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Minimising gear conflict and resource sharing issues in the Shark Bay trawl fisheries and promotion of scallop recruitment

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Non-Technical Summary

Minimising gear conflict and resource sharing issues in the Shark Bay trawl fisheries and promotion of scallop recruitment

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Objectives

1. To determine size specific recapture mortality rates of *Amusium balloti* as a result of repeated capture and release experiments and gear impacts on newly recruited (juvenile) scallops.
2. To determine the impacts of various scallop mesh sizes for the capture of the target size of *Amusium balloti* and its impact on damage to and retention of prawns.
3. To investigate if small-scale spatial closures assist recruitment of *Amusium balloti* by reducing gear impacts and capture mortality but without affecting overall prawn catches.
4. To examine whether existing hydrodynamic models can guide the selection of spatial closures and to investigate the larval transport mechanisms of both prawn and scallop larvae in Shark Bay.

Outcomes achieved

- The likelihood of survival and recapture of discarded scallops was significantly higher in winter than summer months. This suggests that the regulatory discarding of scallops by the prawn fleet in summer prior to 2004 may have had a detrimental impact on the catch and spawning stock. Current management measures take this result into account and are an improvement on historical fishing arrangements although continuing discarding of scallops during the spawning and post-spawning months requires further management review.
- The 60 mm square mesh codend was a more efficient net type to capture large scallops than the standard 100 mm diamond mesh codend used by the scallop fleet. Further benefits include significant reductions in the retention of small scallops and bycatch (including prawns) as well as reduced processing time on board. The Shark Bay scallop industry is considering commercial trialing of this net (or similar) for the 2011 scallop season and the implementation of the improved codend will be considered after this trial.
- The introduction of the Carnarvon-Peron management line did not result in any significant increase in prawn trawl effort in central Shark Bay scallop grounds. In evaluating both the historical and recent catch and effort data of the prawn and scallop fisheries it was apparent that changes in trawl effort distribution was not a major driver of the scallop recruitment in Shark Bay. This result alone does not lend support for spatial closures of key central Shark Bay scallop trawl grounds. However, increased recruitment in more recent years combined with changes to harvesting strategies and overall reduced effort needs to be further evaluated along with key environmental parameters to improve our understanding of scallop recruitment dynamics.
- Hydrodynamic modeling of Shark Bay combined with larval movement identified fishing grounds close to the bay's entrance channels to be highly susceptible to flushing, while there were higher retention rates of larvae in central Shark Bay and lower regions of Denham Sound. The study also showed that connectivity between Red Cliff and NW Peron stocks was possible, while Denham Sound was highly unlikely to be connected to Red Cliff and NW Peron stocks. These findings suggest for a management focus on protecting and maintaining a healthy spawning stock level in each of the main fishing grounds and protection of grounds after larval settlement.

The Shark Bay scallop stocks are fished by two otter trawl fisheries, the Shark Bay Scallop Managed Fishery (14 boats) that is licensed to catch scallops only and the Shark Bay Prawn Managed Fishery (18 boats) predominantly targeting prawn stocks with saucer scallops as a secondary target. This project addresses a number of gear interaction issues between the two fisheries.

1. To determine size specific recapture mortality rates of *Amusium balloti* as a result of repeated capture and release experiments and gear impacts on newly recruited (juvenile) scallops

Survival of repeatedly discarded saucer scallops was estimated for the Shark Bay trawl fisheries using short-term tag-recapture experiments under various fishing and environmental conditions. Survival estimates of discarded scallops were significantly higher in winter (post-spawning) than during summer (pre-spawning), but no large differences in survival between fishing grounds or between post-capture treatment groups (air exposed or hopper). This suggests that thermal stress from large differences in seasonal temperatures was more critical to scallop survival than differences in scallop reproductive condition. Therefore regulatory discarding under past management strategies, which occurred primarily in the warmer summer months, is likely to have resulted in higher discard mortality rates than during winter months. Under current management measures however, regulatory discarding still occurs but is predominantly over winter months when scallops exhibit higher resilience to trawl-induced stress. The results support the current management strategy of both fleets fishing during the warmer pre-spawning months so that the amount of discards is less, a spawning closure period during a cooler period with associated discard mortality at its minimal.

2. To determine the impacts of various scallop mesh sizes for the capture of the target size of *Amusium balloti* and its impact on damage to and retention of prawns

Codend mesh shape and size were examined for the Shark Bay scallop trawl fishery to determine if the selectivity of scallops could be improved by adopting a square mesh codend as an alternative to the conventional diamond mesh codend. Of the three different sized square mesh codends (50, 55, 60 mm) tested against the standard 100 mm diamond mesh codend, the 50 mm square mesh codend performed poorly with relatively high retention of small scallops, while the 55 and 60 mm square mesh codends retained 22 to 33 % less smaller scallops than the diamond mesh codend. Overall, a mean of 5% loss in commercial sized scallops across all three square mesh codends and significant bycatch reductions of up to 95% occurred when operating square mesh codends compared to the diamond mesh. The ratio of small sized scallops retained by the square mesh to that of the diamond mesh codend decreased with increasing mesh sizes and was lowest overall in the 60 mm square mesh codend. The catch rate of prawns in the square mesh codend was less than 2% of that of the standard prawn net. A move to square mesh codends could result in a significant reduction of discards (both small scallop and bycatch) and may increase catches of commercial sized scallops due to improvements in water flow and net efficiency. Thus the performance of the 60 mm square mesh codend presents a good basis for its use in commercial trials in the Shark Bay scallop trawl fishery.

3. To investigate if small-scale spatial closures assist recruitment of *Amusium balloti* by reducing gear impacts and capture mortality but without affecting overall prawn catches.

Extension: **To evaluate both the historical and current spatial effort distribution of the A-class scallop fleet and B-class prawn fleet and to determine if trawl effort intensity during the key scallop spawning period had impacted on the scallop recruitment dynamics.**

In examining the effort levels of both the scallop and prawn fleets on the central scallop grounds (1987 – 1994), peak annual trawl effort occurred during the key scallop spawning months (April to July). The introduction of the Carnarvon-Peron line did not redirect fishing effort onto the scallop grounds so the two fleets can move forward to optimise harvesting of both scallop and prawn stocks without this issue clouding the consultation process. The most notable change in effort and fishing dynamics on scallops occurred after 2004 due to the simultaneous openings of both scallop and prawn fishing. This major change in management strategy reduced total effort levels on scallops during the spawning period as fishing occurred prior to this and resulted in reduced discarding during summer. However regulatory discarding of scallops retained by prawn nets was enforced for the scallop spawning-period. Despite these measures we found no clear correlation between effort levels of either fleet or in combination with scallop recruitment.

This suggests that trawl effort alone is not a major driver of recruitment in central Shark Bay and the examination of effort trends does not provide a strong basis for the implementation of a spatial closure.

4. *To examine whether existing hydrodynamic models can guide the selection of spatial closures and to investigate the larval transport mechanisms of both prawn and scallop larvae in Shark Bay*

The hydrodynamic modelling, which focused on scallop larval advection in Shark Bay, indicated limited larval connectivity between Denham Sound and northern fishing grounds and it appears that the key grounds are primarily self-seeding. Northern Red Cliff and Denham Sound have a higher likelihood of larval loss (flushing) out of Shark Bay under certain environmental conditions. The management implications from these results are that it is essential to retain spawning stock in each fishing ground in order to replenish stocks on each fishing ground. The current management strategy of fishing scallops to a catch rate threshold to ensure carryover of stock is therefore appropriate. Implementation of spatial closures may still be a reasonable strategy to protect spawning stock and newly settled scallops due to the lack of connectivity between fishing grounds.

Keywords: scallops, prawns, discard survival, fishery interaction, *Amusium balloti*, tag-recapture, square mesh codend, otter trawl, recruitment, hydrodynamic models, spatial effort distribution.

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1.0 General introduction

1.1 Background

Shark Bay is a world heritage area in the Gascoyne region of Western Australia's coastline, renowned for its ecological importance and commercial significance (Fig. 1.1). There are two independent otter trawl fisheries operation with a combined value of AUD20-30 million/annum, the Shark Bay Scallop Managed Fishery (14 operating boats) that is licensed to catch scallops only and the Shark Bay Prawn Managed Fishery (18 operating boats) predominantly target king (*Penaeus latisulcatus*) and tiger (*Penaeus esculentus*) prawn species as well as saucer scallops as a secondary but important target component (Sporer *et al*. 2009). Both fisheries operate under a real-time management system to achieve management objectives. Management measures include input and output controls, temporary and permanent spatial closures, variable seasonal openings and closures, and restrictions on gear type, crew and boat numbers. The stock's response to these measures are monitored through daily fisher's logbook and annual stock surveys, which allow managers to evaluate both the performance of the fishery and the effectiveness of the measures in place.

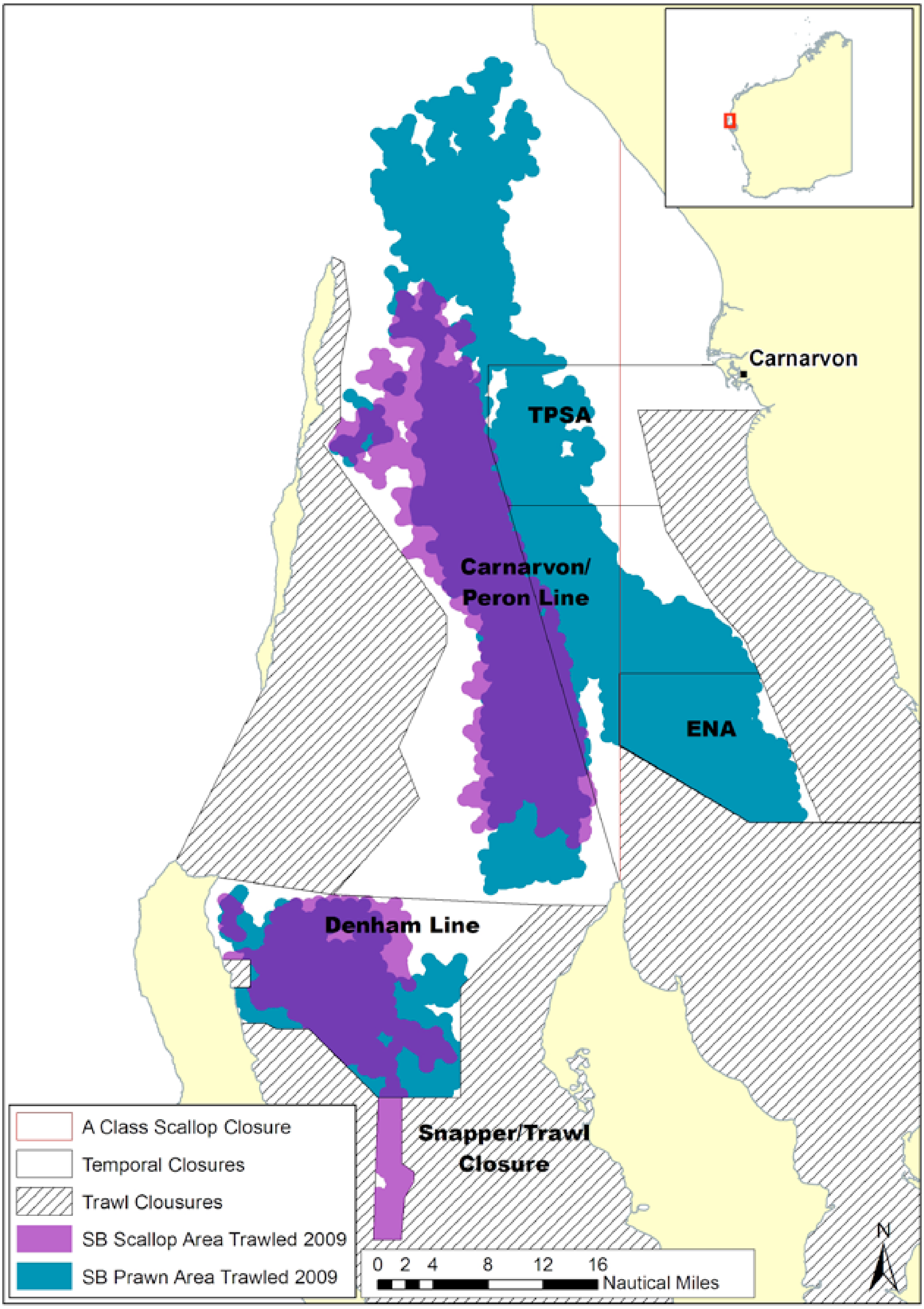


Figure 1.1. General map of Shark Bay with key management lines and the spatial overlap (dark purple) in fishing grounds of the scallop (light purple) and prawn (blue) fleets in 2009. TPSA = Tiger Prawn Spawning Area; ENA = Extended Nursery Area.

1.1.1 Management of the Shark Bay scallop resource

Prior to 1983, scallop fishing was permitted all year, but in response to low residual stock levels and peak spawning in June, the season opening dates were set to 1 March in 1983 and 1984. In 1985, further changes led to the season opening in March followed by a fishing spawning closure period between April and June (inclusive) with reopening in July (Joll 1987). From 1987 to 2004 this temporary (spawning) closure of scallop fishing was no longer enforced and instead fishing usually started in April/May to allow for a conservative level of spawning prior to fishing. The prawn fleet generally commenced fishing before the scallop fleet on the main prawn fishing grounds but they were not permitted to retain any scallops until the scallop season commenced. This meant that there was a period of several weeks when scallops were being continuously captured and discarded, which may have resulted in some trawl-induced mortality as well as unavoidable damage to prawn nets from large amounts of scallops in the nets. The commencement of the scallop season was based on a decision-rule framework called the MATRIX system. Pre-season surveys conducted in October/November provided an index of stock abundance available for the following fishing season. The framework considered the abundance of recruit and residual stock levels and the predicted catch estimates (Table 1.1). For example, in the event of high recruitment levels, it was assumed that large numbers of scallops would be available earlier than May and an earlier opening date would permit the capture of some scallops over the time of better meat yield, without causing levels of breeding stock to fall below a certain level. The timing of opening the scallop seasons and integration of the scallop fishery arrangements with the prawn fishery arrangements, while suitable for protecting the breeding stock, did not necessarily provide the best outcome for maximising the economic yield for the fishery. In 2004, the MATRIX system was abolished and instead both fleets began fishing on the same date (Kangas *et al*. 2011). This however did not apply to the Denham Sound fishing grounds which had its own opening and closure dates based on meat size and quality.

Table 1.1. Schedule linking strength of recruitment and residual stock determined during the November survey with estimated catch producing an appropriate estimated opening date. This decision-rule framework (referred to as the MATRIX system) was used from 1987 to 2004.

Estimated Catch	Abundance Recruits	Abundance Residuals	Opening Date*
Low (<300t)	Low	Low	15 May
Med (300 - 600t)	Moderate	Low	1 May
	Low	Moderate	15 April
High (600 - 1500t)	High	Low	15 April
	Moderate	Moderate	15 April
	Low	High	1 April
Very high (>1500t)	High	Low	1 April
	Low	High	15 March

*Or nearest suitable day

1.1.2 Gear interactions and fishery inter-relationships

Inter-fishery issues have existed between the scallop and prawn fisheries since the scallop fleet became a separately formed fishing entity within Shark Bay. Despite management objectives striving to provide an equitable access to the resource and space, there are ongoing issues concerning gear interactions, annual catch-share, fishing arrangements and stock-recruitment dynamics (Department of Fisheries 2010). A key management issue concerning the common scallop resource is the low and variable recruitment pattern which is thought to be the combined result of environmental conditions (e.g. water temperature and other Leeuwin Current influences), spawning stock and the impact of trawl activities on scallop recruitment. The stock-recruitment-environment relationship for the scallop resource is not strong although some environmental variables show correlation with certain recruitment events (Joll and Caputi 1995b; Lenanton *et al.* 1991, 2009). For example, while all years of good recruitment was associated with a weak Leeuwin Current (associated with El Nino-Southern Oscillation (ENSO) years), some recent ENSO years in 1997 and 2002 have not produced good recruitment. The effect of the Leeuwin Current on water temperature may also be a critical factor given some good recruitment years were associated with cooler water temperatures during the spawning season. Historically, the northern scallop fishing grounds have been treated as a separate stock to that of Denham Sound fishing grounds (Fig. 1.1) where some biological and stock characteristics are different. The hydrodynamics within the Bay is assumed to be responsible for the distinction in stock characteristics between northern and southern regions of Shark Bay.

Variable spawning stock levels in Shark Bay are also due to variations in recruitment and possibly fishing effort levels around the spawning months (Joll and Caputi, 1995b). Catch rate thresholds were implemented in 2005 to ensure adequate breeding stock levels are maintained after the pre-spawning fishing period by both trawl fleets. In 2007 and 2008, a trial catch-share arrangement was undertaken where the prawn and scallop fleets were assigned 28% and 72% respectively share of the scallop harvest. Residual scallops were carried over to the following season's catch to provide additional scallops if low recruitment persisted. From 2011 onwards, the catch share arrangement will be formally implemented as a management strategy.

The interaction of the different fishing gear configurations and fishing dynamics with the benthic habitat and biota means there is potential for the activities of one industry to influence the other in the areas of stock overlap (Fig. 1.1). In recent years, both the prawn and scallop fleets have suggested that gear interactions are having a negative effect on the scallop and prawn fisheries respectively, causing both short-term losses through mortality, as well as possible recruitment impacts. This perceived impact of scallop trawl gear on prawns and the impact of prawn trawl gear on scallops are central to the gear interaction issues between the two fleets and thus the poor fishery inter-relationship that exists. Given the overlap in fishing grounds and fishing periods and the different management arrangements they operate under, there are frequent concerns of incidental mortality rates to the target species and its impact on the sustainability of the resource.

Newly settled and juvenile king and tiger prawns in their nursery areas in the south and the shallows on the eastern banks migrate onto the main Shark Bay trawl grounds during February and March growing to larger adult sizes. Thus risk of incidental fishing mortality on juvenile prawns is lower during this period but increases during May-July when higher abundances of recruiting prawns move onto the central trawl grounds. Interactions between scallop trawl gear and prawns is not however considered to be significant given the large 100 mm diamond mesh codends which does not readily retain prawns unless excessive clogging of the net occurs. The impact of ground chains from scallop gear on prawns buried in the seabed is another issue that lacks any supportive data, as is the indirect fishing mortality to prawns that pass through the nets. Since the scallop fleet is not permitted to harvest or retain prawns, any potential product loss from gear interactions is viewed as a loss in profitability for the Shark Bay prawn industry and thus central to the gear interaction conflict between the trawl fleets.

Unlike prawns, juvenile scallops recruit directly onto the main fishing grounds where adults occur and so become highly vulnerable to gear impacts from both scallop and prawn fleets. Given the smaller mesh size codends used by the prawn fleet and their continued fishing activities during the post-spawning months, the gear interactions are potentially higher and scallops are possibly at a greater risk from incidental mortality. Scallops can tolerate air exposure for longer periods and so discarded scallops are more likely to survive to be recaptured later. However the overlapping fishing grounds where both fleets operate are of high trawl intensity where the rate of repeated scallop discarding is likely to be high and their long-term survival is unknown. Management changes to the scallop fleet have resulted in changes to the scallop fishing period and length, which may have implications to scallop recruitment.

For Shark Bay trawl fisheries, the ongoing implementation of new and modifications to existing management strategies makes their effectiveness difficult to assess, particularly in the absence of long time-series data of any one management measure. Thus identifying key contributing factors that determine and influence scallop recruitment dynamics is a complex task. The research undertaken in this project focused on some aspects of the fishery management, the biology of the target species and the physical environment to better inform future resource management decisions in Shark Bay.

1.2 Need

There is an urgent need to develop an understanding of the impact from gear interactions between the Shark Bay scallop and prawn managed fisheries. The level and type of impact is likely to have varied under different past management measures with the potential to significantly impact scallop recruitment in Shark Bay. Both sectors (prawn and scallop) support the need to fully and rigorously address the issue of gear interactions in those areas of the fishery where the distributions of the target species overlap. The sustainability of the common scallop resource faces greater pressure than the prawn resource since a) it lacks full protection during its spawning period, b) lacks any juvenile habitat protection and c) recruitment is highly variable and susceptible to environmental influences. Therefore the value of protected areas of key scallop grounds is also under consideration and to assist with this evaluation, a better understanding of the hydrodynamic conditions and scallop larval transport mechanisms in Shark Bay is of critical importance.

Completion of this project should therefore result in information required to help optimise the use of the resources and assist in addressing the resource sharing conflicts between sectors within the region.

1.3 Objectives

1. To determine size specific recapture mortality rates of *Amusium balloti* as a result of repeated capture and release experiments and gear impacts on newly recruited (juvenile) scallops.
2. To determine the impacts of various scallop mesh sizes for the capture of the target size of *Amusium balloti* and its impact on damage to and retention of prawns.
3. To investigate if small-scale spatial closures assist recruitment of *Amusium balloti* by reducing gear impacts and capture mortality but without affecting overall prawn catches.

EXTENSION: To evaluate both the historical and current spatial effort distribution of the A-class scallop fleet and B-class prawn fleet and to determine if trawl effort intensity during the key scallop spawning period had impacted on the scallop recruitment dynamics.

4. To examine whether existing hydrodynamic models can guide the selection of spatial closures and to investigate the larval transport mechanisms of both prawn and scallop larvae in Shark Bay.

2.0 Objective 1: Discard mortality rates

Objective 1: To determine size specific recapture mortality rates of *Amusium balloti* as a result of repeated capture and release experiments and gear impacts on newly recruited (juvenile) scallops

2.1 Introduction

For sedentary species such as scallops, discard rates from trawling or dredging can be very high as scallop beds are repeatedly targeted until uneconomical harvest rates are reached (Maguire *et al.* 2002b). A typical trawl capture scenario for *A. balotti* would include physical interaction with trawl gear during capture, encounter with bycatch within the codend during trawling and air exposure and handling after hauling, all culminating in stress and exhaustion. Discarded scallops may experience this process several times within a short or long time interval throughout the fishing season and therefore may be highly vulnerable to cumulative physiological (Maguire *et al.* 1999; Maguire *et al*. 2002a) and physical injuries (Gilkinson *et al*. 1998; Schejter and Bremec 2007) where survival is highly dependent on the influences of various biological and environmental conditions concomitant with capture and processing techniques.

Repeated scallop discarding under different management arrangements and its impact on scallop recruitment in Shark Bay is of concern to both Shark Bay trawl fisheries. The overall discard rate of scallops in Shark Bay is generally greater during winter than summer months due to a higher abundance of small scallops (+0 age cohort), and also a greater proportion discarded by the prawn fleet as they use a smaller mesh size (50 mm) codend than the scallop fleet (100 mm). The overlapping spatial and temporal fishing dynamics of these fleets under different management strategies have also at times enforced scallop discarding to be mandatory. For instance, prior to 2004, the prawn fleet began fishing 2 – 4 weeks prior to the scallop fleet and during this period it was mandatory for all captured scallops to be discarded until the scallop fishing season opened. This discarding practice ceased when management changed to allow both scallop and prawn fishing season to open simultaneously (2005 onwards) thereby only small sized scallops continued to be discarded. During the scallop spawning months in winter, prawn fishing continues and usually on scallop grounds where large sized (or higher abundances) prawns tend to aggregate. In order to optimise spawning success and recruitment settlement (2 – 4 weeks after spawning), all sized scallops retained by prawn nets are required to be discarded, while newly settled scallops become vulnerable to continuing trawl disturbance. Towards the end of the prawn fishing season (October – November) discard rates of juvenile scallops are high due to greater ratio of scallop recruits to adult residual abundance on the trawl grounds. Since prawn fishers use a smaller mesh size codend than scallop fishers, the retention and discarding of small sized scallops is high during this period. Trawl discarded scallops are subject to multiple recaptures and trawl impact on scallop condition can be both direct, from physical injury, and indirect from stress and exhaustion.

Furthermore, *A. balloti* is a sublittoral bivalve that seldom encounters air exposure, therefore post-capture methods and handling practices are additional factors that also impact on its survival (Dredge 1997; Campbell *et al.* 2010). For example, one major change in the handling practices onboard for scallops and bycatch has been the introduction of seawater hoppers (large seawater holding tanks) on prawn boats. The benefits of a hopper system are in reducing the air exposure period for all catch thus increasing their likelihood of survival while improving the product quality of the target species (Heales *et al.* 2003). Thus the survival of saucer scallops under different post-harvest practices also needs to be evaluated to understand its impact on overall recruitment.

In the current study, we investigated spatial and temporal differences in the survival of discard scallops under different post-capture treatments from field experiments simulating commercial scallop trawl activities. Specifically we have used multiple mark-recapture trials to examine 1) seasonality of apparent survival, 2) impact of two post-capture handling methods, and 3) evaluate potential spatial variability in apparent survival. From this we infer the potential impact of discarding on pre and post-spawned scallops. Based on this information, the fishing impact of discarding (differently treated) scallops on the sustainability of the resource was evaluated under past and present management strategies for the Shark Bay trawl fisheries.

2.2 Methods and Materials

2.2.1 Study area

Tag recapture experiments were conducted within the Shark Bay region of Western Australia between 25° 00' and 25º 24' south latitude, and 113° 15' and 113° 25' east longitude (Fig. 2.1). Sites of moderate scallop abundance (~ 3000-5000/trawl (20 min shot duration)) based on data from an annual scallop survey (undertaken in Nov/Dec of 2007 and 2008) were chosen for the tag-recapture experiments. Lower Denham Sound (LDS) and Upper Denham Sound (UDS) sites in the southern region of Shark Bay were selected for winter experiments while East Shark Bay (ESB) and West Shark Bay (WSB) sites in the central region of the bay were selected for summer experiments. Habitat differences between these sites are unknown, but generally the bottom consisted of sand and shell substrates with a trawl depth range from 15 to 25 m across all sites. Different regions within Shark Bay were chosen for winter and summer experiments so as to avoid commercial fishing boats in operation, journey times between sites were within 60 minutes and accessible during favourable weather conditions.

Scallop tagging and recapture experiments were conducted in winter (September 2008) when most scallops were in post-spawning phase and in summer (February 2009) when scallops were in pre-spawning phase (Joll and Caputi 1995a). On both occasions, the research vessel *Naturaliste* was configured to operate as a twin-gear rigged otter trawl system (1.98 m headrope nets), using the standard 50 mm diamond mesh codend used by commercial prawn fishers. All experiments were conducted between the hours of 1830 hrs and 0600 hrs in accordance with commercial prawn operations. Sea surface and air temperatures during winter experiments were 17 to 20°C and 19°C respectively with an average wind speed of 4.5 knots. In summer sea surface and air temperatures were 25 to 28°C and 25 to 30°C respectively with average wind speeds up to 4.8 knots.

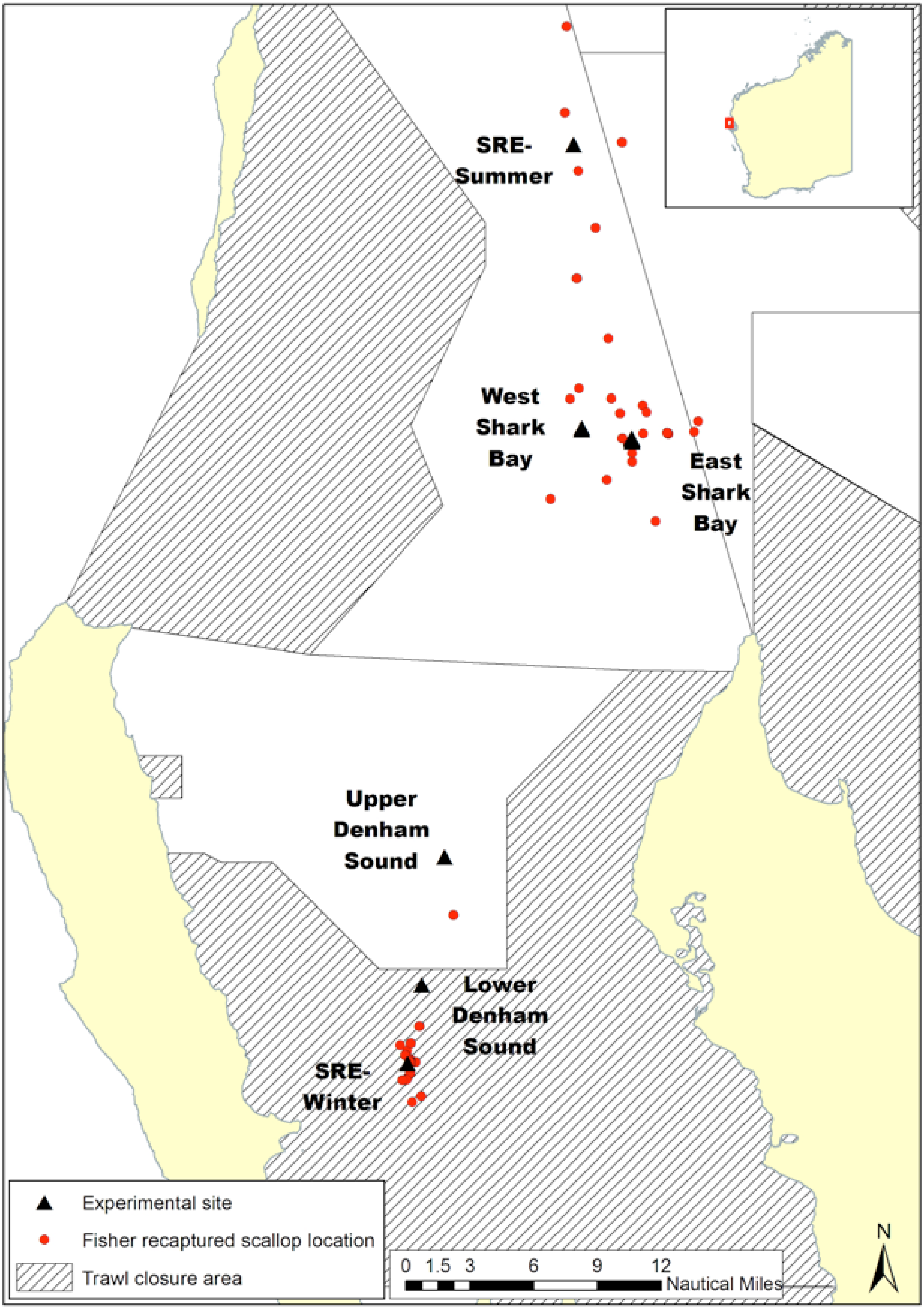


Figure 2.1. Map of Shark Bay showing experimental tagging sites in the central bay region in summer (West Shark Bay, East Shark Bay, Short Recovery Experimental site (SRE)) and lower bay region (Upper Denham Sound, Lower Denham Sound, Short Recovery Experimental site (SRE)). Red circles indicate locations of scallop recaptures by commercial fishers during the scallop fishing season in 2008 (prawn boats) and 2009 (prawn and scallop boats).

2.2.2 Scallop capture and tagging procedure

Experimental sites were trawled (20 min shot duration) to capture ~ 2000 scallops for marking on the tagging night and kept in a recirculating seawater tank. For the air-exposure treatment, batches of 200-250 scallops were removed from the holding tank at a time and were air exposed for approximately 40 minutes during which time they were measured and tagged. A 40-minute air exposure period was chosen, as it is within the upper time limit scallops are handled before being shucked or discarded during commercial operations. For the hopper treatment, scallops were removed from the holding tank one at a time, measured and tagged and immersed in seawater again as fast as possible to minimise air exposure. Batches of tagged scallops from the hopper treatment were released together with tagged air-exposed scallops. Scallops were tagged with individually identifiable glue-on shellfish tags (Hallprint, FPN tags) attached with cyanoacrylate adhesive. It took approximately four hours to complete the tagging and release of scallops. Additionally, a control treatment tank (one each experiment) with flow through seawater and containing approximately 300 trawl captured, untagged scallops were kept onboard and undisturbed for 6-8 days to assess survival and condition of scallops that had experienced minimal trawl disturbance.

Experimental sites were trawled the following 4 nights in winter and 3 nights in summer (bad weather conditions prevented an additional trawl night) after the tagging night to recapture tagged scallops. A total of seven trawl shots of 10 minute trawl duration were conducted over the experimental sites. Recaptured tagged scallops had their tag numbers recorded and separated into their respective treatment conditions. Air treated scallops were kept in baskets on the sorting table while hopper treated scallops were immersed in seawater. At the completion of all seven shots, recaptured tagged scallops were collectively released as precisely as possible on to their capture location. Information on recovered dead tagged scallop shells were retained as additional information but not used in the survival analysis. Analyses of variance (ANOVA) was used to compare differences in the size (shell height) of scallops between treatment groups and between captured and non-recaptured scallops at each of the sampling sites using Statistica (V7.1, Statsoft Inc, Tulsa OK USA).

2.2.3 Damage and adductor muscle weight analyses

Direct damage and injury to scallops were visually assessed from a sub-sample of 300 scallops (tagged and untagged) collected across all trawl sites during the summer experiments using a damage scale from Level 0 (no damage) to Level 5 (dead scallop). Damage scale descriptions are as follows: Level 0 = no external damage or injury to valves or soft tissue; Level 1 = minor chipping to the edges of valves; Level 2 = major chipping to the edges of valves; Level 3 = extensive chipping of valves exposing soft tissue; Level 4 = proportions of valves missing, visible injury to soft tissue but scallop alive; and Level 5 = valves cracked in half or smashed resulting in death of scallop. Please note, otter trawling relies on scallops swimming up into the water column to be captured, therefore dead scallops in the nets were an unexpected result.

A sub-sample of tagged scallops (~50 scallops from each treatment) were retained and frozen whole from ESB, WSB and UDS sites on the last night of the experiments. The adductor muscle from each of these scallops was later dissected and their wet weight recorded.

2.2.4 Short-term trawl recovery experiments

Additional experiments were conducted to determine the survival of scallops after a shorter recovery timeframe (2 hours) between tag and release. In winter, an additional site in Denham Sound (SRE-winter in Fig. 2.1) was trawled (20 min shot) to capture ~2000 scallops. The tagging procedure for air exposed and hopper treated scallops were as described above. The release site was trawled over using 4 shots (10 minute trawl duration) where recaptured tagged scallops were recorded, handled according to their treatment on board and then released back on to capture site before the next trawls. Recovery trawls were planned for this experiment however the time to tag and release the scallops initially allowed only four trawls within night-time hours at the site. This experiment was repeated in summer at a site in Shark Bay (SRE-summer). The experimental design was altered from the winter experiment so that tagged scallops were recovered from 5 consecutive shots (1 trawl impact) of 10 min duration each in the release area and then scallops were re-released on to the site. However, the intended four impact events (a total of 20 shots) were not possible within the night-time hours and so only two were completed. The recapture rates of scallops from these experiments are shown in Table 2.2 but no further analyses were conducted.

2.2.5 Tag-recapture analyses

Maximum likelihood methods were used to estimate the conditional probabilities of apparent survival (ϕ) and resighting (p) of hopper treated and air exposed tagged scallops at the different sites over winter and summer periods. Analyses of survival and resighting estimates were performed on the software Program MARK developed by White and Burnham (1999). The modelling process started with assessing the Goodness-Of-Fit (GOF) of the data to the fully parameterised Cormack-Jolly-Seber (CJS) model with time (t=1 to n repeat trawl nights) and group (g = hopper or air) dependence for survival and resighting (ϕ_{g*t}, p_{g*t}). Information on recovered dead tagged scallop shells were retained as additional information but not used in the survival analyses. GOF testing of both winter and summer data sets detected over-dispersion of the data and so the variance inflation factor ($\hat{c}$) was calculated to adjust the sensitivity of the model selection process to the detection of fine-scale structural features within the data (Anderson *et al.* 1998). We chose to estimate $\hat{c}$ by dividing the observed model $\hat{c}$ by the mean $\hat{c}$ from a bootstrap analysis. Selection of the most parsimonious model from a candidate set of models under consideration was assessed by applying the quasi-likelihood adjusted form of the Akaike's Information ($QAIC_c$) after incorporating the $\hat{c}$ to allow for overdispersion of the data. If the $QAIC_c$ of the simplified model was lower than that of the starting model, the simplified model was adopted as the best general model. Model selection proceeded using ranked $QAIC_c$ values and expressed as $\Delta QAIC_c$ calculated as the difference with the model with minimum $QAIC_c$. These $\Delta QAIC_c$ values were also used to compute model-specific $QAIC_c$ weights, which reflect the proportional support of evidence for a specific model. However, if $\Delta QAIC_c < 2$ then those models were considered to have equal likelihood of describing the data and thus model averaging was applied to derive estimates of survival and resighting probabilities (Burnham and Anderson 2002).

Although trawl sites were open to scallop movement, significant movement of released tagged scallops was not considered to be an issue as *A. balloti* is a relatively sedentary species with limited capacity for movement (less than 20 m) (Joll 1989), and any active migration from the experimental sites were considered to be minimal. We also assumed tag loss and tag induced mortality to be low and equivalent among all treatments at all sites. Assumptions relating to the standard CJS model were:

1. Every marked animal in the population has the same probability of recapture between trawl nights
2. Every marked animal has the same probability of surviving between trawl nights
3. No tags are lost and tags are readable
4. All samples are instantaneous and each release occurs immediately after sampling

To determine the relative survival of hopper treated scallops to air-exposed scallops, data from scallops captured once only (and thus applied with the treatment once) was further analysed using the program SURVIV (available free from http://www.mbr-pwrc.usgs.gov/software/surviv.shtml).

2.3 Results

2.3.1 General recapture information

The total number of scallops tagged and recaptured for each treatment at each site during the experimental period is summarised in Table 2.1. Generally, recapture rates were higher in winter than summer with the highest number of scallops recaptured at UDS. There was also a trend of increasing scallop recapture rate from night 2 to 4 at UDS while recapture rates at LDS was lower and more consistent. Conversely in summer, recapture rates were less than 40% across all the nights at both sites. Recapture rates were higher at ESB for nights 1 and 2 with a rapid decline in recapture rates reaching < 10% on night 3 at both ESB and WSB (Fig. 2.2). In winter, recapture rates from hopper treated scallops were lower than air exposed scallops at UDS but the reverse trend was observed at LDS. In summer, hopper treated scallops showed lower recapture rates than air-exposed scallops at both ESB and WSB (Fig. 2.2). The short-term recovery experiment in winter indicated recovery rates between 9 and 18% for both air and hopper treatments which were much lower than rates observed in longer-term recovery experiments (54 to 61% after 24 hours). The summer experiment was not fully completed but the two sets of trawls indicated very low recapture rates of 1 to 4%, but this reflects the much lower recapture rates also observed in the summer longer-term recovery experiment (20 to 35%). Catchability may therefore be reduced with short recovery times.

Recapture frequency of individually tagged scallops was highly variable across all sites and treatments. The capture rate of scallops caught once and twice only was lower at UDS than at LDS, but the capture rate of scallops caught three times and on all four nights was considerably higher at UDS than at LDS (Fig. 2.3). For summer, the capture rates of scallops caught once, twice and three times were higher at ESB than at WSB. There were no clear, consistent patterns in the overall recapture frequency of individually tagged scallops between hopper and air-exposed treatments across all sites (Fig. 2.3). Less than 20% of tagged scallops were not recaptured during winter, and this proportion increased to 52% at WSB and 78% at ESB in summer. Recapture rates of other encounter histories are shown in Fig. 2.4. A small proportion of scallops recaptured in winter and summer were recovered dead, some with and some without soft tissue attached. The numbers of dead scallops recovered in summer were higher at ESB than at WSB and altogether considerably higher than in winter (Table 2.1). A total of six scallops were found dead at the end of the experimental period in the control treatment tanks in both winter and summer. This indicates that a one-off trawl impact may cause relatively low mortality.

Although a similar size range of scallops were tagged in winter (78 – 111 mm shell height) and summer (50 – 112 mm shell height), there were significant differences in the mean size of scallops tagged between sites in winter (UDS = 91.8 ± 0.3mm, LDS = 89.1 ± 0.2mm) ($F_{1, 3959} = 77.8$, $p < 0.01$) and summer (ESB = 87.2 ± 0.2mm, WSB = 86.0 ± 0.1mm) ($F_{1, 3953} = 28.2$, $p < 0.01$). These significant differences are mostly due to the large sample sizes and the biological difference is not substantial, thus scallop size should not significantly influence the tagging results. There were however no significant differences in the size of scallops between hopper and air-exposed treatment groups and between recaptured and non-recaptured scallops for winter and summer periods ($p > 0.05$).

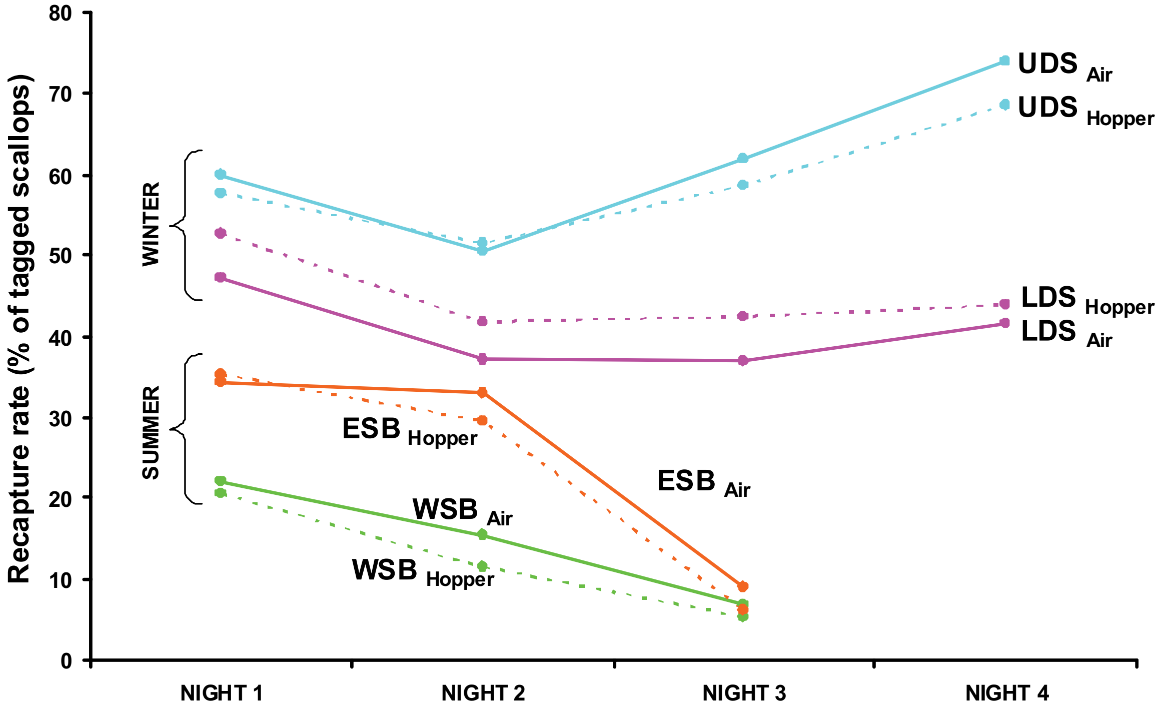


Figure 2.2. Recapture rates of tagged scallops (as a % of total scallops tagged per treatment per site) from each night of repeat-trawling conducted in winter and summer periods. Hopper treatment indicated by broken line and air exposure treatment indicated by solid line. WSB = West Shark Bay, ESB = East Shark Bay, UDS = Upper Denham Sound, LDS = Lower Denham Sound

Table 2.1. Summary of total number of scallops tagged, recaptured, non-recaptured and recovered dead during the summer and winter experiments. Mean size (mm SH) of recaptured and non-recaptured scallops across all treatments and sites are also indicated.

Season →	WINTER				SUMMER			
Sites →	Lower Denham Sound		Upper Denham Sound		East Shark Bay		West Shark Bay	
Treatment →	Hopper	Air exposed	Hopper	Air exposed	Hopper	Air exposed	Hopper	Air exposed
Total tagged	940	944	787	787	951	950	1000	991
Recaptured on Night 1	504	459	467	484	195	209	353	340
Recaptured on Night 2	400	359	420	411	109	147	294	327
Recaptured on Night 3	405	357	476	510	50	65	62	89
Recaptured on Night 4	420	404	559	602	n/a	n/a	n/a	n/a
Not recaptured	116	168	70	44	737	738	517	513
Total dead recoveries	2	5	4	3	54	42	23	36
Mean size (± se) (SH)								
Recaptured scallops	89.5±0.2	89.3±0.2	91.5±0.2	91.4±0.2	87.6 ±0.4	86.6 ± 0.5	86.0 ± 0.3	86.4 ± 0.3
Not recaptured scallops	85.6±1.4	87.8±0.5	86.2±2.0	87.5±2.3	87.6 ±0.3	87.0 ± 0.3	85.4 ± 0.3	86.2 ± 0.3

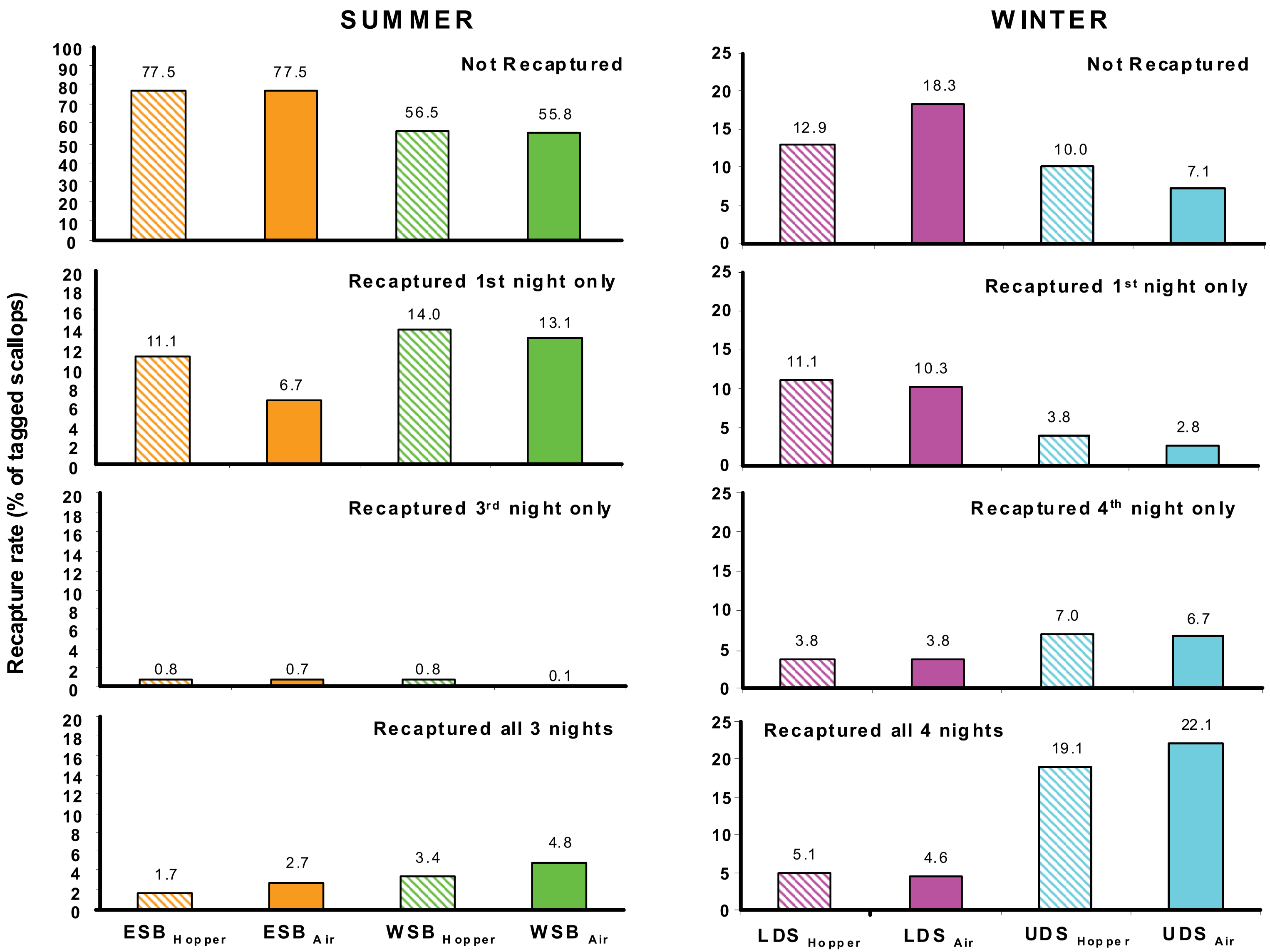


Figure 2.3. Examples of some encounter histories from summer (left column) and winter (right column) experiments. Note the 3rd night in summer and 4th night in winter were the last nights of sampling.

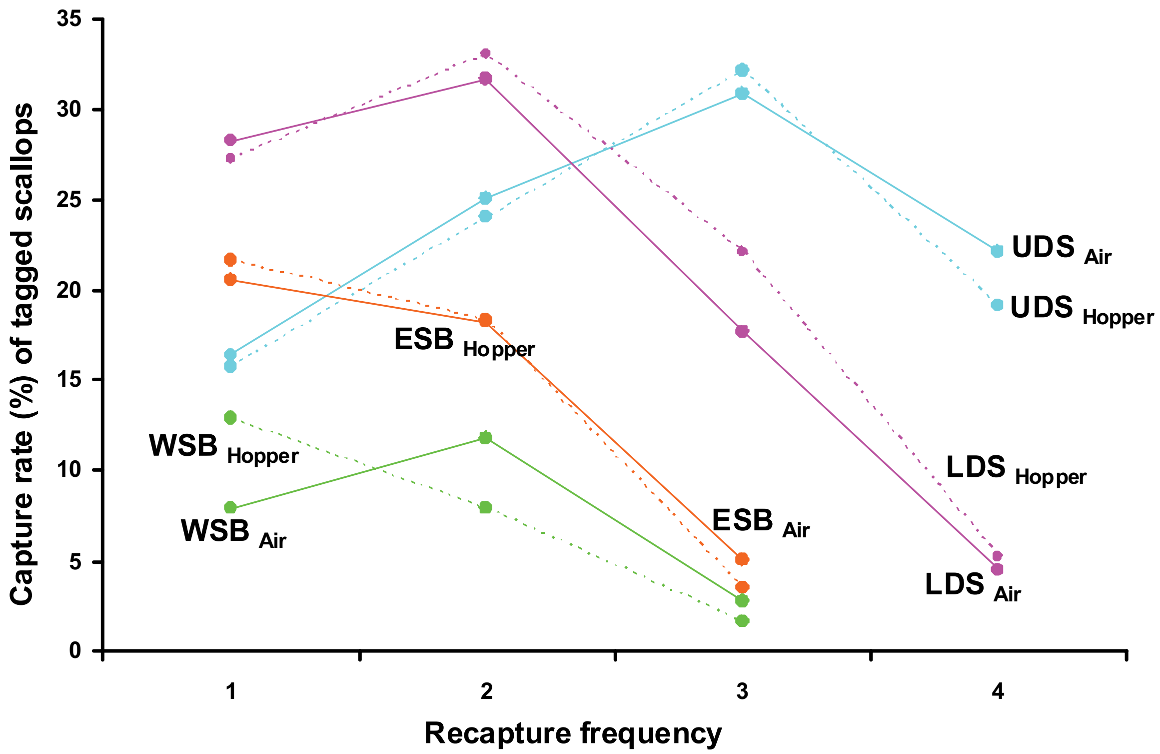


Figure 2.4. The number of recapture events of individual tagged scallops over the summer and winter experimental period expressed as a % of total scallops tagged per treatment per site. WSB = West Shark Bay, ESB = East Shark Bay, UDS = Upper Denham Sound, LDS = Lower Denham Sound.

Table 2.2. Summary of total number of scallops tagged and recaptured during the short-term (2 hour) recovery experiments in winter and summer periods. Differences in experimental design between seasons are explained in Section 2.2.4

WINTER	Hopper	Air exposed
Total tagged	882	858
Shot 1	83	81
Shot 2	120	157
Shot 3	90	89
Shot 4	76	73
SUMMER	Hopper	Air exposed
Total tagged	868	849
1st Impact (total of 5 shots)	13	32
2nd Impact (total of 5 shots)	14	12

2.3.2 Goodness Of Fit (GOF) testing results

The results of the GOF tests revealed over-dispersion for the saturated models for all sites (p<0.05). The poor fit indicated violations of CJS assumption of equal probability of capture and survival of tagged animals. This suggests heterogeneity in survival or capture probabilities among individuals or lack of independent sampling of individuals. The former is more likely from our experimental design where the re-application of either the hopper or air treatment on recapture meant not all tagged scallops experienced the same amount of treatment effects over the experimental period. This was a deliberate component of our experimental design in order to simulate commercial settings where scallops experience cumulative effects of trawling, but it violated the assumption that every tagged animal has the same probability of recapture. Nonetheless, violation of the assumption does not negate a tag-recapture analysis as survival estimates from CJS models are robust to heterogeneity in data (Pollock *et al*. 1990). The results from SURVIV analyses showed the relative survival estimates to be close to 1.0 at all sites indicating no significant differences in survival between treatment effects, thus corroborating the results from the MARK analyses. Since none of the candidate set of models weighted highly for treatment effects for either survival or recapture probabilities, we opted to proceed with the CJS model analyses and estimated $\hat{c}$ to be 3.82 for LDS, 4.84 for UDS, 2.42 for ESB, and 2.67 for WSB. We incorporated these values to calculate the $QAIC_c$ values and adjusted the standard errors associated with parameter estimates.

2.3.3 Scallop survival and recapture estimates

From the candidate set of models from the CJS analyses, resighting probability of discarded scallops was largely a function of time across all sites but survival varied by time, treatment group and was constant with period (Table 2.3). The top model for each site did not get strong support as the following 1 to 2 models were all plausible with similar likelihood and weighting ($\Delta QAIC_c < 2$), and so apparent survival and recapture rates were estimated using model averaging (Fig. 2.5). Survival estimates in summer were highly variable between the two sites for all 3 nights. Survival of scallops on the first night at WSB was 26% higher than at ESB, on the third night however survival was 20% higher at ESB than at WSB (Fig. 2.5a). Scallop survival on the second night was highest at ESB with a range of 85 – 96% and 78% at WSB, however, large variation around these estimates suggests differences may not be significant between nights. Survival estimates in winter were greater than 90% for all 4 nights. Estimates for air-exposed scallops were higher than hopper treated scallops at UDS but lower at LDS (Fig. 2.5b). The high variance around these estimates also suggests no significant differences in survival between sites or treatment groups in winter. Recapture probability estimates in summer decreased from 70% from the first night to 60% on the third night at WSB, while the decline was more significant at ESB where recapture probability estimates dropped from 85% to 55% in air-exposed scallops and 48% in hopper treated scallops (Fig. 2.5c). Recapture estimates in winter ranged between 45% and 55% across the 4 nights at LDS, while at UDS estimates increased steadily from 55% to 84% on the fourth night (Fig. 2.5d).

Table 2.3. CJS models best fitting the data ($\Delta QAIC_c < 2$) to provide estimates of survival (ϕ) and recapture (p) probabilities as a function of treatment group (g) or time (t) across all experimental sites. Shown are the delta Akaike's information criteria ($\Delta QAIC_c$), the QAIC weight, the number of parameters and the likelihood for each model.

	Model	$QAIC_c$	Δ $QAIC_c$	$QAIC_c$ Weight	Model Likelihood	No. Par
Winter	*ø*(g) *p*(t)	2668.96	0.00	0.32	1.00	6
LDS	*ø*(.) *p*(t)	2669.27	0.31	0.27	0.86	5
Winter	*ø*(.) *p*(t)	1692.01	0.00	0.38	1.00	5
UDS	*ø*(t) *p*(t)	1692.54	0.53	0.29	0.77	7
	ø(g) *p*(t)	1692.58	0.57	0.29	0.75	6
Summer	*ø*(t) *p*(g*t)	1386.59	0.00	0.40	1.00	8
ESB	*ø*(g*t) *p*(t)	1387.02	0.43	0.32	0.81	8
	ø(t) *p*(t)	1387.99	1.40	0.20	0.50	5
Summer	*ø*(t) *p*(.)	2016.14	0.00	0.38	1.00	4
WSB	*ø*(t) *p*(t)	2016.72	0.58	0.28	0.75	5
	ø(t) *p*(g)	2017.96	1.83	0.15	0.40	5

The return rates (95% CI) of live scallops for each night of trawling are presented in Table 2.4 and on average across all nights the summer estimates were 35% return rate while winter estimates were 55%. The average return rates between air and hopper treated scallops were almost identical with 48% for air and 47% for hopper treatments. There were spatial differences in return rates with averages for LDS, UDS, ESB and WSB being 47%, 64%, 34% and 36% respectively.

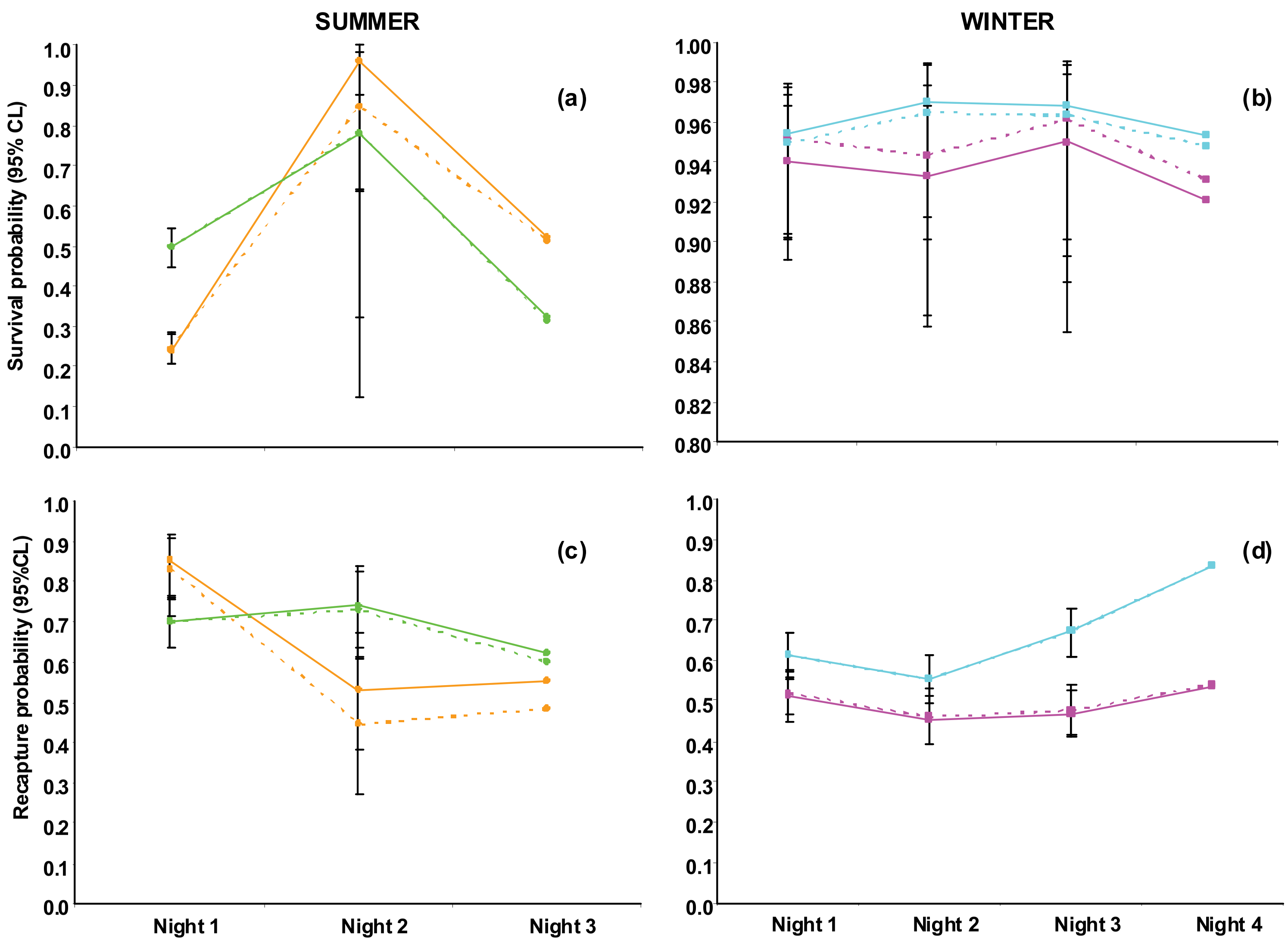


Figure 2.5. Apparent survival and recapture estimates (and 95% CL) for winter (b,d) and summer (a,c) periods derived from the model averaging results based on the candidate set of models for each site (West Shark Bay = green, East Shark Bay = orange, Upper Denham Sound = blue, Lower Denham Sound = purple, Air exposed = solid line, Hopper – broken line) presented in Table 2.3. Confidence intervals could not be estimated for the last night of repeat-trawling.

Table 2.4. Estimates of return rates (95% CI) of live scallops computed as the product of survival and recapture probability model estimates (ϕp) for each night of repeat-trawling by the different post-capture treatment effect at the different sites in winter and summer periods.

Treatment	Re-trawl night	Winter - LDS		Winter - U DS		Summer - ESB		Summer - WSB	
Hopper	Night 1	**0.50**	(0.42 – 0.56)	**0.58**	(0.50 – 0.65)	**0.20**	(0.15 – 0.26)	**0.35**	(0.28 – 0.41)
	Night 2	**0.43**	(0.34 – 0.52)	**0.54**	(0.45 – 0.61)	**0.38**	(0.09 – 0.62)	**0.57**	(0.39 – 0.72)
	Night 3	**0.46**	(0.37 – 0.53)	**0.65**	(0.54 – 0.72)	**0.25**	n/a	**0.19**	n/a
	Night 4	**0.50**	n/a	**0.79**	n/a				
Air	Night 1	**0.48**	(0.40 – 0.56)	**0.59**	(0.50 – 0.66)	**0.20**	(0.15 – 0.26)	**0.35**	(0.28 – 0.41)
	Night 2	**0.42**	(0.34 – 0.50)	**0.54**	(0.45 – 0.61)	**0.51**	(0.05 – 0.67)	**0.58**	(0.39 – 0.73)
	Night 3	**0.45**	(0.35 – 0.52)	**0.65**	(0.55 – 0.72)	**0.29**	n/a	**0.20**	n/a
	Night 4	**0.49**	n/a	**0.80**	n/a				

2.3.4 Damage analysis

The majority of scallops sampled indicated Level 1 injury and 94% of assessed scallops were below a Level 3 damage grading. Level 3-damage was seen in 4% of scallops, followed by 1.1 % with Level 4 damage and absolute mortality in 1.4% of scallops assessed (Fig. 2.6). No strong relationship was observed between adductor muscle weight and capture frequency at any of the sites. Average muscle weight of scallops was 11g for both winter and summer periods and high variability in meat weights across all the sites (Fig. 2.7).

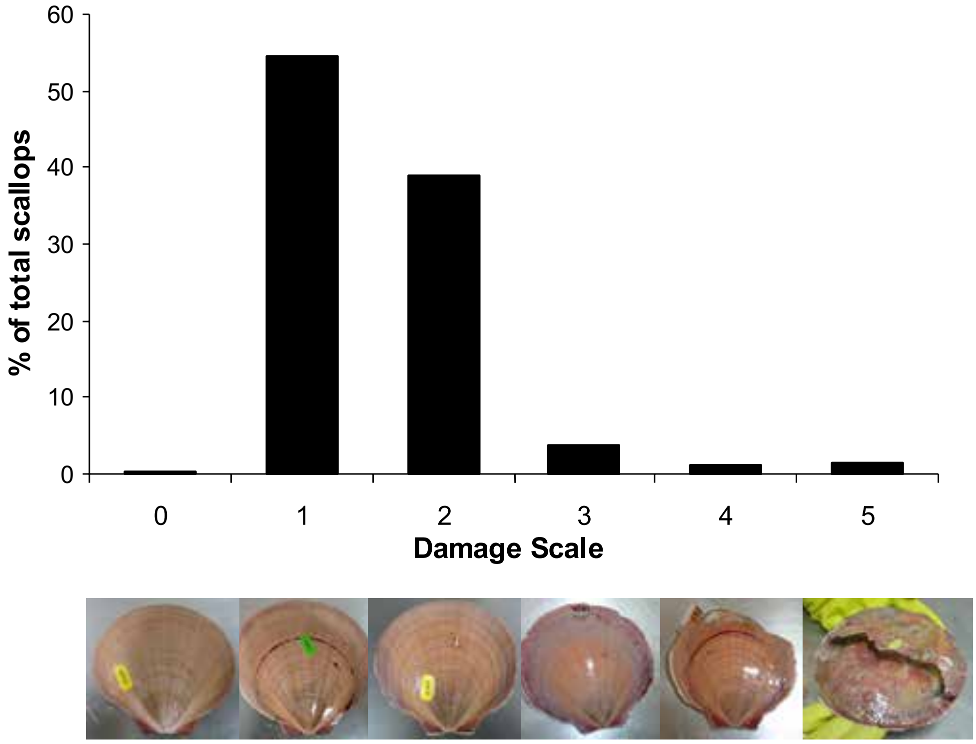


Figure 2.6. Percentage of total scallops with scales of damage assessed from a scale of 0 to 5 (an example of each damage scale is illustrated below the scale).

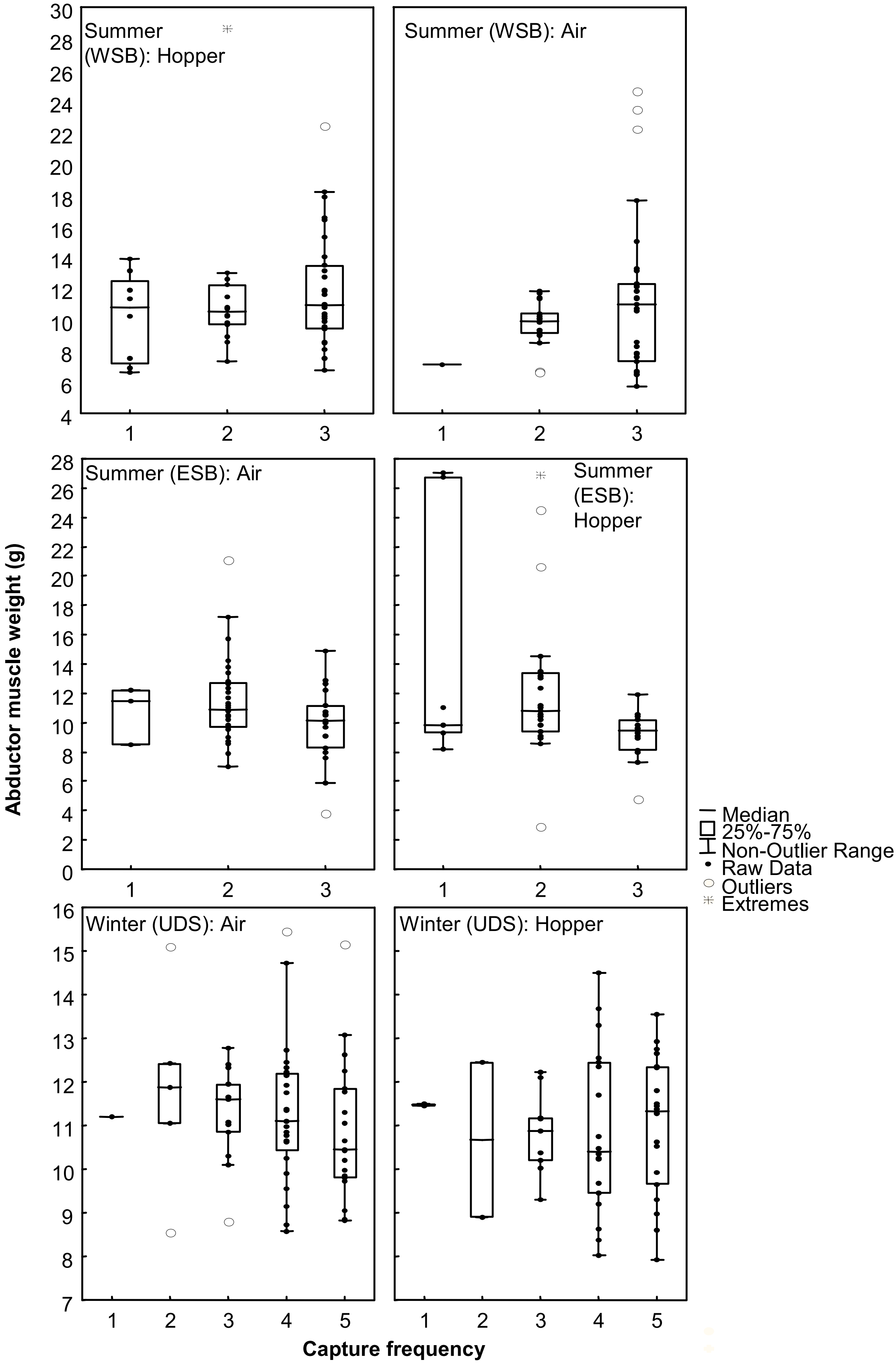


Figure 2.7. Adductor muscle weight (g) of sampled scallops from summer (WSB and ESB) and winter (UDS only) experiments by their recapture frequency.

2.4 Discussion

2.4.1 Survival differences among discarded *A. balloti*

Large differences in the apparent survival of discarded scallops between winter and summer periods highlight the potential significance of seasonal differences in environmental and/or physiological conditions in saucer scallops (Table 2.4). Desiccation is a major factor influencing the survival of scallops during emersion (Dickie 1958; Michin *et al.* 2000; Jenkins and Brand 2001; Chen 2007), and in the current study, scallops experienced mean air temperatures of 18°C in winter and 28°C in summer. One behavioural adaptation by scallops to minimise the effects of desiccation is to control valve gaping, in order to gain maximum benefit from gas diffusion and to optimise survival (Maguire *et al.* 2002a). However *A. balloti* cannot fully seal its shell openings and thus is highly susceptible to desiccation stress. Lower capture rates of live scallops concomitant with greater recovery rates of dead scallop shells in summer than in winter suggests that the summer air temperatures were likely within the upper thermal tolerance range of *A. balloti*. The rapid decline in recapture rate and recapture frequency over the three nights in summer suggests that the cumulative metabolic stress from trawl activities was likely beyond its physiological threshold to either cause death or prolong the recovery phase. Cooler conditions in winter were likely to be more physiologically favourable, and reduced energetic demands during this period may have allowed scallops to sustain greater resilience to stress from the same trawl experience.

The overall capture probabilities of discarded scallops were similar between hopper treated and air exposed discarded scallops (Table 2.4). The provision of a 40-min recovery period in water failed to elicit an improved capture rate in hopper treated scallops to those air-exposed. If desiccation is a major stress factor in the survival of discarded scallops, its unclear why post-harvest treatment differences in survival were not apparent. It is possible that the 40-min hopper treatment was an insufficient period for scallops to begin their recovery period, or the 24-hour recovery period between re-trawls was sufficient for the likelihood of survival from the two groups to become equivalent. In the absence of supportive data from behavioural or biochemical assays it is difficult to assess quantitative differences in stress incurred by scallops from either treatment groups. The 40-minute treatment period applied in our study is the maximum exposure period during commercial operations, but *A. balloti* is reported to withstand exposure periods of up to 2 hours (at 25 °C) before suffering appreciable mortality (Dredge 1997). The 24-hour time interval between trawls and the 10-minute trawl duration applied in our study are however not fully reflective of commercial practices but rather adopted for logistical reasons of the experiment. In Shark Bay, time intervals between trawls on the same grounds can vary from hours to days depending on other factors such as weather conditions, catch rates, bycatch and fleet movement. The frequency of trawls on the same fishing ground is also highly variable and often scallops are not discarded on the same grounds they are captured. Therefore a full evaluation of hoppers on scallop survival would require testing a range of trawl durations and also a range of time intervals between trawls. Nonetheless, the benefits of hoppers include increased survival of invertebrate and soft-bodied bycatch organisms (Heales *et al.* 2003), aids in cleaning the grit from scallops, and retain better meat condition of scallops during sorting process (Chandrapavan, *pers. obs*).

The physiological state of fatigued scallops and their ability to recover may also be a factor of its underlying reproductive condition, which is vastly different between summer and winter periods. The scallop adductor muscle (harvested portion) has a dual role of mobilisation of energy reserves in the form of glycogen during gametogenesis (winter months) and the primary role in fuelling growth (summer months) and locomotion (Chantler 2006). In the current study, post-spawned scallops in winter achieved higher survival and recapture estimates than pre-spawned scallops in summer, which suggests that reproductive investment by *A. balloti* did not significantly influence stress recovery. Campbell *et al.* (2010) also found inter- and intra-seasonal differences in the survival of repeatedly trawled *A. balloti*, but these results were based on scallops being contained within catch bags and placed in trawl codends where scallops were not given the choice to independently respond to trawl gear. In under sized *P. maximus,* stress levels are known to vary by seasonal variation in the glycogen content driven by gonadal development (Maguire *et al.* 2002c), while the tropical scallop *Euvola ziczac* shows decreased capacity to recover from exhaustive exercise following gonadal maturation and spawning (Brodordt *et al*.2000). However, reproductive energy demands during and after spawning did not significantly impact on the escape response performance of adult *Argopecten purpuratus* (Perez *et al.* 2009) or in the scallop *Placopecten magellanicus* (Kraffe *et al.* 2008).

In the current study, tagging and recapturing scallops over a short-time period allowed for the individual capture history of a discarded scallop to be documented. One interesting statistic from this data was that 92% of tagged scallops were recaptured at least once in winter versus only 33% in summer, but of those recaptured, 85% were resighted on the first night after release in summer versus 61% in winter (Fig. 2.8). This suggests that although summer conditions were likely to be detrimental to discarded scallops, those that survive the initial release are able to recover faster due to higher energy reserves, but are unlikely to recover from further cumulative trawl stress. In contrast, winter recapture rates increased with each night at one site and stable at another. Reduced energy reserves of post-spawned scallops in winter may inhibit rapid swimming response to trawl disturbance where discarded scallops may not swim high enough into the water column to be captured, while others may remain non-responsive until they are fully recovered (Joll 1989). This would suggest seasonal differences in the catchability of discarded scallops where the physiological resilience to trawl-induced stress in *A. balloti* is dependent on its temperature tolerance range and available energy levels, and these aspects require further investigation.

Saucer scallops are only able to be captured by trawling because they actively swim into the water column as an escape response (Joll 1989), therefore capture of dead scallop shells by trawl nets is an unusual occurrence. Despite this, high sighting of dead and moribund scallops during summer suggests that a large number of discarded scallops had died directly from desiccation/heat stress in summer, while others may succumb to ongoing mortalities caused by infection and predation (Jenkins *et al*. 2004; Himmelman *et al.* 2009). Some scallops may have also succumbed to tag-induced mortality, but this is expected to be very low given the tagging process was non-invasive and trawl captured scallops maintained within flow-through seawater tanks showed consistently low mortality rates (~3%) for both seasons. Direct damage to shell valves and soft tissue ranged from minor chipping, which can later appear as "shock ring" (growth scars) (Joll 1988), to irrevocable injury that results in immediate death. The current study found similar results to *A. balloti* harvested in the Queensland fishery Campbell *et al.* (2010) where estimates of dead scallops with crushed or cracked valves were very low (1%), while the majority incurred chipping to the outer edges of the valves. It was beyond the scope of this study to quantify other fates of discarded scallops (such as non-responsive scallops to trawl nets and temporary emigration from trawl sites), however the small number of tagged scallops (non-sighted during the experimental period) captured several months later by commercial fishers does lend support to these possibilities.

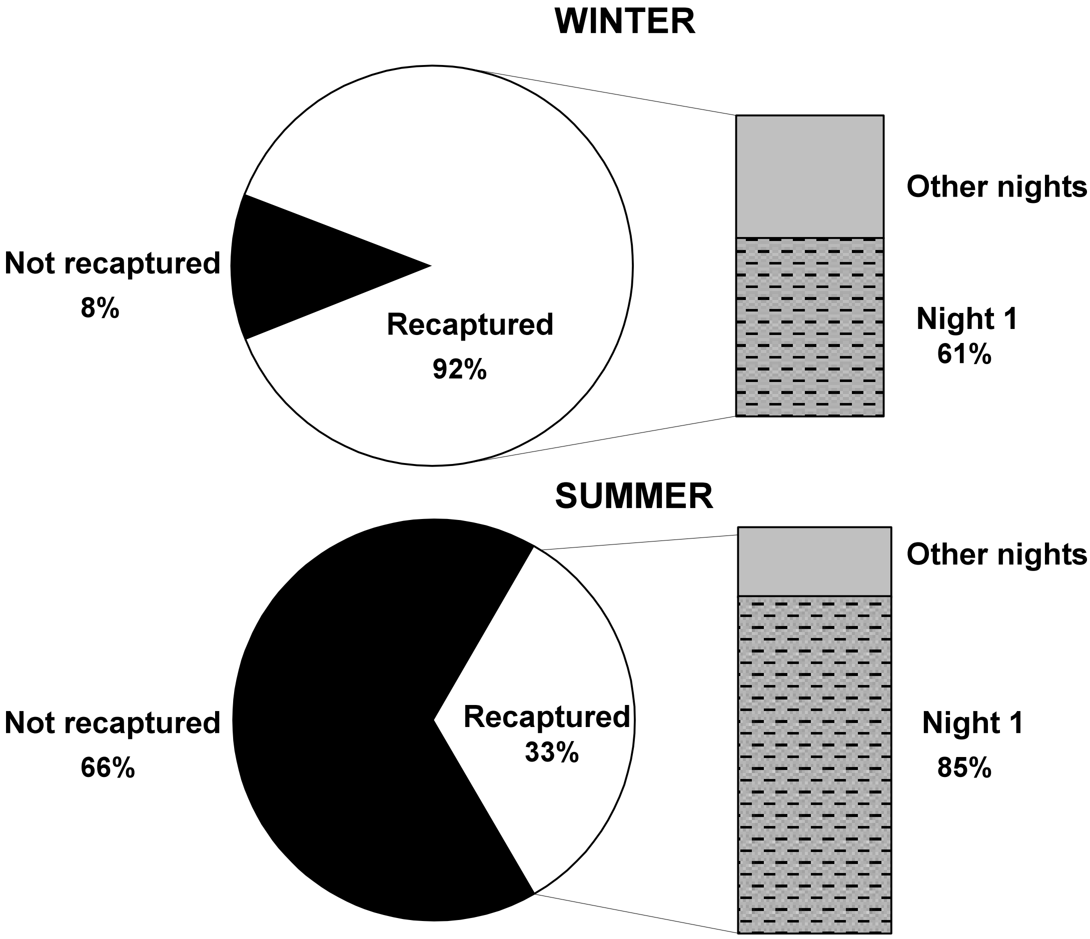


Figure 2.8. Contrasting scallop recapture data between winter and summer periods. Pie chart indicates the % of tagged scallops that were recaptured during the experimental period (white) and not resighted (black). The bar plot indicates the proportion of those tagged scallops that were recaptured during the experimental period, that were sighted on the first night (dashed) vs. those sighted on the remaining nights (grey).

Spatial differences in return rates of discarded scallops were evident both within and between the winter and summer periods, but this is unlikely to be significant given the high variances around the mean estimates. Overall capture probabilities were slightly higher at UDS than at LDS in winter, and higher at WSB than at ESB in summer (Table 2.4). Since different sites were chosen for summer and winter periods, the inter-seasonal spatial variability in survival and recapture rates of discard *A. balloti* is unclear. Given the close proximity of trawl sites within each season, it is also unlikely that oceanographic factors would have influenced return rates although localised tidal movements may have played a role in shifting released scallops. Alternatively, it is possible that spatial differences in the quality of scallops (despite no significant differences in size) may have influenced their capture behaviour. For example, the recapture rate of scallops caught 4 times in winter was approximately 20% greater at UDS than at LDS, while UDS was the only site where the percentage of scallops caught 4 times was greater than it being caught once (Fig. 2.3). Qualitative differences among scallops between different fishing grounds in Shark Bay does occur in terms of meat quality where similar sized scallops show variation in meat size and weight (Sporer *pers. comm.*), and this may explain the small differences in the observed capture rates between sites.

2.4.2 Impact of fishing practices on discarded scallops

Marked seasonal differences in survival and recapture estimates of discarded *A. balloti* highlight the potential impact of past and present management strategies on the sustainability of the scallop resource in Shark Bay. Discarding during the warmer, summer months, as was the case prior to 2004 by the prawn fleet, would have resulted in poor survival and a reduced catch and spawning biomass in the later months. The change in regulation to simultaneous openings for both fleets (from 2004 onwards) reflects a positive change in management strategy where most scallops that are caught in summer are harvested. Scallops of non-market sizes (< 85 mm) would however still continue to be discarded by both fleets and this would require either a change in product marketing for smaller-sized scallop meat or improved gear selectivity to reduce capture of sub-legal sized scallops. The latter is currently under consideration where square mesh codends instead of the traditional diamond mesh codends are being commercially trialled.

The forward shift in scallop season commencement in 2004 meant that the scallop fleet ceased fishing before the peak spawning began which resulted in an overall reduction in fishing intensity during the key scallop spawning months. The prawn fleet however continued their fishing operations during this period but were required to discard all scallops in their nets, so as to maintain scallop abundance for spawning. Cooler conditions during the spawning months would favour greater survival of the discarded spawning scallops, while reproductive energy diverted to spawning is likely to prolong their recovery period, thus decreasing their catchability by trawl nets. To what extent the spawning behaviour is altered due to trawl disturbance is unclear. For instance, it is not known if trawl-induced stress has the potential to delay or hasten spawning thus altering the natural timing of the spawning event. If larvae are produced (as a response to stress) when the environmental conditions are not optimal, then larval survival, movement and settlement processes may be compromised, thus impacting on the overall recruitment to the region. Similarly, trawling over newly settled scallops can be detrimental to their survival despite the seasonal advantage. Scallop spat and juveniles of size < 30 mm (SH) are not readily retained by scallop or prawn nets, but are potentially vulnerable to gear damage as they pass through the fishing gear. Interactions with gear and with other scallops in the net are likely to result in shell damage due to their fragility, but the impact of trawl disturbance on the survival of juvenile scallops has not been investigated. This is another inter-fishery conflict issue between the Shark Bay trawl fisheries, and so the potential benefits of spatial closures in providing temporary protection to areas of high scallop settlement (before they reach sub-adult sizes) is under consideration as a supplementary management strategy.

Tag-recapture techniques have been successful in providing estimates of natural mortality (Naidu 1988), fishing mortality (Gruffydd 1972), and population sizes (Allison and Brand 1995) of major commercial scallop species. Indirect fishing mortality and delayed mortality estimates using tagging techniques are less common and mostly laboratory based. One of the major criticisms of both approaches is that estimates are determined under a limited range of fishing, environmental, and biological conditions and their interactions (Davis 2002). For tag-recaptures studies in particular, Broadhurst *et al.* (2006) commented on the high reliance of adequate tag returns (primarily from fishers) as a limitation of its methodology in providing reasonable survival estimates of discards. The current study attempted to address all these issues by incorporating differences in the seasonal, spatial and post-harvest treatment of scallops into the field experiment so as to simulate a range of fishing conditions that scallops are likely to experience. Successive trawl surveys over a short time period ensured higher tag recapture rates, but most importantly allowed scallops to experience the cumulative stress effects from repeated trawling, thus providing more realistic estimates. Both Dredge (1997) and Campbell *et al*. (2010) tagged and released *A. balloti* after assessing their response to various post-harvest treatments under simulated conditions (onboard tanks and in situ caging), and then relied on fisher tag returns to determine long-term survival estimates. For the current study, fishers were also encouraged (through a tag reward system) to target and return tagged scallops from the experimental sites but fisher tag return rates were poor with return rates of 2 % and 21 % from summer and winter sites respectively.

In conclusion, this study has provided estimates of survival and return rates of discarded scallops for better understanding of the impact of discarding under different fishing conditions. For the management of the scallop resource, the study highlights the importance of minimising discarding as much as possible during the summer months and the protection from trawl disturbance for scallops during the winter months. Achieving these objectives could potentially minimise some of the inter-fishery conflict and promote scallop recruitment in Shark Bay.

3.0 Objective 2: Square mesh codend trials

Objective 2: ***To determine the impacts of various scallop mesh sizes for the capture of the target size of Amusium balloti and its impact on damage to and retention of prawns***

3.1 Introduction

A key difference in the fishing gear between the scallop and prawn fleets is the codend mesh size. The scallop fleet uses a 100 mm diamond (100D) mesh codend to select for scallops greater than 85 mm shell height, while the prawn fleet use a 50 mm diamond (50D) mesh codend to select primarily for prawns. Both codend types have good size selectivity for commercial sized scallops (>85 mm), but non-commercial sized scallops are regularly caught and discarded by both fleets and scallops as small as 30 mm are caught by the smaller 50D net (Joll, 1987). The discard rate of bycatch species by the scallop fleet is relatively low at a 0.5:1.0 ratio (Kangas and Thompson 2004). Further reductions in bycatch rates are desirable, as these reductions will help mitigate the ecological impact of fishing activities.

The aim of current management measures is to ensure adequate breeding stocks are maintained for ongoing sustainable harvest and scallop recruitment under prevailing environmental conditions in Shark Bay. However, when catch rates decline and there is low recruitment over a number of years (as experienced between 2000 and 2005), each fishery blames the other over poor gear selectivity, resource sharing and management regimes (Department of Fisheries 2010). The challenge facing management is to offer options that do not significantly disadvantage either prawn or scallop fishing fleets while maintaining a sustainable and profitable resource and minimising the effects of trawling.

Under current management arrangements, harvesting and potentially repeated discarding of sub-optimal sized scallops is greatest when both prawn and scallop boats are fishing concurrently during pre-spawning months and the prawn fleet during the spawning period with highest effort during Mar/Apr to June. However, discarding continues by prawn boats for all scallops between June and August and then after this period again for suboptimal sized scallops until the end of the prawn season each year. Due to prawn boats primarily targeting prawns and requiring a suitable net mesh size to retain prawns the focus on scallop selectivity is based on scallop boat net mesh sizes. The extent to which trawl capture may impact on scallop recruitment either through reduced spawning stock or reduced spawning potential of discarded scallops are of concern to the scallop industry and addressed in Objective 1.

One option being considered is converting to a square mesh from the conventional diamond mesh codend. Selectivity experiments have shown that square meshes are more size selective for some species (Suuronen and Millar 1992, Sun *et al*. 2006, Broadhurst *et al.* 2004). The advantage of square mesh is that the two sets of twine in square mesh netting are always at right angles to one another and remain open when the codend fills up and the tension on the mesh bars increases, whereas the diamond meshes tend to close (MacLennan 1992). *Amusium balloti* is also a principal component of the Queensland east coast otter trawl fishery. This fishery is currently commercially trialling square mesh codends after experimental trials revealed it could achieve significant reductions in both bycatch and undersized scallops (< 95 mm for the Queensland fishery) compared relative to the standard 88.9 mm diamond mesh codend (Courtney *et al.* 2008). Although both Queensland and Shark Bay scallop fisheries target the same species, differences exist in the gear regulations, and gear selectivity can vary due to other factors including variability in habitat features and tow duration (Broadhurst 2000). While the quantity of bycatch is considered relatively low for the scallop fleet, discard mortality rates for certain species such as tiger prawns, king prawns and juvenile pink snapper are of interest to its related commercial fisheries in Shark Bay. Therefore, as the first step towards improving the selectivity of the current 100 mm diamond mesh codend configuration used by scallop boats, we present experimental results for different sized square mesh codends and discuss their potential benefits for reducing the capture rates of small scallops and selected bycatch.

3.2 Methods and Materials

3.2.1 Selectivity experiments in February 2008

In February 2008, codend mesh selectivity trials were conducted on fishing grounds within the Shark Bay region of Western Australia (between 25° 00' and 25º 24' south latitude, and 113° 15' and 113° 25' east longitude) (Fig. 3.1). Areas of moderate scallop abundance based on information from an annual scallop survey (undertaken in Nov/Dec 2007) were used as the general trawl area for the experiment. The substrate consisted of sand and shell with depths ranging from 15 to 25 m. A commercial prawn otter trawler (21.6 m in length, fitted with a Cummings 299 kw power engine) rigged in a quad-gear net configuration (two nets on each of the port and starboard sides of the boat) was used as it allowed four net types to be towed simultaneously. Four 10.97 m headrope length nets were trialled with four different codend mesh types. The standard 100 mm diamond mesh codend (control) was compared with 50, 55, and 60 mm square mesh codends (referred hereafter as 50S, 55S and 60S) constructed from 6.0, 4.5 and 5.0 mm braided polyethylene twine, respectively. The square mesh codend sizes (Fig. 3.2) were selected after consultation with the scallop industry. Although bycatch reduction devices (BRDs) in the form of grids are compulsory for the scallop fleet, BRDs were not fitted to any of the nets in this study.

Each trawl site was fished once over the eight nights of the experiment and six trawl shots were carried out each night between 1800 hours and 0400 hours (Table 3.1). Each trawl was 20-minute duration with a tow speed around 3.3 to 3.6 knots. Tow durations during commercial operations can range between 5 and 70 minutes. The net position (port inner, port outer, starboard inner, starboard outer) of each codend type was randomly determined at each site and resulted in each codend type in each net position on two nights, resulting in a total of 12 trawls in each position (Fig. 3.3). After each trawl shot, the codends were emptied separately and all catch sorted. All scallops caught were counted and a sub-sample from each shot measured (mm shell height). Among the bycatch, prawn species (*Penaeus latisulcatus*, *Penaeus esculentus*), pink snapper (*Pagrus auratus*) and a number of finfish were counted and measured as these were identified to be of key interest to the industry.

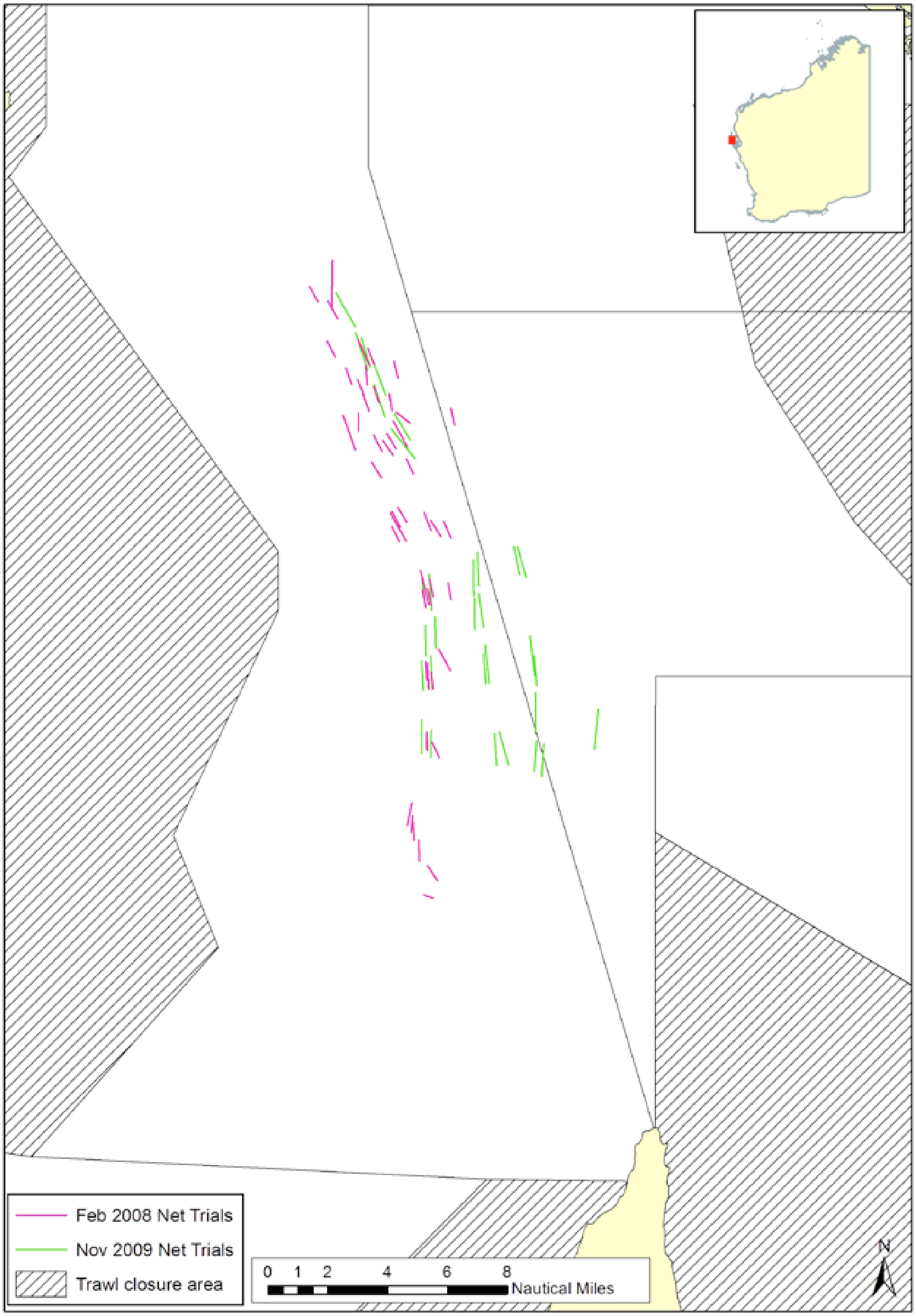


Figure 3.1. Shark Bay saucer scallop fishing grounds showing the area trawled during the mesh selectivity experiments.

Figure 3.2. Examples of meshes trialled; standard 100mm (stretched length) diamond mesh codend used by the scallop fleet (left) and the 60 mm (knot to knot) square mesh codend (right). Mesh sizes refer to the distance between corner knots on the square mesh codend net and the stretched measurement from knot to knot on the diamond mesh codend net.

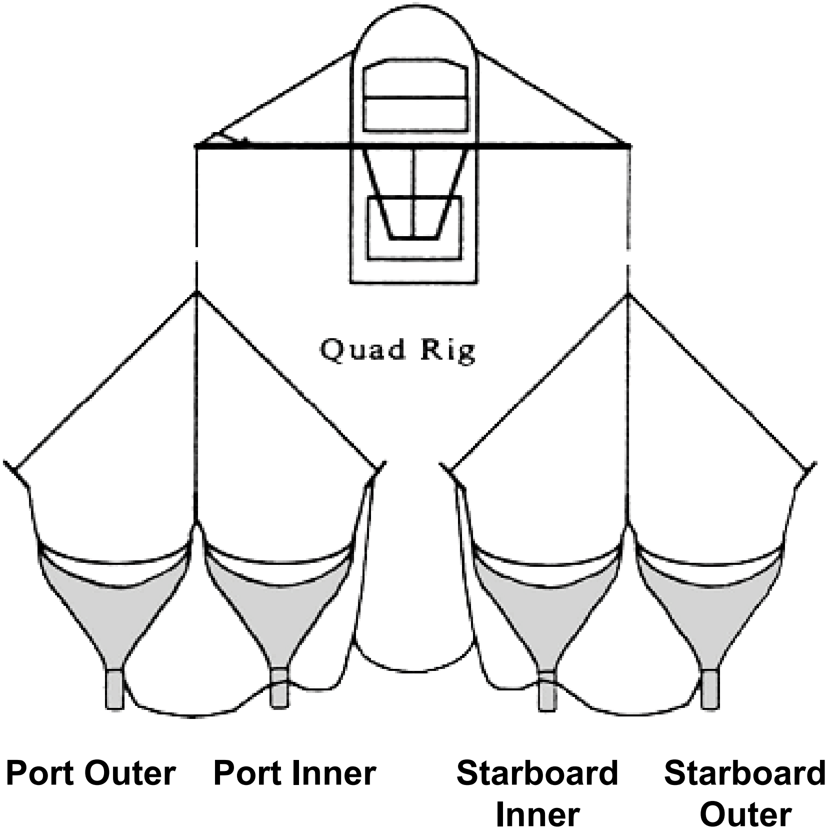


Figure 3.3. Diagram of a quad-rigged prawn boat showing the four net positions used to tow the four net types simultaneously. A twin-rig boat would have only one net on the port and starboard sides. (Source: adapted from Sterling, 1998)

Table 3.1. Sequence of net configuration used in the February 2008 mesh selectivity experiments.

NIGHT	Port Inner	Port Outer	Starboard Inner	Starboard Outer	No. Shots
1	100D	55S	50S	60S	6
2	50S	60S	55S	100D	6
3	50S	100D	55S	60S	6
4	100D	60S	50S	55S	6
5	55S	100D	60S	50S	6
6	60S	55S	100D	50S	6
7	60S	50S	100D	55S	6
8	55S	50S	60S	100D	6

3.2.2 Selectivity experiments in November 2009

Additional mesh trials of the 60S, 100D and 50D prawn mesh codends were conducted during November 2009 on eastern Shark Bay fishing grounds (Fig. 3.1). These additional trials provided data on the selectivity of scallops by the 60S mesh compared to the standard 100D codend when the composition of smaller sized scallops on the fishing grounds was greater and residual prawn abundance were likely to be high. Using a commercial scallop otter trawl boat rigged with twin-gear net configuration (one net on the port and starboard sides of the boat) comparisons of net selectivity were made between the 60S and 100D and between 60S and 50D codends over 4 consecutive nights (Table 3.2). The use of the 50D provided data on prawn abundance on the fishing grounds and allowed for the comparison of prawn selectivity between the 100D and 60S mesh codends. From each trawl shot, the total number of scallops from each codend was counted and a sub-sample of up to 200 scallops was measured. The bycatch component from each codend was sorted into key groups of blue swimmer crabs (*Portunus armatus,* formally *P. pelagicus*), finfish and other invertebrates (soft and hard excluding prawns) and the total weights of these groups were recorded. King, tiger and coral prawns (*Metapenaeopsis crassissima)* were sorted separately, counted and measured.

Table 3.2. Sequence of net configuration used in the November 2009 mesh selectivity experiments. Note that the 50D codend was not trialled on Night 4.

Night	Port	Starboard	No. Shots
1	50D	60S	4
1	100D	60S	4
2	100D	60S	4
2	50D	60S	4
3	60S	50D	4
3	60S	100D	4
4	60S	100D	7

3.2.3 Statistical analyses

The data provides a catch comparison study where we estimate the expected proportions at length of the total catch retained by the test codend relative to the standard net. The approach suggested by Holst and Revill (2009) was adopted for the current data set where polynomial Generalised Linear Mixed Models (GLMM) analyses were performed using the R software package. The GLMM method uses low-order polynomial approximations to fit the proportions retained in the square codend and produce realistic curves and variance estimate bands. A proportion of <0.5 indicates that more scallops of that size were retained by the standard scallop or prawn mesh net than the square mesh codend net. Due to low numbers of scallops of lengths <70 mm and >100 mm across all the mesh types including the control, model analyses were only attainable for the size range 70 to 100 mm from the February 2008 data set and 60 to 110 mm from the November 2009 dataset. Since the model curve is only a proxy of the "true curve", extrapolations beyond the selected size range were not performed.

A combination of analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) were used to compare the catches of commercial and non-commercial size scallops and bycatch groups collected from the February 2008 and November 2009 mesh trials. When assumptions of homogeneity of variances were violated (Shapiro-Wilk W test and normal probability plots), abundance data was square root transformed. Significant effects were further examined using Tukey's post-hoc analysis. Statistical analyses were performed using Statistica (V7.1 Statsoft Inc, Tulsa OK USA). Length frequency comparisons between net types of prawn species were not possible due to overall low numbers retained by some nets.

3.3 Results

3.3.1 Scallop selectivity

February trials

From the February 2008 trials, the size distributions of scallop catch from all three experimental square mesh codends were similar to the catch from the control 100D codend with peak scallop catches in the 86 to 90 mm size range (Fig. 3.4). From the combined shot catch data, the difference in scallop catch between the diamond and square mesh codends showed the 50S caught 73% more, while the 55S caught 22% less and 60S caught 33 % less scallops than the control 100D. There were no significant differences in the mean catch rates (scallops/shot) of either non-commercial sized scallops or commercial sized scallops between all four codend mesh types ($F_{6,326} = 0.89$, $p = 0.50$). Given the closeness of the length frequency distributions among the four nets types, an even spilt in the catch proportion occurred between 75 and 100 mm size classes for all three square meshes (Fig. 3.5). In comparison to the 100D, the 50S net retained greater than 50% of scallops sized < 75mm, while the 55S and 60S nets performed better with retentions of most small sized scallops under 50%. For scallops larger than 100 mm there were some losses by the 60S net but the total number of scallops caught above this size class was relatively small.

The GLMM model curves (fitted with 3rd order polynomials) showed a transition in the scallop retention estimates of small sized scallops (<85mm) from being poor in the 55S net to its improvement by the 60S net (Fig. 3.6). For commercial sized scallops (> 85mm) this transition was less clear, but the 60S net performed the best in retaining the highest proportions of large scallops.

November trials

There were significant differences in the catch rates between the 50D and 60S codend nets ($F_{2,21}$ = 7.7, $p < 0.00$) with the 60S catching significantly less non-commercial sized scallops than the 50D ($p = 0.001$), but no significant differences among commercial-sized scallops ($p = 0.39$) (Fig. 3.7). Conversely, there were no significant differences in the catch rates of scallops between the 100D and 60S ($F_{2,33}$ = 2.2, $p = 0.13$), but the catch rate of non-commercial sized scallops was significantly different ($p = 0.051$) and no differences in commercial sized scallops ($p = 0.9$) (Fig. 3.8). Unlike February 2008, the proportions of scallops retained by the 60S codend relative to the 100D codend increased with scallop size with 24% for 66-75mm, 42% for 76-85mm and 57% for 86-95mm (Fig. 3.9b). Similarly against the 50D, the 60S codend retained 33% for 66-75mm, 40% for 76-85mm and 51% for 86-95mm (Fig. 3.9a). The GLMM model curve for the 60S from the November 2009 trials showed greater reductions in the retention of the small scallops than during the February 2008 trials but also retained 7% less larger scallops than the 100D codend net (Fig. 3.10). The wide confidence bands for all curves are indicative of the large between-shot variations in the dataset.

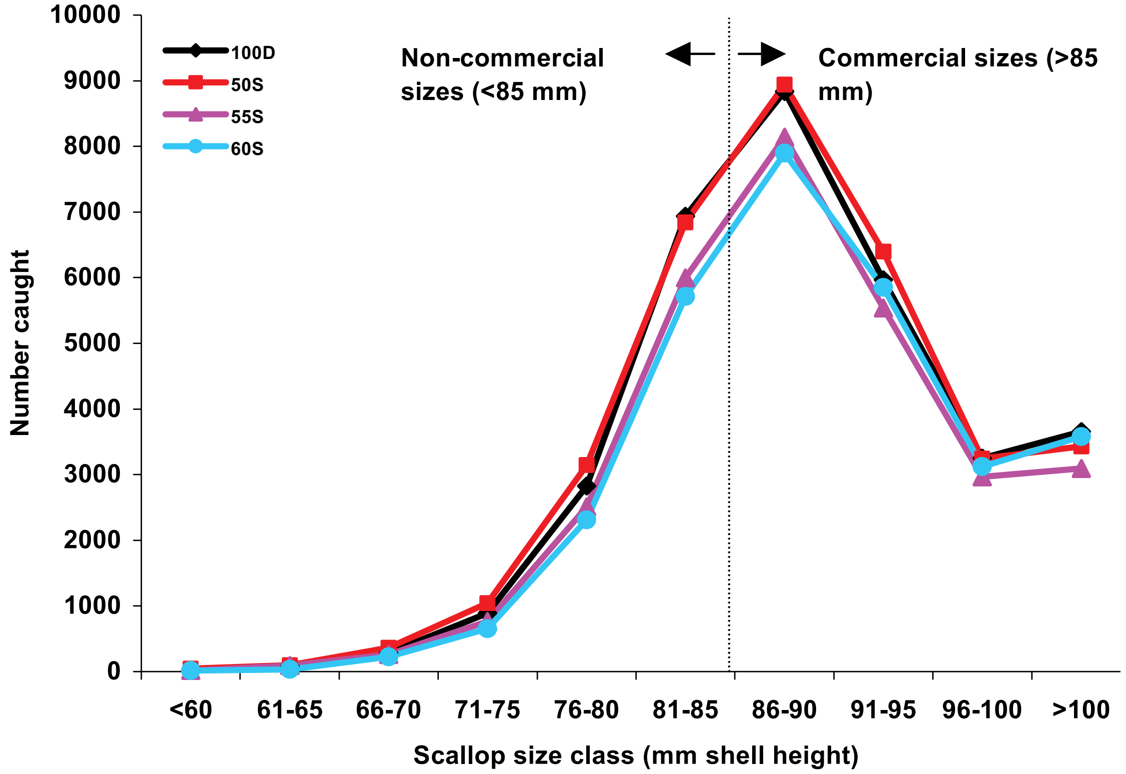


Figure 3.4. Length-frequency distributions of *A. balloti* from the standard diamond (100D) and experimental square mesh codends (representative of 48 shots).

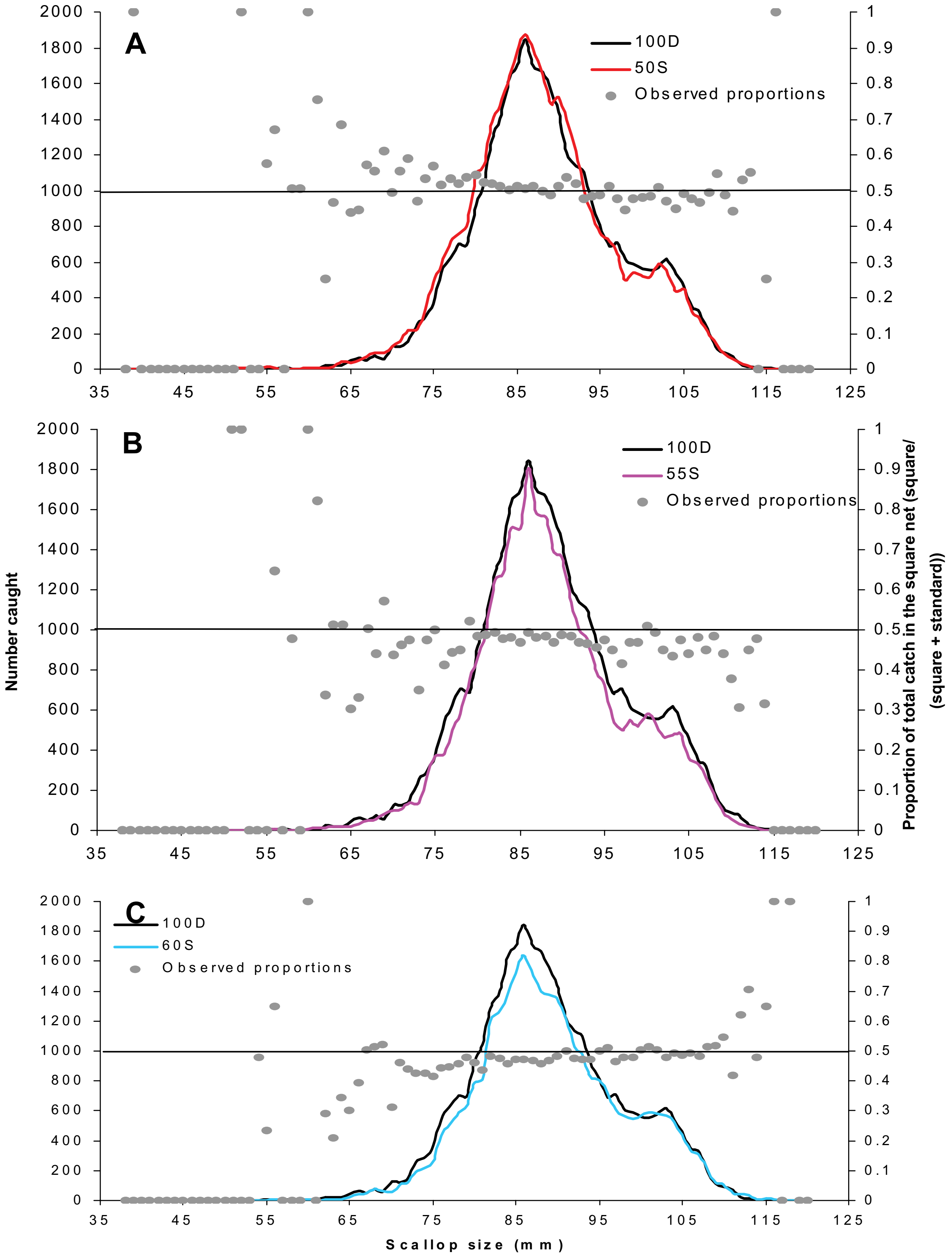


Figure 3.5. Selectivity experiments in February 2008: catch length-frequency distributions of the standard scallop net (100D) vs. the (A) 50 mm (B) 55 mm (C) 60 mm square mesh codend nets and the observed proportions of the total catch in the square mesh codend net. A proportion < 0.5 indicates more scallops at length caught by the 100D and a value of 0.5 indicates even split between the two codends.

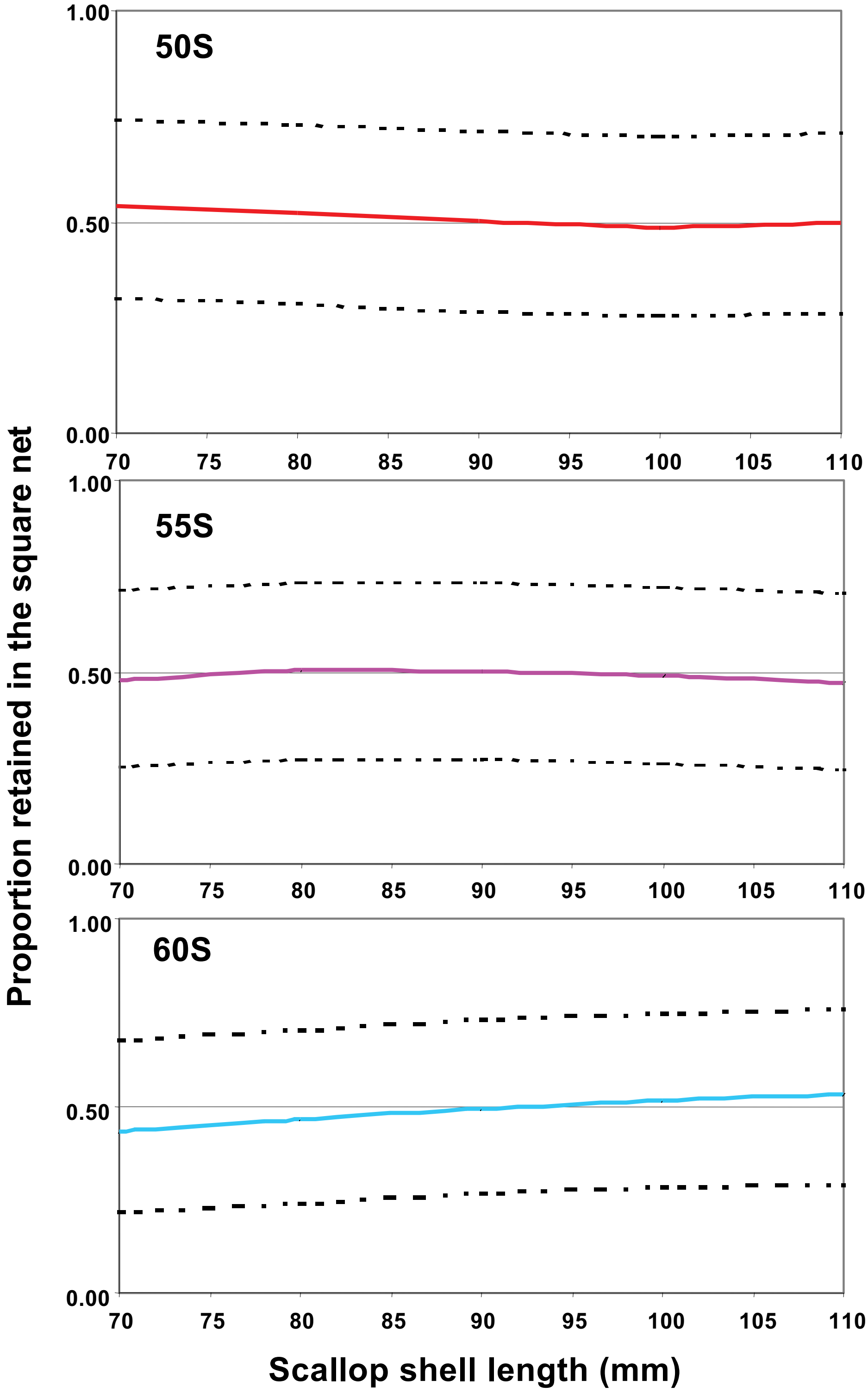


Figure 3.6. GLMM modelled proportion curves (solid line) and the associated 95% confidence interval (broken line) between individual shots of the total scallop catches retained by the different sized square mesh codends relative to the 100D during the February trials. A proportion < 0.5 indicates more scallops at length caught by the 100D and a value of 0.5 indicates even split between the two codends.

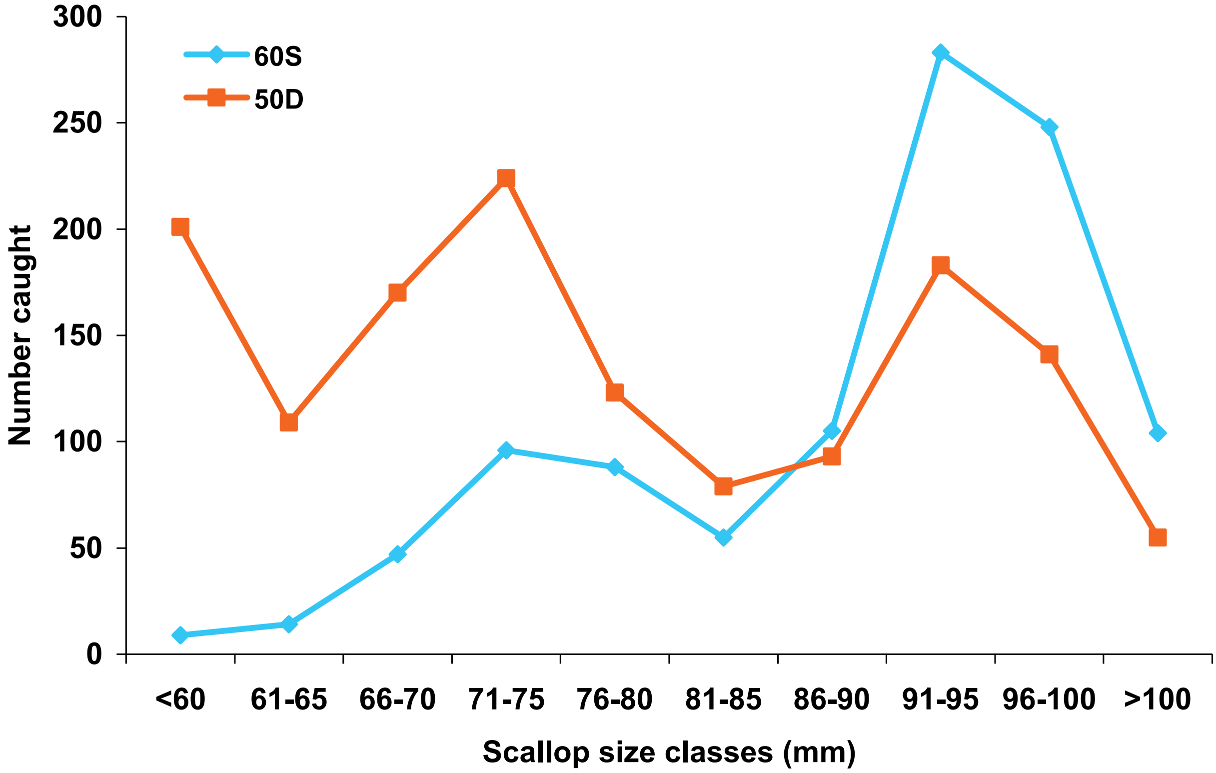


Figure 3.7. Number of *A. balloti* sampled over 5 mm size classes from the standard 50D prawn and experimental 60S codends (representative of 12 shots) during November 2009.

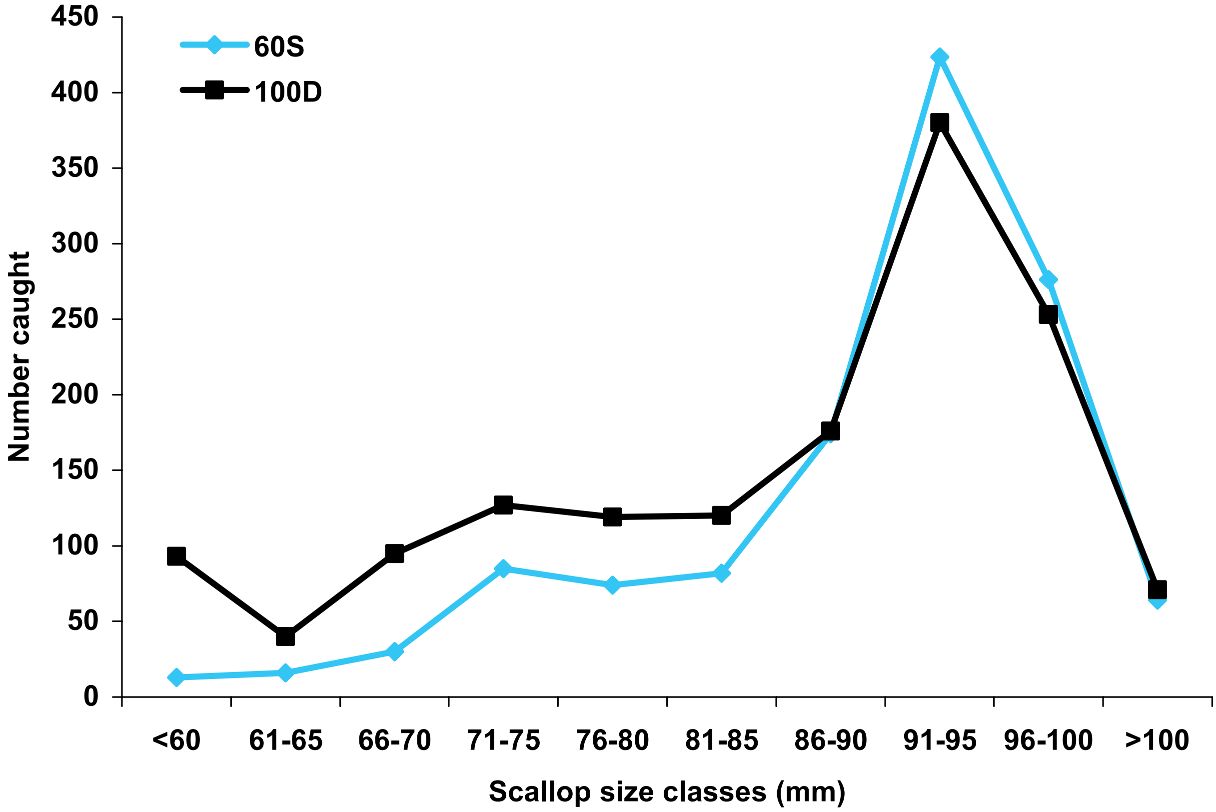
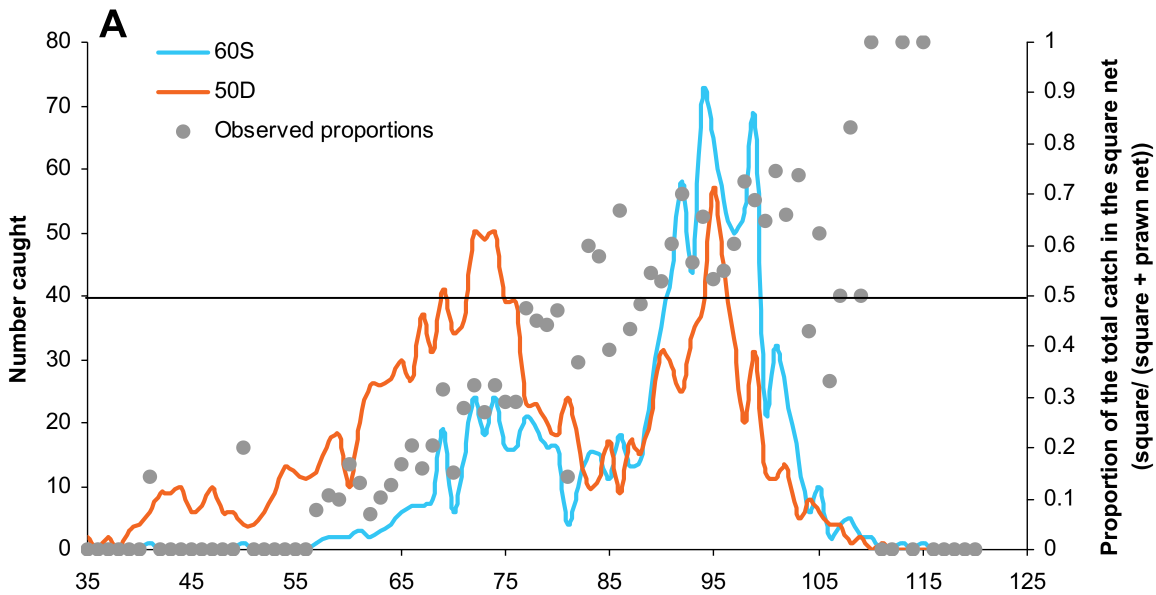


Figure 3.8. Number of *A. balloti* sampled over 5mm size classes from the standard 100D scallop and experimental 60S codends (representative of 18 shots) during November 2009.



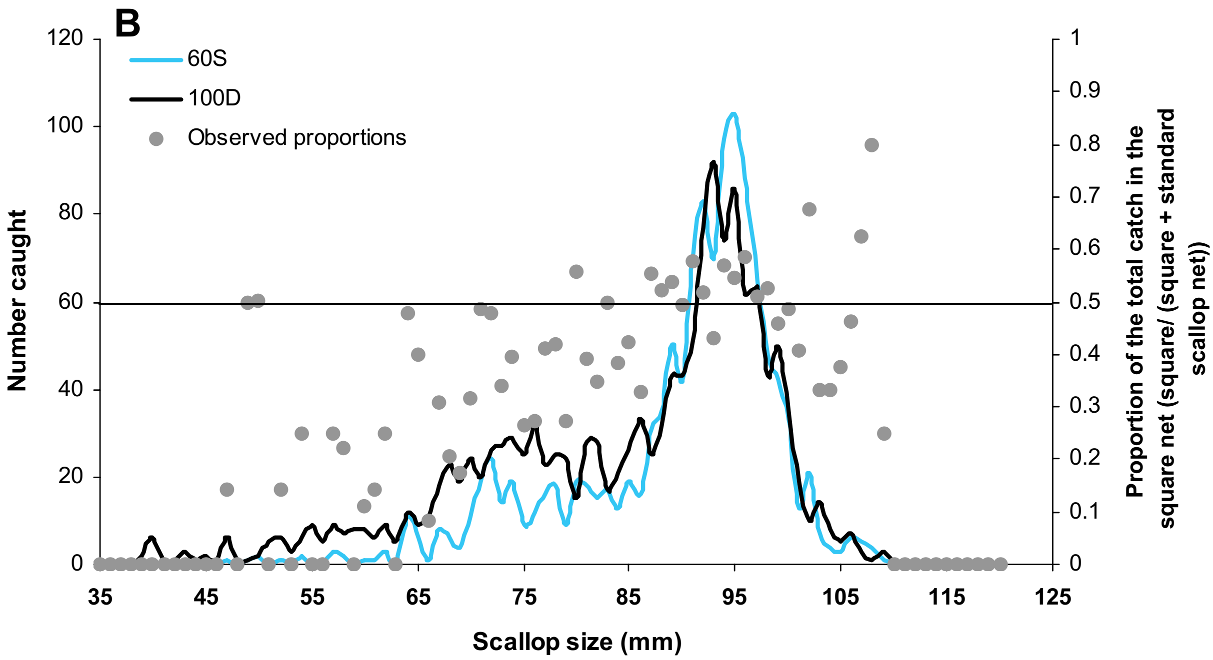


Figure 3.9. Selectivity experiments in November 2009: catch length-frequency distributions of the 60mm square mesh codend scallop net (60S) vs. the (A) 50 mm diamond prawn net (B) 100 mm diamond scallop net and the observed proportions of the total catch in the 60mm square mesh codend net.

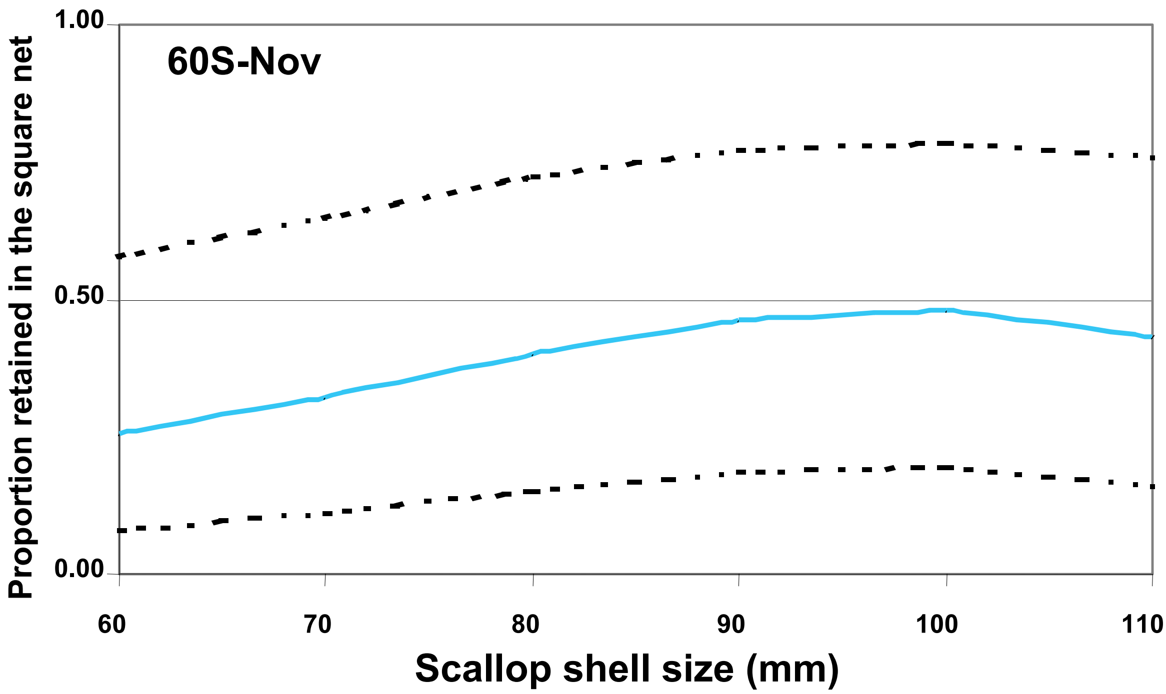


Figure 3.10. GLMM modelled proportion curves (solid line) and the associated 95% confidence interval (broken line) between individual shots of the total scallop catches retained by the 60S net during the November 2009 trials.

3.3.2 Bycatch selectivity

February trials

All three square mesh codends achieved greater than 80% reductions in the total catch of the different bycatch groups relative to the standard 100D mesh codend (Fig. 3.11), but there were no differences in catch rates of bycatch among the square mesh codends (Fig. 3.12). Pink snapper mean (± se) catch rates of 0.26 ± 0.18, 0.42 ± 0.37, 0.11 ± 0.07 (number caught / shot) by the square mesh codends 50S, 55S and 60S respectively were significantly less than that of the 100D (3.0 ± 0.83) ($F_{3,72}$ = 7.12, p<0.01) with 91% reduction on average (Fig. 3.12a). Size ranges (fork length) of pink snapper retained by the respective meshes were 12 to 17 mm (50S and 55S), 11 to 13 mm (60S) and 11 to 19 mm (100D). For finfish bycatch, mean (± se) catch rates of 7.00 ± 0.91 (50S), 7.73 ± 1.10 (55S), 6.27 ± 0.93 (60S) by the square mesh codends were less than the 100D (43.0 ± 8.71) ($F_{3,40}$ = 22.88, $p < 0.01$) by 84 % on average (Fig. 3.12b). Prawn catch rates were also significantly less in the square mesh codends 0.30 ± 0.09 (50S), 0.30 ± 0.10 (55S), 0.43 ± 0.12 (60S) than in the 100D (3.47 ± 0.55) ($F_{3,184}$ = 36.19, $p < 0.01$) by 90% on average (Fig. 3.12c). Sizes ranges (carapace length, mm) of prawns retained by the diamond mesh codend was 29 – 56 mm while in the 50S, 55S and 60S mesh codends it was 33 to 46 mm, 35 to 46 mm, 35 to 57 mm, respectively.

November trials

There were large differences in bycatch volume between the 50D and 60S mesh codends ($F_{2,66}$ = 23.44, $p < 0.01$) mainly due to differences in the volume of the fish group (Fig. 3.14a), but no significant differences were apparent between the 60S and 100D mesh codends ($F_{2,102}$ = 2.81, p = 0.07) (Fig. 3.14b). The mean (±se) catch volume of blue swimmer crabs by the 60S mesh codend net was higher than the 50D (12.3 ± 1.2 kg/shot) and the 100D (8.9 ± 1.0 kg/shot), while the catch volume of the invertebrate group showed the reverse trend with 8.0 ± 2.2 kg/shot with the 50D mesh codend net and 10.6 ± 3.1 kg/shot for the 100D. The mean catch weight of fish was lowest by the 60S at less than 1 kg/shot compared to both 50D and 100D codends.

(Photo: N. Shaw)

Figure 3.11. Examples of comparative catch composition image taken immediately after the emptying of the codends on to the sorting table. Catches from 100D (left) and a square mesh net (60 mm) (right).

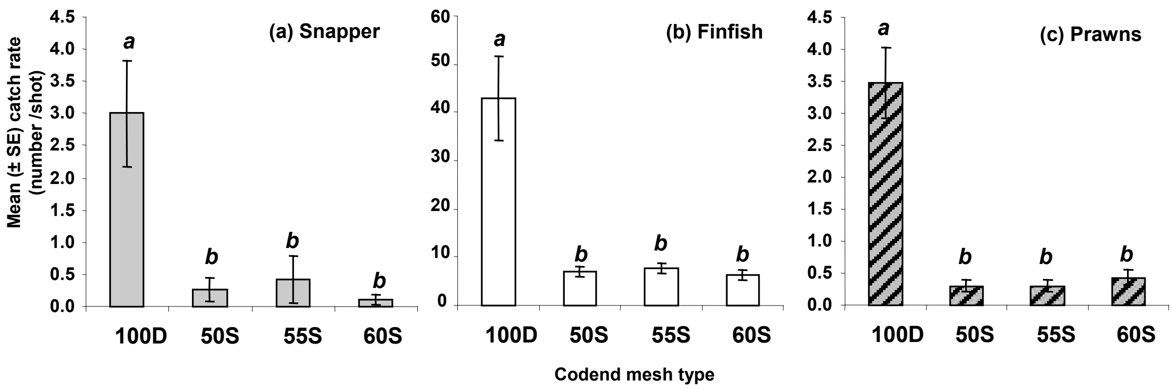


Figure 3.12 Comparisons of catch rates of selected bycatch groups (mean ± se) between all four codend types in the February 2008 trials. Results of the post-hoc Tukey's test are indicated by superscripts where significant differences among codends are indicated by different letters.

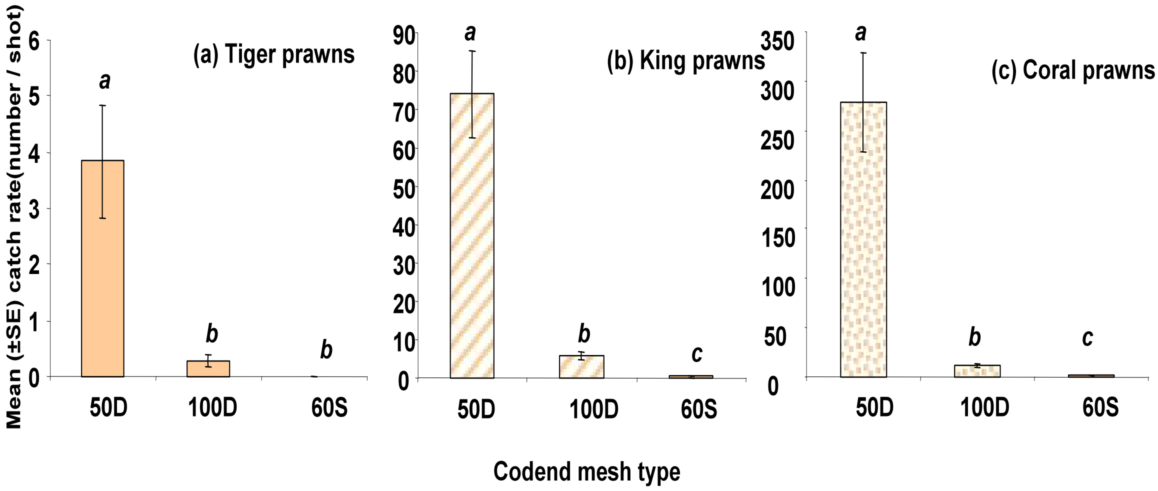


Figure 3.13. Catch rate (mean ± se) comparisons of prawn bycatch of the three codend types trialled during November 2009. Results of the post-hoc Tukey's test are indicated by superscripts where significant differences among codends are indicated by different letters.

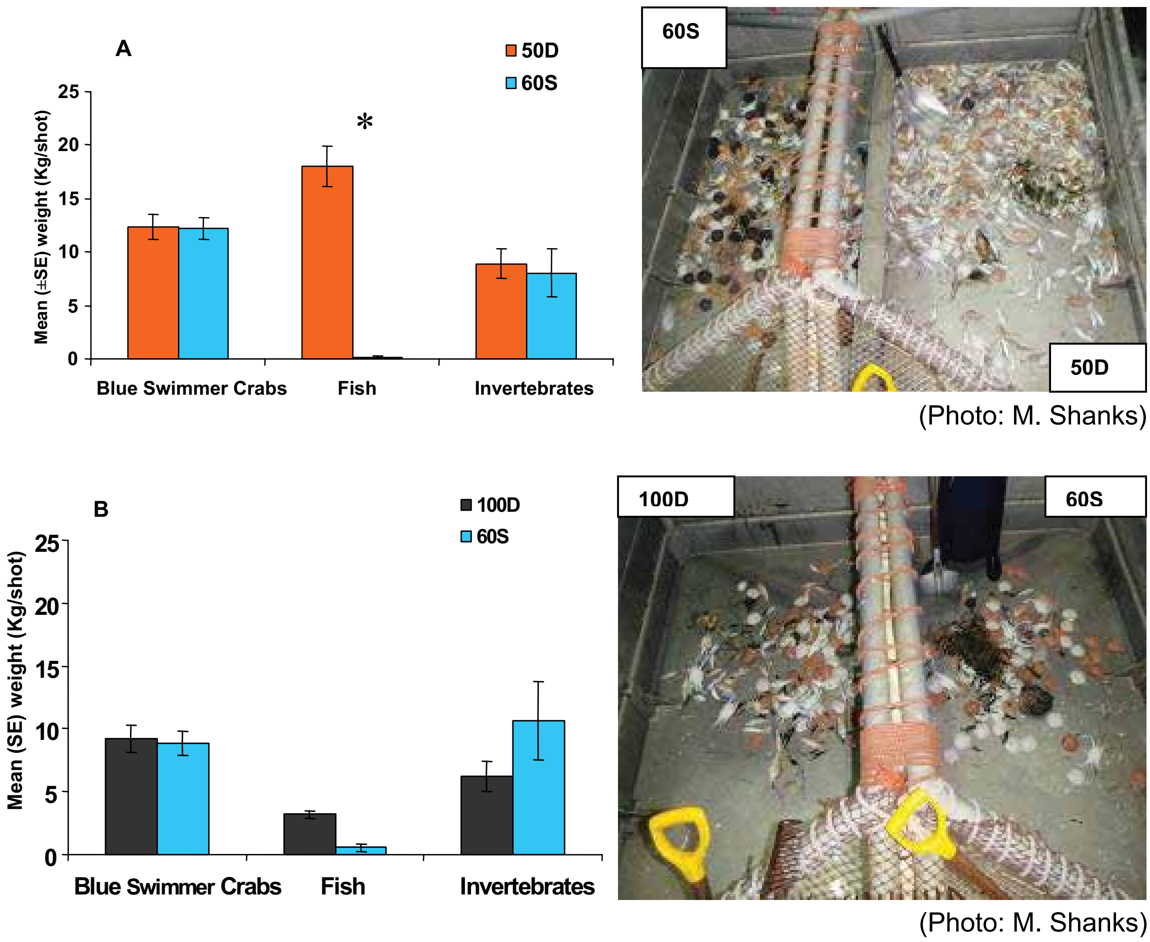


Figure 3.14. Catch rate comparisons (mean ± se) of bycatch groups between the (A) 50D and 60S nets and between the (B) and 100D and 60S net types. An example of the catch composition from the respective codends shown on the right. Significant difference between net type is indicated by *.

Prawn catch rates were significantly different between the codends ($F_{4,171} = 57.24$, $p < 0.01$). Tiger prawn catch rates (number per shot) was the lowest of all retained prawn species with the 50D catching 3.8 ± 1.0 (mean ±se) prawns/shot and 100D and 60S with < 1 prawn/shot (Fig. 3.13a). The king prawn catch rates was the next highest with 74.1 ± 0.3 prawns/shot (Fig. 3.13b) followed by the coral prawns at 278.2 ± 1.8 prawns/shot by the 50D (Fig. 3.13c). The 100D in comparison caught only 7.8 % and 4.4% of the king and coral prawn rates respectively than the 50D. The 60S caught less than 2% of the number of prawns caught in the 50D mesh codend. Damage to prawns passing through any of the nets was not determined from this study as attempts to trial a codend cover to capture prawns was unsuccessful during the experiment.

3.4 Discussion

Initial square mesh codend net trials showed improved performance by two of the three experimental square mesh codends relative to the 100D standard net. Catch rates of small and commercial size scallops were not statistically different among the four nets tested in February 2008, but the lower retention of small scallops by the 60S codend suggested that the largest of the square meshes tested performed the best and was the most feasible as an alternative to the 100D scallop net. In further testing, the 60S performed even better during the November 2009 trials where greater reductions in the capture of small sized scallops was evident compared to the 50D and 100D scallop catch compositions. While the square mesh codends tested may not have produced the ideal mesh shape for the capture of saucer scallops because of the limited range of sizes trialled, the potential benefits of square mesh codends over diamond was realised to the extent that testing of even larger square mesh codends may be an option in the future. The main concern for the scallop industry is the loss of commercial sized scallops, and both the 55S and 60S nets had losses of 9.8% and 4.8% respectively which was acceptable to the industry. Further trials would be required to ascertain if this loss would increase or decrease with larger sized square mesh codends.

In a similar study in the Queensland scallop fishery (based on the same species), mesh trials using a 50 mm square mesh codend resulted in a significant reduction in bycatch (77%) and undersized (<95mm in the Queensland fishery) scallops (39%) particularly in the 60 to 80 mm size range compared to their standard 88.9 mm diamond mesh codend (Courtney *et al.* 2008). Given the focus of the Queensland mesh trials were to reduce bycatch using square mesh, alternative square mesh sizes were not tested, but our study showed that larger sized square mesh codends than those tested in Queensland have the potential to concurrently reduce bycatch and small size scallops with a risk of a small loss of commercial sized scallops. These results are consistent with selectivity studies in other trawl fisheries where square mesh codends have demonstrated their superior performance to diamond mesh codends in reducing bycatch and discard rates particularly in prawn and some fish trawl fisheries (Broadhurst 2000, Ordines *et al.* 2006). Demersal trawl gear selectivity studies for scallops are limited as most other scallop fisheries operate dredging gear. In the North West Atlantic sea scallop (*Placopecten magellanicus*) fishery, both experimental and commercial trials have shown that as the dredge ring size increases the escapement of small scallops increases as well as increased harvest efficiency for larger scallops (DuPaul *et al.* 1996, Rudders *et al.* 2000, Yochum and DuPaul 2008). There have been four dredge ring size changes in this fishery since 1994, which highlights the importance of ongoing gear modifications to improve fishing practices and resource management.

Significant reductions in bycatch numbers and particularly of finfish species during the February 2008 trials demonstrated the low selective power of all three square mesh nets for the common fish species in Shark Bay. However the relatively small difference in fish bycatch weight between the 60S and 100D during the November 2009 trials suggests that large reductions in fish numbers may equate to relatively small weight differences if there were differences in the sizes of finfish retained by the nets. In Shark Bay there is generally a decline in fish abundance (and generally of schooling species) from the start to end of a fishing year which may also explain the overall lower retention of fish in November (Kangas *et al.* 2007a). Several studies have also demonstrated how the shape and size of certain fish species highly influence the capture probabilities of certain sized square meshes (Broadhurst 2002, Broadhurst *et al.* 2002). If the 60S is more selective for larger sized fish, then the inclusions of BRDs such as grids that are mandatory on standard commercial scallop nets may result in further reduction of fish bycatch. Catchability of blue swimmer crabs was not different between all nets. The invertebrate bycatch group which included soft and hard invertebrates (eg. Sea cucumbers, seastars, urchins, small crab species, sponges and molluscs) showed variable catch retention in abundance and by weight between the 60S and 100D nets. This was partly due to catches of large and heavy bailer shells (*Melo sp.*) and large sponges that would have otherwise been excluded from the codend when grids are used.

Collectively from both the February and November trials it is clear that the 60S net retains significantly less prawns than 100D and especially the 50D nets. The catch rate of all prawn species by the 60S was consistently less than 1 prawn/shot across a range of prawn abundances. Although the standard scallop net also showed significant reductions in prawn bycatch, the 60S was clearly a further improvement on the 100D for prawn bycatch. The relatively low numbers of prawns retained by the 100D and 60S prevented any rigorous hypothesis testing regarding prawn size selectivity between net types.

For the scallop fleet there are ongoing interactions with the prawn fleet as well as with the Shark Bay pink snapper (*Pagrus auratus*) fishery. Management regulations such as spatial closure areas where snapper stocks aggregate (Moran and Kangas 2003) and a change from 24-hour fishing to only fishing during daylight hours for scallops (when prawns are less active) in some parts of Shark Bay have reduced these interactions to some extent and thus the associated discard mortality rates of snapper and prawns (Wakefield *et al*. 2007). However, this study demonstrated that the scallop-snapper and scallop-prawn interactions could be further reduced with square mesh codends, given the observed significant reduction in discard rates to less than 1 fish/prawn per shot. Reductions in finfish bycatch are also important as some small fish discards include juveniles of commercial and high-value species. For example, the western butterfish (*Pentapodus vitta*) is endemic to Shark Bay and although the trawl capture of *P. vitta* lightly impacts its population dynamics (Mant *et al.* 2006), this interaction would be reduced by adopting square mesh codends.

Ultimate benefits of improved gear selectivity require high survival rates of escaping target and non-target species. We assume the survival of escaping scallops (and other species) during the trawl to be higher than if the individuals were landed on deck, sorted/handled and discarded. Numerous boats often fish over the same trawl grounds repeatedly and converting to square mesh codend nets will not eliminate the repeat recapture of small scallops, but will reduce the likelihood of retention in the net and thus being subsequently landed, sorted and discarded. Regardless of their selectivity for scallops, all square mesh codends achieved significant bycatch reductions that carries ecological and economic benefits. For the Shark Bay region, a World Heritage Area, reduced impact on the benthic communities through fishing activities is desirable and a decrease in capture and discard rates with square codends is positive. Less bycatch in the codend also translates to reduced mesh clogging during hauls of large catches and may reduce drag and fuel usage. Less physical damage caused to scallops and prawns will also benefit both the scallop and prawn fleets. Reduced bycatch also potentially results in less processing and sorting time onboard thus increasing the fishing efficiency of fleets.

The potential future implementation of square mesh codends, if deemed commercially viable through commercial trials, which have commenced in a limited capacity will address scallop selectivity in only one sector of the trawling fleet within Shark Bay. The prawn fleet also trawl over these trawl grounds for part of the fishing season as prawn and scallop distributions overlap in the central region of Shark Bay. Therefore some of the benefits achieved from reduced capture of small scallops and bycatch by the scallop fleet using square mesh codends may be negated if they are recaptured and discarded by the less selective prawn nets at a later time. The prawn fleet typically captures 20 – 30% of the scallop catch. For the Shark Bay prawn fleet, differences in size, body shape and capture behaviour of prawns and scallops presents a challenge to finding a technical, gear or input solution as a single sized square mesh codend would not be optimally selective for both commercial size prawns and scallops.

Significant reductions in prawn bycatch (even though prawn bycatch with the commercial 100D mesh codends is also low) indicate that all the square mesh sizes trialled were not selective for prawns. Mesh trials in other Australian fisheries on penaeid species have also clearly demonstrated square mesh codends to be significantly more selective with improved size selection of prawns than the conventional diamond mesh codends (Macbeth *et al.* 2005b). Macbeth (2005a)'s study also demonstrated how in the presence of weed (drifting seagrass), small prawns were able to escape more easily through the opened square mesh but not through the restricted diamond mesh codends. This added advantage of square mesh codends may also benefit the scallop and prawn fleets as they also experience mesh clogging by weed at certain times of the fishing season in Shark Bay. Smaller square mesh codends for prawn boats may be an option (primarily to optimise size of prawns caught) with preliminary trials being undertaken in the Exmouth Gulf prawn fishery during the last two years.

3.5 CONCLUSION

A change from diamond to square mesh codend nets has been identified as a good measure to reduce the percentage of undersized scallops and bycatch for several species. The results also indicate that further experimental trials using larger square mesh codends have the potential to achieve greater reductions in bycatch and small size scallops without significant loss in commercial catch. The additional net trials in November to supplement the trials conducted in February highlighted the significance for testing net performance at different times of the year and on different trawl grounds when the catchability and size composition of the scallops and bycatch vary. While different trawl conditions may introduce extra sources of variation, this process is necessary to gain a comprehensive understanding of selectivity of the target and non-target species. Further commercial fishing trials will need to be undertaken to test the experimental results against net performance under commercial operations. The potential benefits of converting to a square mesh codend configuration for scallop boats are reduced fishing-induced mortality on juvenile scallops, prawns and reduced finfish bycatch to sort.

4.0 Objective 3: Spatial distribution of trawl effort

Objective 3: ***To investigate if small-scale spatial closures assist recruitment of Amusium balloti by reducing gear impacts and capture mortality but without affecting overall prawn catches.***

Extension: ***To evaluate both the historical and current spatial effort distribution of the A-class scallop fleet and B-class prawn fleet and to determine if trawl effort intensity during the key scallop spawning period had impacted on the scallop recruitment dynamics.***

4.1 Introduction

The Carnarvon-Peron Line (CPL) was implemented in 1991 in an attempt to protect small sized tiger prawns from being harvested too early in the fishing season by the Shark Bay prawn fleet. This management line provided a temporary spatial closure of the fishing grounds adjacent to the prawn nursery grounds, and the timing of its opening was determined by the size composition of prawns from pre-season surveys. In the years 1991 to 1998 the line was opened completely, but since then the CPL was opened in sections depending on the spatial distribution of prawn grades. This line has been integrated with other management lines such as the Tiger Prawn Spawning Area (TPSA) (north of the CPL) and Extended Nursery Area (ENA) (bottom east of the CPL) (Fig. 1.1 from Chapter 1). The displacement of prawn trawl effort as a result of the CPL introduction and its perceived negative impact on the scallop stocks is an issue creating inter-fishery conflict between the Shark Bay scallop and prawn fishing sectors.

The scallop industry believed that the spatial restriction imposed by the CPL and its position on the boundary of the key scallop fishing grounds in central Shark Bay had shifted greater effort by the prawn fleet onto the main scallop fishing grounds. Increased trawl effort by the prawn fleet during the early part of the fishing season may have adversely impacted on scallop survival and spawning potential through the practice of scallop discarding (and subsequent redistribution). It was mandatory for all scallops to be discarded by the prawn fleet until the scallop fleet commenced fishing. The period of scallop discarding and its intensity was variable from year to year depending on the opening date of the scallop season determined by the relative abundance of recruit and residual scallops (referred to as the MATRIX system). The mortality rate of scallops from this practice was assumed to be high and thus was one of the main motivators to cease using the MATRIX system at the end of 2003 and for both fleets to commence fishing together on the same date. However the impact of scallop discarding on the productivity of the scallop fishery including recruitment dynamics has not been evaluated to date. This is a critical step in not only evaluating the effect of the CPL on scallop stocks, but also in evaluating the impact of trawl effort on scallop recruitment dynamics. If fishing effort is found to be a significant driver of scallop recruitment in Shark Bay, the scallop industry is also in support of exploring the potential benefits of spatial closures of areas within key scallop grounds in Shark Bay.

In the process of addressing the original objective, it was soon realised the shortfall in the fishery-dependent datasets that was being utilised in this desktop study. To evaluate the impact of trawl effort intensity and distribution on scallop recruitment in Shark Bay, additional analyses were required and the current desktop study evolved progressively as follows;

1. We evaluated the impact of the Carnarvon-Peron Line (CPL) management line introduction in 1991 on the historical (1987-1994) spatial effort distribution of the B-Class prawn fleet.
2. We evaluated the impact of the Carnarvon-Peron Line (CPL) management line introduction in 1991 on the more recent (1995-2008) spatial effort distribution of the B-Class prawn fleet.
3. We evaluated both the historical and current spatial effort distribution of the A-Class scallop fleet on the central Shark Bay fishing grounds and its impact on scallop recruitment dynamics.
4. We evaluated temporal effort distribution by the Shark Bay scallop and prawn fleets on the central Shark Bay fishing grounds to determine if the trawl effort during the key scallop spawning period had impacted on the scallop recruitment dynamics.
5. We evaluated if the collective outcomes of the spatial and temporal fishing effort by the Shark Bay trawl fleet support spatial closures as a management tool to promote scallop recruitment.

4.2 Methods and Materials

4.2.1 Historical prawn trawl effort (1987-1994)

Given that the CPL was introduced in 1991, spatial effort analysis of fishing effort was evaluated for the four years prior (1987-1990) and four years after (1991-1994) the CPL introduction. Selection of logbooks for spatial effort analysis was based on the quality and accuracy of spatial information provided by the skipper. Essential data fields included date of fishing, the start and end time of each shot to determine shot duration, catch of king and tiger prawns and scallops, and fishing location. Historical fishing locations included a combination of fishing ground or fishing area names, and fishing blocks and/or sub-block numbers (Fig. 4.1).

The selection of logbooks sub-sampled represented approximately 30% of the annual fishing fleet. This equated to 10 logbooks from 35 for 1987-1989 and 8 logbooks from 27 for 1990-1994. From the selected logbooks, data extraction was restricted to the first 4 months of the prawn fishing season, which represented approximately 30% of the annual fishing effort, as this was the period where the main interaction with the scallop stocks occurred. All estimates of trawl effort were then scaled up to represent the total fishing fleet during these 4 months.

In order to obtain accurate finer scale spatial information from the larger scale fishing locations provided by the skipper on the fishing effort in Shark Bay (and in particular around the CPL), fishing reference points were assigned within each fishing sub-block area by consulting known tiger prawn, king prawn and scallop distributions (Fig. 4.2) in conjunction with the logbook catch data. Therefore each sub-block area had one reference point assigned unless the CP line or a fishing area boundary transected the sub-block in which case more than one reference point was assigned (eg. Block 7907). Assignment of reference points around the CPL depended on the presence or absence of scallop catch data. For instance, if catch included scallops then effort was assigned to a reference point west of the CPL and if the no scallops were caught then effort was assigned to a reference point east of the CPL. The end result consisted of reference points within sub-block areas that represented fishing effort from the immediate vicinity. While these points do not precisely represent the exact location of fishing effort, it provides a finer scale spatial effort distribution taking into account the known distribution of the target species.

4.2.2 Recent prawn trawl effort (1995-2008)

Analyses of the spatial fishing effort distribution for the years 1995-2008 did not include the fine scale spatial analysis as for the historical data set (1987 – 1994). For the years 1995 – 1997 spatial information was provided in the broad latitudinal bands (eg. B, H1 in Fig. 4.1A). GPS technology allowed for exact fishing locations to be recorded for all years after 1998, however to maintain data consistency across all years, fishing grounds were used to analyse spatial fishing effort distribution between 1995 and 2008. Fishing effort was analysed by the separate fishing periods in accordance with the opening dates of the prawn fishing season, scallop fishing season and the opening of the CPL (Table 4.1). From 2005 onwards there was a progressive change from twin to quad-rig configuration for the prawn boats. Thus the effort and catch rate data has been adjusted to standardised twin-gear equivalent.

4.2.3 Scallop trawl effort (1987-2008)

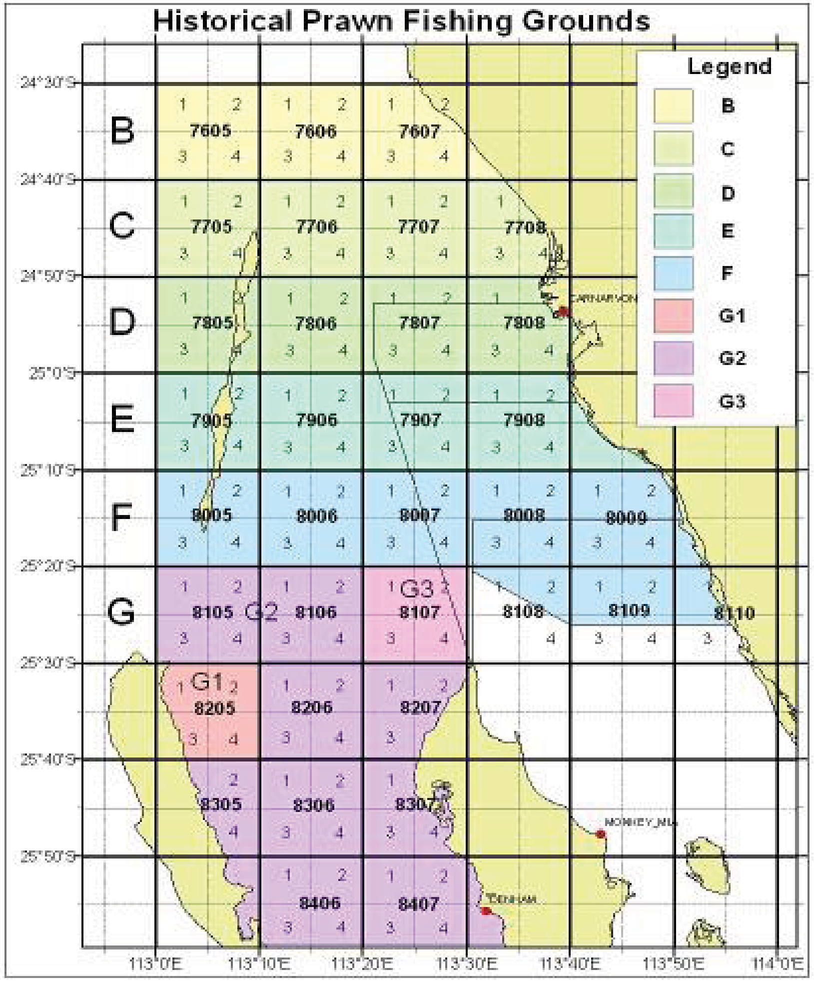
Scallop trawl effort in the period 1987-1994 was extracted from historical logbooks, while existing logbook databases were used to extract effort data for the period 2001 – 2008. Due to time constraints, spatial effort distribution in the years 1995 – 2000 was not examined, as it would have required extensively more manual data extraction from logbooks. Selection of scallop logbooks for spatial effort analysis was based on the quality and accuracy of spatial (block and sub-block numbers) and effort information provided by the skipper. Quality of logbooks was highly variable, thus we sub-sampled five logbooks from the available 14 logbooks and data extraction was restricted to the first four months of the scallop fishing season. These four months generally covered most of the scallop fishing in any year apart from 1991 to 1994 when scallop abundance was very high.

The trawl effort by both fleets was examined for the main scallop spawning months (April – July) when the spawning stock is likely to be most vulnerable. It is unclear how and if spawning behaviour of scallops changes under trawl stress and if this alters the timing of spawning events. Assuming any trawl impact could elicit a negative spawning response, we examined the possible effect of the combined effort of the scallop and prawn fleets on the scallop grounds during the spawning months.

Table 4.1. Opening dates of the prawn fleet, scallop fleet and CPL in the period 1987 – 2008 and other related information (DS – Denham Sound; SB – Shark Bay north; NWP – North West Peron in Shark Bay north; RC – Red Cliff in Shark Bay north).

YEAR	Prawn season opening	Scallop season opening	Carnarvon-Peron line opening	No. Prawn boats	Spatial resolution	Matrix management system
1987	7th March	1st May	NO LINE	35	Reference points	n/a
1988	21st March	21st April	NO LINE	35	Reference points	n/a
1989	15th April	26th May	NO LINE	35	Reference points	n/a
1990	11th April	15th May	NO LINE	27	Reference points	n/a
1991	7th March	20th April	6th May	27	Reference points	n/a
1992	10th March	17th March	25th April	27	Reference points	n/a
1993	13th March	26th March	20th April	27	Reference points	n/a
1994	5th March	3rd May	11th April	27	Reference points	MATRIX
1995	7th March	10th May	21st April	27	Latitudinal fishing block	MATRIX
1996	12th March	9th May	12th April	27	Latitudinal fishing block	MATRIX
1997	12th March	17th April	28th April	27	Latitudinal fishing block	MATRIX
1998	17th March	16th May	16th April	27	Fishing ground	MATRIX
1999	10th March	5th May	16th April	27	Fishing ground	MATRIX
2000	13th March	3rd May	27th April	27	Fishing ground	MATRIX
2001	14th March	28th April	16th April	27	Fishing ground	MATRIX
2002	6th March	6th May (DS) & 16th May (SB)	11th April	27	Fishing ground	MATRIX
2003	6th March	20th May (DS) & 26th May (SB)	24th April	27	Fishing ground	MATRIX
2004	16th March	18th March (DS) & 8th May (NWP) % 17th April (RC)	14th April & 11th May	27	Fishing ground	NO MATRIX
2005	8th March	10th March	4th April & 4th May	25	Fishing ground	NO MATRIX
2006	18th March	1st March (DS) & 18th March (SB)	22nd April & 22nd May	25	Fishing ground	NO MATRIX
2007	19th March	8th March (DS) & 19th March (SB)	16th April	18	Fishing ground	NO MATRIX
2008	5th March	26th Feb (DS) & 5th March (SB)	2nd April	18	Fishing ground	NO MATRIX

(A)



(B)

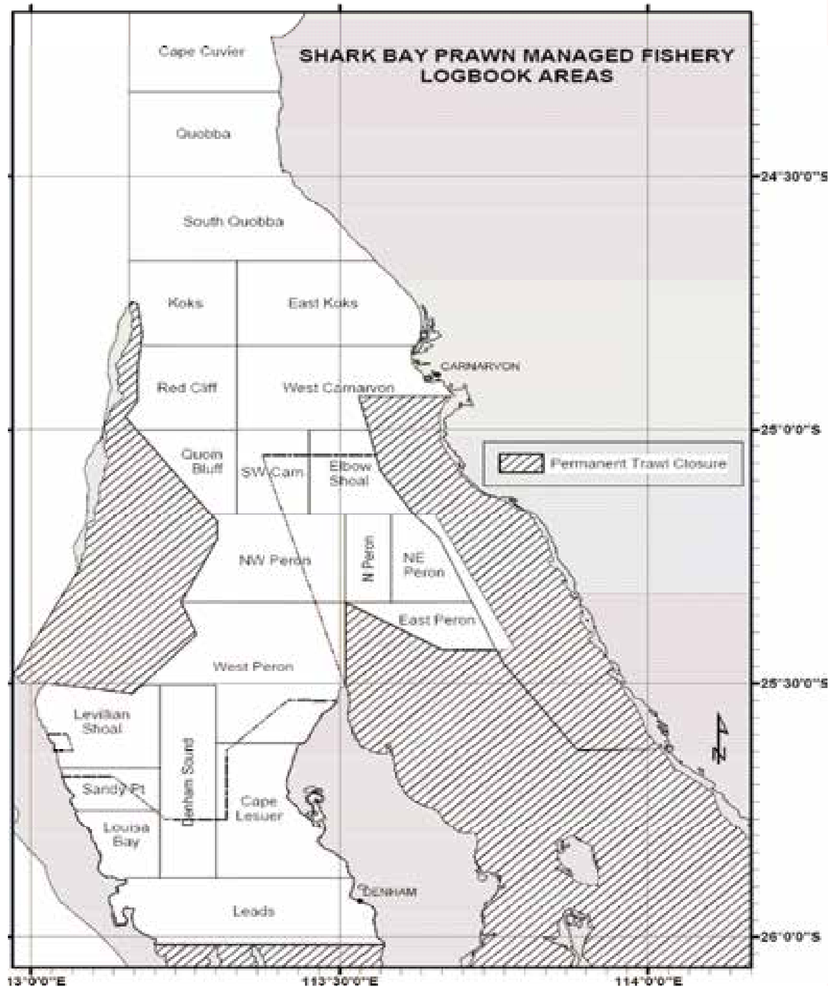


Figure 4.1. Maps of the Shark Bay showing (A) historical spatial block and sub-block number series (eg. 7906.3) as well as latitudinal spatial blocks (eg. B, E, G1) and (B) fishing ground names used to report catch information prior to GPS technology.

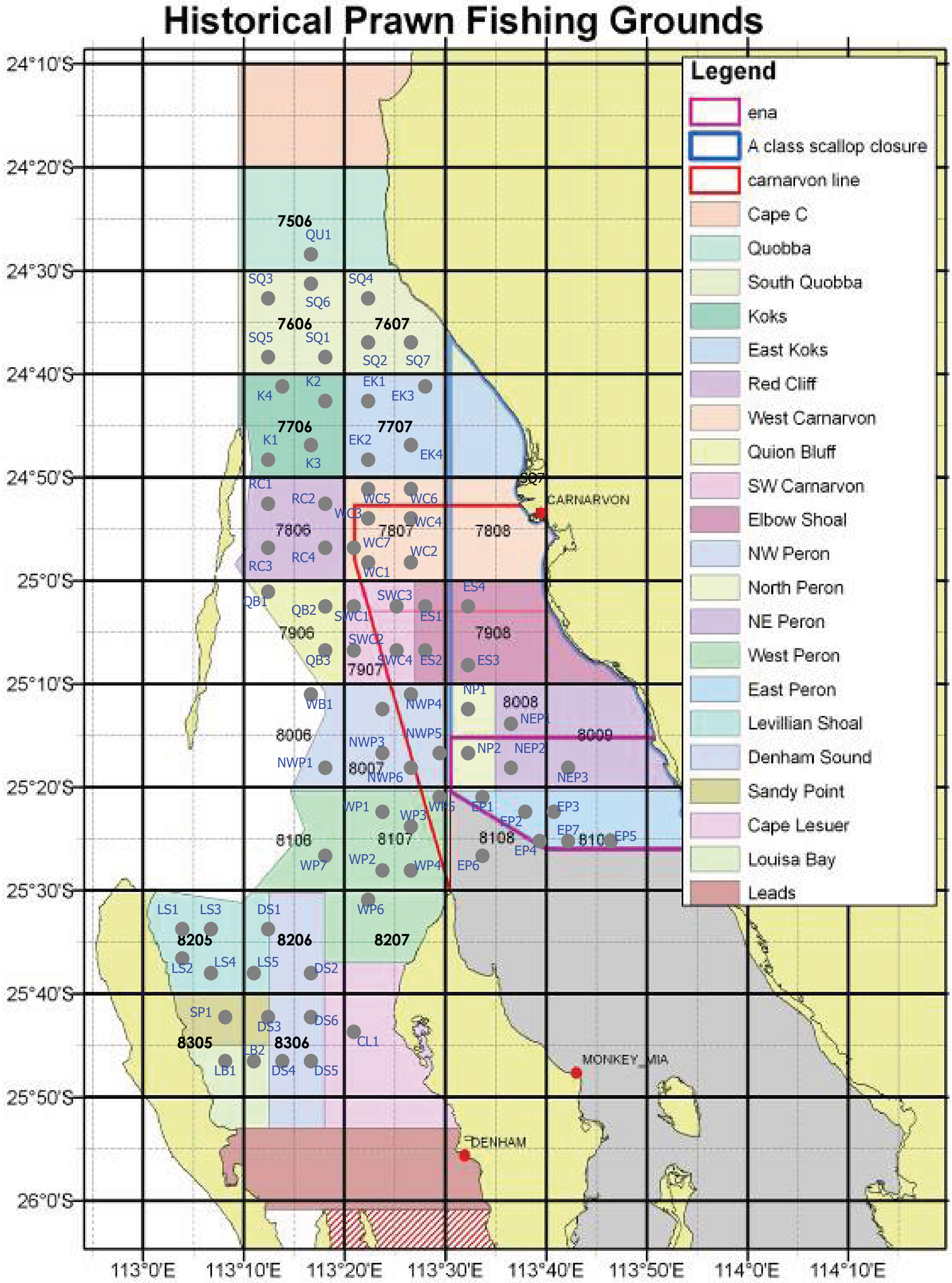


Figure 4.2. Map of Shark Bay showing the different fishing grounds (coloured zones) overlaid with fishing block and sub-block divisions as well as the assigned reference points (grey dots) with their individual codes. Note: Northern Shark Bay region (NSB) denotes area to the north of 24° 50' S; Eastern Shark Bay region (ESB) denotes area east of the CPL; Western Shark Bay region (WSB) denotes area west of the CPL (including WP6); Denham Sound region (DS) denotes area south of 24° 50' S.

4.3 Results

Prawn nominal fishing effort has been declining steadily from 1987 to 2008 with the exception of the years 1990-1992 when a significant drop in effort was observed (Fig. 4.3) due to a fleet restructure and high scallop abundance. Approximately 64 ± 2.4 % (mean ± SD) of the total annual fishing effort by the prawn fleet occurred in the first 4 months of the fishing season for the years 1987 to 1989 when 35 fishing boats were in operation. This effort declined to 55.3 ± 6.2 % (mean ± SD) of the annual fishing effort when fleet reductions took place in 1990 (27 boats), 2005 (25 boats) and 2007 (18 boats) (Table 4.1). The average effort across the Bay prior to the scallop season opening was 22 ± 5.4 % of the annual effort during the pre-CPL years (1987 to1990) and 24 ± 9.4 % of the annual effort during the post-CPL years when the matrix system was in place (1991 to 2004). The mean effort levels on the WSB scallop grounds (Fig. 4.2) prior to scallop season opening was only 0.3 ± 0.4 % of the annual prawn effort during the pre-CPL years and 4.5 ± 3.2 % during the post-CPL years.

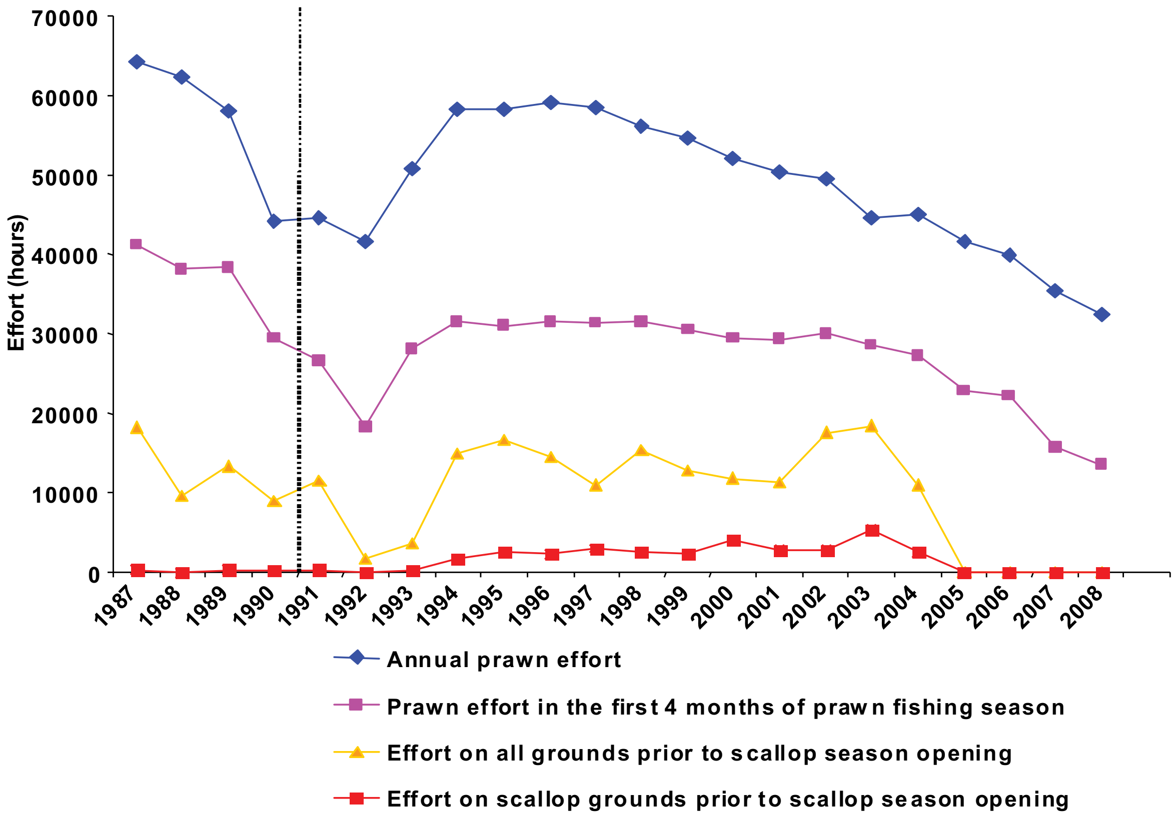


Figure 4.3. Annual trends in prawn fishing effort split by spatial and temporal fishing periods. Effort levels on scallop grounds prior to scallop season opening for 1995 and 1996 are only estimates due to lack of fine-scale spatial information. Vertical line represents CPL introduction.

4.3.1 Historical prawn trawl effort distribution (1987-1994)

Trends in prawn fleet effort (within the first four months of fishing) showed fishing activity mainly across the NSB and ESB fishing grounds during the pre-CPL years (Fig. 4.4), which after the opening of the scallop season increased in intensity in ESB and some effort shifted onto WSB and DS regions (Fig. 4.5). During the post-CPL years when the CPL opened after the scallop season, trawl effort was first concentrated in the NSB region (Fig. 4.6), and then shifted onto WSB and DS scallop grounds after the scallop season began (Fig. 4.7). Effort on scallop grounds was relatively low until both the scallop season and the CPL opened, after which trawl intensity increased in the ESB and WSB regions (Fig. 4.8). From 1994 onwards (with the exception of 1997), the CPL opened before the scallop season commenced. During 1994, the prawn fleet mainly concentrated their fishing in the NSB and DS regions with minimal fishing on scallop grounds on WSB region (Fig. 4.9). The effort on the scallop grounds does not significantly increase after the CPL line opens and instead this occurs only after the scallop season commences when peaks in effort are observed for both ESB and WSB regions (eg. NEP, NWP, EP, ES and RC) (Fig. 4.9).

Prawn fishing effort prior to the opening of the scallop season was significantly higher during the pre-CPL years than during the post-CPL years ($F_{3,24} = 4.67$, $p = 0.01$) (Fig. 4.10a). While effort distribution across the NSB, WSB, and DS regions remained relatively similar between pre and post CPL years, there was a significant effort reduction on the ESB fishing grounds during the post-CPL years largely due to the CPL being opened after the scallop season opened for the years 1991-1993. Thus the recorded effort level during the post-CPL period is solely derived from 1994 where the CPL opened before the scallop season. Closed access to ESB fishing grounds did not however result in a displacement of effort elsewhere and instead mean effort levels for WSB and DS regions showed slightly reduced effort levels during post-CPL years.

Prawn fishing effort after the commencement of the scallop season was not significantly different between pre and post CPL years ($F_{3,24} = 1.17$, $p = 0.34$). Across all the years, effort levels between NSB and DS regions were similar and lower than for WSB and ESB regions. Notably, the effort on the WSB and DS scallop grounds was lower during the post-CPL years than during the pre-CPL years (Fig. 4.10B).

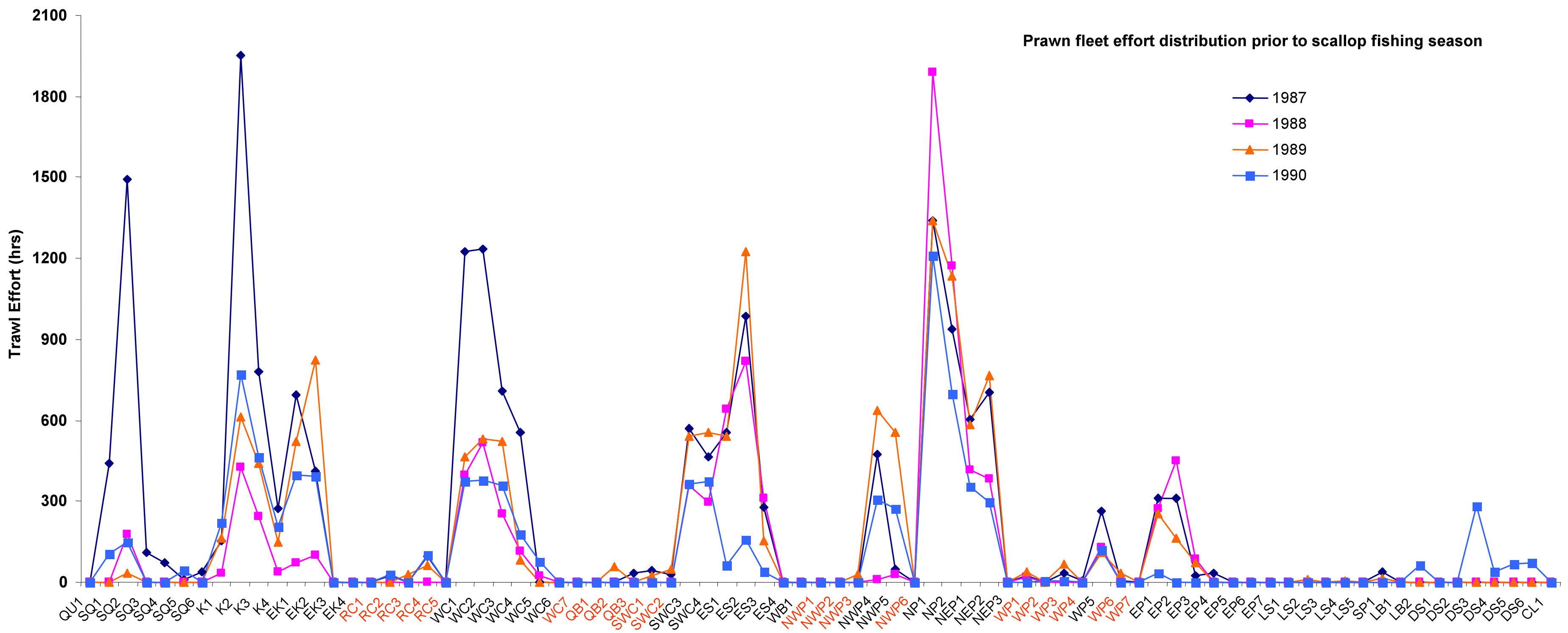


Figure 4.4. Trends in prawn fleet effort across Shark Bay prior to the scallop season opening during the four years prior to the introduction of the CPL. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds. Location labels are as per Fig. 4.2.

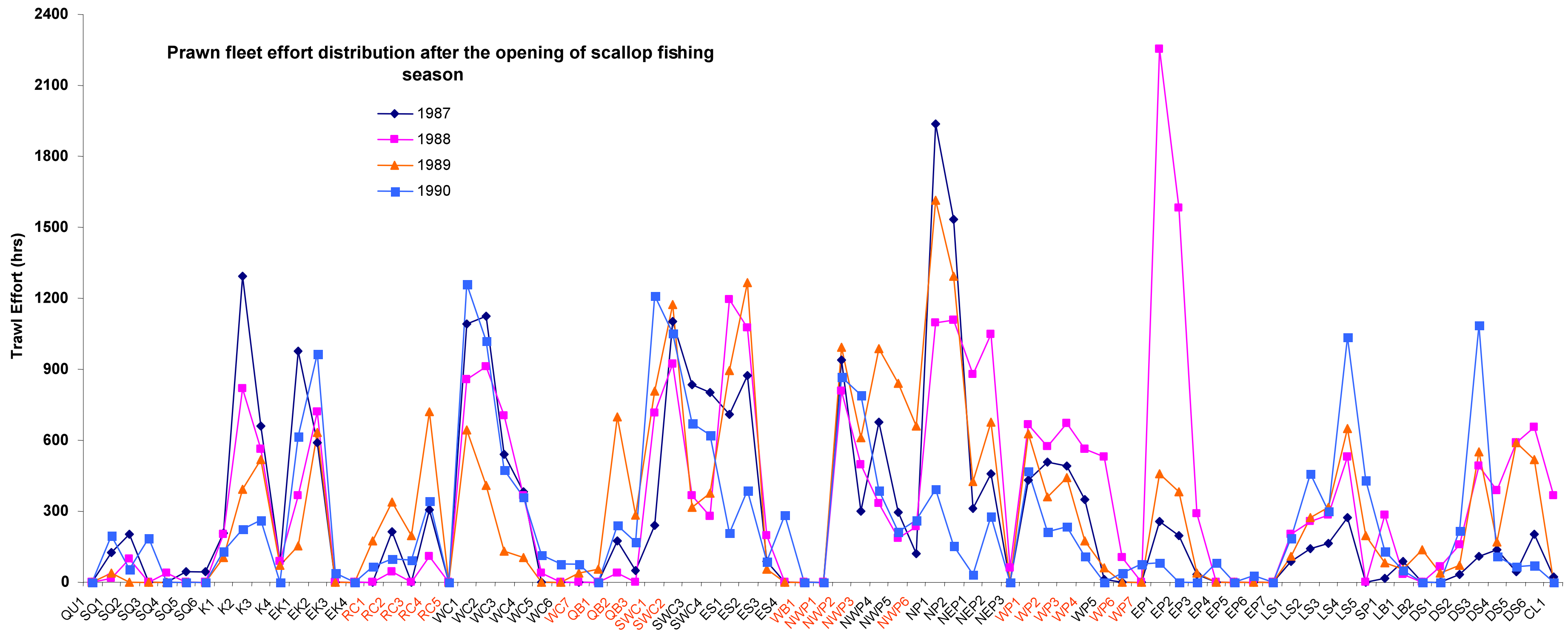


Figure 4.5. Trends in prawn fleet effort across Shark Bay after the scallop season opening during the four years prior to the introduction of the CPL. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds.

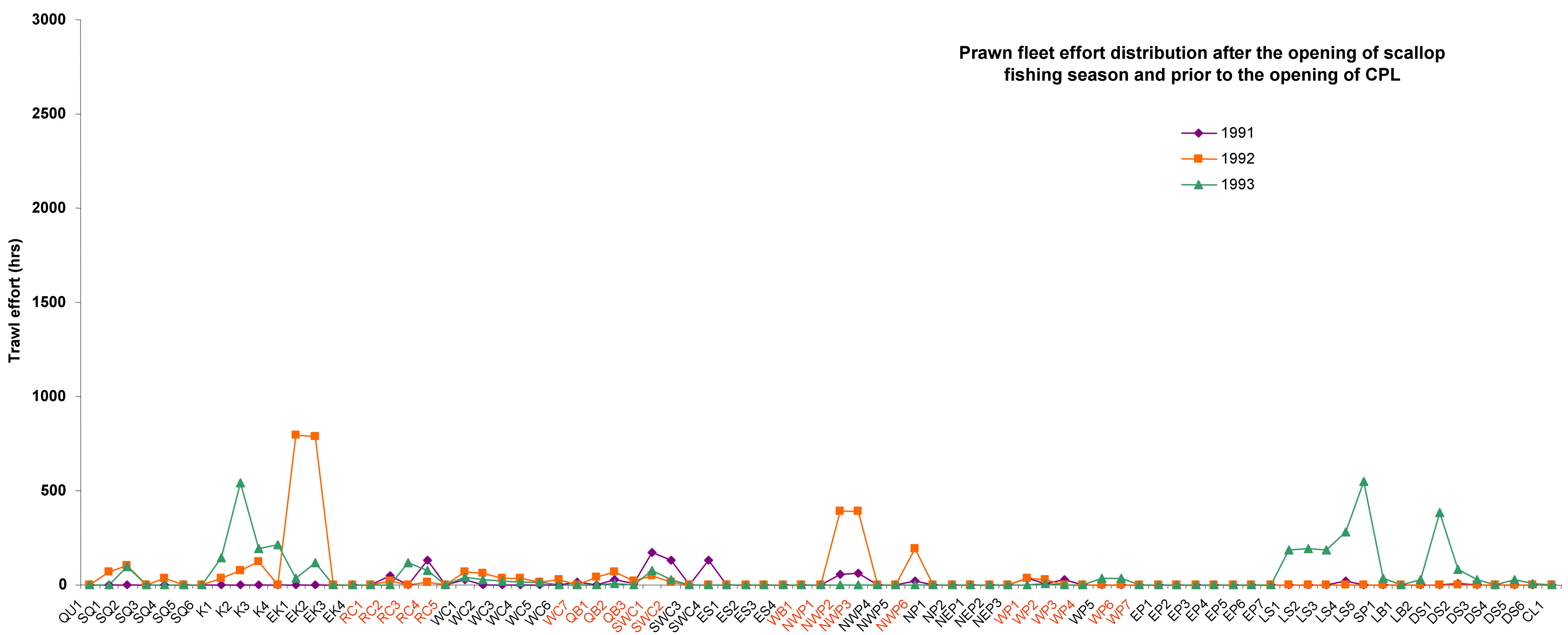


Figure 4.6. Trends in prawn fleet effort across Shark Bay prior to the opening of the CPL and scallop season during the three years after the introduction of the CPL. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds.

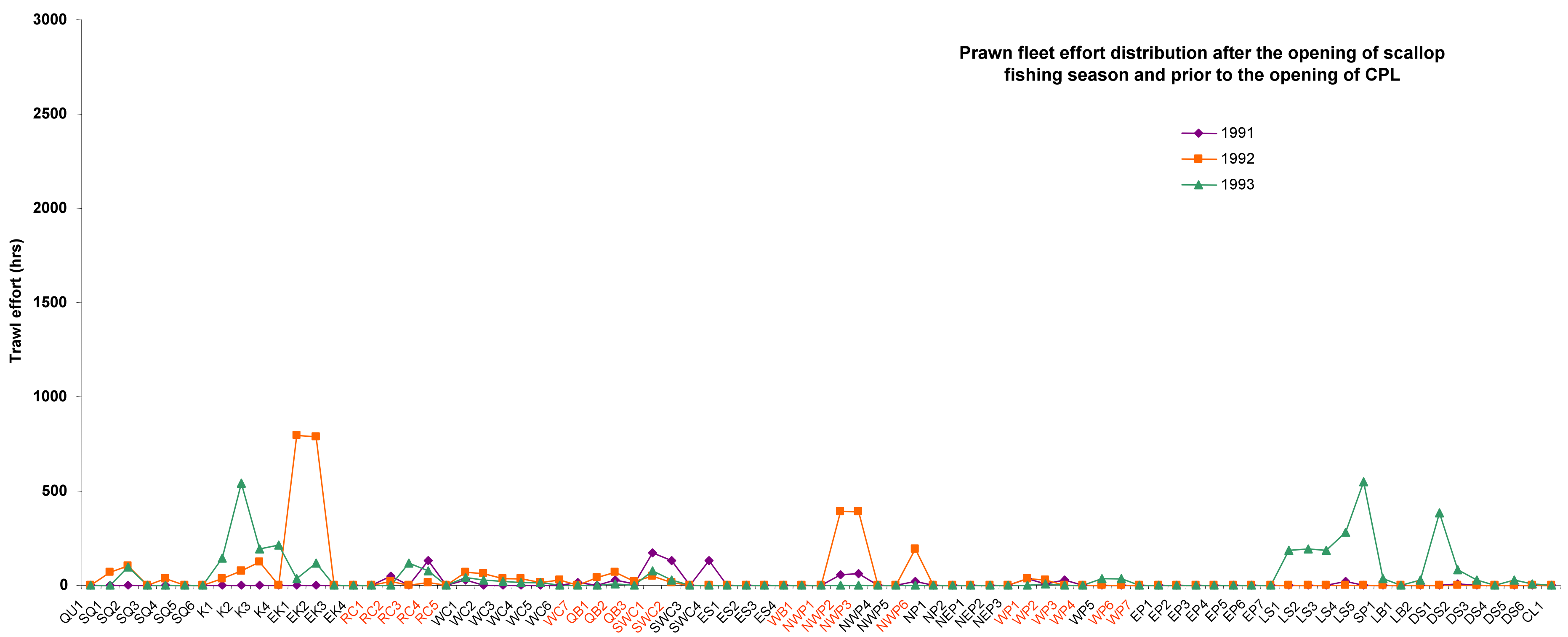


Figure 4.7. Trends in prawn fleet effort across Shark Bay after the scallop season opening and prior to CPL opening during the three years after the introduction of the CPL. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds.

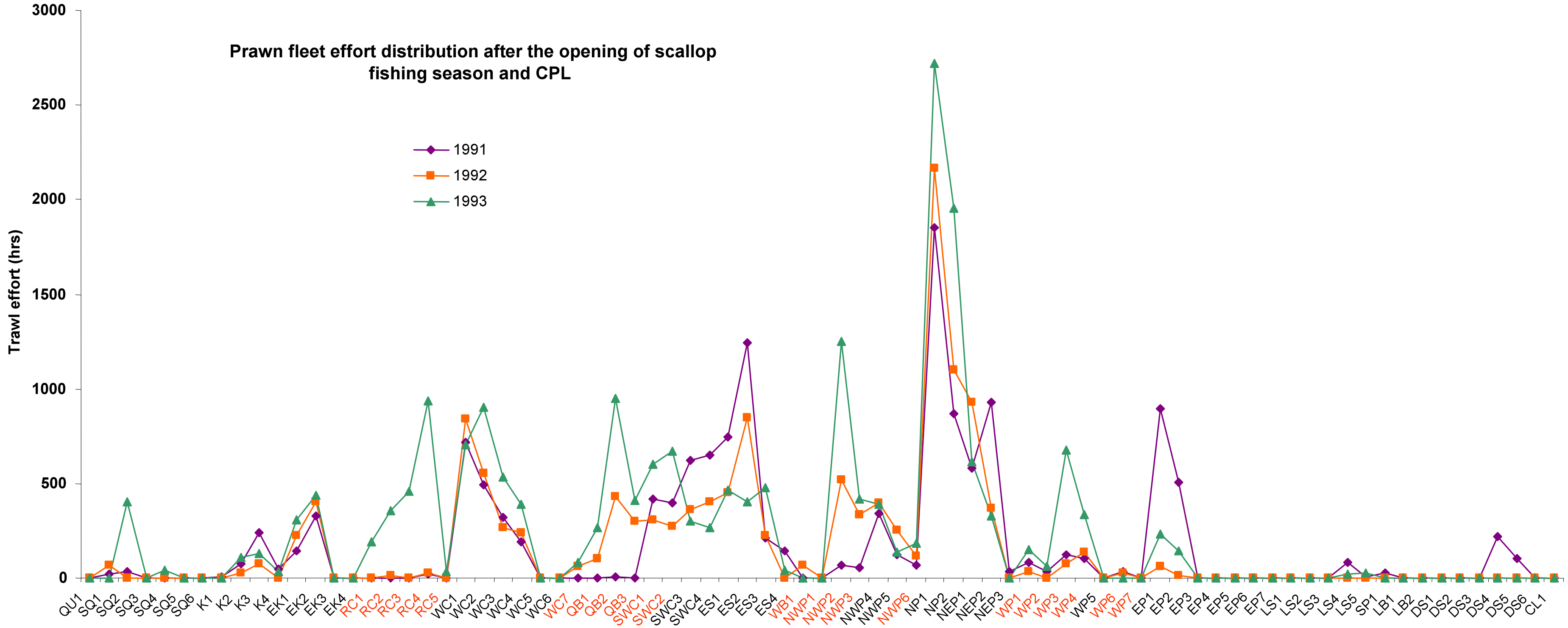


Figure 4.8. Trends in prawn fleet effort across Shark Bay after the opening of both the scallop season and CPL during the three years after the introduction of the CPL. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds.

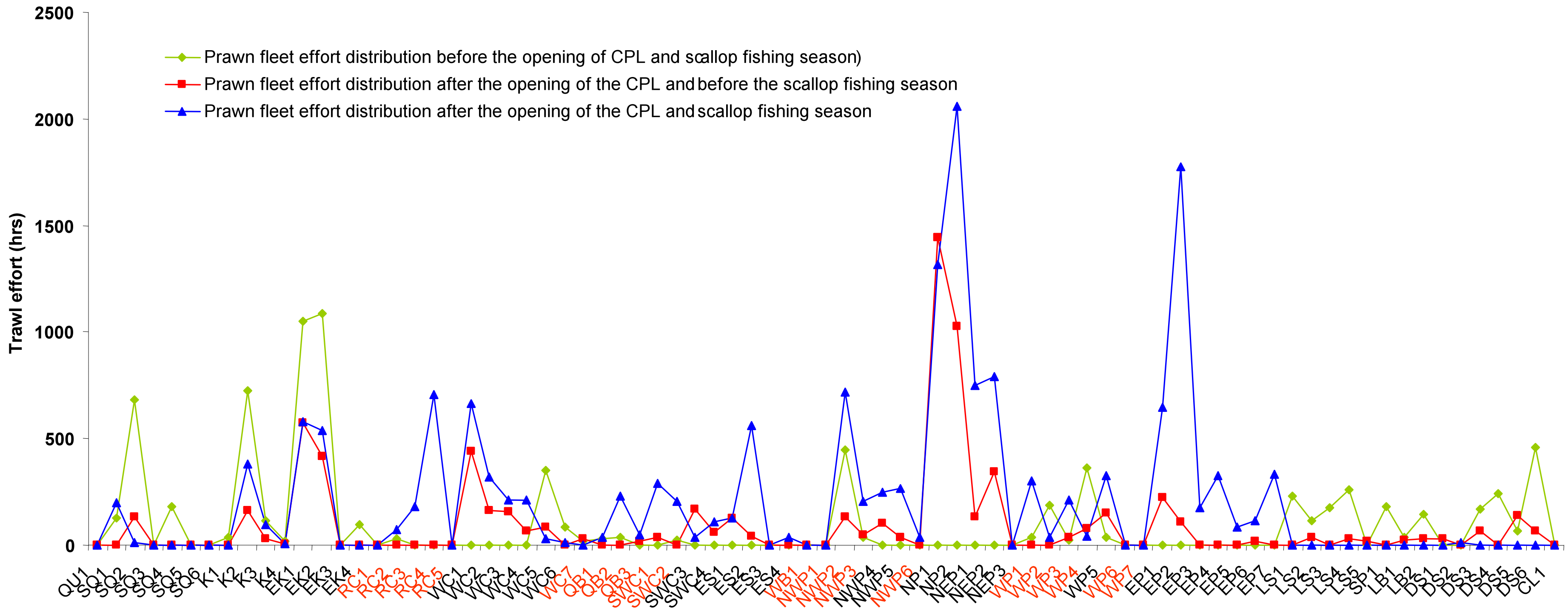


Figure 4.9. Trends in prawn fleet effort across Shark Bay in 1994 for the different time periods before, after and between the openings of the CPL and the scallop season. Reference locations shown in red text relate to those locations on the western Shark Bay (WSB) scallop grounds.

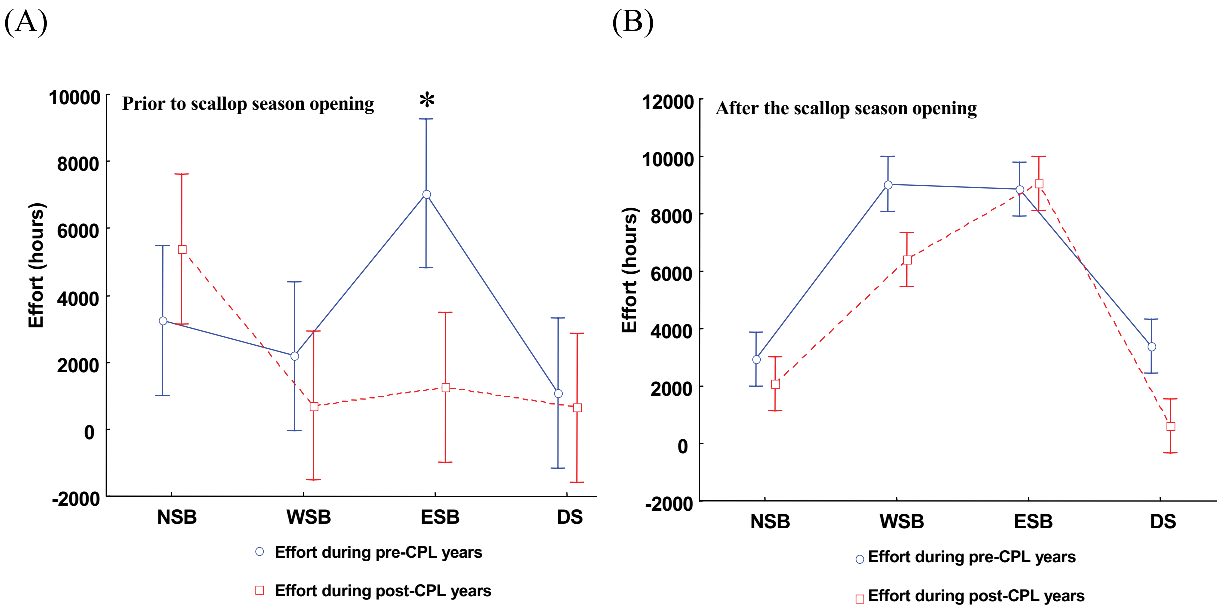


Figure 4.10. Comparisons of mean (± 95% CI) prawn trawl effort between pre and post CPL years in the period (A) prior to and (B) after the opening of the scallop season. An asterisk (*) indicates significant difference in effort between the time periods within each site.

4.3.2 Recent prawn fishing effort (1995-2008)

For the years between 1995 and 2008 (with the exception of 1997), the CPL opened prior to the scallop season (Table 4.1). Prior to the opening of the CPL, prawn trawl effort on scallop grounds had increased to levels of above 2000 hours/annum in the period 1995-2003 and then dropped to levels less than 2000 hours/annum after 2004. Very high effort peaks occurred in 2000 and 2003 with levels reaching ~ 4000 and 5000 hours/annum (Fig. 4.11).

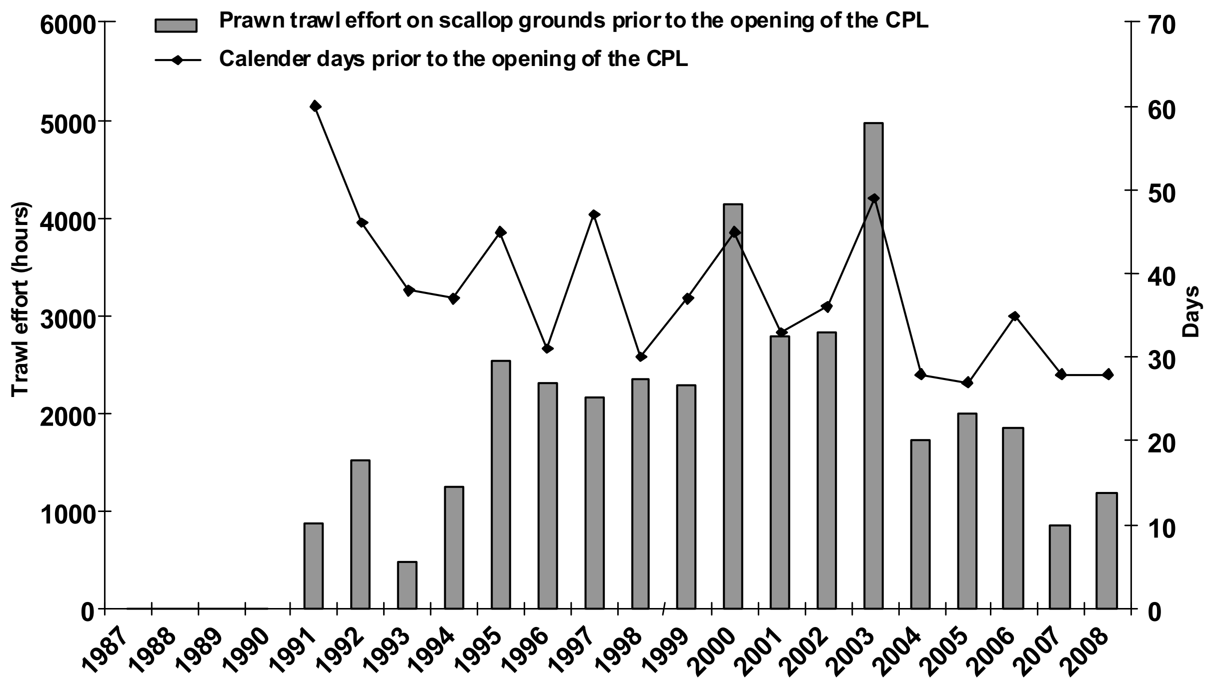


Figure 4.11. Trends in prawn trawl effort on WSB scallop grounds prior to the opening of the CPL.

Prior to the opening of the scallop season, prawn trawl effort on scallop grounds showed effort levels between ~ 2000 and 5000 hours/annum in the period 1994 to 2004 (Fig. 4.12). Some variation in effort levels between 1994 and 2004 could be accounted for by the difference in fishing days prior to the opening of the scallop season. From 2005 onwards both the prawn and scallop fleet began fishing on the same date. Prior to 1994, effort levels are relatively low and below 500 hours/annum (Fig. 4.12). This low effort was due to high scallop abundance in Shark Bay between 1991 and 1994. However effort on scallop grounds had increased substantially in the period between 1995-2004, which would have been associated with scallop discarding.

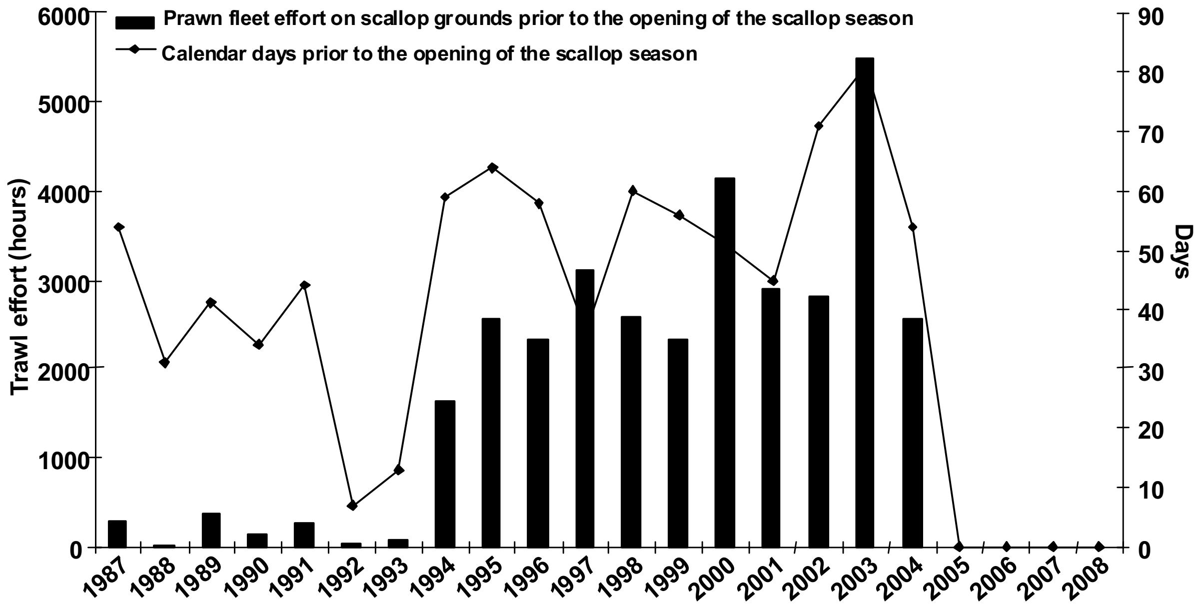


Figure 4.12. Trends in prawn trawl effort on WSB scallop grounds prior to the opening of the scallop season.

4.3.3 *Scallop fishing effort distribution*

Scallop trawl effort varied greatly between the fishing grounds as well as within each ground in the years before and after the CPL introduction. For example, in the Red Cliff fishing ground annual effort levels ranged from < 500 hrs to > 6000 hrs, while effort levels in the most northern Shark Bay grounds (KO) has been more consistent at less than < 1000 hrs (Fig. 4.13). In the period 2001 to 2008 the Denham Sound (DS) fishing grounds had specific opening and closure dates. From 2002 onwards DS fishing grounds opened prior to central Shark Bay grounds (due to better meat size and quality and significant scallop abundance) and this is reflected in the higher effort levels in DS over other areas (Fig. 4.14). Overall effort levels have decreased from 1994 to 1997 to the most recent years with effort levels in any one fishing ground not exceeding 4000 hrs.

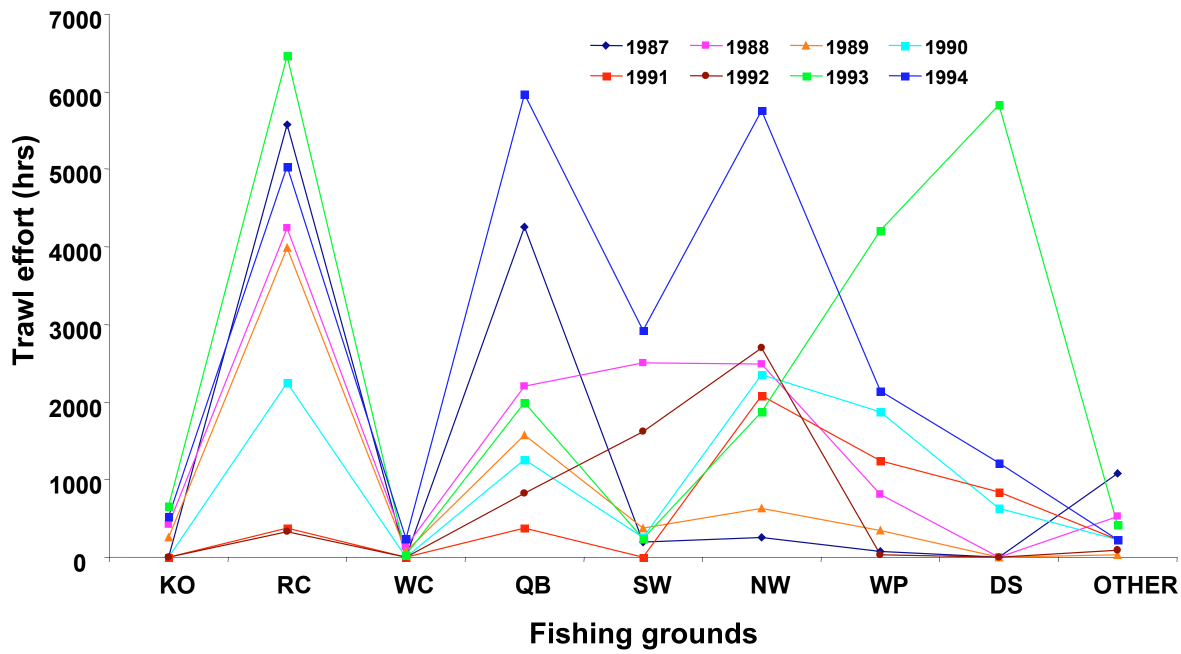


Figure 4.13. Spatial distribution of scallop fleet effort across all the Shark Bay fishing grounds from 1987 to 1994.

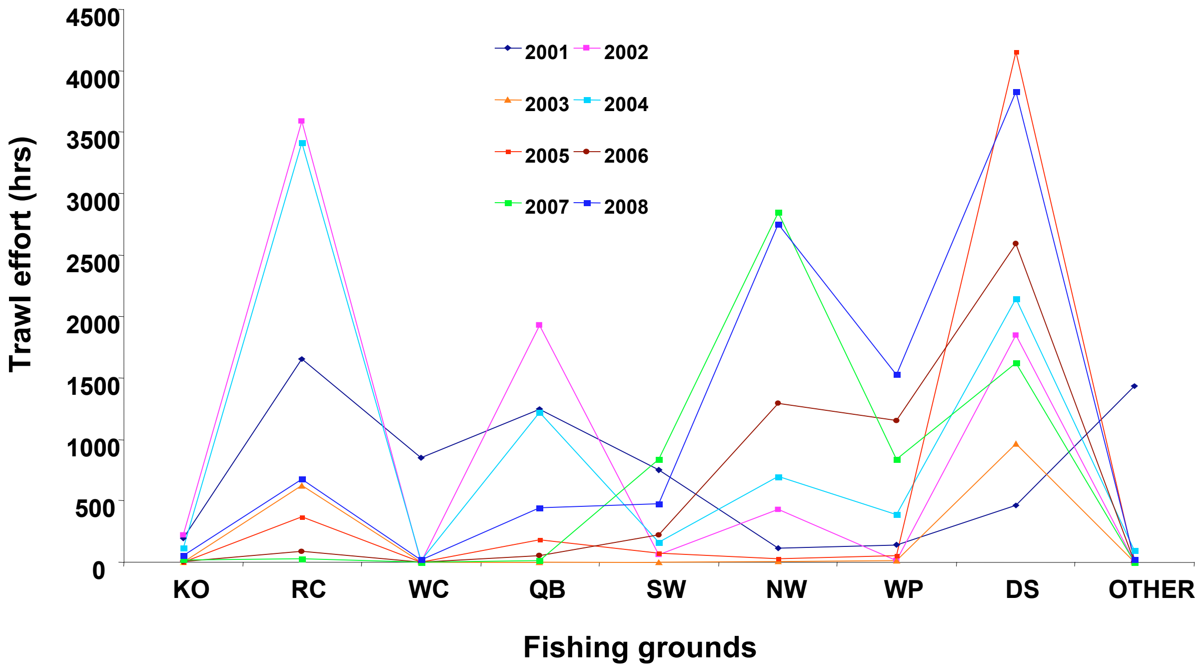


Figure 4.14. Spatial distribution of scallop fleet effort across all the Shark Bay fishing grounds from 2001 to 2008.

4.3.4 Temporal fishing effort distribution by the scallop and prawn fleets

Monthly trends in prawn trawl effort differed little between the periods 1987 to 1994 and 2001 to 2008 (Fig. 4.15a,b), while fleet reductions were reflected in the lower effort levels in the latter years. For the scallop fleet however, temporal trends in effort were dramatically different for the two time periods (Fig. 4.15c,d). Long fishing period of months (March to October) from 1987 to 1994 was significantly shortened to February to June during 2001 to 2008. A shift to early fishing by the scallop fleet since 2005 (non-Matrix years) has also reduced the effort levels during the key spawning months.

When the fishing effort from both fleets were combined, the data showed highest effort levels during the key spawning months from May to July in the years 1987 to 1994 (Fig. 4.16a). During the pre-CPL years (1987 to 1990), 1987 and 1988 showed similar monthly effort trends, while in 1989 a later fishing start by both fleets in April/May meant peak effort occurred in June/July. The 1990 effort levels were lower than the preceding years but peak effort levels remained within the spawning period. During the post-CPL years (1991 to 1994), effort levels in 1991 and 1992 were the lowest during the first four months of the season and this was largely due to high catch rates of scallops that resulted from the huge scallop recruitment event of 1990. In contrast, the effort levels in 1993 and 1994 were overall the highest with peak effort levels occurring between May and July.

Monthly effort trends in the period 2001-2004 were similar to the historical monthly trends of 1987 to 1994 where the peak fishing period occurred between May and July (inclusive) (Fig. 4.16b). However during the period 2005 to 2008, peak effort levels had shifted to earlier in the year to March/April followed by consistent low effort levels between May and July. This shift was predominately due to changes in the harvesting strategy for scallops within Shark Bay. The shift in peak effort from the key spawning period to pre-spawning period was a result of the previous decision-rule framework (called the MATRIX system that was used for opening the scallop fishery) being abolished in 2004 and the scallop fleet commencing fishing on the same date as the prawn fleet, generally in March. The scallop fleet also ceased fishing during the main spawning season (from May/June to July/August) while the prawn fleet continued to fish for scallops after this closure until October/November when the prawn season ended.

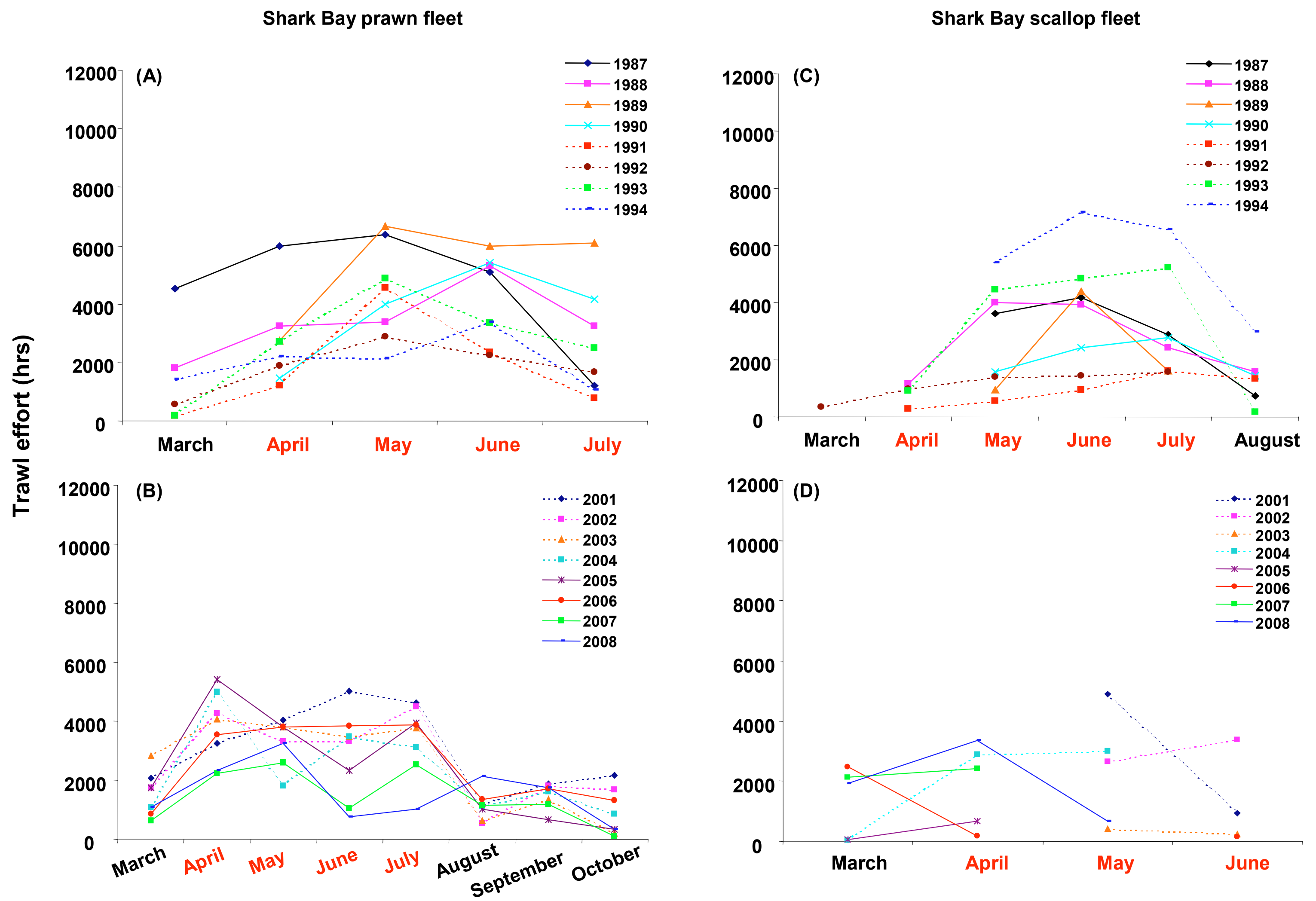


Figure 4.15. Monthly effort trends across central Shark Bay scallop grounds by the prawn fleet during; (A) the pre-CPL (solid) and post CPL years (broken) years; (B) MATRIX (broken) and non-MATRIX years (solid). Monthly effort trends across central Shark Bay scallop grounds by the scallop fleet during; (C) the pre-CPL (solid) and post CPL years (broken) years; (D) MATRIX (broken) and non-MATRIX years (solid). Key spawning months is indicated in red.

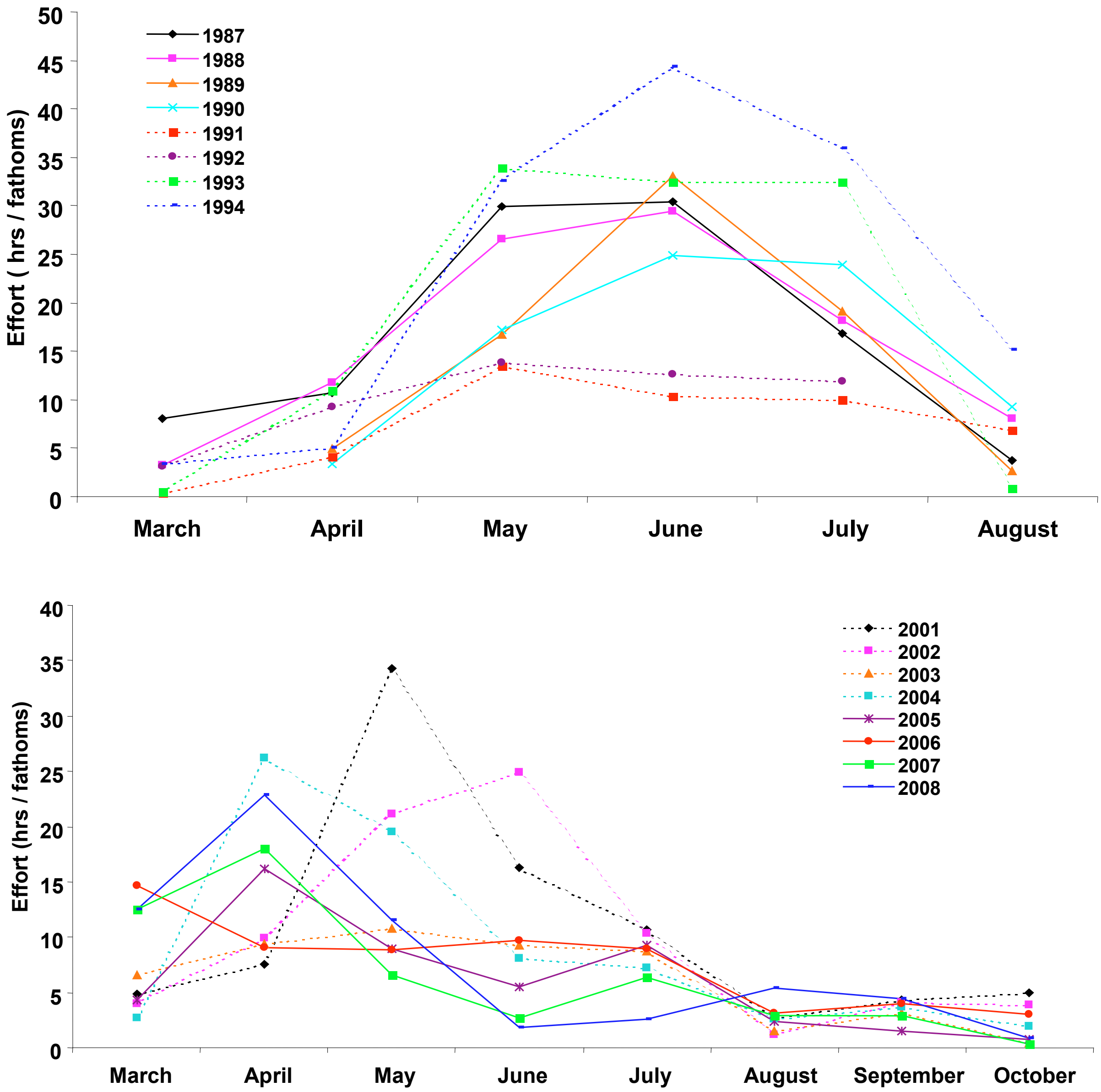


Figure 4.16. Monthly trends in the combined trawl effort of both the prawn and scallop fleets on the central Shark Bay grounds during (A) historical (1987 to 1994) and (B) current (2001 to 2008) years.

The relatively lower effort levels after May are a combination of this management change where only one fleet is fishing on the central Shark Bay grounds and also due to a boat reduction within the prawn fleet (from 27 to 18 operating boats). This boat reduction however, only represents an 8% reduction in net headrope as the remaining boats tow larger nets than previously.

4.4 Discussion

The introduction of the Carnarvon-Peron Line (CPL) management line in 1991 altered the spatial fishing dynamics of the Shark Bay scallop and prawn fleets, however spatial displacement of trawl effort in the years after 1991 were largely driven by external factors such as the timing of the scallop seasonal opening, exceptionally high scallop recruitment years and prawn fleet reductions. In assessing the trawl effort expended by both the prawn and scallop sectors, the results showed peak trawl activity during the scallop spawning-period.

4.4.1 Spatial fishing effort distribution by the Prawn fleet

The Shark Bay scallop industry had concerns that increased prawn effort levels on central Shark Bay scallop grounds had negatively impacted scallop stocks through periodic regulatory discarding of scallops. In evaluating the impact of the Carnarvon-Peron Line (CPL) management line introduction in 1991 on the historical (1987 to 1994) spatial effort distribution of the B-Class prawn fleet, the desktop study did not find the CPL to be a significant driver of effort displacement that affected the scallop grounds. While effort distribution across the northern Shark Bay (NSB), western Shark Bay (WSB) and Denham Sound (DS) regions remained relatively similar between pre (1987 to 1990) and post (1991 to 1994) CPL years, there was a significant reduction in hours trawled on the eastern Shark Bay (ESB) fishing grounds for the post-CPL years as expected. Thus closed access to ESB fishing grounds during the post-CPL years did not result in a large displacement of effort elsewhere, and instead mean effort levels for WSB and DS regions showed slight reductions. Thus effort levels associated with scallop discarding actually decreased during the post-CPL years, and this was largely due to factors that were not related to the implementation of the CPL. Firstly, a very high scallop recruitment event in 1990 had resulted in unprecedented high abundance of scallops across Shark Bay. This meant trawl shot durations were significantly reduced from the usual 60 to 75 min shots to 5 to 15 minutes. Residual scallop abundances were carried over to 1992 and 1993 fishing seasons thus keeping effort levels also low in the subsequent years. Secondly, reduction in operating prawn boat numbers from 35 to 27 also occurred in 1990 (based on a buyback and a total headrope reduction for the fleet), which as intended, reduced the overall effort expended by the prawn fleet. Coincidently both of these unrelated events occurred when the CPL was introduced, thus the full impact of effort displacement due to the CPL was not possible to isolate, hence the extension of the desktop study to 2008 became necessary.

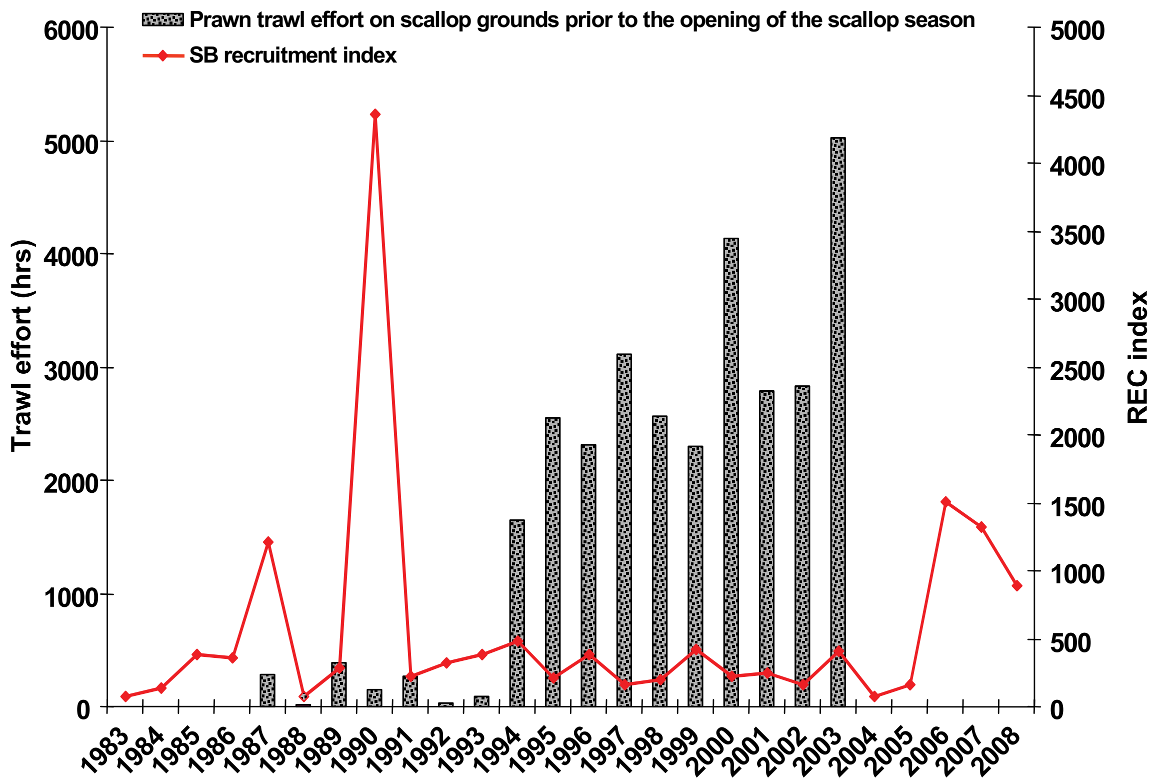


Figure 4.17. Comparison of Shark Bay scallop recruitment index with prawn trawl effort on scallop grounds prior to the opening of the scallop season.

The opening of the CPL before the scallop season during the period 1995 to 2008 led to increasing prawn effort levels on scallop grounds. Anecdotal reports suggested that the prawn fleet actively avoided high abundance scallop grounds as much as possible before the opening of the scallop season to achieve greater fishing efficiency for prawns with minimal quantities of scallops in the nets. In relating the prawn effort levels on scallop grounds to the annual scallop recruitment index, we found low and consistent scallop recruitment years between 1994 and 2003 to coincide with the prawn effort levels associated with discarding (Fig. 4.17). However, the intensity of scallop discarding by the prawn fleet appears to be associated with the timing of the opening of the scallop season rather than from spatial restriction imposed through the CPL implementation. The simultaneous opening of both the prawn and scallop seasons from 2004 onwards appears to be a positive management measure that eliminated discarding of adult scallops (apart from small scallops) by the prawn fleet at the beginning of the fishing season.

4.4.2 Spatial fishing effort distribution by the scallop fleet

Under the MATRIX system during 1987 to 2004, the commencement of the scallop season was always after the prawn fishing season began to ensure spawning abundance was adequate and the product was at reasonable marketable quality. Regulatory discarding of scallops by the prawn fleet prior to scallop fishing opened would have resulted in potentially high mortality rates (results from Objective 1) but this is difficult to assess as there are no records of the amount of scallops discarded. Effort trends of the scallop fleet in the years 1987 to 1994 are variable and reflective of the annual spatial variation in scallop settlement patterns and abundance rather than the management measures. The exception was Denham Sound which was subject to temporary closures. In the latter years (2001 to 2008) and particularly 2004 onwards, the scallop trawl effort levels decreased largely due to the shortened scallop fishing season, improved catch efficiency and the introduction of threshold catch rates to ensure higher residual abundance remaining the following season. However no clear relationship was observed for scallop fleet effort on the central Shark Bay grounds and scallop recruitment patterns (Fig. 4.18). High and low peaks in effort levels did not correspond with low or high scallop recruitment events in the years examined.

4.4.3 Temporal fishing effort distribution by the scallop and prawn fleets

We next examined the combined trawl activities of both fleets during the key spawning months as the final component of this desktop study.

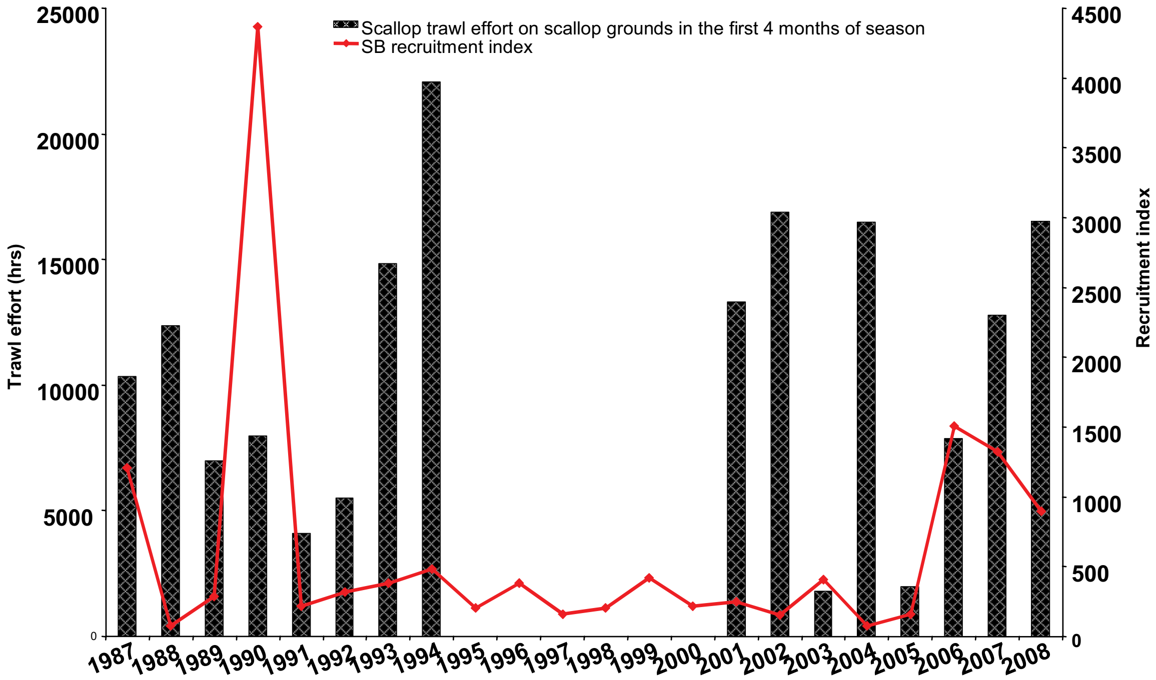


Figure 4.18. Comparison of Shark Bay scallop recruitment index with scallop trawl effort on scallop grounds in the first four months of the scallop fishing season. Effort data was not available for 1995 – 2000.

Examining trawl effort trends (on the central Shark Bay grounds) on a temporal scale highlighted the critical relationship between effort and scallop spawning months. Until 2004 when the MATRIX system was being utilised, the combined trawl effort by both fleets was highest during the spawning months (April to July). The impact on recruitment from the disturbance to the natural spawning behaviour through trawling and biomass removal is largely speculative. Trawl impact on discarded scallops was examined as part of Objective 1 and showed mortality rates of discarded scallops to be significantly higher during the summer than winter months. Given the spawning months are generally considered to be of autumn/winter conditions, we presume moderate survival of discarded scallops. Nonetheless, the trawl impact on the spawning behaviour remains largely unknown. For instance, we are unsure if the stress from trawl disturbance delays or hastens spawning thus altering the natural timing of the spawning event. If larvae are produced (as a response to stress) when the environmental conditions are not optimal, then larval survival, movement and settlement processes may be compromised, thus impacting on the overall recruitment to the Bay. We assume a proportion of harvested scallops to have spawned prior to capture while others may not had the opportunity to spawn.

Despite peak effort levels on scallop grounds when they are most vulnerable there was no clear relationship between trawl effort during the scallop spawning months and scallop recruitment measured later that year (Fig. 4.19). Trawl effort levels either by the individual prawn and scallop fleets or as a combined fleet did not reveal any clear or significant relationship with recruitment levels. Peak recruitment events in 1987, 1990 and successive recruitment pulses in 2006, 2007, and 2008 did not correspond with any notable effort trends. The low and consistent recruitment levels between 1991 and 2005 occurred across low and high effort levels by both fleets.

The overall lack of correlation between effort and recruitment seems to suggest;

1. The breeding stock that is being impacted by trawling on the central scallop grounds may not be the source population of recruitment to these grounds; or
2. Effort levels recorded in the Shark Bay fishery do not play a major role in the overall recruitment dynamics of saucer scallops;
3. Other factors (such as environmental) or a combination of effort and these external factors are more likely to drive recruitment success.

Changes in management measures (eg. CPL, MATRIX system, boat reductions, Denham Sound season opening) were highly influential in the spatial and temporal fishing dynamics of the trawl fleets and subsequently on the effort trends observed across historical (1987 to 1994) and current (2001 to 2008) time series. But we found no evidence to suggest that effort levels alone by either fleet or combined to be the dominant factor driving scallop recruitment in Shark Bay, although it may be a contributing factor. A comprehensive re-evaluation of the stock-recruitment-environment relationship is currently underway where different indices of spawning stock levels are being analysed together with a range of environmental variables. The effect of fishing effort distribution combined with environmental factors will also be examined to improve our understanding of scallop recruitment dynamics.

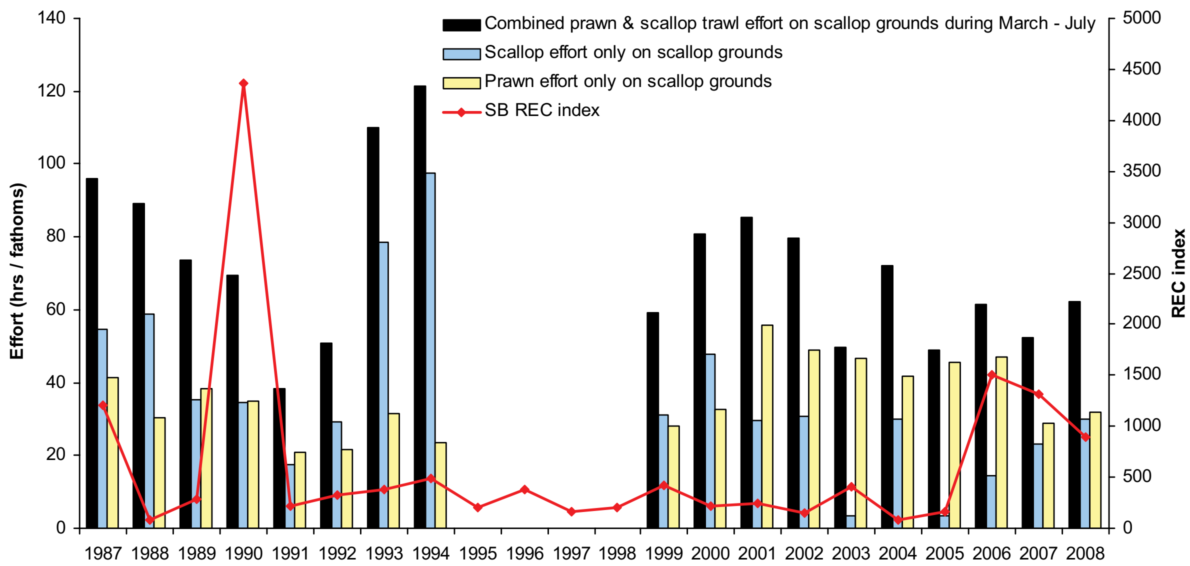


Figure 4.19. Comparison of Shark Bay scallop recruitment index with trawl effort trends on scallop grounds during the key scallop spawning months.

The use of spatial closures as a management tool to reduce total effort levels and to promote recruitment is not strongly supported by the results of the desktop study. Instead, spatial closures could be more beneficial as a management measure to protect newly settled scallops from trawl impact. There are currently no estimates of mortality or injury to juvenile scallops (< 50mm) that come in contact with trawl gear during the post-spawning months (July to October) when primarily the prawn fleet continue fishing in Shark Bay. However shock rings (scars) on scallop shells are a common occurrence and are evidence that small scallops are captured, discarded and impacted by trawl nets. This may be an area of valuable research focus in the future. The final outcome of the hydrodynamic modelling component of this FRDC project is a valuable input into this research.

5.0 Objective 4: Hydrodynamic larval transport modelling

Objective 4: ***To examine whether existing hydrodynamic models can guide the selection of spatial closures and to investigate the larval transport mechanisms of both prawn and scallop larvae in Shark Bay***

5.1 Introduction

Successful recruitment of many marine mollusc species is strongly dependent upon hydrodynamic conditions that retain or transport larvae to favourable settlement grounds (Levin 2006). In Shark Bay, where the saucer scallop (*Amusium balloti*) trawl fishery experiences dramatic inter-annual variability in catch, it is thought that changing environmental conditions associated with ENSO events such as currents and/or temperature have a significant effect on the variability in annual recruitment (Joll and Caputi 1995b; Kangas *et al*. 2007b, 2011). However, there is presently a lack of understanding of the detailed hydrodynamic processes that are required to interpret the recruitment dynamics in this region.

Circulation within Shark Bay is mostly driven by mixed tides with a range of about one metre, and seasonally by persistent southerly winds. In the eastern part of the Bay, the tide is mostly semi-diurnal while in the western part it is mainly diurnal. Resulting tidal currents and winds create a well-mixed environment where exchange is inhibited by persistent temperature and density fronts across the channels. Additionally, the warm southward flowing Leeuwin Current (LC) offshore intrudes into the bay entrances affecting the location of the fronts (Burling *et al*. 2003; Nahas *et al*. 2005). The relative stability of this system would in theory be beneficial to scallop larval retention, however, environmental influences such as hydrodynamic flushing may negatively influence recruitment (Joll and Caputi 1995b). To understand this process, the effects of buoyancy (density) must be examined in addition to wind and tide on stratification and circulation.

Low rainfall and extremely high evaporation rates create a regime in which the upper reaches of the Bay maintain salinity levels up to twice that of ocean water (Logan and Cebulski 1970; Burling 1998). The resulting large salinity (density) gradients drive an important component of the bay's circulation. James *et al*. (1999) and Woo *et al*. (2006) inferred the existence of an outflow of hypersaline water based on observations of sediments and salinity, but did not directly measure exchange flows near the entrance channels which are adjacent to where scallop fishing grounds are located. These outflows may provide a mechanism for larvae to be flushed from the scallop grounds or even out of the Bay.

Using a combination of field measurements and numerical modelling, we examined the dynamics of circulation throughout the scallop trawl grounds during the scallop spawning season, with the aim of establishing source-sink relationships for larvae. The study consisted of four critical components, each of which built upon the previous:

1. Review of historical environmental variables (wind and Leeuwin Current)
2. Physical oceanographic field measurements
3. Development of a 3-D hydrodynamic model
4. Passive particle larval dispersal modelling

The review of the historical strength of the LC and winds in the context of scallop recruitment helped with the design of the field experiment, and allowed us to target relevant seasons for the model and ultimately incorporate all of the results into a broader temporal context. The lack of available oceanographic data (e.g. current velocity and structure) necessitated the second component of the project where we solidified our knowledge of the important hydrodynamic features around the scallop fishing grounds.

The resulting field measurements of currents, salinity, temperature, and water levels allowed for identification of relevant processes and provided necessary validation for the hydrodynamic and dispersal models. The hydrodynamic model investigated the effects of the region's principal hydrodynamic forces of tide, wind, and the Leeuwin Current. Finally, the hydrodynamic model was coupled with a passive particle tracking model to simulate potential transport pathways of scallop larvae.

5.2 Methods and Materials

5.2.1 Historical environmental variables

Analysis of historical data focused on years of high and low scallop recruitment. An attempt was made to identify anomalous years to gain an idea of potential links between the physical environment and scallop recruitment variability. The focus was on wind conditions and the strength of the LC, both of which are believed to be critical to circulation and exchange in Shark Bay. A practical application of this review was to identify two seasons (2007 and 2009) of high and low recruitment with varying environmental conditions appropriate for modelling.

Wind

Analysis was carried out on both measured Shark Bay Airport wind data (hourly and daily averages) from the Bureau of Meteorology and wind fields extracted for Shark Bay by Haigh (2009) from the US National Center for Environmental Prediction (NCEP) global reanalysis. This data set provides a 60-year 6-hourly time series (1949 to 2009) at 2.5 degree spatial resolution in contrast to the measured data which starts from 2001. Data for Carnarvon starts in 1993, but this still does not include 1990, a record year for scallop recruitment. Comparisons between measured (averaged to the same daily temporal resolution) and the reanalysis model data (daily average) showed a close fit. Due to the dominant southerly wind, and its importance for circulation in the bay, comparisons were made using the southerly component of wind stress ($\tau=\rho*C_d|\upsilon|\upsilon$) where ρ is the density of air, C_d is a drag coefficient, and υ represents the southerly component of wind velocity. In order to make inter-seasonal comparisons of the strength and timing of wind conditions, we used a cumulative method similar to that used to study upwelling along the west coast of the United States (Bograd *et al*. 2009; Schwing *et al*. 2006). This method calculates the area under the curve for a plot of alongshore wind stress over a chosen wind 'season'. In order to highlight differences in wind conditions during scallop spawning, the wind year was defined as March to March. This allows the parsing out of anomalously windy/calm years in a lengthy data set.

Leeuwin Current strength

Year-to-year analysis of the strength of the LC at Shark Bay is difficult due to a lack of suitable data. The focus therefore has been on the height of the Fremantle sea level as a proxy for the strength of the current (Pearce and Phillips 1988). In addition, we examined the work of Berthot (2007) who using the Simple Ocean Data Assimilation (SODA) reanalysis model (Carton and Giese 2008) to extract current transport data for a transect along a latitude of 26 deg. S., near to Shark Bay, which complements the Fremantle sea level data for the years 1959 to 2001.

Sea surface temperature

Directly related to wind conditions and the strength of the LC, sea surface temperatures (SST) are also important. Although there is a lack of a cohesive time series of directly measured temperatures in the scallop grounds, satellite derived analysis is still possible. The NOAA optimum interpolation (OI) SST analysis (Reynolds *et al*. 2007) uses in situ data to calibrate satellite data to recreate calibrated global daily average SSTs with ¼ degree (~ 30km) spatial resolution. A comparison of temperatures inside the bay and offshore in the LC is presented for the years 2002-2009. Higher spatial resolution (1 km) MODIS satellite measured SSTs were also used to examine the spatial characteristics of the frontal features in the entrances, however this higher resolution data is not appropriate for continuous time series analysis as the sky must be cloud free at the time the satellite passes for good data.

5.2.2 Field measurements

Currents and water levels

The overall aim of the field experiment was to quantify, for the first time, circulation and exchange through the channel, as well as provide validation for the numerical model. The field studies (25/06/09 to 23/7/09) involved two cruises aboard the 20 m fishing charter boat *Equador* leaving from and returning to Denham. The objective of the first cruise was to deploy a number of instrument moorings near the southern entrance to the Bay in the Naturaliste Channel (Fig. 5.1, Table 5.1) as well as collect in-situ temperature and salinity (CTD or conductivity, temperature, depth) data along transects. This area was chosen as most relevant to scallop larval transport as it lies between the two main fishing grounds of Denham Sound and Northwest Peron, and is a likely outlet for possible hydrodynamic flushing of larvae. On the second cruise, after one month, the moorings were retrieved and more CTD transects measured.

Measurements included current velocity profiles from two moored Acoustic Doppler Current Profilers (ADCP's), Lagrangian surface drifter pathways, temperature profiles, and water levels at the mooring location sites, as well as in the eastern and western gulfs. The temperature and salinity profiles were measured along a repeated 45 km east-west transect using a Sea Bird Electronics (SBE 19plus) CTD instrument. This transect was coincident with the moorings that were located near the temperature front, and was intended to capture the transition from cooler, higher salinity bay water to the intrusion of warmer shelf water. The key mooring at the frontal boundary in 16m of water consisted of a 1200 kHz RDI Workhorse ADCP measuring 0.5m depth bins at 1 second intervals. Also at this location was a moored chain of 4 SBE39 thermistors measuring temperature stratification and water levels. Further seaward, but still within the confines of the bay at 15m depth was a 600 kHz RDI ADCP sampling with 0.5 m bins at 1-minute intervals. This data was found to be very similar to the data recorded in the 1200 kHz instrument however due to the sampling interval it contained more noise and thus the 600 kHz data has not been presented for clarity. In addition to the thermistors in the channel, two SBE39s measuring pressure as well as temperature were deployed near Denham and Monkey Mia. These were used for validation of the model.

Lastly, four satellite-tracked (GPS) ocean drifters were also built and released along the transect. These floating "drifters" follow a parcel of water along its path, transmitting position data via satellite every ten minutes. The drifters were designed to follow the surface currents with a 'holey sock' type drogue extending to two metres below the water surface. This position and thus velocity data is useful for validation of hydrodynamic as well as larval dispersal models and to infer circulation patterns over a large area.

Table 5.1. Summary of field measurements collected in June/July 2009

Data type	Instrumentation	No. of instruments	Location	Duration
Water level & temp	SBE39 pressure sensors/thermistors	2	Denham, Monkey Mia	1 month
Temperature profile	SBE39 thermistors	7	Naturaliste channel	1 month
Current velocity	RDI Workhorse ADCP	2	Naturaliste channel	1 month
Temperature & Salinity	CTD probe	1	Ship-borne transects	variable
Lagrangian Currents	Satellite tracked ocean drifters	4	variable	1-6 months

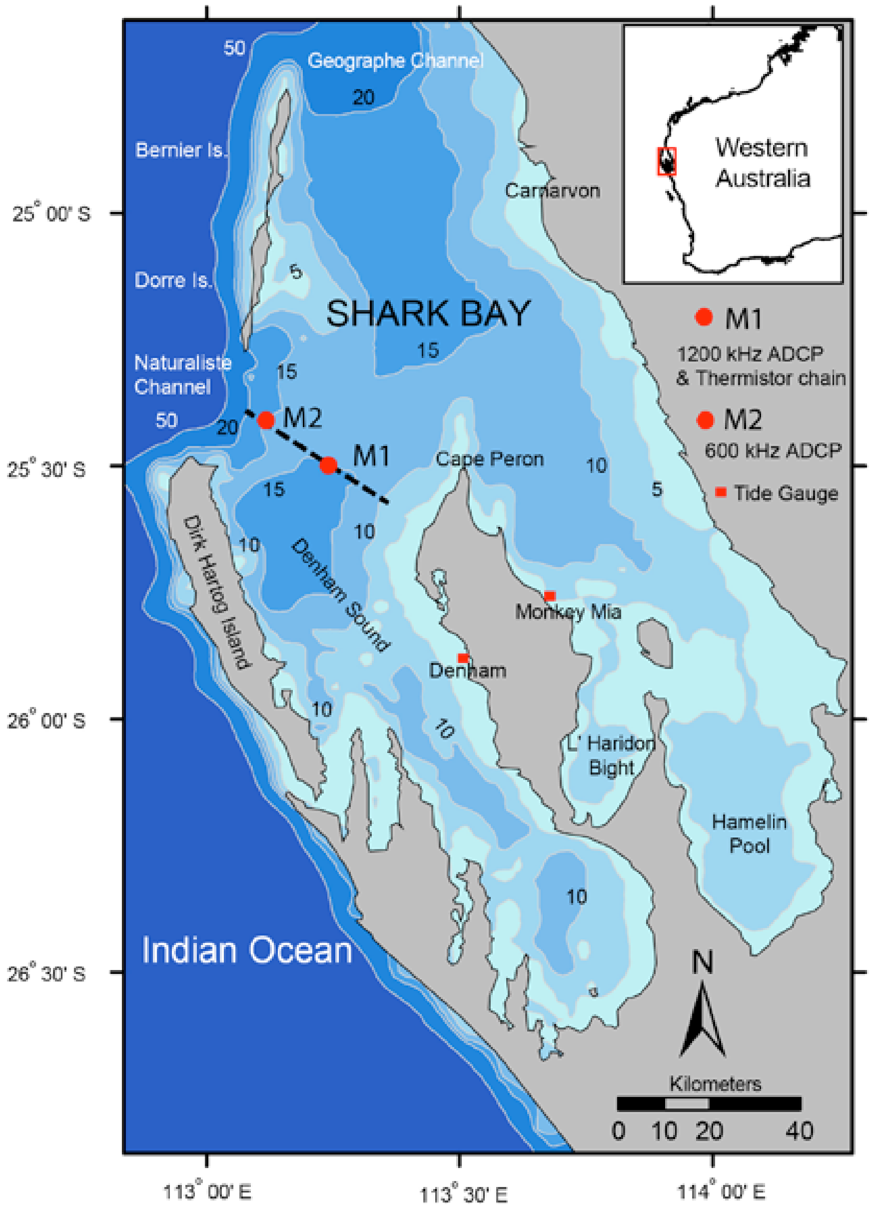


Figure 5.1. Map of the study area showing location of field instrumentation deployed in June/July 2009 and ship-borne CTD transect (dotted line).

5.2.3 Hydrodynamic model

Model description

The 3D General Estuarine Transport Model (GETM) hydrodynamic model (Burchard and Bolding 2002) was chosen for this study given its ability to simulate processes such as density-driven bottom currents and stratification. For this investigation, a curvilinear model grid (Fig. 5.2) was used with a horizontal resolution varying from 2 km offshore to ~500 m in the scallop fishing grounds. Sigma vertical coordinates allowed 10 vertical layers and 'zooming' near the surface and bottom in order to provide higher resolution where the important processes take place. The offshore boundary followed the shelf break along the 200 m contour and was forced with tidal elevations calculated with the OSU Tidal Inversion Software (OTIS) (Egbert and Erofeeva 2002) and 3D temperature and salinity profiles from the HYCOM (www.hycom.org) global ocean model reanalysis (George *et al*. 2010) which provides global oceanographic data at 1/12 degree (~10km) resolution for 2003 to the present. The Leeuwin Current was parameterised by analysis of southward-velocity HYCOM data, and driven by corresponding sea surface height gradient (Fig. 5.5). Measured data from the Bureau of Meteorology's station at Shark Bay Airport provided all other environmental forcing.

The GETM hydrodynamic model was run in 3D baroclinic mode (including density effects) enabling simulations of such processes as density-driven outflows, which has not previously been completed for Shark Bay. Realistic runs of the model were performed for 2007 and 2009, two years with high/low scallop recruitment. Simulations covered the main scallop spawning season from April to August, after allowing for 30 days of model spin-up. Preliminary runs for the period of field data collection allowed for validation of the model.

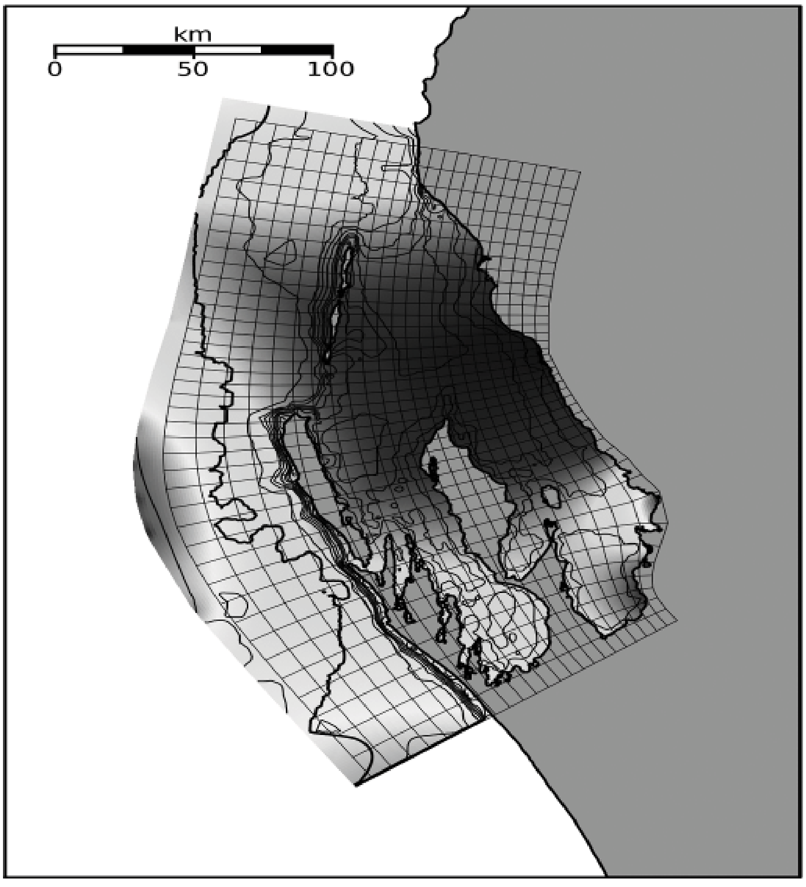


Figure 5.2. Curvilinear model grid developed for Shark Bay. Spatial resolution varies from 2 km on boundaries to 500m near the entrances. Shading represents spatial resolution with darker shading in areas of higher resolution. Not all grid lines have been drawn.

5.2.4 Passive particle dispersal model

Model description

Studies of other well-studied scallop species off the east coast of the United States (Tremblay *et al.* 1994) and in the Irish Sea (Hartnett *et al*. 2007) have used numerical models to simulate larval transport pathways and connectivity between stocks. They acknowledged the large source of error introduced by parameterising the various stages of the larval life cycle—namely mortality, growth, and (perhaps most importantly) vertical swimming ability. In general, simulated scallop larvae were released at the bottom to spend a period of time (~2 days in the case of the Irish Sea study) floating passively in the current. They then acquired some vertical swimming ability and swam toward the surface before finally swimming or sinking to settle on the bottom after 18-42 days. These studies highlighted the importance of the location of the simulated larvae in the water column—a behaviour that is likely to vary for specific marine environments (Manuel *et al*. 1996). In addition, factors such as stratification, thermal fronts, and salinity could influence larval behaviour. Tremblay *et al*. (1994) noted that in well-mixed environments (often the case in Shark Bay), larvae are often distributed throughout the water column as they are unable to overcome vertical turbulent velocities. Hartnett *et al*. (2007) found passive behaviour simulations to be useful in defining potential transport pathways, as this highlights the effects of physical processes (eg. currents, fronts) on larval transport. Validation of a hydrodynamic model is also much easier to quantify than a simulation of a living organism. As such this study focuses on understanding larval transport based on physical processes rather than introducing even more sources of error due to, for example, swimming abilities.

The passive particle dispersal model Cpart, developed by Cyprien Bosserelle at the University of Western Australia, was based on a simple Lagrangian design, where movements are driven by the following equations:

$$\frac{dx}{dt} = U + u' \qquad \frac{dy}{dt} = V + v'$$

Where U and V are advective velocities and u' and v' are turbulent velocity fluctuations, parameterized using a proven random-walk technique. This type of model simulates the real world situation where tracers, such as dye, can be physically introduced into the marine environment and tracked as they follow a body of water. Likewise, in the numerical simulation, ‘particles’ are traced as they are transported with the currents.

Given that very little is known about the larval behaviour of *A. balloti* in their natural habitat we chose to simulate the larvae as passive (non-swimming) particles with two scenarios: (1) following surface currents and (2) following bottom currents. This is justified as in a well-mixed environment they will likely spend time at both the surface and near the bottom. These model runs represent two extreme situations, but in reality it is likely to be a combination of both as the larvae migrate from the bottom to the surface and back to the bottom to settle. The results presented here therefore must be interpreted in this context. Sensitivity studies can be performed for both the surface-tracking and bottom-tracking particles and conclusions drawn based on all available data.

Initially, 100 neutrally buoyant particles were seeded into the model at three survey sites coinciding with the areas of highest recruitment during the preceding years’ November survey. This provides the best estimate as to the location of the dominant spawners during the modelled year. Particles were released at the surface and bottom of the water column at two-week intervals from April to the end of July, the main spawning season. The particle location at each time step (hourly) was recorded and later plotted and analysed in Matlab. This provided initial estimations of transport pathways for the particles (larvae) at the surface and at the bottom, throughout the spawning season.

For the calculation of catchment areas for each area more than 13,000 particles were released randomly throughout the Bay, and allowed to move with the currents for two weeks, releases were staggered through the season from April to July. The origin of the particles that were found within each fishing ground polygon after two weeks was plotted to illustrate potential areas from which larvae could be transported into each fishing ground. The same method was applied to find which areas were more likely to be flushed by bottom currents. Particles that moved out of the Bay within two weeks were mapped back to their origin.

For a more in-depth look at connectivity and source-sink relationships between the stocks it was necessary to average out the effects of tides and weather conditions in order to obtain statistically relevant estimates of the transport of particles. Because we were interested in what happens between the defined fishing grounds (Red Cliff, NW Peron, and Denham Sound) and for computational efficiency, particles were released only within the polygons enclosing the fishery (~1300 particles). The polygon borders were drawn to include the locations of the yearly Department of Fisheries scallop survey sites. Particles were then released every two hours for the duration of each two-week period from April through July. Cumulative counts of particles then allowed for the calculation of percent retention within each polygon as well as what portion of particles travelled between the areas. Particles that were not found within any of the polygons after 2 weeks were classified as 'lost' since they did not reach the trawl grounds. The difference between the percentages given here and 100% represents this proportion of the particles.

5.3 Results

5.3.1 Environmental influences

Winds

The year of highest recorded scallop recruitment, 1990, was one of the windiest years in the data set (Figs. 5.3a,b). The last few years (2006, 2007, 2008) have seen reasonably high recruitment, and have also been windy. In contrast, 1999 (a strong La Niña year) had some of the lowest winds but average (not low) recruitment. Stronger southerly winds could limit hydrodynamic flushing by acting against the formation of stratification needed for the development of density (gravity) driven outflows. The effects of wind on circulation needs to be further addressed in future numerical studies.

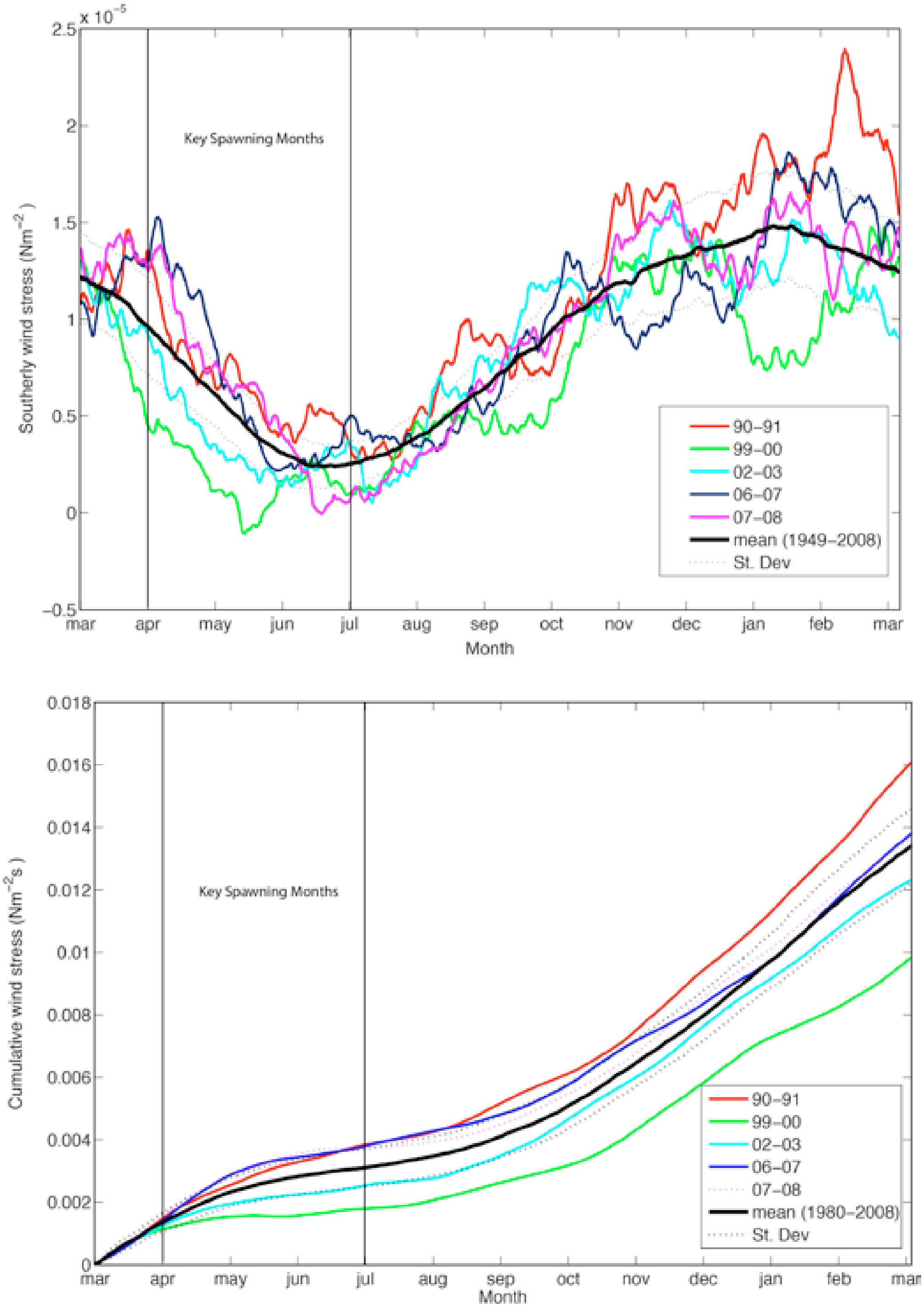


Figure 5.3. (A) Southerly wind stress for Shark Bay computed from NCEP reanalysis data (daily averages). Anomalous years are shown. 2007 – 2008 season is omitted for clarity but closely resembles that of 2006 – 2007 and (B) Cumulative southerly wind stress is calculated as integral with respect to time of (A) to highlight year-to-year differences in wind conditions during the scallop spawning season.

Sea surface temperature

Although our study was confined to two years it was useful to asses the inter- annual temperature variability and the time lag in surface heating/cooling for Shark Bay and offshore. The years 2007 and 2009 were similar to each other, however other years, such as 2004 and 2008 were more variable (Fig. 5.4). Within-bay temperatures may have a distinct signature from offshore waters for a given year. For example, from 2007 to 2009, there was a larger difference in winter temperatures offshore and within the Bay compared with 2002 to 2006. This could be related to wind conditions or to the intrusion of the Leeuwin Current into the Bay, or to other variables. This is another part of the key to understanding recruitment variability, and is beyond the scope of the current study.

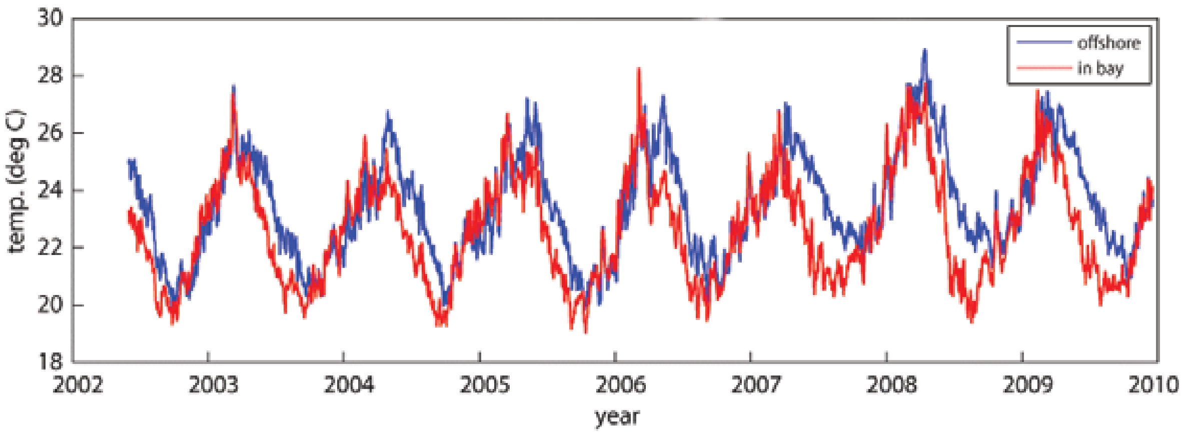


Figure 5.4. NOAA optimum interpolation (OI) sea surface temperature (SST) analysis data, derived from both in-situ and satellite data, shown for points within the bay (north of Cape Peron) and outside of Shark Bay for the years 2002 – 2009.

Leeuwin Current

In the context of recruitment, the years highlighted in Table 5.2 were more closely examined. Table 5.2 provides a general summary of our existing understanding of the physical environment-recruitment relationship and served as a guide for model runs. Mean winter season southward velocity of the current for 2007 was found to be minimally stronger than for 2009, according to HYCOM reanalysis data (Fig. 5.5). Values for both years were close to 10 cm s^{-1} and were not expected to have much effect on the model.

Table 5.2. Summary of relevant years and environmental conditions affecting scallop recruitment. 2007 and 2009 were chosen as representative of high/low recruitment years for which reliable data was available for forcing the model. NB- WL = water level

Year	S Wind stress (April–Jul)	El Niño/ La Niña	Fremantle WL	Recruitment (Red cliff)	Recruitment (NWP)	Recruitment (Denham sound)
1990	very high	neutral	low	high - 608	extremely high -3756	high - 631
1999	very low	La Niña	very high	average - 347	low -71	average - 352
2002	low	neutral	low	low - 138	low -17	low -84
2006	very high	El Niño	med	average (+) - 392	very high - 1116	average (+) - 412
2007	very high	El Niño	med	average (+) - 392	high (+) -927	very high - 900
2009	very high	neutral	med	low - 110	low - 153	low (+) - 257

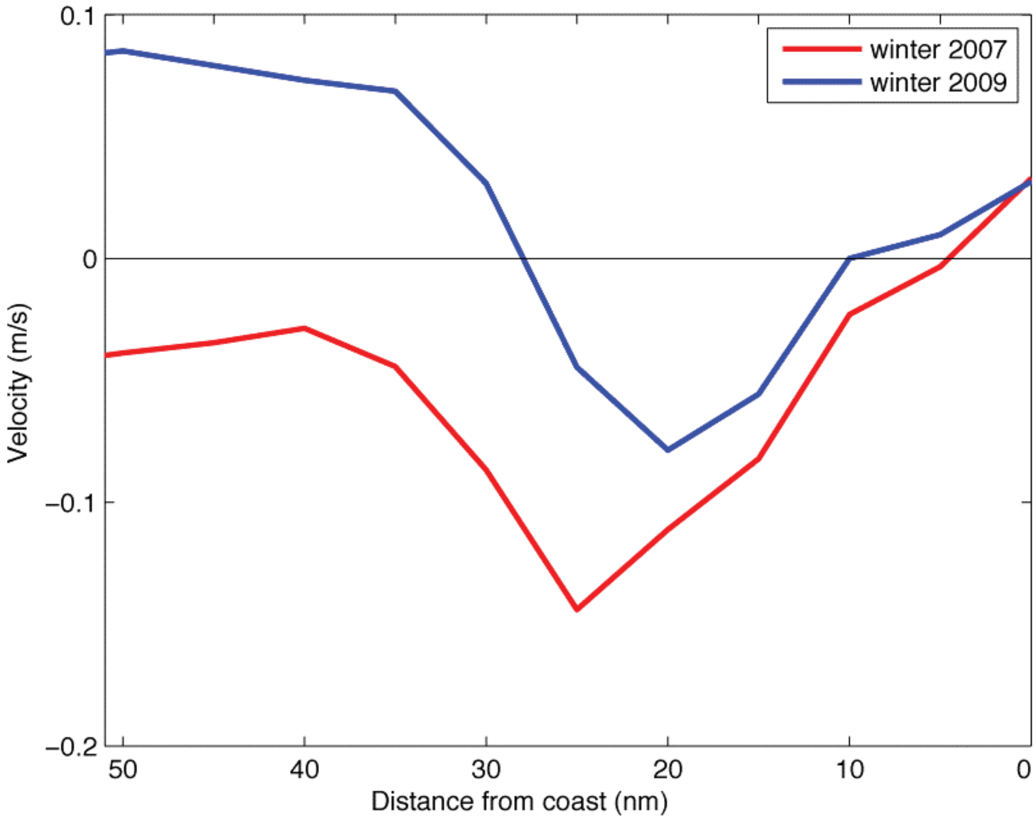


Figure 5.5. Longitudinal profile of the seasonal mean of the southward flowing current (HYCOM data) across two transects at the latitude of Shark Bay. The coast is on the right side. The max (most negative) southerly velocities were used to compare the strength of the Leeuwin Current in 2007 and 2009.

5.3.2 Field measurements

The most important contribution of the field data to our understanding of the system was the identification of density-driven outflows of bottom waters during periods of stratification, and a cohesive record of current profiles not previously measured. In addition, a convergence of currents over the NWP/RC scallop grounds was identified with GPS drifter tracks.

Drifter tracks

All four drifters were released in Naturaliste Channel. They spent several tidal cycles going in and out in the channel, with an excursion of 7-8 km, before drifting east and north through the centre of Shark Bay and the Red Cliff/Northwest Peron trawl grounds (Fig. 5.6). Two of the drifters washed ashore on Bernier Island (after 1-2 weeks), and two drifted out of the northern end of Shark Bay (after 2 weeks) before being swept south in the Leeuwin Current. A counter-clockwise recirculation path around Bernier and Dorre Islands that had been previously hypothesised from modelling was very nearly documented with the drifters. However, as the drifters neared the south end of Dorre Island, strong easterly winds pushed them offshore into the core of the southward flowing Leeuwin Current. One of these drifted to within 60 miles of the Abrolhos Islands, then was entrained in a Leeuwin Current eddy for three months, moving slowly offshore and northward. The other followed a similar path, but did not get caught in the eddy. It drifted instead to the north and east before washing ashore at the base of the Zuytdorp

Cliffs south of Dirk Hartog Island. Connectivity between Shark Bay and the Abrolhos Islands, it seems, would be buffered by the presence of persistent eddies in this region. Of course, the speed at which the drifter moved to the south (within 2 weeks almost reaching the Abrolhos Is) suggests that it would be possible under the right conditions. Interestingly the drifters, while in the Bay, converged moving northwards along all the major trawl grounds, signifying a link between circulation and scallop larval drift and settlement patterns.

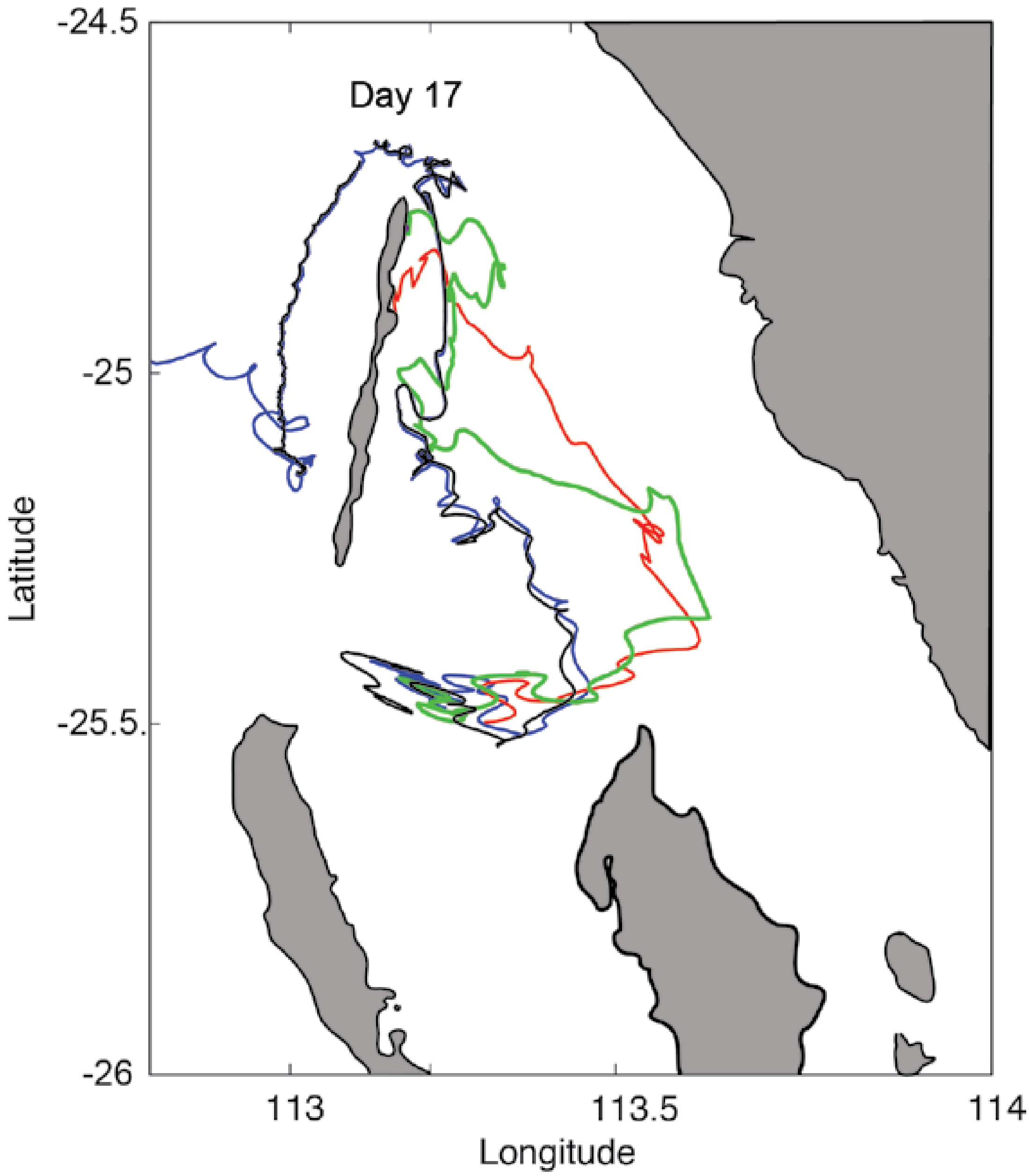


Figure 5.6. Drift paths of 3 of 4 satellite-tracked Lagrangian ocean drifters released in June 2009. For clarity the path of one drifter is not shown as it very closely followed the trajectory of the blue drifter plotted here. (see Appendix 3 for video of drifter movement).

Density-driven outflows

Data from the two current profiler moorings (ADCPs) recorded periods of two layer flows (out on the bottom, in on the surface), a phenomenon previously thought to be restricted in this shallow, energetic, well-mixed environment. Sub-tidally averaged (38 hour low-pass filtered) current profile data from the inshore ADCP mooring and temperatures from the thermistor chain (Fig. 5.7) revealed that during periods of low available mixing energy (i.e. low winds and tidal currents) the normally well-mixed system became stratified and density-driven bottom outflows on the order of magnitude of 10 cm/s (and thickness of ~2-3 m) at the mooring developed. During these events (three occurred during the experiment around: June 30, July 13, and 19), the colder, more saline, and thus denser water from further up in the Bay flowed out underneath the warmer, less dense surface water. Interestingly it was not during the neap tide, but rather during periods where the semi-diurnal component of the tide reached a minimum that stratification developed. For this region this appears to be most likely to occur about 2 days after the first and last quarter moons due to lunar effects on the tidal dynamics. Also notable was the stronger north-south component of the outflow as compared to the east-west component. This is attributed to the bathymetry channelling the outflow toward the deeper channel near Dirk Hartog Island. The further offshore ADCP (600 kHz) measured similar patterns but the outflows were less pronounced, and plots are not included here as the purpose is to document the existence of these flows. Data from both ADCPs was used when assessing the ability of the model to reproduce the flow regime. Theoretically these outflows would have a profound effect on larvae near the bottom, and we examined the likelihood of flushing in the particle (larval) modelling component.

5.3.3 Hydrodynamic model

Model validation

Overall, confidence in the hydrodynamic model is very high as it reproduced in three dimensions the processes necessary to model larval dispersal, and closely resembled measured data. The ability of the model to include the Leeuwin Current (Fig. 5.8) and density effects was critical for the study, although difficult to quantify. The lack of available information about the vertical distribution of the scallop larvae within its life cycle, however, is likely to introduce more error than the hydrodynamic model, and this has been addressed in the methodology of the dispersal model. The details of the validation are given below.

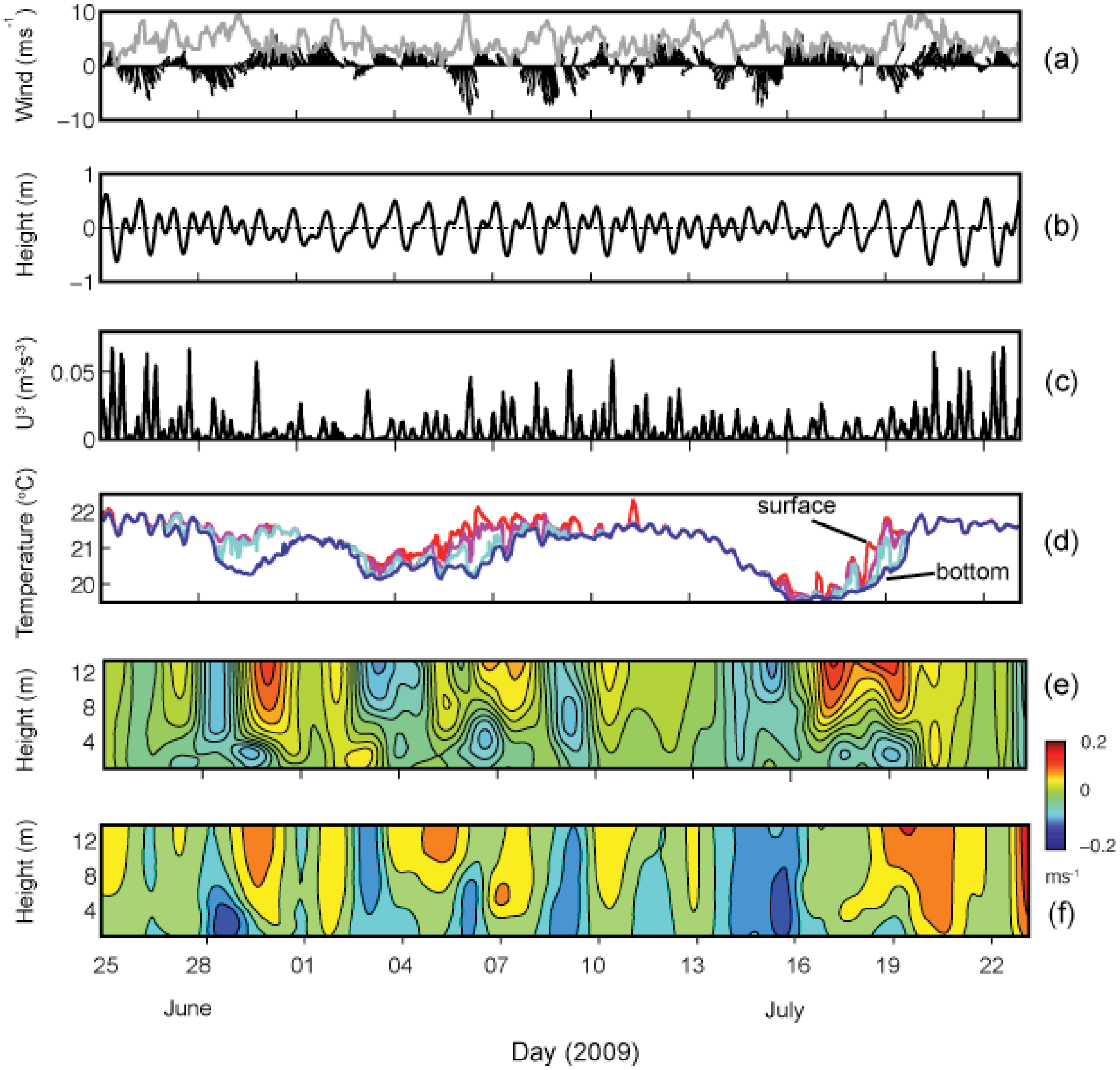


Figure 5.7. Wind and mooring data for July 2009; (a) wind velocity vectors for Denham Sound (black) and wind speed (gray) (b) unfiltered water levels (c) cubed bottom current speeds showing available mixing energy (d) temperature profile from thermistors (e) N-S current velocity profile (from ADCP) (f) E-W current velocity profile. Tides were filtered out using 32 hour filter. A vertical profile of subtidal averaged currents is shown with time along the x-axis. Bottom outflows are seen in blue with red inflows above. Outflow events occurred around June 30, July 13, and July 19.

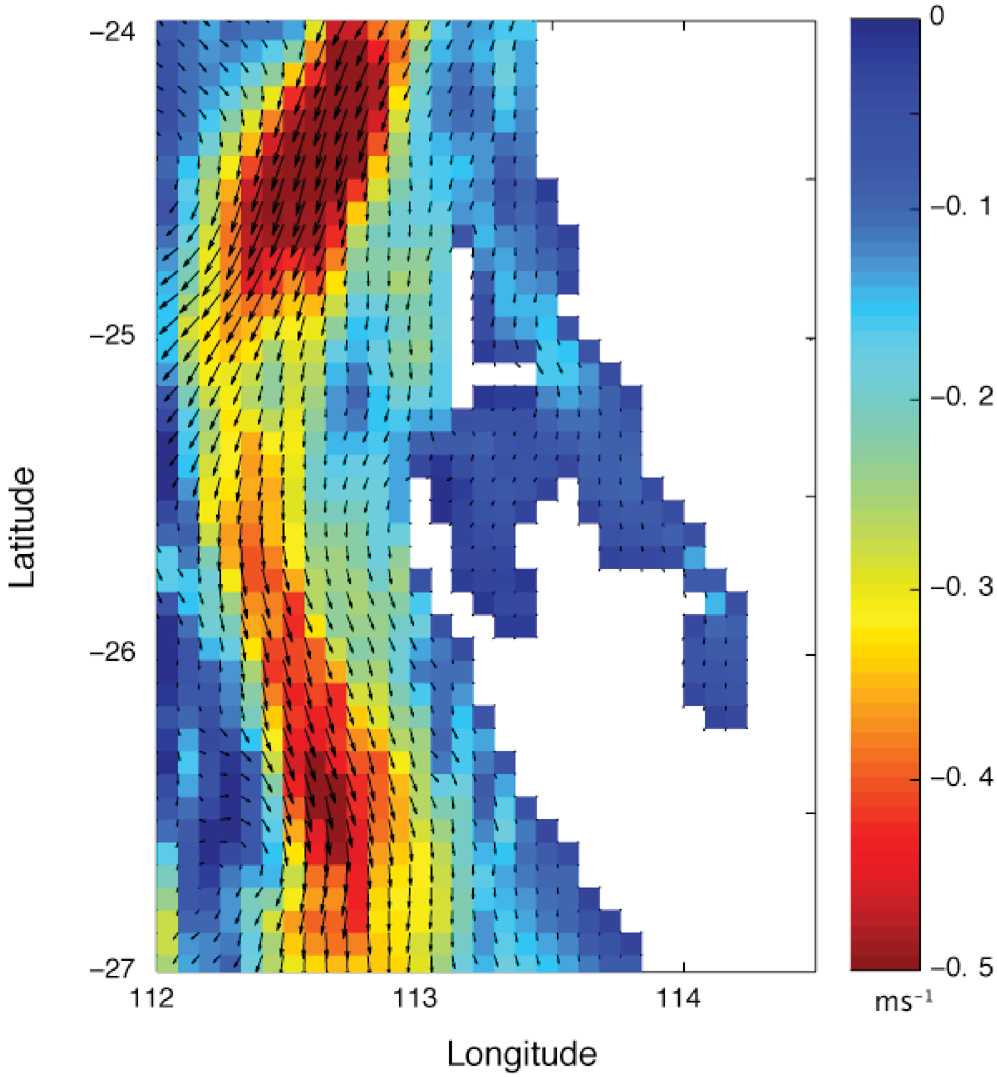


Figure 5.8. Example of HYCOM ocean model reanalysis data for 15 July 2009 used to quantify the strength of the Leeuwin Current along the model boundary. The red (-) shows the southward flowing current along the 200m isobath, which reached speeds of > 1m/s in May 2009.

Water levels

The model satisfactorily captured both the phase and magnitude of the tides in the areas of the Bay where measurements from the field data were available for comparison (Fig. 5.9). This is important as the main driving force of the currents in Shark Bay is the tides. A slight underestimation of the magnitude of the spring tides was evident, but this was thought not to have a significant on overall circulation patterns.

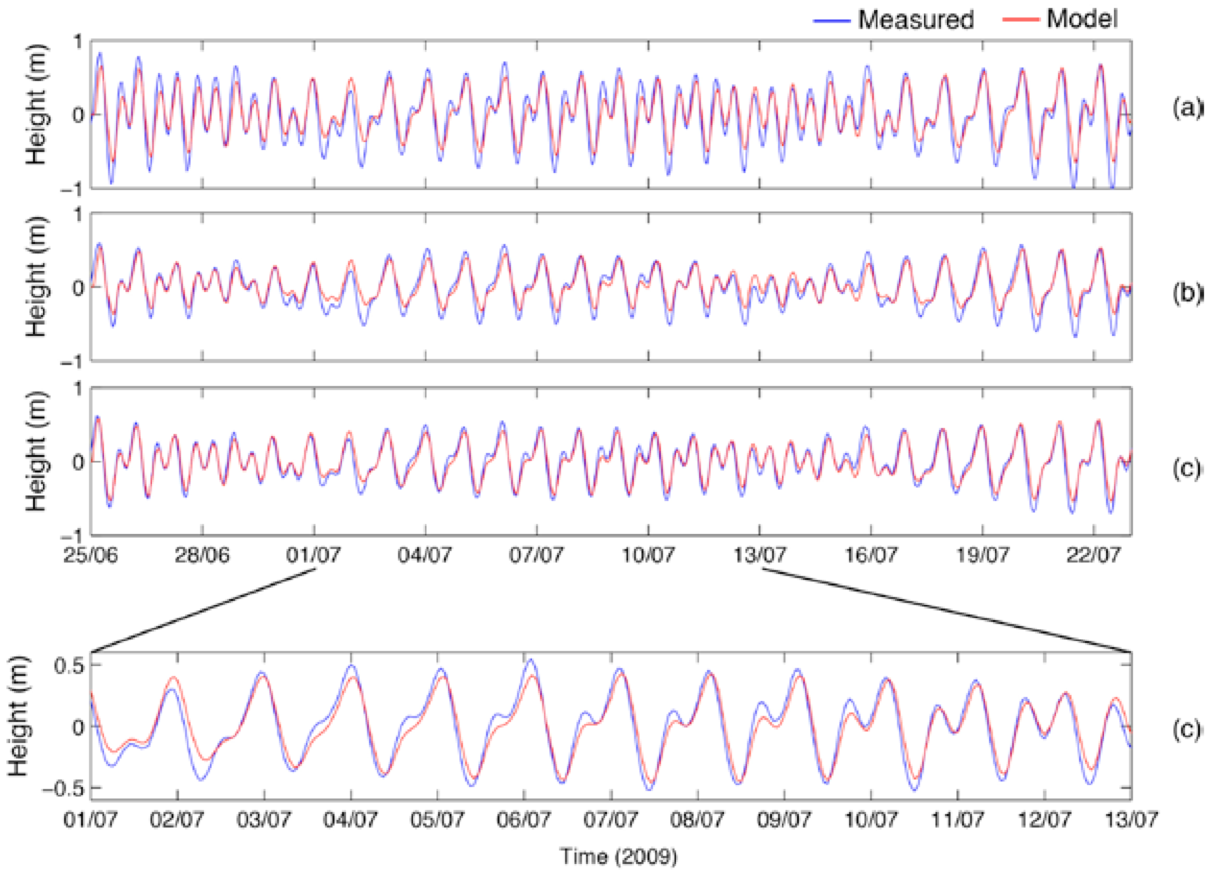


Figure 5.9. Comparison of measured and modelled water levels in Shark Bay in June – July 2009 at: (a) Monkey Mia (b) Denham (c) Naturaliste Channel. A more detailed view of Naturaliste Channel is shown at (d).

Current Velocities

The phase and magnitude of both the surface and bottom currents was also sufficiently close to measured speeds to give confidence to the model (Fig. 5.10). A small underestimation of maximum tidal velocities was visible for the surface and slightly less so for the bottom. This can be attributed to the presence of surface waves, and small disparities in bottom roughness, bathymetry, and available wind data. Taken in the context of the limited available data and the overall questions the study aims to examine, the current fields computed by the model were deemed to be a minimal source of error.

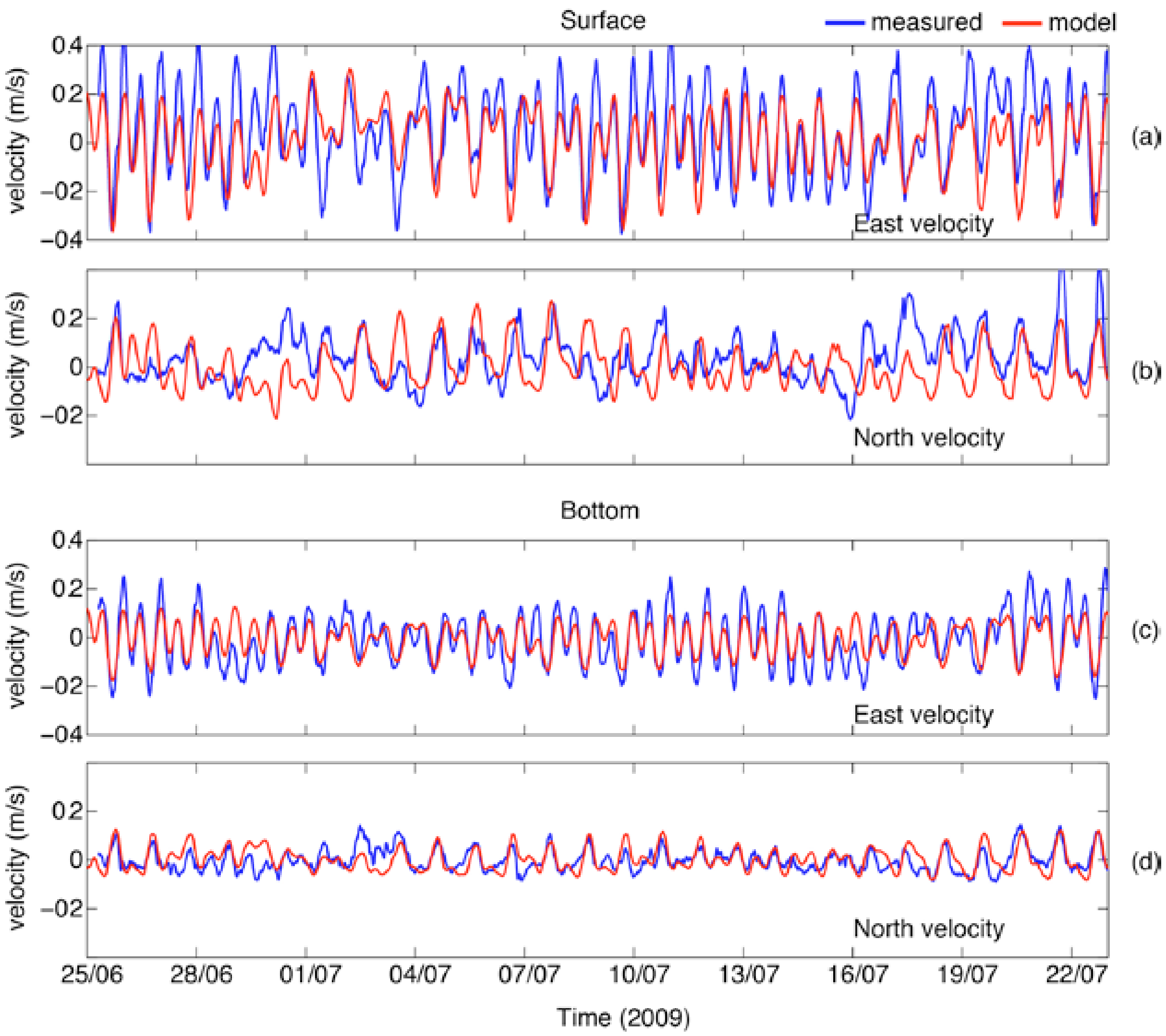


Figure 5.10. Comparison of measured (1200 kHz ADCP) and modelled surface and bottom currents in Naturaliste Channel in June – July 2009. Panels show (a) surface east velocity (b) surface north velocity (c) bottom east velocity (d) bottom north velocity. Comparison for 600 kHz ADCP showed similar results and are not shown.

Temperature, Salinity, and Density

A CTD transect measured on July 23rd (Figs. 5.11, 5.12) was compared to model data (Fig. 5.13) for the same date. The relative salinity and temperature levels were similar and the physical structure of density (due to temperature and salinity) was maintained. Specifically, the temperature and density fronts occurred in the same general locations, and the measured saline plume of bottom water was apparent in the model.

Temperature fronts are persistent features in the entrance channels to Shark Bay and are an important control on exchange with the ocean. In addition to the CTD transects it is possible to compare the modelled sea surface temperatures (SST) to satellite-measured SST (Figs. 5.14, 5.15), although it was not possible to plot satellite SST for the date of the CTD transect due to cloud cover. The model satisfactorily reproduced these features throughout the modelling period while slightly under predicting SSTs.

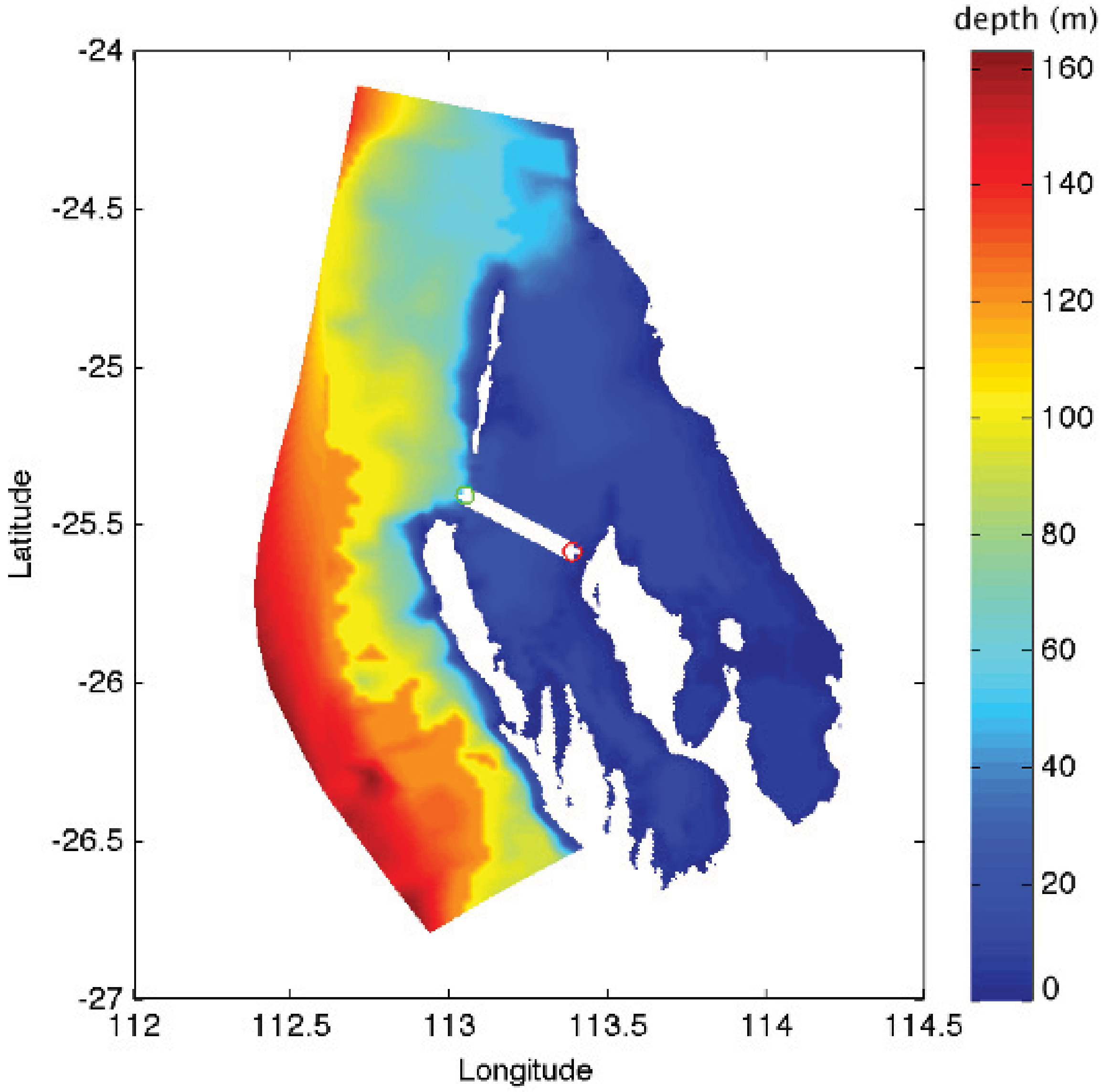


Figure 5.11. CTD transect profile measured on July 23, 2009 and extracted from model for comparison. The colour scale shows depth in metres.

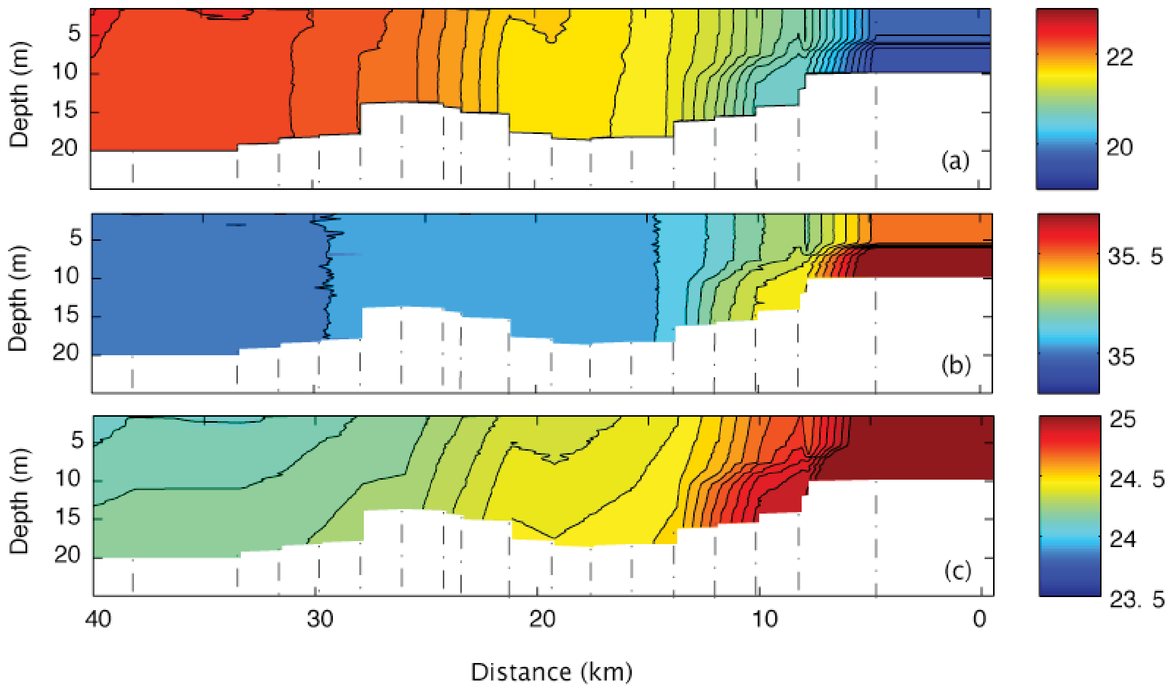


Figure 5.12. CTD transect profile of measured on July 23, 2009 between Cape Peron (right) and Naturaliste Channel (left). (a) Temperature in deg. C (b) Salinity (PSU) does not have units, (c) Sigma-t is density (kg •m^{-3}) – 1000. Scales differ between measured and model output to highlight important features.

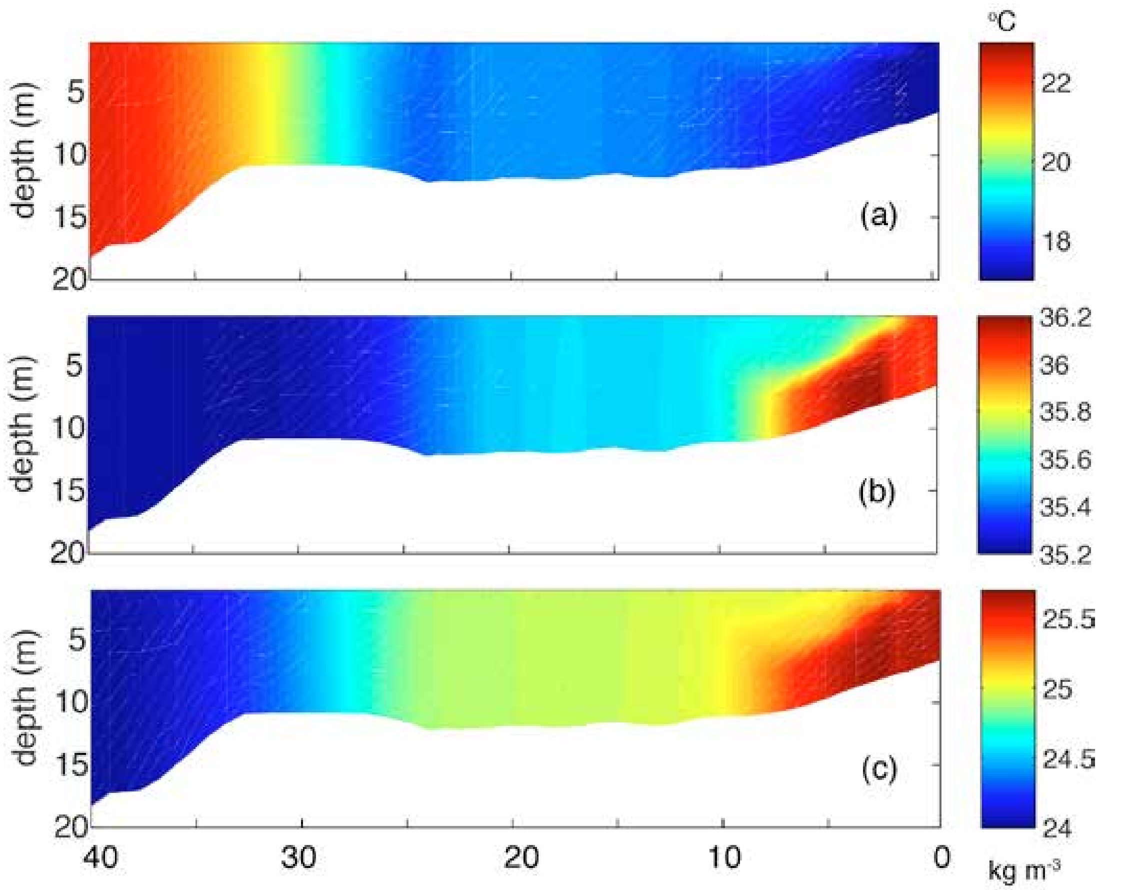


Figure 5.13. Similar transect profile extracted from model for July 23, 2009 between Cape Peron (right) and Naturaliste Channel (left). (a) Temperature in deg. C (b) salinity (PSU) does not have units (c) sigma-t is density (kg •m^{-3}) –1000.

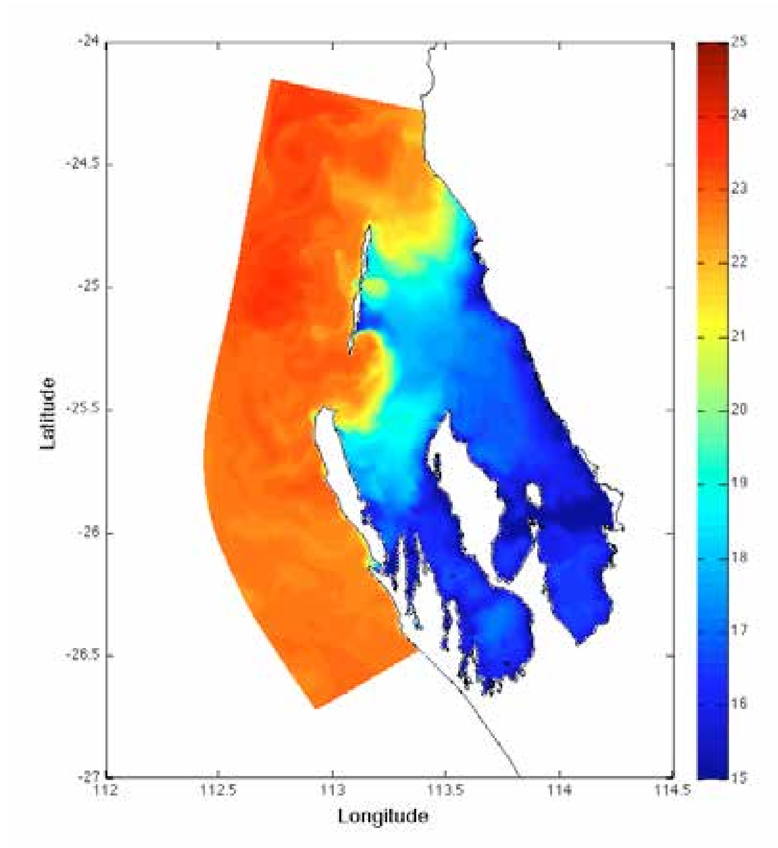


Figure 5.14. GETM model output surface temperature (deg. C) for Shark Bay, July 26, 2009.

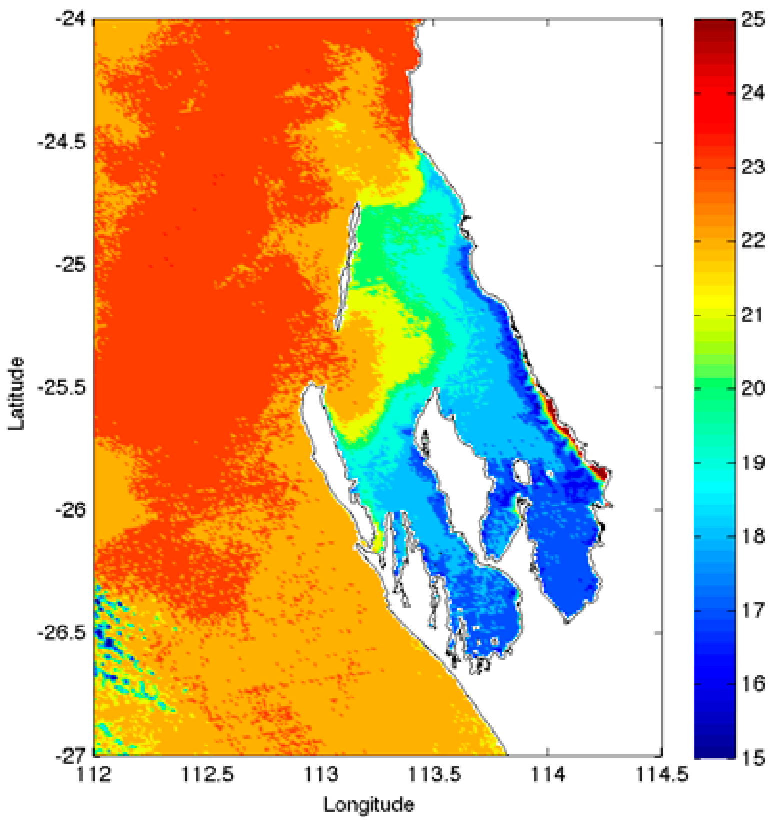


Figure 5.15. Satellite (MODIS 1km resolution) measured sea surface temperature (deg. C) for Shark Bay, July 26, 2009. Cloud cover restricted the ability to plot measured SST for date of CTD transect, so the closest clear image was selected.

Mean flow patterns

Average flow patterns for the winter seasons simulated (Figs. 5.16, 5.17) confirmed that a net influx of water occurred on the surface through both the northern and southern channels while a balance was maintained with a net flow out of the Bay along the bottom. Stronger current speeds at both the surface and bottom were restricted to shallow areas or through the entrance channels (Figs. 5.16, 5.17). The southern part of the Denham Sound trawl area contained a small residual eddy and weaker currents — a potential larval retention hotspot. Other areas of weaker residual currents, and thus likely areas for retention included the lower part of the Northwest Peron trawl grounds, as well as a strip northward toward Red Cliff. Current patterns for both 2007 and 2009 were similar and so results from 2007 are not shown here.

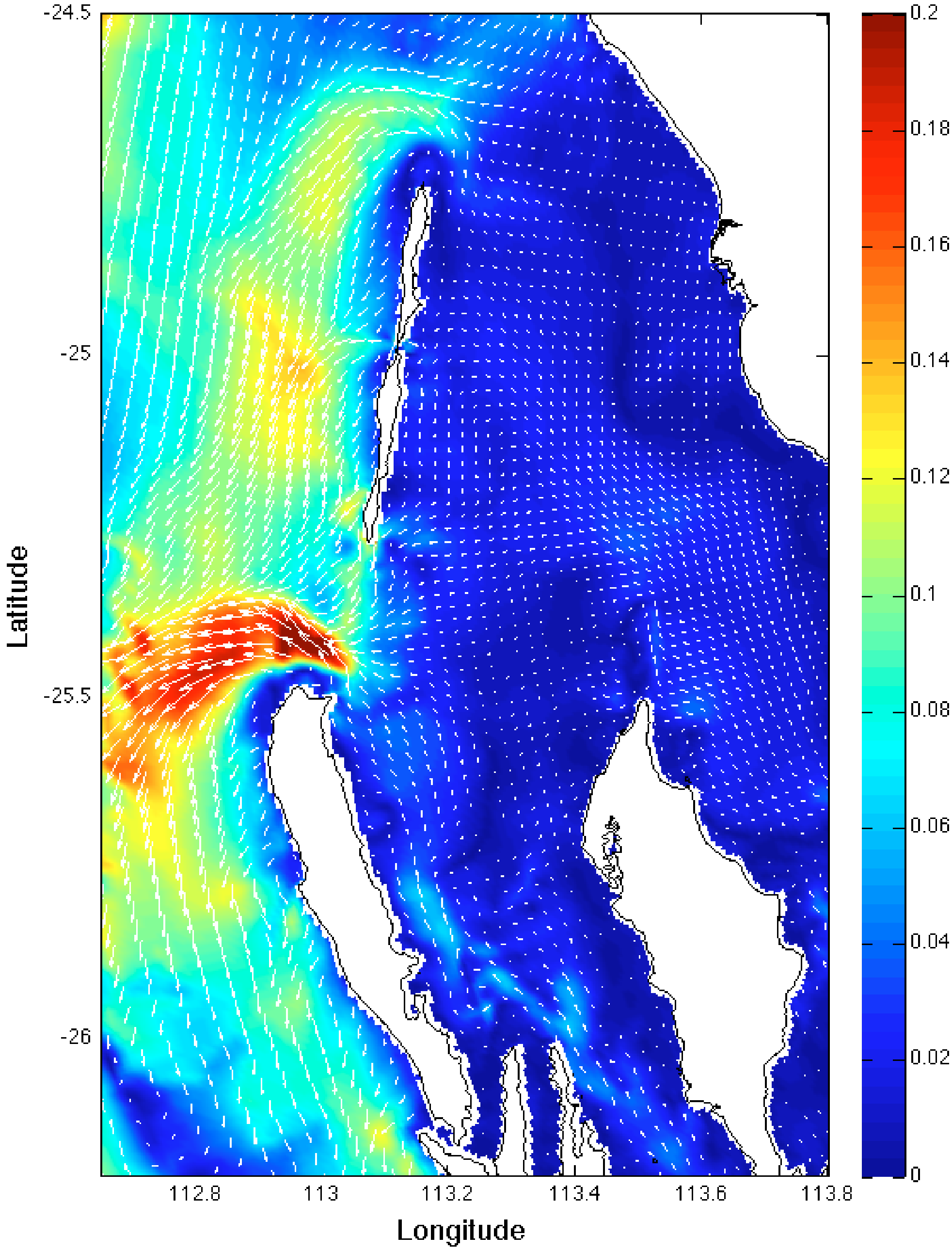


Figure 5.16. Residual bottom currents calculated by averaging over the winter season (April – August 2009). Vectors show direction and colour scale shows current speed (ms^{-1}). Note net outflow out of the Bay (density-driven currents) with weak residual currents inside the Bay.

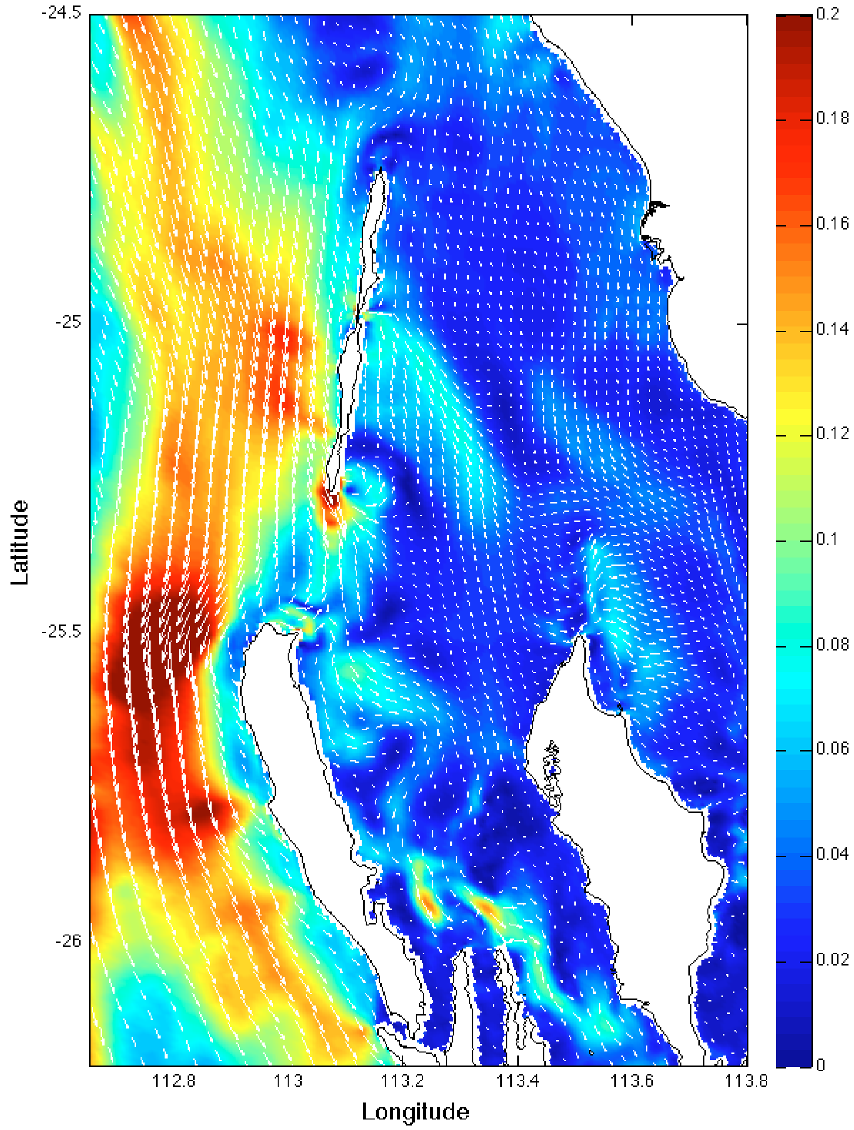


Figure 5.17. Residual surface currents calculated by averaging over the winter season (April – August 2009). Vectors show direction and colour scale shows current speed (ms^{-1}). Note net inflow to the Bay on surface with weak residual currents inside the Bay.

Density-driven outflows and comparison between years

Model results revealed spatial and temporal patterns of saline (and thus dense) outflows (Figs. 5.18, 5.19) from the Bay. These outflows move along the deeper channels of the Bay and release salt from the upper reaches of both gulfs. It appears that a majority of the high-salinity water exiting through Geographe Channel (northern Shark Bay) originates in the Eastern Gulf while the source of the dense water flowing out through Naturaliste Channel is in the Western Gulf. The spatial patterns during both of the simulated years appeared to be similar, as did the mean temporal pattern. In general, the flows seem to gradually increase as the water within the Bay begins to cool in March or April. As water temperatures drop further into May and June, flows increase in intensity and duration, reaching a peak around July. A 'pulsing' of the outflows is observed on both tidal and subtidal timescales, and it is within the subtle differences of these 'pulses' that variations between years are likely to be observed. The saline water exiting through the northern entrance to the Bay appears to move slower but more consistently, exhibiting less of this 'pulsing' behaviour whereas the flows exiting through Naturaliste Channel are predominately of this nature. In the northern channel (Geographe Channel), the structure observed was as follows: an outflow along the bottom in the western region of the channel and an intrusion of water from the shelf into the bay on the surface and in the shallower regions. The outflow 'piled up' along the western edge due to the rotation of the earth (Fig. 5.20).

A comparison of outflows for 2007 and 2009 is possible by averaging the flows (April-Aug) across a transect connecting the mainland to the northern tip of Bernier Island (Figs. 5.20, 5.21). This comparison revealed that outflows during 2009 were slightly weaker than for 2007. However, the difference was too minimal to draw conclusions as to the importance of this difference for larval transport.

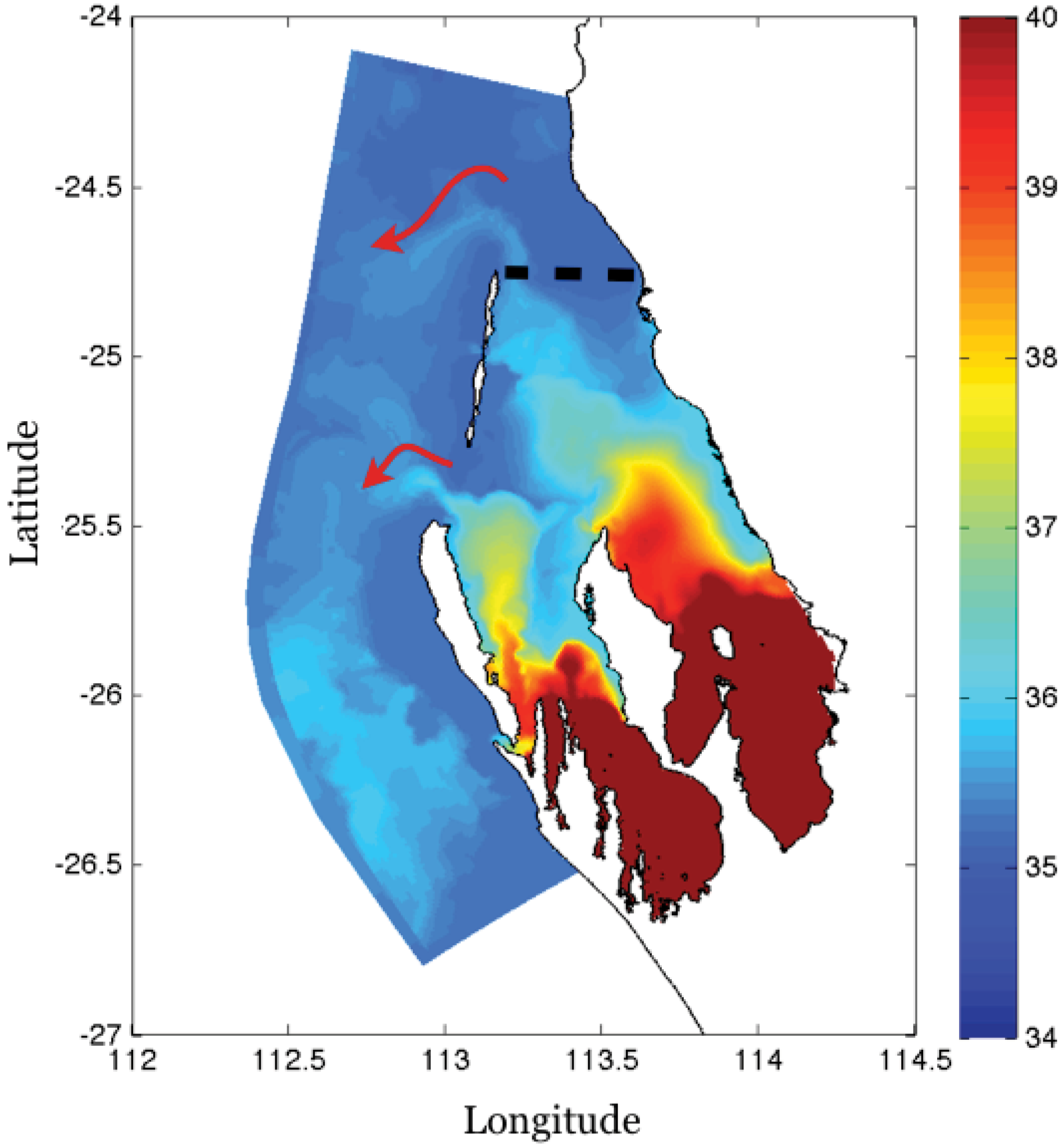


Figure 5.18. Bottom salinity from model run for 2009 showing the release of salt (practical salinity scale) through gravity currents out of both large entrance channels in Shark Bay. Arrows highlight outflow pathways and dashed line marks transect extracted in Figures 5.20 - 5.21.

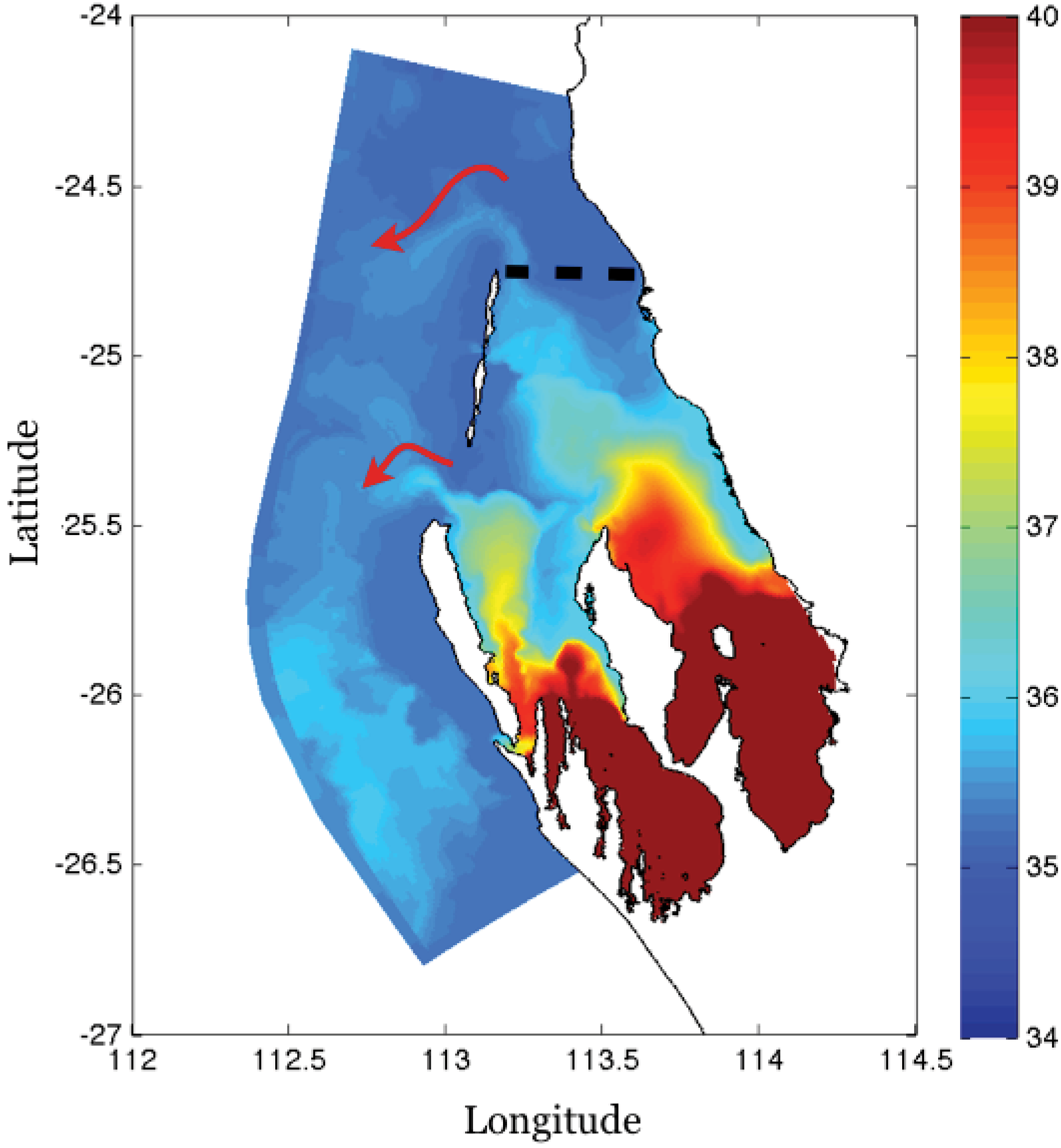


Figure 5.19. Snapshot of bottom current speed (ms-1) during time of maximum flow speeds. Note the strong currents through the channels and over the shallow sand banks north of Cape Peron. In contrast, and relevant to larval dispersal, weaker currents coincide with the main scallop settlement areas.

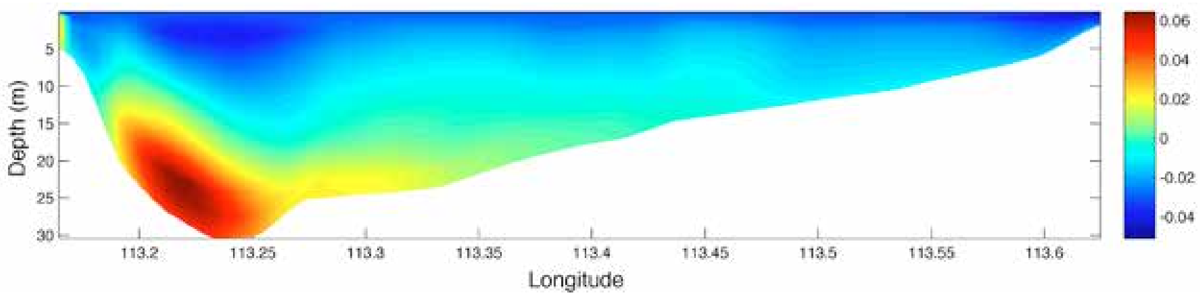


Figure 5.20. Vertical slice of seasonally averaged velocities (m/s) into/out-of Geographe Channel during winter 2007. Negative (blue) values represent the outflows along the bottom in the western (deepest) region of the channel and positive (red) values show the intrusion of water from the shelf into the bay on the surface and in the shallower regions.

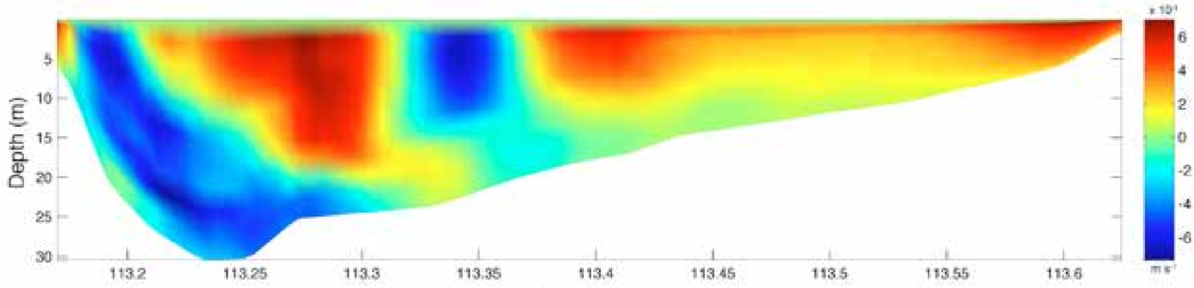


Figure 5.21. Difference (ms^{-1}) between mean flow velocities along the Geographe Channel transect between 2007 (Figure 5.20) and 2009 (not shown). This was calculated as the mean velocity for 2009 - 2007, therefore a negative value (blue) indicates that flows in this region were weaker during 2009.

Another way to quantify the differences in exchange through the entrance channel is to calculate volume transport through the entrance (Fig. 5.22). By summing the transports in and out of the channel over a long period of time (i.e. the winter season in this case) a picture of the net flow emerges. Once again, the outflow in the western region of Geographe Channel is visible (shown as positive values) as is the inflow of water on the eastern side of the Bay. Taking the sum of these depth and time-averaged velocities along the transect shows Geographe Channel to have a net influx of water into the Bay. It is important to consider that overall net transport might be less important for flushing of larvae than currents in specific geographic areas. This method of comparing 2007 and 2009 supports the observation that 2009 had marginally weaker outflow than 2007, however the difference should be interpreted with caution.

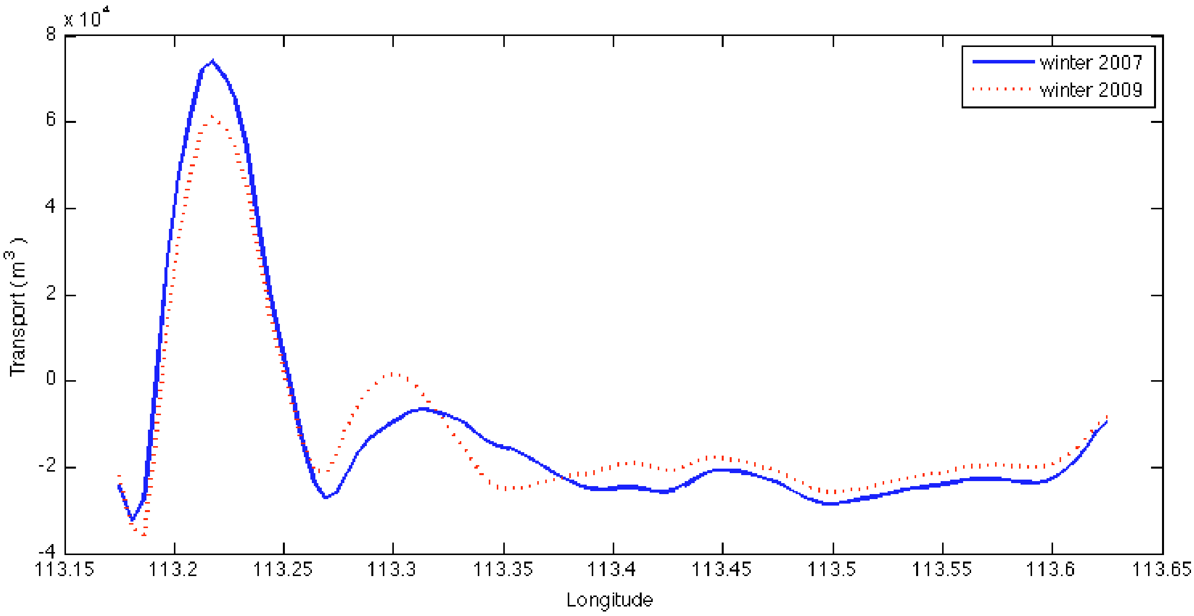


Figure 5.22. Net seasonal transport through Geographe Channel for 2007 and 2009. Positive (+) values indicate net outflow and (-) values indicate net inflow.

5.3.4 Larval dispersal model

The final stage of the study involved analysis of outputs from a number of simulations of the passive particle-tracking model. This allowed for visualisation of the effect of the hydrodynamics on ‘larval’ transport. The lack of data regarding the larval phase of the scallop life cycle meant that the most useful approach was to use a simplified method that involved the release of thousands of ‘passive particles’ released randomly in space throughout the spawning season. Particles were advected by either the surface or bottom currents and no ‘swimming’ behaviour was assumed. Because it is likely that the larvae spend part of their life near the surface and also near the bottom, these model runs represent two extreme scenarios, while reality is likely to be a combination of both as the larvae migrate from the bottom to the surface and back to the bottom to settle. The results presented here therefore must be interpreted in this context.

Analysis focused on the following questions:

- Where do the settled larvae (particles) come from?
- Where do they go after release?
- Which areas are more vulnerable to hydrodynamic flushing?
- How isolated or connected are the three fishing grounds (Red Cliff, NW Peron and Denham Sound)?

Although hydrodynamic conditions change with time some general patterns were revealed that allow us to address the questions above:

- The three fishing grounds appeared to be somewhat self-contained with the exception of RC and NWP between which there was some exchange.
- Significant exchange of particles (larvae) between Denham Sound and the other areas did not occur for any of the model runs.
- Surface particles were more likely to move into the Bay than bottom particles (Figs. 5.24, 5.25, 5.26).
- Particles that ended up in the fishing grounds had relatively localised origins; i.e. small catchment areas (Fig. 5.26).
- Denham Sound and NW Peron had smaller catchment areas and were less variable than Red Cliff (Fig. 5.26).
- Particles at the surface travelled further than those at the bottom and were more susceptible to varying weather conditions. Thus catchment areas for surface particles were larger than for bottom-tracking particles (Fig. 5.26).
- The northern section of Red Cliff and Denham Sound were most likely to be flushed from the Bay, especially when near the bottom (Fig. 5.27) and the extent of this varies between days of release (Fig. 5.24).

It is clear from the simulations completed thus far that particles released in the Northwest Peron (NWP) grounds are more likely to be retained within the local area, regardless of whether they are at the surface or the bottom (Figs. 5.23, 5.24, 5.25, 5.26). Particles from the other areas might move into the NWP grounds, but those released there moved very little. This potentially explains a reason why these scallop grounds experience relatively successful recruitment from year-to-year.

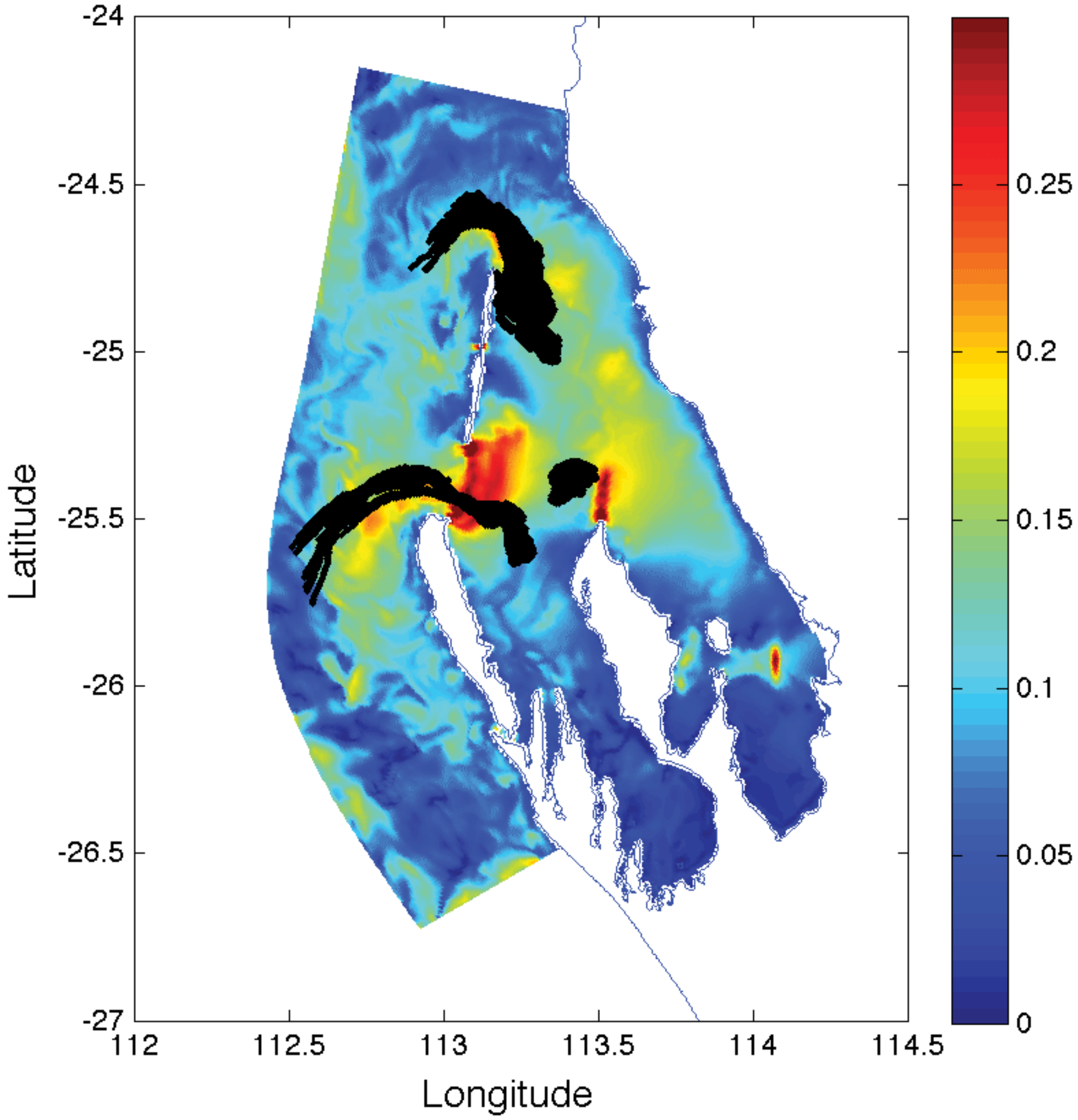


Figure 5.23. Bottom-Tracking. Trajectories of 100 passive particles released at Red Cliff (RC), Northwest Peron (NWP), and Denham Sound (DS) trawling grounds (Dept. of Fisheries survey sites 13, 41, 50) and advected with bottom currents for the first 2 weeks of July 2007. Colour scale shows current speed in ms^{-1}.

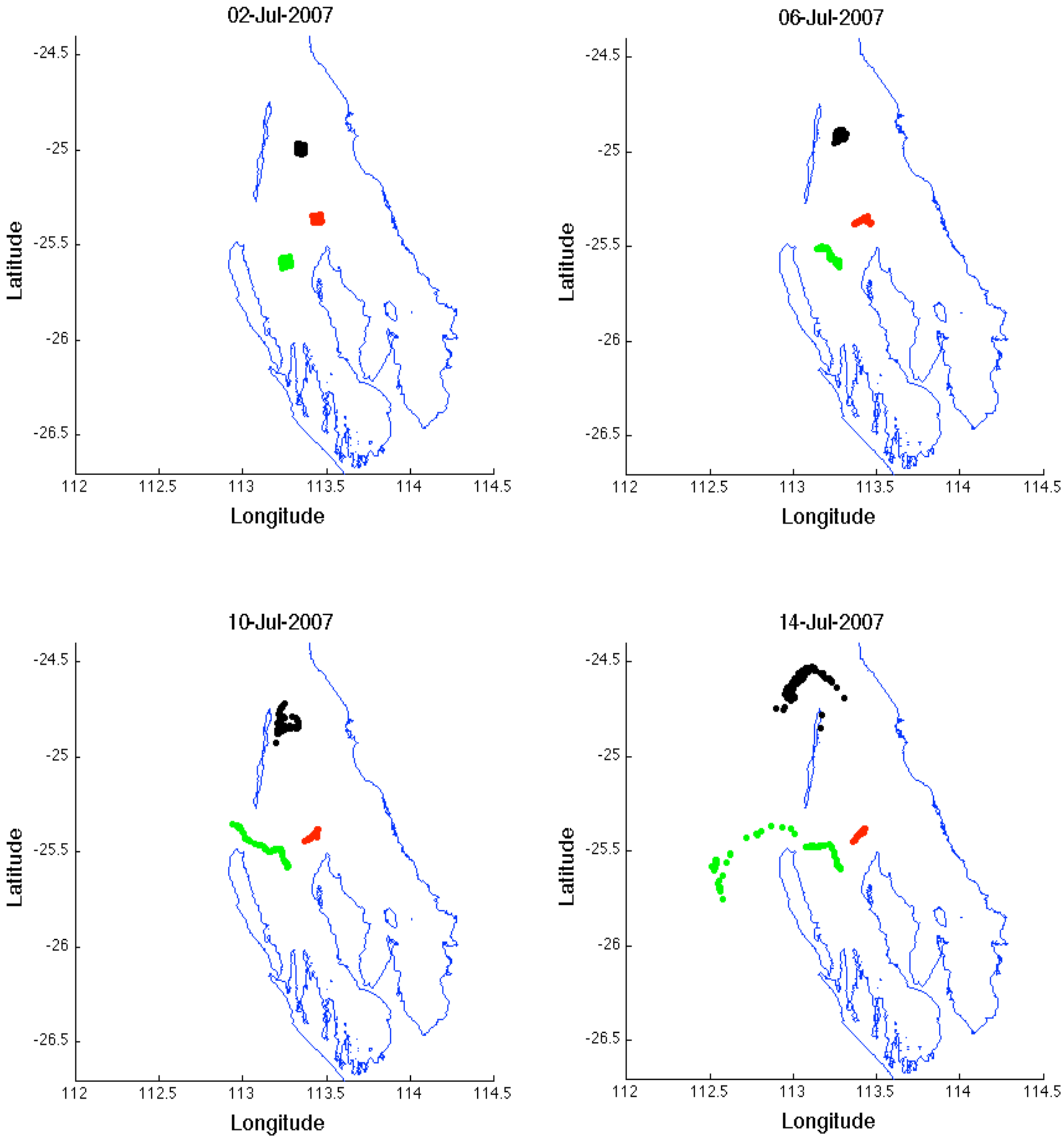


Figure 5.24. Bottom-Tracking. Snapshots of passive particles following bottom currents during first 2 weeks in July 2007. Black dots at Red Cliff (RC), Red dots at Northwest Peron (NWP), and green dots at Denham Sound (DS) trawl grounds (DoF survey sites 13, 41, 50). (see Appendix 3 for simulations)

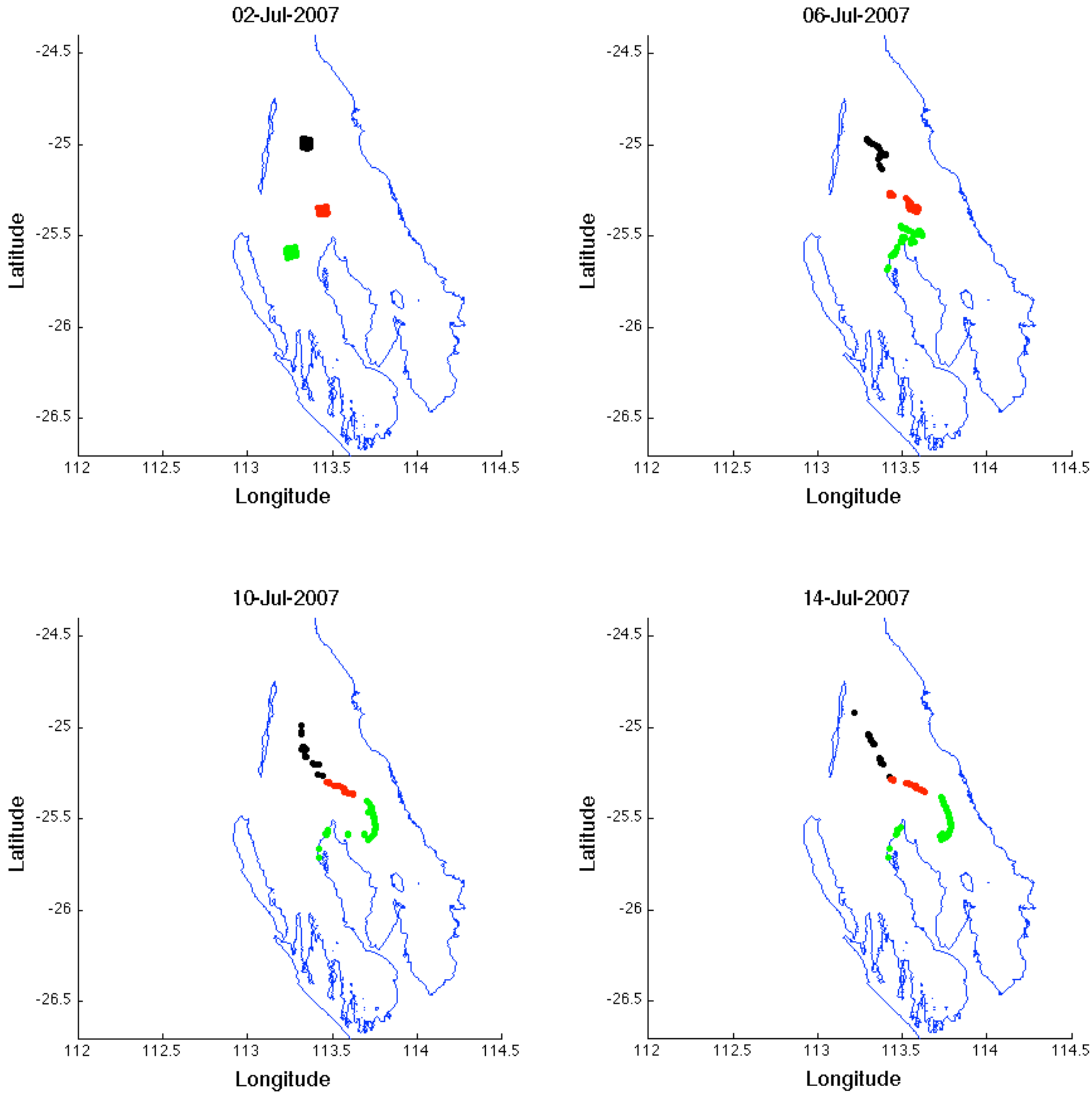


Figure 5.25. Surface-Tracking. Snapshots of particles following surface currents during first 2 weeks in July 2007. Release points: Black dots at Red Cliff (RC), Red dots at Northwest Peron (NWP), and green dots at Denham Sound (DS) trawl grounds (DoF survey sites 13, 41, 50). (see Appendix 3 for simulations)

Catchment Area

A useful way to interpret where potential recruits come from is to find which particles end up in specific fishing grounds and then back-calculate where they originated. This is analogous to calculating the catchment area for a river system e.g. finding the source region of waters that eventually end up at the river mouth. For the purposes of this study, we delineated likely origins for particles (larvae) for each fishing area (RC, NWP and DS).

Although the timing of particle release resulted in different catchment areas, the spatial patterns were similar for all the simulations. Surface particles tended to come more from the north and west while bottom particles travelled more from south to north. This is consistent with the residual hydrodynamic flows where inflow occurs on the surface and water is transported out along the bottom. Northwest Peron appeared to have a smaller catchment than the other fishing grounds on the bottom tracking, but was not so limited when surface-tracking particles were taken into consideration (Fig. 5.26 centre bottom/top). The catchment of Denham Sound extends mostly to the south, but also toward Cape Peron. The large catchment area of Denham Sound is directly linked to the large area of the fishing ground itself. Overall the most important conclusion that can be drawn is that there is to some degree a hydrodynamic barrier between Denham Sound and the other two fishing grounds. In contrast there is some limited exchange between NW Peron and Red Cliff, especially near the boundary between them.

Hydrodynamic flushing

Many particles released near the entrance channels that followed bottom currents were swept from the bay within two weeks (Figs. 5.23, 5.24, 5.27). The fishing grounds affected most by the outflow were Denham Sound and Red Cliff. As particles neared the entrances, their velocities increased and they tended to converge in the deeper channels. None of the particles released at Northwest Peron were swept from the Bay. Particles following the surface currents were much less likely to be flushed from the Bay as the residual circulation tended to cause them to converge in the middle of the Bay (Fig. 5.25). It should be noted that the release location in Denham Sound was critical in determining the trajectory of the surface particles. Releasing the particles slightly more to the west caused the particles to travel further south into the western reach of Bay.

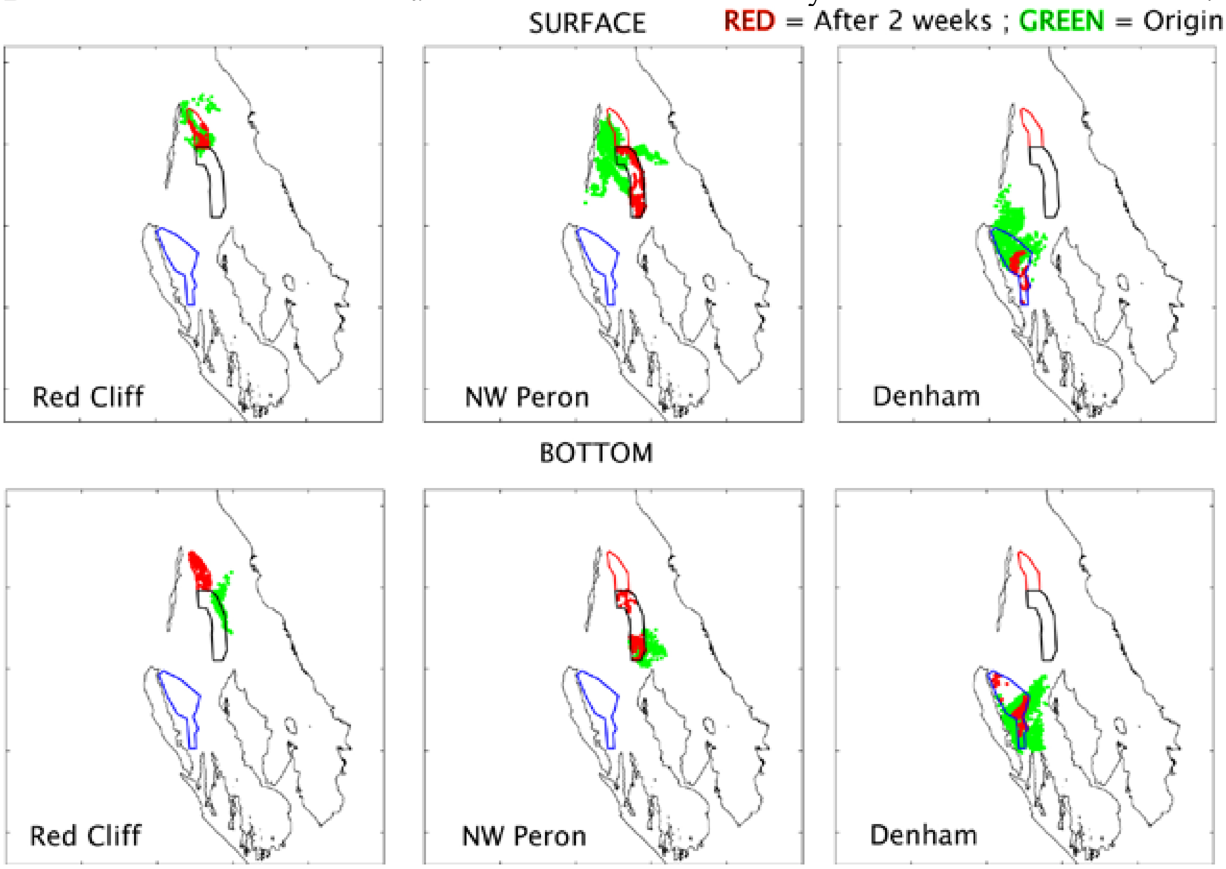


Figure 5.26. Catchment area for surface and bottom particles derived from June 2009 model run. Red particles represent particle location after 2 weeks and green particles represent origin of those particles. Surface-tracking and bottom-tracking particles are shown. The polygons used for analyses delineate the trawling grounds and contain Department of Fisheries survey sites (red = Red Cliff, black = NW Peron, blue = Denham Sound).

Very few surface-following particles were transported out of the Bay, even near the entrances as residual flows at the surface flow into Shark Bay. The opposite occurs near the bottom and significant portions of particles released near the entrances were flushed out (Fig. 5.27) and this varies depending on the day of release. It is important to note that the northern portions of Denham and Red Cliff can still have scallops under this scenario, it would however require larvae to either come from the more southern areas or to migrate quickly to the surface where they are more likely to be retained. Timing of spawning in relation to the pulsing outflow events would also be critical.

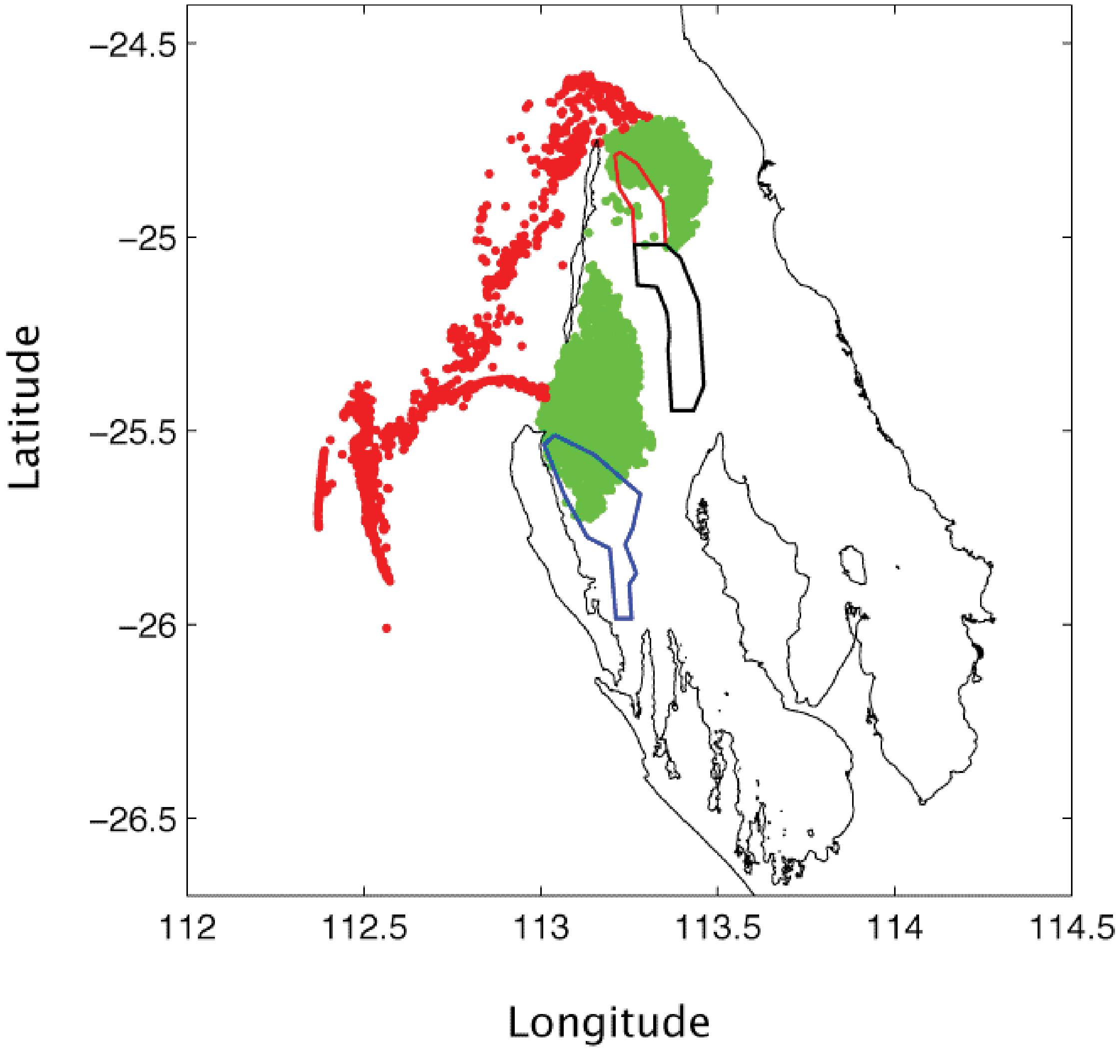


Figure 5.27. Origin (green) of bottom-tracking particles flushed from Shark Bay (red) over 2 weeks in June 2009 simulation. The polygons used for analyses delineate the trawling grounds and contain Department of Fisheries survey sites (red = Red Cliff, black = NW Peron, blue = Denham Sound). Very few surface-tracking particles were flushed from the Bay.

5.4 Discussion

The likelihood of particles being retained within each fishing ground appears to vary spatially as well as temporally (Tables 5.3 to 5.6). Retention was found to reach a maximum around May/June, which could be explained with the seasonal relaxation of strong winds. Earlier in the year stronger southerly winds persist and later in the season winter storms become more frequent. It is important to note that although this is generally true, it varies from year to year and a general climatology cannot be inferred from only one or two seasons of analysis.

There is a very small percentage of transport between the three fishing areas. Exchange between NW Peron and Red Cliff is generally less than 10 % for both the bottom and surface while retention was mostly between 25-50% (Tables 5.3 to 5.6). There was one event in April that caused 61% of the particles released in Red Cliff to move to NW Peron on the surface (Table 5.5) but this is an anomaly, and can be attributed to anomalous weather conditions. Transfer between the other areas was mostly less than 1%, implying restricted connectivity between areas. Each area appeared more isolated for bottom-tracking particles compared to surface-tracking particles. This general relationship of connectivity is graphically illustrated in Fig. 5.28 for 2007, and Fig. 5.29 for 2009. For both years, NWP and DS retained more particles than RC. Numbers should be interpreted in a qualitative manner, as they are dependent somewhat on the size of the polygon and true larval transport pathways are likely to be a combination of the surface plus the bottom scenarios.

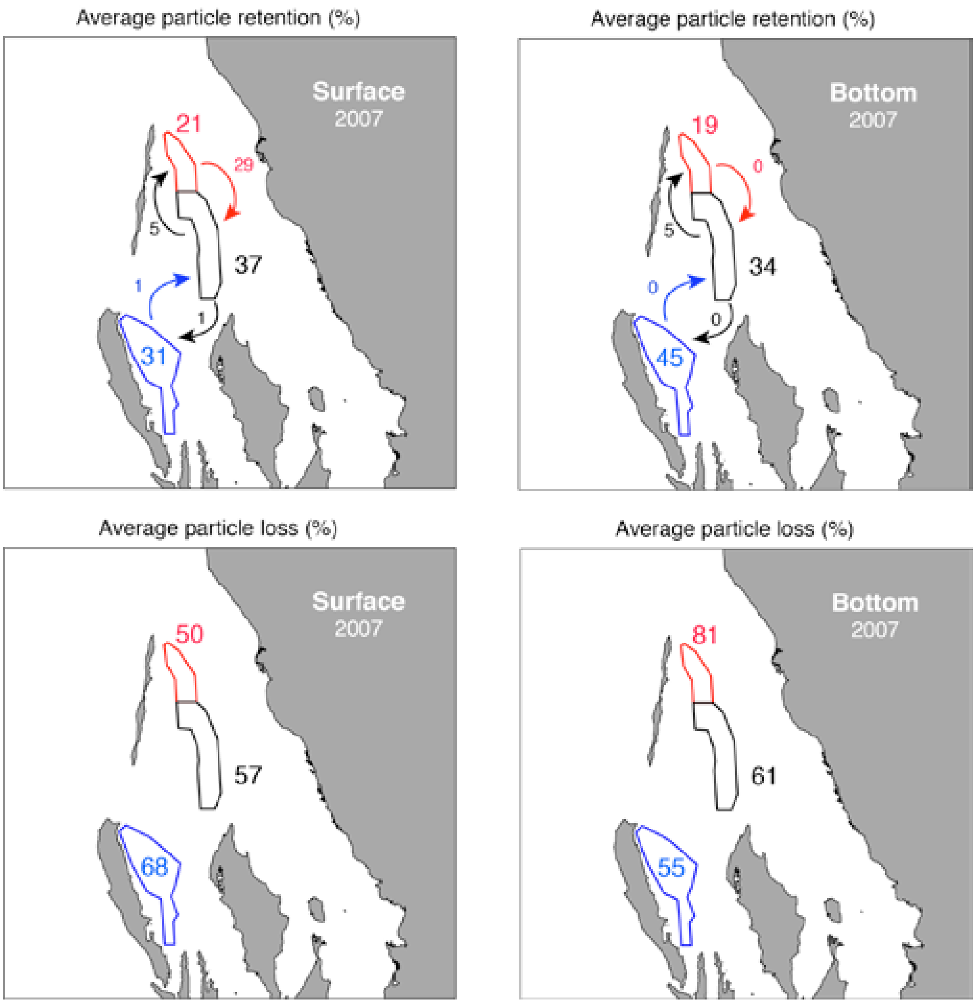


Figure 5.28. Graphical depictions of mean 2007 seasonal connectivity results (Tables 5.3 to 5.6) showing the average percentage of particles which were either retained (large #s), transported to neighbouring fishing grounds (arrows), or lost—defined as particles not ending up in any of the trawling grounds (lower panels).

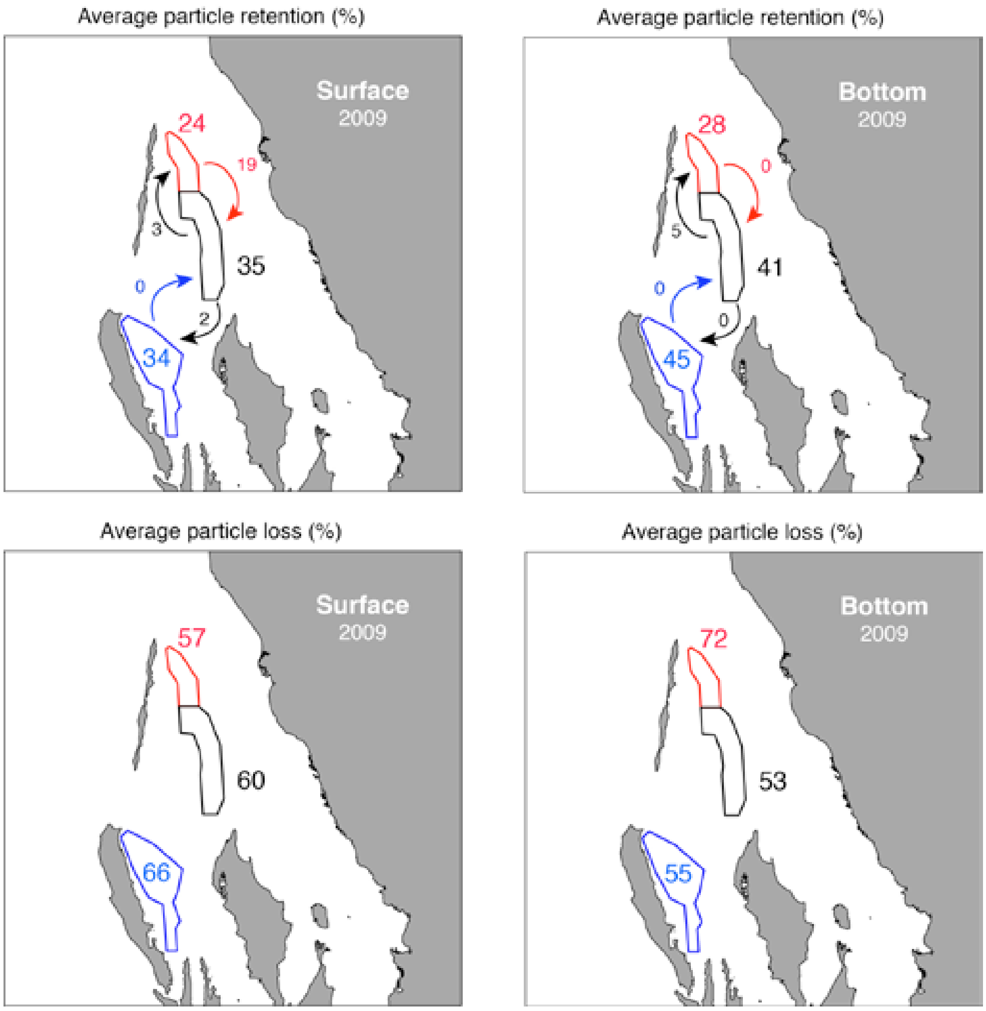


Figure 5.29. Graphical depictions of mean 2009 seasonal connectivity results (Tables 5.3 to 5.6) showing the average percentage of particles which were either retained (large #s), transported to neighbouring fishing grounds (arrows), or lost—defined as particles not ending up in any of the trawling grounds (lower panels).

Table 5.3. Percent retention and exchange of surface-tracking particles released in main fishing grounds over the 2007 spawning season.

		Particle Movement - Surface 2007 (percent)							
Start Location	**Finish Location**	**April 1-15**	**April 15-30**	**May 1-15**	**May 15-31**	**June 1-15**	**June 15-30**	**July 1-15**	**Mean**
Red Cliff	**Red Cliff**	**21**	**18**	**11**	**38**	**21**	**33**	**3**	21
Red Cliff	NW Peron	32	34	54	14	35	1	34	29
Red Cliff	Denham	2	0	0	0	0	0	0	0
NW Peron	Red Cliff	1	2	0.138	7	2	24	0	5
NW Peron	**NW Peron**	**30**	**51**	**33**	**15**	**37**	**45**	**48**	37
NW Peron	Denham	4	0	0.002	0	0	0	0	1
Denham	Red Cliff	0	0	0	0	0	0.002	0	0
Denham	NW Peron	0	0	0	0	0	6	0	1
Denham	**Denham**	**24**	**14**	**35**	**51**	**40**	**20**	**34**	31

Table 5.4. Percent retention and exchange of bottom -tracking particles released in main fishing grounds over the 2007 spawning season.

		Particle Movement - Bottom 2007 (percent)							
Start Location	**Finish Location**	**April 1-15**	**April 15-30**	**May 1-15**	**May 15-31**	**June 1-15**	**June 15-30**	**July 1-15**	**Mean**
Red Cliff	**Red Cliff**	**24**	**28**	**16**	**14**	**23**	**13**	**17.98**	19
Red Cliff	NW Peron	0.011	0.009	0.009	0.004	0.354	0.086	0.02	0
Red Cliff	Denham	0	0	0	0	0	0	0	0
NW Peron	Red Cliff	4	6	6	3	5	4	10	5
NW Peron	**NW Peron**	**25**	**21**	**34**	**19**	**52**	**40**	**45**	34
NW Peron	Denham	0	0	0	0	0	0	0	0
Denham	Red Cliff	0	0	0	0	0	0	0	0
Denham	NW Peron	0	0	0	0	0	0	0	0
Denham	**Denham**	**39**	**28**	**51**	**51**	**52**	**37**	**54**	45

Table 5.5. Percent retention and exchange of surface-tracking particles released in main fishing grounds over the 2009 spawning season.

		Particle Movement - Surface 2009 (percent)							
Start Location	**Finish Location**	**April 1-15**	**April 15-30**	**May 1-15**	**May 15-31**	**June 1-15**	**June 15-30**	**July 1-15**	**mean**
Red Cliff	**Red Cliff**	**13**	**22**	**29**	**19**	**51**	**5**	**31**	**24**
Red Cliff	NW Peron	61	26	0	32	4	7	0.37	**19**
Red Cliff	Denham	0	2	0	0	0	0	0	**0**
NW Peron	Red Cliff	0.02	0	1.975	0	4	0	**16**	**3**
NW Peron	**NW Peron**	**30**	**39**	**51**	**25**	**53**	**13**	**33**	**35**
NW Peron	Denham	1	9	0	3	0	0	0	**2**
Denham	Red Cliff	0	0	0	0	0	0	0	**0**
Denham	NW Peron	0.00	0.00	0.00	0.00	0.08	0.00	0.07	**0**
Denham	**Denham**	**18**	**42**	**52**	**36**	**53**	**9**	**29**	**34**

Table 5.6. Percent retention and exchange of bottom -tracking particles released in main fishing grounds over the 2009 spawning season.

		Particle Movement - Bottom 2009 (percent)							
Start	**Finish**	**April 1-15**	**April 15-30**	**May 1-15**	**May 15-31**	**June 1-15**	**June 15-30**	**July 1-15**	**mean**
Red Cliff	**Red Cliff**	**39**	**31**	**29**	**26**	**28**	**27**	**17**	**28**
Red Cliff	NW Peron	0.24	0.01	0.03	0.02	0.13	1.27	0.12	**0**
Red Cliff	Denham	0	0	0	0	0	0	0	**0**
NW Peron	Red Cliff	1	**5**	2	14	7	3	2	**5**
NW Peron	**NW Peron**	**31**	**34**	**45**	**47**	**47**	**53**	**34**	**42**
NW Peron	Denham	0	0	0	0	0	0	0	**0**
Denham	Red Cliff	0	0	0	0	0	0	0	**0**
Denham	NW Peron	0	0	0	0	0	0	0	**0**
Denham	**Denham**	**31**	**48**	**62**	**49**	**53**	**34**	**40**	**45**

Through field measurements, hydrodynamic, and particle (larval) modelling we identified residual current patterns over the fishing grounds as well as a pulsing density-driven bottom current with the potential to flush larvae from the Bay. In contrast, wind and tidally driven currents on the surface were found to retain particles in the Bay and were the dominant force distributing simulated larvae between the three fishing areas of Red Cliff, Northwest Peron, and Denham Sound. Areas of weaker surface and bottom currents were more likely to retain particles, and higher retention rates were found in the lower end of NWP and inner regions of DS. Overall, connectivity between RC and NWP stocks was possible, particularly if larvae were near the surface, while Denham Sound was highly unlikely to be connected to RC and NWP stocks. The largest weakness in the study was the lack of available knowledge about the larval life cycle of *A. balloti*, particularly of their distribution in the water column. The simplified qualitative dispersal modelling methods used to determine movement on the bottom as on the surface, however, still gave us a much clearer picture of the relative connectivity of stocks and of areas more susceptible to hydrodynamic flushing.

Future improvements to the modelling would be largely dependent upon improved knowledge of the precise timing of spawning, larval behaviour and movement in the water column and settlement cues. This additional information would enhance the accuracy of the simulated larval pathways but it is unlikely the generalised conclusions drawn here would dramatically alter.

6.0 General Discussion

The project was successful in addressing the four objectives.

1. To determine size specific recapture mortality rates of *Amusium balloti* as a result of repeated capture and release experiments and gear impacts on newly recruited (juvenile) scallops

Survival of repeatedly discarded saucer scallops was estimated for the Shark Bay trawl fisheries using short-term tag-recapture experiments under various fishing and environmental conditions. The Cormack-Jolly-Seber model outcomes estimated significantly higher survival of discarded scallops in winter (post-spawning) than during summer (pre-spawning), but there were no differences between fishing grounds or between post-capture treatment groups (air exposed or hopper). This suggests that stress from being exposed to higher summer air temperatures was more critical to their ongoing survival than differences in their reproductive condition.

Regulatory discarding under past management strategies, which occurred primarily in the warmer summer months, is likely to have resulted in higher discard mortality rates. Under current management regulatory discarding still occurs but is predominantly over winter months when scallops exhibit higher resilience to trawl-induced stress. The results support the current management strategy of both fleets fishing pre-spawning so that the amount of discarding is significantly reduced.

2. To determine the impacts of various scallop mesh sizes for the capture of the target size of *Amusium balloti* and its impact on damage to and retention of prawns

Codend mesh shape and size were examined for the Shark Bay scallop trawl fishery to determine if the selectivity of scallops could be improved by adopting a square mesh codend as opposed to the conventional diamond mesh codend. Differences in the catch rates of target species and selected bycatch groups were examined by simultaneously towing three different-sized square mesh (50, 55, 60 mm) and the standard 100 mm diamond mesh codends.

The 50 mm square mesh codend performed poorly with relatively high retention of small scallops, while the 55 and 60 mm square mesh codends retained 22–33 % less smaller scallops than the diamond mesh codend. A mean of 5% loss in commercial sized scallops across all three square mesh codends and significant bycatch reductions of up to 95% occurred when operating square mesh codends compared to the diamond mesh. Further testing of the 60 mm square mesh codend against the standard scallop and prawn nets also resulted in reduced retention of small scallops and finfish bycatch. Catch rate of prawns by the square mesh codend was less than 2% of that of the standard prawn net. Thus the performance of the 60 mm square codend in the experimental trials presents a good basis for its use in commercial trials in the Shark Bay scallop trawl fishery and subsequent implementation at an appropriate size.

3. To investigate if small-scale spatial closures assist recruitment of *Amusium* balloti by reducing gear impacts and capture mortality but without affecting overall prawn catches.

To evaluate both the historical and current spatial effort distribution of the A-class scallop fleet and B-class prawn fleet and to determine if trawl effort intensity during the key scallop spawning period had impacted on the scallop recruitment dynamics

Historical prawn trawl effort levels associated with scallop discarding on the central Shark Bay scallop grounds was less in the years after (1991 to 1993) the implementation of the Carnarvon-Peron management line (CPL) than in years before (1987 to 1990) it was introduced, but overall there was no significant difference in the mean effort levels between the two time periods. This result was primarily due to other factors unrelated to the introduction of the CPL, such as the very high scallop recruitment event of 1990 (that resulted in unprecedented high abundance of scallops across Shark Bay and reciprocal low fishing effort due to the time required to process the catch), and also the reduction in the number of operating prawn boats from 35 to 27 in 1990.

The analysis was extended to explore prawn fleet effort levels associated with discarding on scallop grounds during the period 1995 to 2004 (i.e. prior to the scallop season opening). We found effort levels to be greater during these years than previously (1987 to 1994), although not considered significantly high relative to the overall annual prawn effort, and also relative to the scallop effort levels after its season opening. In further examining the effort levels of both the scallop and prawn fleets on the central scallop grounds, peak annual trawl effort occurred during the key scallop spawning months (April – July).

The most notable change in effort and fishing dynamics occurred after 2004 due to the simultaneous openings of both scallop and prawn fishing. This major change in management strategy reduced total effort levels on scallops during the spawning period as fishing occurred prior to this and resulted in reduced discarding during summer. Regulatory discarding of scallops retained by prawn nets was enforced for the scallop spawning period but better survival is expected during this winter period. Despite these measures we found no clear correlation between effort levels of either fleet or in combination with scallop recruitment. This strongly suggests that trawl effort alone is not a major driver of recruitment in central Shark Bay, and/or there are large annual differences between source and sink regions within the Bay that are driven by environmental conditions. The introduction of the Carnarvon Peron line was demonstrated to not redirect fishing effort onto the scallop grounds so this hypothesis is not supported and the two industries can move forward to optimise harvesting of both scallop and prawn stocks without this issue clouding the consultation process.

The use of spatial closures as a management tool to reduce total effort levels and to promote recruitment is not strongly supported by the results of the desktop study. However, low recruitment levels over an extended number of years, including years when environmental conditions were considered to be conducive for improved scallop recruitment indicate that even though a strong effort/recruitment correlation is not evident it cannot be completely dismissed, particularly in light of more recent improved recruitment levels during periods of much reduced overall effort during the spawning period and prior to the fishery opening.

4. To examine whether existing hydrodynamic models can guide the selection of spatial closures and to investigate the larval transport mechanisms of both prawn and scallop larvae in Shark Bay

The hydrodynamic modelling indicated limited scallop larval connectivity between southern and northern fishing grounds and it appears that the key grounds are primarily self-seeding. Northern Red Cliff and northern Denham Sound has a higher likelihood of larval loss (flushing) out of Shark Bay under certain environmental conditions. The management implications from these results are that it is essential to retain spawning stock in each area in order to replenish stocks on each fishing ground. The current management strategy of fishing to a catch rate threshold to ensure carryover of stock is therefore appropriate. Implementation of spatial closures to reduce effort was not supported by the effort assessment of recruitment however due to the lack of connectivity between fishing grounds closures may still be a reasonable strategy to protect spawning stock and newly settled scallops within a fishing ground.

7.0 Benefits and Adoption

The objectives of this project were developed in light of a review which identified gaps in research knowledge that would assist in the management and reduction of resource sharing conflict between prawn and scallop licensees in Shark Bay. The specific outputs of this project have direct benefits to the commercial prawn and scallop industries and to fisheries researchers and managers in WA as they address these research gaps. The project has also benefited research and management in the Queensland scallop fishery with the results of the mesh-trial experiments of the project being discussed with DEEDI researchers with comparisons with their square-mesh trial findings. The project also fostered research training in hydrodynamic modelling and research collaboration with hydrodynamic modellers in Australia and overseas. Specifically the result of the hydrodynamic modelling of larval movement within Shark Bay has also been discussed with SARDI researchers, with some potential for collaboration in this area in the future.

The information gathered during this project will enable the Department of Fisheries and Industry to identify and further develop management strategies and adopt new fishing methods to effectively address reduction of bycatch and capture of juvenile scallops by the scallop fleet in the first instance. The almost total elimination of catch of prawns when using a square mesh cod-end for the scallop boats (that cannot commercially retain prawns) and the T-90 mesh trials undertaken in Queensland and South Australia with recent adoption of this gear type by the Gulf St Vincent (GSV) prawn fishery (C. Dixon, pers. comm.) may be another impetus for change.

Overall, the WA community will benefit from the optimal utilisation of marine resources with more robust management strategies being implemented. Conservation groups and SEWPAC will be better informed of reduced trawl impacts and reduction of bycatch by both management and gear modifications that are suitable for these fisheries.

Specific benefits of the information related to each objective are:

Objective 1

The repeat recapture mortality experiments conducted in summer and winter indicate higher mortality of discards during summer months and the results support the current management strategy of both fleets fishing prior to spawning so that the amount of discarding is significantly reduced. This strategy has been in place since 2004 but the benefits were validated by this project. Also fishing at this time of year by the scallop fleet has resulted in them ceasing fishing earlier and at higher catch rates (due to cessation of fishing at a catch rate threshold) also reducing overall fishing effort and increasing fishing efficiency. For the management of the scallop resource, the study highlights the importance of minimising discarding as much as possible during the summer months and the protection from trawl disturbance for small scallops during the winter months.

Objective 2

The square mesh codend trials and the preliminary results of commercial trials in the Abrolhos Islands scallop fishery indicates that the move to square mesh codends will result in a significant reduction of discards (both small scallop and bycatch) and may in fact increase the catches of commercial sized scallops due to improvements in water flow and net efficiency. The potential benefits of converting to a square mesh codend configuration for scallop boats are reduced fishing-induced mortality on juveniles and potential increase in scallop recruitment for the Shark Bay trawl fisheries.

Objective 3

The introduction of the Carnarvon Peron line was not demonstrated to redirect fishing effort onto the scallop grounds. This information will assist in the ongoing management of the prawn and scallop resources.

Objective 4

The hydrodynamic modelling component is pointing to low levels of connectivity between fishing grounds indicating that the areas are primarily self-seeding with two out of three areas having a higher likelihood of larval loss under certain environmental conditions. These results have management implications in that it is essential therefore to retain spawning stock in each of these areas in order to be able to replenish stocks on each fishing ground. The current management strategy of fishing to a catch rate threshold to ensure some carryover of scallops in each fishing ground is therefore an appropriate management strategy and will be continued.

8.0 Further Developments

Full commercial trials of square mesh codends are still required to determine their effectiveness and durability under commercial fishing conditions prior to discussions on full adoption by the scallop industry. In 2010/11, trials using T-90 mesh in Qld and SA has also shown positive results in reduction of bycatch and smaller scallops/prawns with the GSV prawn fishery adopting this gear in 2012. The development of a collaborative national approach to evaluate the effectiveness of this mesh type in other prawn/scallop fisheries may result in adoption of modified cod-ends in both the scallop and prawn fisheries in Shark Bay in the future. In any collaborative study, WA research observers will accompany commercial boats during any trials to collect additional information on net performance and to compare them with the square mesh cod-ends used in this study.

The effectiveness of small-scale spatial closures to protect recruiting scallops was proposed as part of this study but they were not implemented during this study. Both sectors of industry have instead been considering voluntary closures of areas where there are high proportions of small scallops in abundance. This may be a preferred option instead of formalised closures thus giving industry the flexibility and ownership of temporary closures to protect small scallops from all impacts of trawling until the following fishing season.

During the period of this study, differences in productivity between the southern part of Shark Bay in Denham Sound and northern Shark Bay have shown different levels of scallop productivity. Examination of the reason behind these differences were not part of this FRDC project but discussions with industry confirm the need to better understand the various systems in Shark Bay.

The fishing strategy in Denham Sound has been different to northern Shark Bay since 2004. Denham Sound has an extensive area that is permanently closed to trawling in the southern parts (snapper-trawl closure) and within this area a very small proportion is only opened to fishing if the abundance (sampled during annual survey) is high enough to be fished (a kind of rotational closure). In the areas open to scallop fishing, fishing is pre-spawning and then no fishing takes place in the area for at least 2-3 months giving protection to newly settled scallops. Conversely, in northern Shark Bay even though no scallops can be retained during the spawning closure there can still be trawling by the prawn fleet (with discarding of scallops) during this time. Further evaluation on whether the absence of trawling during the early settlement growth period of scallops is important in more consistent recruitment in the fishery is required.

The hydrodynamic modelling study in Shark Bay will also be expanded to model prawn larval movement and will have additional benefits to other researchers and managers for other commercial and recreational fisheries in Shark Bay as the models can also be adapted to study larval movement, pink snapper (*Pagrus auratus*) and blue swimmer crabs (*Portunus armatus*). The hydrodynamic model and its associated environmental data will also be valuable in the assessment of the low recruitment and adult mortality of scallops (and blue swimmer crabs) during 2011 that appears to have been influenced by an extreme marine heatwave (SST up to 4.5^{o}C above average) affecting the Gascoyne region in early 2011.

9.0 Planned Outcomes

The Shark Bay prawn and scallop fisheries are the direct beneficiaries with improved understanding of larval movement dynamics, fleet gear interactions and improved methods of resource allocation and utilisation between sectors. The overall WA community will benefit from the optimal utilisation of marine resources.

For an improved understanding of gear interactions the project quantified repeat-recapture mortality rates of scallops and highlighted seasonal differences in mortality which was mostly attributed to thermal stress. These results validated the benefits of the current management strategy of combined fleet fishing with reduced discarding during warm-water periods at the start of the scallop season. An added benefit will be estimates of scallop growth rates with longer-term recapture of tagged scallops left on the fishing grounds after these experiments. A newsletter was circulated to all prawn and scallop skippers in September 2008 to highlight the tagging project and inform of rewards (scratchie ticket) for return of tagged scallops. A second component to understanding gear interactions in this project was the evaluation of current scallop mesh size and alternative larger mesh size selectivity which provided guidance into improved cod-end mesh sizes that would reduce the take of small scallops as well as bycatch.

The evaluation of improved methods of resource allocation through spatial closures could not be undertaken during this project but was replaced by the examination of fleet spatial effort dynamics before and after the implementation of temporal closure lines for the prawn fleet which was believed (by the scallop fleet) to have a detrimental shift of effort on scallop stocks. This was expanded to examine the scallop fleet effort distribution as well as that combined for both fleets. These effort levels were correlated to annual scallop recruitment levels. No strong correlation was seen and it was evident that recruitment dynamics are highly complex and not just related to the amount of spatial extent of fishing. The examination however facilitated discussions between industry members including consideration of temporary spatial closures in areas of high abundances of small scallops.

Resource sharing conflict was, in part reduced by this project allowing a more informed debate and removing perception from facts.

The collaboration with University of Western Australian oceanographic modellers and a postgraduate student to undertake the modelling aspect of this project will increase the modelling capacity for fisheries within the state. Information on the relatively low connectivity between fishing grounds and potential flushing of larvae from Shark Bay has validated the management strategy of separately retaining spawning stock in each fishing ground to ensure retention of larvae/recruits in each fishing ground under normal environmental conditions.

Other information disseminated during the course of this project:

- General Articles:
  - A brief article on the commencement of the project was published in the *Western Fisheries* magazine in April 2008.
  - The mesh trial research and outcomes was published in the magazine *WESTERN FISHERIES* in June 2009.
  - Highlights of the square mesh trials research and outcomes was published in the FRDC magazine *FISH* in the December 2009 issue.

- Presentations:
  - o The project objectives and results of the mesh trials and tagging experiments were presented in an oral presentation at the 8th Indo Pacific Fish Conference and 2009 Australian Society for Fish Biology Workshop and Conference held in Fremantle, Perth.
  - o Hetzel, Y., C.B. Pattiaratchi, R. Lowe, and R. Hofmeister, 2010. Bay-Ocean exchange processes in Shark Bay, Western Australia and implications for scallop larval survival, Oral Presentation, 15th Physics of Estuaries and Coastal Seas (PECS) Conference, Colombo, Sri Lanka. 13 – 17 September 2010.
  - o Outcomes of the scallop discard survival experiments and the square mesh codend trails are being presented through oral presentations in the 18th International Pectinid Workshop in Qingdao, China (April 20 – 26th 2011).
  - o Hetzel, Y., C.B. Pattiaratchi, R. J. Lowe, M.I. Kangas, and A. Chandrapavan, 2011. Gravity currents in Shark Bay, Western Australia: Implications for scallop larval dispersal, 48th Annual Conference for the Australian Marine Sciences Association (AMSA2011), Fremantle, Australia. 1 – 7 July 2011.
  - o Hetzel, Y., C.B. Pattiaratchi, R. J. Lowe, M.I. Kangas, and A. Chandrapavan., 2011. Hydrodynamic flushing in Shark Bay, Western Australia: Implications for Amusium balloti larval dispersal, Oral Presentation, 18th International Pectinid Workshop (IPW), Qingdao, China. 20 – 26 April 2011.
  - o Hetzel, Y., Pattiaratchi, C.B., Lowe, R.L., 2012. Dense water outflows in Shark Bay, Western Australia, Poster Presentation, 2012 Ocean Sciences Meeting, Salt Lake City, UT, USA. 20 – 24 February 2012.
- Journal Publications
  - o Chandrapavan A, Kangas M, Sporer E. Performance of square mesh codends in reducing discards and bycatch in the Shark Bay scallop fishery. Marine and Freshwater Research – Special Shark Bay Florida Bay issue. *In press*.
  - o Hetzel, Y., Pattiaratchi, C.B., Lowe, R.L. Intermittent dense water outflows under variable tidal forcing in Shark Bay, Western Australia. Continental Shelf Research. *In review*.
  - o Chandrapavan A, Kangas M, Sporer E. Short-term survival estimates of repeatedly discarded scallops highlight the impact of past and present management strategies in the trawl fisheries of Shark Bay, Western Australia. Journal of Shellfish Research. *In press*.
  - o Hetzel, Y., Pattiaratchi, C.B., Lowe, R.L. Varying exchange flow for two entrances in a subtropical inverse estuary. Estuarine, Coastal and Shelf Science. *In preparation*.

10.0 Conclusion

The four project objectives of this project were successful in providing information to industry and managers to assist in reducing resource-sharing conflicts and to provide a better understanding of drivers of recruitment. The repeat discard mortality trials indicated much higher mortality rates of scallops during warm summer months and that the current management strategy of early (pre-spawning) fishing by both fleets reduces discarding whilst retaining commercial sized scallops. This strategy combined with the implementation of a catch rate threshold to cease fishing results in scallops being left on the fishing grounds during the spawning period (April to July) which is an improvement of historical fishing practices. The square mesh codend trials identified a more optimal mesh size/configuration that would significantly reduce the retention of small scallops and fish and prawn bycatch by the scallop boats.

The evaluation of changes to prawn fishing fleet dynamics by the introduction of the Carnarvon-Peron Line (which is important for tiger prawn sustainability) did not identify any significant shift or increase in prawn trawl effort in the central Shark Bay scallop grounds. Examination of both the historical and recent catch and effort data of the prawn and scallop fisheries with trends in recruitment, showed that trawl effort was not a major driver of scallop recruitment in Shark Bay. This result does not lend support for spatial closures of key central Shark Bay scallop trawl grounds. However, low recruitment levels over an extended number of years, including years when environmental conditions were considered to be conducive for improved scallop recruitment indicate that even though a strong effort/recruitment correlation is not evident, it cannot be completely dismissed, particularly in light of more recent improved recruitment levels during periods of much reduced effort during the spawning period and prior to the scallop fishery opening. The hydrodynamic modeling of Shark Bay combined with larval movement identified fishing grounds close to the bay's entrance channels to be highly susceptible to flushing, while there were higher retention rates of larvae in central Shark Bay and lower regions of Denham Sound. The study also showed that connectivity between Red Cliff and NW Peron stocks was possible, while Denham Sound was highly unlikely to be connected to Red Cliff and NW Peron stocks. These findings support a management focus on protecting and maintaining a healthy spawning stock level in each of the main fishing grounds. Furthermore, protection of grounds after larval settlement may increase/stabilise scallop recruit survival and could be achieved through temporary spatial closures.

11.0 References

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12.0 Appendices

Appendix 1: Intellectual Property

No intellectual property has arisen from this research.

Appendix 2: Project Staff

Principal Investigator:	Dr Mervi I Kangas
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Appendix 3: Additional data

Drifter tracking movie and model simulations of the bottom and surface particle tracking scenarios can be provided by the author.