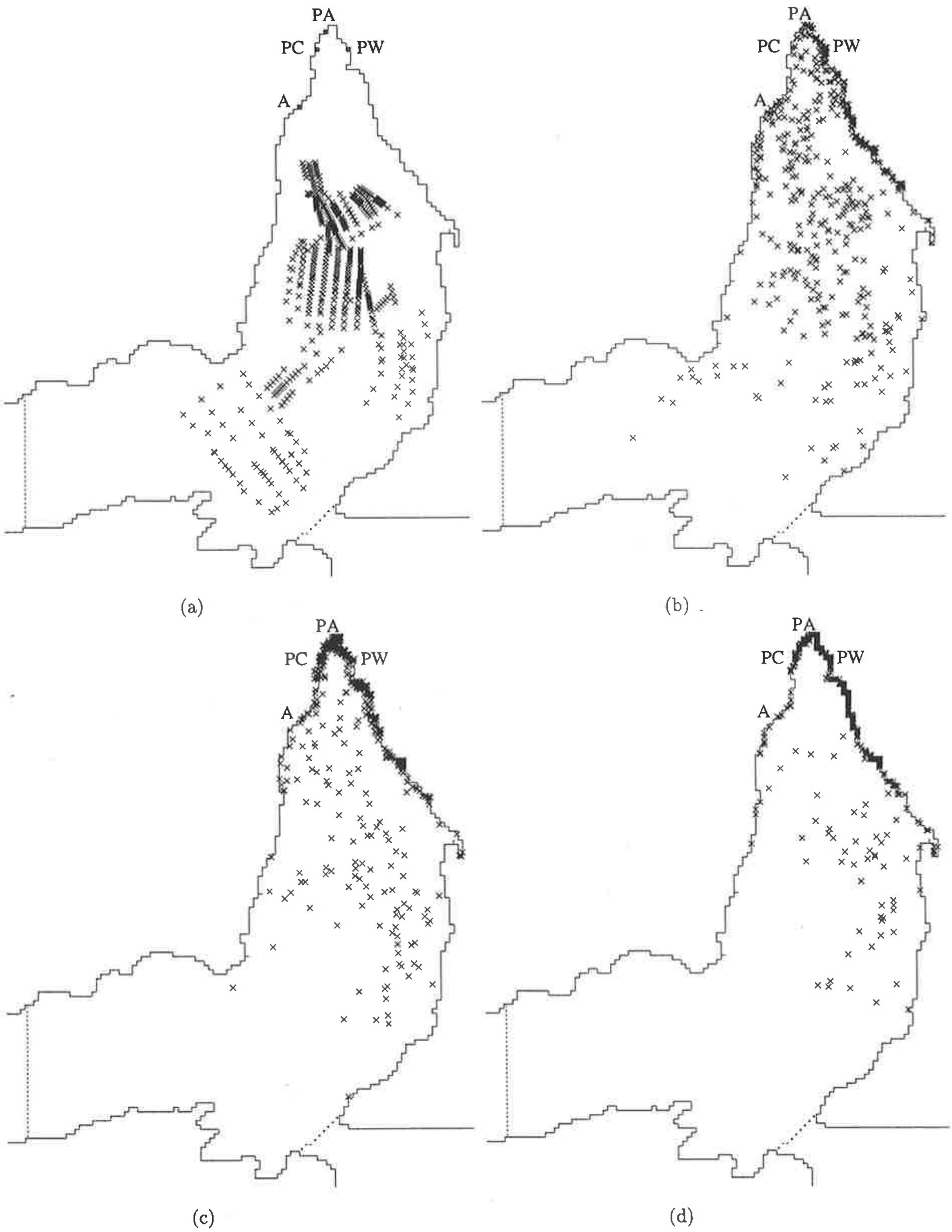
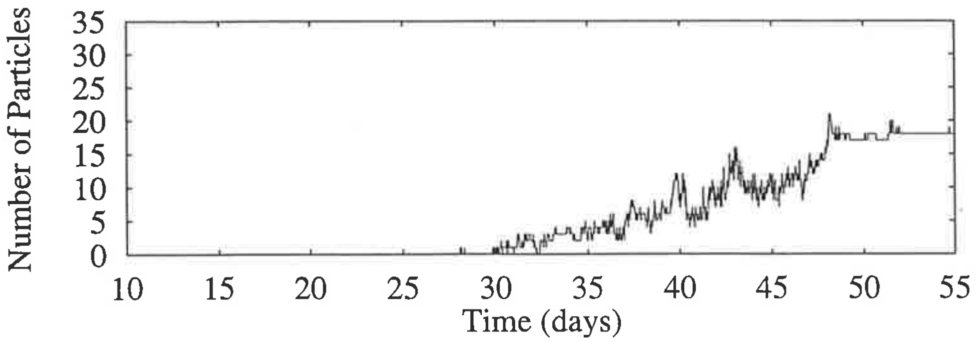
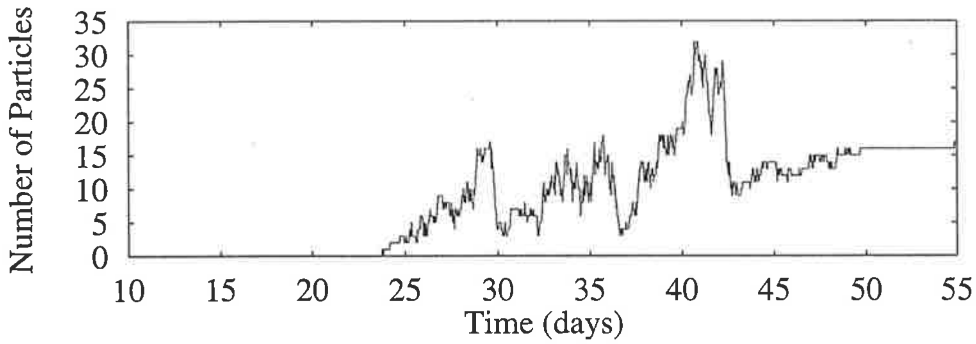


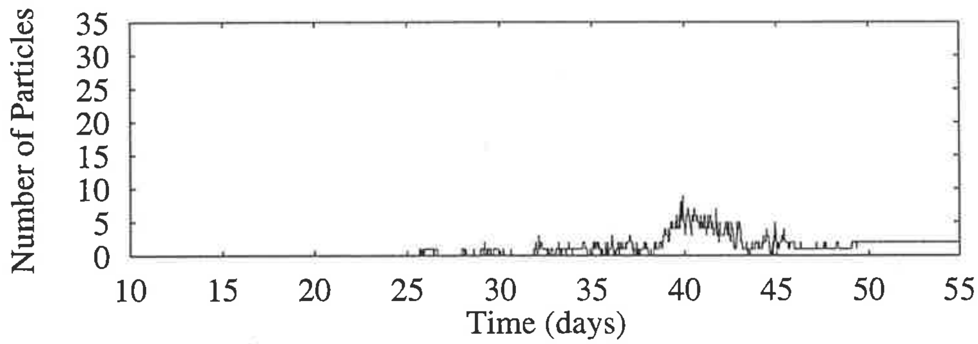
Figure 5.2 a) Initial egg production of *Penaeus latisulcatus* in Gulf St Vincent during November 1989 (a) and advection and diffusion of larvae at four (b), six (c) and eight weeks (d) after spawning on 20 December 1989 (over a week period). PW - Port Wakefield, PA - Port Arthur, PC - Port Clinton and A - Ardrossan. x = 30 million eggs.



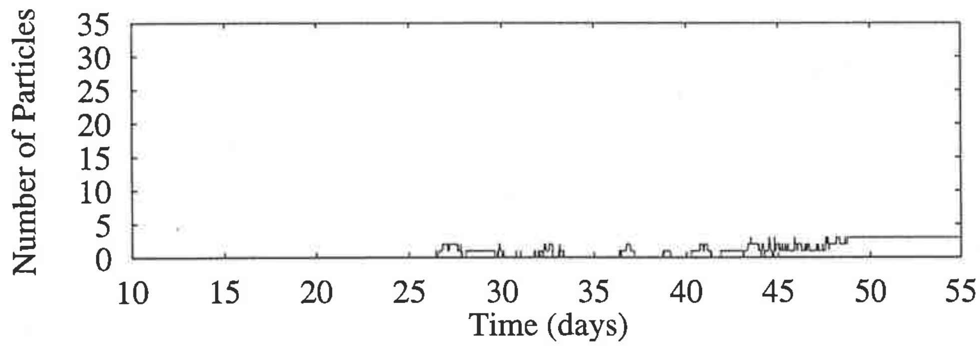
(a) Port Arthur



(b) Port Wakefield



(c) Port Clinton



(d) Ardrossan

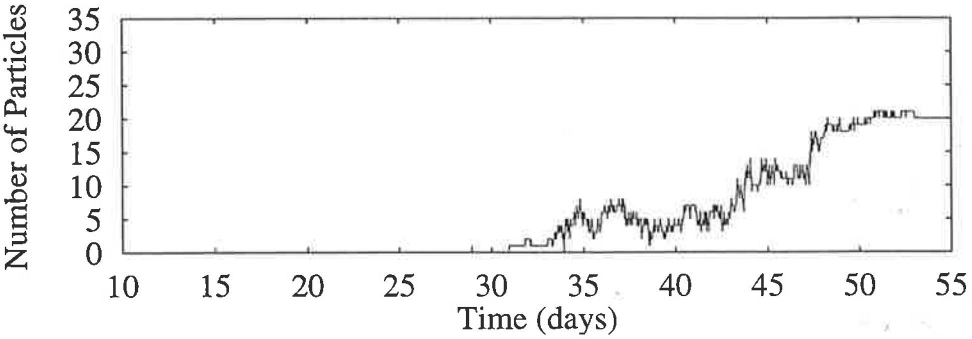
Figure 5.2 b) Time-series of particle density settlement at nursery sites between 10 and 55 days after spawning on 20 December 1989.

The January 1990 simulation (Figure 5.3 a and b) predicts that first settlement occurs at Ardrossan and Port Wakefield, 26 days after spawning. This was at a very low level. At around 30 days after spawning, a pulse of settlement is predicted to occur at Port Wakefield followed by another pulse, 40 days after spawning after which settlement increases until 50 days after spawning. Port Arthur is predicted to receive particles from 31 days after spawning at lower levels compared to Port Wakefield but with a build up from 44 days after spawning to levels similar to Port Wakefield. Low levels of settlement were predicted for both Port Clinton and Ardrossan between 30 and 50 days after spawning. Port Wakefield received the most particles during the simulation period.

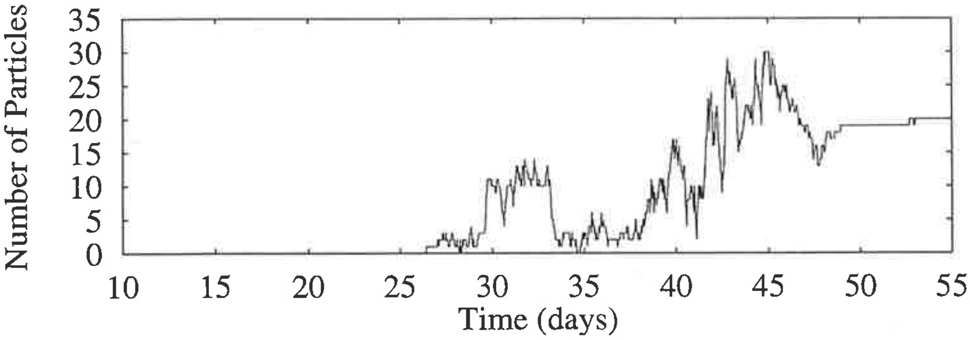
The spawning dates depicted for 1991 settlement were; 27 November 1990 to represent an early spawning period that produced early postlarval settlement in 1991, 22 January 1991 to represent the spawning period estimated to produce peak settlement in 1991 and 19 February 1991 to represent a period at the end of spawning.

The November 1990 simulation predicts that generally, particles (larvae) moved in a northeasterly direction (Figure 5.4a). The eastern shoreline received more particles. For those sites regularly monitored, Port Wakefield was the first site predicted to receive particles (larvae), 24 days after spawning. Broad pulses of settlement were then predicted to occur at Port Wakefield at weekly intervals. Port Wakefield received the highest number of particles over this simulation period (Figure 5.4 b). After 31 days from spawning, low levels of settlement were predicted at Port Arthur with a slight pulse (peak) at this site at 40 to 45 days after spawning. Very low settlement was predicted for Port Clinton between 28 and 50 days after spawning. The modelling predicted only a very small level of settlement at Ardrossan during 38 to 45 days from spawning.

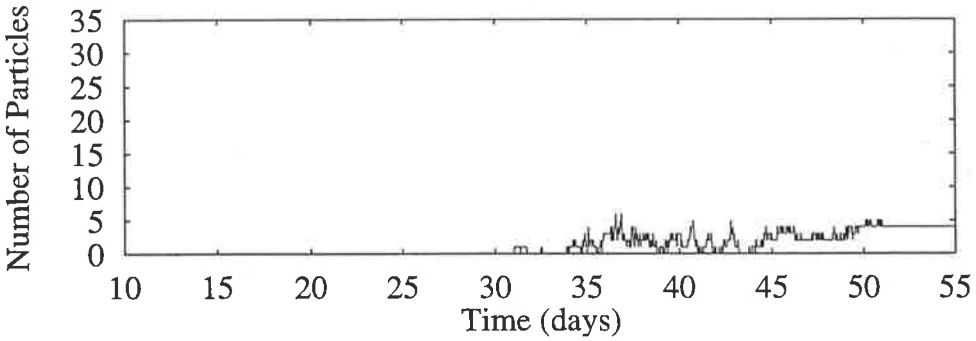
Figure 5.3 a) Initial egg production of *Penaeus latisulcatus* in Gulf St Vincent during November 1989 (a) and advection and diffusion of larvae at four (b), six (c) and eight weeks (d) after spawning on 14 January 1990 (one week period). PW - Port Wakefield, PA – Port Arthur, PC - Port Clinton and A – Ardrossan. x – 30 million eggs.



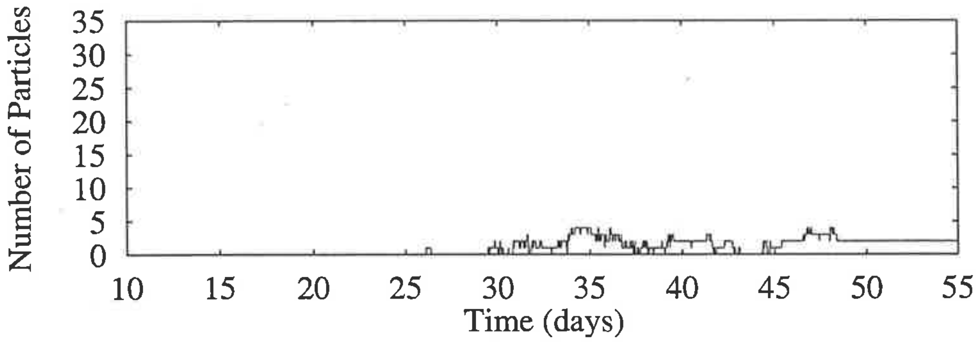
(a) Port Arthur



(b) Port Wakefield



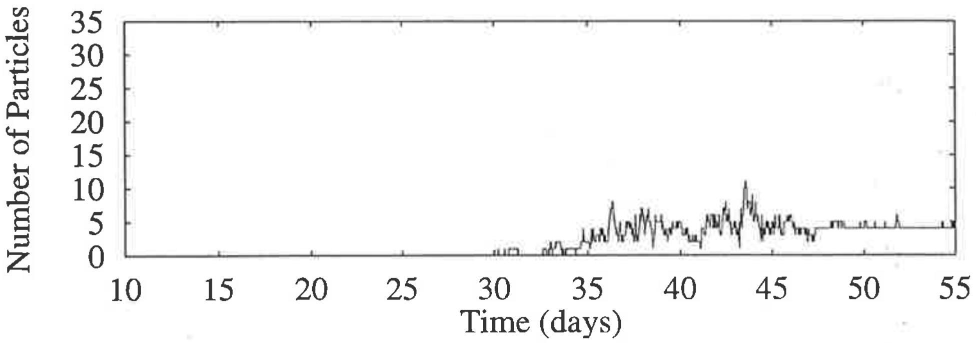
(c) Port Clinton



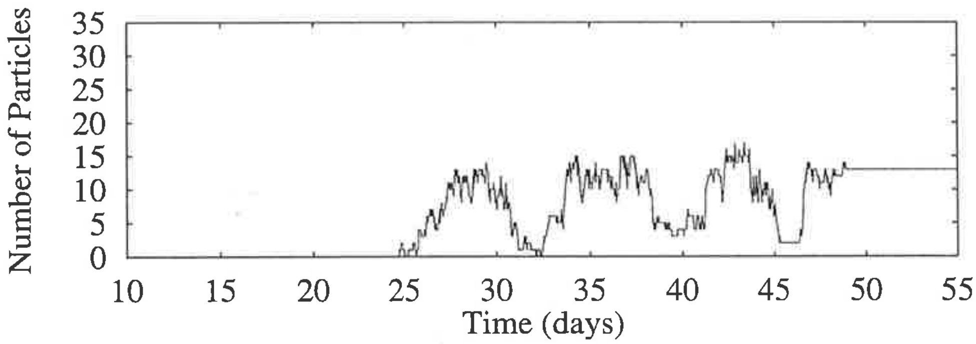
(d) Ardrossan

Figure 5.3 b) Time-series of particle density settlement at nursery sites between 10 and 55 days after spawning on 14 January 1990.

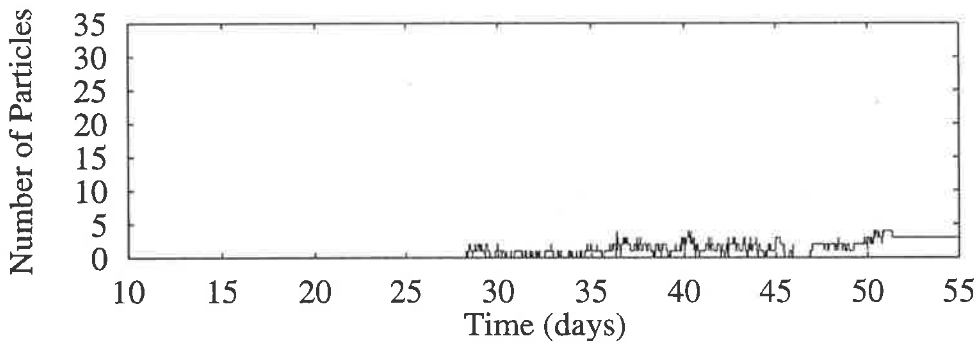
Figure 5.4 a) Initial egg production of *Penaeus latisulcatus* in Gulf St Vincent during November 1990 (a) and advection and diffusion of larvae at four (b), six (c) and eight weeks (d) after spawning on 27 November 1990 (one week period). PW - Port Wakefield, PA - Port Arthur, PC - Port Clinton and A – Ardrossan. x – 30 million eggs



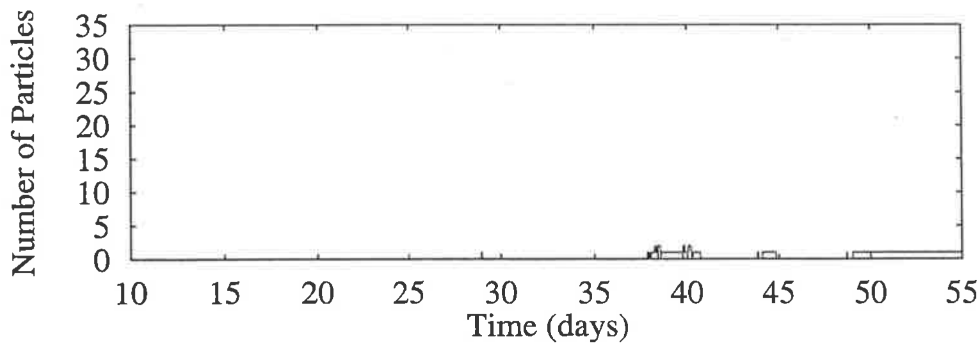
(a) Port Arthur



(b) Port Wakefield



(c) Port Clinton



(d) Ardrossan

Figure 5.4 b) Time-series of particle density settlement at nursery sites between 10 and 55 days after spawning on 27 November 1990.

The January 1991 simulation predicts that those particles released in the central to northern portions of the gulf are transported in a north, north-easterly direction but those particles released in IS are moved west (Figure 5.5a) away from the gulf. In all simulations a small portion of particles that are released in the eastern part of IS end up in Backstairs Passage and out of the gulf. Of the regularly monitored sites, Port Wakefield is the site predicted to first receive particles (Figure 5.5b) at 27 days after spawning. For the duration of the simulation at Port Wakefield, particle settlement occurs in broad pulses at around weekly intervals. Particle settlement is predicted to commence at Port Arthur at 32 days after spawning and to continue at levels similar to Port Wakefield for the rest of the simulation period. Very low levels of settlement is predicted for Port Clinton (from 28 days after spawning) and Ardrossan (from 29 days after spawning) for the rest of the simulation period.

As with the January 1991 simulation, the February 1991 modelling (Figure 5.6 a and b) predicts that particles released in central and northern Gulf St Vincent generally move in a north, northeasterly direction, moving inshore from Barker Inlet to just south of Port Wakefield on the eastern side of Gulf St Vincent. Particles released in southern GSV and in Investigator Strait generally move west. Relatively more particles are moved out through Backstairs Passage compared to any other simulation. The overall numbers settling into nursery areas are generally lower than for any of the other three simulations during 1991. Port Wakefield is the first site predicted to receive settlement, 30 day after spawning. Small regular pulses are predicted up until 50 days from spawning. Settlement is first predicted to occur in Port Arthur at approximately 34 days after spawning with continuous low settlement until 53 days after spawning. Both Ardrossan and Port Clinton received relatively fewer particles between 40 to 50 days after spawning.

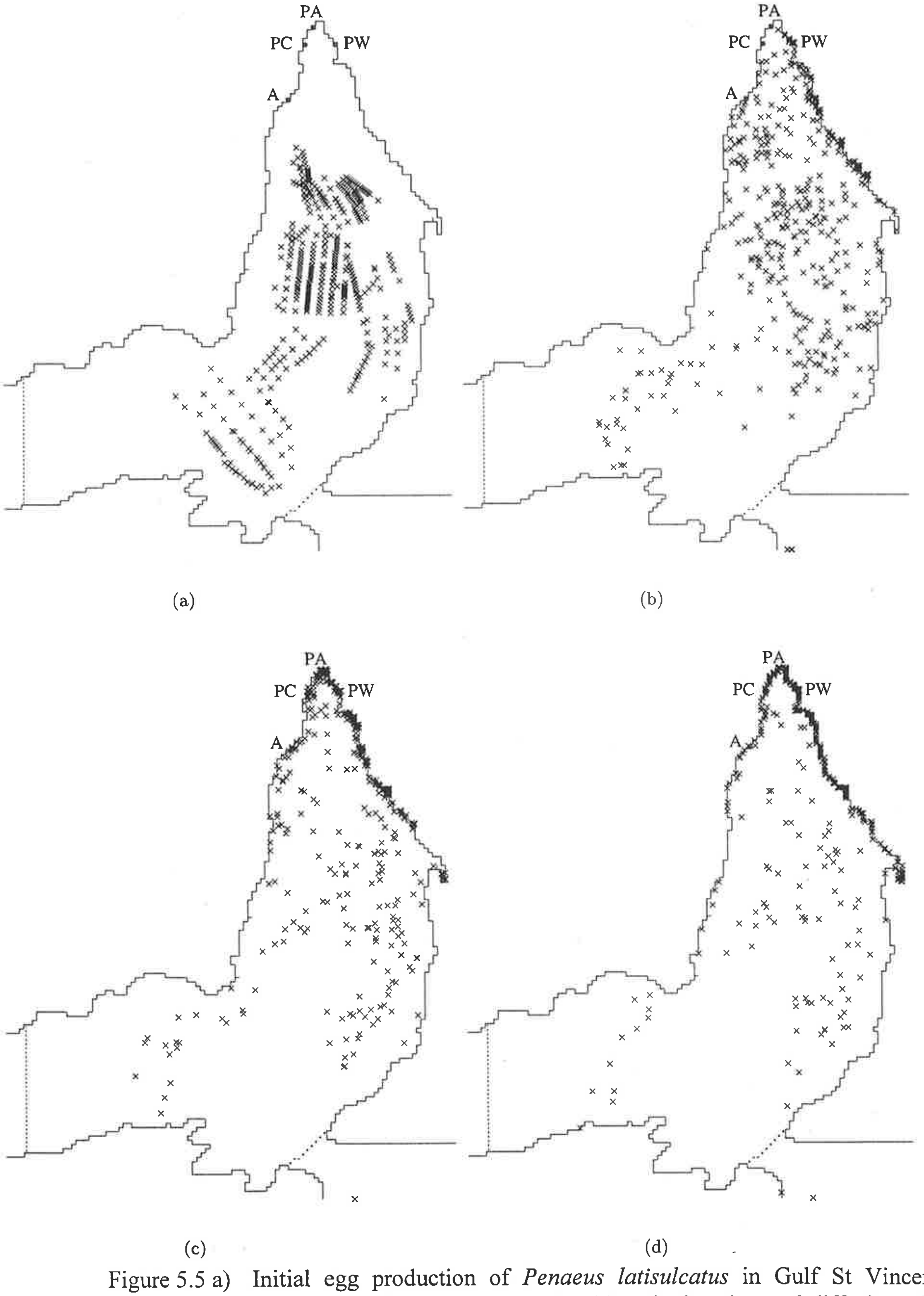
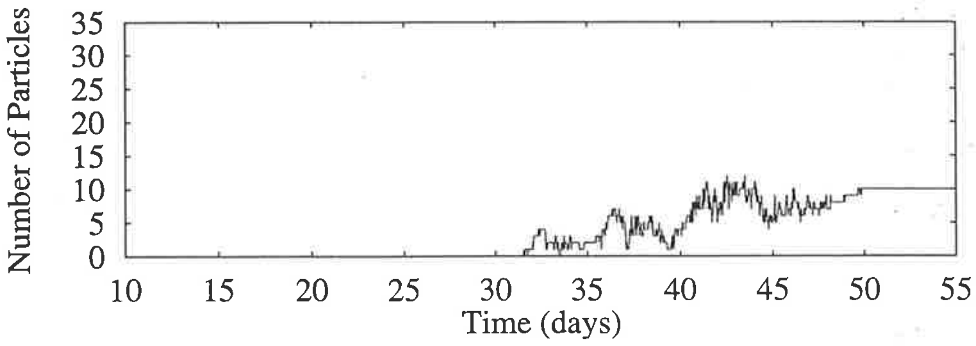
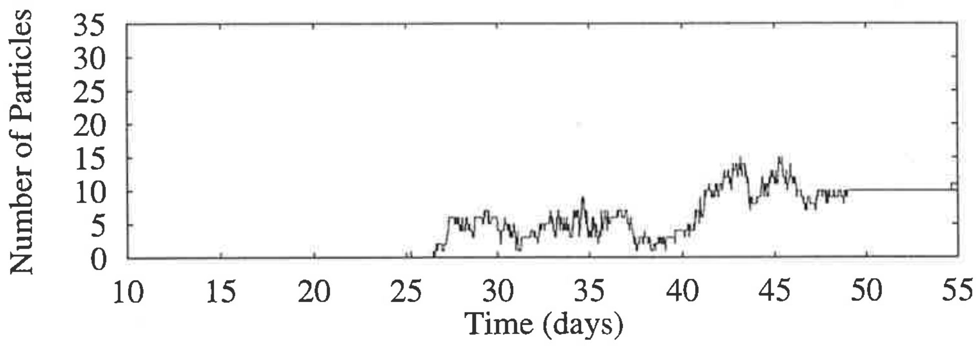


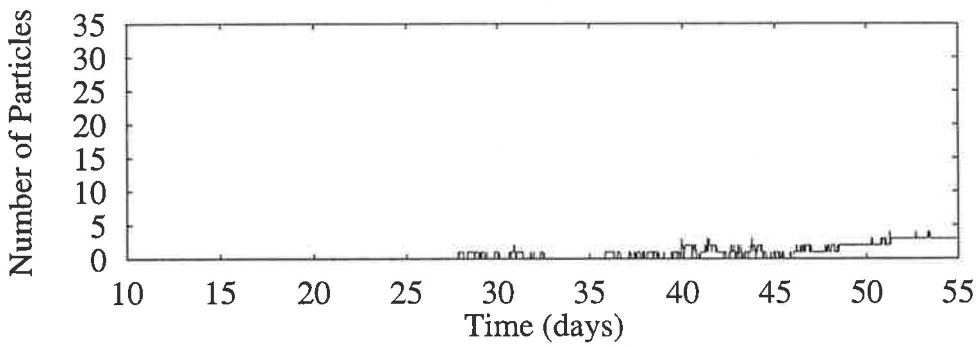
Figure 5.5 a) Initial egg production of *Penaeus latisulcatus* in Gulf St Vincent during November 1990 and March 1991 (a) and advection and diffusion of larvae at four (b), six (c) and eight weeks (d) after spawning on 22 January 1991 (one week period). PW - Port Wakefield, PA - Port Arthur, PC - Port Clinton and A – Ardrossan. x –30 million eggs.



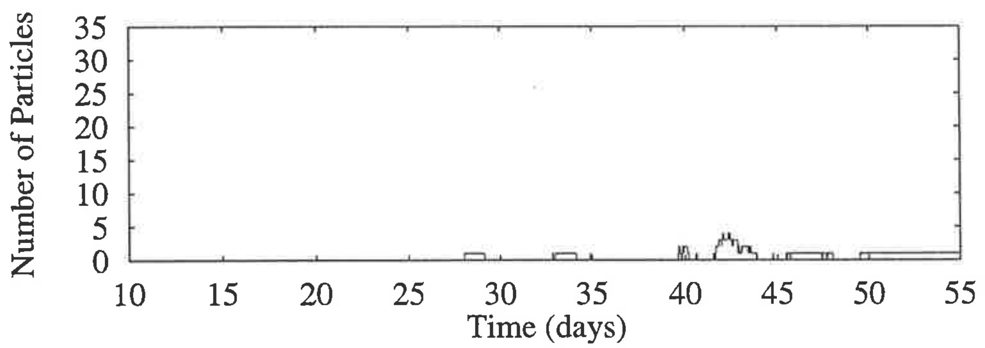
(a) Port Arthur



(b) Port Wakefield



(c) Port Clinton



(d) Ardrossan

Figure 5.5 b) Time-series of particle density settlement at nursery sites between 10 and 55 days after spawning on 22 January 1991.

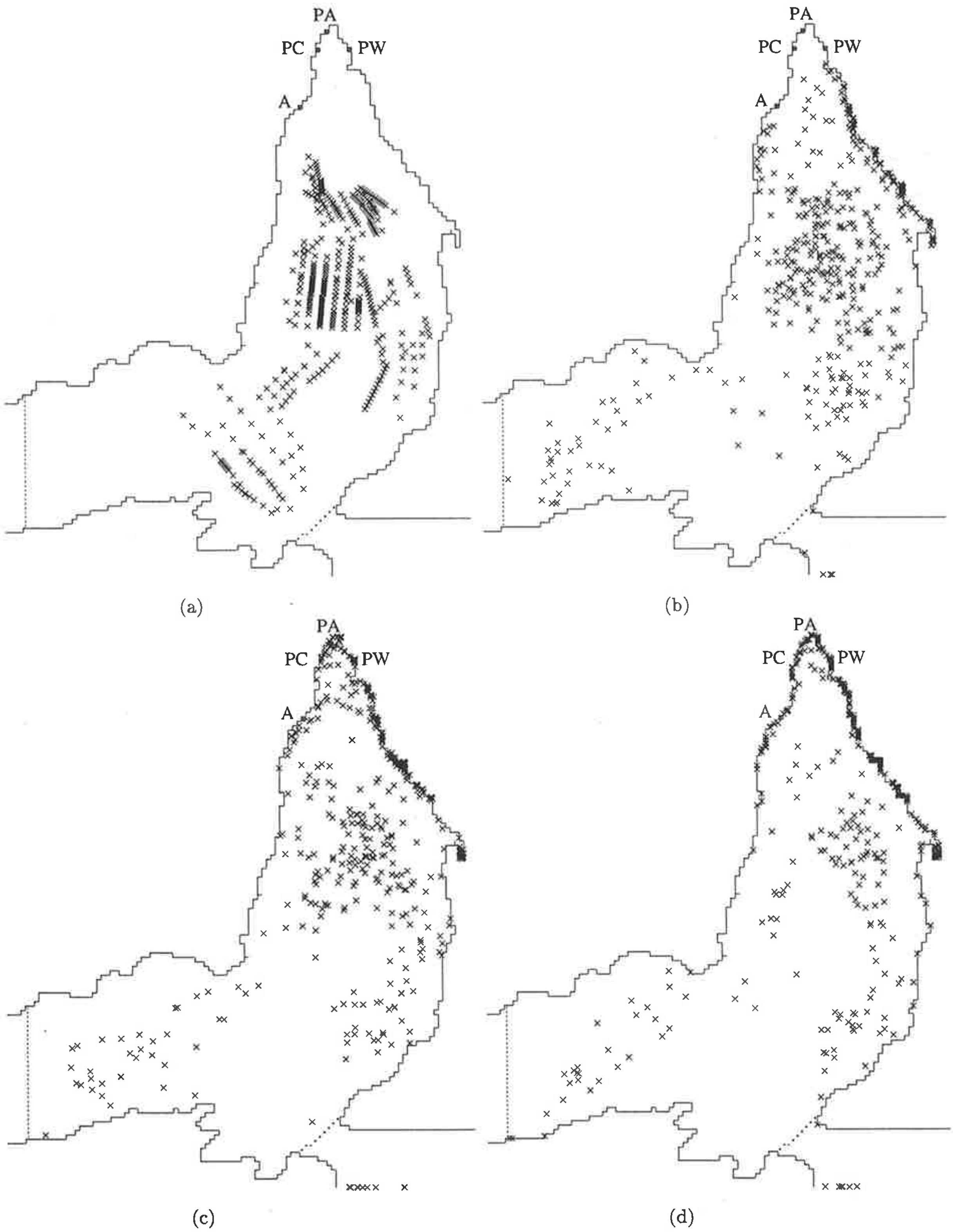
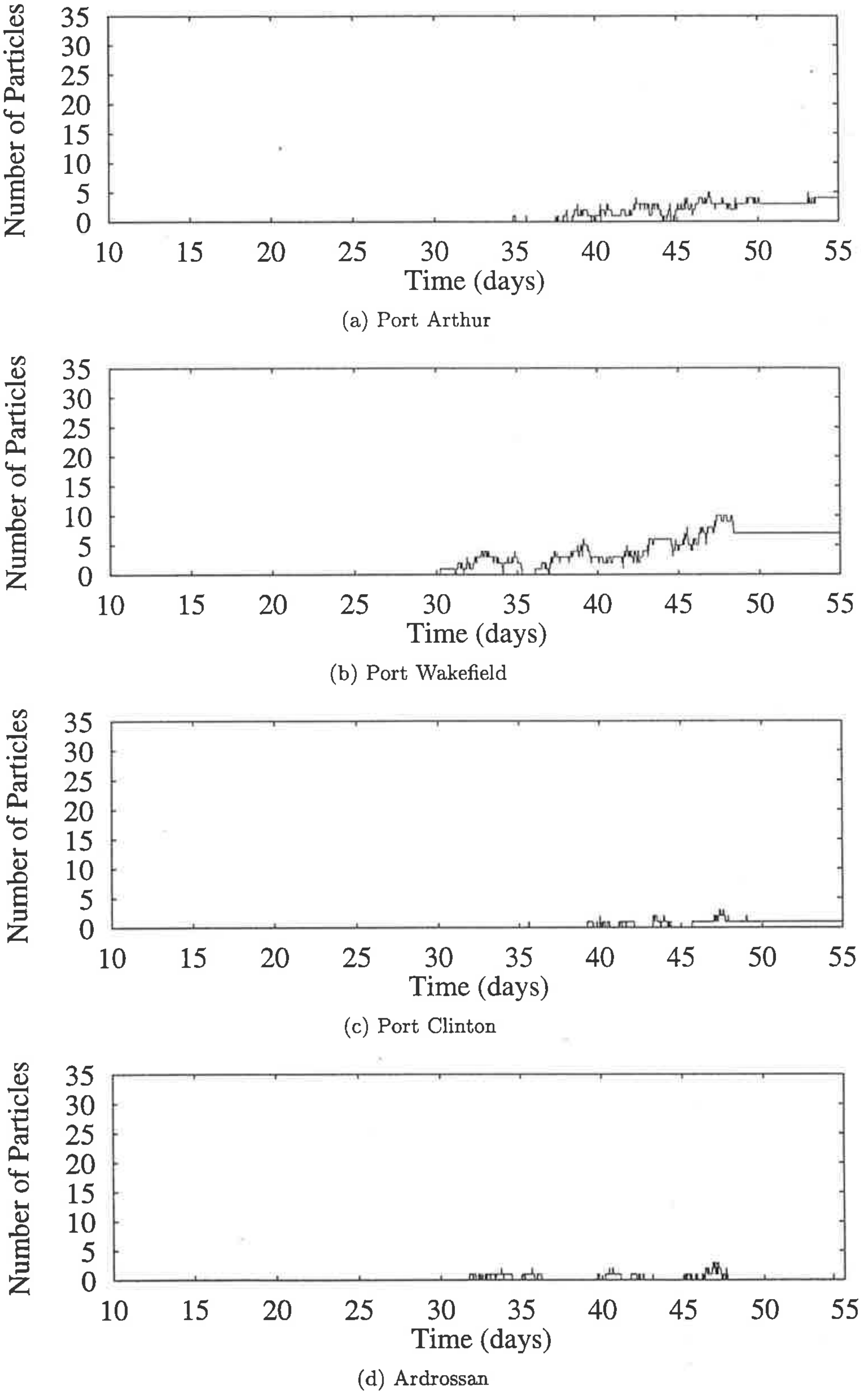


Figure 5.6 a) Initial egg production of *Penaeus latisulcatus* in Gulf St Vincent during November 1990 and March 1991 (a) and advection and diffusion of larvae at four (b), six (c) and eight weeks (d) after spawning on 19 February 1991 (one week period). PW - Port Wakefield, PA - Port Arthur, PC - Port Clinton and A – Ardrossan. x – 30 million eggs.



(a) Port Arthur

(b) Port Wakefield

(c) Port Clinton

(d) Ardrossan

Figure 5.6 b) Time-series of particle density settlement at nursery sites between 10 and 55 days after spawning on 19 February 1991.

5.3.3 Postlarval settlement abundance and patterns from field sampling

During 1989/90, first settlement of postlarvae was observed at Port Wakefield in January 1990 (Table 5.2). Postlarval settlement continued at this site until late April at a relatively lower level compared to Port Arthur. Port Arthur, on the western side of GSV had the highest postlarval settlement overall with a settlement period between mid February and late May 1990. Postlarval settlement was only observed in Port Clinton between mid February and late April and at Ardrossan during March 1990. Both of these sites had much lower settlement abundance compared to Port Arthur.

During 1990/91, postlarval settlement commenced earlier at all sites in comparison to 1989/90 (Table 5.2). Port Wakefield was observed to have high postlarval settlement in December 1990 and both Port Arthur and Ardrossan also recorded postlarval settlement in this month but it was comparatively lower. Port Wakefield, on the eastern side of GSV had the highest postlarval settlement during 1990/91 with a settlement period between December 1990 and June 1991. Postlarval settlement continued until mid to late May for all the other sites. Overall the postlarval settlement in 1990/91 was higher and continued over a longer period compared to 1989/90.

Table 5.2 Mean number (± 1 s.e.m.) m^{-2} of postlarval *Penaeus latisulcatus* sampled in nurseries either fortnightly or monthly during the main settlement period, December 1989 to June in 1990 and December 1990 to June 1991.

Date	Port Wakefield		Port Arthur		Port Clinton		Ardrossan	
	No.	s.e.m	No.	s.e.m	No.	s.e.m	No.	s.e.m
15 Dec 89	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15 Jan 90	0.030	0.002	0.000	0.000	0.000	0.000	0.000	0.000
15 Feb 90	0.327	0.096	0.433	0.119	0.017	0.001	0.000	0.000
2 Mar 90			0.310	0.025				
12 Mar 90	0.127	0.058	1.017	0.041	0.173	0.123	0.123	0.018
30 Mar 90			0.543	0.096				
10 Apr 90			0.143	0.039				
25 Apr 90	0.140	0.017	0.277	0.029	0.047	0.009	0.000	0.000
8 May 90			0.013	0.009				
23 May 90	0.003	0.003	0.033	0.009	0.000	0.000	0.000	0.000
21 Jun 90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20 Dec 90	0.903	0.052	0.013	0.003	0.000	0.000	0.013	0.009
9 Jan 91			0.027	0.012				
22 Jan 91	0.833	0.042	1.023	0.135	0.003	0.003	0.007	0.003
4 Feb 91			0.710	0.121				
14 Feb 91	0.797	0.149	0.077	0.014	0.030	0.025	0.033	0.012
5 Mar 91			0.967	0.255				
19 Mar 91	1.607	0.169	0.900	0.145	0.757	0.313	0.240	0.053
4 Apr 91			0.120	0.036				
16 Apr 91	0.533	0.061	0.327	0.017	0.297	0.248	0.390	0.056
1 May 91			0.347	0.029				
13 May 91	0.130	0.076	0.100	0.010	0.007	0.003	0.010	0.006
31 May 91			0.017	0.003				
22 Jun 91	0.003	0.003	0.000	0.000	0.000	0.000	0.000	0.000

5.3.4 Comparison of predicted mean settlement and observed settlement in nursery sites

No correlation was observed between mean number of postlarvae (number m^{-2}) in nursery sites and predicted particles settlement for Port Wakefield (Figure 5.7 a) in 1990 and 1991 (combined) (r = 0.349, P = 0.651). Similarly no correlation was observed between predicted particle settlement and abundance of postlarvae sampled at Port Arthur (Figure 5.7 b) during 1990 (r = 0.8506, P = 0.149) and 1991 (r = 0.295, P = 0.705). For Port Arthur, in 1990, it appears that there may be some exponential relationship between predicted settlement and postlarval abundance from field sampling but this is not seen for 1991.

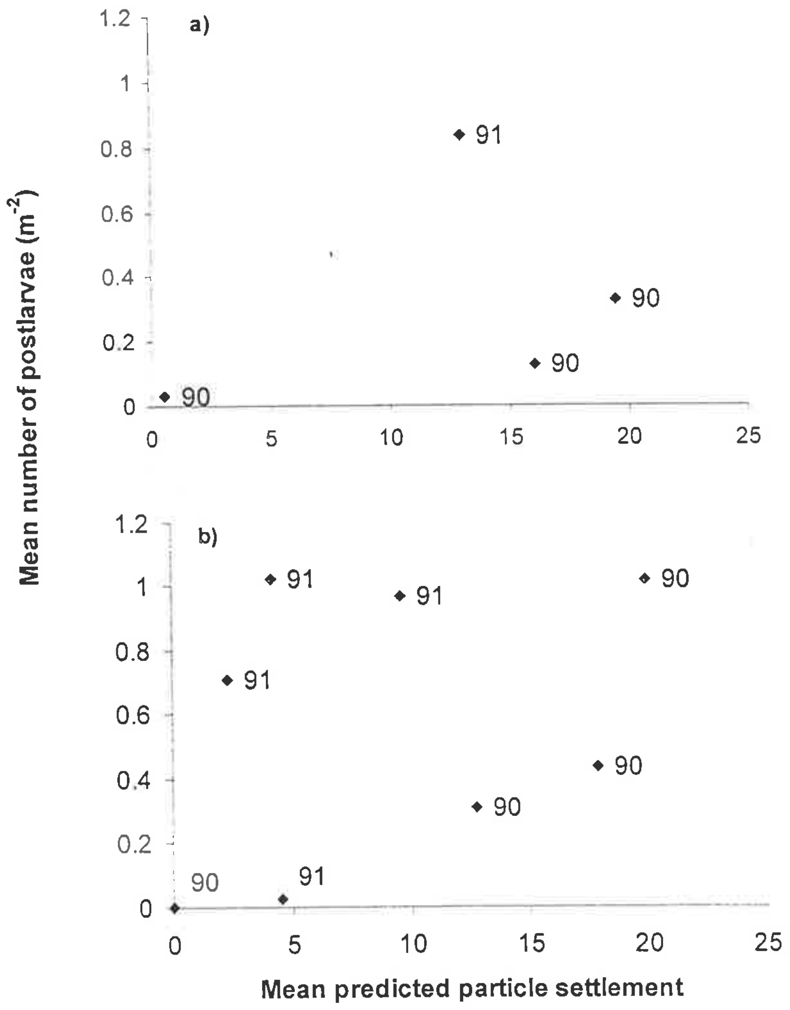


Figure 5.7 Relationship between mean predicted particle settlement abundance (from modelling) and postlarval abundance from field sampling at a) Port Wakefield and b) Port Arthur during 1990 and 1991 .

5.4 Discussion

Larval advection modelling was used to elucidate reasons for observed differences in settlement patterns between 1989/90 and 1990/91 and general settlement trends observed over the seven year study. With reference to the three biological questions that were posed in this chapter, the modelling provided the following information.

1. Differences in east-west settlement patterns between 1989/90 and 1990/91.

In 1989/90, the hydrographic model of larval transport predicted higher settlement for the northeastern shores of Gulf St Vincent from a December and January spawning. The number of particles predicted to arrive on the northwestern shore from the January spawning was higher than predicted from the December spawning. Field sampling indicated that settlement during January-February (derived from December spawning) first occurred at Port Wakefield on the western side of GSV but settlement abundance was similar between Port Wakefield and Port Arthur. However, field sampling in late February-March showed settlement (derived from January spawning) was higher at Port Arthur during this period. The predictions from modelling for the second simulation more closely resembled settlement patterns observed from field sampling but the relative abundance was not precise. Lower settlement abundance was predicted for the two southern sampling sites compared to northern sites, which was confirmed by field sampling. However, settlement abundance during March was underestimated in the modelling for both of these areas.

In 1990/91 the modelling predicted higher postlarval settlement on the eastern shores. It was predicted that Port Wakefield was the first site to receive particles and that it received the highest number of particles over the simulation period. This was consistent with the pattern seen from the field sampling. However, the comparative settlement abundance predicted by the model for Port Arthur, Port Clinton and Ardrossan was lower than that actually observed in the field.

The modelling predicts relatively higher settlement abundance in nurseries during 1989/90 compared to 1990/91 whereas field sampling indicated higher settlement abundance in 1990/91.

2. Settlement patterns between northern and southern nursery sites

Consistently lower numbers of particles were predicted to settle in the two southerly nursery sites, Port Clinton and Ardrossan, compared to the northern sites. This was consistent with patterns from field sampling. However, the levels of settlement predicted by the model were lower than actually seen in field sampling.

3. Key spawning areas

The northern spawning areas appear to be most important for successful larval movement into key nursery sites. Larvae released in these areas were shown to move north, northwest, east or northeast towards the shores over the eight-week period. These larvae are transported to the sheltered nursery areas in the northern parts of GSV. Larvae released in southern regions appear to move into areas of more exposed coastline which is unsuitable as a nursery habitat, while some move into Investigator Strait or Backstairs Passage and so are lost from the gulf.

Modelling was useful in providing general, broad information on yearly differences in overall larval advection pathways and postlarval settlement patterns. For the two years compared, field sampling showed similarities to the distribution patterns predicted through modelling. The modelling could not however, precisely predict the settlement time, location or abundance at specific sites.

The model although mathematically complex was based on a number of assumptions about the biology and behaviour of *Penaeus latisulcatus*. Detailed knowledge of the spatial and temporal variation in spawning throughout Gulf St Vincent is lacking. Therefore, for each simulation, all prawns throughout the gulf spawned over a week. This type of synchrony in spawning is unlikely. Larger females appear to spawn earlier than smaller individuals (Carrick 1996). The waters in the northern and shallower parts of the gulfs warm up earlier than southern waters and this may affect timing of spawning. Carrick (1996) suggested for *P. latisulcatus* in Spencer Gulf that the eggs released by larger individuals may be more viable due to a higher insemination rate. Total potential egg production was used in the modelling which was calculated from the abundance of all female prawns ≥ 30mm CL. Calculation of potential egg production of females of sizes ≥ 42 mm CL showed a very similar overall distribution pattern as all female prawns ≥ 30 mm CL and so this was used.

Improvement in modelling precision require more detailed and specific knowledge of the actual spawning time, the spatial and temporal differences between spawning patches and the viability of eggs released. It may require more than just the measurement of total spawning stock including identification of those parts of the spawning stock that are likely to be most important in postlarval settlement and subsequent recruitment to the fishery (Caputi 1993). Modelling the advection of larvae from each major region (Block) individually could provide some further information on the importance of each region to postlarval settlement abundance.

No estimate of larval mortality was incorporated into the modelling. Larval mortality can be high, varies with larval stage and may vary in the spatial and temporal scale. Carrick (1996) estimated that for larval *P. latisulcatus* in Spencer Gulf SA, mortality was 23% per day for zoea stage to mysis and 3% per day for mysis stage to postlarvae during 1992/93.

Munro *et al.* (1968) estimated that only 0.05% of larvae of *P. duorarum* in the Gulf of Mexico reach nursery areas after a larval period of 35 days. Significant changes in larval mortality between years and on a spatial scale could impact overall numbers reaching nurseries. This may explain differences in the relative abundance of predicted settlement and observed settlement in nursery sites and between the two years. To gain quantitative data on settlement, modelling would need to include estimates of larval mortality. However, acquisition of this type of information would be difficult, costly and labour intensive.

Another limitation of the current modelling is that it incorporated wind data from widely separated stations. Localised information, particularly in northern Gulf St Vincent, was not available. Improvement in the predictive ability of the model for specific nursery sites and for actual timing of settlement would require input of wind data and physical oceanographic characteristics at a much finer resolution.

With the current level of knowledge of the biology of *Penaeus latisulcatus* in Gulf St Vincent and the limitation in the resolution of physical oceanographic characteristics within the gulf, modelling has provided only a very broad-scale interpretation of larval advection and postlarval settlement processes; it cannot be used to predict postlarval settlement strength. Modelling does however, identify areas of the biology and behaviour of *P. latisulcatus* that require further research for a better understanding of factors affecting postlarval settlement into nurseries. The modelling also emphasises the importance of larval advection processes and larval supply for postlarval settlement into nurseries and subsequent recruitment to the fishery.

6. SIZE STRUCTURE, GROWTH AND MORTALITY ESTIMATION OF JUVENILE *Penaeus latisulcatus* IN NURSERIES AND VALIDATION OF GROWTH INCREMENTS UNDER LABORATORY CONDITIONS

6.1 *Introduction*

The productivity of a nursery area for *Penaeus latisulcatus* is determined by the initial numbers settling in the area, the growth patterns of individual prawns and their mortality rates. The variation in growth and mortality between sites and from year to year provides us with some understanding of the natural dynamics of populations and the factors that provide variability of recruits to the fishery. Observations of the size structure of populations between nursery sites and between months at a site provides information on the timing of settlement, an indication of growth patterns and timing of emigration out of nurseries. Studies of population dynamics of prawns in nurseries for more than a couple of years are scarce.

Penaeid prawns, like other Crustacea, increase in size in a series of steps. They undergo a rapid enlargement at ecdysis (moult) which is followed by a period of little or no increase (intermoult period) until the next ecdysis (Hartnoll 1982, Dall *et al.* 1990). The moult frequency and intermoult period may be dependent on the sex and size (age) of the individual as well as environmental factors such as food quality and quantity, population density, light, temperature and salinity (Dall *et al.* 1990).

Various methods are available to determine growth in adult populations including tagging by internal or external tags, modal progression over time-series or laboratory studies. Tagging is not a viable method of determining growth in postlarval or juvenile prawns. They are highly vulnerable to tagging mortality. Low survival rates have been noted for tagged *P. monodon* (Primavera & Caballero 1992), *P. esculentus* (Hill & Wassenberg 1985) and *P. vannamei* (Menz & Blake 1980) less than 18mm CL. Even if tagging mortality could be reduced in juvenile prawns, the numbers that would need to be tagged for sufficient numbers to be returned would be impracticable. The best method to determine growth for postlarval and juvenile prawns is by length-frequency analysis, that is, following cohorts or modal progression over time-series. However, when settlement of postlarvae occur continuously or 'in pulses' over several months, with subsequent emigration of larger prawns offshore, following modes can be difficult. In addition, if spatial differences occur for distribution of different sized individuals, modes may represent migration patterns rather than growth (Dall *et al.* 1990).

Laboratory or controlled field experimentation can provide information on individual growth rates under various environmental conditions but results may not reflect true conditions in natural populations. A combination of experimental studies and field observations can provide a better understanding of growth patterns in juvenile prawn populations.

Modal progression analysis has been used to determine growth rates of juveniles of *P. latisulcatus* (Subramaniam 1990), *P. aztecus* (Knudsen *et al.* 1977), *P. esculentus* (O'Brien 1994a, Loneragan *et al.* 1994), *P. indicus* (Benfield *et al.* 1990, Subramaniam 1990, Mohan & Siddeek 1996), *P. merguiensis* (Staples 1980b, Staples & Vance 1985, 1986, Haywood & Staples 1993), *P. monodon, P. japonicus* (Doi 1981) and *P. vannamei* (Menz & Bowers 1980). Laboratory or controlled field experiments have been conducted to determine growth in juvenile *P. latisulcatus* (Kathirvel *et al.* 1986), *P. duorarum, P. notialis, P. schmitti, P. setiferus, P. stylirostris* (Menz & Bowers 1980), *P. merguiensis* (Staples & Heales 1991), *P. vannamei* (Edwards 1977, Menz & Blake 1980) and *P. esculentus* (O'Brien 1994b). Most results for either modal progression or laboratory experiments have displayed a highly variable growth rate, both within (seasonal) and between years. Loneragan *et al.* (1996) determined the growth differences of *P. semisulcatus* in enclosures excluding predators and found that growth rates were density and habitat dependant.

Several studies have estimated the natural mortality rates of juvenile *Penaeus* species and mortality has been shown to be highly variable within years, between years and with the size of the individual. Length-frequency measurements from field sampling have been used for *P. latisulcatus* in Spencer Gulf (Carrick 1996), *P. aztecus* in Gulf of Mexico (Rothschild & Brunenmeister 1984) and Galveston Bay, Texas (Minello *et al.* 1989), *P. merguiensis* in Gulf of Carpentaria (Haywood & Staples 1993) and *P. esculentus* in south Queensland (O'Brien 1994a). The length-frequency distribution is separated into cohorts either by eye or by computer packages such as ELEFAN (Gayanilo *et al.* 1989) or MIX (MacDonald & Green 1988). The number of individuals in a cohort can then be followed over time and mortality is estimated by regressing the natural logarithm of cohort density over time (Beverton & Holt 1957). Edwards (1977) estimated the natural mortality of *P. vannamei* in a Mexican lagoon using wire enclosures with individually marked juvenile prawns.

This study determines the size structure of populations of postlarvae and juveniles in nursery sites for each month and for all sampling periods and compares the growth rate of *P. latisulcatus* between some sites, years and some seasons. Yearly variability in growth rate during the summer period is compared for Port Arthur during 1990 to 1996. These comparisons illustrate the range of variability in natural growth rate for postlarval and juvenile *P. latisulcatus* in Gulf St Vincent. Results of field measurements of growth are compared to laboratory-based growth experiments on postlarval and juvenile *P. latisulcatus*. Prawns were kept for a period of seven weeks at $19.5^{\circ} \pm 1.5^{\circ}$C to determine the growth rate between moult increments.

This study provides estimates and comparison of natural mortality for postlarval and juvenile *P. latisulcatus* in Gulf St Vincent. Natural mortality rates of postlarval and juvenile prawns in nurseries may be determined by measuring the decline in numbers of individuals during a period of time when there is no settlement into, or emigration out of nurseries (Carrick 1996). The difficulty in ensuring no settlement or emigration means these calculations can be made only for short periods of time during winter; dynamic settlement and emigration processes operate at other times. To gain some estimate for mortality during the summer period, an alternative approach was taken. A cohort was identified and followed over three sampling periods. These estimates provide information on the range of mortalities for postlarval and juvenile *P. latisulcatus* in nurseries.

6.2 *Methods*

6.2.1 Population size structure

The overall size structure of prawns in nurseries was studied by pooling measurement data into 1 mm size classes for all sites and sampling periods. All sampling periods for each nursery site were also pooled to compare size structure between nursery sites. Measurements from nursery sites with similar size structure were then pooled to determine monthly size structure for the seven-year period.

6.2.2 Growth determination from field measurements

Growth was determined by following cohorts or peaks in numbers over time. Cohorts were separated using MIX (MacDonald & Pitcher 1979). Continuous settlement during January to April made this procedure difficult; only those periods where cohorts could be separated for at least three successive times were analysed (Table 6.2). For each sampling sequence, normal distribution curves were fitted to each of the component size classes and the growth of each size class (cohort) from one sampling period to the next was calculated using the mean size of each size class. MIX requires the input of initial estimates of the number of size classes, the mean size of each size class and the variance around each mean size. The package then allows both manual and automatic search routines to improve the overall fit and presents the resulting curve graphically.

6.2.3 Laboratory growth trials

Thirty aquaria (20cm x 30 cm, ten litre capacity) were set up with a flow through seawater system with a flow rate of 35 litres per minute and the temperature was set to 19.5^{o} $\pm$ 1.5^{o}C. The water flow system was circular to allow even pressure to all 30 aquaria. As prawns bury in the sediment during the day, sediment was collected from Port Arthur on 4

April 1997 and 1.5 litres of sediment was placed in each aquarium. Juvenile prawns were collected on 7 April 1997 from Port Wakefield using a beam trawl, just before sunrise. The prawns were immediately placed in drums of aerated seawater and transported back to the laboratory.

Five size classes were selected for the trials: Size Class 1: <4 mm CL, Size Class 2: 5-10mm CL, Size Class 3: 11-14 mm CL, Size Class 4: 15-18mm CL and Size Class 5: >18mm CL. Two individuals of each size class were measured under a microscope with an ocular micrometer, weighed in a beaker of seawater and randomly placed in one of the 30 aquaria. Only two individuals in Size Class 5 were caught so the remaining four aquaria allocated to this size class were used for smaller size classes. Prawns were fed equal quantities of squid or fish pellets three times a week with any remaining food removed at each feeding. Observations of moults and dead individuals were made each day. The moults for the two smaller size classes were not observable in the aquaria, as they were transparent. Moults that were found were measured and matched to an individual in that particular tank.

Random samples of one third of all prawns were taken every week (7 days) from 7 April 1997 for three weeks (Figure 6.1). During each successive sampling, prawns that were sampled the previous week were also re-measured and weighed. The original design was to complete the trial at the end of four weeks but some individuals had not moulted during this period and prawns appeared in reasonable condition so the trial was continued for a further three weeks. CL measurement and weight was recorded for each surviving prawn once a week for the extended period.

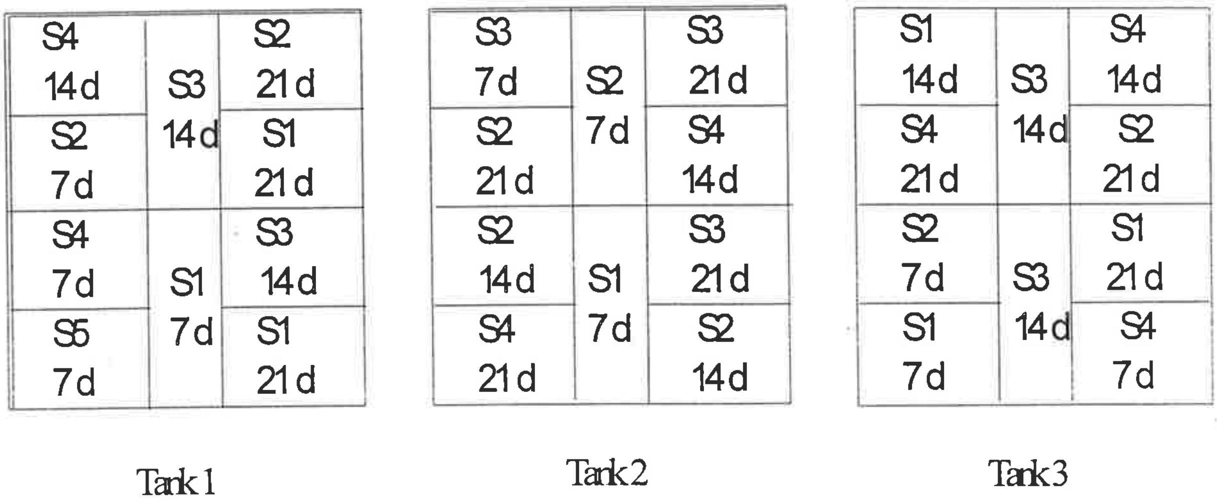


Figure 6.1 Sampling design of growth experiment for juvenile *Penaeus latisulcatus* indicating tank set-up, size class and sampling interval. S indicates size class, d indicates the time (days) between initial and subsequent measurement.

Growth was determined from the increase in size (CL) or weight (g) of each individual over the seven-week period. In addition, when a moult was observed, this was measured and the time noted so moult frequency could be calculated. For the small individuals, it was assumed that increase in size (CL) and weight indicated that it had moulted since exuviae could not be readily located in the tanks.

6.2.4 Mortality determination from field measurements and data analysis

The decline in number of individuals in nursery sites was considered to represent natural mortality. All prawns ≥3mm CL were used in the analysis. Mortality was estimated as the slope of the regression line of $\log_e N$ against time (Ricker 1975) using: $\log_e N = -MT + a$, where N = number of prawns at each time period T, M = natural mortality, and a = the intercept. The percentage natural mortality (or conditional natural mortality rate, Ricker (1975) per week was also calculated: $(1 - e^{-M}) \times 100$.

Winter mortality rates are estimated for Port Wakefield, Port Arthur, Port Clinton and Ardrossan between 1990 and 1994 and for Webb Beach in 1994. The years 1990 to 1994 were analysed because in 1995 and 1996 only January to June were sampled.

A two-way ANOVA was used to determine whether the mortality rate of juvenile prawns differed amongst sites and years. Site and Year were treated as fixed factors. The data sets were checked for normality using Wilk-Shapiro Rankit plots, homogeneity of variances by the Cochran's test (Winer 1971, Underwood 1981) and for non-additivity using Tukey's 1 Degree of freedom test. Where ANOVA showed significant differences, Bonferroni multiple range tests were used to determine which means were significantly different at the 0.05 level of probability.

The relationship between initial densities in nursery sites and estimated mortality rate was tested using a linear regression. The equation is in the form: Mortality = a Density + b, where a is a constant relating to Density and b is the y-intercept.

Summer mortality rates were determined from the decline in numbers of one cohort over three times series. For each size distribution, normal distribution curves were fitted to each of the component size-classes using MIX (MacDonald & Pitcher 1979). The fitting procedure also calculates the proportion of the total for each curve. The number of individuals in each curve can then be determined. This was possible for Port Arthur in 1991, 1992, 1994 and 1995, Port Clinton in 1992, Ardrossan in 1994 and 1995 and Webb Beach in 1995.

6.3 *Results*

6.3.1 Population size structure

Juvenile *Penaeus latisulcatus* up to 20 mm CL occur in nurseries and the size distribution is highly skewed (Figure 6.2) with size classes between 2 and 7 mm CL comprising 90% of the population.

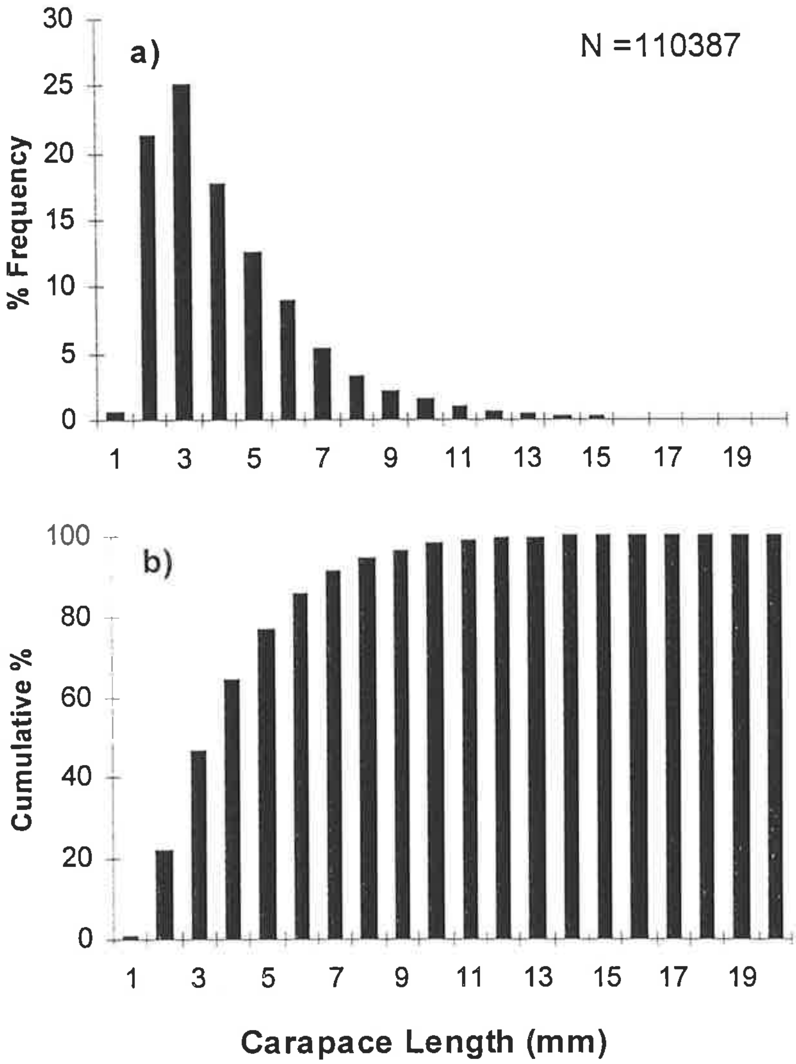


Figure 6.2 Percentage size frequency of all postlarval and juvenile *Penaeus latisulcatus* sampled in nurseries between October 1989 and June 1996. a) percentage frequency b) cumulative percentage.

Comparison of size structure between sites (Figure 6.3) indicate that Webb Beach, Port Wakefield and Port Arthur have a similar size structure overall. They display a highly skewed size distribution with most prawns found being 2-7 mm CL. The size structure at Port Clinton and Ardrossan are similar to each other with a less skewed size distribution due to lower postlarval settlement abundance. However the size range found in all nurseries is similar.

For the northern sites, monthly size structure indicates highly skewed size distributions during January to April (Figure 6.4) when high postlarval settlement is occurring. These three months (and sites) dominate the overall size structure seen in nurseries for all periods (Figure 6.2) due to the proportionally high numbers encountered in nurseries during this time. Between April and November a slow progression in size is observed for juvenile prawns (Table 6.1) from a size range of 1 to 14 mm CL in April to a range of 6 mm to 16 mm CL in November. Very little change in size structure is observed during winter (July and August). In December, a new group of postlarvae is observed in nurseries with low numbers of larger juveniles still found from the previous years' settlement.

The southern sites, Port Clinton and Ardrossan show a highly skewed size distribution during March and April when postlarval numbers are at their highest, with prawns 2-7 mm CL dominating the catches (Figure 6.5). Proportionally higher numbers of larger individuals are found in the southern sites during December to February compared to northern sites. Again very little change in size structure is observed during July to August (Table 6.1), suggesting very little growth. Between May to November the size range of individuals change from 1 mm - 15 mm CL to 6 mm – 18 mm CL.

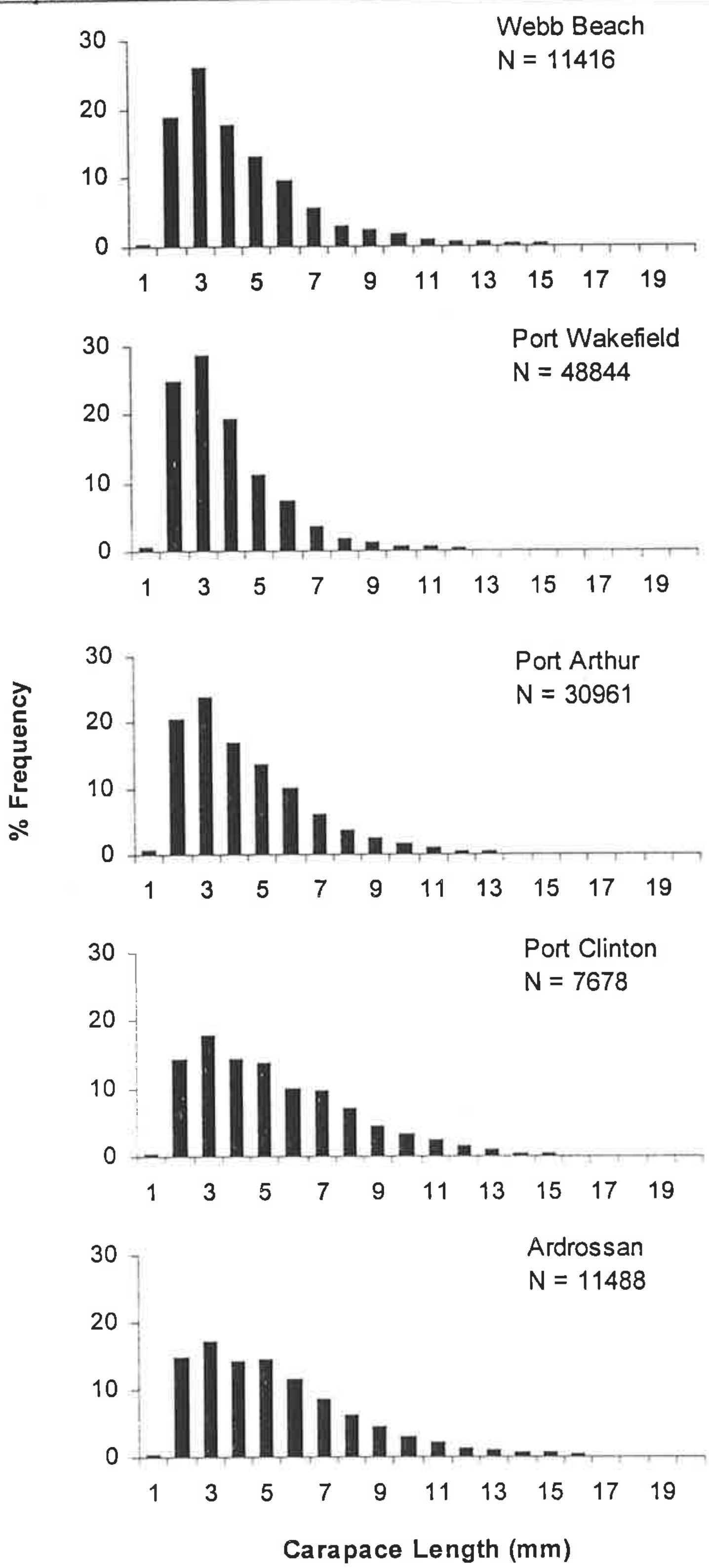


Figure 6.3 Percentage size composition of postlarval and juvenile *Penaeus latisulcatus* found in individual nursery sites for all sampling periods between October 1989 and June 1996. **Note**: For Webb Beach, February 1992 to June 1996.

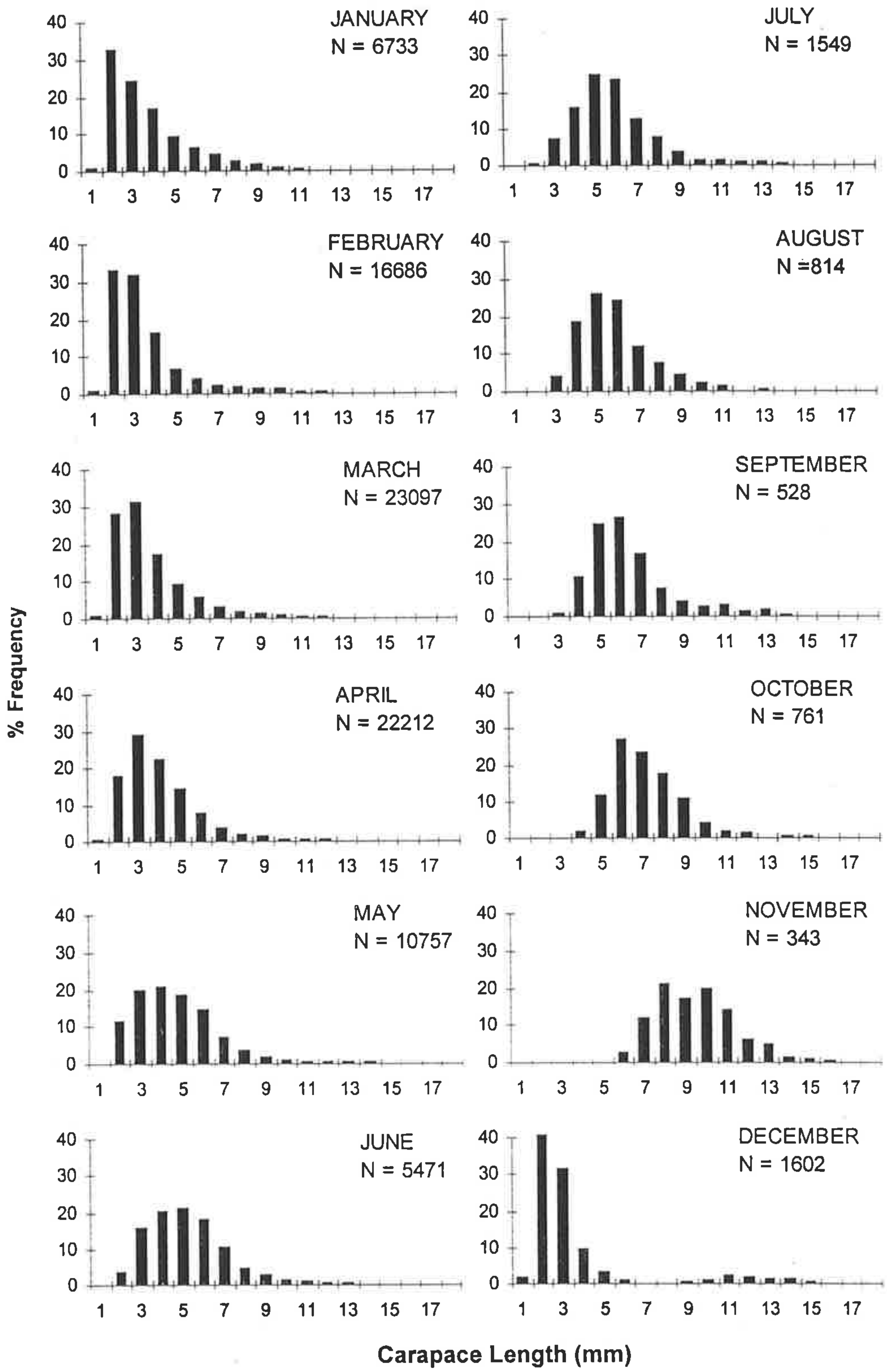


Figure 6.4 Monthly percentage size frequency of postlarval and juvenile *Penaeus latisulcatus* found in Webb Beach, Port Wakefield and Port Arthur (combined), between October 1989 and June 1996.

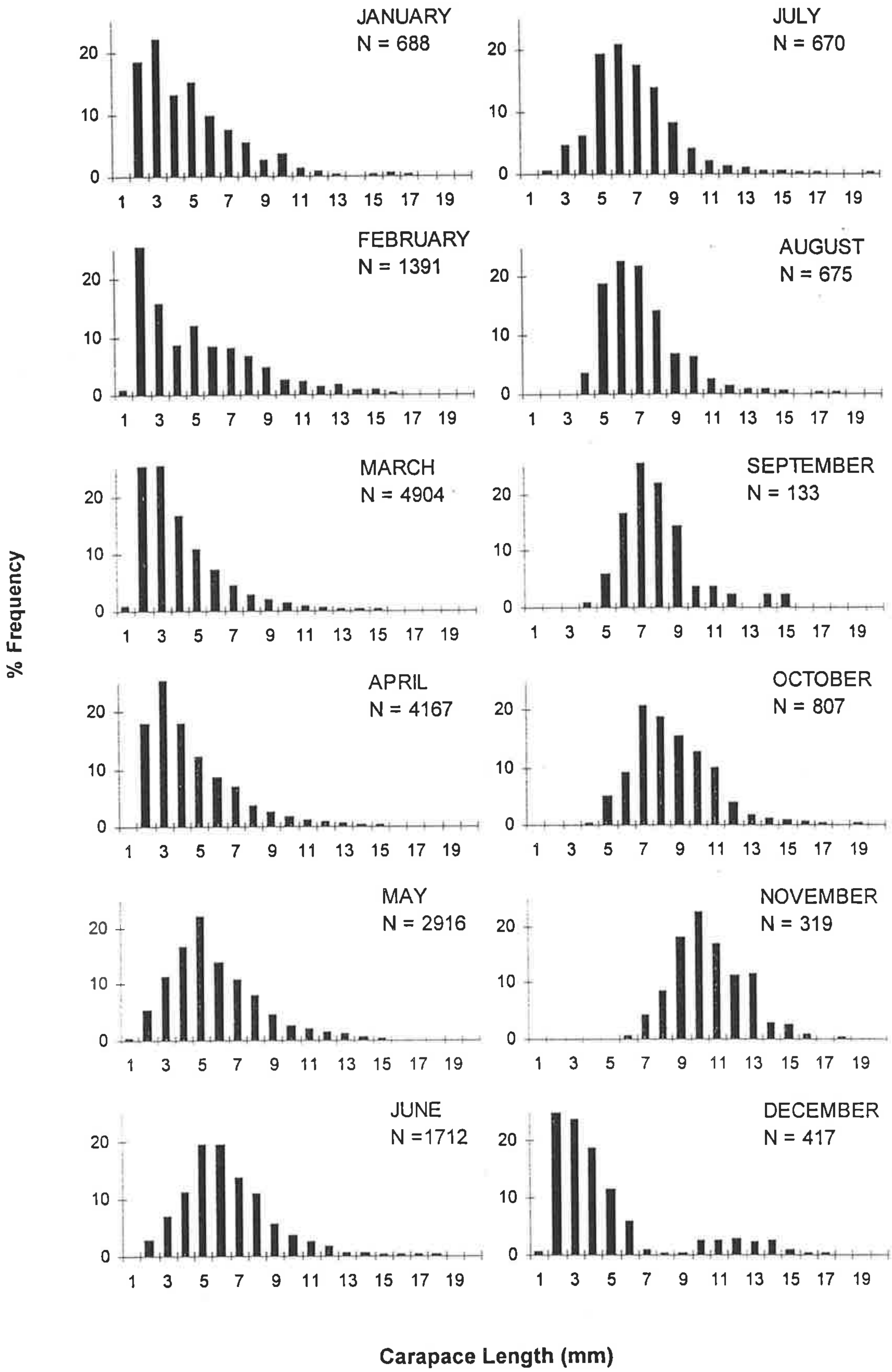


Figure 6.5 Monthly percentage size composition of postlarval and juvenile *Penaeus latisulcatus* found at Port Clinton and Ardrossan (combined) between October 1989 and June 1996.

Table 6.1 Mean carapace length (mm) of juvenile *Penaeus latisulcatus* sampled in nursery sites for each month over seven years (October 1989 and June 1996), separated into northern sites (Webb Beach, Port Wakefield and Port Arthur) and southern sites (Port Clinton and Ardrossan). **Note:** For Webb Beach, February 1992 to June 1996.

Month	Mean CL (mm)	
	Northern sites	Southern sites
January	3.7	4.8
February	3.5	5.0
March	3.7	4.1
April	4.0	4.5
May	4.7	5.7
June	5.2	6.3
July	5.9	6.7
August	5.8	7.1
September	6.5	7.9
October	7.1	8.5
November	9.5	10.6
December	12.2	12.0

6.3.2 Growth using field measurements

Inability to follow cohorts over time-series limited periods when growth could be investigated. The highly skewed size distributions, with high numbers of individuals ≤ 7 mm and very low numbers of larger sizes (8-18 mm), meant that for larger sizes cohort determination was based on very small variations (one to five individuals) between number at size. An example of the resultant curve from separation of cohorts for Ardrossan during 14 May 1996 is seen in Figure 6.6.

Growth rates varied between 0.50 mm CL^{-wk} at Port Clinton to 1.89 mm CL^{-wk} at Port Arthur (Table 6.2, Figures 6.7 - 6.11). The data suggest that growth during winter is lower than for other periods while growth is highest in summer (Table 6.3). Yearly variability in growth is also evident (Table 6.4).

Table 6.2 Summary of estimation of growth rates of *Penaeus latisulcatus* from cohort progression using MIX. Each time-series encompasses at least three consecutive sampling periods.

Location	Period over which growth estimated	Number of days	Starting size (mm CL)	Growth rate (mm CL^{-wk})
Pt Wakefield	20 July 1990 to 13 September 1990	55	5.6 ± 0.1	0.62
	6 May 1993 to 4 June 1993	29	4.5 ± 0.1	1.21
Port Arthur	20 October 1989 to 14 December 1989	55	6.9 ± 0.3	0.61
	9 January 1991 to 4 February 1991	26	4.1 ± .02	1.89
	23 January 1992 to 8 March 1992	43	2.4 ± 0.2	1.02
	20 August 1992 to 15 December 1992	57	4.0 ± 0.1	0.70
	30 December 1993 to 14 February 1994	46	1.9 ± 0.5	1.06
	28 February 1994 to 29 March 1994	29	4.3 ±0.4	0.83
	18 January 1995 to 17 March 1995	57	2.6 ± 0.2	0.71
		57	5.1 ± 0.2	0.88
	17 March 1995 to 12 May 1995	56	2.3 ± 0.7	0.77
Port Clinton	13 March 1990 to 24 June 1990	102	2.0 ± 0.1	0.53
	16 April 1991 to 20 June 1991	64	2.2 ± 0.1	0.50
	7 February 1992 to 31 March 1992	51	2.5 ± 0.2	0.68
		51	5.2 ± 0.4	0.75
	29 April 1992 to 24 June 1992	56	2.8 ± 0.1	0.61
	3 June 1993 to 11 August 1993	69	4.5 ± 0.6	0.53
Ardrossan	14 March 1990 to 25 May 1990	72	2.6 ± 0.1	0.82
	16 August 1990 to 16 November 1990	92	4.8 ± 0.3	0.56
	29 December 1993 to 1 March 1994	56	3.1 ± 0.1	0.99
	26 April 1994 to 20 June 1994	55	3.7 ± 0.1	0.82
	19 January 1995 to 16 March 1995	55	4.7 ± 0.1	0.92
	5 April 1995 to 14 June 1995	70	5.2 ± 0.3	0.64
	20 March 1996 to 12 June 1996	84	3.2 ± 0.2	0.94
Webb Beach	30 December 1993 to 15 February 1994	32	2.2 ±.0.08	1.42
		32	1.8 ± 0.05	1.76
	12 April 1994 to 29 June 1994	78	2.4 ± 0.3	0.65
	20 February 1995 to 13 April 1995	51	3.3 ± 0.2	0.99
	23 February 1996 to 19 April 1996	54	1.9 ± 0.03	0.95

Table 6.3 Seasonal growth rate (mm CL^{-wk} ± 1 s.e.m) of *Penaeus latisulcatus* in nursery sites. ne – no estimation as cohorts could not be followed.

Site	Season			
	Summer	Autumn	Winter	Spring
Port Wakefield	ne	1.21	0.62	ne
Port Arthur	1.06 ± 0.21	0.77	ne	0.65 ± 0.05
Port Clinton	0.71 ± 0.03	0.55 ± 0.03	0.53	ne
Ardrossan	0.95 ± 0.02	0.76 ± 0.06	ne	0.56
Webb Beach	1.28 ± 0.18	0.65	ne	ne

Table 6.4 Summer growth rates (mm CL^{-wk} ± 1 s.e.m) of *Penaeus latisulcatus* estimated for Port Arthur between 1991 and 1995.

Year	Growth rate (mm CL^{-wk})
1991	1.89
1992	1.02
1993	1.06
1994	0.83
1995	0.79 ± 0.08

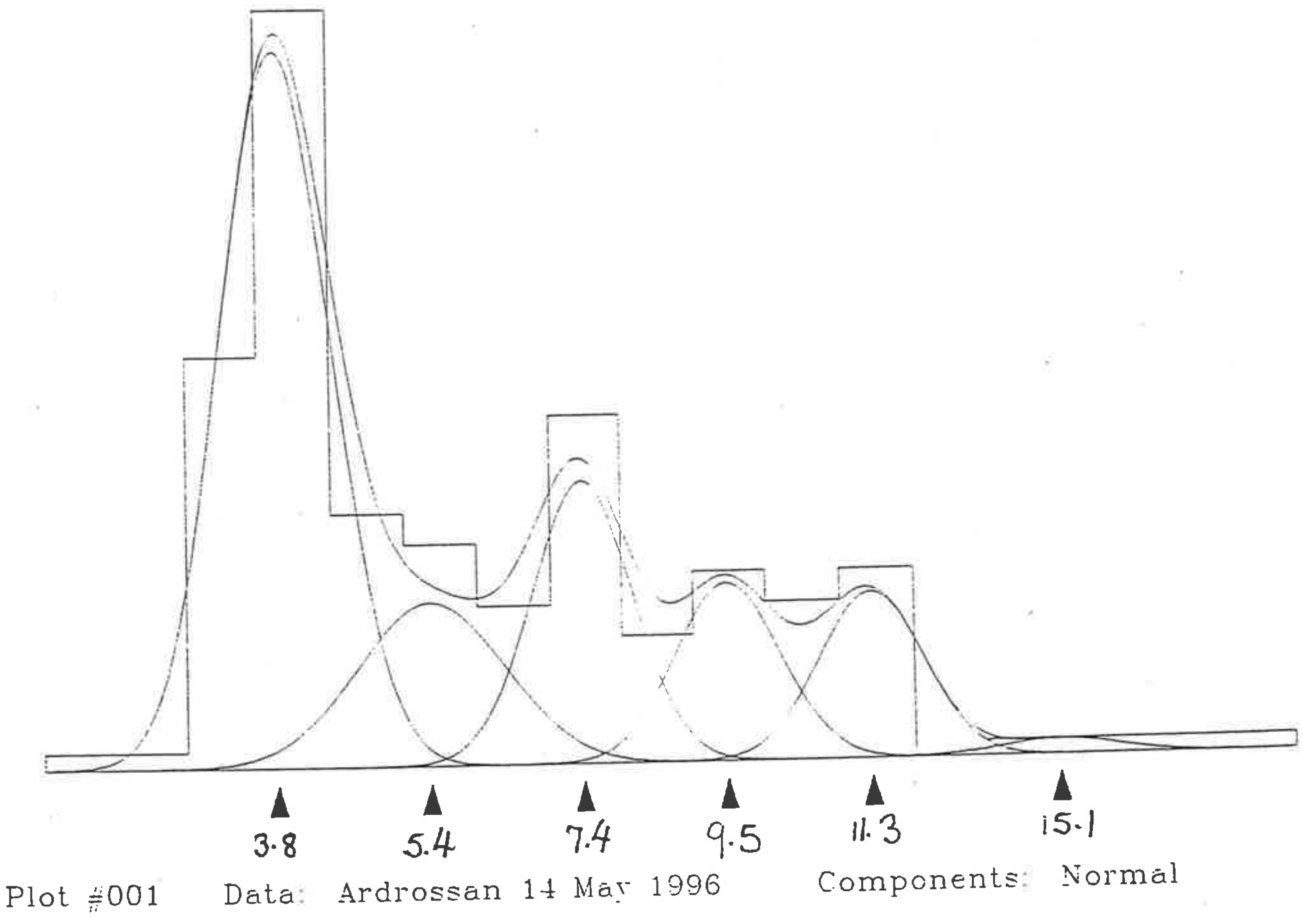


Figure 6.6 Length-frequency distribution of total numbers of juvenile *Penaeus latisulcatus* caught for four trawls at Ardrossan on 14 May 1996 and its component cohorts as estimated by MIX. Dashed line: component cohorts, continuous line: sum of components. Mean CL of each cohort is indicated by arrows.

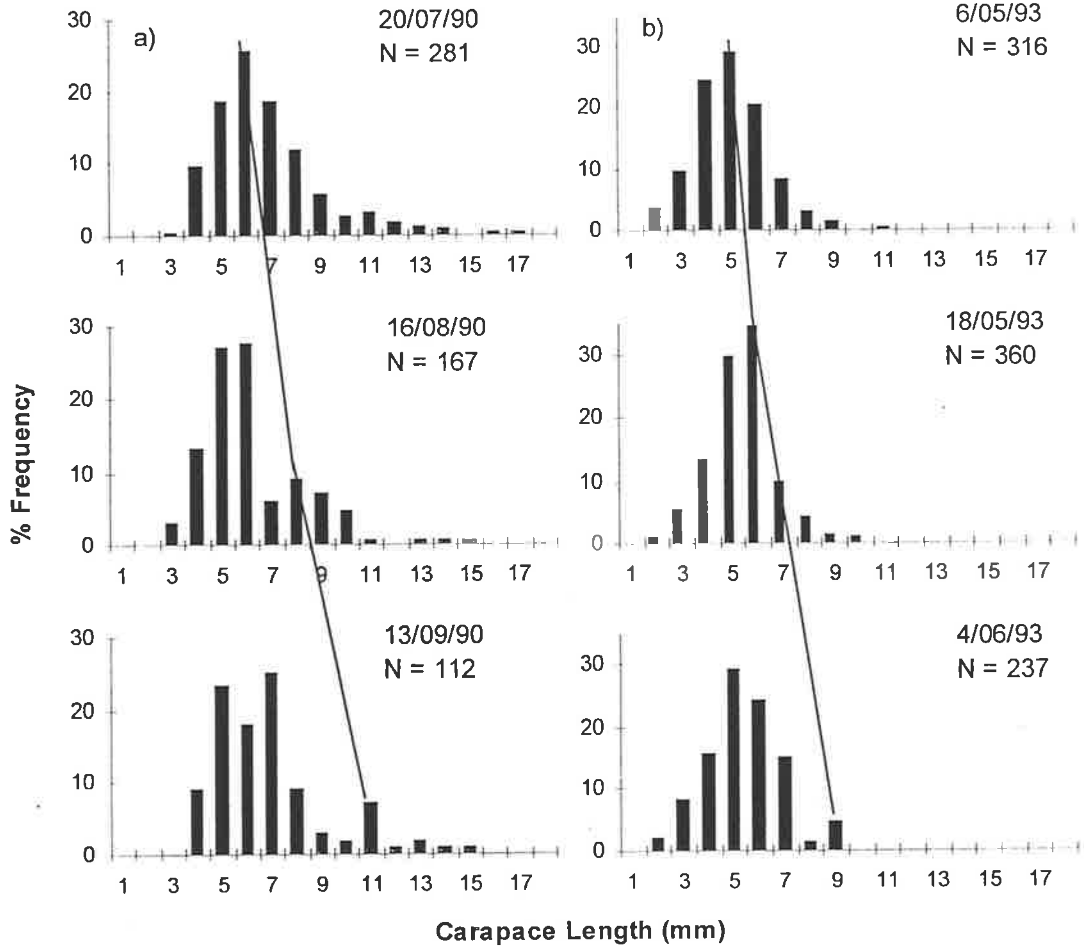


Figure 6.7 Cohort progresssion of *Penaeus latisulcatus* used in the estimation of growth rates at Port Wakefield. a) 20 July 1990 to 13 September 1990, b) 6 May 1993 to 4 June 1993.

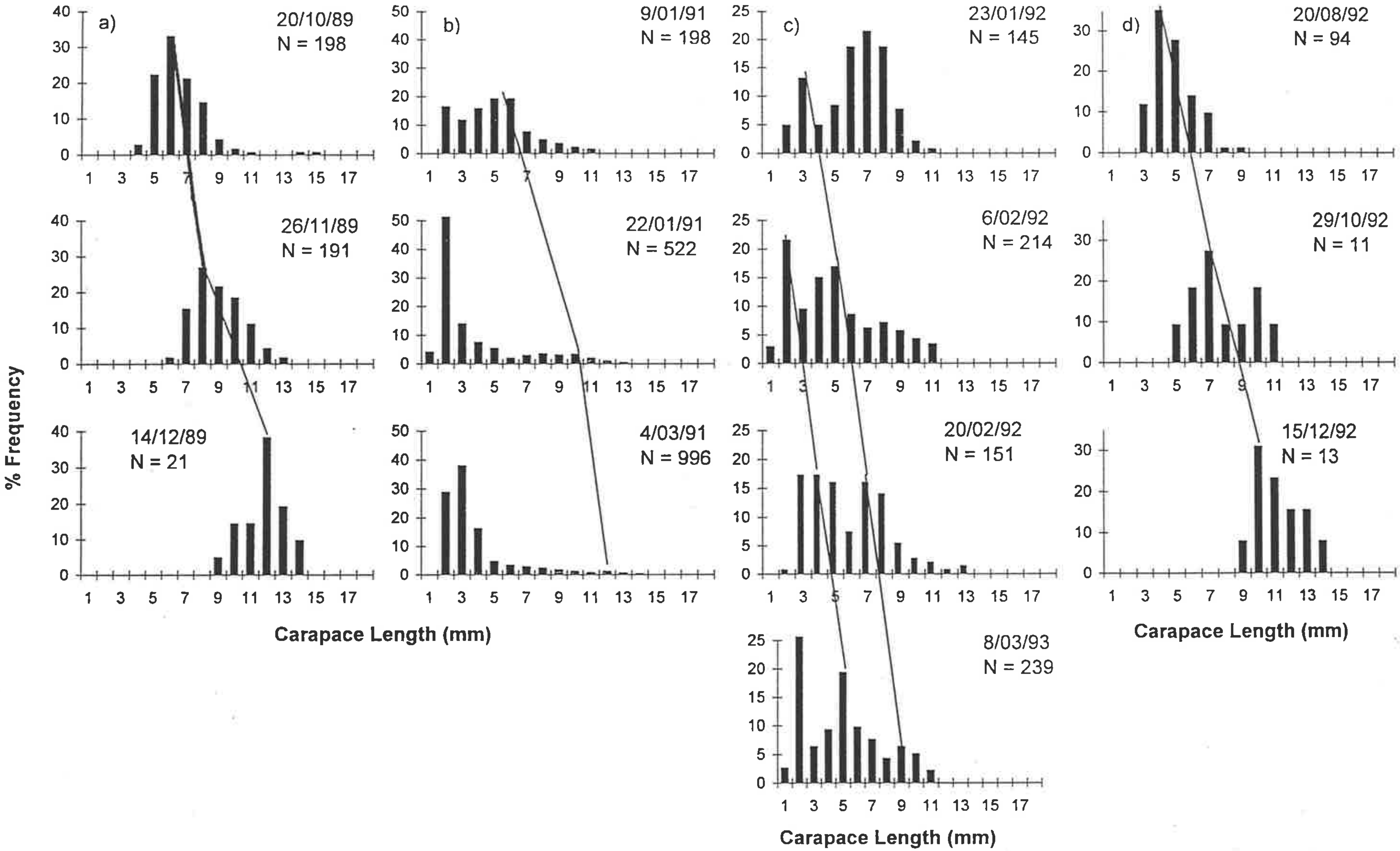


Figure 6.8a Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Port Arthur. a) 20 October 1989 to 14 December 1989, b) 9 January 1991 to 4 March 1991, c) 23 January 1992 to 8 March 1992, d) 20 August 1992 to 15 December 1992.

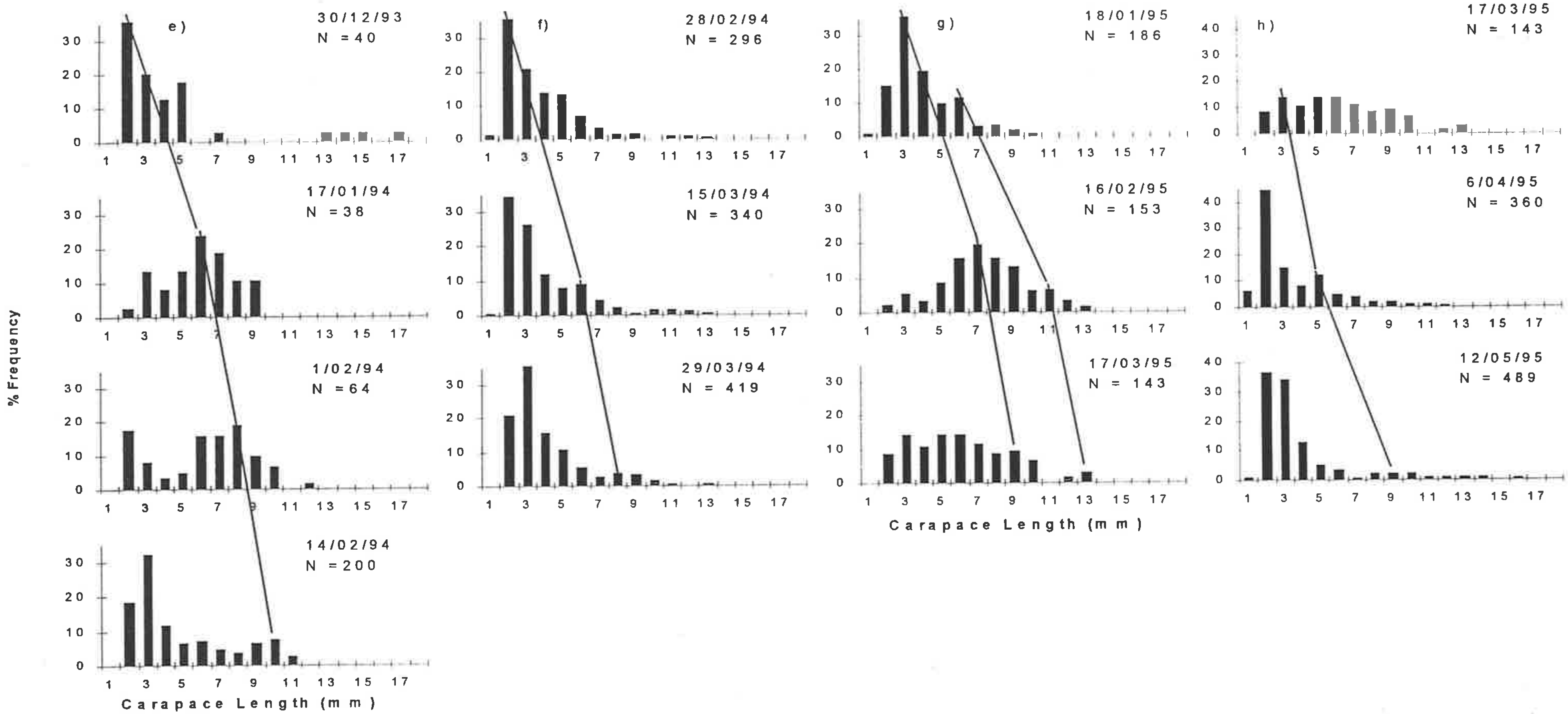


Figure 6.8b Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Port Arthur for, e) 30 December 1993 to 14 February 1994, f) 28 February 1994 to 29 March 1994 g) 18 January 1995 to 17 March 1995 and h) 17 March 1995 to May 12 1995.

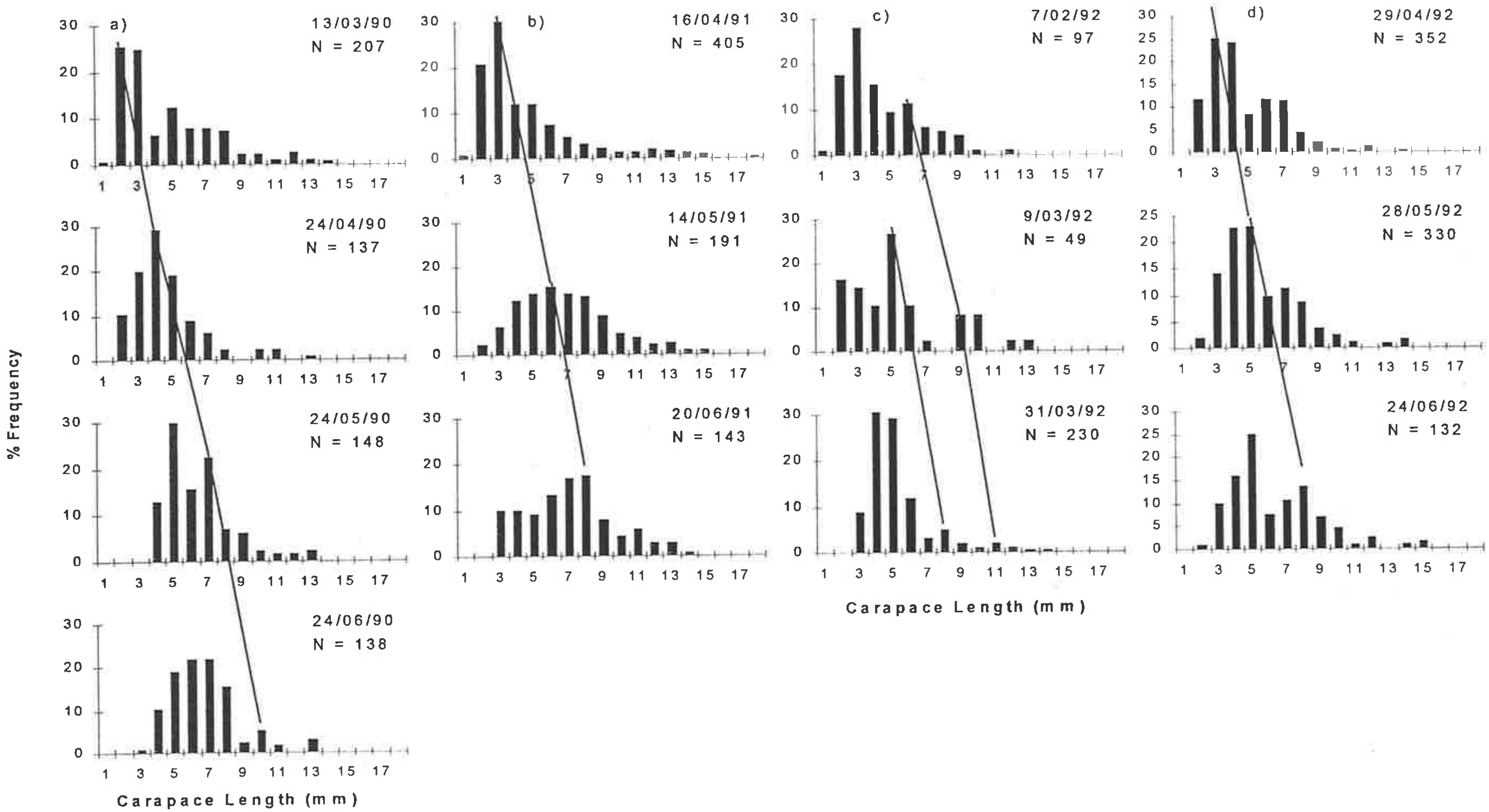


Figure 6.9a Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Port Clinton for 13 March 1990 to 24 June 1990, b) 16 April 1991 to 20 June 1991, c) 7 February 1992 to 9 March 1992, d) 29 April 1992 to 24 June 1992.

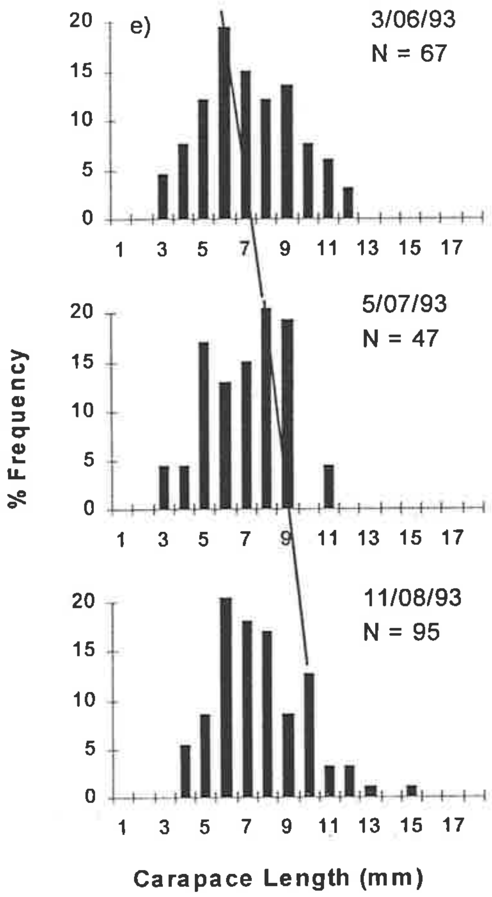


Figure 6.9b Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Port Clinton for e) 3 June 1993 to 11August1993.

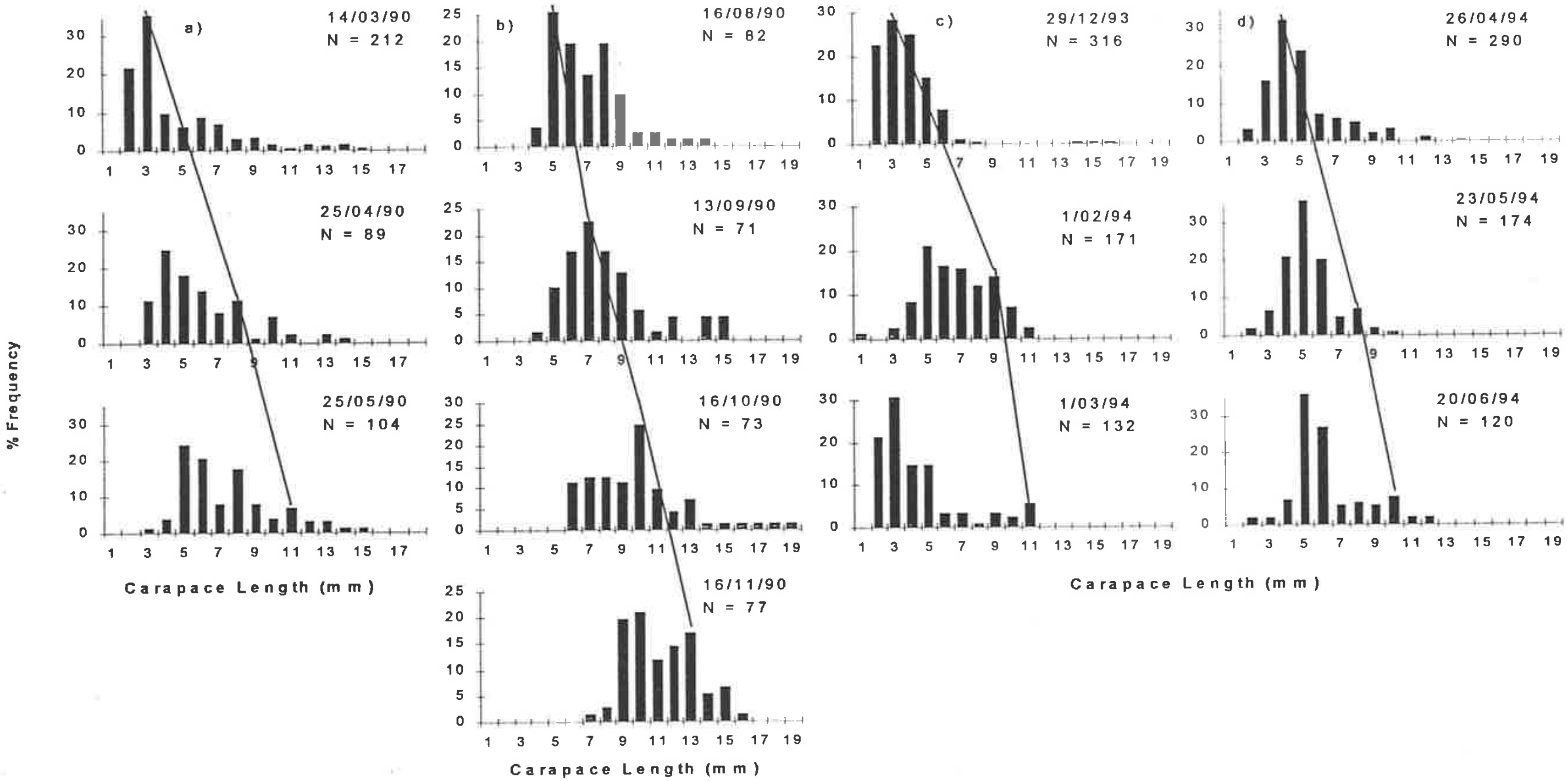


Figure 6.10a Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Ardrossan for a) 14 March 1990 to 25 May 1990, b) 16 August 1990 to 16 November 1990, c) 29 December 1993 to 1 March 1994, d) 26 April 1994 to 20 June 1994.

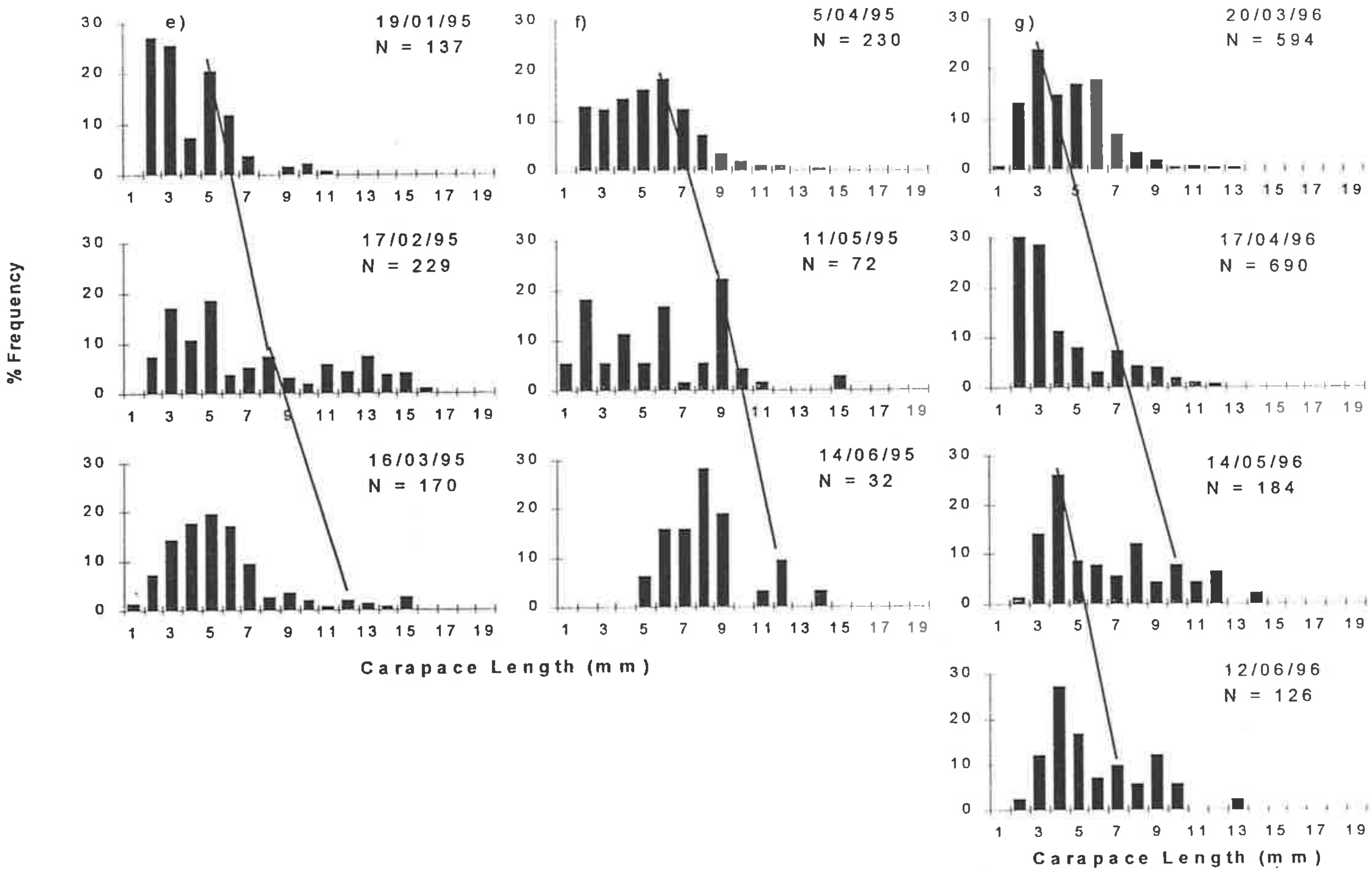


Figure 6.10b Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Ardrossan for, e) 19 January 1995 to 16 March 1995, f) 5 April 1995 to 14 June 1995 g) 20 March 1996 to 12 June 1996.

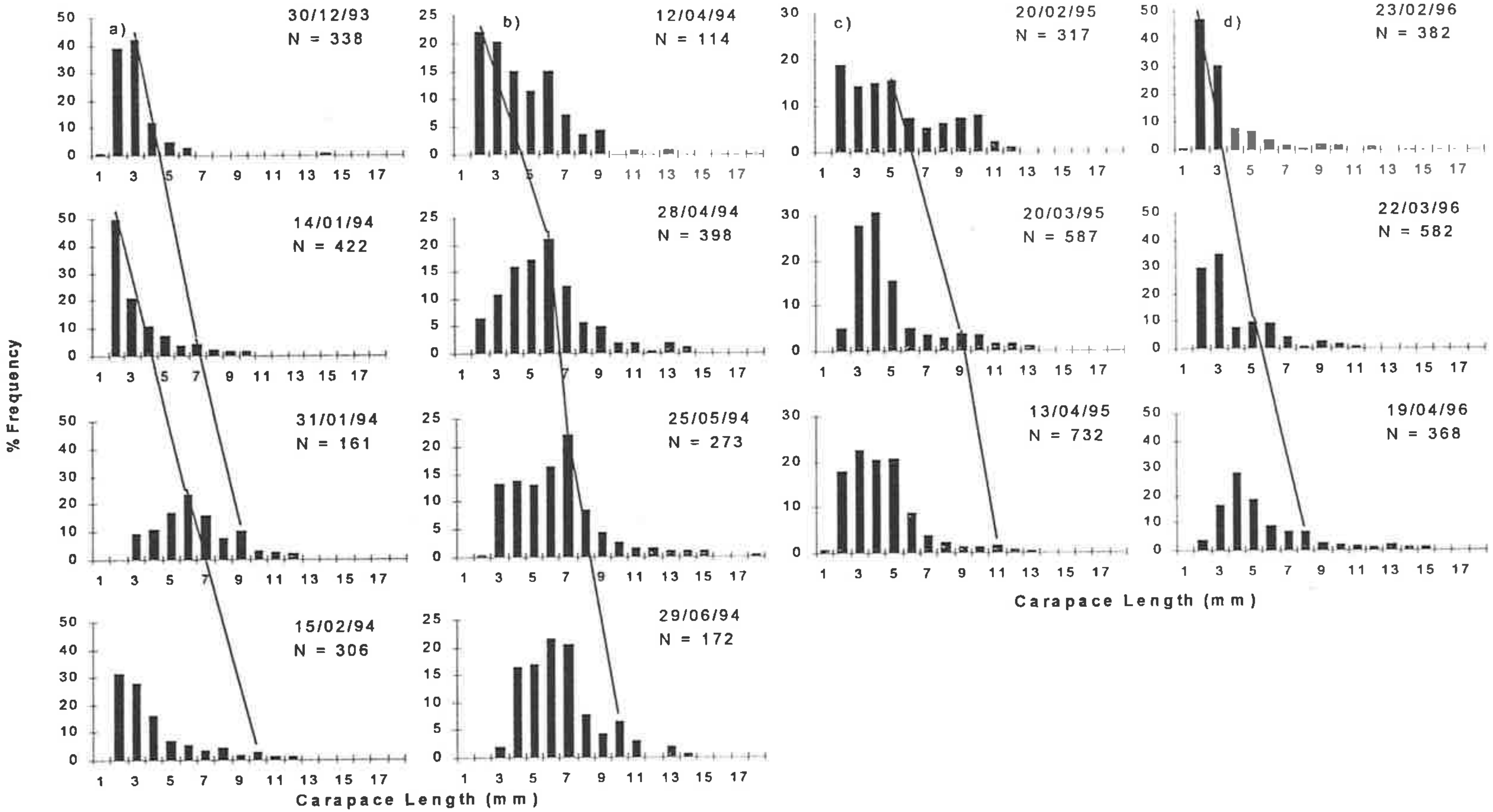


Figure 6.11 Cohort progression of *Penaeus latisulcatus* used in the estimation of growth rates at Webb Beach for, a) 30 December 1993 to 15 February 1994, b) 12 April 1994 to 29 June 1994, c) 20 February 1995 to 13 April 1995, d) 23 February 1996 to 19 April 1996.

6.3.3. Laboratory growth trials at 19.5°C

6.3.3.1 Relationship between moult increment and intermoult period with size/weight

The moult increment (MI) in weight increases with the weight of the individual (Figure 6.12). The relationship has the form: MI = 0.0946 weight (g) + 0.023, ($r = 0.802$, $P < 0.0001$). High variability is observed in weight gain with moult increment at one size. The intermoult period (IP) also increases with increasing size (CL) of the individual (Figure 6.13). The relationship has the form: IP = 0.1847CL + 0.4199 ($r = 0.818$, $P < 0.0001$).

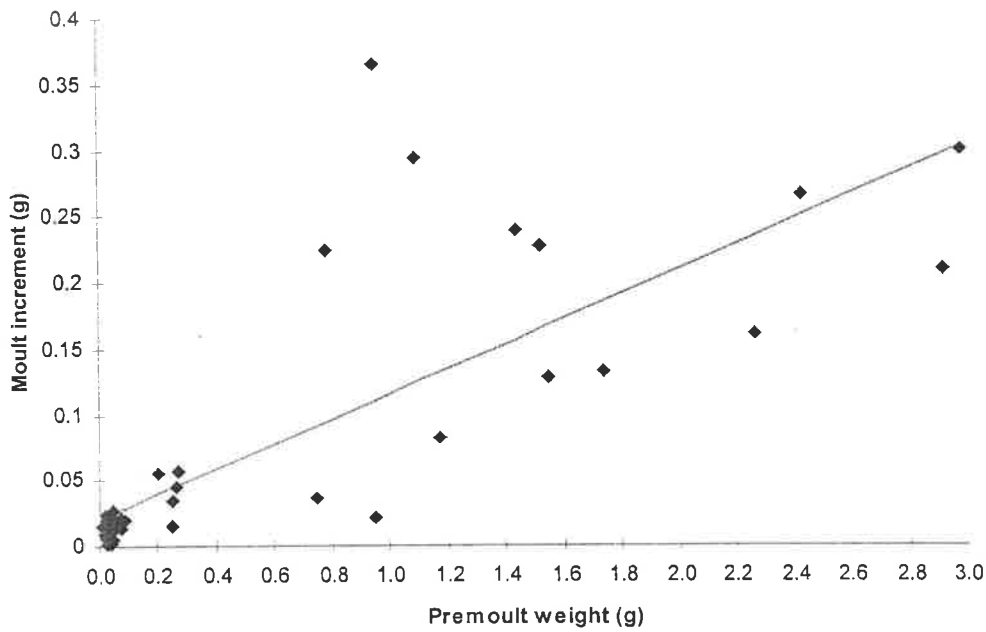


Figure 6.12 Relationship between premoult weight and moult increment (MI) in juvenile *Penaeus latisulcatus* held in pairs under laboratory conditions at 19.5°C and fed three times a week. The relationship has the form:
MI =0.0946 weight (g) + 0.0203, (N = 41, r = 0.802, $P < 0.0001$).

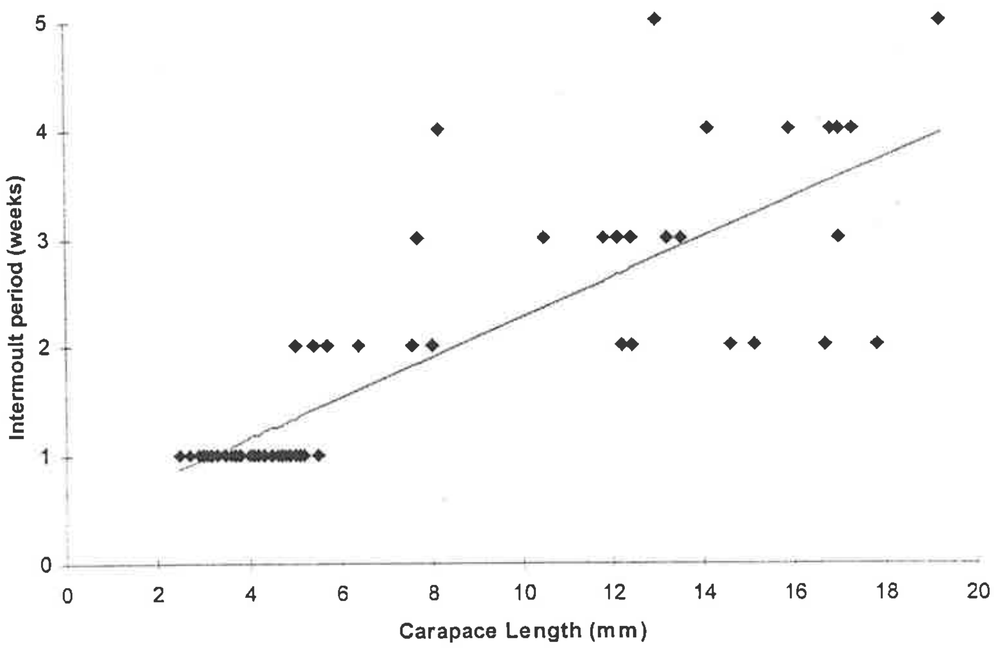


Figure 6.13 Relationship between carapace length (CL) and intermoult period (IP) in juvenile *Penaeus latisulcatus* held in pairs under laboratory conditions at 19.5°C and fed three times a week. The relationship has the form: IP = 0.1847CL + 0.4199 (N = 65, $r = 0.818$, $P < 0.0001$).

6.3.3.2 Juvenile length/weight relationship

Data collected during the experiment on prawn length and weight were combined with measurements of juvenile prawns that were excess to the experiment (total N = 325) to provide a length/weight relationship. The relationship is in the form: Weight (g) = a CL ^{b} and is: Weight (g) = 0.000662 CL $^{2.9076}$ (Figure 6.14).

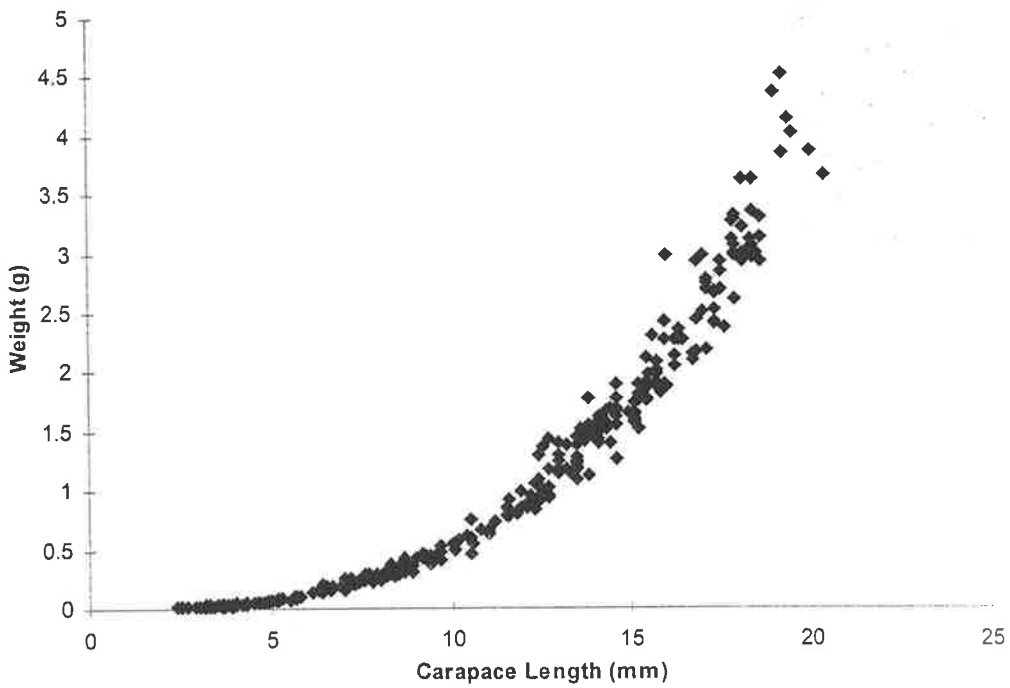


Figure 6.14 Relationship of size (mm CL) to weight (g) for juvenile *Penaeus latisulcatus* (N = 325) caught at Port Wakefield during April 1997. The equation for the relationship is Weight (g) = $0.000662\ CL^{2.9076}$.

6.3.3.3 Average growth pattern of Penaeus latisulcatus with size (CL) and weight

The estimated step-wise weekly growth of *P.latisulcatus* from an initial size of 3.2 mm CL is depicted in Figure 16.15. On average, for the first ten weeks, the growth rate was approximately 1 mm per week. However, a prawn may not moult each week. Over the following seven weeks as the individual became larger, average growth rate was approximately 1.4 mm CL per week (at a constant temperature of 19.5°C). Generally moulting occurs at three-week intervals. The estimated growth in weight (g) is calculated from the length/weight relationship described in 6.3.3.2 and shows a proportionately higher step-wise increase for weigth- increase over time (Figure 16.16).

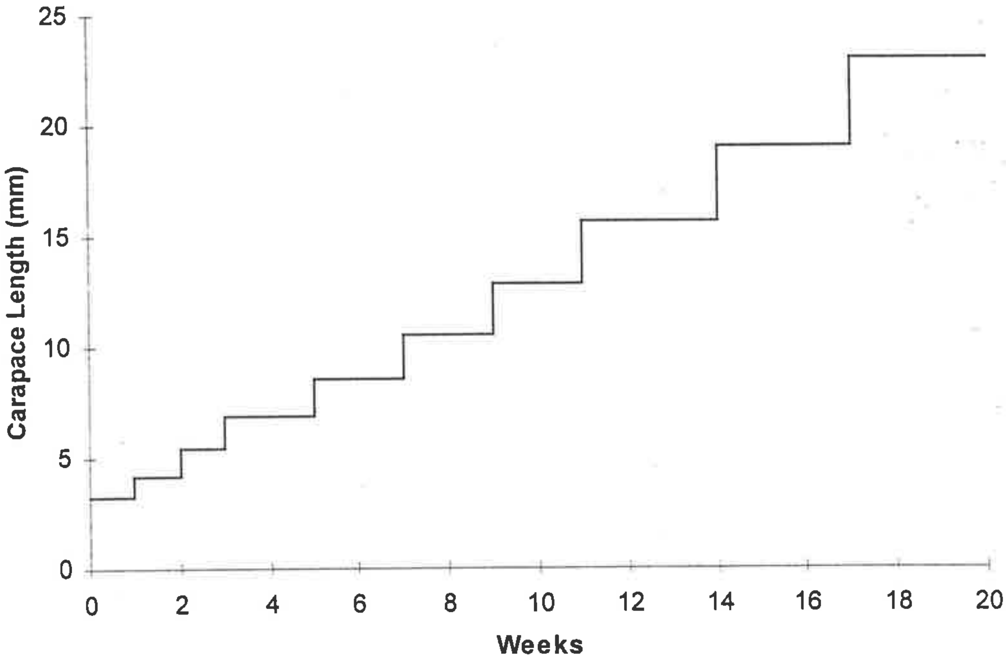


Figure 6.15 Average growth pattern (CL) of juvenile *Penaeus latisulcatus* under laboratory conditions at 19.5°C with an initial size of 3.2 mm CL.

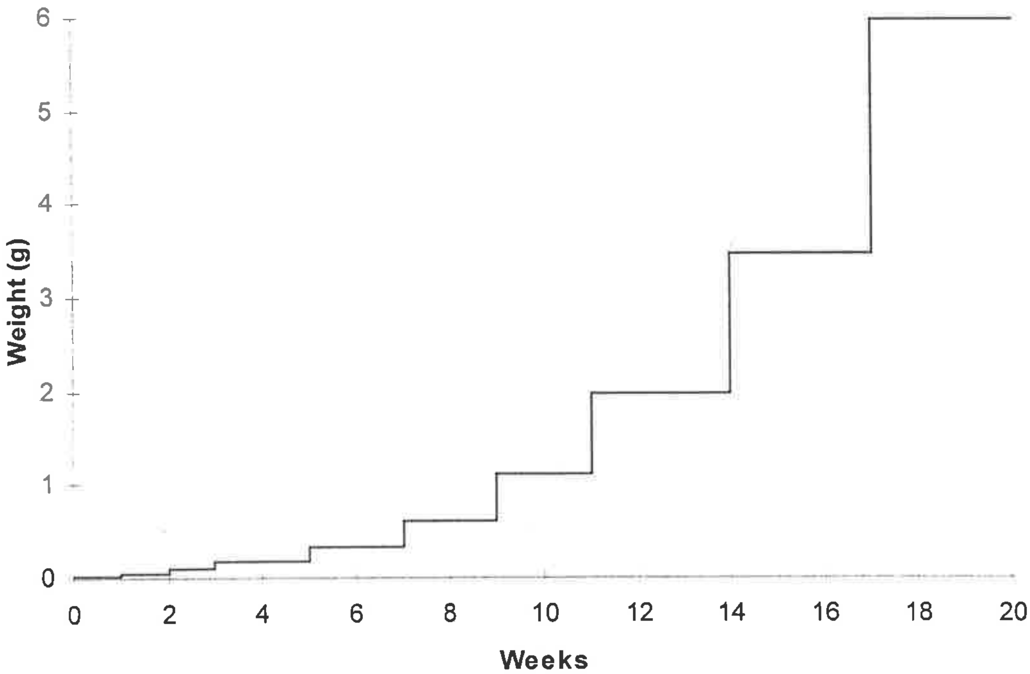


Figure 6.16 Average growth pattern (g) of juvenile *Penaeus latisulcatus* under laboratory conditions at 19.5°C with an initial weight of 0.019g.

6.3.4 Mortality

6.3.4.1 Variation in mortality between sites and years

Variation in mortality is observed between sites and years (Table 6.5). Yearly variability within a site shows no consistent pattern between sites.

Table 6.5 Natural mortality and percentage mortality per week for juvenile *Penaeus latisulcatus* (≥ 3 mm CL) in nursery sites during June/July to November 1990 to 1994. ns – no sampling

Site	Port Arthur		Pt Wakefield		Port Clinton		Ardrossan		Webb Beach	
Year	M^{-}	$\%^{-week}$	M^{-}	$\%^{-week}$	M^{-}	$\%^{-week}$	M^{-}	$\%^{-week}$	M^{-week}	$\%^{-week}$
1990	0.083	7.95	0.180	16.48	0.139	13.02	0.010	1.02	ns	ns
1991	0.090	8.61	0.104	9.84	0.102	9.70	0.009	0.94	ns	ns
1992	0.098	9.32	0.063	6.07	0.120	11.28	0.002	0.20	ns	ns
1993	0.143	13.36	0.129	12.12	0.040	3.88	0.074	7.09	-	-
1994	0.065	6.26	0.114	10.75	0.077	7.42	0.026	2.60	0.078	7.49

A two-way ANOVA without replication for Year and Site indicated no significant variation between Years ($P = 0.6083$) but showed a significant variation among Sites ($P = 0.0033$). A Bonferroni multiple range test indicated that all sites were similar except Ardrossan, which was significantly different from all other sites.

6.3.4.2 Variation in mortality with initial density

The slope of the line for a linear fit of initial density and weekly instantaneous mortality was significant ($r = 0.605$, $P = 0.004$) indicating evidence of density dependence in mortality rates in nurseries (Figure 6.17).

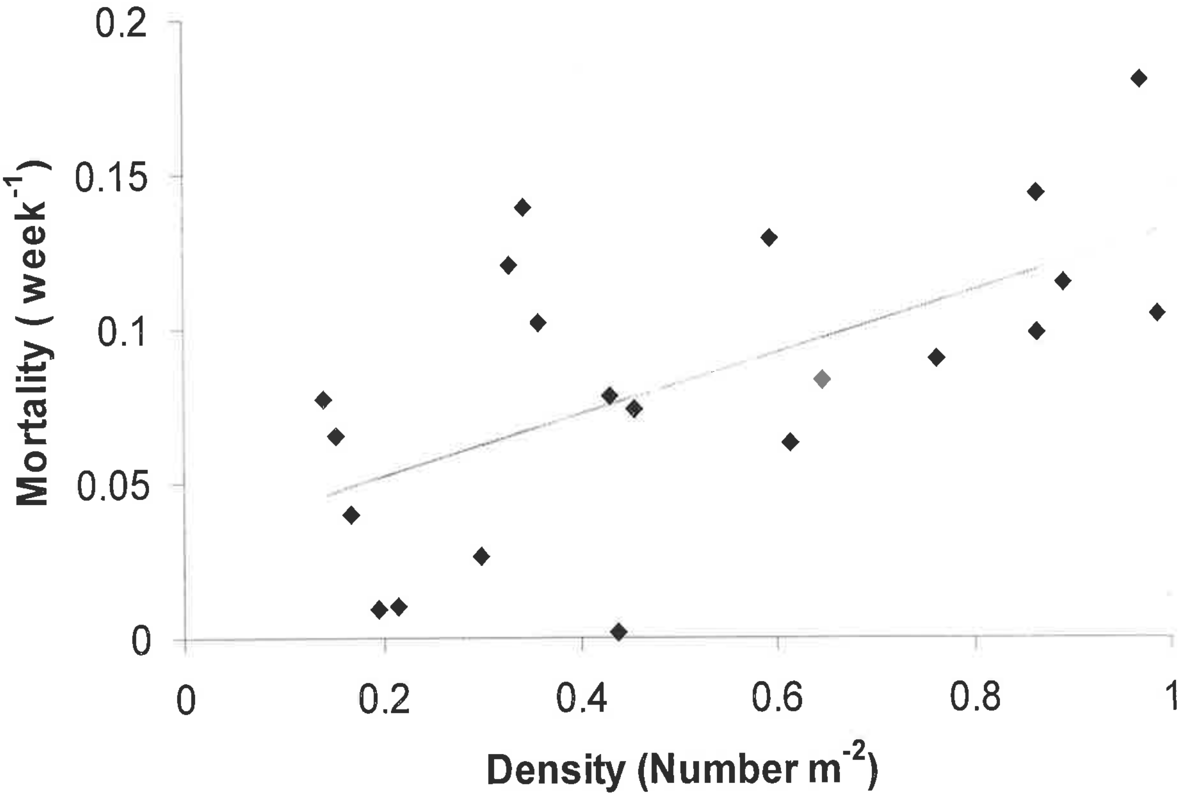


Figure 6.17 Relationship between density of prawns in nurseries (all sites) during June 1990 to 1994 (only June 1994 for Webb Beach) and estimated mortality between June and November for each year (1990 to 1994). The linear regression of the form: Mortality = 0.100097*Density + 0.032046 (r = 0.605, P = 0.004).

6.3.4.2 Mortality estimation during summer 'settlement' period

Summer mortality appears variable between years and higher mortality rates are observed over summer (Table 6.6), compared to winter months (Table 6.5).

Table 6.6 Mortality rate and percentage mortality per week for juvenile *Penaeus latisulcatus* over summer periods for Port Arthur in 1991, 1992, 1994 and 1995, Port Clinton in 1992, Ardrossan in 1994 and 1995 and Webb Beach in 1995.

Location	Year	Mortality ($^{-week}$)	% Mortality ($^{-week}$)
Port Arthur	1991	0.43	42.07
	1992	0.17	16.42
	1994	0.27	26.44
	1995	Cohort 1: 0.18	Cohort 1: 17.42
		Cohort 2: 0.24	Cohort 2: 22.88
Port Clinton	1992	Cohort 1: 0.15	Cohort 1: 14.61
		Cohort 2: 0.15	Cohort 2: 14.93
Ardrossan	1994	0.34	33.37
	1995	0.29	28.35
Webb Beach	1995	0.28	28.34

6.4 Discussion

Juvenile *Penaeus latisulcatus* up to 20 mm CL occur in nurseries. Their size distribution is highly skewed with 2 to 7 mm CL sizes comprising 90% of the catches overall. This skewness can be attributed to the high numbers of postlarvae that settle into nurseries between January and April dominating the catches. Highly skewed size distributions have also been observed in nurseries for *P. latisulcatus* and other prawn species. In Spencer Gulf, SA (Carrick 1996), *P. latisulcatus* 3-7 mm CL comprised 69% of the population in nurseries. A similar size distribution was observed for *P. esculentus* in Moreton Bay, Queensland (O'Brien 1994a). Very few individuals > 10 mm CL of *P. semisulcatus* and *P. esculentus* were found in the Embley River estuary, Queensland (Haywood *et al.* 1995) or in shallow seagrass communities on Groote Eylandt, Gulf of Carpentaria (Loneragan *et al.* 1994) while over a six-year study Vance *et al.* (1996) found that only 1.3% of *P.semisulcatus* were over 10 mm CL in the Embley River estuary. In Gulf St Vincent, this skewness in size distribution is most obvious in the northern sites, Webb Beach, Port Wakefield and Port Arthur, that have highest settlement abundances.

The decline in numbers of larger individuals (> 10 mm CL) may indicate mortality, movement out of the sampling area, emigration out of the nursery site or a combination of all three. Potter *et al.* (1991), sampled the Peel-Harvey estuary in WA using a beach seine and found considerable numbers of individuals of *P. latisulcatus* which were greater than 12 mm CL, including some around 20 mm CL. Sampling at the entrance channel to the estuary indicated that prawns around 20mm CL emigrated out into shallow offshore areas. Carrick (1996) sampled areas offshore of nursery areas in Spencer Gulf and ascertained that prawns were at least 15 mm CL when they moved out of nurseries. This is most likely the same for prawns in GSV, although on occasion prawns as small as 12 mm CL have been observed in offshore commercial catches and research survey trawls (personal observation).

The low numbers of prawns above 7 mm CL within the areas sampled probably reflects the true size composition in these narrow bands between the high water mark and seagrass beds (100-300 m wide). Only a small number of larger prawns > 15 mm CL were captured when the same areas have been sampled using a beam trawl (February 1992 (3.2.2) and April 1997 (6.2.3)) indicating that not many large prawns occur in the areas. Similarly, O'Brien (1994a) found that he had to sample more intensively to capture substantial numbers of the larger individuals of *P. esculentus* in Moreton Bay, Queensland.

Comparison of the jet net and a beam trawl indicated they caught a similar size range of individuals, although the proportion of smaller individuals caught by the jet net was higher (3.4.7.). The jet net is used during the day when all prawns are buried and should have similar vulnerability to the sampling gear. Penn and Stalker (1975) observed that escape from their jet net was unlikely since turbulent flow generated by the water jets and the forward movement of the sled would prevent disturbed prawns from burying before the collecting net reached them and that the prawns remained buried prior to the jets passing over them. The jet net is an effective sampling system that collects representative size distributions. The low numbers of larger individuals requires the sampling of a larger area to collect higher numbers of larger individuals.

Investigation of the monthly size structure in northern (three sites combined) and southern sites (two sites combined) indicate similar patterns in changes of size structure, although some differences in the timing of these changes are observed. These differences are also apparent between years and sites and within sites between years. High settlement is observed between January to April. During this period, the mean size of individuals range between 3.5 mm and 3.75 mm CL in northern sites (range 1-12 mm CL) and 4.1 to 5.0 mm CL in southern sites (range 1-17 mm CL).

Low or no settlement is observed between May and November. During May to September, mean size of individuals change from 4.7 mm CL to 6.5 mm CL in northern sites and 5.7 mm CL to 7.9 mm CL in southern sites. This indicates a period of little or slow growth. During October to December faster growth is apparent with the mean size changing from 7.2 mm CL to 12.2 mm CL (excluding newly settled individuals) for northern sites and 8.5 mm CL to 12.0 mm CL in southern sites.

In December, newly settled postlarvae are apparent as well as a small number of larger individuals from the previous year's settlement. The low number of larger individuals may indicate mortality and emigration out of nurseries. The largest individuals found in nurseries were 20 mm CL and it appears that most juvenile prawns have moved out of the sampling area by this size. It may be possible that a change in habitat preference of larger individuals occurs and they occupy areas further offshore but still inshore of fishing grounds.

Juvenile prawns may move out of nurseries as a response to their size (Benfield *et al.* 1990, Dall *et al.* 1990, Potter *et al.* 1991, O'Brien 1994a, Loneragan *et al.* 1994) or due to changes in environmental conditions, particularly high rainfall events (Staples and Vance 1986, Haywood and Staples 1993). In Gulf St Vincent, environmental conditions do not fluctuate as greatly as conditions in tropical regions and size is probably more important as a cue for emigration than environmental variables. The residence time in nurseries may vary depending on the time of settlement into nurseries. With continuous settlement during January to April, a distinct change in size composition is not obvious and therefore the timing of emigration is unclear. However, new recruits to the fishery (≤ 33 mm CL males, ≤ 35 mm CL females, see 7.2.1.6.) are observed in higher numbers between April and June indicating that emigration from nurseries has taken place just prior to or during this period. A distinct decline in numbers is observed between November and December indicating a second emigration from nurseries of overwintered individuals.

Estimation of growth and mortality rates for each nursery site was possible using field abundance and size composition information for some seasons and years. It was difficult to follow cohorts over three or more consecutive sampling periods, and so only a few data sets could be used for growth estimation. This was also the case for *P. latisulcatus* in Spencer Gulf (Carrick 1996) and *P. esculentus* and *P. semisulcatus* (Loneragan *et al.* 1994). The limited number of estimates of growth have meant that the results are descriptive only.

Growth appears to be seasonal with highest growth in summer. Yearly differences in growth rates were observed at Port Arthur during summer between 1991 to 1995. Mean growth rates varied from 0.53 mm for Port Clinton and 0.65 mm CL per week for Port Wakefield in winter and 0.71 mm for Port Clinton and 1.28 mm CL per week for Webb Beach in summer. Spring and autumn growth rates were intermediate of winter and summer growth rates.

Laboratory trials using prawns (range, 3-18 mm CL) collected from Port Wakefield indicated that both moult frequency and moult increment increased with increasing size of individual. This is the pattern for many Crustacea, although the exact nature of the change depends on the species studied (Dall *et al.* 1990). A linear relationship was found between the premoult weight and moult increment in weight. Similar linear relationships have been found for adult *P. setiferus* (Lindner & Anderson 1956) and *P. monodon* (Motoh 1981), juvenile *P. merguiensis* (Staples & Heales 1991) and with log transformed data for small *Cherax destructor* (Geddes *et al.* 1988).

Very small individuals (< 4 mm CL) moulted at least once a week. It was difficult to observe moults of the small prawns and a more precise determination of moult frequency could not be made. Heales *et al.* (1996) have estimated that small (2-5 mm CL) tiger prawns, *P. semisulcatus* moult every three days in tropical waters. Larger individuals (4-18 mm CL) moulted less frequently, from every week to every three weeks.

Laboratory results in this study indicate that over a ten-week period, 3 mm CL postlarvae show an average growth rate of approximately 1.0 mm CL per week at a temperature of 19.5°C. When the individuals were larger (14 – 20 mm CL), the average growth rate was approximately 1.4 mm CL per week. Growth did not necessarily occur each week due to a longer intermoult period for larger prawns. These estimates are higher than those quoted by Wu (1990) who determined growth rates between 0.7 and 0.8 mm CL per week for juvenile *P. latisulcatus* (7-15 mm CL) at 21°C and salinities 32‰ to 44‰ under laboratory conditions.

Under field conditions in Peel Inlet Western Australia, *P. latisulcatus* reached around 8 mm CL from September to December (Potter *et al.* 1991) which is approximately 0.6 mm CL per week and in east Africa the estimated growth in total length (TL) was 10 mm per month (Subramaniam 1990).

Winter growth rates, estimated from modal progression is similar to growth estimates of *P. latisulcatus* by other researchers (Subramaniam 1990, Potter *et al.* 1991). Estimated summer growth rates are higher than in those studies. The apparent higher rate of growth observed over summer is probably related to water temperature. Water temperatures in nurseries decreased to 11.5°C in winter whilst summer temperatures reached 24.4°C. Even higher temperatures can be experienced in nurseries in summer when tidal flats are exposed in the heat of the day. Sampling on a summer afternoon has shown water temperatures as high as 28.5°C. Increasing growth rate with increasing temperature has been demonstrated for a number of prawn species (Edwards 1977, Staples 1980b, Benfield *et al.* 1990, Dall *et al.* 1990, Staples & Heales 1991, Haywood & Staples 1993, O'Brien 1994a,b) and occurs within specific zones of tolerance for Crustacea (Stevens 1990). The increase in growth is due to a greater activity and feeding producing a decrease in the intermoult period (Hartnoll 1982) at warmer temperatures.

Variation in growth rates between years was seen for summer periods at Port Arthur. This was the only site where estimates of growth rates were possible for the same season over several years. Inter-annual differences in growth patterns have also been observed for *P. esculentus* in Moreton Bay, Qld.(O'Brien 1994a)

Salinity did not have an apparent effect on growth in *Penaeus latisulcatus*. Change in salinity throughout the year is small in Gulf St Vincent compared to most estuarine and tropical prawn nurseries. Lowered salinities have been shown to affect growth of *P. latisulcatus* (Kathirvel *et al.* 1986) at below 15‰ but these low salinities were not experienced in the nursery areas sampled. Salinities greater than 48 ‰ had effect on growth of *P. latisulcatus* under laboratory conditions (Wu 1990) but this was not significant. Generally, salinities encountered by *P. latisulcatus* under natural conditions in GSV are within their broad tolerance range (Zed 1977, Wu 1990).

Haywood & Staples (1993) used MIX to separate cohorts and showed that for *P. merguiensis,* whilst temperature explained 40% of the variance in growth, an additional 20% was explained by the density of prawns four weeks after settlement. Edwards (1977) showed that for *P. vannamei* under natural conditions growth was density dependent at densities higher than 2.5 prawns m^{-2} whereas under outdoor pond culture conditions 10-15 prawns m^{-2} resulted in optimum growth and survival (Wyban 1987) for the species. Maguire and Leedow (1983) showed an exponential decrease in the growth of pond reared *Metapenaeus macleayi* when stocking densities were increased from 6.1 to 21.2 prawns m^{-2}. For *P. latisulcatus*, Wu (1990) undertook initial experimentation to determine appropriate stocking densities for juveniles in the laboratory and found that 31 to 37 prawns m^{-2} to be an acceptable rate. The highest density of prawns sampled in nurseries was 6.12 prawns m^{-2} and no effect of density was observed on growth even in summer when highest densities were encountered.

Penaeus latisulcatus can grow quickly over the summer period and growth rates observed are comparable to growth rates in tropical regions. Those postlarvae that settle in late December to January can increase in size rapidly to a size (around 20 mm CL) at which they move out of nurseries. These contribute to the fishery as 'direct' recruits; that is, they are spawned late the previous year and move out of nurseries by May/June of the following year. As growth decreases with decreasing temperatures over autumn and winter, those prawns that do not reach a size at which they emigrate or those that settle later in the season (March and April), remain in the nurseries over the cooler periods. The overwintering juveniles are the 'indirect' recruits to the fishery.

The range of mortalities found during June-July to November 1990 to 1994 was 0.20-16.48% per week with a mean of 7.88% per week. When all sites are combined, there was no significant difference in mortality between years even though individual sites show some yearly variation. Carrick (1996) estimated the natural mortality of *P. latisulcatus* in Spencer Gulf during July to November for 1992 to be 6.20% per week and 1993 to be 3.63% per week. He suggested summer mortality rates would be at least three times these levels. In GSV, summer mortalities were estimated for some sites and some years and varied between 14.61% per week at Port Clinton in 1992 to 42.07% per week at Port Arthur during 1991. Estimated summer mortality rates were generally higher than mortality rates estimated for the June-July to November period. Summer mortality rates may, however, be an overestimate as fast growth during this period could result in some emigration out of the area, resulting in lower numbers of larger individuals. Mortality in GSV during winter was similar but slightly higher than reported for Spencer Gulf (Carrick 1996) and may reflect geographic differences in mortality patterns or just the characteristics of the two years studied in Spencer Gulf.

Most studies estimating natural mortality for juvenile prawns have been over one or up to three years. Most exhibited high variability in mortality rates. The winter mortality rates in Gulf St Vincent are generally much lower than those quoted for most other species. Summer mortalities in GSV are higher and may be closer to other estimates. In Queensland, O'Brien (1994a) found for *P. esculentus,* natural mortality rates to vary between 5.8 to 25.2% per week over two years with higher mortality occurring over summer. Haywood & Staples (1993) found over a three-year study of *P. merguiensis* that mortality ranged from 20.5% to 60.9% per week and increased with temperature. Edwards (1977) estimated the mortality rate of *P. vannamei* in enclosures within a Mexican coastal lagoon complex to be 41% per week. McCoy (1972) found weekly mortality rates for juvenile *P. duorarum* to be 45.6% and for *P. aztecus* to be 43.5% in North Carolina and Minello *et al.* (1989) found for postlarval and juvenile *P. aztecus* in Galveston Bay salt marshes, that mortalities were between 33% and 61% in 1982 and in 1987 they were between 23% and 39%.

The principal cause of mortality in juvenile prawns is considered to be predation (Dall *et al.* 1990). In 1987 Minello *et al.* (1989) used predator-exclusion cages with *P. aztecus* and found mortality to be less than 3% per week overall. Fish are key predators as well as crabs and birds. Fish size influences the extent to which they feed on prawns. Very small fish feed on penaeids to only a minor extent. Fish around 10 to 30 cm total length feed heavily on prawns but larger fish feed on them to a lesser extent (Dall *et al.* 1990). Carrick (1996) observed that in Spencer Gulf, several fish species had substantial numbers of juvenile prawns in their guts. These fish predators were pleuronectids, sillaginids and platycephalids. Large numbers of small (20 to 24 mm CL) sub-adult prawns were observed in the guts of the flounder *Pseudorhombus arsius*. He also conducted bait trials using squid, mullet, meat and prawns and found that most fish were attracted to prawns compared to the other baits. The species captured were, striped perch *Pelates sexlineatus*, tommy rough *Arripis georgianus*, salmon trout *Arripis trutta*, yellowfin whiting *Sillago schomburgkii*, juvenile King George whiting *Sillaginodes punctata*, long toothed flounder *P. arsius*, greenback flounder *Rhombosolea tapirina* and small flathead *Platycephalus spp*. All of these species occur in GSV and could be predators of juvenile prawns. In addition, large numbers of gobies are found in both gulfs that may be significant predators. At times, relatively high numbers of blue swimmer crabs, *Portunus pelagicus,* and pebble crabs, *Philyra* spp., are also caught in juvenile sampling trawls and could contribute to predation. The influence of birds on predation in GSV is unknown but studies on wading, swimming and diving birds (Forbes & Benfield 1986) suggest that prawns in intertidal and shallow nursery areas are vulnerable to bird predation. Since *P. latisulcatus* remains buried in exposed or semi-exposed intertidal areas during the day in GSV, birds could probe and find them in the sediment during daytime. Prawns in deeper water are unlikely to be eaten by birds.

For the Gulf of Mexico fishery, Nance & Nichols (1988) found that mortality can vary substantially over years and throughout the spring within a year but that size is important. Mortality of different cohorts during the same sampling period varied from 73% for small individuals to 1% for large juveniles. In this study, due to the low number of individuals sampled at larger sizes it was not possible to determine differences in mortality with size. It is likely that larger individuals become less vulnerable to predation as observed by Carrick (1996) in Spencer Gulf.

There is a correlation between mortality and high initial densities in nurseries. Carrick (1996) also reported this for *P. latisulcatus* at False Bay, Spencer Gulf. Higher densities may result in intra-specific competition larger numbers of prey may attract predators into an area making individuals more vulnerable.

Most studies on juvenile prawn growth and mortality have been undertaken in estuarine conditions where postlarval and juvenile prawns can experience large and often unpredictable fluctuations in environmental conditions. For these prawns, mortality appears to be large and highly variable, with the estuarine period in the life cycle being critical in the regulation of recruitment to the fishery (Nance & Nichols 1988). Staples & Vance (1985, 1987) highlighted that environmental conditions encountered during the nursery phase of *P. merguiensis* influenced whether a particular cohort of juvenile prawns contributed significantly to the offshore population, through its effects on both survival and growth of the cohort. However, O'Brien (1994a) considered that productivity of *P. esculentus* in Toondah Harbour, Queensland was influenced by the size of the settling cohort rather than by environmental effects on mortality. He found that for *P. esculentus* mortality levels were relatively low and more constants. This is also the case for prawns in Gulf St Vincent where a constant, predictable environment leads to relatively low and predictable mortality.

Thus, the yearly mortality overall appears similar over the seven years studied and hence the amount of settlement will play an important role in regulating juvenile numbers. The timing of settlement and temperatures experienced while in the nurseries will determine how fast the prawns will grow and when they move out of nurseries. The processes controlling spawning events and the direction and timing of larval advection appear to be very important in the life-history pattern of *P. latisulcatus* and subsequent success of recruitment to the fishery.

In nurseries in Gulf St Vincent, settlement in late December to early January would allow fast growth of individuals during warm months and leads to prawns leaving the nursery areas by May/June onto fishing grounds as direct recruits to the fishery. Mortality acting on these individuals appears high for much of the four to five months they spend in nurseries. Those prawns settling later, (late March to early April) may spend twice as long in nurseries because growth is comparatively slow until water temperatures increase after September/October. These prawns move out of nurseries in late December to early February as indirect recruits. Although they spend a longer period in the nursery, mortality rates are lower during these 10 months and so similar numbers of prawns may survive overall to become the overwintered recruits to the fishery. The strength of either recruitment will therefore depend on the timing and initial numbers settling in nursery areas.

7. COMMERCIAL FISHERY FLEET DYNAMICS AND HARVESTING PRACTICES, RELATIONSHIPS BETWEEN LIFE-HISTORY STAGES AND THE EFFECTIVENESS OF A TWO-YEAR CLOSURE ON POSTLARVAL SETTLEMENT, JUVENILE ABUNDANCE AND RECRUITMENT TO THE FISHERY

7.1 Introduction

Establishing linkages and a possible relationship between life-history stages of *Penaeus latisulcatus* could allow for prediction of yield from the fishery. This would aid in sustainable management of stocks, particularly in years when below average catches are likely. An early warning would allow conservative harvesting practices and management strategies to be put in place. Conversely when higher catches than average are indicated, then the overall effort and the return on the fishery could increase, with lower risk of over-exploitation.

Difficulties in determining relationships between life-history stages occur due to the short life span and strong environmental factors structuring recruitment in many tropical prawn fisheries (Staples *et al.* 1984). In these situations, the abundance of a particular life history stage or following the progression of stages provides little information on future catches. Instead, for some species such as *P. merguiensis* in Qld., commercial catches have been strongly correlated with rainfall (Vance *et al.* 1985, Staples & Vance 1986). During a six-year study of *P. semisulcatus* in the Embley River, Qld., Vance *et al.* (1996) found that, although some relationships were seen between environmental and catch variables that there was still much unexplained variation in their catch models and the use of environmental measures could not be used to predict catches accurately.

In South Australia, prawns have a longer life span than prawns in tropical regions and environmental factors do not apparently dominate the settlement/recruitment processes. Therefore, it may be possible to observe a correlation with postlarval or juvenile abundance and commercial catches or catch rates. Successful use of larval settlement indices for catch prediction occurs for the western rocklobster *Panulirus cygnus* in Western Australia (Hancock 1981, Morgan *et al.* 1982, Phillips 1986), and mixed success has been shown for catch prediction from sampling postlarval brown shrimp *(Penaeus aztecus)* in Galveston Bay (Christmas & van Devender 1981).

This study has had postlarval and juvenile prawns in nurseries as its main focus. However, at the time of this study, commercial catch monitoring provided information on the sex and size structure of commercially caught and landed prawns and fishery independent surveys were also conducted on commercial stocks. These surveys commenced in Gulf St Vincent in April 1984 and continued until February 1995. During December 1991 to October 1993 the fishery was closed and the number of surveys conducted was reduced. The spatial coverage of these surveys was less than during years when commercial fishing took place.

Fishery independent surveys were introduced to provide an unbiased assessment of the stocks that could be used in conjunction with fishery dependent (catch and effort statistics) information being collected from licence holders. There were several objectives for the surveys:

- provide information on the trends in stocks over time including, levels of recruitment, spawner biomass and potential egg production;
- allow assessment of growth and movement patterns;
- allow determination of catchability effects;
- provide an estimate of natural and fishing mortality rates;
- provide an understanding of spatial and seasonal distribution patterns in conjunction with tagging;
- link with other programmes (postlarval and juvenile studies, environmental parameters) to provide an understanding of the factors which structure recruitment into the fishery.

In this study, Gulf St Vincent fishery fleet dynamics are described in relation to the spatial and temporal changes in fishing patterns through a season and the highly 'targeted' nature of fishing practices in GSV with respect to prawn size. Comparisons are made between the size composition of prawns on the fishing grounds using fishery independent survey information and the size composition of the commercial catch at a similar time.

Relationships between various life-history stages are tested to determine if there may be any predictive capability with respect to future catches. Fishery independent survey information is used to estimate the number of eggs produced by the spawning stock and the recruitment strength to the fishery. The linkages are complex due to the differences in timing of spawning, settlement and recruitment each year and because the longer life span of *P. latisulcatus* means that more than one year-class is fished. Comparisons are made using:

1. Early spawning (October-November), leading to early settlement (December-January), followed by direct recruitment from nurseries to the fishery (April to June). Due to targeting of larger (older) prawns by the commercial fleet, catch per unit effort in the commercial fishery is compared for a calendar year, in the second year after recruitment.
2. Later spawning (February-March), leading to late settlement (April-May) and followed by recruitment of overwintered individuals from nurseries (the following January-February). Commercial catch per unit effort is compared for a financial year, July to December the year after recruitment and January to June two years after recruitment (Figure 7.1).

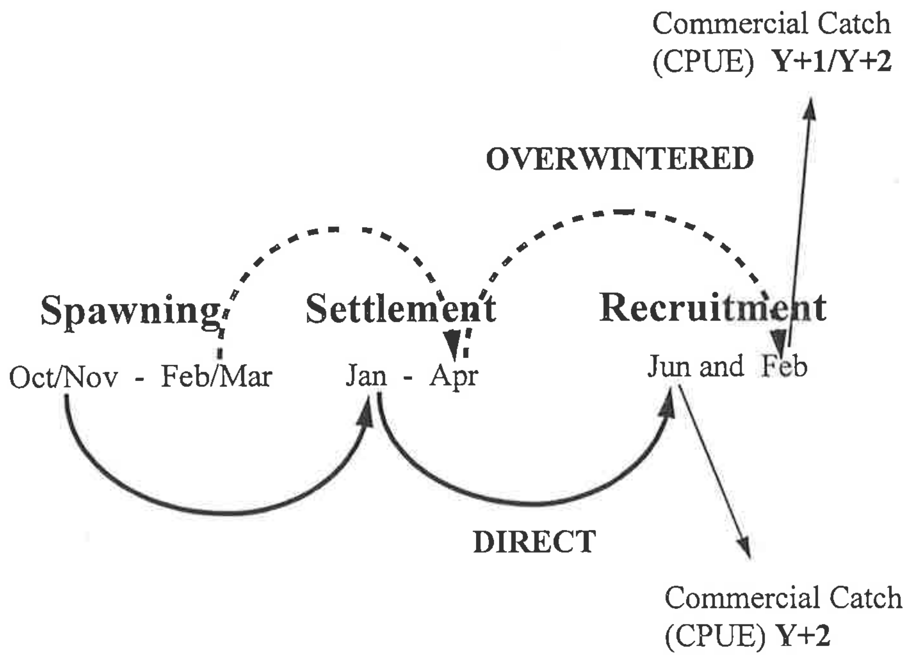


Figure 7.1 Schematic diagram of linkages between life-history stages of *Penaeus latisulcatus* in Gulf St Vincent indicating the timing of spawning, postlarval settlement, recruitment to the fishery and principal time of major catch of each 'year class'.

7.1.1 Management and two year closure of the fishery

Over-exploitation is a major problem for many of the worlds' fisheries. Over capacity in fisheries was a keynote topic for the 1996 World Fisheries Congress (Mace 1997). Numerous management options are available in dealing with over-exploitation, some more politically acceptable than others are. Traditional fisheries theory postulated that penaeid prawns, because of their high fecundity rates and short life spans, were not susceptible to recruitment overfishing (Garcia 1983). This presumed that the spawning stock could not be fished so low that the level of resultant recruits to the fishery was affected. It was considered that environmental factors were the main controlling factors behind yearly recruitment successes or failures (Gunter & Edwards 1969, Neal 1975, Garcia 1984). Other authors highlighted the difficulties in determining stock-recruitment relationships (Walters & Ludwig 1981, Morgan & Garcia 1982, Garcia 1989). However, over the last 10 to 15 years it has been demonstrated that prawns could be susceptible to over-exploitation and could suffer both recruitment and growth overfishing (Penn & Caputi 1985, 1986, Penn *et al.* 1989, 1995, Gracia 1991, 1996, Wang & Die 1996).

As a response to overfishing and concerns about affecting the spawning and recruitment potential of a fishery, a variety of management strategies have been applied. In prawn fisheries, these have included reduction in targeting of a particular species and directing effort on other less vulnerable species (Penn and Caputi 1985), severe restrictions in fishing (Penn & Caputi 1986), and total closure (Carrick 1996). The GSV prawn fishery suffered apparent over-exploitation in the late seventies to early eighties. Increased effort was related to too many participants, increasingly effective fishing gear without corresponding reduction on overall effort and targeting of harvesting on highly vulnerable and important stock components, the key spawner aggregations prior to the spawning period. In response to concerns about the stock, an array of management strategies has been implemented in the GSV fishery.

In 1984 management strategies were put in place to reduce the overall effort in the fishery. In addition to the vessel size, horsepower, headline length and mesh size regulations already in place, supplementary input controls were implemented including area and seasonal closure lines to protect key spawning populations and new recruits. The targeting of larger sized prawns (anecdotal information suggests that during the high exploitation period, overall size of prawn caught was also smaller) and an overall reduction in the number of nights fished. These strategies were instigated to rehabilitate depleted stock levels and these represented substantial changes to traditional fishing practices. The benefits of these measures were seen as increased recruitment levels into the fishery by the late eighties (unpublished). Catch levels had however, not increased due to restrictive harvesting practices. The slow rate of improvement of catches was also related to the life history and longevity of *P. latisulcatus*. With a life expectancy of three to four years (Carrick & Correll 1989, Carrick 1996), several years may be required to detect an improvement in catches, particularly when targeting larger individuals (two to three year olds).

During rehabilitation, continued fishing at relatively low levels allowed cash flow to be generated and provided employment for crew and associated industries. Total closure was always considered as an option during this period, but not implemented due to its extreme impacts on the industry. However, with continued lower catches, in late 1991 the fishery was closed for a period of two and a half years. The fishery re-opened in February 1994. A complete closure is a very drastic management strategy where the income source and employment of numerous individuals are removed. This was particularly the case in GSV where the licence holders had no other options for generating income such as transfer of effort into another fishery.

This closure offered a unique opportunity to investigate the effectiveness of a total closure of fishing on the postlarval settlement rates and subsequent recruitment to the fishery. Although not planned as such, it could be viewed as an adaptive management experiment. Walters (1986) strongly endorsed the use of fleet or fishery manipulation to provide information on the response of stocks to fishing pressure or absence of fishing pressure. Often the variation seen during normal fishing operations does not allow any postulation or extrapolation of stock response in the extremes. However, fleet manipulation is extremely difficult and requires voluntary compliance and cooperation. In practice, very few studies have been possible (Carrick 1988, Sainsbury 1988, Collie & Walters 1991, Walters *et al.* 1993).

7.2 Sampling Methods and Statistical Analysis

7.2.1 Sampling Methods

7.2.1.1 Environmental parameters

During postlarval settlement studies and fishery independent surveys, surface water temperature was recorded at the time of sampling and water samples for salinity were collected at each site. The salinities were later measured using YEO-KAL inductively coupled salinometer and results entered onto an Excel spreadsheet.

7.2.1.2 Commercial catch monitoring of sex ratio and size of prawns caught

Researchers and/or fishers conducted catch monitoring on commercial vessels during normal fishing operations. All fishers and processing staff participating in monitoring were properly trained in unbiased sampling procedures, sexing and measuring. Generally, during a fishing period, at least three vessels participated in monitoring. For each night of fishing, at least one sample of approximately 200 prawns was collected from a trawl, separated into sexes, weighed and measured. In some instances, the sample was collected, labelled and brought ashore. The sample was then later measured at the factory by processing staff or by researchers. Commercial catch size distributions were smoothed using moving averages with an interval of three.

7.2.1.3 Fishery independent stock survey design

Survey design and sampling methodology is described in 5.2.1. Surveys were scheduled (but not always undertaken) to take place four times a year, to coincide with important life-history components. These are spawner abundance and distribution in October-November and February-March and recruitment in February-March, April-May and June. Data from surveys was stored in a Dataflex database and manipulated using FOCUS. Survey size distributions were smoothed using moving averages with an interval of three.

7.2.1.4 Potential egg production

Female prawns $\geq$ 30 mm CL were generally considered to contribute to egg production. Using the fecundity relationship; Fecundity = 1.641 $CL^{3.257}$ (Kangas & Stewart-Rowe, unpublished) for prawns in GSV, the total number of eggs produced by females at each station was calculated using the total number and size of females caught per nautical mile. Carrick (1996) postulated that egg production from larger females may be more viable and therefore egg production from female prawns $\geq$ 42 mm CL was also estimated. In 5.3.1 it was observed that most egg production occurs in northern GSV. These regions were used to estimate egg production for correlation analysis. For February surveys in 1990, 1991, 1994 and 1995, the mean number of eggs produced per nautical mile trawled was calculated for 50 stations in

Blocks 1, 2 and 5 (Figure 7.2) and then an estimate was made for Block 1 (17 stations) only. These stations were consistently sampled in all years. For November surveys in 1990, 1991, 1992 and 1993, 48 stations were consistently sampled in Blocks 1, 2 and 5 and 15 stations were used to estimate egg production in Block 1 only.

7.2.1.5 Postlarval settlement and juvenile prawn indices

Monthly sampling with the jet net was made at Port Wakefield, Port Arthur, Port Clinton and Ardrossan from October 1989 to June 1996 as described in 4.2. Fortnightly samples were additionally taken during peak settlement times (January to June) at Port Arthur from January 1990 to April 1994 and at Port Wakefield from December 1991 to April 1994. The standard sampling procedure consisted of making three to four 100m long trawls at the sampling site, which was identified by buoys or marks from shore. The net was retrieved after the trawl, prawns emptied into a container and the prawns sorted on shore. The samples were then fixed in 5% formalin and returned to the laboratory where they were counted and measured to the nearest 0.1mm with an ocular micrometer. Data was stored on a DBIII$^+$ database and summary information accessed through FOCUS.

Postlarval prawns were considered to be < 3 mm CL and juvenile prawns ≥ 3 mm CL. For testing correlations, estimates of mean number of postlarvae and juveniles m^{-2} for three trawls were made for Port Wakefield, Port Arthur, Port Clinton and Ardrossan, then combined. Two comparisons were made for each year, an early settlement period (late December to early February) and a later settlement period (late February to late April). Using the results of correlations between postlarvae and juveniles for various lag times (4.3.4), a monthly (four-week) lag time was incorporated for comparison of postlarvae and juveniles.

For the evaluation of the fishery closure on postlarval settlement the mean number of postlarvae m^{-2} from three trawls during February to May was estimated for all nursery sites then combined. Juvenile abundance (number m^{-2}) was estimated from information from all nursery sites (combined) during January to June. The years, 1990 and 1991 represent before closure, 1992 and 1993 represent during closure period and 1994 and 1995 represent after closure.

7.2.1.6 Recruitment indices using fishery independent surveys

Sampling methodology is described in 5.2.1. Recruitment can be defined as small prawns moving out onto the fishing grounds from nurseries that become vulnerable to the fishing gear. Fishers in their normal fishing operations do not generally target these prawns. In these analyses, the size of recruits was considered to be ≤ 33 mm CL for males and ≤ 35 mm CL for females. February-March surveys indicated the level of overwintered recruitment to the fishery and June showed the extent of direct recruitment to the fishery. For February-March surveys, the mean number of recruits per nautical mile trawled was calculated for 27 stations that had been consistently sampled in Blocks 1, 2 and 5 during each survey. For June surveys, the mean number of recruits per nautical mile trawled was calculated for 63 stations that had been consistently sampled in Blocks 1, 2, 4, 5 and IS (Figure 7.2). Investigator Strait and Block 4 was included in June recruitment estimations because by June, recruitment into the fishery has spread throughout the gulf and could be underestimated if only using the northern blocks.

For an evaluation of the fishery closure on recruitment, April-May, June and February-March surveys (in the following year) were combined. Due to the absence of surveys for all time periods 1989/90 and 1991 was used to represent the period before closure and 1993/94 and 1994/95 to represent during closure period. No surveys were undertaken after February 1995 so an after closure recruitment index could not be estimated. A total of 36 consistently sampled stations from Blocks 1, 2, 4 and 5 were used (Figure 7.2). Investigator Strait could not be included in the recruitment estimations as it was omitted in survey sampling during March 1991.

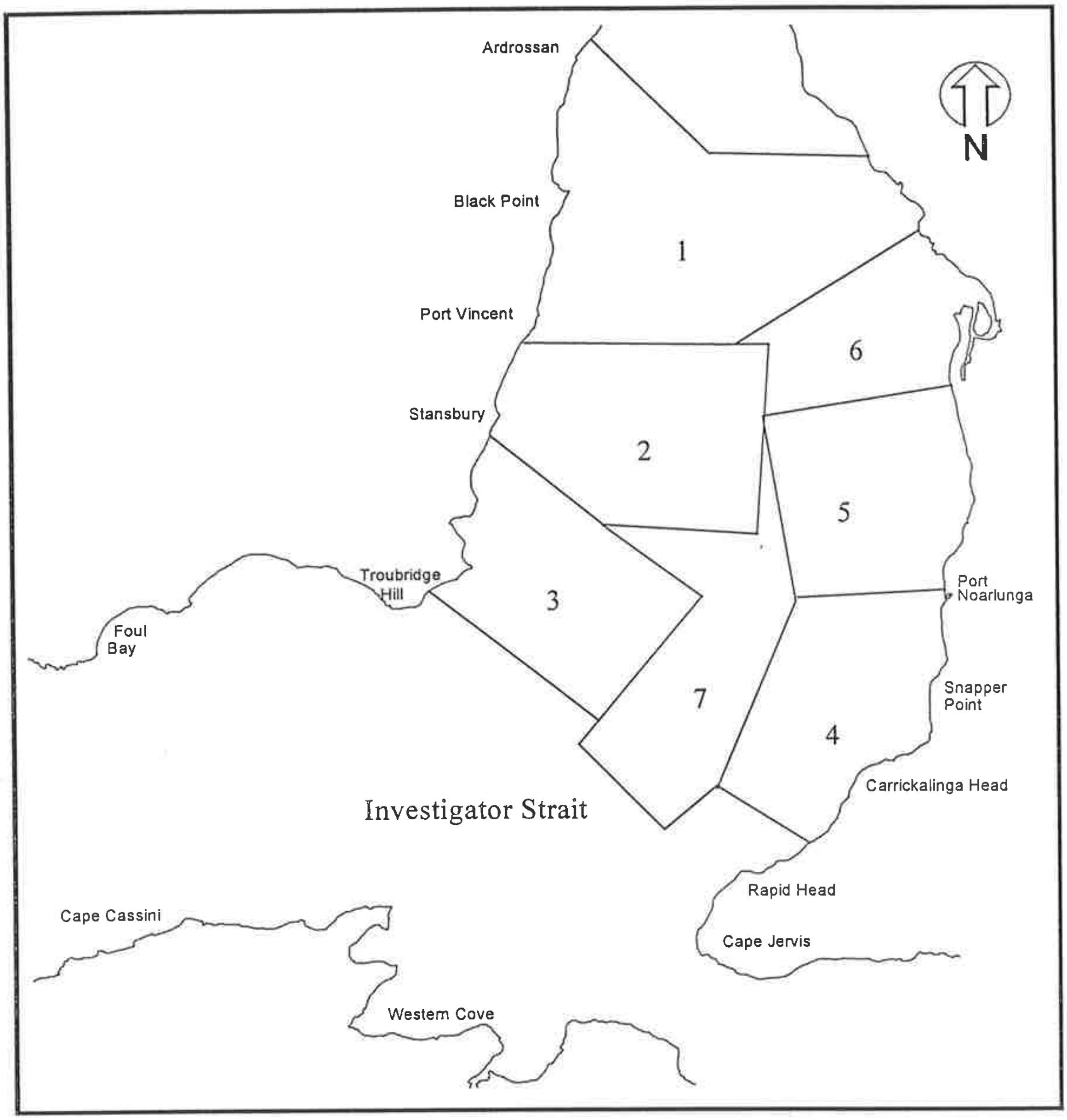


Figure 7.2 Map of Gulf St Vincent indicating survey blocks. Blocks 1, 2 and 5 were sampled during October-November 1989, 1990, 1991 and 1993 and February-March 1990, 1991, 1994 and 1995 and used for estimation of mean number of eggs produced per nautical mile trawled. Blocks 1,2 5 were sampled during February-March 1991,1994 and 1995 and Blocks 1,2,4,5 and IS were sampled during June 1991, 1993 and 1994 for mean number of recruits per nautical mile trawled.

7.2.1.7 Commercial catch and effort statistics

Completion of daily fishing returns is compulsory in the SA prawn fisheries. For each night of fishing and for each trawl shot undertaken, fishers provide information on trawl location (fishing block, Figure 7.3), time of commencement of trawl, duration of trawl (minutes) and estimated catch. At the completion of each month (or fishing period) actual weight landed at processors is also provided. This information allows the collation of spatial and temporal commercial catch and effort information from the fishery. The nominal catch per unit effort (kg/hr trawled) for each calendar and financial year (Figure 1.4 c) is used in these comparisons.

7.2.2 Statistical Analysis

The carapace length frequencies of prawns were compared between fishery independent surveys and commercial catches using non-parametric Kolmogorov-Smirnov tests. These comparisons were for surveys conducted in March, April, May and November 1989 (combined) and commercial catches during fishing periods in March, April, May, June, November and December 1989. Comparisons were also made for a survey conducted in April 1994 and commercial catches for April 1994 separately and April, May and June 1994 combined. Since the Kolmogorov-Smirnov test is sensitive to small differences in size distribution (differences in location, spread and shape of the distributions) the results were considered to be biologically significant on at a the $P < 0.01$ level.

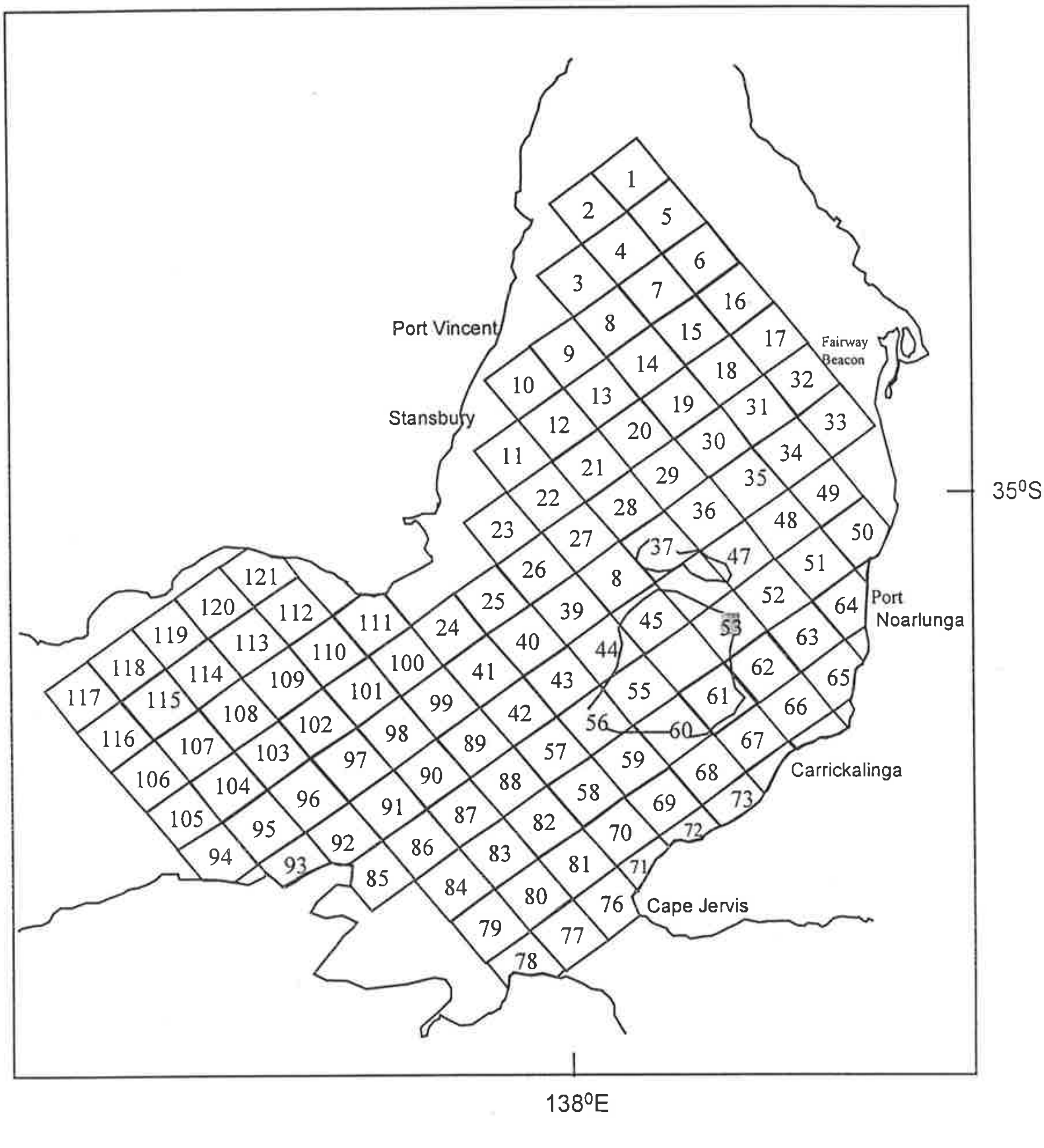


Figure 7.3 Fishing blocks used to indicate the fishing location for the Gulf St Vincent prawn fishery. Lines indicate areas of deeper water (>20m).

Relationships between life history stages were tested using correlation regressions for:

- Egg production and postlarval settlement;
  - egg production from female prawns ≥ 30 mm CL in October-November and postlarval settlement in January-February for Block 1 individually and Block 1, 2 and 5 combined;
  - egg production from female prawns ≥ 30 mm CL in February-March and postlarval settlement in April-May for Block 1 individually and Blocks 1, 2 and 5 combined;
  - egg production from female prawns ≥ 42 mm CL in October-November and postlarval settlement in January-February Block 1 individually and Blocks 1, 2 and 5 combined;
  - egg production from female prawns ≥ 42 mm CL in February-March and postlarval settlement in April-May Block 1 individually and Blocks 1, 2 and 5 combined;

- Postlarval settlement and juvenile abundance;
  - postlarval settlement in January with juvenile abundance in February;
  - postlarval settlement in April with juvenile abundance in May;

- Juvenile abundance and recruitment;
  - juvenile abundance in February with recruitment to the fishery in June;
  - juvenile abundance in May with recruitment to the fishery in February-March;

- Juvenile abundance and commercial catch rates;
  - juvenile abundance in January-February with the commercial catch rate in May-June (one fishing period) in the same year (direct recruits) and in May-June (one fishing period) the following year and in May-June another 12 months later;
  - juvenile abundance in January-February with commercial catch rates in the calendar year, January to December (Y+2);
  - juvenile abundance in April-May with the commercial catch rate in February-March (one fishing period) the following year (overwintered recruits), February-March (one fishing period) 12 months later and February-March, 24 months later;
  - juvenile abundance in April-May with commercial catch rates for the financial year, July to December (Y+1) and January to June (Y+2);

- Recruitment and commercial catch rates;
  - recruitment in February-March and commercial catch rates in February-March (one fishing period) after 12 months and February-March 24 months later;
  - recruitment to the fishery in February-March with commercial catch rates in the full calendar year (Y+2);
  - recruitment in June and commercial catches in February-March (one fishing period, six months later) and in February-March 18 months later;
  - recruitment to the fishery in June with commercial catch rates for the full financial year July to December (Y+1) and January to June (Y+2.).
  - recruitment to the fishery in April, June and February (Y+1) combined with commercial catch rates for the full financial year July to December (Y+1) and January to June (Y+2).

For an evaluation of the effectiveness of the closure on postlarval settlement and juvenile abundance in nurseries, the mean number of postlarvae m^{-2} sampled between February and May and mean number of juveniles m^{-2} sampled between January and June at Port Wakefield, Port Arthur, Port Clinton and Ardrossan was compared using a three-way ANOVA. Factors considered were Period, Site and Month. Period referred to before (1990/91), during (1992/93) and after (1994/95) fishery closure. Recruitment abundance between the period before and during closure was compared using a t-test.

7.3 Results

7.3.1 Environmental parameters

The range of temperatures (9.7° to 25.0°C) and salinities (36.7‰ to 42.2‰) experienced in nursery areas is much greater than those experienced by prawns in deeper waters (temperature, 14.8 ° to 22.5 ° C, salinity, 36.3‰ to 37.7‰, Figure 7.4). Temperature varies seasonally. Block 1, the most northern and shallowest region has higher temperatures in summer and lower temperatures in winter compared to Blocks 2 and 5. The shallower areas also warm up and cool down earlier than deeper areas. Surface salinities also display seasonal and temporal variation although the range of overall salinities is relatively small. Higher salinities were observed in Block 1, the northernmost region compared to Blocks 5 and 2.

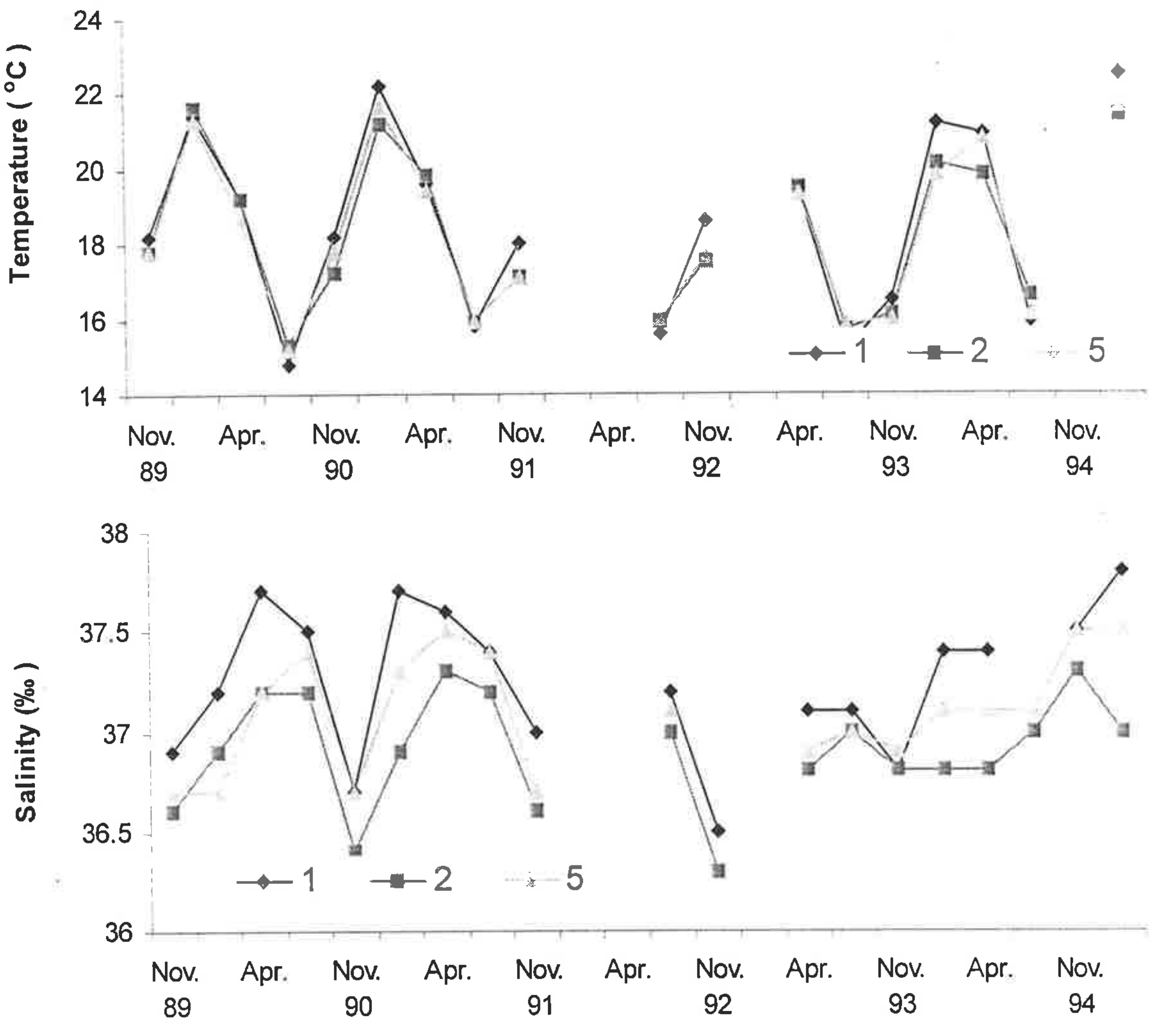


Figure 7.4 Mean surface water temperature (°C) and salinity (‰) for Blocks 1 (8 stations), 2 (12 stations) and 5 (9 stations) sampled in Gulf St Vincent during fishery independent surveys between 1989 and 1995.

7.3.2 Fishery dynamics and spatial and temporal distribution of effort

7.3.2.1 Fishery dynamics

The number of participants in the Gulf St Vincent fishery is small. Since 1989/90, the commercial fishery in GSV has consisted of eleven licence holders. During the fishery closure (November 1991 to February 1994) one additional vessel surrendered their licence and currently only ten vessels operate in the fishery. The commercial fishery and effort applied in the fishery is spatially and temporally limited. Fishing normally takes place between November and December, and then the fishery is closed between January and early February. This closure is in place because female prawns are spawning during this time and a high proportion of prawns is moulting, soft and easily damaged. Fishing resumes late February to June. No fishing takes place during winter and early spring.

The total number of nights fished during 1989/90 to 1997/98 has ranged from around 30 to 40 nights per year. Fishing is scheduled to take place either side of the new moon, from last quarter to first quarter. Not all-available nights are fished because there is an overall limit on the total number of nights fished or some are missed due to bad weather. At the beginning of a season, the number of nights to be fished is determined by a management committee. The number of nights may be altered as the season progresses depending on the catch rates and observed size composition of the catch.

Prior to February 1995, fishery independent surveys provided broad size composition and distribution information for fishers that allowed them to determine where to commence fishing and to develop their harvesting strategies. A management committee also used this information to determine closure lines for each fishing period. This was, short-term, applied use of research information.

Since February 1995, in the absence of surveys, the whole fleet lines up (one to two nautical miles apart) at the start of each fishing period, and samples a predetermined area to find out the size composition and catch rates within that area. The vessels generally do four or five trawls before the information is relayed to coordinators amongst the skippers and the best place (in terms of catch rate and appropriate size) is communicated to all fishers. All vessels then assemble in the selected area and the area is fished until catch rates are reduced. The fleet then moves onto the next best area or commences another search. Currently the vessels work in close proximity to each other, almost 'as a unit'. No single vessel can operate independently. This method has some benefits, with information shared by all participants in the fishery, and allows the fleet to become highly efficient in capturing aggregations of prawns when they are located. However, some inefficiency is introduced because often an area that has been sampled once is not re-sampled at a later date when the distribution of prawns may have changed. Also, the requirement to accommodate all ten vessels in one patch often precludes fishing in small areas that may have sustained fishing by one or two vessels only.

7.3.2.2 Spatial and temporal distribution of catch and effort

The Gulf St Vincent (including Investigator Strait) fishery has been divided into 125 fishing blocks for catch statistics purposes. Each block is approximately five square nautical miles. The proportion of fishing blocks fished in any one fishing period varies from 4.8% to 36% (Table 7.1). However, the proportion of fishing blocks that contribute to at least 80% of the catch for each fishing period varies between 1.6% and 10.4%. For the whole season, 7.2% to 12% of fishing blocks contribute to at least 80% of the total catch.

The proportion of blocks fished during a whole fishing season (financial year) is as high as 35% to 63% (Table 7.1). This is because the areas where fishing takes place from one fishing period to another changes as the season progresses. Generally, the fishers move from north to south during the season (Figures 7.5 to 7.8). The main factor causing fishers to move south is a reduction in catch rates of larger prawns in northern areas after November-December and February-March. This reduction is due to the removal of prawns by fishing and to an influx of newly recruited prawns into these areas. This influx reduces the overall size of prawns to a size not targeted. It also appears that some larger prawns move out of these northern areas towards southern regions due to density-dependent effects of new recruits. Recruitment can occur from February until June and at times the fleet is driven as far south as IS in search of larger prawns (Figure 7.6).

Table 7.1 Proportion (%) of fishing blocks fished in Gulf St Vincent during each fishing period and the proportion (%) of fishing blocks contributing to at least 80% of the total catch for a fishing period for financial years, 1989/90 to 1997/98. NF – no fishing

	November		December		February		March		April		May		June		Overall	
Year	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch	Blocks fished (%)	% > 80% of catch
89/90	11.2	2.4	4.8	2.4	NF	-	27.2	9.6	15.2	7.2	20.0	5.6	NF	-	35.2	12.0
90/91	NF	-	13.6	3.2	NF	-	13.6	3.2	22.4	3.2	36.0	11.2	21.6	8.0	52.8	11.2
91/92	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-
92/93	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-	NF	-
93/94	NF	-	8.8	3.2	NF	-	16.8	5.6	8.0	2.4	18.4	4.8	3.2	1.6	40.0	8.0
94/95	NF	-	NF	-	NF	-	2.4	1.6	13.6	4.0	27.2	3.2	22.4	10.4	48.0	7.2
95/96	20.8	2.4	11.2	2.4	NF	-	18.4	5.6	17.6	5.6	17.6	4.8	NF	-	46.4	11.2
96/97	24.0	1.6	16.8	2.4	NF	-	30.4	4.0	13.6	2.4	27.2	4.8	24.8	4.8	63.2	11.2
97/98	12	3.2	13.6	3.2	12.8	1.6	28.0	5.6	23.2	4.0	17.6	4.0	NF	-	50.4	12.0

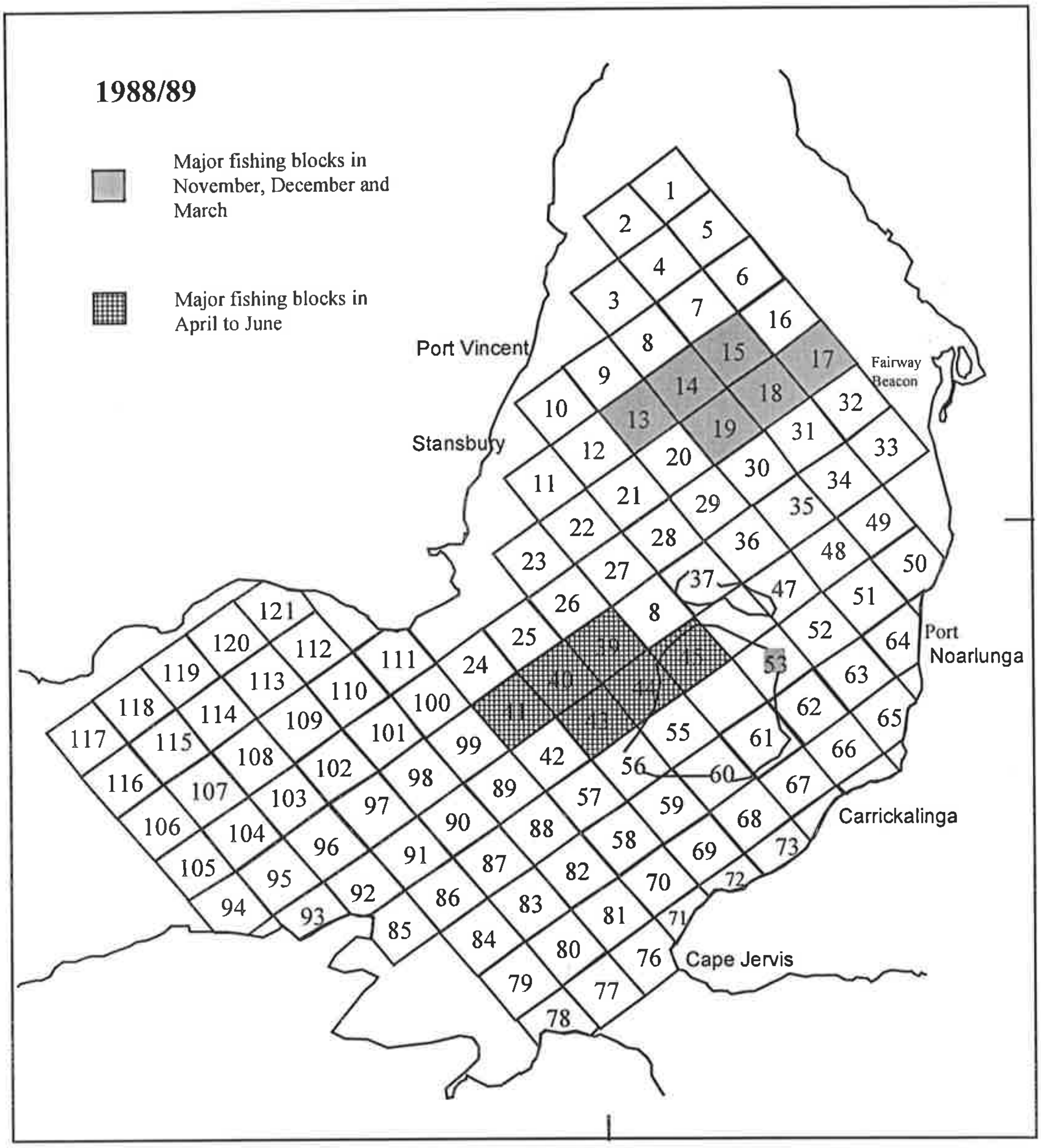


Figure 7.5 Fishing blocks in Gulf St Vincent and Investigator Strait, which contribute to the major part of the catch of *Penaeus latisulcatus* during November, December and March and April to June in1988/89.

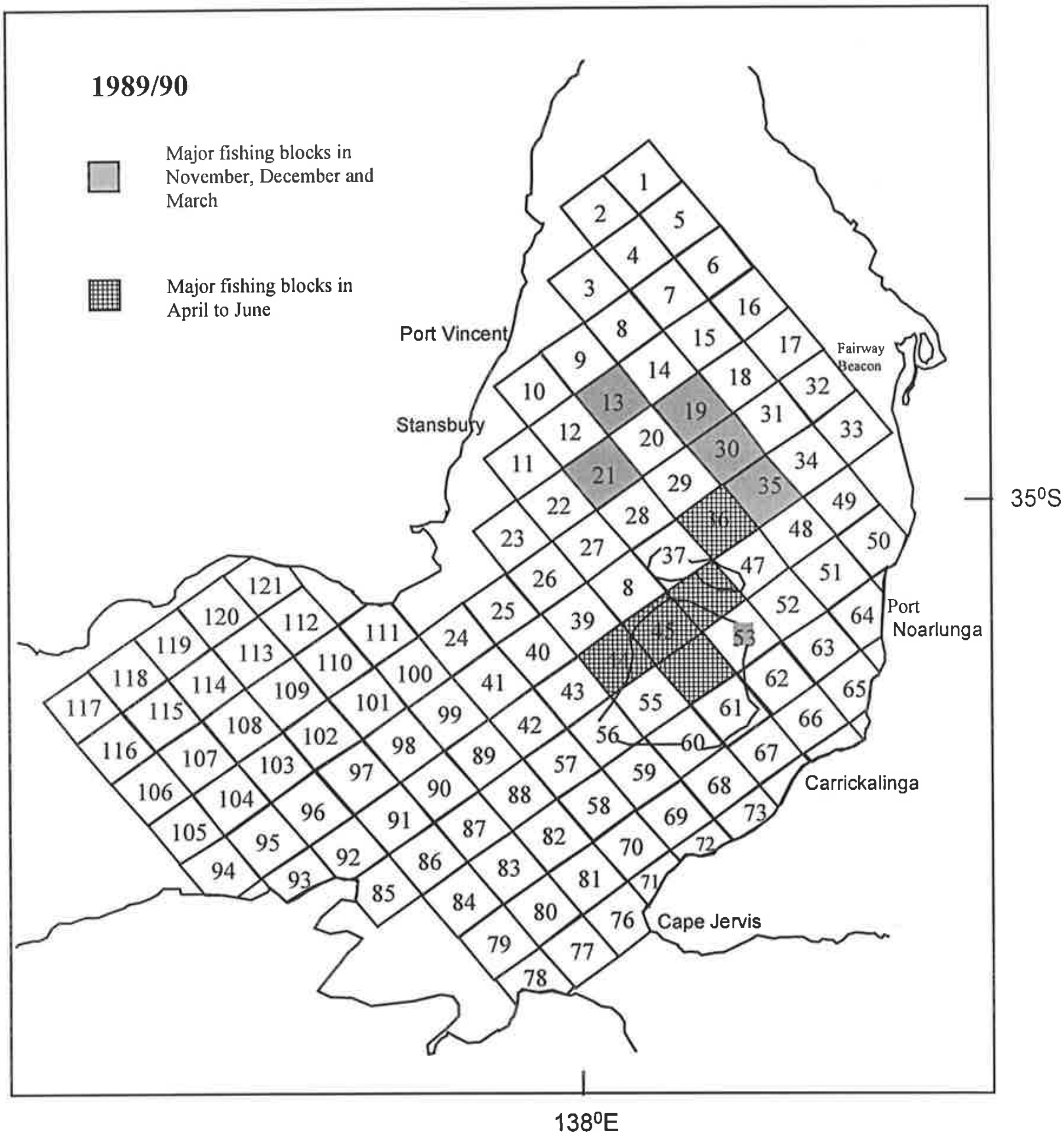


Figure 7.6 Fishing blocks in Gulf St Vincent and Investigator Strait, which contribute to the major part of the catch of *Penaeus latisulcatus* during November, December and March and April to June in1989/90.

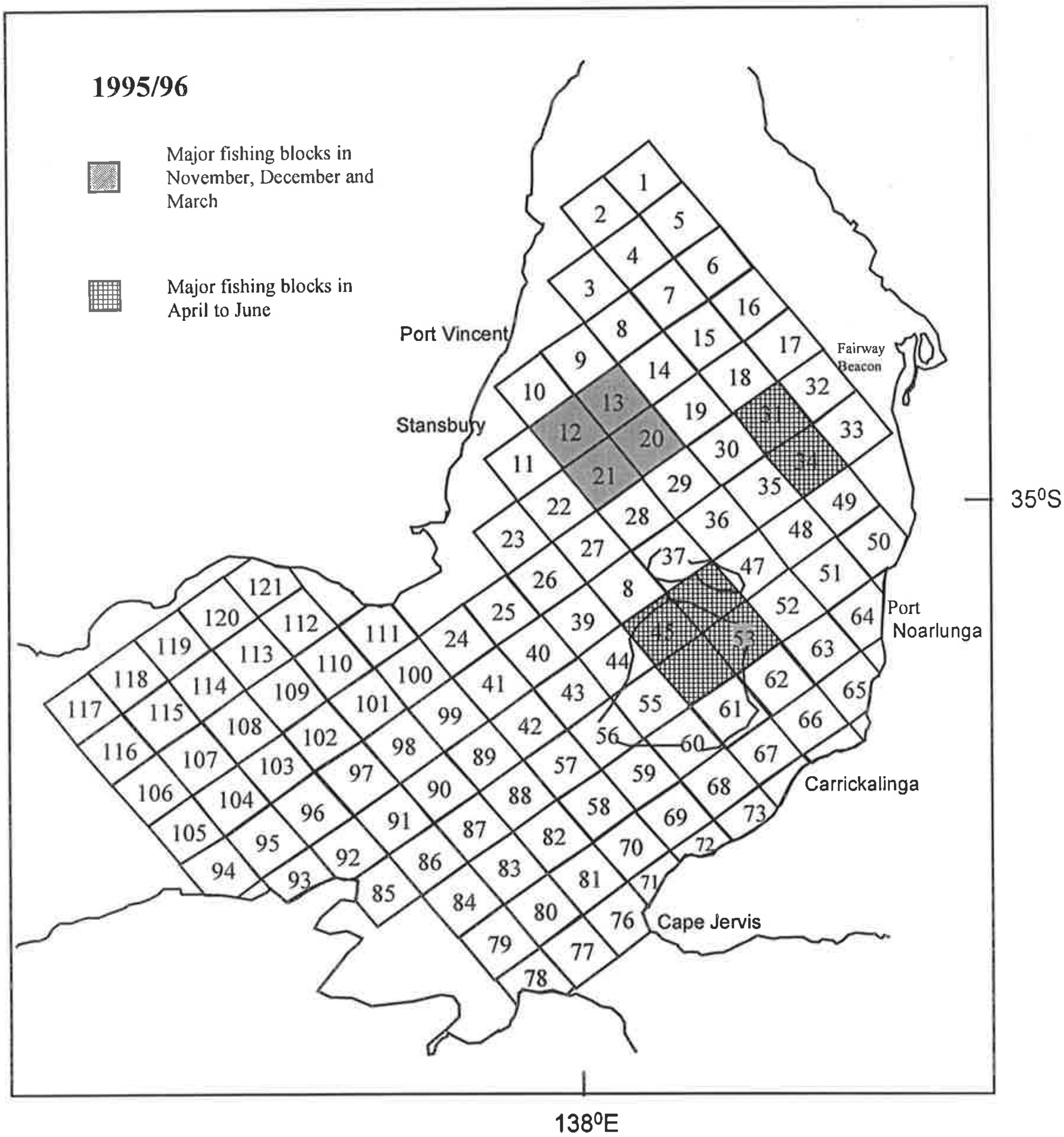


Figure 7.7 Fishing blocks in Gulf St Vincent and Investigator Strait, which contribute to the major part of the catch of *Penaeus latisulcatus* during November, December and March and April to June in1995/96.

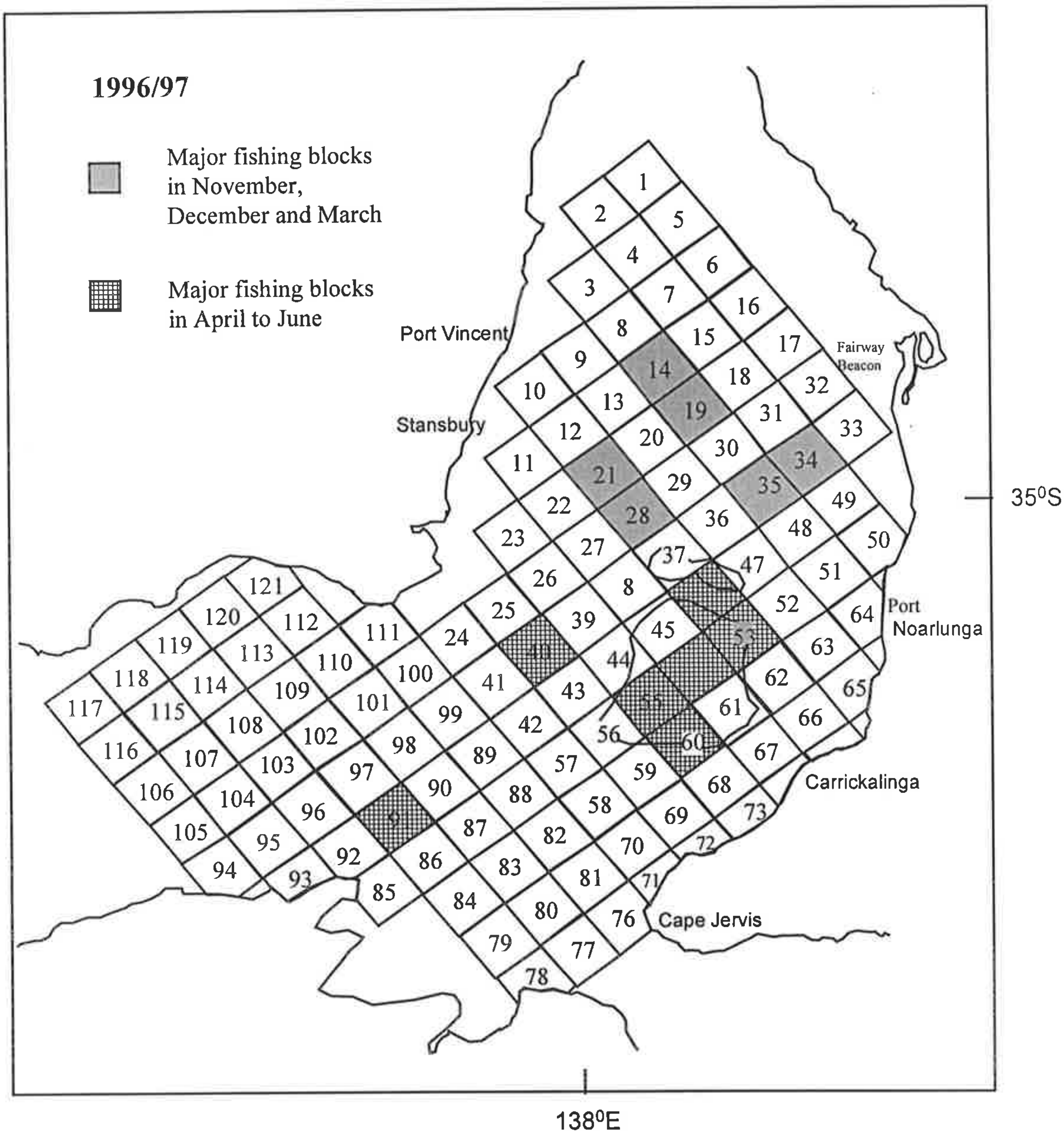


Figure 7.8 Fishing blocks in Gulf St Vincent and Investigator Strait, which contribute to the major part of the catch of *Penaeus latisulcatus* during November, December and March and April to June in1996/97.

7.3.3 Comparison of commercial catch size composition and size composition of prawns on fishing grounds

Fishers in the GSV fishery target particular-sized individuals. Prior to 1988/89, information on the size composition of the commercial catches in Gulf St Vincent is limited and largely anecdotal. It is believed that during the early years of the fishery (late 1960's to mid 1970's) larger prawns were targeted. As effort levels and therefore exploitation rates of prawns increased, the size of prawns caught became smaller.

To control the apparent reduction in the size of prawns that were landed, a size target was implemented. This size was based on the optimal yield-per-recruit (Carrick, unpublished) and was derived using the growth rate of male and female prawns (Carrick and Correll 1989) in GSV, their estimated mortality (Kangas and Jackson 1997) and market value of different sized prawns. The size criterion established, represented a distribution of prawns with an average size of 27 whole prawns to the kilogram. Principally, this criterion was followed until 1991 when for a short period prior to the closure of the fishery; a highly conservative size criterion of 22 whole prawns to the kilogram was implemented. This resulted in very low fishing effort because of the scarcity of very large prawns.

At the end of the fishery closure in February 1994, the 22 whole prawns to the kilogram criterion was continued for a short time. This was revised to an average of 24-25 whole prawns per kilogram with an upper limit of 27 whole prawns per kilogram. This size criterion is currently used.

Size selectivity occurs during fishing operations. The size distribution of prawns on fishing grounds and commercial catch size composition were significantly different in 1989 and 1994 (Kolmogorov-Smirnov, $P = 0.000$). Generally, larger individuals are targeted (Figure 7.9 b) in comparison to the size distribution found on the fishing grounds (Figure 7.9 a). Square mesh cod-ends and/or wings in the trawl nets since the end of 1996/97 have additionally altered the size composition of prawns captured, reducing the proportion of small prawns retained in the nets.

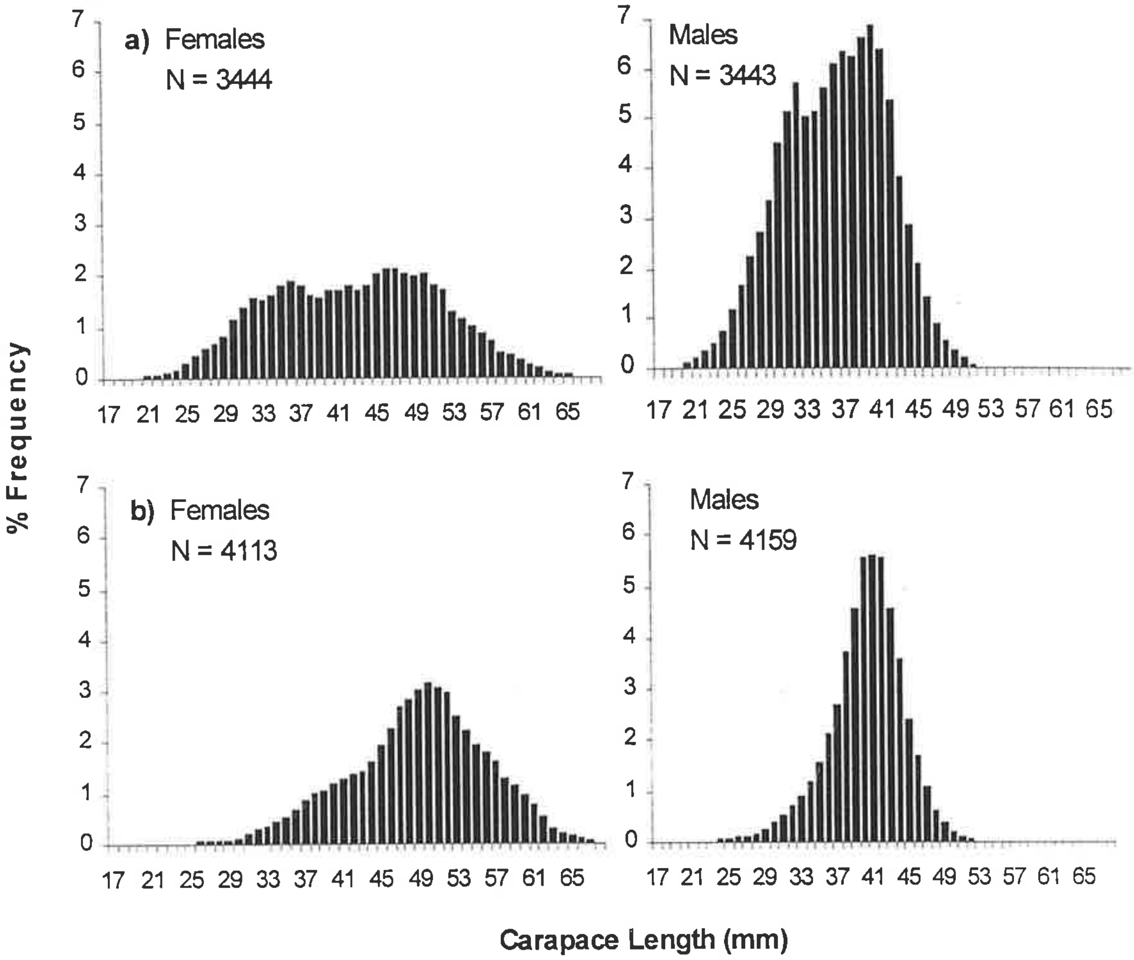


Figure 7.9 % Size distribution of females and male *Penaeus latisulcatus* sampled a) during fishery independent surveys in March, April, May and November 1989 (combined) compared with the % size distribution b) of females and males from the commercial catch, measured on board commercial vessels during the fishing periods March, April, May, June, November and December 1989 (combined).

7.3.3.1 Unusual size distribution of prawns captured after the two and half year fishery closure

Usually when the size distribution of a population is examined, there are higher numbers of smaller individuals and declining numbers of larger individuals (Figure 7.10 a). This type of distribution is due to mortality and the effects of fishing over time. An examination of the size distribution of prawns in April 1993 shows an unusually high proportion of larger individuals compared to smaller individuals (Figure 7.10 b). The unusual distribution can be explained by the accumulation of larger individuals in the absence of fishing due to the complete closure of the fishery between November 1991 and February 1994. It was enhanced by an apparent high recruitment event in 1991 (unpublished). This strong year-class was only subjected to natural mortality during the fishery closure and therefore prawns were still available in significant numbers two years later due to the longer life span of *P. latisulcatus* in SA. It also appeared, through limited survey information, that recruitment levels during the closure period were relatively low and therefore the accumulation effect of larger prawns was not masked by any subsequent strong year classes. In the year following reopening of the fishery the proportion of larger individuals is reduced (Figure 7.10 c) due to removal by fishing (Figure 7.10 d) and effects of natural mortality. The reduction of the proportion of larger individuals in commercial catches is evident between 1993/94 and 1996/97 (Figures 7.11 a-d).

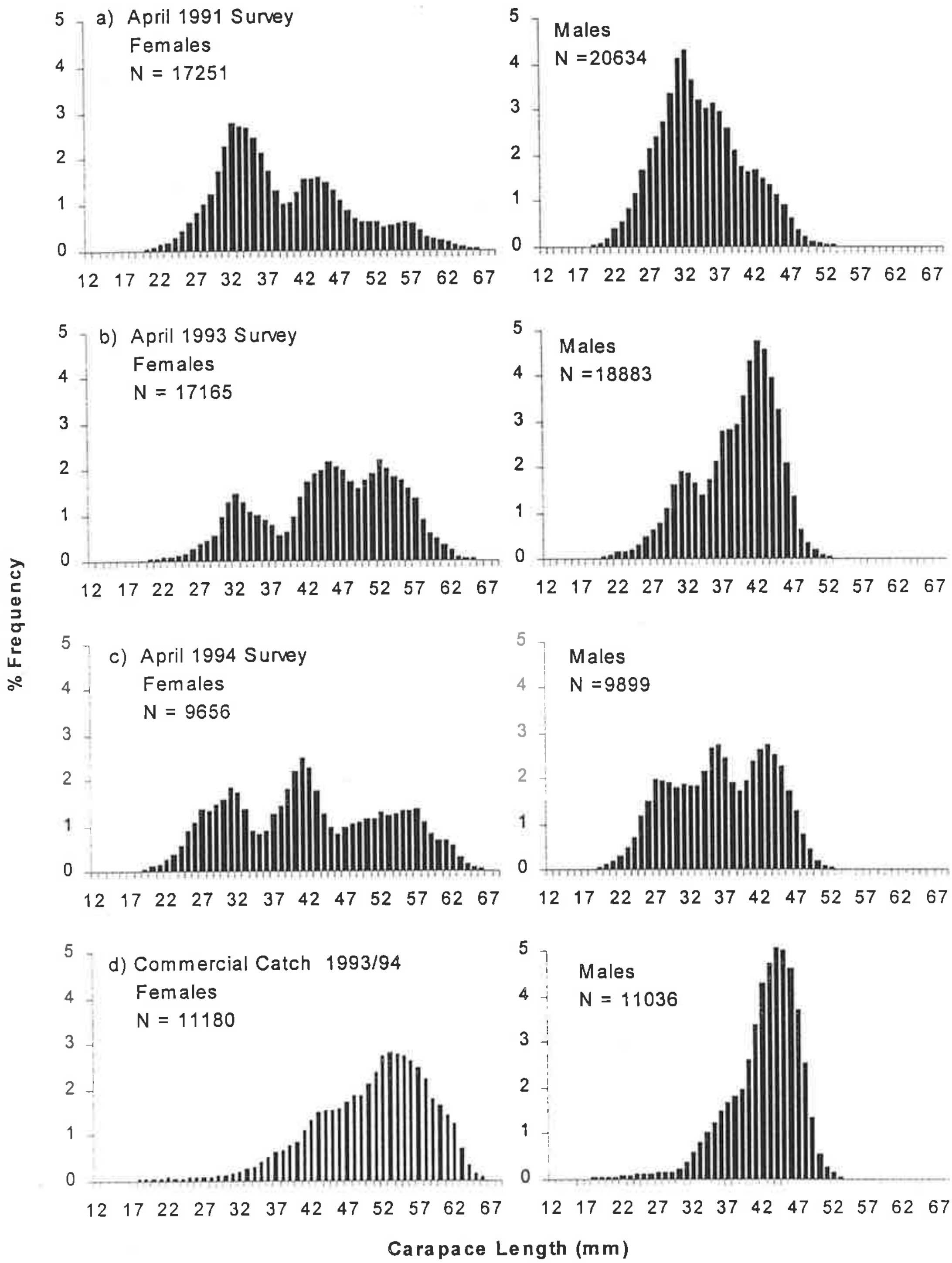


Figure 7.10 % Size distribution of *Penaeus latisulcatus* sampled during fishery independent surveys in, a) April 1991, b) April 1993 and c) April 1994, compared with the % size distribution of prawns captured by commercial fishers after the reopening of the fishery in 1993/94 (d).

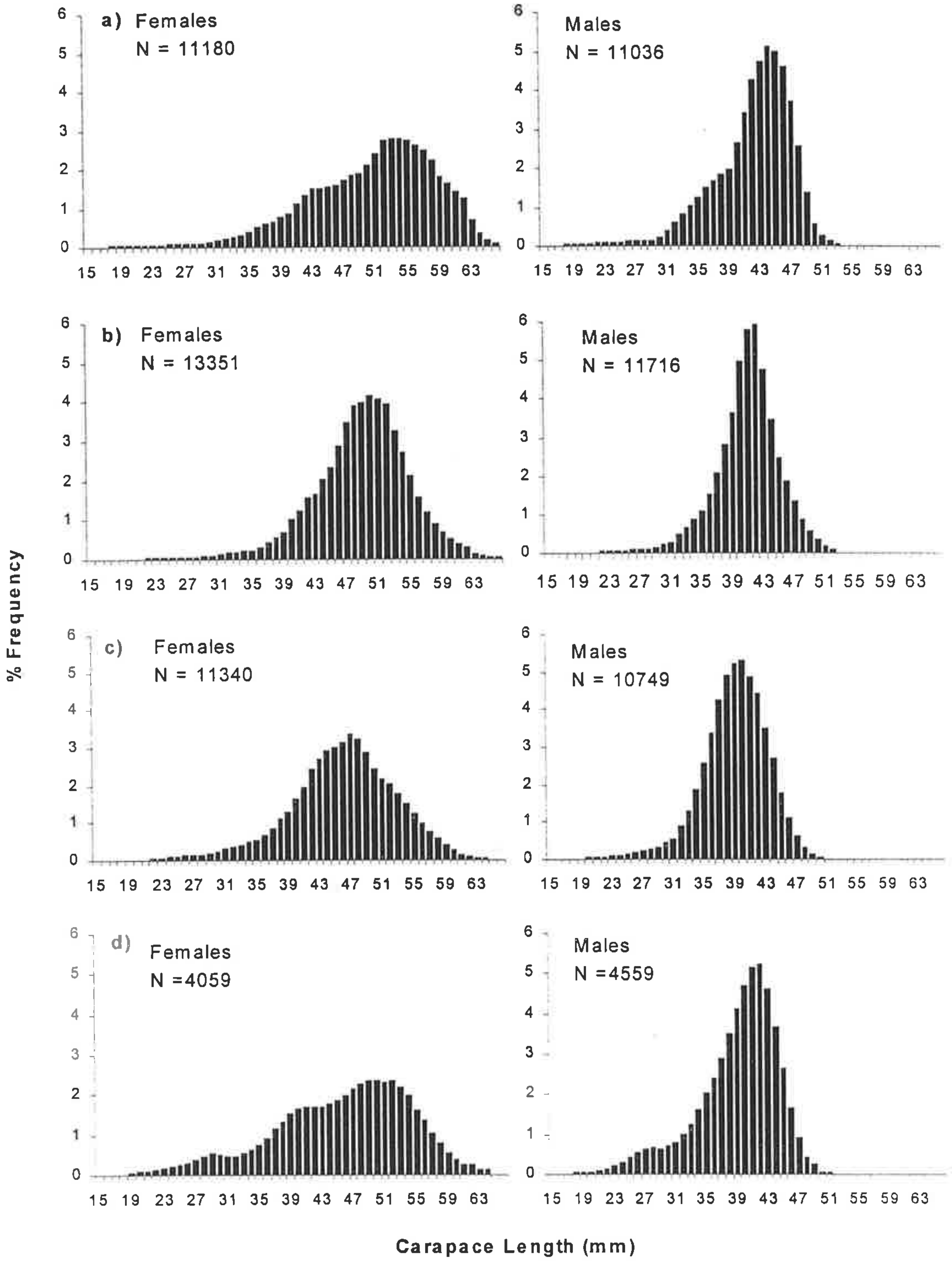


Figure 7.11 % Size distribution of the commercial catches of *Penaeus latisulcatus* in Gulf St Vincent since the reopening of the fishery in 1993/94 (a). % Size distribution in subsequent years, b) 1994/95, c) 1995/96 and d) 1996/97.

7.3.4 Correlation between egg production, postlarval settlement, juvenile abundance, recruitment to the fishery and commercial catch rates.

During the study period, sampling for all life history stages of *Penaeus latisulcatus* was limited in some years (Table 7.2). Not all surveys were done and therefore information on egg production and recruitment to the fishery in some years is not available. During the closure of the fishery in 1992 and 1993, commercial catch information is unavailable.

Table 7.2 Data available for correlation analysis for life-history stages of *Penaeus latisulcatus* in Gulf St Vincent during 1990 to 1996 using fishery independent survey information for egg production and recruitment, postlarval settlement and juveniles in nurseries and commercial catch and effort information. Each row of the table indicates the hypothesised timing of each life-history stage. Egg production is mean number of eggs (billions) per nautical mile trawled from female prawns ≥ 30 mm CL, postlarvae and juvenile abundance is mean number m^{-2}, recruit abundance is mean number per nautical mile trawled and catch per unit effort (CPUE) is kg/hr trawled.

Date	Eggs	Date	Postlarvae	Date	Juveniles	Date	Recruits	Date	CPUE
Feb90	0.085	Apr90	0.360	May90	1.00	Feb91	172.45	92/93	
Oct90	0.061	Jan91	0.498	Feb91	1.08	Jun91	136.92	93	
Feb91	0.068	Apr91	0.913	May91	1.50	Feb92		93/94	68.64
Oct91	0.115	Jan92	0.240	Feb92	0.739	Jun92		94	72.58
Feb92		Apr92	0.912	May92	1.458	Feb93		94/95	82.09
Oct92	0.103	Jan93	0.321	Feb93	0.593	Jun93	65.35	95	93.23
Feb93		Apr93	0.850	May93	1.752	Feb94	319.29	95/96	86.18
Oct93	0.069	Jan94	0.231	Feb94	0.717	Jun94	128.08	96	83.60
Feb94	0.116	Apr94	0.537	May94	0.742	Feb95	71.41	96/97	65.24
Oct94		Jan95	0.306	Feb95	0.962	Jun95		97	66.12
Feb95	0.122	Apr95	0.286	May95	0.519	Feb96		97/98	70.42
Oct95		Jan96	0.773	Feb96	1.257	Jun96		98	
Feb96		Apr96	0.508	May96	0.757	Feb97		98/99	

7.3.4.1 Time-series

Only three complete time-series are available over the seven years of postlarval and juvenile sampling (Figure 7.12). The relative number in Figure 7.12 refers to the relative number of a life-history stage in one year compared to the other years, not between life-history stages for one time-series. Actual numbers were modified to fit within a common range for graphical presentation. No significant correlation was seen between the three time-series (Pearson correlation for all, r = 0.788 - 0.800, P = 0.104 - 0.113). A similar response was observed from eggs to postlarvae to juveniles but recruitment and commercial catch rates display different responses in each time-series.

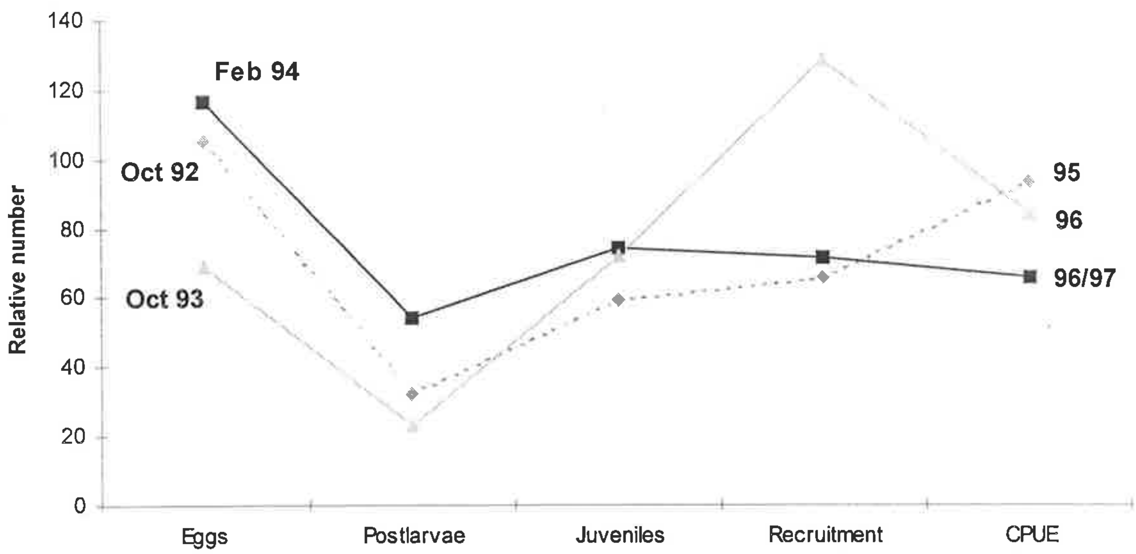


Figure 7.12 Relative number (between the three time-series) of eggs, postlarvae, juveniles, recruits and commercial catch rates of *Penaeus latisulcatus* in Gulf St Vincent between spawning in October 1992 to catches in 1995, spawning in October 1993 and catches in 1996 and spawning in February 1994 and catches in 1996/97.

Comparison of two successive life history stages at a time result in more data being available for analysis of correlations.

7.3.4.2 Egg production and postlarval settlement

No significant correlation was observed with postlarval settlement and estimated egg production of females for either prawns ≥ 30 mm CL or ≥ 42 mm CL. Separating Block 1 egg production from the other northern regions did not improve any correlation (Table 7. 3).

Table 7.3 Pearson correlation regression of egg production with postlarval settlement. Egg production was estimated for *Penaeus latisulcatus* in Block 1 and Blocks 1, 2 and 5 during February-March and October-November for females ≥ 30 mm CL or ≥ 42 mm CL. Corresponding postlarval settlement was estimated for April-May (February-March eggs) or January-February (October-November eggs). NS – not significant.

Egg production	Postlarvae	*r*	r^2	*P*
February ≥ 30mm CL Blks 1,2 and 5	April-May	-0.699	0.488	0.311 NS
February ≥ 30mm CL Blk 1	April-May	0.710	0.505	0.290 NS
February ≥ 42mm CL Blks 1,2 and 5	April-May	-0.711	0.505	0.289 NS
February ≥ 42mm CL Blk 1	April-May	-0.011	0.000	0.989 NS
November ≥ 30mm CL Blks 1,2 and	January-February	-0.540	0.296	0.460 NS
November ≥ 30mm CL Blks1	January-February	-0.542	0.294	0.458 NS
November ≥ 42mm CL Blks 1,2 and	January-February	-0.533	0.284	0.467 NS
November ≥ 42mm CL Blk1	January-February	-0.740	0.547	0.260 NS

7.3.4.3 Postlarval settlement and juvenile abundance

A significant correlation is observed between postlarval settlement and juvenile abundance (r = 0.871, P = 0.000) with a time lag of four weeks. The relationship between postlarval settlement and abundance of juveniles in nurseries one month later is given by: Juveniles = 1.289*Postlarvae + 0.338 (Figure 7.13).

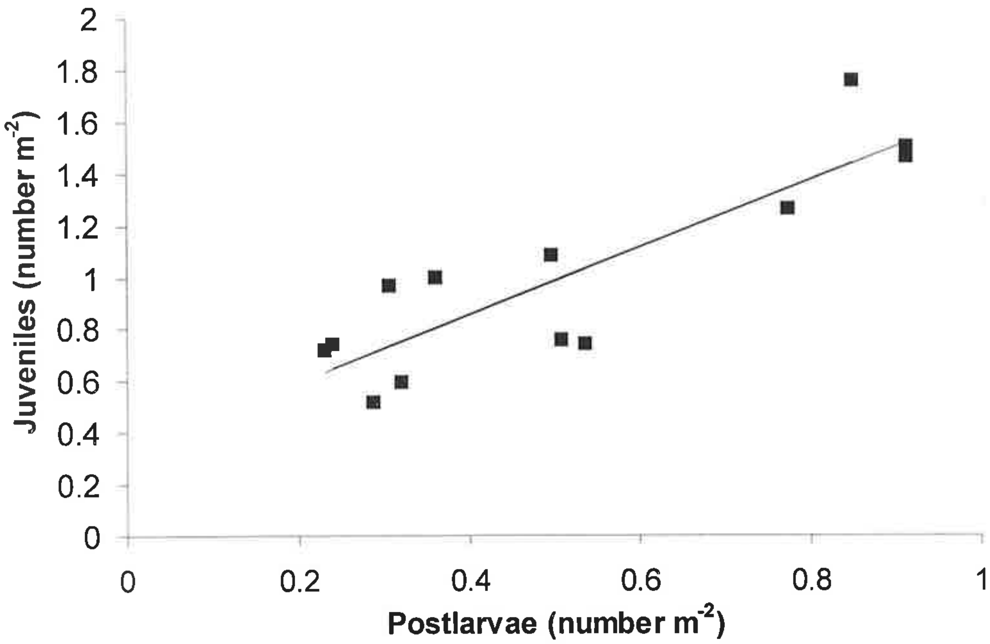


Figure 7.13 Relationship between mean number m^{-2} of postlarval (<3 mm CL) *Penaeus latisulcatus* during early (December-February) and late (February-April) settlement for all nursery sites combined and the mean number m^{-2} of juveniles (≥3 mm CL) four weeks later for years 1990 to 1996. The relationship (line) is described as: Juveniles = 1.289*Postlarval abundance + 0.338 (r = 0.871, P = 0.000).

7.3.4.4 Juvenile abundance and recruitment to the fishery

A significant correlation is observed between the abundance of juveniles in nurseries and recruitment to the fishery (r = 0.959, P = 0.002). The linear relationship for juveniles and recruitment to the fishery is given by: Recruitment = 211.725 Juveniles – 58.777 (Figure 7.14). Removal of the high point in the data makes the correlation non-significant (r = 0.785, P = 0.115).

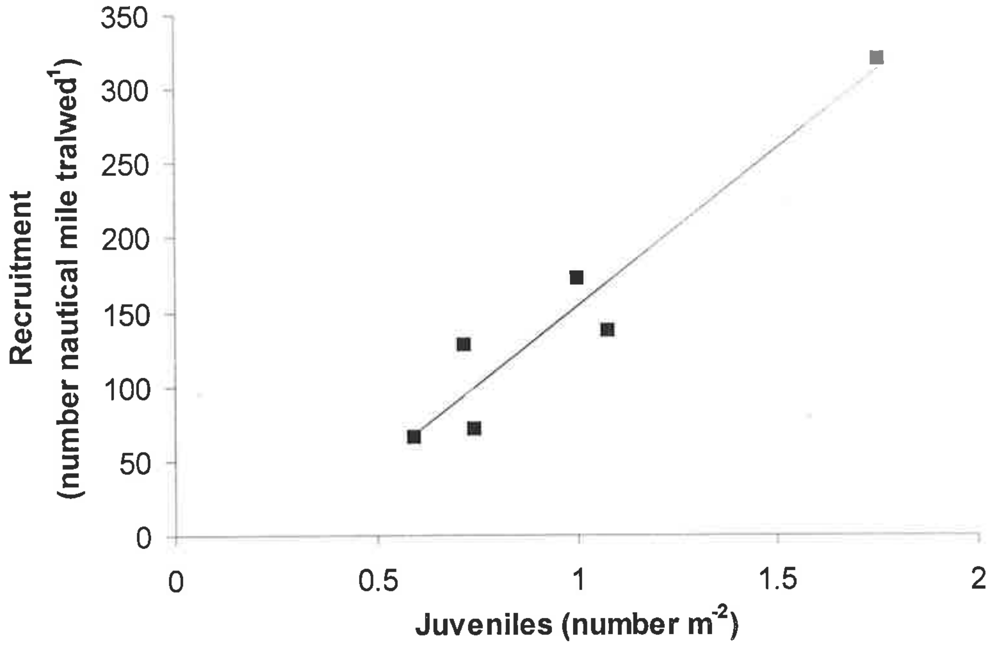


Figure 7.14 Relationship between the mean number m^{-2} of juvenile (≥3 mm CL) *Penaeus latisulcatus* sampled in nursery sites (combined), during January-February and May-June and subsequent recruitment (number per nautical mile trawled) to the fishery in Gulf St Vincent in June (juvenile abundance in January) and the following February (juvenile abundance in June) for years 1991 to 1995. The relationship (line) is described as: Recruitment = 211.725*Juvenile abundance – 58.777 (r = 0.959, P = 0.002).

7.3.4.5 Juvenile abundance and commercial catch rates

No significant correlation was observed for juvenile prawn abundance in January-February with commercial catch rates in May-June in the same year (r = 0.391, P = 0.608), twelve months after (r = 0.167, P = 0.833) or 24 months after (r = - 0.355, P = 0.558). No significant correlation was seen for juvenile prawn abundance with commercial catch rates for the full calendar year in Y + 2 (r = - 0.913, P = 0.087).

Similarly, no significant correlation was observed for juvenile prawn abundance in April-May with commercial catch rates in February-March the following year (r = - 0.021, P = 0.973), after a further 12 months (r = 0.091, P = 0.884) or after 24 months (r = 0.819, P = 0.090). No significant correlation was observed with juvenile abundance in April-May with commercial catch rates for a full financial year, the following year ($r = 0.284$, $P = 0.644$) or two years after ($r = 0.703$, $P = 0.185$).

7.3.4.6 Recruitment abundance and commercial catch rates

During the study period, correlation analysis was only possible for the February and April recruitment periods because only three data points were available for June. No significant correlation was observed when catch rates during a February-March fishing period (the following year) or for a full financial year (Y+1) was compared with individual recruitment periods (Table 7.4).

Table 7.4 Pearson correlation regression of recruitment with commercial catch rates. Recruitment was estimated for *Penaeus latisulcatus* in Blocks 1, 2 and 5 during February and April and in Blocks 1,2,4,5 and IS in June. Corresponding commercial catch rates were estimated for the February-March fishing period in (Y+1/Y+2) and for the full financial year Y+1/Y+2 and for the full calendar year (y+1). NS – not significant.

Recruitment	Catch rate	r	r^2	P
February (Y)	Financial:Y/Y+1	0.513	0.263	0.487 NS
February (Y)	February-March (Y +1)	0.254	0.064	0.746 NS
April (Y)	Financial: Y/Y+1	0.800	0.640	0.200 NS
April (Y)	Calendar: Y+1	0.761	0.579	0.239 NS
April (Y)	February-March (Y+1)	0.415	0.173	0.585 NS

The lack of correlation with individual recruitment periods and catch rates may be explained by the size-targeted nature of fishing in GSV and the longer life span of *Penaeus latisulcatus* whereby more than one recruitment event contributes to the commercial catch of any one year. When all recruitment periods (April, June and February (Y+1)) were combined and incorporated with data gathered two years prior to the commencement of this study (to provide sufficient data points for correlation analysis), a significant correlation was observed with recruitment and commercial catch rates in the financial year (Y+1/Y+2) (Figure 7.15, $r = 0.974$, $P = 0.026$). The equation to describe the relationship is:

Commercial catch rate (kg/hour trawled) = 0.324*Recruitment + 4.88.

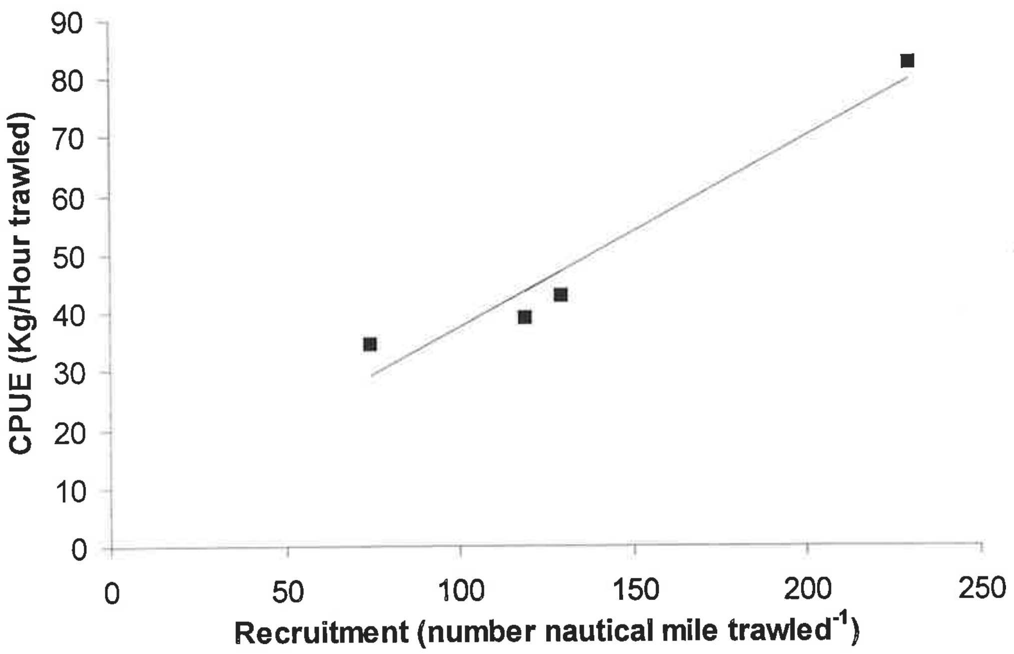


Figure 7.15 Relationship between the mean number of recruits per nautical mile trawled in Gulf St Vincent in April, June and February (Y + 1) and commercial catch rates (kg/hour trawled) in a full financial year (Y+1/Y+2) (r = 0.974, P = 0.026).

7.3.5 Comparison between postlarval settlement, juveniles and recruitment to the fishery before during and after closure

7.3.5.1 Postlarval settlement and fishery closure

For postlarvae, all factors and interactions were significant (Table 7.5, Figure 7.16) for combined years before (1990/91), during (1992/93) and after (1994/95) the fishery closure. The highest mean square was for Site, followed by Month, then Period. For Site (mean ± 1 s.e.m.), Port Wakefield (0.66 ± 0.09) is significantly different to the other three sites and Port Arthur (0.31 ± 0.04) is also significantly different to Port Clinton (0.10 ± 0.02) and Ardrossan (0.12 ± 0.02). For Month, March (0.47 ± 0.07) and April (0.33 ± 0.06) are similar to each other but significantly different to February (0.26 ± 0.04) and May (0.13 ± 0.14). Interactions between Site and Month were discussed in detail in 4.3.3. For Period, only the closure period (0.46 ± 0.07) is significantly different from the after closure period (0.13 ± 0.04).

Table 7.5 Three-way ANOVA of mean number of postlarval (m^{-2}) *Penaeus latisulcatus* sampled in all nursery areas combined for the periods, before (1990/91), during (1992/93) and after (1994/95) closure of the Gulf St Vincent prawn fishery. *** = $P \leq 0.001$

Source	df	SS	MS	F	P
Site (S)	3	12.356	4.119	38.935	0.000***
Period (P)	2	1.790	0.895	8.461	0.000***
Month (M)	3	5.149	1.716	16.226	0.000***
P*S	6	4.555	0.759	7.177	0.000***
P*M	6	2.613	0.436	4.118	0.001***
P*M*S	18	5.429	0.302	2.851	0.000***
Error	249	26.339	0.106		
Total	287	31.892			

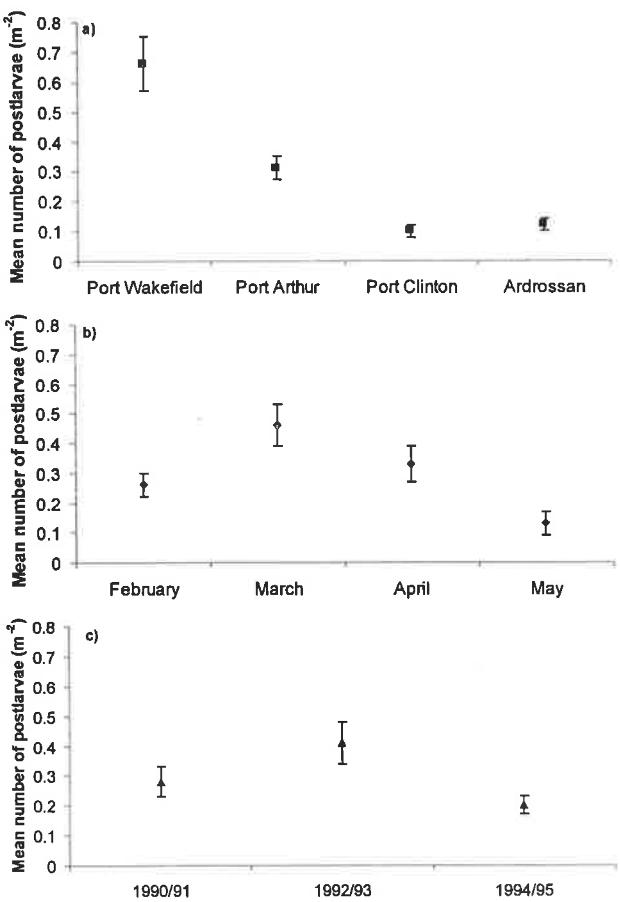


Figure 7.16 Mean number (m^{-2}) of postlarval *Penaeus latisulcatus* sampled at Port Wakefield, Port Arthur, Port Clinton and Ardrossan (a) then combined during February to May (b) for periods before (1990/91), during (1992/93) and after (1994/95) the closure of the Gulf St Vincent prawn fishery (c).

7.3.5.2 Juvenile abundance and fishery closure

For juvenile prawns, a three way ANOVA indicated that Site, Month and Period were significant but not their interactions (Table 7.6, Figure 7.17) for combined years for before (1990/91), during (1992/93) and after (1994/95) the fishery closure. The highest mean square was for Site, followed by Month, then Period. Site and Month were discussed in detail in 4.3.3 for juvenile *Penaeus latisulcatus*. For Period, the mean number (± 1 s.e.m.) before closure (0.82 ± 0.06) and during the closure (0.84 ± 0.07) are significantly different to the after closure period (0.60 ± 0.04).

Table 7.6 Three-way ANOVA of mean number of juvenile (m^{-2}) *Penaeus latisulcatus* sampled in all nursery areas combined for the periods, before (1990/91), during (1992/93) and after (1994/95) closure of the Gulf St Vincent prawn fishery.

Source	df	SS	MS	F	P
Site (S)	3	64.565	21.522	24.773	0.000***
Period (P)	2	5.369	2.685	3.093	0.047*
Month (M)	5	28.347	5.669	6.526	0.000***
P*M	10	15.023	1.502	1.729	0.072 NS
P*S	6	6.387	1.064	1.225	0.292 NS
P*S*M	36	11.593	0.386	0.445	0.996 NS
Error	376	326.65	0.869		
Total	432	457.934			

* $= 0.01 < P < 0.05$, *** $= P \leq 0.001$, NS – not significant

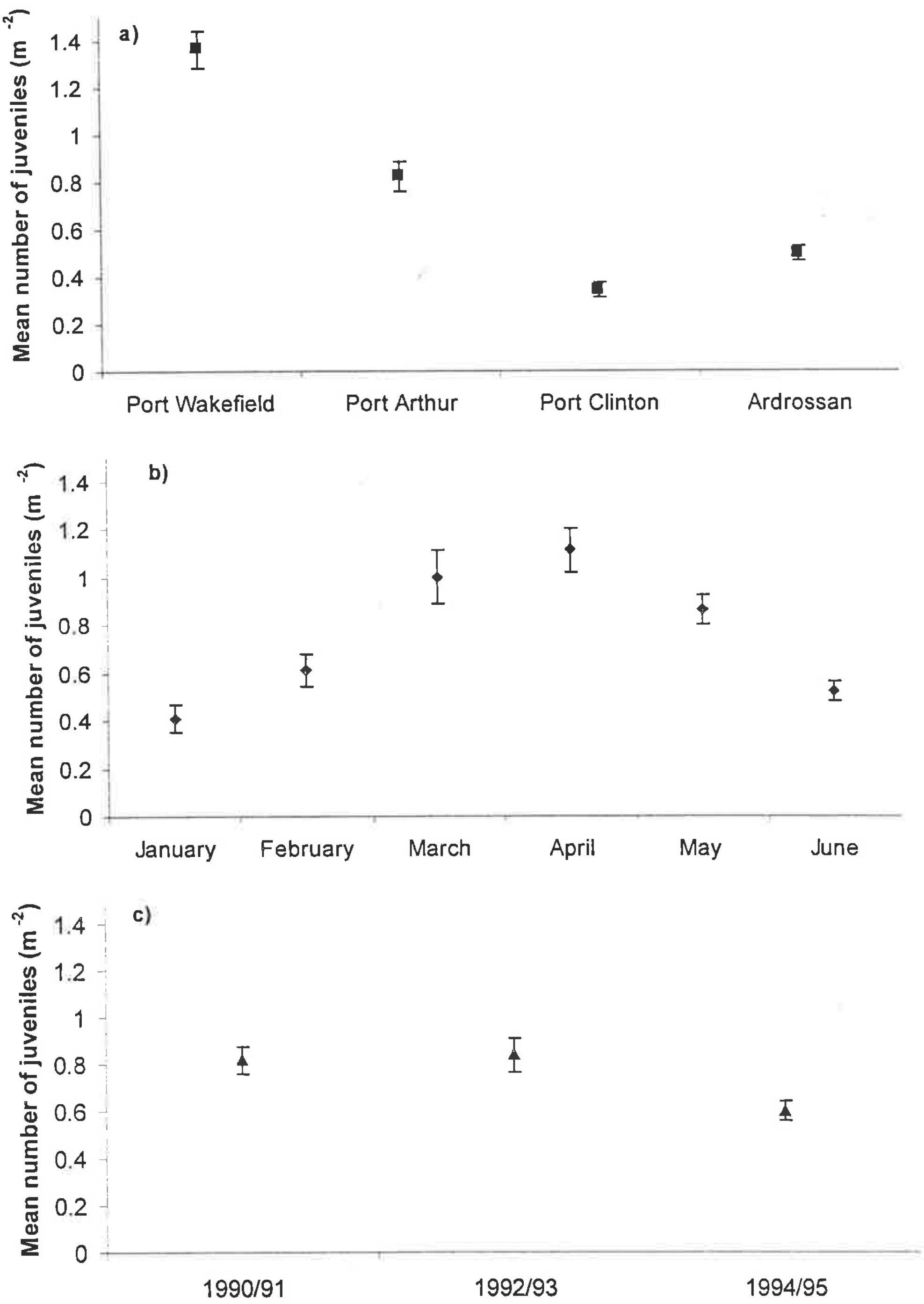


Figure 7.17 Mean number (m^{-2}) of juvenile *Penaeus latisulcatus* sampled at Port Wakefield, Port Arthur, Port Clinton and Ardrossan (a) then combined during January to June (b) for periods before (1990/91), during (1992/93) and after (1994/95) the closure of the Gulf St Vincent prawn fishery (c).

7.3.5.3 Recruitment abundance to the fishery

A significant difference is observed between mean recruitment (mean ± 1 s.e.m.) to the fishery before (9.46 ± 0.5) and during closure (7.83 ± 0.56). The period before the fishery closure had a slightly higher recruitment that the period following the closure (t-test, P = 0.0183).

7.4 Discussion

Seasonal fluctuations in the temperature of surface waters are evident in deeper water but they are less pronounced that those observed in nursery areas. Reduced water temperatures during winter result in the cessation of spawning activity in *Penaeus latisulcatus* in Gulf St Vincent. Penn (1980) suggested a threshold temperature of 19° C for spawning activity in *P. latisulcatus* in Western Australia whereas in GSV this may be at about 17° C. Cooler temperatures in winter also reduce the activity and emergence of *P. latisulcatus* and no fishing takes place during this time. Only minor salinity changes are experienced in the deeper waters where adult prawns occur.

The fishing practices and fleet dynamics in Gulf St Vincent appear unique compared to other prawn fisheries within Australia and around the world. Most prawn fisheries involve individual licence holders operating highly competitively and independently of other operators. In Gulf St Vincent, particularly in the last few years, the fishing vessels operate cooperatively, fish in close proximity to each other and being size-selective in their harvesting strategies. Fishing is both spatially and temporally limited. At the beginning of a fishing season (usually November-December) fishing commences in northern GSV and as the year progresses, the fleet moves in a southerly direction, following aggregations of larger individuals. The pattern of fishing from one year to the next may vary depending on the size distribution and abundance of prawns throughout the fishing grounds. Around 7% to 12% of fishing blocks contribute to at least 80% of the total catch for each year.

Fishers in the GSV fishery target particular-sized individuals. The size composition of the commercial catch is significantly different to the overall size of prawns sampled throughout the fishing grounds. Larger prawns are targeted while areas showing recent recruitment are avoided. The longer life span of *P. latisulcatus* in SA allows for more that one year-class to be fished and generally the size targeted are around two to three year olds. This was particularly evident following the reopening of the fishery after more than two years of closure. In recent years, due to the reduction of the proportion of very large individuals (due to fishing and effects of natural mortality), a few smaller individuals are also caught.

Some linkage between life-history stages of *P. latisulcatus* was evident. Complete trend analysis from egg to commercial catches was not possible due to incomplete data series for all but three periods. For these three time-series, similar responses were observed between egg, postlarvae and juvenile stages but not with recruitment or commercial catch rates. The limited number of time-series available constrains any interpretation. When comparing relationships between two life-history stages at a time, more data was available.

Total egg production appears not to be a useful index for comparison with postlarval settlement. No correlation between egg production for prawns ≥ 30 mm CL or ≥ 42 mm CL was seen even when only the northernmost region (Block 1) was used. This area has the highest egg production for the gulf. The absence of a relationship between egg production and postlarval settlement may be due to the importance of the spatial pattern of spawners and movement and advection processes of larvae. Pooling regions for spawners and all nursery sites may not account for the spatial and temporal complexities within the system. This was also shown in Chapter 5 where different larval advection pathways resulted in substantial differences in settlement patterns between 1990 and 1991 even though the overall spatial egg production appeared similar for the two years. Larval survival and transport mechanisms may be more important than overall egg (spawner) abundance so long as that abundance does not fall below a critical level. Rothlisberg (1982), Rothlisberg *et al.* (1985) and Carrick (1996) provided evidence of mismatches between high abundance of spawners or larvae that resulted in relatively low postlarval settlement in nurseries while a lower abundance of spawners could result in high postlarval settlement due to favourable conditions for larval survival and transport into nurseries. During the study period, the level of spawning stock (egg production) may have been relatively stable in GSV, providing insufficient variation for detection of trends.

A significant correlation was seen between postlarval settlement abundance and juveniles in nurseries with a time lag of four weeks. Similar correlations have been observed for *P. latisulcatus* in East Africa (Subramaniam 1990), *P. merguiensis* in Gulf of Carpentaria (Rothlisberg *et al.* 1985, Staples 1985, Staples & Vance 1987) and *P. semisulcatus* in Embley River, Qld. (Vance *et al.* 1996). Utilising two settlement periods each year that coincide with 'theoretical' early and late spawning times provide a more detailed picture of the settlement process. The exact times of highest settlement vary from year to year but can be apportioned 'early' and 'late' during the overall settlement period of December to May.

Recruitment strength to the fishery in many tropical prawn fisheries has been strongly correlated with environmental cues particularly rainfall and/or lowered salinity (Staples 1980b, Rothlisberg *et al.* 1985, Dall *et al.* 1990). In these fisheries, the number of individuals moving out into the fishery is not necessarily related to juvenile abundance in nurseries but intensity of rain. The abundance of juveniles may be important only if numbers fall very low. In GSV rainfall is not the mechanism that induces prawns to move out of nurseries. Size or age of individual may be the cue to emigrate. This has been postulated as the mechanism for emigration in *P. latisulcatus* (Potter *et al.* 1991), *P. indicus* (Benfield *et al.* 1990), and *P. esculentus* (Loneragan *et al.* 1994).

In Gulf St Vincent, a correlation is observed between abundance of juveniles in nurseries and overall recruitment to the fishery. Due to limited data points, one very high point drives the apparent relationship and removal of this point makes the correlation non-significant. However, the high level of juvenile abundance and strong recruitment into the fishery that this high point represents was a real event during the period of this study and therefore should not be rejected. Juvenile abundance in nurseries appears to provide a useful index for monitoring trends in recruitment to the fishery. Juvenile abundance indices provide for an earlier warning mechanism when very low postlarval settlement and juvenile numbers are sampled in nurseries. This would allow for earlier implementation of conservative fishing practices.

No significant correlation was observed for juvenile prawn abundance and commercial catch rates. Although a relationship was evident between recruitment and juvenile abundance, it was not carried through to commercial catches. The length of time from a juvenile prawn to its contribution to the exploited stock is at least two years. During this time, factors such as dispersion, mortality, density dependent effects and fleet dynamics appear to reduce any correlation. Similarly, no correlation was observed with individual recruitment periods and commercial catches. This is because the exploited stock is comprised of larger individuals which are from more that one recruitment event. When all recruitment periods (April, June and February (Y+1)) were combined a relationship with commercial catch rates was observed. However, this relationship is based on only a few data points and several years of sampling would be required to confirm the relationship. Caputi (1993) suggests that for penaeids, which generally have an annual life cycle, that at least ten years of data should be collected to allow for a preliminary examination of relationships. This is still only possible if sufficient variation is seen in the data to provide some contrast. For *Penaeus latisulcatus* in Gulf St Vincent, which has a longer life span than most penaeids, the time required may be even longer. The challenge in establishing relationships is maintaining industry and government support and cooperation in data collection for at least ten years.

A full evaluation of the 'adaptive management' experiment, the complete closure of the fishery for over two years was not possible. "Active adaptive management should be a highly focussed, foresightful process in which the management system makes every effort to predict possible outcomes of its actions, attempts to detect (monitor) which outcome is occurring and plans a response to the future threats or opportunities that each outcome represent" (Milliman *et al.* 1987). With the GSV prawn fishery closure there was neither opportunity for a structured approach nor any lead up time for modelling/prediction of likely outcomes. Insufficient monitoring took place before, during and after the closure. However, it was apparent that the absence of fishing for more than two years did not result in increased postlarval settlement or juvenile abundance in nurseries. Postlarval settlement and juvenile abundance prior to the closure (1990/91) and during the closure (1992/93) were similar and then decreased slightly during the period following re-opening (1994/95) of the fishery. The variation between each time period is relatively small and may be due to differences in larval movement and survival in nurseries. Overall the abundances observed over the three periods reflect relative stability in the system.

Recruitment to the fishery could only be assessed before and during the closure as no fishery independent assessment is available since February 1995. The level of recruitment to the fishery appeared to decline slightly during the closure. Since there was no fishing of the spawning population for an extended period (November 1991 to February 1994), a positive response in recruitment levels was expected. Possibly only small changes in the overall spawning population occurred, the key components of the spawning population remained relatively stable and/or larval survival and movement patterns during the closure period were not 'ideal'. Hence the fishery could not capture the opportunity for a significant increase in recruitment. The paucity of information during all stages of the 'experiment' highlights the need for a planned approach to adaptive management so that the relevant information is collected for a proper assessment of the impacts before, during and after a change in a management strategy particularly one as extreme as a total closure.

8. SUMMARY AND CONCLUSIONS

The Gulf St Vincent prawn fishery targets a single species, the western king prawn, *Penaeus latisulcatus* Kishinouye. The fishery is relatively small and contributes to about ten percent of the total prawn production (2000 to 2500 tonnes) per year within South Australia. The fishing practices and fleet dynamics in Gulf St Vincent prawn fishery appear unique compared to other prawn fisheries within Australia and around the world. Fishing is both spatially and temporally limited. Fishing vessels work cooperatively, in close proximity to each other and fishers are very size-selective.

The understanding of the dynamics of exploited populations is necessary if they are to be managed on an ecologically sustainable basis. The understanding of recruitment processes and recruitment variability in fisheries is fundamental to their management. Information needs to be collected over fine and broad, spatial and temporal scales. In South Australia, *P. latisulcatus* is relatively long-lived and harvested populations may comprise up to three-year classes. Therefore any studies on population dynamics should be for at least three years to begin to understand some of the complexities within the system.

A seven year study, between October 1989 and June 1996 was undertaken on the variability of postlarval settlement and juvenile abundance of the western king prawn *P. latisulcatus*, in nurseries within Gulf St Vincent. This study focussed on the nursery stages of the life history but also incorporated information on adult stocks and recruits to the fishery to develop a model of the dynamics of prawn populations and to try to elucidate some of the factors which are important in the regulation of stocks. Some of the methodologies employed in this study may be applicable for other prawn or invertebrate fisheries.

Key nursery areas were established. The main nursery areas occur north of Port Gawler on the eastern side of Gulf St Vincent around to Ardrossan on the western shore. Favoured nursery habitats tend to be shallow and sheltered with sand-mud sediments and often associated with mangrove areas. The tidal flats throughout these areas can extend from 200m up to one km offshore and major nurseries encompass approximately 150 km^2. Prawn nursery habitats within GSV cover a relatively small area overall, and the likely loss or substantial impact on these areas requires their protection from additional or continuing pollution sources and major coastal developments.

Visible changes to some nursery areas have occurred during the history of the prawn fishery. During the early 1970's, the Barker Inlet system was thought to be a significant prawn nursery. Only few *P. latisulcatus* are now found in the area. The apparent loss of some nurseries is of concern and may be due to high nutrient loading causing extensive growth of epiphytes and *Ulva* that smothers the substrate making the area unsuitable for postlarval settlement.

One aim of this study was to determine an acceptable semi-quantitative measure of the number of prawns within a nursery area that will be comparable within and between years as well as between sites. *Penaeus latisulcatus* is nocturnal and buries in the sediment during the day. This led to the development of a day-time sampling device, the jet net which was shown to be an efficient sampling device, minimising catchability effects by sampling prawns during the day when they are buried within the substrate. It is more efficient in capturing the available juvenile prawns than a traditional beam trawl commonly used in juvenile prawn studies. The habitat preference of *P. latisulcatus* for sand-mud sediments in the intertidal zone inside seagrass beds, allows the use of the jet net without damage to seagrasses.

From a number of trials investigating the small-scale spatial and temporal variability within a nursery site, it was determined that the best sampling technique for *P. latisulcatus* was to use a fully enclosed jet net, towed perpendicular to the shore or covering the width of the available nursery area to incorporate any depth preference for different sized individuals. At any site, there was no significant difference in the abundance of postlarval or juvenile prawns caught using three or four separate trawls. A mean index of abundance calculated from these trawls is considered to provide a good estimate of the relative abundance in the area sampled. The diagonal sampling method provides a reliable relative measure from one time to the next and samples from one or a few sites within this extended region is representative of the true relative abundance of prawns at that region.

Most juvenile prawn studies in Australia have been restricted in either space or time. Ideally a large number of sites would be sampled to provide a good geographical representation of the variability within a system and should be undertaken for at least two years to provide some indication of annual variability. During this study, a large scale sampling program was made initially to locate key nurseries, then finer scale variability within these nursery sites was investigated to determine their suitability as a general indicator of postlarval settlement and juvenile abundance given that not all nursery sites could be sampled on a regular basis. Five sites were chosen to be sampled regularly. Logistically, the five sites that were situated approximately 15-30 km apart were relatively easy to sample and could all be completed in two to three days. Sampling of this frequency could easily be maintained to provide long-term information on the health of nurseries and the prawn fishery. The development, maintenance and assessment of long-term data sets for stock assessment are essential.

It was found that variation in postlarval settlement occurs on a seasonal, spatial and annual basis. Variation between years was smaller than observed for months and sites. Site was the most significant effect. Postlarval settlement and juvenile abundance was higher in the northern sites compared to the two southern sites. For six of the seven years, the eastern side of GSV had higher settlement that the western side. These differences may reflect the spatial distribution and abundance of spawning females and larval advection. The postlarval settlement pattern appears to be continuous between mid December and early June. No postlarvae were found in nursery areas during winter. Juvenile prawns are found in nurseries throughout the year with highest numbers occurring in late February to late May. The number of juvenile prawns in nurseries depends on the strength of postlarval settlement and overall prawn production from nurseries is dependent on the survival and growth characteristics within each nursery area. A decline in juvenile prawn abundance in late May and again in late November probably indicates movement out of nurseries. These periods correspond to recruitment peaks in the commercial fishery.

It was not possible to sample larvae during this study. However, using information from adult population stock monitoring, the potential egg production at the beginning of the spawning period (October-November) and towards the end of the spawning period (February-March) was available for some years. Tidal and wind modelling was undertaken to follow larval movement from main spawning areas within the gulf where aggregations of spawning females were found. The years, 1989/90 and 1990/91 were used for the modelling because wind and tide information was available at regular intervals. The northern spawning areas were more important than southern regions as the larvae were advected to key nursery areas in either the eastern or western side of the gulfs. Differences in settlement patterns between the two years were predicted from the modelling and there was some reflection of these in field sampling. Modelling however, could not predict the timing, specific location or abundance of settling postlarvae precisely. Oceanographic and wind information on a finer spatial scale along with more accurate information on the reproductive biology, timing of spawning, distribution patterns and larval behaviour of *P. latisulcatus* is required to increase the precision or predictive ability of modelling.

The initial numbers of postlarvae in nurseries depend on larval supply. A correlation was observed between postlarval settlement and juvenile abundance. In general it is expected that a pulse of postlarval settlement gives rise to a pulse of early juveniles about four weeks later. Furthermore a correlation was seen between juvenile numbers and recruits to the fishery as well as with recruitment and commercial catch rates. However, the number of data points is small and additional sampling should be undertaken to further validate these relationships. The relative cost of undertaking the sampling is low compared to other field stock assessment methods. Knowing these relationships could allow for an earlier assessment of the health of the fishery and the adoption of conservative harvesting strategies to reduce the risk of over-exploitation.

Juvenile *Penaeus latisulcatus* up to 20 mm CL occur in nurseries. Their size distribution is highly skewed with 2 to 7 mm CL sizes comprising 90% of the catches overall. The low numbers of prawns above 7 mm CL within the areas sampled probably reflects the true size composition in these narrow bands between the high water mark and seagrass beds. Not many larger juveniles occur in these areas. It appears that emigration out of nurseries is size dependent and most juvenile prawns have moved out of the sampling area by the time they reach 20 mm CL.

Length frequency distributions were used to estimate growth in nurseries. Growth was seasonal. During May to September little growth was evident. Faster growth is apparent between October to December. Mean growth rates varied from 0.53 mm to 0.65 mm CL per week in winter and 0.71 mm to 1.28 mm CL per week in summer. Spring and autumn growth rates were intermediate of winter and summer growth rates. Laboratory results in this study indicate that 3 mm CL postlarvae grew at approximately 1.0 mm CL per week at 19.5°C.

The range of mortalities found during June-July to November 1990-1994 was 0.20-16.48% per week with a mean of 7.88% per week. Summer mortalities were estimated to be higher than winter mortality rates. There was some evidence of density dependent mortality with higher mortality at higher densities. No significant difference was observed for mortality rates between years although individual sites showed some annual variation. Therefore the amount of postlarval settlement will play an important role in regulating juvenile numbers. The timing of settlement and temperatures experienced while in the nurseries will determine how fast the prawns will grow and when they move out of nurseries. The processes controlling spawning events and the direction and timing of larval advection appear to be very important in the life history pattern of *P. latisulcatus* and subsequent success of recruitment to the fishery.

Overall, during the seven-year study period, no particular trend in postlarval settlement patterns and juvenile abundance was obvious. Some cyclic pattern may exist but the period of sampling is too short to confirm this trend. This may indicate stability in the population during the study period. This stability was evident even with a two-year closure of the fishery. The impact of the closure on the fishery was not significant in terms of postlarval settlement, juvenile abundance or recruitment to the fishery. A longer time frame may be required to observe significant changes in a relatively long-lived prawn species.

For the Gulf St Vincent prawn fishery, although there was some evidence of a relationship between recruitment and commercial catch rates, it appeared that the level of recruitment did not drive the level of catches during the period of this study. This may be due to other factors being more important in determining catch rates namely, low overall fishing effort, large harvest size and spatial and temporal fishing strategies. With current harvesting practices in place, postlarval settlement indices could not be used to predict the level of catch in the fishery. Sampling in key nursery sites would, however, provide a cost-effective means of maintaining long-term monitoring the health of nurseries and can detect low settlement years.

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Appendix 1 Publications

1. Chapters 2 and 3 - attached

Kangas, M I and W B Jackson (1998). Sampling juvenile *Penaeus latisulcatus* Kishinouye with a water-jet net compared with a beam-trawls: spatial and temporal variation and nursery areas in Gulf St Vincent, South Australia. *Marine and Freshwater Research,* **49**: 517-23.

2. Chapters 4 and 6

Kangas M I. Growth, mortality and spatial and temporal variability in settlement of juvenile *Penaeus latisulcatus* Kishinouye in Gulf St Vincent, South Australia over seven years. *Mar Freshwater Res.,* (submitted, currently undertaking editorial changes and suggestions by reviewers).

M. I. Kangas and W. B. Jackson (1998) Sampling juvenile Penaeus latisulcatus Kishinouye with a water-jet net compared with a beam-trawl: spatial and temporal variation and nursery areas in Gulf St Vincent, South Australia.
Marine and Freshwater Research, v. 49 (6), pp. 517 – 523, 1998