Final Report

Aquafin CRC - Southern Bluefin Tuna Aquaculture Subprogram: Tuna environment subproject - Development of regional environmental sustainability assessments for tuna sea-cage aquaculture

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Non Technical Summary

2001/104 Aquafin CRC – Southern Bluefin Tuna aquaculture subprogram: Tuna environment subprojects – Development of regional environmental sustainability assessments for tuna sea-cage aquaculture

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OBJECTIVES:

1. Establish a steering committee of stakeholders and hold a Steering Committee for Fisheries and Aquaculture Environmental Sustainable Development reporting workshop to develop a set of operational parameters for regional scale environmentally sustainable development (ESD) assessment.
2. Develop a set of methodologies for measuring and evaluating each of the parameters in order to provide an ESD assessment.
3. In collaboration with researchers involved in the development of ecosystem scale models for salmon farming, identify the key information/data required to parameterise and validate these models for the tuna industry.
4. Integrate the field and remote data collection systems, necessary to provide the data required for the parameterisation of these ecosystem scale models, into the regional ESD assessments.

Note, the original objective 3 (Using knowledge gained through this process and in consultation with stakeholders develop target levels for key parameters as a basis for effecting management responses) was dropped from the project due to considerable problems that were experienced with the SCFA-ESD reporting approach taken. At the same time, it was agreed that the remainder of the project should be refocused towards providing a lead-up to the FRDC 2005/059 Aquafin CRC-SBT Aquaculture Subprogram: risk and response – understanding the tuna farming environment. As a consequence, this report has become somewhat fragmented.

NON-TECHNICAL SUMMARY:

Outcomes Achieved to Date:
This project has provided the tuna industry, regulators and researchers with a suite of important information on the environment around Port Lincoln at a regional scale, how it interacts with tuna farming, and how to characterise environmental conditions. From a methodological perspective, it has delivered a report on the applicability of remote sensing for environmental monitoring in the region, which makes several recommendations on how this relatively new technology could be used, and it has developed a telemetered environmental monitoring system that is used on a regular basis by some industry members to help understand conditions on their leases. In addition, a model of waste deposition on the sea-floor has been developed, and this will be made available to industry so that they can examine likely waste deposition patterns on their individual leases, allowing them to place pontoons in an arrangement that minimises the interaction between adjacent pontoons. This waste deposition model, along with the nutrient model, have been further refined as part of FRDC 2003/222, and they are now used by PIRSA Aquaculture to help set initial maximum stocking rates for aquaculture zones as they are revised. This thus meets the planned outcomes of a system for modelling the impact of tuna farming activities at regional scales, and regional modelling to assist in determining carrying capacity. The project has also generated the first quantitative data on how seabirds respond to tuna farms, and has shown that an economically important fraction of feed can be consumed primarily by seagulls if no measures are taken to reduce scavenging. New data have also been collected on oceanographic conditions in the tuna farming zone which has been used in the waste deposition model and provided a useful precursor for the Risk and Response project. Additional data that has been useful for this project has also been documented. Finally, the perceptions of a range of stakeholders as to the environmental risks associated with tuna aquaculture have been assessed, and addressed by way of a literature review.

The environmental risk assessment conducted was one of the first such assessments of an aquaculture industry using the Standing Committee for Fisheries and Aquaculture framework developed for risk assessment of wildfisheries. As such, it identified a number of issues that need to be dealt with by those conducting such risk assessments. In particular, there is a need to have a broad range of representation at the workshop, and it can be difficult to come to a consensus opinion. Indeed, for contentious issues, such an approach is likely to leave no-one happy with the final outcome. It is also important for the participants to have access to the latest information prior to the workshop, so that they could make informed judgements rather than relying on perceptions often based on incomplete or out of date information. In this project, we conducted a literature review of priority issues after the workshop, in order to inform the final rankings with the latest information available. While producing this review prior to the workshop may have made discussions easier, it would also have involved a greater amount of work, as all issues would have to have been covered, rather than just the priority issues. In this case, that means 69 compared to the 20 that were dealt with here. Ideally, this review would also have been conducted by an expert in the field for each issue, but this was beyond the scope of the project, and so the authors often had difficulty with assessing areas completely outside their field. Of the 69 issues addressed, ten were not considered relevant to SBT, and 49 were considered of negligible or low risk. Following a literature review and reassessment, the remaining ten issues were classified as either low (feed composition, nutrients, common dolphins) or moderate (sharks, seals, sea lions, bottlenose dolphins and seabirds), or were not addressed as they were considered to be outside the

scope of this report (site constraints, navigation). This ranking means that while improvements need to be made in either industry practises to reduce the actual risk, or the information available to reduce the risk due to uncertainty, these changes can occur on a time scale of 3-5 years.

A review of the potential for the use of remote sensing in the management of tuna aquaculture was commissioned from Adelaide University. This review has identified that satellite-based remote sensing could be useful for mapping algal blooms (but not as an early warning system, and not in waters close to the coast), water quality (primarily chlorophyll levels) and sea surface temperature. Pontoon locations should also be able to be determined. Oil slicks and sea state can be measured; however remote sensing is unlikely to be cost-effective for these.

To improve the availability of data on basic water quality and meterological parameters in the farming zone, a series of experimental telemetred water quality monitoring systems were developed and trialled. In the latest version, data are delivered via a web-based system in order to make the data more widely available. A website hosted by an external server was set up to deliver near real-time environmental data being collected by the systems to authorized users. The data available include temperature, salinity, dissolved oxygen, wind speed and direction. Chlorophyll has just been added to the system, and further developments are being made to provide current and wave data.

Multivariate analysis of the Tuna Environmental Monitoring Program infauna data from 2001-2003 showed that compliance and control sites did not differ in their infaunal assemblages. Instead, there was substantial geographic and annual variation in the data. The later indicates that the multivariate analysis is sensitive enough to pick up patterns in the data, and the former gives a rigorous indication that SBT farming is having undetectable impact on the benthos at the compliance sites (150 m from lease boundaries). There is, however, some indication of regional effects in the data.

The study of seabirds around tuna farms showed that they could scavenge in excess of 10% of feed, depending on feed type and feeding method, although on most farms losses would be considerably less. The pneumatic feeding of baitfish caused greatest feed losses, while feeding frozen blocks of baitfish resulted in near zero losses. Pellets were scavenged considerably less than baitfish. The main scavengers were seagulls, although Pacific gulls also consumed substantial amounts of tuna feed. The numbers of silver gulls in the Port Lincoln area were assessed, with approximately 10,000 breeding pairs being present in 2003 compared to ~5,000 in 2000.

A comparison of oceanographic conditions between winter and summer shows that the waters of the farming zone are not only cooler and denser in winter, but also fresher, due to the wintertime density-driven exchange of water across the mouth of Spencer Gulf. There were no increases in chlorophyll *a* or nutrient levels through the tuna farming season, suggesting that the area is sufficiently well flushed to remove added nutrients, although interestingly the farming area had elevated chlorophyll levels compared to nearby areas without farms both before stocking commenced as well as during the farming season.

Two preliminary models of carrying capacity were developed for the tuna farming zone. The first was a zone-based model to predict the likely increases in dissolved nutrients in the water column with a given level of aquaculture production. This model suggests that if production increased by only ~6000 tonnes from current levels, then breaches of water quality guidelines for ammonia would result, although the model does make a number of simplifications. The second model looks at carbon deposition on the seafloor at a lease scale. It shows that the likely overlap in deposition between adjacent cages is relatively low unless they are very closely spaced (a few tens of metres). Sensitivity analysis suggests that it is important to know respiration and feeding rates, but not so important to know FCR's when making predictions about carbon deposition.

A literature review of existing data for the tuna farming region that could be useful for future modelling has highlighted a general paucity of long-term well-collated and available data, especially in relation to hydrodynamic and biogeochemical variables. This is despite the area being relatively heavily studied compared to many other areas in South Australia, and highlights the need for routine studies to be as comprehensive as possible, and more importantly, to use standard techniques whee possible and to provide readily accessible data and metadata. Recent work undertaken by SARDI Aquatic Sciences has, however, resulted in a good understanding of the current biogeochemical status of the farming zone.

KEYWORDS: Aquaculture, Remote sensing, Environmental sustainability, Tuna farming, Oceanography, Environmental risks, Seabirds, Waste deposition modelling

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Thank you to all those who have been involved in the project. The primary contributors are listed in Appendix 2, although many volunteers have also contributed to various aspects of the project. Special thanks to Prof. Anthony Cheshire, who originated this project, and who acted as its Principal Investigator in the early stages. Dr Rick Fletcher facilitated the risk assessment workshop reported in chapter 1.

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Background

Southern bluefin tuna sea-cages are known to be sources of both particulate and dissolved waste, and as with other finfish farmining operations, these have the potential for risk to both the farmed stock and supporting environments (Gowen and Bradbury 1987, Frid and Mercer 1989, Mayer and McLean 1995, Troell and Norberg 1998). Cheshire *et al.* (1996a, b) demonstrated a severe benthic impact within the immediate vicinity of the tuna cages extending out to a distance of 20 m and a lesser impact for a further 100 to 150 m. At a distance of 200 m, there was no evidence of an impact relative to control sites situated >1 km distant. The nature of the impact was found to be comparable to those described for many salmonid farm sites and was consistent with those described in the Port Lincoln Aquaculture Management Plan (Bond 1993) for which the current management strategies are tailored.

Since the work by Cheshire *et al.* (1996a, b) a number of other studies have been undertaken in an attempt to characterise the nature of impacts associated with tuna farming (eg Bruce 1997, Cronin *et al.* 1999). These studies considered a range of indices including those indicative of the health of pelagic systems (water quality and phytoplankton community structure) as well as the structure of epibenthic and infaunal communities (Clarke *et al.* 1999, 2000). Not-withstanding this previous work, much of it was undertaken when the industry was based within Boston Bay. The movement of farms to more exposed locations has made this earlier work less relevant to the current context. There is a need, therefore, to reconsider some aspects of this earlier work in order to evaluate the extent to which it can be applied to farming in a more general sense.

Research and compliance monitoring to date has largely focussed on impacts near cages (or on farm), and primarily deals with particulate fallout from cages (uneaten food, faecal matter, carrion etc) and fails to consider the cumulative affect of farming operations in a wider spatial context. More mobile waste, such as dissolved carbon, nutrients and fats and oils, from several farming operations has the potential to disperse over a large area and may pose threats to systems that are remote from tuna operations (off farm risks). In addition, highly mobile organisms such as sea birds and marine predators (sharks, dolphins and seals) may be affected by farming operations.

There is a need, therefore, to develop assessment strategies aimed at expanding our understanding of the environmental implications of tuna aquaculture at regional scales. This will ensure the ecological sustainability of the industry that will in turn ensure reduced health risks to stock and allow for longer term industry planning and security of tenure. There is also a need for the regulatory framework to be adequately codified to include regional level impacts of sea-cage aquaculture. This will increase confidence for industry, government and the public through the establishment of an appropriate set of operating guidelines.

Regional environmental monitoring for the tuna industry is anticipated to require an approach with two aspects. Firstly, the development of a monitoring program for the current regional influence of the industry and secondly, the development and parameterisation of large-scale models to understand the environmental implications of expansion into new lease areas.

The Standing Committee on Fisheries and Aquaculture (SCFA) with funding from the FRDC produced the SCFA-FRDC ESD Project, as a guide to the development of a framework for ESD reporting within Australian fisheries and aquaculture. It provides the means for all stakeholders (industry, government regulators and non-government organisations) to participate in the development of an ESD reporting framework that will underpin the adaptive management of the industry. The process requires identification of appropriate environmental performance indicators though an assessment combining current knowledge with an analysis of risks through which a set of research and management priorities can be designated. This information can be further developed into an information gathering process to increase understanding (knowledge) and facilitate the setting of target levels (reducing risk). In the wider context, external threats to the industry and the environment (such as other sources of pollutants other than sea-cages) can be identified. For example, the ESD reporting process may identify white shark abundances and/or areal extent of seagrass beds as indicators of environmental health which may be adversely affected by sea-cage operations. The establishment of a sampling protocol may identify the number of shark entanglements or sightings, while seagrass beds could require measurements of cover or density that may be achieved through a number of methodologies (e.g. diver counts *in situ*, swathe mapping, etc). The status of these parameters can then be employed in the development of target levels as part of ongoing monitoring. Such a process requires close consultation between industry, regulatory authorities and NGO's all of which must agree to contribute to and abide by the reporting process.

The above process will be enhanced through the development and parameterisation of integrated regional scale ecosystem models. This will assist in understanding what impacts might be expected under different farm management regimes within established areas, but will also help determine the likely result of expansion of the industry into new lease zones. Such models are currently being developed for the Tasmanian salmon farming industry and these will be further developed for application in the tuna aquaculture industry. While this model development is not a part of this project, the project will provide a lead-in to developing these models.

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Need

The identification of additional farm sites (to underpin the expansion of the current industry) is fundamentally limited by our lack of knowledge about the regional-scale impacts associated with sea-cage farming. There is a need to provide both industry and regulators with a greater degree of certainty in relation to both planning and environmental assessments of the industry.

Current approaches to monitoring only consider cage-level impacts (on-farm influences). There is no information on the potential effect of the industry on ecosystems that are more remote from operations (off farm influences) or to organisms that may pass through lease areas. Furthermore, there is no information as to the sorts of data that should be collected as measures of sustainability at regional scales. Nor is there any ability to make predictive assessments of the large-scale implications of changes in management or the effect of expansion of farming operations into new areas.

There is a need to develop an understanding of the broader perceptions of the environmental consequences of the tuna industry to allow perceived risks to be independently assessed using existing data from both the local region and international studies, and to allow targeted research on those risks identified as being real and of high priority. This will be achieved through the implementation of the SCFA-FRDC ESD reporting framework.

There is a need to develop a predictive capacity to assess the likely impacts of sea-cage aquaculture on new sites and also the impact of other industries on existing sites. To facilitate this an integrated model incorporating hydrodynamics, nutrient fluxes and ecosystem responses is required. This project will provide some of the information necessary for this model, which will be developed at a later date.

Objectives

1. Establish a steering committee of stakeholders and hold a Steering Committee for Fisheries and Aquaculture Environmental Sustainable Development reporting workshop to develop a set of operational parameters for regional scale environmental sustainable development (ESD) assessment.
2. Develop a set of methodologies for measuring and evaluating each of the parameters in order to provide an ESD assessment.
3. In collaboration with researchers involved in the development of ecosystem scale models for salmon farming, identify the key information/data required to parameterise and validate these models for the tuna industry.
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Chapter 1 Identification and assessment of potential environmental risks for tuna aquaculture in South Australia

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1.1 Executive Summary

Southern bluefin tuna (SBT) aquaculture is the single most valuable sector of South Australia's aquaculture industry. The value of SBT production has risen from $166.7 million in 1998/99 to $266.9 million in 2002/03 (Knight *et al.* 2004). Over the past few years, however, the rise in production and value of this industry sector has levelled off and has even declined as the full available quota was farmed (Knight *et al.* 2004). By 2003/04 the production value of SBT was $151 million (Knight *et al.* 2005). With discussions of longer-term holding, propagation and the possibility of other species being farmed in the vicinity, ecologically sustainable development (ESD) is becoming increasingly important for ensuring the long-term viability of the industry. To further promote, expand, and ensure ESD of the SBT aquaculture industry sector there is a need to assess the risks of associated environmental impacts. This report documents the discussions and comments from a risk assessment workshop held in Adelaide on 6th December 2002 to assess the environmental risks associated with the tuna aquaculture industry in South Australia. This report also includes a literature review conducted in early 2005 of the issues that were considered to be of moderate or high risk. While it was originally intended for the workshop to quantify actual risks, it rapidly became evident that this was not possible, and rather it gave attendees an opportunity to identify what they individually perceived as the risks. In many cases, these perceptions were not backed up by data, so the risk should be considered potential and not actual. The purpose of the subsequent literature review was to further define the risks based on actual data available, either for tuna farming or for other aquculture industries where little or no information could be obtained on tuna farming.

The risk assessment workshop was conducted using the National ESD Reporting Framework for Australian Wild Capture Fisheries. At the time of the workshop, a supplement designed to customise the framework for the aquaculture sector was still under preparation, so could not be used. However, the broad principles and reporting strategies are similar for both sectors. Of the three generic component trees outlined in the framework, two were addressed during the workshop: Component Tree 1 is for the whole of industry issues while Component Tree 2 is for the cumulative impacts that may operate at the catchment or regional level. Component Tree 3, which was not discussed during the workshop due to time constraints, is for effects of individual facilities. Component Trees 1 and 2 were modified so that they were specific for the SBT aquaculture industry. Each issue was discussed in terms of current knowledge and management, and assigned a ranking in terms of the perceived level of risk associated with it. The risk ranking was determined using the Risk Analysis tool outlined in the ESD framework, which was based on the Australian Standard for Risk Management (AS/NZS 4360 SAoA 1999). To assign a level of risk to an issue, two factors must be determined – the potential consequences arising from a particular activity, and the likelihood that these consequences will occur.

The combination of the level of consequence and the likelihood of this consequence gives an estimate of the risk. During the workshop, the risk ranking obtained reflected what the participants considered to be an issue at the time of the workshop given the current situation, rather than what may be expected in the near future if management practices change.

Forty-nine of the 69 issues discussed at the workshop were given a "negligible" or "low" ranking, while a further seven were given either a "low to moderate", or "moderate" ranking. Of the remaining 13 issues, three were given a "moderate to high", "high" or "moderate to extreme" ranking, while the remaining ten issues were not discussed in detail as they were not considered relevant to the SBT industry. After reviewing the available literature, most of the issues identified during the workshop were given a "low" to "moderate" risk ranking for the specific reasons summarised in the table below. While those issues ranked as moderate do need attention, this does not need to be immediate or drastic. An appropriate response to these issues would involve their improvement over a 3-5 year time span to try and reduce the risks to low.

Summary Table of issues originally ranked as moderate or higher risks

Issue	Final Risk Ranking	Specific reasons
1. Impact of feed composition on other species/ community processes	**Low**	▪ Industry has now become less reliant on imported pilchards as the total allowable commercial catch for SA caught sardines has increased. ▪ SA sardines are the most common species of baitfish used as tuna feed. ▪ Enriched diets in pellet form are being developed and tested.
2. Impact of SBT aquaculture on sharks (e.g. dusky & bronze whalers, great whites)	**Moderate**	▪ Industry is concentrated in an area frequently inhabited by sharks, including great whites, thus interactions will continue. ▪ Industry is reliant upon wild captured tuna, which causes interactions with sharks during the towing process. ▪ The risk may be lowered in the near future if devices to repel sharks from cages prove to be effective. ▪ As long as current regulations are followed, it is unlikely that the risk will increase in the near future. ▪ A better system needs to be put in place to significantly improve industry involvement in reporting shark interactions.
3. Effect of nutrients on natural background levels of nutrients	**Low**	▪ Ranking is based on impacts at a regional level; risk would be higher at the farm level. ▪ It is difficult to distinguish the broader effects of tuna farming from natural variability in nutrient levels and other anthropogenic influences. ▪ The ranking should be re-evaluated if farming practices change in the future, in conjunction with current research findings.

Issue	Final Risk Ranking	Specific reasons
4. Impact of SBT aquaculture on bottlenose dolphins	**Low**	▪ Need for more information on the behaviour, ecology and population dynamics of dolphins in order to determine the impacts of tuna aquaculture. ▪ Mortalities have been eliminated due to the removal of predator nets. ▪ Consequence of an interaction is higher for Bottlenose dolphins than Common dolphins due to the low reproductive potential of the population. ▪ Ranking must be reviewed if deterrents or farming practices change.
5. Impact of SBT aquaculture on common dolphins	**Low**	▪ Mortalities have been eliminated due to the removal of predator nets. ▪ Ranking must be reviewed if deterrents or farming practices change.
6. Impact of SBT aquaculture on seals	**Low/Moderate**	▪ Mortalities have been reduced due to the removal of predator nets and introduction of electric fences. ▪ A better system needs to be put in place to significantly improve industry involvement in reporting seal interactions. ▪ Ranking should be reassessed if farming practices change and more information is available in the future.
7. Impact of SBT aquaculture on sea lions	**Moderate**	▪ Slightly higher risk for sea lions than seals as the population is relatively small, static and entanglements are reportedly higher. ▪ Mortalities have been reduced due to the removal of predator nets and introduction of electric fences. ▪ A better system needs to be put in place to significantly improve industry involvement in reporting sea lion interactions. ▪ Ranking should be reassessed if farming practices change and more information is available in the future.
8. Impact of SBT aquaculture on seabirds	**Moderate**	▪ Seagulls may be displacing less common seabirds and disrupting migratory shorebirds. ▪ Seagulls will continue to be a problem as long as baitfish is used as feed. ▪ Ranking should be reviewed if feeding methods change in the future and once current research is complete.
9. Impact of site constraints (e.g. waves, currents)	-	This issue is not a direct risk to the environment so is not discussed further here.
10. Effect of physical structures & construction on navigation	-	This issue is not a direct risk to the environment so is not discussed further here.

1.2 Introduction

Based on successful technology transfer, research and development, and commercialisation (Clarke 1996), a well-established sea-cage southern bluefin tuna (SBT, *Thunnus maccoyii*) aquaculture industry exists in the coastal waters adjacent to Port Lincoln, South Australia. However, there remains some concern to the industry and the wider community of the effects of this sea-cage farming on the local marine environment, while recognising that there are social and economic benefits of aquaculture (Mazur *et al.* 2004). Industry recognises the need to maintain a healthy environment for the fish in order to ensure productivity and commercial viability of the industry, while the wider community wants any effects on the environment to be minimised for other users of the waterways and for environmental conservation (Clarke *et al.* 1999, Clarke *et al.* 2000). As such, to address environmental concerns and to continue working towards environmentally sustainable development (ESD), there is an ongoing need to assess the environmental risks associated with SBT aquaculture in South Australia.

The present report provides a summary of the outcomes from an environmental risk assessment workshop that was held in late 2002 to assess and prioritise the environmental issues associated with SBT aquaculture in South Australia. The main aims of this report are:

1. To document the outcomes from the workshop.
2. To provide a literature review of the issues that were considered to represent a moderate or high risk to the environment. This literature review was undertaken in early 2005.
3. To provide modified risk rankings based on the outcomes of the literature review and stakeholder comments.
4. To update research findings and present current information (as at early 2005) on the environmental status of the tuna industry.

At the time of the SBT workshop in 2002, the Tuna Environmental Monitoring Program (TEMP) was already in place. Therefore the broad intent of the workshop was to create a register of environmental impacts that arise from the farming of SBT and rank them using the ESD risk assessment process. The risk assessments completed at the SBT workshop were based on the National ESD Reporting Framework for Australian Wild Capture Fisheries (Fletcher *et al.* 2002). The aquaculture supplement to the ESD Reporting Framework, which was published in 2004 (Fletcher *et al.* 2004) was not available at the time of the workshop, but the draft was available for use by a series of ESD risk assessment workshops conducted in 2003 as part of the "Environmental audit of marine aquaculture developments in South Australia" project. This series of workshops covered Marine Finfish Aquaculture, Intertidal Shellfish Aquaculture and Land-Based Abalone Aquaculture. The main objective of this 'audit' project was to develop aquaculture sector-based optimal environmental monitoring programs, including identifying the parameters to be measured (environmental as well as farm management), the spatial and temporal frequency of monitoring required, and select critical decision points against which ESD performance can be measured.

1.2.1 History

The global fishery for SBT began in the 1950's with Japan exploiting stocks on the high seas, and Australia within its coastal waters. The Australian industry continued to expand over the next 30-40 years, with the introduction of larger pole boats and purse seiners and the use of long range spotting aircraft to detect schools of fish (Hayes 1997). Major increases in fishing effort saw a peak in the total catch of SBT by the mid 1980s. Over the next few years, catch limits were rapidly reduced to allow the spawning stock to regain the abundance levels present in 1980 by the year 2020. The most dramatic cuts in catch limits available to the Australian industry were seen in 1989 (Young 2001).

Following this reduction in catch limits, the first experimental tuna farm was established in Boston Bay, Port Lincoln in 1991 by the Japanese Overseas Fishery Cooperation Foundation (OFCF) in collaboration with the South Australian Government and the Tuna Boat Owners Association of South Australia (TBOASA) and funding from FRDC Project Number 1991/056. However, it was not known whether tuna could be successfully captured live, and held and grown in sea cages (or pontoons) (PIRSA Aquaculture 2002). The experimental farm proved to be a success and the tuna aquaculture industry began to develop rapidly. During the first few years (1992/93) of farming, the industry turned over $6 million and has grown significantly since then. In 1999/2000, farms produced about 7,780 tonnes (gilled and gutted) of tuna valued at over $202 million. By 2002/03 the production was 9,100 tonnes with a value of $266 million ((Knight *et al.* 2004). By 2003/04, all available quota was being farmed, and production remained at about 9,290 tonnes but value decreased to $151 million because of changes in market competition (Knight *et al.* 2005).

1.2.2 The present situation

Currently, the farming of SBT is the single most valuable sector of South Australia's aquaculture industry. The value of SBT equated to 81% ($151 million) of the total value of aquaculture production in South Australia during 2003/04 (Knight *et al.* 2005). There were 16 companies potentially using 29 lease sites in 2004 (Figure 1.1). Farming sites range from 20 to 200 ha in area with a total of 1794 ha allocated for SBT production, although only a portion of this area is used in any one season (PIRSA-Aquaculture 2005). Consequently, the industry has become a significant employer in the Port Lincoln region (EconSearch 2004). Considerable research in areas such as tuna nutrition, health and environment are in progress and these are currently being conducted primarily through the Cooperative Research Centre for the Sustainable Aquaculture of Finfish (Aquafin CRC). Findings from these projects are facilitating more efficient production, and are also helping to minimise impacts of tuna aquaculture on the environment.

Juvenile fish (15-25 kg) are caught from December to March in the Great Australian Bight using purse seine techniques under a strict quota system. The fish are then transferred through underwater raceways to special purpose-built towing cages. These cages are then towed at a slow steady speed of no more than 1 knot to Port Lincoln where the fish are transferred into sea cages. A standard holding sea cage consists of single or double circular rings made from high-density polyethylene plastic, usually 40 m in diameter. A net, generally 150 mm in mesh size, is attached to the floating pontoon and has sides that drop to not less than 5 m above the sea floor (in water depths ~ 20 m). Initially, predator nets were widely used to keep sharks and seals away from the tuna. However, the use of predator nets was discontinued in the mid to late 1990's. A sea cage can hold up to 2,000 tuna, depending on the diameter of the cage and the maximum stocking rate set by the licence, which is currently 4 kg/m^3 (PIRSA Aquaculture 2002), but generally farms have only about 1700 fish in a 40 m diameter cage. Tuna are fed once or twice daily, six or seven days a week depending on season, with sardines (*Sardinops neopilchardus*) caught in South Australian waters being the most common species of baitfish used, along with Australian caught redbait (*Emmelichthys nitidus nitidus*). Enriched diets in pellet form have been developed and tested commercially, but at present they are not competitive in price with local caught baitfish.

SBT are fattened and conditioned in the sea cages and reach a suitable condition and a marketable size of 30-40 kg in approximately 3 to 5 months; however, this largely depends on the size of the fish at capture and the condition index the fish has attained at harvest time. Once the tuna are harvested, they are exported whole for the sashimi market in Japan. Approximately 75% of the tuna are sent as fresh product by air, and the balance as frozen product by sea, although these figures do change annually (PIRSA Aquaculture 2004). Generally, tuna fetch approximately \$20 to \$30 per kg depending on the method of sale (David Ellis, pers. comm. 20th May 2005).

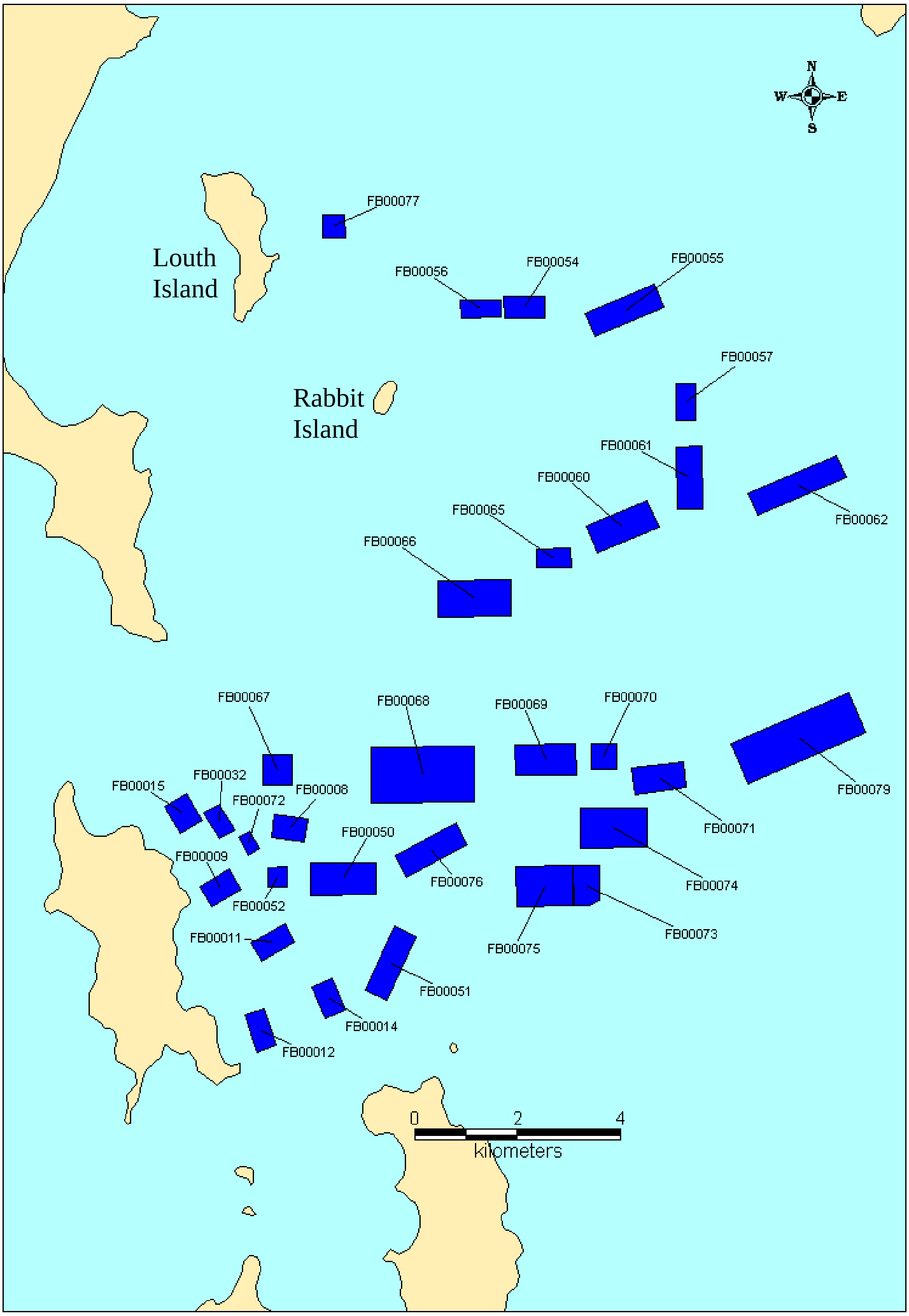

Figure 1.1. Map of Port Lincoln region, South Australia, showing the locations of SBT aquaculture leases in the 2004/05 farming year (from PIRSA Aquaculture, 2004).

1.3 Risk Assessment

Framework

In order to identify and prioritise the potential environmental issues associated with SBT aquaculture in South Australia, a formal risk assessment process was used. The risk assessment was conducted using the National ESD reporting framework for Australian Wild Capture Fisheries (Fletcher *et al.* 2002, see http://www.aquaesd.com for further references). This "How To" report provided a framework that could be used consistently across all fishery sectors in Australia (Fletcher *et al.* 2002). The framework is based on the Australian standards for risk management (AS/NZS 4360 SAoA 1999), which is used to conduct risk assessments for a wide variety of other industries. To assist in identifying issues specific to the aquaculture industry, a set of generic "component trees" were developed in conjunction with the National Aquaculture Council (Fletcher *et al.* 2004) and the Marine and Coastal Committee of the Natural Resources Management Committee (NRMC). These component trees are a mechanism to simplify the identification process by subdividing the variety of potential environmental impacts into different categories:

1. General or industry level impacts
2. Catchment or regional level impacts
3. Farm or site level impacts

Each issue within a tree is assigned a ranking using a risk analysis tool outlined in the ESD framework (Fletcher *et al.* 2002). To assign a level of risk to an issue, two factors must be determined – the potential consequence arising from a particular activity, and the likelihood that this consequence will occur. The combination of consequence and likelihood produces an estimate of the risk associated with a particular issue. The main aim of the risk assessment is to determine if current management practises are sufficient, so these need to be considered when determining the consequence and likelihood levels. Each issue is assigned a level of consequence (from negligible to catastrophic) and likelihood (from remote to likely). In assigning a likelihood level it is important to remember that an assessment is being made of the likelihood of that consequence occurring and not the likelihood of that particular activity occurring. The consequence and likelihood levels are determined using the tables outlined in the framework (Table 1.1 and Table 1.2). The risk value and ranking for each issue are then determined using a risk matrix (Table 1.3). Each risk ranking has an associated level of management response and reporting requirements (Table 1.4).

Assignment of likelihood and consequence levels is best done in a workshop involving all relevant stakeholders, including industry, government and commercial representatives. These levels are somewhat subjective, and therefore a process to develop a consensus view is needed for the subsequent risk rankings to be generally accepted. If a specific group is allowed to dominate, the results of the workshop could be skewed towards the views of that group, thus care needs to be taken to ensure that all views are fully heard and considered.

Table 1.1. The Consequence Table for use in ecological risk assessments related to aquaculture (adapted from Fletcher *et al.* 2002).

Level	Descriptor
Negligible (0)	Very insignificant impacts. Unlikely to be even measurable at the scale of the stock/ecosystem/community against natural background variability.
Minor (1)	Possibly detectable but minimal impact on structure/function or dynamics.
Moderate (2)	Maximum appropriate/acceptable level of impact (e.g. full assimilation rate for nutrients).
Severe (3)	This level will result in wider and longer-term impacts now occurring (e.g. increased plankton blooms).
Major (4)	Very serious impacts now occurring with relatively long time frame likely to be needed to restore to an acceptable level.
Catastrophic (5)	Widespread and permanent/irreversible damage or loss will occur – unlikely to even be fixed (e.g. extinctions).

Table 1.2. Likelihood definitions (adapted from Fletcher *et al.* 2002).

Level	Descriptor
Remote (1)	Never heard of, but not impossible
Rare (2)	May occur in exceptional circumstances
Unlikely (3)	Uncommon, but has been known to occur elsewhere
Possible (4)	Some evidence to suggest this is possible here
Occasional (5)	May occur
Likely (6)	It is expected to occur

Table 1.3. Risk matrix – the numbers in the cells indicate the risk value and the shaded boxes indicate the various levels of risk ranking (adapted from Fletcher *et al.* 2002).

		Consequence					
		Negligible	**Minor**	**Moderate**	**Severe**	**Major**	**Catastrophic**
Likelihood		**0**	**1**	**2**	**3**	**4**	**5**
Remote	**1**	0	1	2	3	4	5
Rare	**2**	0	2	4	6	8	10
Unlikely	**3**	0	3	6	9	12	15
Possible	**4**	0	4	8	12	16	20
Occasional	**5**	0	5	10	15	20	25
Likely	**6**	0	6	12	18	24	30

Note: The risk level is calculated by multiplying the likelihood value by the consequence value

Table 1.4. Suggested risk rankings and outcomes (adapted from Fletcher *et al.* 2002).

Risk Rankings	Risk Values	Explanation & Likely Management Response	Likely Reporting Requirements
Negligible	0	Nil	Short justification only
Low	1 – 6	Non-specific	Full justification needed
Moderate	7 – 12	Specific management needed	Full performance report
High	13 – 18	Possible increases to management activities needed	Full performance report
Extreme	> 19	Likely additional management activities needed	Full performance report

Workshop

To undertake a successful environmental risk assessment, all of the relevant environmental issues need to be identified. Identification of all issues can only be achieved when opinions and thoughts are obtained from a number of stakeholders/stakeholder groups. Workshops have been widely recognised as one of the most efficient ways to gather all of the information required for a formal risk assessment. Consequently, an environmental risk assessment workshop was held at the South Australian Aquatic Sciences Centre on the 6th December 2002 using the National ESD Reporting Framework for Australian Wild Capture Fisheries (Fletcher *et al.* 2002). Various stakeholders, including government, industry and community groups, were invited to participate in the workshop. Attendees came from 13 different organisations, comprising SARDI Aquatic Sciences, PIRSA Aquaculture, Environmental Protection Agency, Department of Environment and Heritage, Whale and Dolphin Society, CSIRO Marine Research, Planning SA and industry representatives (section 1.11). The convener for the workshop was Dr Stephen Madigan (then at SARDI Aquatic Sciences, currently PIRSA Aquaculture) and the facilitator was Dr Rick Fletcher (ESD Subprogram Leader, Department of Fisheries, Western Australia).

Three component trees modified from the generic trees for wild capture fisheries were presented at the workshop. Component Tree 1 (Figure 1.2) is for the whole of industry issues while Component Tree 2 (Figure 1.3) is for the cumulative impacts that may operate at the catchment or regional level. Component Tree 3 (section 1.12), which is for effects of individual farms or sites, was not discussed during the workshop due to time constraints.
During the workshop, each generic component tree was further modified to produce trees specific to the South Australian SBT aquaculture industry. This process either added issues or identified issues that did not pose an immediate risk (highlighted grey boxes in the component trees), although their level of risk may change with time. Each issue was then discussed in terms of the current knowledge and management and assigned a risk ranking based on the perceived risk associated with that particular issue. The participants of the workshop were asked to score consequences and likelihood based on current control measures, and not what they perceived to be a risk in the near future (i.e. five years), thus potential changes in management practices were not taken into account. Furthermore, comments and justifications from workshop participants leading to these rankings were also limited. Comments given for the risk rankings during the workshop are included in the appropriate sections of this report and summarised in section 1.13.

Although a modified version of the National ESD reporting framework for Australian Wild Capture Fisheries was used to perform the risk assessment for SBT Aquaculture, it is not the aim of the present document to produce a full ESD assessment and report. The workshop was aimed at creating a register of the main potential environmental impacts that arise from the farming of SBT. Therefore in this report, a brief literature review is given for all issues rated as moderate, high or extreme risk, without conducting a full performance report. This literature review re-evaluated the risk rankings and subsequently helped to prioritise the potential environmental impacts of SBT aquaculture in South Australia.

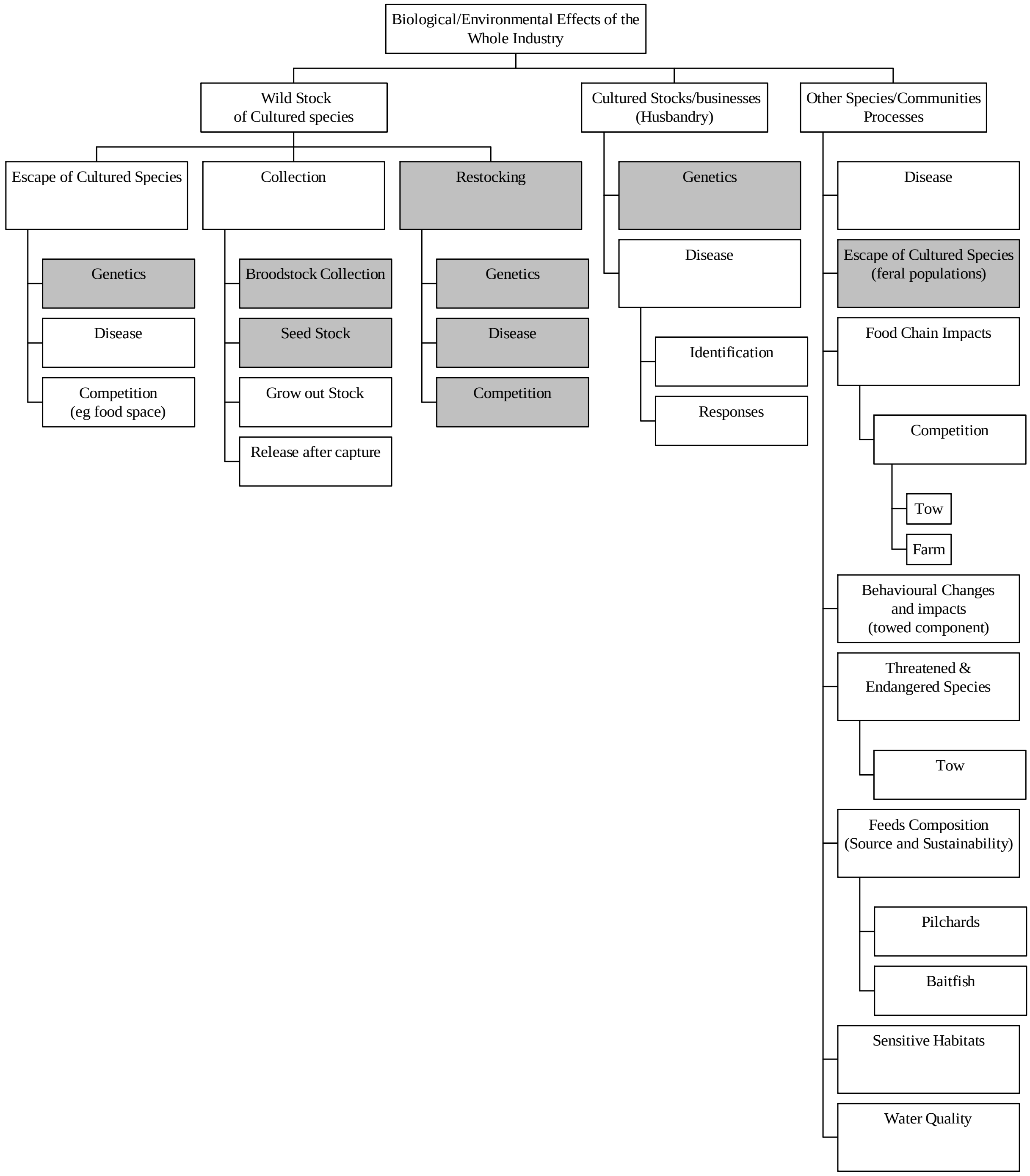

Figure 1.2. Component Tree 1 - General or whole industry level impacts of SBT aquaculture on the environment (adapted from Fletcher *et al.* 2002 and modified during workshop). Issues highlighted in grey were not discussed during the workshop

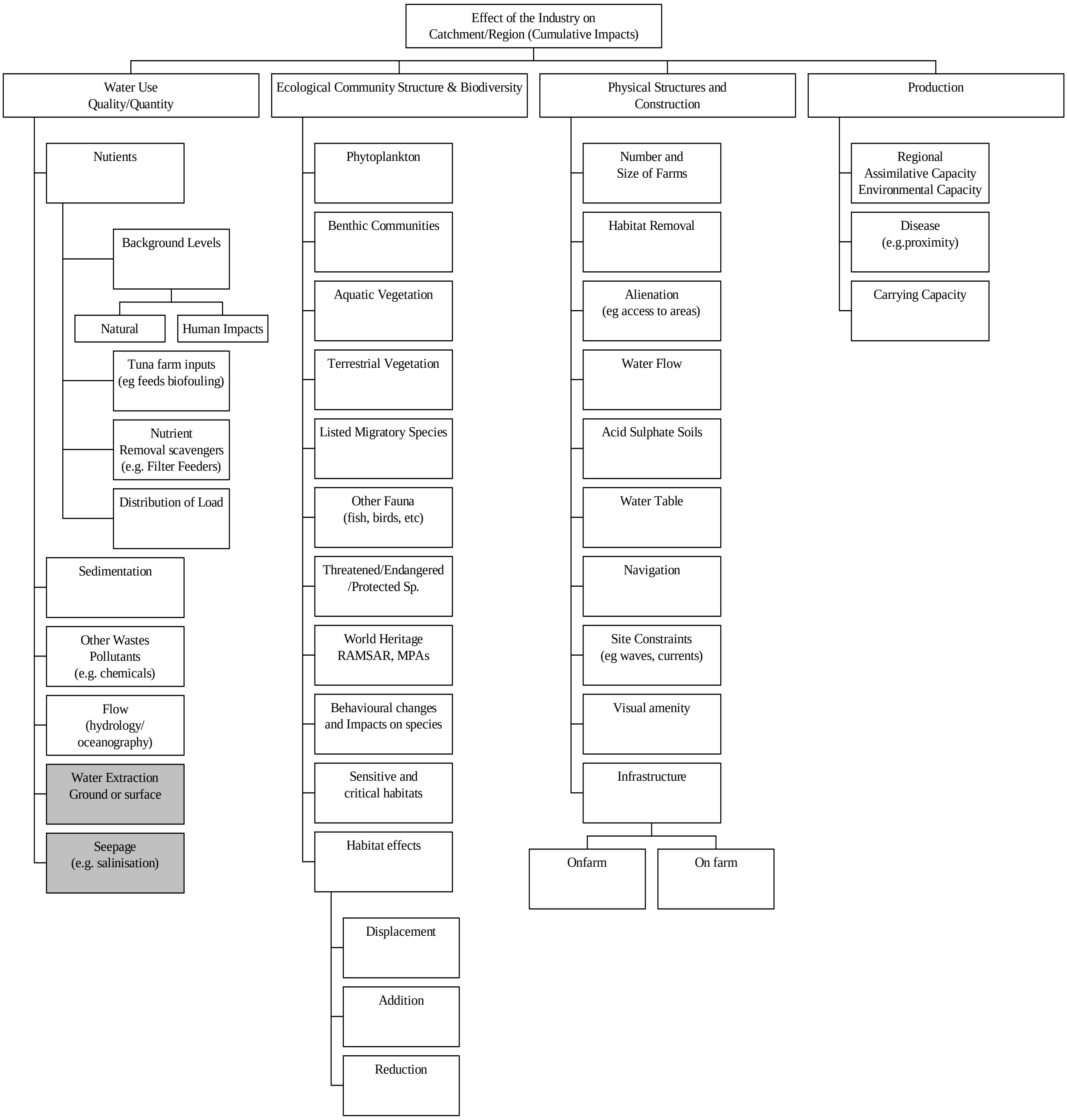

Figure 1.3. Component Tree 2 – Catchment or regional level impacts of SBT aquaculture on the environment (adapted from Fletcher *et al.* 2002 and modified during workshop). Issues highlighted in grey were not discussed during the workshop.

1.4 Results

Component Tree 1 (General or Industry) and Component Tree 2 (Catchment or Regional) were discussed in detail. Of the 69 issues discussed during the workshop, ten issues received low/moderate to extreme risk rankings (Table 1.5). Nine of these issues are discussed in this report. Issues relating to the effects of physical structures and construction associated with the industry on navigation received a high risk ranking during the workshop, but are not covered in this report, as these issues were not considered a direct risk to the environment (Table 1.5). Issues with a risk ranking of moderate or high fell into three broad groups. The first group were issues related to Threatened/Endangered/Protected species, where risk rankings ranged from low/moderate to extreme. The second group consisted of a single issue related to feed composition with a low/moderate risk ranking. Similarly the third group had a single issue on water quality, mainly related to nutrient levels, which had a moderate risk ranking (Table 1.5). These rankings could be viewed as a negative outcome for the SBT aquaculture industry because a high ranking indicates a need for immediate increased management, and an extreme ranking suggests that careful consideration needs to be given to the continued existence of the industry. However, it must be noted that these risk rankings are based on the perception of individuals who may not have access to all available data and it was acknowledged that a fully informed assessment was not possible. Accordingly, these rankings were reassessed after an extensive literature review, as described later in this report.

The remaining seven issues discussed in this report had a low/moderate or moderate risk ranking, indicating that they may require further management or research. However, management responses to moderate issues do not need to be immediate or drastic, and would generally involve continuous improvements over the next five to ten years to reduce the risk to a low ranking.

Table 1.5. List of environmental issues from Component Tree 1 (General or Industry) and Component Tree 2 (Catchment or Regional) that were given a low/moderate, moderate and high risk rankings during the workshop. The consequence, likelihood and risk values are given.

Issue	Component Tree	Consequence	Likelihood	Risk Ranking	Revised Risk Ranking*
1. Impact of feeds composition on other species/ community processes	Tree 1 General or Industry	3	1-4	3-12 Low-Moderate	**Low**
2. Impact of SBT aquaculture on sharks (e.g. dusky & bronze whalers, great whites)	Tree 1 General or Industry	3	1-3	3-9 Low-Moderate	**Moderate**
3. Effect of nutrients on natural background levels of nutrients	Tree 2 Catchment or Regional	3	4	12 Moderate	**Low**
4. Impact of SBT aquaculture on bottlenose dolphins	Tree 2 Catchment or Regional	3-4	4-5	12-20 Moderate-Extreme	**Low**
5. Impact of SBT aquaculture on common dolphins	Tree 2 Catchment or Regional	3	4	12 Moderate	**Low**
6. Impact of SBT aquaculture on seals	Tree 2 Catchment or Regional	1-2	4	4-8 Low-Moderate	**Low - Moderate**
7. Impact of SBT aquaculture on sea lions	Tree 2 Catchment or Regional	3	4	12 Moderate	**Moderate**
8. Impact of SBT aquaculture on seabirds	Tree 2 Catchment or Regional	3-4	4	12-16 Moderate-High	**Moderate**
9. Impact of site constraints (e.g. waves, currents)	Tree 2 Catchment or Regional	2	6	12 Moderate	**Not a direct risk to the environment**
10. Effect of physical structures & construction on navigation	Tree 2 Catchment or Regional	4	4	16 High	**Not a direct risk to the environment**

*The revised risk ranking resulted from re-evaluation after the literature review.

1.5 Discussion

Extensive research overseas has demonstrated the various potential effects of sea cage finfish farming on the environment (e.g. Pearson and Rosenberg 1978, Gowen and Bradbury 1987, Gowen 1991, Findlay and Watling 1995, Henderson and Ross 1995, Pearson and Black 2001, Gardner and Peterson 2003, Weber 2003, Boyra *et al.* 2004). SBT aquaculture in Port Lincoln has been in operation since 1991. In 1992, a workshop was organised by the former Department of Fisheries to assess available information on the environmental effects of fish farming and prioritise elements for a proposed environmental monitoring program (Clarke *et al.* 1999, Clarke *et al.* 2000). Although the majority of the information was from countries other than Australia, many of the issues discussed in the literature were relevant to the South Australian tuna aquaculture industry. The workshop reaffirmed findings in the literature, which suggested that significant localised impact would likely result from commercial scale SBT aquaculture. The three potential impacts highlighted were:

- Shading and reduced amount and intensity of light reaching the benthos as a consequence of the pontoons, their nets and associated biofouling communities.
- Smothering of benthic communities due to increased particulate matter, surplus food, organic excretory wastes and the deposition of biofouling from the nets and pontoons.
- Increased nutrient levels in water column and phytoplankton abundance resulting from nutrients from SBT excretory products and leaching from feeds.

These impacts were expected to be most pronounced in the vicinity of the pontoons and decline rapidly with increasing distance from the pontoons. Cheshire *et al.* (1996) found that epibenthic communities were impacted up to a distance of 150 m and benthic infauna were impacted up to 20 m from tuna cages in Boston Bay. Resuspension of seafloor sediments that smother benthic communities was the most likely factor responsible for the mass mortalities of farmed SBT within and adjacent to Boston Bay in April 1996 (Clarke 1996). In order to reduce the impacts of SBT aquaculture on the marine environment, tuna cages were moved to more exposed sites offshore from Boston Island. A monitoring program was therefore established in 1996 to assess the extent of impacts from the tuna farms on the environment and to ensure the productivity and commercial viability of the farms (Clarke *et al.* 1999). The monitoring program involved:

- Monitoring of water quality including nutrients and physical parameters.
- Monitoring of phytoplankton composition and abundance from water samples.
- Monitoring of benthic conditions including sediment particle size, organic content, infauna, waste feed, undulations and organic detritus.

This form of monitoring was carried out until 1999, after which time the focus was changed from broad-scale sampling to one that focussed on changes along gradients away from pontoons (Clarke *et al.* 2000). This monitoring program was further revised in 2001 and now involves monitoring the influence of the industry on the environment using a license-based monitoring approach (Madigan *et al.* 2001). As of 30th June 2003, the Environmental Monitoring Program (EMP) requirements for a Marine Tuna Aquaculture license comprised of two components, namely Farm Management and Benthic Assessment (PIRSA Aquaculture 2003a). The Benthic Assessment component (PIRSA Aquaculture 2003a) consists of:

- A qualitative comparison of the biota and the sediment appearance videotaped from transects on the sea floor, from two on-site (lease) transects and one off-site (control) transect. This has since been dropped.
- A quantitative comparison of the characteristics of the benthic infaunal communities at potentially impacted locations of the licence area (150 m from the lease boundary) being monitored and control locations.
- A quantitative comparison of particle size of the sediment at potentially impacted locations and control locations.

No effects of aquaculture had been discernible from the video recordings in the previous four years of the Monitoring Program, so the video method was excluded from the 2004 Program at the request of PIRSA. The assessment of benthic sediment samples gives a measure of the abundance of infauna (number of individual organisms) and the number of taxonomic groups of infauna (e.g. families or species). Any differences between naturally undisturbed communities and potentially impacted communities give an indication of environmental impact from organic enrichment (Pearson and Rosenberg 1978).

The data collected from these monitoring programs not only fulfil licensing requirements, but also describe the spatial and temporal patterns of the "natural" environment as well as those associated with SBT farms. Additionally, research projects associated with SBT aquaculture provide the opportunity to develop methods for assessing environmental changes and a better understanding of the underlying processes, which maintain the ecosystem (Madigan *et al.* 2001).

The issues presented in the following sections were given a risk ranking of 'moderate' or higher during the workshop. For each issue, the comments and risk assessment values determined during the workshop are summarised (Table 1.6 to Table 1.14). All the issues discussed and comments given during the workshop are tabled in 1.13.

Each summary table of the issues presented below is followed by a brief review of the current knowledge and literature and these are discussed in terms of their implications for the South Australian SBT aquaculture industry.

1.6 Other species/communities and processes

Four issues relating to SBT Aquaculture were identified under the 'other species/communities and processes' level of the whole industry component tree (Figure 1.2). These issues were:

1. Disease of escaped farmed species
2. Competition by farmed species
3. Sharks (e.g. dusky & bronze whalers, great whites)
4. Impacts of imported feed on other elements

Only issues relating to impacts of imported feed on other elements (#4, Table 1.6) are discussed in this section as the risk associated with issues 1 and 2 were identified as "low" and issues relating to sharks (#3) are included in the Threatened/Endangered/Protected species section (Section 1.7).

1.6.1 Impact of imported feed on other elements

The risk assessment values for impact of imported feed on other elements included a score of 3 for consequence and a likelihood of 1/4 giving a risk value of 3/12 and a risk ranking from low to moderate (Table 1.6).

Table 1.6. Summary of workshop comments and risk assessment values for the issue relating to the use of imported feed for tuna aquaculture. Wherever possible the exact comments have been included, however, additional words and phrases may have been added to improve readability and understanding.

Description	*What are the impacts of imported feed on other elements?*			
Level of impact	Whole of Industry			
Workshop comments	▪ Disagreement on the level of consequence based on whether or not previous "pilchard kill" incidents were associated with the importation of pilchards for feeding tuna. ▪ Incidents have occurred twice over the past 10 years; therefore it is possible that it may occur again. ▪ Biosecurity Australia should address this issue. ▪ Management plans put in place by Biosecurity Australia have reduced this risk to negligible, therefore the likelihood, based on current management practices, is low. ▪ Are the management changes making any substantial differences in risk/likelihood?			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3	1/4	3/12	Low to Moderate

Current knowledge

There were differences in opinions during the workshop on the level of consequence based on whether previous "pilchard kill" incidents were associated with the importation of pilchards for feeding tuna. Tens of thousands of tonnes of imported, untreated (frozen whole) pilchards, *Sardinops sagax,* and other baitfish species, were placed annually into the marine environment to feed caged SBT, as well as for lobster, long-lining and recreational fisheries. From the beginnings of the SBT industry, the amount of imported tuna feed gradually increased from around 10,000-16,000 tonnes in 1995 to 40,000-50,000 tonnes in 2001 (Gaughan 2002). However, this has now decreased as the Total Allowable Commercial Catch (TACC) for the local pilchard (now Australian sardine) fishery has increased since 2000 (Ward *et al.* 2004). While imported feed is still used, it is now in the minority.

Mass mortalities of pilchards spread rapidly throughout this species' range in Australia during 1995 and 1998/1999. These 'pilchard kill' events dramatically decreased the population size and represent the two most extensive mass mortalities recorded for marine organisms (Gaut 2000, Gaughan 2002). Mortalities spread around the temperate and subtropical coastline of Australia from the central coast of South Australia. A majority of the affected fish were adults (>10 cm in length) and mortalities in other species of finfish or even juvenile pilchards were not recorded (Whittington *et al.* 1997, Fletcher *et al.* 1995). No predators or scavengers died from consuming any infected pilchards, and fatalities lasted for only a few days at any one location, diminishing with time and distance from the origin (Fletcher *et al.* 1995). Following the second event, the Joint Pilchard Scientific Working Group oversaw the production of a report that thoroughly reviewed all documented work on the mortality events (Gaut 2000), and this remains the most comprehensive source of information on these events.

During the 1995 incident, pilchard mortalities were first reported in March in South Australia in the eastern region of the Great Australian Bight (western Eyre peninsula). Dead pilchards were subsequently found to the east and west of this point and the spread reached Albany in Western Australia and Bass Strait in Victoria by May (Fletcher *et al.* 1995). By the end of June, dead pilchards had been found up both coasts, reaching Carnarvon in Western Australia and Noosa Heads in Queensland, thereby spanning 6700 km of Australian coast (Fletcher *et al.* 1995, Department of Agriculture Fisheries and Forestry 2003)(Figure 1.4). Similar mortalities also occurred on the north east coast of New Zealand, which continued to spread towards the north and south islands (Whittington *et al.* 1997).

A similar outbreak occurred during 1998/1999, however, the spread of mortalities was considerably slower than that seen in 1995. Pilchard mortalities spread from South Australia to the south coast of Western Australia, the coast of Victoria and then to the New South Wales coast, north of Sydney (Gaughan 2002) (Figure 1.4). Even though the geographical distribution of this incident was more 'patchy' than in 1995, mortality rates in Australia's largest pilchard fisheries, located in Western Australia and South Australia, were independently estimated to be around 60-70% of the spawning biomass (Ward *et al.* 2001).

Both incidents not only impacted the Australian pilchard population size, but may have also impacted on a number of vertebrates that are known predators of pilchards, including penguins (Jarman *et al.* 2004), gannets (Brothers *et al.* 1993), Australian fur seals (Jarman *et al.* 2004), short-beaked common dolphins and Indo-Pacific dolphins (Kemper and Gibbs 2001, Kemper *et al.* 2003). It has recently been concluded that the death and the decreased breeding success of little penguins (*Eudyptula minor*) (Macleod *et al.* 2004a) and the decreased breeding success and survival of the Australasian gannet (*Morus serrator*) (Bunce and Norma 2000) was a result of the "pilchard kills' in 1995 and 1998/1999, respectively.

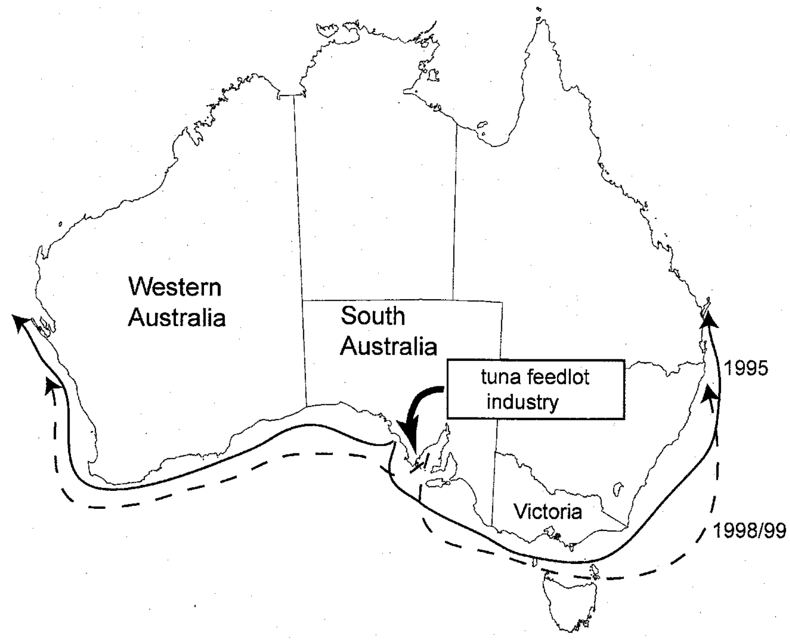

Figure 1.4. Geographical distribution of the mass mortalities of pilchards during 1995 and 1998/1999; starting from central South Australia and spreading to as far as northern New South Wales in the east and south-western Western Australia in the west (from Gaughan 2002).

The pathogen responsible for the mass mortalities during 1995 and 1998/1999 was eventually identified as a previously unknown herpes virus(es) and was named 'Pilchard Herpes Virus' or PHV (Hyatt *et al.* 1997). Both incidents occurred in a way (i.e. dramatic spread through the species' entire range, focal origin, no previous similar events) that was indicative of a novel Herpes virus to which the Australian pilchards had not been exposed to previously (Gaughan 2002, Fletcher *et al.* 1995). PHV causes thickening of the gill epithelium (hyperplasia) and leads to death by asphyxiation.

Several hypotheses have been investigated to explain the apparent introduction of the pathogen responsible for the 'pilchard kills', including ballast water, seabirds, imported baitfish, and the remote possibility of a latent herpesvirus (Whittington *et al.* 1997). Given that the two mass mortalities of pilchards occurred in Australian waters within the 6-year period that this same species was imported in large quantities and the non-random origin of both incidents close to where the largest quantities of imported pilchards entered the water, it has been suggested that imported pilchards might be the source of PHV (Gaughan 2002). While neither event appeared to start in the immediate vicinity of the tuna farming operations off Port Lincoln, they did occur close enough that it is reasonable to expect pilchards to be able to swim from this area to the areas where mortalities were first reported within the latent period of the virus (Ward *et al.* 1999). However, while the 1995 event occurred in the middle of the farming season, the 1998 event occurred after the farming season finished (Gaut 2000). Thus, there is no definitive evidence that the virus was introduced in frozen pilchards fed to tuna, although this possibility cannot be ruled out (Ward et al. 1999, Gaut 2000). It is highly likely that this pathogen was translocated across geographic boundaries because the Australian pilchards (*Sardinops*) had a different immunity profile to the imported pilchards (Gaut 2000, Gaughan 2002).

The current quarantine conditions for importation of marine fish are based on an import risk analysis (IRA) conducted in 1999. These import conditions distinguish between 'non-specified' and 'specified' species, where 'specified' species are those that pose a significantly higher quarantine risk with regard to identified diseases (Biosecurity Australia 2001). As PHV has not yet been traced back to imported pilchards and pilchards currently have a 'non-specified' status, there has been no IRA on pilchards in Australia, despite the magnitude of the past two incidents (Gaughan 2002).

More recently, Biosecurity Australia reviewed quarantine conditions for Californian pilchards (*Sardinops sagax*), and closely related species, following the discovery of a viral haemorrhagic septicaemia virus (VHSV) in 2001 (Biosecurity Australia 2002). Interim quarantine measures were put in place to reduce the risk of translocating VHSV into Australian waters. These measures were additional to those determined by the 1999 IRA for the importation of marine fish in general. VHSV is a significant disease in a range of fish species exotic to Australia; it is often lethal to susceptible fish (Biosecurity Australia 2001). VHSV, the causative agent, is a rhabdovirus that does not necessarily cause visible lesions during early stages of development, but is easily spread among cultured and feral or wild fish. It is therefore listed as a notable disease by the Office International des Epizooties (OIE) and the latest version of the OIE Aquatic Animal Health Code/Manual lists pilchard as a VHSV susceptible species (Biosecurity Australia 2001). The quarantine risk associated with VHSV is related to ambient water temperature and is restricted to periods of low water temperature (agent transmission is not reported to occur above 15^{o}C) (Biosecurity Australia 2001).

Even though several hundred thousand tonnes of pilchards were imported for use as bait and tuna feed prior to the introduction of restrictions in 2002, VHSV has never been reported in Australia (Biosecurity Australia 2003) and was not linked to the 'pilchard kill' in 1995 and 1998/1999. A draft policy review by Biosecurity Australia is now complete and indicates that the VHSV risk associated with importation of frozen pilchards for bait or aquaculture is very low and therefore does not require additional risk management measures beyond those established by the 1999 IRA (Biosecurity Australia 2003). These conditions allow the Australian Quarantine and Inspection Service to grant import permits for low risk (or 'non-specified') species on the basis that health certification is provided. Therefore, the interim control measures for managing VHSV risk have been lifted.

As a result of the mass mortality events in South Australia, SARDI Aquatic Sciences started annual assessments of the spawning biomass of Australian sardine. These assessments have shown that the South Australian sardine population has recovered rapidly from these events (Ward *et al.* 2001, Ward *et al.* 2004). The most recent stock assessment (2004) showed that the pilchard stock is continuing to recover, with an estimated 9% increase (292,076 tonnes) in the spawning biomass when compared to the 2003 spawning biomass (269,063) (Ward *et al.* 2004). The TACC for the fishery has consequently also increased rapidly since 2000.

A risk ranking of "low" is more appropriate than "moderate" as the industry has now become less reliant on imported pilchards. This change is related to the increase in TACC for the pilchard fishery, which has made South Australian caught pilchards (officially now known as Australian sardines) the most common species of baitfish used as tuna feed. Enriched diets in pellet form have been developed and tested commercially, but at present they are not competitive in price with local caught baitfish. However, it is important that the tuna aquaculture industry continues to have such strategies to minimize reliance on the importation of pilchards for use as feed. Continued use of imported fish feed may allow the entry, establishment and spread of disease agents.

Revised Risk Ranking: Impact of Imported Feeds – Low

1.7 Protected/Threatened/Endangered species

Five issues relating to Threatened/Endangered/Protected species were identified in the Region/Catchment level component tree for SBT aquaculture (Figure 1.3). These issues were:

1. Bottlenose dolphins
2. Common dolphins
3. Seals
4. Sea lions
5. Seabirds

The first two issues on dolphins have been combined in the ensuing discussion even though they received different risk rankings during the workshop. The risk ranking for dolphins ranged from "moderate" to "extreme" (Table 1.7 and Table 1.8).

Seals and sea lions have also been combined in the discussion with risk rankings ranging from "low" to "moderate" (Table 1.9 and 1.10). The risk ranking for issues relating to seabirds was "moderate" to "high" (Table 1.12). While issues relating to sharks were identified with a risk ranking of "low" to "moderate" at the whole industry level under "Other species/communities and processes" (Section 1.6), they also are being discussed in this section as the great white shark is a protected species and other shark species are considered 'near-threatened'.

1.7.1 Dolphins (Bottlenose & Common)

The risk ranking for entanglement of bottlenose dolphins was "moderate to extreme" while that for common dolphins was "moderate" (Table 1.7 and Table 1.8).

Table 1.7. Summary of workshop comments and risk assessment values for the issue of bottlenose dolphin entanglements in tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What impact does entanglements in tuna cages have on bottlenose dolphins?*			
Level of impact	Whole of Industry			
Workshop comments	▪ Higher consequence score based on smaller family/gene/pod population size, not the entire stock/population level. ▪ What level of mortality is occurring? ▪ Predator nets have been removed and entanglement has been reduced, but this may not stop changes in feeding behaviour.			
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b).			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3/4	4/5	12/20	Moderate/Extreme

Table 1.8. Summary of workshop comments and risk assessment values for the issue of common dolphin entanglements in tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What impact do entanglements in tuna cages have on common dolphins?*			
Level of impact	Whole of Industry			
Workshop comments	▪ More work required because individuals around tuna pontoons have different stomach contents, reflecting altered diet. ▪ Detrimental changes in feeding behaviour in young may occur. ▪ Tuna pontoons only present for 5 months of the year.			
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b)			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3	4	12	Moderate

A literature review on the interaction between dolphins and finfish aquaculture has been conducted (De Jong and Tanner 2004). While the review covered issues discussed during the "Environmental Risk Assessment Workshop for Marine Finfish Aquaculture in South Australia", many references were made to the tuna aquaculture industry in South Australia. As such, parts of the review, with modifications, are included in this section.

Current knowledge

A number of dolphin species are found in the Spencer Gulf region (Parsons Brinkerhoff and SARDI Aquatic Sciences 2003a, 2003c, 2003b). There are some anecdotal observations of behavioural changes in dolphins around aquaculture leases, but these have not been quantified. The potential impacts of aquaculture on dolphins can be either direct, by incidental capture, or indirect, through competition for food and changes in habitat. Dolphins can be attracted to farms due to the increased number of wildfish that feed on the excess feed around the farms or use the cages as fish attracting devices (Wickens 1995, Kemper and Gibbs 1997, 2001, Kemper *et al.* 2003). Dolphins can become entangled in the sea cage nets if they are not properly installed, or anti-predator nets (although these are no longer used by the SBT industry), even though they are aware of the nets (Kemper 1998). It is thought that they may be distracted while feeding (Kemper 1998).

A study was conducted during 1994-1999 on dolphins entangled in tuna farm nets near Port Lincoln (Kemper and Gibbs 1997, 2002). During this period 15 bottlenose dolphins (*Tursiops aduncus*) and 9 common dolphins (*Delphinus delphis*) died from entanglements with the nets, and their carcases were examined and compared to dolphin carcases washed up or floating in Port Lincoln and other parts of South Australia. An additional 13 dolphin entanglements were reported but not collected and there was evidence that at least another eight dolphins died due to entanglements but were not officially reported. Of the 37 entangled animals, 24 were juveniles or young sexually mature females. Most of the sexually mature dolphins were also pregnant or lactating. Three of the entangled animals were calves. The remains of fish species that were common around tuna cages were found in the stomachs of entangled dolphins. However, there is not enough information on the behaviour, ecology and population dynamics of dolphins in South Australia to properly assess if marine finfish aquaculture is having a measurable effect on dolphin populations.

From the results of their studies, Kemper and Gibbs (1997, 2002) made several recommendations, including the removal of anti-predator nets. Anti-predator nets are no longer in use in South Australia, and indeed some industry members had dispensed with them prior to the 1997 report, thereby eliminating entanglements. Kemper *et al.* (2003) summarised a range of recommended mitigation methods for reducing interactions between finfish aquaculture and marine mammals. These recommendations included the use of appropriate net design (semi-rigid or well-tensioned net material; mesh size of 6 cm), minimisation of food wastage, use of pellet feed, appropriate location of farms, prompt removal of dead fish, gear maintenance and constant vigilance. Kemper *et al.* (2003) also listed several methods that were not recommended, including the use of acoustic devices, trapping and relocation, and chasing. Dolphins are a protected species and therefore it is illegal to kill them. Farmers must attempt to safely release any trapped or entangled animal.

Given that predator nets are no longer used by the tuna industry, and other improvements such as reductions in feed wastage, decreased mortalities, and regular removal of dead fish, which have eliminated mortalities through entanglements, and until more research and collection of information on inshore dolphins has been done, a lower risk ranking is probably more appropriate for both species of dolphins. Given the likelihood of entanglement has been practically eliminated, a low risk ranking is probably appropriate at the regional level for both species. If farm operators do not properly manage their cages, and allow the nets to hang loosely, then this should be raised to moderate, at least for bottlenose dolphins. However, this ranking should be reviewed if other deterrents are introduced or if farming practices are further changed.

Revised Risk Ranking: Impacts on Bottlenose/Common Dolphins –Low

1.7.2 Seals and Sea lions

Issues relating to seals received a risk ranking of "low to moderate" (Table 1.9) while the sea lions received a risk ranking of "moderate" during the workshop (Table 1.10).

Table 1.9. Summary of workshop comments and risk assessment values for issues related to seal interactions with tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What are the issues associated with the interaction between seals and tuna cages?*			
Level of impact	Regional impacts			
Workshop comments	▪ Once electric fences were put in place around tuna pontoons, seal mortality was reduced. ▪ An appropriately managed farm will have few, if any, issues regarding seals and proximity to colonies becomes less of an issue. ▪ A distinction needs to be made between breeding and haul out colonies with respect to proximity.			
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b).			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	1/2	4	4/8	Low to Moderate

Table 1.10. Summary of workshop comments and risk assessment values for issues related to sea lion interactions with tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What are the issues associated with the interaction between sea lions and tuna cages?*
Level of impact	Regional impacts
Workshop comments	▪ More vulnerable species given they feed closer to shore. ▪ Tuna pontoons only present 5 months of the year. ▪ Unsure of cause of sea lion mortality.
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b).

Workshop risk assessment values	Consequence	Likelihood	Risk Value	Risk Ranking
	3	4	12	Moderate

Current knowledge
A number of pinniped species have been documented to interact with aquaculture operations worldwide (damage to gear, stock predation, etc.) (e.g. Pemberton *et al.* 1991, Pemberton and Shaughnessy 1993, Wickens 1995, Harun and Savas 2003, Kemper *et al.* 2003, Quick *et al.* 2003). In Australia, interactions between fur seals/sea lions, and finfish farms, are numerous. Salmon farming, and tuna aquaculture, have experienced extensive damage as a result of pinniped interactions, however, the level of interactions vary widely between the two industries (Pemberton and Shaughnessy 1993, Kemper *et al.* 2003). These interactions can lead to fatal and non-fatal entanglement, illegal and permitted killing, injuries, habitat loss or disturbance and altered ecological parameters such as diet and distribution (

Table 1.11, Kemper *et al.* 2003). Pinnipeds can be attracted to finfish farms for a number of reasons. They can be attracted to the fish that are already herded together in farms (Wickens 1995), or to the increase of fish feeding on the excess feed around the farms (Kemper and Gibbs 1997, 2001).

At Port Lincoln, anecdotal evidence suggests that pinniped interactions began about four years after tuna aquaculture began (Pemberton 1996, in Kemper *et al.* 2003). At that time, farming techniques were still being developed and as a result, the sides of the cage nets were quite loose. Consequently, seals/sea lions were able to push the netting inwards in an attempt to access fish inside, especially mortalities lying on the cage floor. In South Australia, the seal/sea lions' strong teeth would enable them to chew through the netting or they would find holes and chew their way through to get to the fish. Improved net weighting techniques, which keep the sides of nets taut, were introduced to stop the seals from pushing on the nets (Kemper *et al.* 2003). However, the seals quickly adapted and were seen sitting on pontoons and attempting to leap over the top net which extended about 60-80 cm above the top of the net ring. Even though this interaction is more of an impact on the industry itself (e.g. fish losses), it is possible that the process may lead to fatal and non-fatal entanglement, illegal killing, and injuries of seals, although this is not a problem at present.

Table 1.11. Demonstrated negative interactions of pinnipeds with aquaculture in the southern hemisphere (taken from Kemper *et al.* 2003). "?" refers to interactions that have not been demonstrated equivocally or that species identification was in question.

Species	Fatal entanglements	Non-fatal entanglements	Illegal killing	Gear damage	Fish stock loss
Australian sea lion	Tuna farms	-	Tuna farms	Tuna farms	Tuna farm
South American sea lion	Salmonid farms	Salmonid farms	Salmonid farms	Salmonid farms	Salmonid farms
South American fur seal	Salmonid farms	-	-	Salmonid farms	Salmonid farms
New Zealand fur seal	Tuna farms? Salmonid farms	-	Salmonid farms	Salmonid farms	Tuna farms Salmonid farms
Australian fur seal	Salmonid farms	-	Salmonid farms	Salmonid farms	Salmonid farms
Southern	Salmonid farms	-	-	-	-

elephant seal					
Leopard seal	Salmonid farms	-	-	-	-

A majority of the interactions with tuna cages involved the Australian sea lion (*Neophoca cinerea*) with only occasional interactions involving New Zealand fur seals (*Arctocephalus forsteri*), which are attracted to the baitfish. Almost all (89%) of the carcasses retrieved in the Port Lincoln area since tuna aquaculture began, as well as two documented entanglements (Kemper and Gibbs 1997), were sea lions. Of the two entangled sea lions collected for analyses, one was a pregnant female and the other was a sub-adult male. Indirect evidence of entanglements and intentional killings have been obtained by studying the carcasses of seals washed up on shore (Kemper and Gibbs 1997). For example, four seal carcasses were discovered on the western side of Boston Island during 1997, of which one had been shot, although these cannot be attributed to the tuna industry.

An unpublished report (Pemberton 1996 in Kemper *et al.* 2003) for the Tuna Boat Owners Association of South Australia and PIRSA pointed out that anti-predator nets were problematic for entanglements of seals (as well as dolphins). A number of major drawbacks were identified with anti-predator nets, which included:

- Too large mesh size
- Holes not repaired
- Nets not enclosed at the bottom
- Nets often loose and baggy

It is likely that some of these drawbacks were also responsible for seals gaining access to cages and killing or damaging tuna. The report also suggested that feeding practices, such as shovelling of baitfish, encouraged marine mammals to visit cages in the first place. Furthermore, the problem with seals getting over the top of pontoons was because fences were not high enough above the water level or poorly maintained and the pontoon design acted as a platform from which the seals could launch themselves into the cage.

A range of recommended mitigation methods for reducing interactions between finfish aquaculture and pinnipeds were summarised in the report (Pemberton 1996 in Kemper *et al.* 2003). These recommendations included regular maintenance of all nets to reduce billowing and holes, extension of fencing to 1.5 m above water level, cleaning of oil slicks and dead fish around cages, enclosing anti-predator nets at the bottom and using smaller mesh size (e.g. 6 x 6 cm) for anti-predator nets. For a variety of reasons, anti-predator nets are no longer used by the tuna industry in South Australia. The use of higher (up to 1.5 m) fences and electric fences around tuna cages has proven to be effective in deterring pinnipeds since the late 1990's. Unlike in the northern hemisphere, acoustic harassment devises (AHD's) are not used as they were found to be unsuccessful in the long term.

It was suggested that the number of attacks by pinnipeds on tuna at Port Lincoln may be related to the proximity of the sea cages to the second largest breeding colony of Australian sea lion at Dangerous Reef, approximately 25 km to the east (Kemper *et al.* 2003). The size of the colony is estimated to be between 1,500 and 2,000 animals. Breeding colonies have also been observed at Albatross, English and Gambier Isles (Edyvane 1999). Breeding also possibly occurs on Lew Isle, Smith Rock and Buffalo Reef and the Neptune Isles, with haul-out sites at many more locations within the area. Recently, Dr. S. Goldsworthy of SARDI Aquatic Sciences discovered a new Australian sea lion colony at East Island (North

Neptune Islands). There is also a New Zealand fur seal colony about 60 km away at Neptune Island, which was estimated to have between 21,000 and 27,000 animals in the summer of 1999/2000.

It is possible that pinniped interactions with tuna cages go unreported because operators fear reprisal and public/market reactions to events that are negative to marine mammals. Seals and sea lions are protected species and therefore it is illegal to kill them. Farmers must attempt to safely release any trapped or entangled animals. A more rigorous reporting system may be required in order to properly assess the effect of tuna aquaculture on seal and sea lion populations in the Port Lincoln area. In addition, there is the need for more information on the behaviour, ecology and population dynamics of seals and sea lions in the Port Lincoln area.

Currently scientists at SARDI Aquatic Sciences are undertaking several projects on seals/sea lions. One such project involves the use of satellite transmitters on Australian sea lions at Dangerous Reef to assess their movement patterns and spatial overlap with finfish aquaculture. The results of this tracking work has led to recommendations being made by the Marine Mammal-Marine Protected Area Aquaculture Working Group, which is comprised of experts from the Minister for Environment and Conservation's Wildlife Advisory Committee and the Minister for Agriculture, Food and Fisheries' Aquaculture Advisory Group. The group has recommended that fish farms are not allowed within 5 km of all Australian sea lion colonies and 15 km of the eight major breeding colonies.

Another project involves the mark-recapture assessment of New Zealand fur seal pup production at three colonies (North and South Neptune Island, and Liguanea Island) where over 3,500 pups were marked in three days. Follow up recaptures indicate that the populations are still increasing rapidly, with approximately 10,000 pups born across the three sites during the 2005 breeding season. A final report discussing the impediments to the growth of Australian sea lion populations is in preparation.

Given that the likelihood of an adverse interaction between tuna farms and seals and sea lions has been lowered due to the use of electric fences and the removal of predator nets, coupled with the limited research on seal interactions with tuna aquaculture, the risk rankings given during the workshop are appropriate. Compared to a "low to moderate" ranking for New Zealand fur seals, a slightly higher ranking of "moderate" is appropriate for Australian sea lions given that the population is relatively small (about 11,000 animals) and fairly static (Goldsworthy *et al.* 2003) and entanglements in tuna nets are reportedly more frequent. Also, if the aquaculture zoning regulations allow farms to be situated closer to Australian sea lion colonies, they may be at a greater risk of entanglements or illegal killing. The risk ratings should be re-assessed in the near future if farm management practices change and when more research has been conducted on the impacts of tuna aquaculture on pinniped population dynamics.

Revised Risk Ranking: Impacts on Seals/Sea Lions – Low to Moderate/Moderate

1.7.3 Seabirds

The risk ranking for issues associated with the interaction of seabirds and tuna aquaculture was "moderate" to "high" (Table 1.12).

Table 1.12. Summary of workshop comments and risk assessment values for issues related to seabird interactions with tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What are the issues associated with the interaction between seabirds and tuna aquaculture?*			
Level of impact	Regional impacts			
Workshop comments	▪ Elevated gull population levels following introduction of farming and some impacts on other species noted. ▪ Impacts may have declined when subsurface feeding was introduced. ▪ Data lacking.			
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b.			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3/4	4	12/16	Moderate/High

A literature review on the interaction between seabirds and finfish aquaculture has been conducted (De Jong and Tanner 2004). While the review discussed issues from the "Environmental Risk Assessment Workshop for Marine Finfish Aquaculture in South Australia", the discussion was directly related to the tuna aquaculture industry in South Australia. As such, parts of the review with modifications are included in this report.

Current knowledge

Some species of birds interact with aquaculture farms on a daily basis. A Flinders University Honours project investigated the interactions between seabirds and SBT aquaculture farms in the Port Lincoln region in 2003 (Harrison *et al.* 2003 – see chapter 5 of this report). The study showed that silver gulls were the most abundant seabirds at tuna farms and they were also the main scavenger of tuna feed. They were attracted to these sites due to baitfish (e.g. pilchards) used as feed for the tuna, although regional population increases would also be related to other anthropogenic sources of food from Port Lincoln. Potentially as a result of this readily available food source, it is estimated that the number of breeding pairs of silver gulls has doubled from 10,200 in 2000 to 20,776 in 2003. This increased population may cause social and environmental problems when the tuna season ends in October.

The same study estimated that silver gulls were consuming up to 70 tonnes of tuna feed per year with a general preference for baitfish over pellets when both types of feed were available at the same time. However, feeding frozen blocks and not shovelling baitfish could easily decrease this consumption of baitfish by birds, as could placing bird nets over the top of the pens (Harrison *et al.* 2003). Improved feeding practices are now used by many in the industry.

The seagulls may be displacing less common seabirds such as terns and may also cause disturbance to migratory shorebirds (The Conservation Council of Australia 2002). Behavioural changes were observed in the seagulls that foraged at the tuna farms (Harrison *et al.* 2003). Although the gulls are not migratory, this suggests that behavioural changes might occur in migratory birds also. Two listed migratory species were observed visiting the tuna farms. Short-tailed shearwaters (*Puffinus tenuirostris*) ate a very small proportion of the total feed taken by seabirds at farms that use either baitfish or pellets. They were observed in very low numbers within the sea cages (average 2 at any one time) compared to the larger number observed nearby but outside the sea cages (average 60-70 at any one time). Southern giant petrels (*Macronectes giganteus*) were seen to visit the sea cages, however they did not eat the feed.

There may also be flow-on effects on migratory species due to the inflated populations of gulls and this warrants further investigation (Harrison *et al.* 2003). In addition, the population size and reproductive output of short-tailed shearwaters requires further investigation to determine whether the feed taken from the aquaculture farms is having any effect on the population of that species.

Previous studies in other parts of the world on bird interactions with aquaculture were not particularly relevant for assessing the interactions in South Australia, because these studies focused on land-based aquaculture where small fish were cultured, and sick or dying fish were taken by predatory or scavenging birds (Harrison *et al.* 2003). In South Australia the main marine finfish species cultured are SBT, yellowtail kingfish, mulloway, Atlantic salmon and ocean trout, and these species are large predatory fish that are unlikely to be preyed or scavenged upon by the seabirds, in which case the most common source of interaction is the consumption of feed (Harrison *et al.* 2003). However, Harrison's (2003) argument did not take into consideration the possibility that the fingerlings of all species, other than tuna which is not propagated, recently transferred from the hatchery to the sea cages can be preyed upon by seabirds. One SBT farming company is also looking at propagation of tuna (Young 2001). If this is successful, it is highly likely that tuna fingerlings will be vulnerable to seabird predation and the use of surface netting of sea cages may grow, thereby increasing the potential of bird entrapment.

Given that pellets are no longer economically competitive with baitfish due to increased quota and reduced prices of local pilchards, seabird interactions with tuna farms will continue to be a problem. In addition, if fingerlings are introduced to sea cages, the risk ranking will increase. Therefore, the "moderate" ranking given during the workshop is appropriate at this point in time. However, the ranking should be reviewed if new farming or feeding methods are introduced. Further research is currently in progress as part of a PhD project by Shelley Harrison, focussing on the recommendations given for future research in her Honours thesis. This implies the need to review the risk ranking when more information is available on the interaction of seabirds with SBT aquaculture.

Revised Risk Ranking: Impacts on Seabirds – Moderate

1.7.4 Sharks (e.g. dusky & bronze whalers, and great white sharks)

Issues relating to sharks were identified with a risk ranking of "low to moderate" (Table 1.13) at the whole industry level under "Other species/communities and processes" (Section 1.6). They are being discussed in this section as the great white shark is a protected species and other shark species are considered 'near-threatened'.

Table 1.13. Summary of workshop comments and risk assessment values for the issue of sharks caught in tuna cages. Wherever possible the exact comments were included, however additional words and phrases may have been included to improve readability and understanding.

Description	*What are the issues associated with sharks becoming caught in tuna cages?*			
Level of impact	Whole of Industry			
Workshop comments	▪ How frequently are sharks caught in cages? There have been only two reported incidents of shark interactions with towing process in 10 years. ▪ Little is known about status of shark stocks in the state and there is the possibility that some shark species could be in danger. ▪ Need to codify practices to minimise captures. ▪ Address mortalities during tow if sharks are caught. ▪ Consequence level of 3 (severe) relates to status of stocks if they are endangered.			
Current regulations	▪ Must take all reasonable and practical measures to minimise adverse interactions with seabirds and marine animals (PIRSA Aquaculture 2003b).			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3	1/3	3/9	Low/Moderate

A literature review on the interaction between sharks and finfish aquaculture has been conducted (De Jong and Tanner 2004). While the review covered issues discussed during the "Environmental Risk Assessment Workshop for Marine Finfish Aquaculture in South Australia", many references were made to the tuna aquaculture industry in South Australia. As such, parts of the review with modifications are included in this section. In addition, some outcomes from a shark interaction workshop are also discussed (Murray-Jones 2004).

Current knowledge

Currently, there is an active program of research being conducted by CSIRO Marine Research in Hobart that will help address many of the basic unanswered questions about great white shark biology. At PIRSA, Keith Jones is collating existing data for bronze whaler sharks in South Australia, including shark mortalities associated with sea cage aquaculture and will make recommendations regarding the need for biological studies in the future.

A shark interaction workshop funded by FRDC was held by the Department of Environment and Heritage in 2003 in Adelaide. Various stakeholders attended the workshop and the outcomes of the workshop were published in 2004 (Murray-Jones 2004). The workshop indicated that more information on shark movements in South Australia was required. The workshop reached general agreement on several other issues:

- Aquaculture in sea-cages does not appear to be attracting sharks to the region.
- The main factor triggering attacks is the presence of freshly dead fish in cages, which is a farm husbandry issue.
- There is an urgent need for best practice guidelines for managing interactions.
- Interactions with bronze whalers are more frequent than white sharks and interactions with both species vary with site, season and operator.
- There is a need for better (and faster) reporting of interactions, and better communication between industry, researchers and regulators. Concerns of

operators about reporting interactions with white sharks (with regard to punitive measures when a shark dies) need to be addressed.

- More research is required on shark behaviour, stock structure and population status.
- There is an increased awareness of the need to conserve great white sharks after the successful release, with no danger to staff or loss of tuna, of white sharks in tuna cages.

In South Australia, most of the interactions between sharks and sea cages are with bronze whaler sharks. Bronze whaler sharks are not a protected species and are usually killed if they enter the sea cages. The great white shark, *Carcharodon carcharias,* is the only protected species of shark in South Australia and it is found in all the aquaculture regions. Farmers are not permitted to kill great white sharks and must attempt their safe release if they enter the sea cages. Farmers can seek approval from the Director of Fisheries to destroy a great white only if it is endangering lives. A Marine Animal Interaction Working Group (MAIWG) was established in 1996 as a result of a growing number of at-sea fish farms. Workshops are held annually and provide the opportunity for all stakeholders (industry, government, and environmental groups) across Australia to meet, discuss and have input into the responsible management of a range of issues associated with interactions between marine animals (sharks, mammals, birds) and at-sea fish farms.

Malcolm *et al.* (2001) conducted a review on the status of great white sharks in Australian waters and noted there were several reported incidents where these sharks were inadvertently caught either in tuna tow cages or inshore farm sea cages. In 1999 there were three confirmed captures and one unconfirmed capture in tuna sea cages. Over a period of about five years, there was a total of nine captures by the tuna industry. Six of these captured sharks were killed, usually by power-head, and the other three were already dead when found. Both sexes of the great white shark have been captured in tuna sea cages and they ranged between 3.0 to 5.0 m in length. In addition, the capture and towing of tuna stocks to farm sites expose a different mix of shark species to these activities and thus there will be a different type and magnitude of interaction than those at the actual farming site.

There have been three reported attempts to release sharks that were captured in the tuna sea cages. In 1999, a diver tied a rope to the tail of a shark that was found in poor condition but still alive at the bottom of a tuna tow cage (Malcolm *et al.* 2001). The shark was lifted out of the tow cage and released over the side where it then sank. The next attempt was in 2000, but there is no information available on the release attempt.

In 2003 a great white shark entered a SARDI Aquatic Sciences' experimental tuna sea cage (Buchanan 2005). This event provided SARDI staff with an opportunity to trial a number of different methods for removing the shark safely (for both shark and human) while preventing the tuna from escaping. After trying several different methods over a period of seven days, the shark was successfully released by using a part of the net as a "corridor" for the shark to swim out. Only two tuna were observed to escape in the process, although more were found to be missing at harvest. This method of release showed some potential for the safe release of sharks with minimal fish loss. More recently, the tuna industry has developed the technique further and have released alive white pointer sharks found within cages.

Given the regular interactions between sharks and aquaculture, and the low reproductive rate of sharks, a "moderate" risk ranking is probably more appropriate than a "low to moderate" ranking. As the industry is concentrated in an area frequently inhabited by sharks, especially great white sharks, it is unlikely that the risk will be lowered in the near future. However, if the devices that are currently being tested to repel sharks from tuna cages prove to be effective, the risk may be lowered. Also, unless the industry becomes less reliant upon wild captured tuna, interactions with sharks will continue during the towing process. Essentially, as long as current regulations are followed, it is unlikely that the risk will increase in the near future. Even though whaler sharks are not a protected species, they have been classified as 'near-threatened' because of commercial shark fisheries, by-catch, and recreational fishers (Pogonoski *et al.* 2002). Therefore, the consequence level of 3 (severe) (mainly given due to great white sharks) may also be appropriate for whaler sharks as their numbers continue to decrease. Again, more information on their distribution, movement patterns and behaviour in South Australia is required.

Revised Risk Ranking: Impacts on Sharks – Moderate

1.8 Nutrients

Four issues relating to nutrients were identified in the Catchment or Regional level component tree for SBT aquaculture (Component Tree 2, Figure 1.3). These issues were:

1. Background levels
   a. Natural
   b. Human Inputs
2. Tuna farm inputs
3. Nutrient removal scavengers (e.g. filter feeders, biofouling)
4. Distribution load

The risk associated with issue 1a received a ranking of "moderate" (Table 1.14) while the remaining issues received either "negligible" or "low" risk rankings and are not discussed further in this report.

1.8.1 Natural background levels of nutrients

Issues relating to natural background levels of nutrients received a "moderate" risk ranking during the workshop. However, this was based on varying consequence levels, which was due to uncertainty amongst some participants on natural background levels of nutrients in the Port Lincoln region (Table 1.14).

Table 1.14. Summary of workshop comments and risk assessment values regarding issues related to water quality and tuna cages.

Description	*What are the issues associated with the water quality and tuna aquaculture?*			
Level of impact	Regional impacts			
Workshop comments	▪ Are nutrient levels themselves an environmental issue? ▪ Given the amount of data collected since 1994, there is little evidence to show that levels are any different from natural variability. ▪ Consequence level varies as natural variability in nutrient levels not known.			
Workshop risk assessment values	**Consequence**	**Likelihood**	**Risk Value**	**Risk Ranking**
	3?	4	12?	Moderate

A literature review on issues pertaining to impacts of finfish aquaculture on water quality has been conducted (De Jong and Tanner 2004). While the review discussed issues brought up during the "Environmental Risk Assessment Workshop for Marine Finfish Aquaculture in South Australia", it is directly related to the tuna aquaculture industry in South Australia. As such, parts of the review with modifications are included in this report.

Current knowledge

In Australia, marine finfish aquaculture is relatively new compared to places in Europe and North America, and therefore there is less information regarding the impacts of this industry on the environment. Tuna aquaculture is also a relatively new activity itself, and appears to differ in its environmental issues to established species such as salmonids. Reasons for this include that tuna tend to be farmed in warmer waters than salmonids, they are frequently fed baitfish as compared to pellets, stocking densities are much lower (2-4 kg m^{-3} in South Australia compared to 10 m^{-3} for many salmonid fasrming operations), and farming tends to occur in more open waters. In South Australia, publications on impacts of marine finfish industry inputs in the marine environment are limited to a few environmental monitoring reports, site surveys and impact assessments by consultants and government agencies. As a result, workshop attendees struggled to assign a consequence level, mainly due to uncertainty regarding natural variability of nutrient levels in and outside Boston Bay. Boston Bay has various sources of pollutants including the SA Water effluent outfall on the southern side of Billy's Lights Point that was untreated prior to 1994, and the fish processing industry on the northern coast of Proper Bay. It was estimated that these sources contributed between 0.3-0.8 mg/L of total nitrogen daily to the bay waters. (Walters, 1989 in Paxinos *et al.* 1996). In addition, Boston Bay, where tuna farming occurred prio to 1997, is well mixed during winter and is flushed during both winter and summer (Bond 1993, in Paxinos *et al.* 1996). Now that the farms have moved out of Boston Bay, and are 4-10 km offshore, they are even more exposed to strong currents and mixing.

Impacts of waste

Inputs from marine finfish aquaculture can increase nutrient loads, which in turn can impact on the marine environment in a number of ways. The ecological impacts of wastes and organic enrichment from marine finfish aquaculture have been variously reviewed (Gowen and Bradbury 1987, Pillay 1992, Wu 1995, Pearson and Black 2001). The main impacts of nutrient enrichment in the marine environment are eutrophication, which can lead to increased biological oxygen demand, hypoxia and altered benthic community structure (Gowen 1994, Findlay and Watling 1995), excessive epiphytic growth on seagrasses that smothers the plants (Cancemi *et al.* 2003), increased growth of macroalgae, and harmful algal blooms (HABs).

Changes to the phytoplankton community can potentially promote HABs. HABs can cause fish kills and contaminate filter-feeding shellfish, and are a major concern for both marine finfish and marine shellfish aquaculture sectors. Marine finfish aquaculture can alter some of the environmental factors that may promote HABs. These factors include circulation, turbulence (intensity of vertical mixing), nutrients, light, temperature, and salinity, although nutrient enrichment is generally the only factor influenced by aquaculture. Anderson *et al.* (2002) reviewed the impacts and possible causes of HABs and eutrophication, and acknowledged that marine finfish aquaculture can increase nutrients in some cases, leading to increased phytoplankton production, although this is primarily a problem in enclosed or semi-enclosed areas, and not in open areas such as the tuna farming zone at Port Lincoln. The study suggested that the occurrence and impacts of HABs were dependent on the presence of harmful species, the relative abundance of the nutrients, the mixing and hydrographic characteristics of the area, and other factors such as grazing intensity or light availability.

Phytoplankton composition was initially monitored as part of the Tuna Environmental Monitoring Program (TEMP) (Clarke *et al.* 1999). However, it was difficult to distinguish between changes in phytoplankton due to aquaculture and changes due to natural variability or other sources of nutrient input such as pollution from urban development, industry and shipping (Clarke *et al.* 1999). Results from the TEMP showed higher total algal counts and chlorophyll-*a* around sea cages compared to controls, which did suggest that marine finfish aquaculture may have increased phytoplankton levels.

A phytoplankton monitoring program conducted by the Tuna Boat Owners Association of South Australia (TBOASA), took a few samples a week for a period of 18 months at Boston Island and surrounds, and thus provided more details on the occurrence and temporal patterns of several algal species of concern to marine finfish farmers (Clarke *et al.* 1999). A few algal blooms occurred during this period, but were not toxic to marine finfish. However, the cysts of species toxic to marine finfish were found in some sediment samples (Clarke 1996, Paxinos *et al.* 1996). A feasibility study investigating the phytoplankton dynamics of Boston Bay found that chlorophyll-*a* levels varied greatly on a daily basis particularly around tuna sea cages (Clarke 1996, Paxinos *et al.* 1996).

Around the world, the severity of impacts of wastes from marine finfish aquaculture has varied from negligible to serious. For example, in England, Frid and Mercer (1989) did not find any difference in community structure along a transect that ran from under a salmonid sea cage to a distance of 50 m. In contrast, Brown *et al.* (1987) found distinct changes in the benthic community in the area around a fish farm in a sea loch in Scotland, with the greatest impact occurring underneath the sea cage where no benthic fauna were found. Sánchez-Gonzáles *et al.* (2001) found that since the onset of fish farming in an embayment in southeastern Spain, 53% of *Posidonia oceanica* seagrass meadows had been either lost completely or significantly degraded. In Japan, Sakamoto (1986) calculated that nutrients released from aquaculture sites could affect an area three to nine times the size of the aquaculture zone.

The greatest impact of nutrient enrichment on benthic communities occurs underneath and in the near vicinity of the sea cages. The degree of impact decreases with increasing distance away from the sea cages (Weston 1990, Findlay and Watling 1995, Pearson and Black 2001). The level of impact is thought to be dependant on a combination of factors including the species being cultured, husbandry practices, feed type, level of inputs, hydrology and the nature of the receiving environment in terms of physics, chemistry and biology (Pearson and Black 2001).

In South Australia, studies have shown that the degree of impact of tuna marine finfish aquaculture waste was also varied. Cheshire *et al.* (1996) found that epibenthic communities were impacted up to a distance of 150 m and benthic infauna were impacted up to 20 m from tuna sea cages in Boston Bay. The tuna cages have now been moved to more open-ocean sites offshore from Boston Island. Subsequent monitoring of the industry using licence-based monitoring of sites under the TEMP indicated that there were no impacts at a distance of 150 m from any lease boundary (Madigan *et al.* 2003, Loo *et al.* 2004, Loo and Drabsch 2005). This monitoring program was not designed to investigate impacts in the immediate vicinity of the cages. More specific studies aimed at looking at the waste stream from sea cages are ongoing in an Aquafin/FRDC project[1] and these studies will give more conclusive information regarding the impact of SBT aquaculture on the environment in South Australia (Fernandes *et al.* 2003).

Modelling

Numerous models have been developed to predict various aspects of wastes in the environment such as production of fish waste, nutrient enrichment in the water column and sediments, deposition of particulate and organic matter and impacts on the benthos (e.g. Silvert 1992, Hargrave 1994, Findlay and Watling 1997, Cromey *et al.* 1998, Wu *et al.* 1999, Morrisey *et al.* 2000). Silvert and Sowles (1996) provided a summary of many of the developed models, including explanations of assumptions and limitations of the models. Even though these models have been developed in other parts of the world, the principles behind them are likely to be relevant to Australian marine finfish aquaculture and the models provide a useful starting point for developing models specific to South Australian aquaculture.

There are two major problems associated with the development and use of models to predict the impacts of marine finfish aquaculture. The first problem is the lack of baseline information available to parameterise the models. Without accurate data on factors such as water currents, generation of waste, flushing dynamics, and carbon accumulation for each aquaculture site, it is difficult to make any accurate predictions. The second problem is that

[1] Aquafin CRC/FRDC Project 2001/103: Aquafin CRC - Southern Bluefin Tuna Aquaculture Subprogram: tuna environment subproject - evaluation of waste composition and waste mitigation strategies.

these models are often over-simplified due to knowledge gaps in our understanding of the behaviour of wastes in the environment and their impacts on biological communities. Where knowledge gaps exist, a precautionary approach has been taken and a number of assumptions have been made that produce the highest amount of nutrient deposition and enrichment. For example, in some cases the amount of nutrients and organic matter assimilated by phytoplankton, benthic communities and pelagic fish has not been considered, resulting in an over-estimation of deposition on the seafloor. Although a precautionary approach is ideal for reducing the risk of environmental impacts, an underestimate of carrying capacities could unnecessarily hinder the growth of this valuable industry, and significant investment opportunities could be lost. These factors therefore need to be investigated and quantified in order to develop more accurate models.

Estimates of the carrying capacity of the aquaculture management zones for Fitzgerald Bay (Oceanique Perspectives 1998, Parsons Brinkerhoff and SARDI Aquatic Sciences 2003c), Franklin Harbour (Oceanique Perspectives 1999), Arno Bay (Parsons Brinkerhoff and SARDI Aquatic Sciences 2003a) and Rivoli Bay (Parsons Brinkerhoff and SARDI Aquatic Sciences 2003b) have been calculated. Estimates of the carrying capacity for Boston Bay was determined by Petrusevics (1996) in relation to SBT. The carrying capacity for the production of finfish was estimated using a mass balance model described by Beveridge (2004). In its simplest definition, the carrying capacity is the maximum level of fish production that is sustainable for a given region or site, which depends on the environment's capacity to assimilate increased nutrient inputs (Beveridge 2004). With the increasing emphasis on ecologically sustainable development, the carrying capacity of a region is more commonly defined in terms of the maximum level of fish production that does not cause significant changes in the ecosystem. The most widely accepted indicator of ecosystem change used to calculate carrying capacities is water quality, and in South Australia carrying capacities are calculated by determining the maximum level of fish production possible without exceeding the recommended water quality guidelines for a region.

Estimates of the carrying capacity in Boston Bay based on SBT aquaculture ranged from 1200 to 2400 tonnes per year (Petrusevics 1996). However, the SBT industry has since moved seaward out of Boston Bay, making previous estimates of carrying capacity for SBT non-applicable. In addition, current knowledge of the South Australian marine environment and the interactions between aquaculture and the environment are insufficient to develop precise models to calculate carrying capacities. A range of models could be developed and used as a part of adaptive management programs. As new information becomes available on the interactions between the environment and aquaculture, the carrying capacity models can be adapted to integrate this new information (see chapter 7).

Monitoring and Management

A list of the various biological and chemical variables that can be used as indicators of environmental change in order to monitor the ecological effects of aquaculture wastes have been summarised (Gowen 1994, GESAMP 1996). Gavine and McKinnon (2002) reviewed appropriate methods for environmental monitoring of marine aquaculture in Victorian waters. They separated the possible indicators of environmental change into three main categories: (1) impacts on sediment quality, (2) impacts on water quality and (3) biological impacts. Work on finfish aquaculture in Tasmania by Macleod *et al.* (2004b) resulted in the development of a suite of techniques for the assessment of sediment condition. A guide was subsequently developed to enable industry to readily incorporate the findings from the above project into farm management protocols (Macleod and Forbes 2004).

Biological variables are usually measured since these are often the attributes of the ecosystem of most concern. Changes in chemical variables can also be measured and are often indicative of potential problems, but of themselves may not be of direct environmental concern (lowered dissolved oxygen being an obvious exception). Biological measurements are often a better reflection of integrated effects whereas chemical measurements may show short-term variability that is harder to interpret. Management authorities are often faced with the challenge of deciding which factors are most appropriate for monitoring programs, and it is common for the monitoring regime to include a mixture of chemical and biological measurements.

Many studies have shown that benthic infauna are a reliable indicator of near-field environmental change caused by increases in nutrients and sedimentation (e.g. Brown *et al.* 1987, Ritz *et al.* 1989, Weston 1990) and as such, infauna sampling has become a common tool in environmental monitoring programs worldwide. Work in Tasmania used the benthic infaunal community as the basis for evaluating other techniques for the assessment of sediment condition (Macleod *et al.* 2004b). In South Australia all license holders are required to submit an environmental monitoring report annually as a part of their "Marine Tuna Aquaculture License" (granted under the *Aquaculture Act 2001*) in accordance with the monitoring protocol outlined by PIRSA Aquaculture (PIRSA Aquaculture 2003a). This monitoring program is license-based and will only detect impacts caused by individual facilities (150 m from the lease boundaries). There is a need to assume that the control sites for this monitoring, which are only required to be > 1 km away from any lease site, aren't being affected by larger regional scale impacts. Given that it is difficult to distinguish the broader effects of tuna farming from natural variability in nutrient levels and other anthropogenic influences such as agriculture, industrial and urban activities (Clarke *et al.* 2000), a low risk ranking is more appropriate at the regional level. In addition, a lack of background data prior to the commencement of SBT Aquaculture in Port Lincoln area implies that attempts need to be made towards designing and implementing a monitoring program at the regional level to establish industry impacts, especially if production increases in the future. The moderate ranking given during the workshop is appropriate at the individual farm level, based on a high likelihood and moderate consequence, but not at the regional level being discussed here. While the production of tuna has levelled off, any expansion of the industry in the future due to longer term holding of tuna (for multiple seasons) or stocking of propagated fish (unlikely in the near future) may lead to increased risk at both the individual farm and regional levels. The risk ranking should therefore be re-evaluated if farming practices change in the future, in conjunction with any new research findings.

Revised Risk Ranking: Effect of Nutrients on Natural Background Levels of Nutrients – Low

1.9 Conclusion

While there were some differences of opinion about appropriate risk rankings for some issues, there was general agreement among the workshop participants for most issues. Participants struggled to determine a risk ranking for some issues due to a lack of knowledge in that scientific area and as a result, a higher risk ranking tended to be assigned to the issue, based on a worst-case scenario. In addition, due to the selective coverage of issues resulting from the particular interests of the participants, not all issues were sufficiently discussed. However, the workshop did identify various knowledge gaps and needs regarding SBT aquaculture in South Australia.

Of the 69 issues discussed during the workshop, 49 were given a "negligible" or "low" ranking while ten other issues were not discussed in detail as they were not considered relevant to SBT aquaculture. Most of the remaining ten issues were given a "low to moderate" or "moderate" ranking, and only two issues were given a "moderate to high" and "moderate to extreme" ranking. After reviewing the available literature associated with these ten higher-ranking issues, a "low" or "moderate" risk ranking was considered to be more suitable for a majority of the issues identified. The issues with a final "moderate" ranking included impacts on bottlenose dolphins, sharks, sea lions, seabirds and effects of baitfish imports. This ranking is based on the "possible" likelihood of an event occurring and a "moderate" consequence as a result of an event occurring. The risk associated with the impact on seals was identified as appropriate and thus remained a "low" to "moderate" ranking. Two issues related to site selection were also ranked as "moderate" or higher during the workshop, but were not discussed further here as they were not a direct impact on the environment and should be addressed during the planning phase (i.e. location of farm sites). A majority of the above issues need improved monitoring and reporting in order to gain further understanding of the possible long-term impacts of SBT farming on the marine environment. Each issue should be reviewed and possibly re-ranked if there are changes to farming practices or the available knowledge base in the future. It is important to remember that issues ranked as "moderate" do not need immediate or drastic attention, but rather they need to be the subject of continuous improvements over roughly a 3-5 year timeframe.

Workshop participants identified four of the six "moderate" ranked issues as a concern to the Port Lincoln region. The remaining two issues were found to be a concern at the whole of industry level. Even though it has been widely documented that sea-cage farming has significant effects on the environment in the immediate vicinity of pontoons, the workshop did not address potential issues at the individual farm level, as this was not its purpose, the focus being on the development of methodology for "regional environmental sustainability assessment".

As a result of the workshop and literature review a number of knowledge gaps about the impacts of SBT aquaculture in South Australia were identified. Some of these are currently being investigated or are proposed to be investigated (listed below). In addition, those issues that required monitoring and management programs have also been identified.

1.9.1 Current research

- Investigation of the impacts of wastes from tuna aquaculture on the environment using improved experimental design and developing appropriate monitoring techniques being undertaken by Dr M. Loo & Dr M. Fernandes, SARDI Aquatic Sciences (FRDC 2001/102 & 2001/103: Aquafin CRC – SBT Aquaculture Subprogram: tuna environment subproject 1 – development of novel methodologies for cost effective assessment of the environmental impact of aquaculture, tuna environment subproject 2 – evaluation of waste composition and waste mitigation strategies and tuna environment subproject 3 – development of regional environmental sustainability assessments).

- Assessing the sustainability of interactions between fishing, aquaculture and dolphins in Spencer Gulf being undertaken by C. Kemper, R. Harcourt, S. Gibbs and K. Bilgmann (South Australian Museum and Macquarie University).

- Assessment of Australian sea lion movement patterns at Dangerous Reef and spatial overlap with finfish aquaculture being undertaken by Dr S. Goldsworthy, SARDI Aquatic Sciences (FRDC 2004/201).

- Assessment of the New Zealand fur seal pup production at three colonies (North and South Neptune Island, and Liguanea Island) being undertaken by Dr S. Goldsworthy, SARDI Aquatic Sciences. A report outlining the results from this survey will be available soon, entitled "Understanding the impediments to the growth of Australian sea lion populations".

- Investigation of the behaviour, ecology and population dynamics of great white sharks being undertaken by CSIRO Marine Research. (http://www.marine.csiro.au/research/whitesharks/index.html)

- Proceedings of the Shark Interactions with Aquaculture Workshop and Discussion Paper on Great White Sharks by S. Murray-Jones were recently released (FRDC 2002/040).

- Collation of existing data for bronze whaler sharks in South Australia, including shark mortalities associated with sea cage aquaculture and recommendations for the need of biological studies in the future being undertaken by Dr K. Jones, PIRSA (FRDC 2004/067).

- PhD study investigating the impacts of SBT aquaculture on seabirds by S. Harrison, Flinders University

1.9.2 Research required

- Possibly some need for more information on the behaviour, ecology and population dynamics of dolphins in order to determine the impacts of tuna aquaculture.

- Investigation of the impact of tuna aquaculture on the composition and abundance of phytoplankton communities and the direct contribution of the industry to the cause of harmful algal blooms. This is now being investigated under a new Aquafin CRC/FRDC project (2005/059), "Aquafin CRC-SBT Aquaculture Subprogram: Risk and Response – Understanding the tuna farming environment".

1.9.3 Monitoring and Management required

- Marine Tuna Aquaculture Environmental Monitoring Program (EMP)
  Each licensee must submit a report that addresses conditions laid out for farm management and benthic assessment. The continuation of this program is essential and may change over time to reflect the commitment of PIRSA and other agencies for continuous improvement and adaptive management.

- Monitoring of the frequency, intensity and composition of algal blooms.
  It is understood that some farms monitor phytoplankton levels on a regular basis as part of their operating procedures. However, the current SBT Aquaculture Environmental Monitoring Program (EMP) does not require licensees to monitor phytoplankton levels. This is now being included in a new Aquafin CRC project (2005/059), "Aquafin CRC-SBT Aquaculture Subprogram: Risk and Response – Understanding the tuna farming environment".

- Monitoring and reporting of interactions with sharks, sea lions, seals and dolphins. The SBT Aquaculture EMP requires licensees to report the details (date, time, location) of interactions with sharks, sea lions, seals and dolphins. An incentive based system may need to be introduced to ensure full industry involvement with the assurance that these reports will not be misused or misrepresented.

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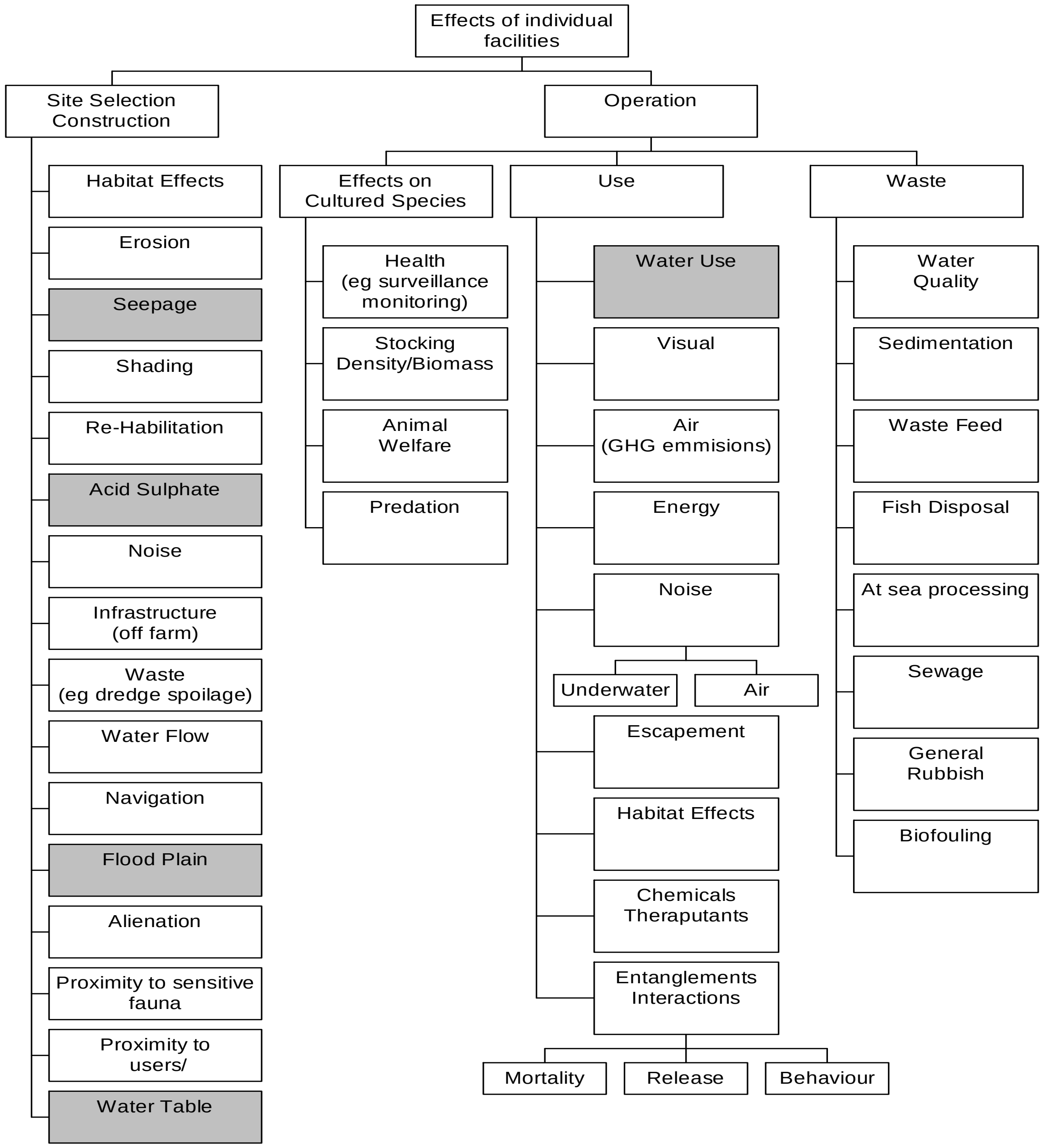
1.11 Appendix I: List of invitees and attendees

Table I. 1 List of invitees and attendees of the SBT Environmental Risk Assessment Workshop held at SARDI Aquatic Sciences on the 6th December 2002.

First Name	Surname	Organisation	Attended
Julie	Arnold	Planning SA	No
Andy	Bodsworth	Australian Fisheries Management Authority	No
Gloria	Booker	Planning SA	Yes
Val	Boxall	DEH	Yes
Simon	Bryars	Primary Industries and Resources	No
Carina	Cartwright	PIRSA	Yes
Anthony	Cheshire	SARDI Aquatic Sciences	Yes
Steven	Clarke	SARDI Aquatic Sciences	Yes
John	Cugley	EPA	No
Michael	Deering	Aquaculture SA	No
Peter	Dolan	Environment Protection Authority	No
David	Ellis	Tuna Boat Owners Association of SA	No
Daryl	Evans	Marnikol Fisheries Pty Ltd	Yes
Milena	Fernandes	SARDI Aquatic Sciences	Yes
Tony	Flaherty	SA Marine & Coastal Community Network	No
Rick	Fletcher	WA Department of Fisheries	Yes
Roger	Freeman	Planning SA	No
Sue	Gibbs	DEH	Yes
Louisa	Halliday	PIRSA	Yes
Chris	Halstead	Department of Environment and Heritage	No
Tony	Huppatz	DEH	Yes
Brian	Jeffries	Tuna Boat Owners Association of SA	Yes
Cath	Kemper	South Australian Museum	No
Tania	Kiley	EPA	Yes
Maylene	Loo	SARDI Aquatic Sciences	Yes
Stephen	Madigan	SARDI Aquatic Sciences	Yes
Peter	Montague	Aquafin CRC	Yes
Sue	Murray-Jones	DEH	Yes
Vic	Neverauskas	Primary Industries and Resources	No
Ian	Nightingale	Aquaculture SA	No
Margie	Prideaux	Whale & Dolphin Conservation Society	Yes
Kirsten	Rough	MG Kailis Seafood Pty Ltd	Yes
Stephanie	Seddon	SARDI Aquatic Sciences	No
Alastair	Smith	Planning SA	Yes
Ib	Svane	SARDI Aquatic Sciences	No
Jason	Tanner	SARDI Aquatic Sciences	No
Jeff	Todd	EPA	Yes
John	Volkman	CSIRO Marine Research	Yes
Michael	Walmesley	Planning SA	No
Tim	Ward	SARDI Aquatic Sciences	No
Kane	Williams	PIRSA	Yes

1.12 Appendix II: Component Tree 3



Note: On-site or farm level impacts of SBT aquaculture on the environment (modified from Fletcher *et al.* 2002). This component tree was not discussed during the workshop or presented in this report.

1.13 Appendix III: Summary of issues determined and discussed during the workshop

Table III. 1 Component Tree 1- Biological or environmental effects of the whole industry - Risk rankings and comments for issues discussed during the workshop. Numbers in bold were determined during the workshop. (C = Consequence level, L = Likelihood level, RV = Risk Value, RR = Risk Ranking).

Issue		C	L	RV	RR	Justification for ranking/comments
1	**Whole Industry Effects**					
1.1	**Wild SBT Stocks**					
1.1.1	Escape of SBT					
1.1.1.1	Genetics	**0**	-	**0**	Negligible	*What impact will the escape of farmed individuals have on the genetics of wild stock?* ▪ Not an issue as wild populations already present
1.1.1.2	Disease	**3**	**2/1**	**6/3**	Low	*Will the release of farmed individuals increase the risk of disease introduction to the wild stock?* ▪ Debate over likelihood ▪ No diseases recorded for farmed or wild stocks in Australia ▪ If diseases are detected then this risk is to be re-ranked
1.1.1.3	Competition	**0**	-	**0**	Negligible	*Will the escape of farmed animals cause problems to the wild stock through increased competition for resources (e.g. food and space)?* ▪ Small numbers escaping relative to size of wild population
1.1.2	Collection of SBT					
1.1.2.1	Brood stock	-	-	-		▪ Not an issue ▪ Agreed by all
1.1.2.2	Seed stock	-	-	-		▪ Not an issue ▪ Agreed by all
1.1.2.3	Grow-out stock	-	-	-		▪ Not an issue ▪ Compliance issue for AFMA ▪ Agreed by all
1.1.2.4	Release after capture (excess to quota)	**0**	**0**	**0**	Negligible	▪ Only occurred twice in 8 years ▪ Approximately 10-15 tonnes out of approximately 5000 tonnes in any one year ▪ Mortality in farm is low (approx 2%) compared with wild stocks (~30%)

Issue		C	L	RV	RR	Justification for ranking/comments
1.1.3	Restocking					
1.1.3.1	Genetics	-	-	-		▪ Not an activity ▪ Agreed by all
1.1.3.2	Disease	-	-	-		▪ Not discussed
1.1.3.3	Competition	-	-	-		▪ Not discussed
1.2	**Cultured Stocks/Businesses (husbandry)**					
1.2.1	Genetics	-	-	-		▪ Not discussed
1.2.2	Disease					
1.2.2.1	Identification	-	-	-		▪ Not discussed
1.2.2.2	Response	-	-	-		▪ Not discussed
1.3	**Other Species/Communities & Processes**					
1.3.1	Disease	-	-	-		▪ Not discussed
1.3.2	Escape of cultured species (feral populations)	-	-	-		▪ Not an issue ▪ Agreed by all
1.3.3	Food chain impacts					
1.3.3.1	Competition with other species (escapes)	-	-	-		▪ Not discussed
1.3.3.1.1	Towed	**0**	**0**	**0**	Negligible	▪ Not when they are released from where they are caught
1.3.3.1.2	Farmed	**1**	**2**	**2**	Low	▪ No comments
1.3.4	Behavioural changes and impacts (towed component e.g. migratory species)					
1.3.4.1	Sharks (e.g. Dusky & Bronze Whalers)	**3**	**1/3**	**3/9**	Low/ Moderate	*How frequently are sharks caught in cages?* ▪ Need to codify practices to minimise captures ▪ Address mortality during tow if sharks are caught ▪ Consequence level 3 (severe) relates to status of stocks if they are endangered ▪ More information required on stock status
1.3.4.2	Mammals	0	-	0	Negligible	▪ None known
1.3.5	Threatened & endangered					

	species					
1.3.5.1	Towed component	0	-	0	Negligible	▪ None known?
Issue		**C**	**L**	**RV**	**RR**	**Justification for ranking/comments**
1.3.6	Feeds composition (source & sustainability impacts)					
1.3.6.1	Pilchards	-	-	-		▪ Not an issue ▪ Pilchard quotas are set by relevant fisheries management agencies in their processes
1.3.6.2	Baitfish	-	-	-		▪ Not an issue ▪ As above ▪ Applies to this category to – require feed supplier to "do the right thing"
1.3.6.3	Impacts of imported feed on other elements	**3**	**1/4**	**3/12**	**Low/ Moderate**	*What are the impacts of imported feed on other elements?* ▪ Disagreement on the level of consequence based on whether or not the previous "pilchard kill" incidents were associated with the importation of pilchards for feeding tuna ▪ Incidents have occurred twice over the past 10 years; therefore it is possible that is may occur again ▪ Biosecurity Australia should address this issue ▪ Management plans put in place by Biosecurity Australia have reduced this risk to negligible, therefore the likelihood, based on current management practices, is low ▪ Are the management changes making any substantial difference in risk/likelihood?

Table III. 2 Component Tree 2 – Catchment or Regional level effects – Effect of the Industry on Port Lincoln - Risk rankings and comments for issues discussed during the workshop. Numbers in bold were determined during the workshop. C – Consequence level, L – Likelihood level, RV – Risk Value, RR – Risk Ranking.

Issue	C	L	RV	RR	Justification for ranking/comments
1 **Effect of the Industry on Port Lincoln (Cumulative Impacts)**					
1.1 **Water Use (Quantity & Quality)**					
1.1.1 Nutrients					
1.1.1.1 Background levels					
1.1.1.1.1 Natural	**3?**	**4**	**12?**	Moderate	▪ Consequence level varies as natural variability in nutrient levels not known
1.1.1.1.2 Human inputs	**0**		**0**	Negligible	▪ Does not include inputs from tuna farms ▪ 12 miles offshore, unlikely to occur
1.1.1.2 Tuna farm inputs (eg feeds, biofouling)	**1**	**6**	**6**	Low	▪ Already a management scheme in place to minimise this and monitoring in place ▪ Given current levels of farming, inputs may increase if the number of farms increased - what is the maximum allowable for the region?
1.1.1.3 Nutrient removal scavengers (filter feeders, biofouling)	**0**	**0**	**0**	Negligible	▪ No comments
1.1.1.4 Distribution of Load	**1**	**4**	**4**	Low	▪ No comments
1.1.2 Sedimentation	**1**	**5/6**	**5/6**	Low	▪ Not a significant issue at the regional level given the current production levels ▪ Requires re-evaluation if production levels change
1.1.3 Other wastes/pollutants (eg chemicals)	**0**		**0**	Negligible	▪ No chemicals are to be used unless there is permission
1.1.4 Flow (hydrology/ oceanography)	**0**		**0**	Negligible	▪ This relates to the offshore areas – buffer zones? ▪ Not as this scale
1.1.5 Water extraction					▪ Not an issue ▪ Agreed by all
1.1.6 Seepage (salinisation)					▪ Not an issue ▪ Agreed by all

Issue		C	L	RV	RR	Justification for ranking/comments
1.2	Ecological Community Structure & Biodiversity					
1.2.1	Phytoplankton	**1**	**4**	**4**	Low	▪ No comments
1.2.2	Benthic communities	**1**	**3**	**3**	Low	▪ Based on current farming levels
1.2.3	Aquatic vegetation	**0/1**		**0**	Negligible	▪ Lease sites not allowed on aquatic vegetation
1.2.4	Terrestrial vegetation/communities	**1**	**3**	**3**	Low	▪ Bird faeces on islands and on-shore cage construction
1.2.5	Listed migratory species					
1.2.5.1	Birds	**0**	**-**	**0**	Negligible	▪ Not known
1.2.5.2	Whales	**0**	**-**	**0**	Negligible	▪ Only one incidence recorded and it was released alive
1.2.6	Threatened/endangered/ protected species					
1.2.6.1	Bottlenose dolphins	**3/4**	**4/5**	**12/20**	Moderate/High	*What impact does entanglements in tuna cages have on bottlenose dolphins?* ▪ Higher consequence score based on smaller family/dene/pod population size, not the entire stock/population level ▪ What level of mortality is occurring? ▪ Predator nets have been removed and entrapment frequency reduced, but this may not stop changes in feeding behaviour
1.2.6.2	Common dolphins	**3**	**4**	**12**	Moderate	*What impact do entanglements in tuna cages have on common dolphins?* ▪ More work required because individuals around tuna pontoons have different stomach contents, reflecting altered diet ▪ Detrimental changes in feeding behaviour in young may occur ▪ Tuna pontoons only present for 5 months of the year

Issue	C	L	RV	RR	Justification for ranking/comments
1.2.6.3 Seals	**2/1**	**4**	**8/4**	Low/Moderate	*What are the issues associated with the interaction between seals and tuna cages?* ▪ Issue addressed using electric fences – this management practice has reduced mortality ▪ An appropriately managed farm will have few, if any, issues regarding seals and proximity to colonies becomes less of an issue ▪ A distinction needs to be made between breeding and haul out colonies with respect to proximity
1.2.6.4 Sea lions	**3**	**4**	**12**	Moderate	*What are the issues associated with the interaction between sea lions and tuna cages?* ▪ More vulnerable species given they feed closer to shore ▪ Tuna pontoons only present 5 months of the year ▪ Unsure of causes of sea lion mortality
1.2.6.5 Sea birds	**3/4**	**4**	**12/16**	Moderate/High	*What are the issues associated with the interaction between seabirds and tuna aquaculture?* ▪ Elevated gull population levels following introduction of farming and some impacts on other species noted ▪ Impacts may have declined when subsurface feeding was introduced ▪ Data lacking
1.2.7 Other fauna (fish, birds etc)	**1**	**3**	**3**	Low	▪ Few cages and present only part of the year
1.2.8 Scavengers	**1**	**3**	**3**	Low	▪ Few cages and present only part of the year
1.2.9 World Heritage/ RAMSAR/MPA's	**3**	**1**	**3**	Low	▪ Management practices would not allow this to occur
1.2.10 Behavioural changes & impacts on species	**0**	**-**	**0**	Negligible	
1.2.11 Sensitive & critical habitats	**3**	**1**	**3**	Low	▪ Not allowable given the current planning procedure do not occur on sensitive habitat
1.2.12 Habitat effects					
1.2.12.1 Displacement	**1**	**2**	**2**	Low	▪ Not sure what the impact is? Space between cages and space between leases unknown

Issue	C	L	RV	RR	Justification for ranking/comments
1.2.12.2 Addition	**0**	-	**0**	Negligible	
1.2.12.3 Reduction	**0**	-	**0**	Negligible	
1.3 Physical Structures & Construction					
1.3.1 Number & size of farms	-	-	-	Negligible	▪ Planning issue currently capped but would be bigger if increases occurred – may need to determine upper limit
1.3.2 Habitat removal	-	-	-	Negligible	▪ Not an issue
1.3.3 Alienation (access to areas)	-	-	-	Negligible	▪ Because they have moved offshore
1.3.4 Visual amenity	-	-	-	Negligible	▪ No comments
1.3.5 Navigation	**4**	**4**	**16**	High	▪ Navigation channels have been taken into account in the planning process but the areas have been used by other fishers
1.3.6 Infrastructure					
1.3.6.1 On-farm	-	-	-	Negligible	▪ None apart from the cages
1.3.6.2 Off-farm	-	-	-	Negligible	▪ Not a lot of off farm infrastructure
1.3.7 Site constraints (waves, currents)	**2**	**6**	**12**	Moderate	▪ Picked up in the planning procedures
1.4 Production					
1.4.1 Regional assimilative/environmental capacity					▪ Planning
1.4.2 Carrying capacity	-	-	-	Negligible	▪ No comments
1.4.3 Disease (e.g. proximity of facilities, translocation policy)					▪ Planning

Chapter 2 Potential for use of remote sensing in the management of marine finfish aquaculture in South Australia

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2.1 Executive Summary

Research is critical to the management and improvement of the aquaculture industry. In particular, environmental processes and their interaction with aquaculture operations require a much greater understanding. In comparison with traditional ground-based techniques, remote sensing potentially provides an efficient multi-scale monitoring method for these environmental processes.

The objective of this project was to review and evaluate the feasibility of current remote sensing systems to detect and monitor selected environmental phenomena and general aquaculture management needs. In particular, the study focussed on the industries of southern bluefin tuna (*Thunnus maccoyii)* at Boston Bay, and yellowtail kingfish (*Seriola lalandi*) at Boston Bay, Arno Bay and Fitzgerald Bay in Spencer Gulf, off the Eyre Peninsula. The review was conducted with the aim of assisting in the management and operation of South Australian finfish aquaculture.

Discussions held at SARDI, West Beach, on October 14, 2004, identified interactions between marine finfish aquaculture and the environment that would be beneficial to monitor with remote sensing. The interactions identified could be categorised into aquaculture industry and government interests:

1. Environmental phenomena impacting on existing marine aquaculture (primarily industry interest); and
2. Existing marine aquaculture impacting on environmental systems (primarily government/SARDI interest).

The project comprised a literature review and compilation of a catalogue of sensor specifications. Using this information, a feasibility analysis was conducted to assess the suitability of remote sensing systems for detecting and mapping selected marine environmental phenomena. Based on the outcomes of the feasibility analysis, pilot programs were recommended to develop further understanding of the roles, capability and suitability of selected remote sensing products for South Australian conditions and applications, as well as to develop local capacity for analysis and delivery of products.

2.2 Literature Review

A number of studies have demonstrated the ability of ocean colour sensors to detect and map concentrations of water constituents. Total suspended sediment (TSS), coloured dissolved organic matter (CDOM), and chlorophyll concentrations have been retrieved from SeaWiFS (Hendiarti *et al.* 2004; Richardson *et al.* 2004), MODIS (Hu *et al.* 2004), hyperspectral imagery (Hoogenboom *et al.* 1998) and Landsat imagery (Phinn *et al.* 2005; Populus *et al.* 1995). Similar techniques have also been used for the mapping of algal blooms (Gower *et al.* 2004; Stumpf and Richard 2001; Tang *et al.* 2003). A recently launched research sensor MERIS, has demonstrated great potential in the realm of algal bloom mapping (Furevik *et al.* 2004; Gower *et al.* 2004).

No published local studies on remote monitoring of water quality, or the detection of algal blooms within Spencer Gulf have been located. Nor was there information available on the extent, time and duration of historical algal blooms to provide a clear understanding of the nature and magnitude of these phenomena. Sediments and faecal deposits from the aquaculture cages are expected to contribute to the TSS, which potentially could be detected by remote sensing and *in situ* measurements (*pers. comm.* Peter Petrusevics, Oceanique Perspectives, 2004). Further study is required to address this knowledge gap.

Benthic mapping has had more prominence in the local context. Studies by Hart and Cameron (1998) and Hart (1999) have shown the potential of aerial photography and Landsat imagery for the broad-scale mapping of seagrass in South Australian Gulf waters. However both these mapping methods were only able to generate a two-class 'substrate' and 'seagrass' map. HyMap hyperspectral airborne imagery was used by Dunk and Lewis (2000) to discriminate and map *Posidonia*, *Zostera* and two sediment types near Port Pirie. Within the areas of interest, Kinhill (1995) has conducted a study in Boston Bay to assess the potential of aerial photography for monitoring the impacts of the sea cage tuna farming on macrophyte communities. However, the photography was found to be of limited value, and could only reliably map areas of shallow water distant from sea-cage tuna farms. Thus the method was not able to quantify the environmental influences of tuna farming compared with those resulting from significant land based discharges (Kinhill 1995).

In the assessment of both water quality and benthic composition, progress has been made with modelling approaches (Dekker *et al.* 2001; Hoogenboom *et al.* 1998; Klonowski *et al.* 2004). Proponents of this approach have demonstrated the use of bio-optical radiative transfer models to increase the accuracy and validity of benthic and water column measurements.

2.3 Feasibility Analysis

Four phenomena (or grouped phenomena) were evaluated for suitability of detection, mapping and monitoring with various forms of remote sensing: algal blooms, water constituents, sea surface temperature and benthic communities. Each phenomenon was characterised in terms of spectral response, spatial extent and temporal dynamics, and selected sensors were evaluated in relation to these criteria. The sensor parameters considered were spatial and spectral resolution, temporal frequency and archival history as well as cost and access suitability. While spatially limited, MODIS scored highest for the suitability of detecting water constituents and sea surface temperature. The higher spatial resolution of SPOT and Landsat were found to be more suitable for mapping algal blooms. Airborne hyperspectral sensors appear to be spectrally and spatially suitable for benthic mapping.

2.4 Recommendations

Using current remote sensing systems and technical expertise available within Australia, several roles for remote sensing can be identified that are relevant to the South Australian finfish aquaculture enterprises:

- Increasing understanding of the regional characteristics and dynamics of the surface water in Spencer Gulf and adjoining southern waters. Better information about the spatial and temporal dynamics of this region would improve understanding of the environmental context of the aquaculture enterprises and enable stronger predictions of influences and events relating to specific locations. The high temporal frequency and spectral capability, as well as low cost of MODIS makes this sensor the obvious choice for further study of the Spencer Gulf waters;
- Detection and mapping of specific events at particular locations (e.g. algal blooms), with acquisition of imagery triggered by other early warning systems. Such mapping might use relatively high resolution imagery, such as SPOT or Landsat, or airborne hyperspectral imagery, to provide detailed documentation and evidence on the distribution and dynamics of a particular event of concern in a limited area;
- Mapping and monitoring benthic composition in shallow waters. Several airborne and satellite-borne remote sensing systems have the capability to map variations in benthic cover and their imagery could be used to map benthic cover and variations in composition in selected areas of interest. Airborne hyperspectral systems have demonstrated capability in spectral and spatial resolution for this task;
- Analysis of the bio-optical properties of southern Australian coastal waters as a foundation for future analysis and monitoring of water composition using a variety of remote sensing data sources. Such research would enhance capability to exploit current and future remote sensing data for marine monitoring applications.

Based on the literature and the feasibility analysis, identified management needs, as listed in the Terms of Reference, were reviewed for their current operational potential. The following table lists these management needs and briefly states the potential (if any) for current operational assessment using remote sensing.

Management need	Current operational potential
Harmful algal blooms - detection, mapping and possible warning system	While there is little scope for using remote sensing as a warning tool, mapping the dynamics of an existing algal bloom is currently feasible. SPOT, Landsat or airborne systems would be suitable for this task. Basic remote sensing skills are required to map and calculate bloom areas.
Water quality – identification and concentration of water constituents	Retrieving water quality parameters from MODIS data is currently feasible. However, accurate retrieval from MODIS imagery is a complex task and requires quantitative image analysis and calibration with field samples. A South Australian company, Oceanique Perspectives, currently extracts these parameters for the Gulf of St. Vincent.
Sea state (SS) for effect on access and work operations – identification of high SS periods	A current SAR system such as Radarsat-1 is able to provide information on sea wave height with the assistance of costly extraction software. However, the process is time consuming and the accuracy is uncertain. It is unlikely this would be a cost-effective method of assessing the number of work days on aquaculture operations.

Sea surface temperature (SST) – mapping temperature gradients	At the present time, ACRES does not provide SST products for MODIS and NOAA. However, DEH can provide the NOAA and MODIS (slightly more complex) algorithms to users with reasonable remote sensing ability and access to image processing software. As they are adapted from North American algorithms, further calibration would be required before they could be used operationally in SA waters.
Sea surface salinity - mapping concentrations	There are currently no remote sensing systems available for measuring sea surface salinity. Sensors such as the Soil Moisture and Ocean Salinity instrument (SMOS) (see Appendix Table 4) may be useful in the future.
Oil slicks from sea-cages – detection and mapping of oil slicks	Mapping oil slicks is a currently feasible and well-developed technique. When conditions are favourable, Radarsat-1 could detect slicks from the sea-cages if they were at least approx. 120 m^2. Basic remote sensing skills are required to map and measure slick areas. However, Radarsat-1 imagery (and other radar data) is costly, and therefore it is unlikely this method would be cost-effective.
Potential farm impacts to benthic communities in vicinity & broader region - mapping of benthos	Accurately mapping potential farm impacts on benthic communities would appear to be infeasible at the current time. The limitations of light penetration of water make it difficult to assess the area in the region of the sea-cages situated at depths of 15-25 m. However, there may be scope for mapping any areas of impact in shallower regions closer to shore. Benthos mapping methods are in a research phase.
Pontoon locations (coordinates) – monitoring for general mgt	Locating pontoons should be a straightforward task with a capable sensor. For pontoons of 40m–50m diameter, a high-resolution multispectral sensor such as SPOT 5 (10 m multispectral and a 5 m panchromatic band) should be suitable, and has cost and temporal advantages over airborne systems. Pontoons and their coordinates could be fairly quickly and easily identified from the acquired geo-referenced imagery using appropriate (and low/no cost) viewing software.

While the study has evaluated current remote sensing systems for monitoring selected marine water quality phenomena in specific South Australian contexts, pilot programs should be conducted to build understanding of the capability of remote sensing systems and associated analytical requirements for local applications. Even for systems that could be implemented now, it would be appropriate to have an evaluation phase. The following pilot programs were suggested for implementation:

1. Monitoring water quality of the Spencer Gulf with MODIS

Aims: To evaluate the suitability of MODIS for monitoring water quality parameters at Gulf-scale.

The temporal and spectral frequency of the MODIS sensor potentially provides an effective means of monitoring water quality parameters in Spencer Gulf. Simultaneous data collection with existing SARDI in situ sensors would provide calibration over a range of values. The study would place in a broader regional context the water quality measurements acquired in the immediate vicinity of the aquaculture pontoons. Overpasses are routinely acquired by the Australian Centre for Remote Sensing (ACRES[2]), and the data are free to download for recent acquisitions within the last 7 days.

[2] [http://www.ga.gov.au/acres/].

2. Triggered high-resolution multispectral imagery for post-event algal bloom mapping

Aims: To assess the value of high-resolution SPOT imagery for mapping algal blooms that have formerly been detected with ground-based monitoring.

While remote sensing has shown to have little use in the warning or prediction of algal blooms, it has been successful in mapping the extent and temporal changes of an existing bloom. This study would use existing SARDI in situ sensors and user response to trigger the acquisition of SPOT imagery. The constellation of SPOT satellites provides a high temporal resolution allowing a reasonable response time.

3. Modeling of water quality parameters from field data and hyperspectral imagery

Aims: To evaluate the capability of using *in situ* sampling of water quality parameters and develop algorithms to calibrate measurements from hyperspectral imagery.

In comparison with empirical methods, the modelling approach establishes physical relations between water quality parameters, the underwater light field and remotely sensed measurements. Proponents of this approach have demonstrated the use of bio-optical radiative transfer models to increase the accuracy and validity of benthic and water column measurements. The study would require the collection of detailed water quality measurements with in situ sensors. An inversion model can then be built from these measurements and used to calibrate the hyperspectral imagery. However, this recommendation may be limited by available modelling software and expertise, and is unlikely to be cost-effective at the current time.

2.5 Introduction

The southern bluefin tuna and yellowtail kingfish aquaculture industries are, respectively, the largest and second-largest marine finfish industries in South Australia. As the structures and fish involved in aquaculture enterprises are in direct contact with the marine environment, it is paramount that these operations are, and remain, economically and environmentally sustainable. The southern bluefin tuna R&D strategic plan (Fisheries Research and Development Corporation 2001) highlights the importance of the interaction between marine aquaculture and the environment:

> *The long-term future of finfish aquaculture at sea requires the use of practices that ensure the continued health of the marine environment. It also requires recognition of the conservation value placed by society on the marine ecosystem and recognition that sea-based aquaculture activities can be rapidly and substantially affected by the environment (e.g. storms, phytoplankton blooms, and discharge of pollutants).*

Aquaculture directly impacts on the water quality. Studies by Burford *et al.* (2003) show that phytoplankton response to nutrients is a key ecological process and indicator for measuring the impacts of aquaculture discharge. Harmful and toxic phytoplankton blooms (sometimes visible as 'red tides') have become an issue of concern. In April 1996, a mass mortality event caused the death of 75% of southern bluefin tuna stocks in Boston Bay. The microscopic toxic alga, *Chattonella marina,* was thought by some to have reduced oxygen levels and caused extensive gill damage (Cannon 1997). However, a formal South Australian Government report (Clarke 1996) discounted microalgae as the cause of the tuna mortalities, although some species of concern did appear after the event. Furthermore, the toxic *Chattonella* alga was not recorded during surveys immediately after the mortality incident, making it unlikely to have been involved. The effects of the suspended sediments are considered to have caused the mucus build-up observed on the gills of the tuna, which led to respiratory difficulties and asphyxiation.

Aquaculture research is critical to the improvement and management of the industry. In particular, environmental processes and their interaction with aquaculture operations require a much greater understanding. Modelling tidal flows and seasonal algal patterns and indicator species are research issues that have been identified in the Yellowtail Kingfish Aquaculture Strategic Research and Development Plan 2003-2008 (Hernen and Hutchinson 2003). The plan also identified the value of sea floor impact analysis, and the ecology of different benthic systems.

Remote sensing provides an efficient broad-scale monitoring method for marine processes in comparison with traditional ground-based techniques. The potential of satellite remote sensing for marine applications has been recognised since the 1960s, although developments have been made only recently due to factors such as easier data access, new sensors with improved spatial and radiometric resolution, and increasing awareness by potential users (Santos and Miguel 2000). Despite providing a comprehensive historical review of airborne and satellite sensors in international fisheries research and operational support, Santos (2000) suggests that the practical application of remote sensing techniques in aquaculture remains largely experimental.

This report seeks to promote the aforementioned 'experimental' phase of aquaculture remote sensing research by identifying current systems that have the ability to address current management needs. The report also suggests feasible pilot programs aimed at progressing South Australia's finfish aquaculture industry toward an 'operational support' phase.

2.6 Terms of Reference

This project is a direct outcome of the remote sensing workshop held at SARDI Aquatic Sciences, West Beach, in August 2003. It is associated with the Cooperative Research Centre for Sustainable Aquaculture of Finfish (Aquafin CRC), which aims to meet the needs of the Australian finfish aquaculture industry through innovative, collaborative and commercially - focussed research (Aquafin CRC 2004).

The project content and design is modelled from discussions held at SARDI, West Beach, on October 14, 2004. The discussion identified interactions between marine aquaculture and the environment that would be of value to monitor with remote sensing. These interactions are a two-way exchange, and hence are of interest to both the South Australian finfish aquaculture industry and government:

1. Environmental phenomena impacting on existing marine aquaculture (primarily industry interest); and
2. Existing marine aquaculture impacting on environmental systems (primarily government/SARDI interest).

Southern bluefin tuna (SBT) (*Thunnus maccoyii)* and yellowtail kingfish (YTK) (*Seriola lalandi*) were the main focus of the project, with the selected interest areas at and offshore of Boston Bay (SBT & YTK), Arno Bay (YTK) and Fitzgerald Bay (YTK) in the Spencer Gulf, off Eyre Peninsula. The map in Appendix 1 (Figure 2.8) details these locations. A number of specific phenomena associated with these finfish industries were discussed and are summarised in Table 2.1.

Table 2.1. Environmental phenomena and management needs identified for investigation at discussions held October 14, 2004

1. Environmental phenomena impacting on aquaculture	2. Aquaculture impacting on environmental systems	3. Other research
Harmful algal blooms - detection, mapping and possible warning systems Water quality – identification and concentration of water constituents Sea surface temperature (SST) – mapping temperature gradients Sea state (SS) for potential effect on access and work operations – identification of high SS periods Sea surface salinity - mapping concentrations	Oil slicks from sea-cages – detection and mapping of oil slicks Potential farm impacts to benthic communities in vicinity & broader region - mapping of benthos	Pontoon locations (coordinates) – monitoring for general management Satellite sensor specs, frequency, costs etc. – information required Imagery interpretation and expertise levels – information required

2.6.1 Objectives

The objectives of this project were to:

1. Review and evaluate the feasibility of current remote sensing systems to detect and monitor selected environmental phenomena and general management needs.

2. To make recommendations about the immediate use of remote sensing for use in finfish aquaculture management and operation at Boston Bay, Arno Bay, and Fitzgerald Bay.

3. To suggest pilot programs that show potential for aiding the management of finfish aquaculture management and operation.

In particular, the review and recommendations are focussed on the southern bluefin tuna (*Thunnus maccoyii)* and yellowtail kingfish (*Seriola lalandi*) industries in the Spencer Gulf, off Eyre Peninsula.

2.6.2 Scope

The project comprised the following tasks:

1. Review of literature and past studies
   A literature review of local, national and international studies that have used remote sensing to detect, quantify, map, or warn of environmental phenomena. The review aims to present examples that demonstrate relevant research findings, remote sensing capabilities and methodologies, as well as operational applications, rather than a comprehensive account of all existing research.

2. Feasibility analysis
   An evaluation of using selected remote sensing systems to detect, quantify, or map a selection of marine environmental phenomena. The analysis uses the information available and a scoring system to determine sensor feasibility.

3. Recommendations
   Based on the outcomes of the feasibility analysis, recommendations are made on the roles that various forms of remote sensing might play in the management of aquaculture in the Spencer Gulf of South Australia.

4. Pilot programs
   Since it is unlikely that local knowledge or experience with analysis of remote sensing for marine applications would enable immediate adoption of operational programs, the study also recommends pilot programs for implementation in the near future. The recommendations include brief aims and suggested method relevant to South Australian finfish aquaculture enterprises and contexts.

2.7 Review of Relevant Studies

This literature review does not aspire to be an all-inclusive review of previous local, national and international studies relevant to aquaculture. Rather, it considers examples of remote sensing-based methodologies and research findings, as well as operational programs that may be applicable in the Spencer Gulf context, in relation to the phenomena identified in the Terms of Reference.

2.7.1 Ocean Colour Sensors

There have been significant advances in the development of satellite sensors for assessing coasts and oceans over the past two decades. A selection of tools that are useful for ocean modelling of sea wave height (SWH), sea surface temperature (SST), sea surface salinity (SSS) and ocean colour have been compiled by UNESCO's Intergovernmental Oceanographic Commission, and are listed in Appendix Table 2.5.

Satellite ocean colour sensors[3] that have been used for coastal ocean research include the Coastal Zone Color Scanner (CZCS, 1978-1986), the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, 1997-present) and the two Moderate Resolution Imaging Spectroradiometer sensors (MODIS 1999-present on the satellite 'Terra' and 2002-present on the satellite 'Aqua'). Similar sensors will be available in the forthcoming NPOESS (National Polar-Orbiting Operational Environmental Satellite System) project mission (starting 2005 and becoming operational by 2009) (Hu *et al.* 2004). The recently launched satellite ENVISAT carries the sensor MERIS, which has demonstrated great potential. A number of non-ocean specific satellites such as SPOT and Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper + (ETM+) have also been evaluated for their use in

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[3] Ocean colour is used to indicate the visible light spectrum as observed at the sea surface, which is related, by the processes of absorption and scattering, to the concentration of water constituents (Barale and Folving 1996).

assessing oceanic environmental parameters. The reliability of remote sensing techniques for coastal monitoring will continue to improve with developments in sensors. These include increases in spectral channels within the ultra-violet/visible region of the spectrum, decreases in the spectral width of recording channels, and increases in spatial resolution (Clementson *et al.* 2004).

The advantages of these space-based tools over conventional oceanography are obvious. Satellites offer rapid, repeated and concurrent synoptic assessment of environmental parameters, sampling over much greater spatial scales than are possible with ships and at frequencies which are impossible to match by any other sampling procedure (Hu *et al.* 2004; Joint and Groom 2000).

NASA's ocean colour sensors SeaWiFS and MODIS have further advantages as they have been tailored to marine applications. SeaWiFS views the earth in six bands in the visible, including a 412 nm channel to detect coloured dissolved organic matter (CDOM) and an additional blue channel at 490 nm at medium phytoplankton absorption (Joint and Groom 2000). The newer MODIS sensor has increased capability compared to SeaWiFS with more wavebands, higher signal to noise ratio, more complex on-board calibration, and the capability of simultaneous observation of ocean colour and sea surface temperature (Joint and Groom 2000). The two MODIS sensors also ensure continuity of ocean colour data by providing two observations per day (passing at 10:30 and 14:30 hrs local time). Furthermore, MODIS is broadcast continuously (and so can be acquired by anyone with an appropriate receiver) and can be used without any commercial restrictions (Joint and Groom 2000).

The aim of the SeaWiFS project is to provide quantitative data on global ocean bio-optical properties through ocean colour. Visible light (wavelengths of 400-700 nm) reflected from the world's oceans varies with the concentration of chlorophyll and other plant pigments present in the water. Typically, the greater the concentration of plant pigments, the greener the water. Hence phytoplankton concentration can be derived from quantification of such ocean colour (NASA 2004b). Figure 2.1 depicts a SeaWiFS chlorophyll image of South Australian waters.

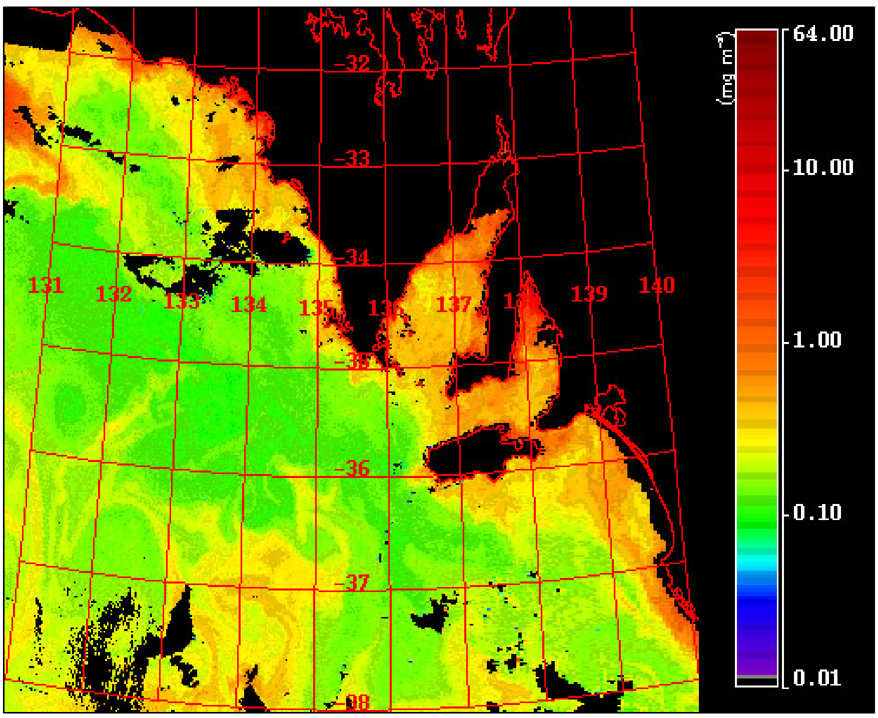

Figure 2.1: SeaWiFS chlorophyll *a* image acquired on January 9, 2002. Source: Oceanique Perspectives.

The MODIS system is a more all-encompassing sensor designed to improve understanding of global dynamics and processes occurring on the land and in the oceans and lower atmosphere (NASA 2004a). MODIS is also the prototype for the Visible Infrared Imager/Radiometer Suite (VIIRS) instrument, which will be flown operationally on the next series of the U.S. polar-orbiting meteorological satellites (NPOESS) (See Appendix Table 2.4). While MODIS low resolution bands 8 through 16 (1 km) are usually reserved for ocean colour and phytoplankton detection, Hu *et al.* (2004) explored the potential for using the medium-resolution bands (at 250 and 500 m) for monitoring water quality in estuaries. The MODIS medium-resolution bands (250m and 500m) were found to be 4–5 times more sensitive than the Landsat7/ETM+ bands, but 3–4 times (250 m, red and near-IR) and 1–2 times (500 m, blue and green) less sensitive than the corresponding SeaWiFS bands. However, they found the MODIS 1 km resolution ocean bands to be 3–6 times more sensitive than SeaWiFS bands, enabling detection of subtle ocean features. Figure 2.2 is a true colour 500 m MODIS image showing complex patterns of variations of surface water colour in the Spencer Gulf in 2001.

However, limitations such as the 1 km spatial resolution of the SeaWiFS and MODIS sensors are evident when imaging coastal environments (Hu *et al.* 2004). Clemenston *et al.* (2004) could not validate remotely sensed chlorophyll a in the Huon River Estuary due to the spatial resolution of the SeaWiFS sensor and small scale of the estuary. Atmospheric correction and sensor calibration have been very apparent limitations, as accurate measurements are required to extract useful information from the color of coastal ocean waters. Few bio-optical algorithms have been devised to convert coastal ocean observations to meaningful, consistent, and accurately retrieved water-quality parameters (Hu *et al.* 2004). Though perhaps the most fundamental limitation to ocean colour observation is cloud cover as it masks the sea-surface, and varies with location and season (Joint and Groom 2000).

Another important consideration in the use of coarse resolution imagery for mapping and quantification of parameters in near-coastal environments is the fact that a significant proportion of the signal apparently coming from a specific area represented by an image pixel actually comes from the surrounding pixels. This arises because of several factors including the optics, detector and electronics of the sensing instrument as well as scattering of radiation by the atmosphere (Townshend *et al.* 2000). This effect can reduce the ability of a user to reliably retrieve values for pixels in contrasting areas such as a coast, although appropriate processing of the imagery can minimise the error. As this effect is most pronounced with coarse resolution imagery (e.g. SeaWiFS or MODIS), information retrieval could therefore not be used reliably within 1 to 2 km of the coast without additional image correction.

Figure 2.2. Surface water colour variations in Spencer Gulf (blue-green swirls) acquired 20th October 2001 from the MODIS sensor. Source: NASA's visible earth

2.7.2 Water Quality

There are a number of bio-optical indicators in the water column that allow remote sensing techniques to make observations of environmental processes. Table 2.2 describes these indicators.

Table 2.2. Bio-optical indicators of ecological health. Source: Hu *et al.* (2004).

Indicator	Description
Chlorophyll concentration	Indicator of biomass, phytoplankton
Coloured dissolved organic matter concentration (CDOM)	Indicator for freshwater content and plant derived organic matter
Total suspended sediment concentration (TSS)	Indicator of turbidity and coastal erosion, and wind or current generated resuspension

A study in Moreton Bay, Queensland, measured the spectral absorption of these indicators (Figure 2.3). Water that is rich in phytoplankton will absorb more strongly in the blue and red wavelengths than green, hence its green appearance. Water bodies with large suspended sediment loads will reflect more strongly in all wavelengths due to particulate scattering (Phinn *et al.* 2005).

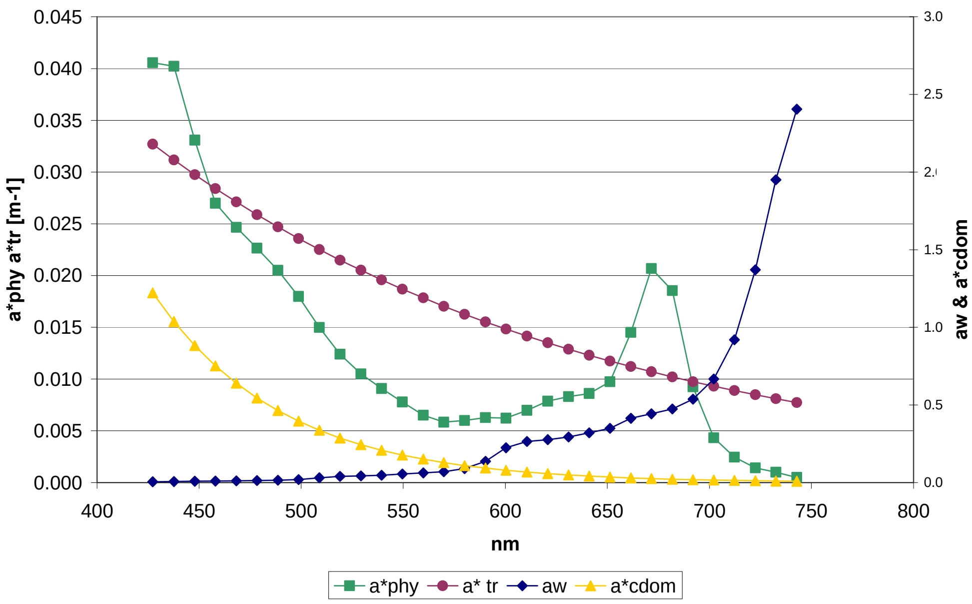

Figure 2.3. Absorption coefficients of water (aw - blue) and water constituents: chlorophyll (a*phy - green), TSS (a*tr - maroon), CDOM (a*cdom - yellow) over wavelengths 420 – 750 nm. Source: Phinn *et al.* (2005).

One of the limitations to mapping water quality parameters is that substrate features may influence the measurements in shallow clear waters. As a result, variations in the signal recorded by the sensor may not be due to the water column or surface features (Phinn *et al.* 2005). The euphotic depth (by definition the depth at which one percent of the surface light intensity can be detected) appears to be the depth at which the observer is confident the signal is a measurement of the water column and not the bottom surface (*pers. comm.* David Ellis, Adelaide Coastal Waters Study, 2004). Islam *et al.* (2004) arrived at a solution for mapping the shallow coastal zone of Moreton Bay to 3 m. They used a multiple zone depth of penetration (DOP) approach to exclude bottom reflectance and more accurately map TSS concentration with Landsat TM. The image was segmented into four DOP zones from calculated depths and bathymetric data. *In situ* water samples were collected concurrently with the recording of the Landsat satellite image, and used to establish regression models for TSS concentration and secchi depth associated with a particular DOP zone. The mapping was accomplished more accurately using a multiple DOP zone than using a single zone in shallower areas.

The mapping of water quality parameters is also affected by water type. Case 1 waters are those in which the optical properties are dominated by phytoplankton and its degradation products, and generally considered 'clear'. In comparison, the optical properties of case 2 waters, which are typically coastal, such as in Spencer Gulf, derive mainly from scattering and absorption by suspended matters of coloured dissolved organic material (CDOM) of terrestrial origin. Due to the physical properties of case 2 waters, phytoplankton biomass is difficult to accurately assess. The influence of CDOM and suspended particulate matter makes the estimation of chlorophyll concentrations by remote sensing problematic (Gohin *et al.* 2003; Joint and Groom 2000), whereas studies of case 1 waters (Gohin *et al.* 2003; Richardson *et al.* 2004) have shown chlorophyll concentrations derived from the SeaWiFS data to be more reliable.

In situ instruments, such as buoys or moorings, are an important part of water quality monitoring when they can be used concurrently with satellite-based remote sensing devices. *In situ* instruments can provide continuous monitoring of parameters such as temperature, salinity, and dissolved oxygen. However, they have been too limited on temporal and spatial scales; typically there are only a few such stations in any one region, and very few, if any, of these systems provide routine, long-term observations (Glasgow *et al.* 2004; Hu *et al.* 2004). *In situ* systems are also limited by 'bio-fouling' of the instruments, cost and real-time access to data, though advancements in real-time remote monitoring (RTRM) systems have made progress in addressing some of these issues (Glasgow *et al.* 2004).

2.7.2.1 Modeling and Empirical Approaches

The majority of studies measuring water quality parameters opt for an empirical approach: relating sensor values from the imagery to field values collected *in situ,* and then using these quantitative relationships to map or predict field values more widely. However, Dekker *et al.* (1994 in Populus *et al.* (1995)) indicate that this method is valid only for a given situation where remote sensing data are acquired simultaneously with *in situ* data in sufficient quantities to be statistically representative; the resulting relationships between water properties and remote sensing data values cannot necessarily be applied to other situations or times. Permanent variations in irradiation, atmosphere, water surface and composition make empirical methods notoriously unreliable.

Few studies (e.g. Dekker *et al.* 2001; Hoogenboom *et al.* 1998; Oubelkheir *et al.* 2004; Phinn *et al.* 2005) have taken the 'modelling' or 'analytical' approach, establishing physical relations between water quality parameters, the underwater light field and the remotely sensed measurements (Barale and Folving 1996; Van der Woerd and Pasterkamp 2001). Modeling the interaction of light with the water is complex due to the intricate optical response of its various constituents, and requires numerous *in situ* measurements modeled through a bio-optical model such as HYDROLIGHT (Sequoia Scientific Inc. 2000). Subsequently, an algorithm for estimating water quality parameters from satellite imagery can be developed (Van der Woerd and Pasterkamp 2001). Such regional algorithms have been applied to accurately estimate chlorophyll concentrations in case 2 waters in Florida (Tomlinson *et al.* 2004), and the Java Sea (Populus *et al.* 1995). The strength of this approach lies in the fact that once the inherent optical properties of water, phytoplankton and other constituents have been determined for a region, and an appropriate model developed, imagery which measures changes in the environment over space and time can be inverted to provide estimates of the concentrations of these variables. However, this requires a combination of costly remote sensing techniques and highly specialised teams (Populus *et al.* 1995).

2.7.3 Algal Blooms

A number of international studies have recently explored the realm of detecting and observing algal blooms with SeaWiFS data. Subramaniam *et al.* (2001) discriminated and mapped the cyanobacteria *Trichodesmium* (which blooms on occasion off Port Lincoln in late summer) from other phytoplankton blooms in the South Atlantic Bight. Tomlinson *et al.* (2004), Stumpf *et al.* (2003) and Stumpf and Richard (2001) concentrated their efforts on detecting harmful *Karenia brevis* blooms in the Gulf of Mexico. Gohin *et al.* (2003) made observations of a phytoplankton bloom in the Bay of Biscay, and Tang *et al.* (2003) measured water parameters associated with a harmful bloom in the Pearl River estuary in China.

However, the advent of enhanced sensor technology has provided improved detection with MERIS. A paper presented by Gower *et al.* (2004) at the recent ENVISAT Symposium claims that MERIS can be used to detect a peak in the optical spectrum of water-leaving radiance at about 705 nm, providing a signature of intense plankton blooms. The MERIS band at this wavelength is an essential part of the bloom detection, but not present in SeaWiFS or MODIS. The combination of wide area coverage, 300 m spatial resolution, and appropriate spectral bands makes MERIS a unique and important tool for intense plankton bloom monitoring (Gower *et al.* 2004).

Sensing of algal blooms by ocean colour sensors is limited to near surface waters because of the combined absorption of light by the water and pigments. If the maximum development of algae occurs below the surface layers, chlorophyll concentration for the total water column will be under-estimated (Joint and Groom 2000).

Furevik *et al.* (2004) have taken a different approach to the remote detection of algal blooms using Synthetic Aperture Radar (SAR). When blooms are characterised by high biomass and chlorophyll concentration in the upper layer of the water column such that they lead to accumulation of biological matter at the sea surface, they are distinctly observable in SAR images of the area. Such were the characteristics of the algal *Chattonella* sp. detected with ERS_SAR off the coast of Denmark. The texture and shape of the bloom area from the radar data provided a valuable addition to signatures detected by optical colour sensors. The clear advantages of such a system are the monitoring of these bloom events during cloudy periods (Furevik *et al.* 2004). The study looked to explore the possibilities of ENVISAT data given the data simultaneity of MERIS and ASAR and increased spatial resolution.

There are several approaches for identifying harmful algal taxa in natural samples:

(1) direct visualisation of individual cells using microscopy;
(2) portable and in situ sensors capable of detecting optical features of cells; and
(3) molecular probes that detect individual taxa, in particular detection of cell-surface moieties and nucleic acids (RNA, DNA). (Glasgow *et al.* 2004).

The presence or absence of diagnostic (or marker) pigments, which relate specifically to an algal class, can provide an indication of the composition of a phytoplankton community. This includes identifying classes of small flagellates that cannot be determined by light microscopy techniques (Clementson *et al.* 2004). Approaches with remote sensing are generally regarded to be unsuccessful in determining community composition (Furevik *et al.* 2004; Glasgow *et al.* 2004; Hu *et al.* 2004). However, Jupp *et al.* (1994) were able to distinguish blue-green algae (cyanobacteria) from different types of algae in the Hawkesbury River, using CASI data. The success was attributed to the sensitivity of the CASI sensor and its high spectral resolution (Jupp *et al.* 1994).

2.7.3.1 Warning Systems

Warning systems are instrumental in guarding against the potentially harmful effects of phytoplankton blooms. Stumpf *et al.* (2003) outline the detection and forecast components of harmful algal blooms (HABs):

(a) monitoring the movement of an algal bloom that has previously been identified as a HAB (type 1);
(b) detecting new blooms as HAB or non-HAB (type 2);
(c) predicting the movement of an identified HAB (type 3);
(d) predicting conditions favorable for a HAB to occur where blooms have not yet been observed (type 4).

Types 1 and 2 involve methods of bloom detection and require routine remote sensing and *in situ* data, though remote sensing cannot alone define a bloom as harmful or non-harmful (type 2). Prediction (types 3 and 4) builds on the monitoring capability by using interpretative and numerical modeling (Stumpf *et al.* 2003). At present remote sensing techniques can, at certain spatial scales, map the extent of a bloom once developed, but not predict the occurrence or the toxicity of a bloom (Clementson *et al.* 2004). Field surveys remain as the critical component required on a regular basis to maintain monitoring programs (Gohin *et al.* 2003; Roelfsema *et al.* 2002).

In a review of current applications for real-time remote monitoring (RTRM) of water quality, Glasgow *et al.* (2004) present some recent engineering and deployment of RTRM technologies. Among them is a web-based early-warning bloom alert network developed by the Centre for Applied Aquatic Ecology (CAAE), North Carolina State University (Figure 2.4). The network was designed for immediate notification and rapid response to algal blooms by university researchers and state resource managers through 4-10 instrumented platforms capable of measuring meteorological and hydrological parameters, supplemented with remote biological and chemical sampling (Glasgow *et al.* 2004).

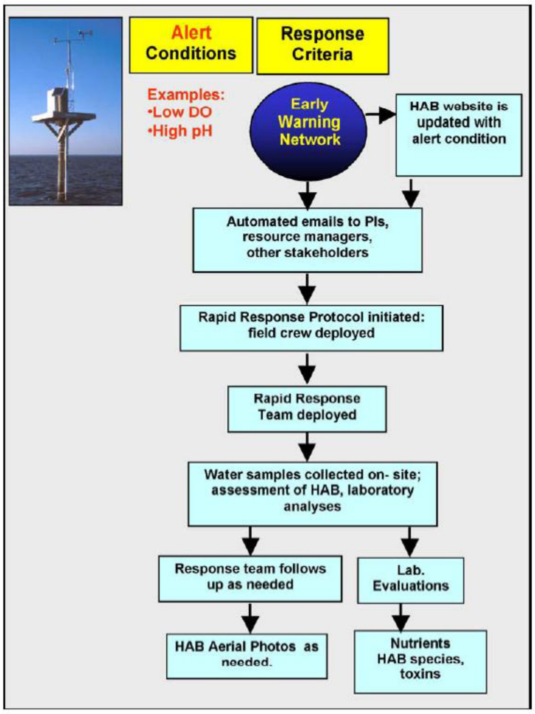

Figure 2.4. Example of an operational web-based RTRM alert response system developed by CAAE. Source: Glasgow *et al.* (2004).

This alert system is an example of a type 4 prediction, *predicting conditions favorable for a HAB to occur where blooms have not yet been observed.* Routine remote sensing is not used in the prediction or alert phases. In the flowchart Figure 2.4, it is evident that aerial photographs of the HAB event are only acquired as needed after the HAB event has been detected.

An operational system has been designed and implemented by local Marine Parks personnel for monitoring the extent of the toxic cyanobacteria blooms of *Lyngbya majuscula* in Moreton Bay, Queensland (Roelfsema *et al.* 2002). The approach integrates field video surveys with classified Landsat ETM+ data as an accurate and cost effective means to regularly map the extent of the bloom as a monthly procedure. Quantitative field estimates of *Lyngbya majuscula* percentage cover for select areas in Moreton Bay coincide with acquired Landsat ETM+ imagery to indicate the extent of the bloom. This system is an example of successful adoption of a combined field and remotely sensed approach to monitoring and understanding a critical environmental hazard (Roelfsema *et al.* 2002). Indeed, Barale and Folving (1996) maintain the value of 'integrated observation systems'.

2.7.4 Sea State

A number of satellites can provide information for wave modelling through altimeter, scatterometer and synthetic aperture radar (SAR) data. However, information from radar altimeters (e.g. Jason-1) is limited to data on significant wave height (SWH) (Greenslade 2001; Symbios Communications 2004). Whereas SAR instruments can accurately measure changes in ocean waves and winds, including wavelength and the direction of wave fronts, regardless of cloud, fog or darkness (Figure 2.5) (Greenslade 2001; Symbios Communications 2004).

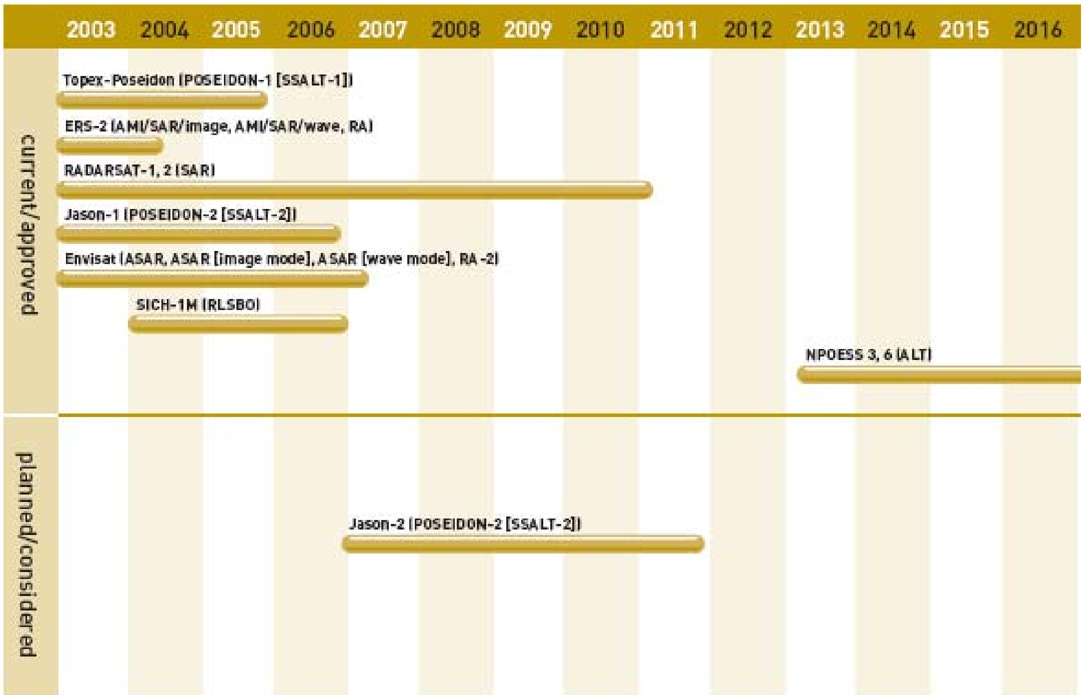

Figure 2.5. Current and planned instruments used for measuring wave height and spectrum. Source: Symbios Communications (2004).

The ASAR instrument on ENVISAT provides wave mode products, but with improved quality. At the recent ENVISAT symposium in Austria this year, Auof *et al.* (2004) presented a validation of ENVISAT ASAR data for three months based on wave model outputs. ASAR data has made available directional, spectral information from the sea, and when compared with the wave model, observations show that it provides a better estimate of the sea state (wave height, mean direction and period), especially when swell is dominant (Aouf *et al.* 2004).

However, these preliminary studies have shown limitations in quality control. In order to eliminate erroneous data, the signal to noise ratio and the retrieved ASAR wind speeds need to be closely examined (Aouf *et al.* 2004).

2.7.5 Sea Surface Temperature

The National Oceanic and Atmospheric Administration (NOAA) satellite series each carry an Advanced Very High Resolution Radiometer (AVHRR) sensor. Among other applications, they provide information on global sea surface temperature measurements. While the resolution at nadir is approximately 1.1 km, the four currently transmitting satellites (NOAA 12, 15, 16 and 17) transmit direct broadcast data to ACRES several times a day.

The MODIS and the Advanced Along Track Scanning Radiometer (AATSR on ENVISAT) are the medium resolution sensors that provide accurate sea surface temperatures. The design of the MODIS instrument is built on several decades of NOAA infrared radiometer use, to develop a state-of-the-art complex algorithm for the estimation of sea surface temperature (*SST*) (Brown and Minnett 1999). An intensive validation of the accuracy of SST retrievals from AATSR has shown that the sensor is currently meeting its objective to determine accurate global SST measurements to within 0.3°C (Corlett *et al.* 2004).

2.7.5.1 Upwellings

Hendiarti *et al.* (2004) studied upwelling events along the southern coast of Java during the southeast monsoon. SeaWiFS derived chlorophyll concentrations higher than 0.8 mg/m^3 and sea-surface temperatures lower than 28˚C were found to be indicative of upwellings, while concentrations of about 0.5 mg/m^3 and SST of higher than 29.5˚C characterize the through flow in the Sunda Strait. Utilization of the SeaWiFS imagery was found to improve previous observations based on SST images.

2.7.6 Sea Surface Salinity

No satellite sensors currently in orbit are able to measure salinity. However, a new Soil Moisture and Ocean Salinity instrument (SMOS) (see Appendix Table 2.4), among others, is planned for launch in February 2007. The instrument will record long-wavelength microwave radiation emitted from the earth, and will have the ability to monitor sea surface salinity.

Sensors such as SMOS may prove to be an invaluable measuring technique, as there is an increased awareness that sea surface salinity variability is important in ocean and climate dynamics that may impact on finfish aquaculture. Much of the southern Australian coastal waters are more saline than the open ocean because of the dominance of evaporation over rainfall and the virtual absence of river runoff. These coastal waters become highly saline as they circulate in the South Australian gulf system where salinities increase in summer to over 60 dS/m (40 ppt) in Spencer Gulf (De Silva Samarasinghe *et al.* 2003), whereas typical EC values for seawater are around 55 dS/m (36.5 ppt).

2.7.7 Oil Slick Detection

Asia-Pacific Applied Science Associates and The Ecology Lab (2003) provide a summary of the satellite sensors that have been available for observation of oil pollution in the open ocean. A number of optical (e.g. Landsat TM and SPOT) and active systems (e.g. Synthetic Aperture Radar (SAR)) have provided some capability of detecting oil slicks from the background and can return varying levels of information on slick area, shape and distribution (Asia-Pacific Applied Science Associates and The Ecology Lab 2003). However, passive optical satellite sensors are limited, as they cannot function through cloud or fog cover, or at night. In comparison, SAR systems are 'all-weather' operators and for this reason have most commonly been used for the detection of oil slicks.

The detection of oil slicks by SAR is a well-developed technique that is commonly used in Australia (Glenn 2002). There are presently three SAR satellites in orbit that are used for this procedure: RADARSAT, ERS-2 and ENVISAT (ASAR).

However, SAR systems also have their limitations. The major obstacles have been area of coverage, wind and sea state conditions and limited spatial resolution (Asia-Pacific Applied Science Associates and The Ecology Lab 2003). Current Radarsat 1 and ERS_SAR sensors can detect slicks with a minimum size of approximately 120m^2 (about 4 to 5 pixels). However, the advent of Radarsat 2, with significantly improved spatial resolution, will greatly reduce the detectable slick size (*pers. comm.* Geoff O'Brien, *Santos Petroleum Engineering*, 2004). The temporal resolution and timing of these radar systems may also restrict their use for operational slick detection from SBT and YTK pontoons.

2.7.8 Benthic Mapping

Finfish aquaculture in inappropriate sites could potentially affect seagrasses in the vicinity of the pontoons through feed deposits and excreta, increasing nutrient input and leading to eutrophication and sedimentation (Department for Environment and Heritage 2004b). An investigation into the tuna cages when they were in Boston Bay (Cheshire *et al.* 1996) observed four zones of influence around each cage extending out to 150m, with an area of high impact (from organic detritus) roughly 5m from the cage margin. Eutrophication that occurs in response to the release of excessive nutrients (e.g. nitrates and phosphates) could potentially promote epiphytic growth on the surfaces of seagrass fronds, and smother the plants. The seagrass can lose its ability to photosynthesise and gradually die (Department for Environment and Heritage 2004a). There is a need to map and monitor the benthos associated with the finfish aquaculture at, and offshore from, Boston, Fitzgerald and Arno bays for such potential effects.

A number of local studies have shown the capability of aerial photography for broad-scale mapping of seagrass in South Australian gulf waters (Hart 1999; Hart and Cameron 1998; Hart and Clarke 2002). A study of Boston Bay and Port Lincoln proper (above the 10 m depth contour) by Hart (1999) determined there was a 1.7 km^2 loss of seagrass measured between the mid 1970s and 1996 due to unknown causes. However, no field-work was undertaken in this study to verify the mapping. Landsat satellite imagery has similarly been trialed as a more cost effective means to map seagrass in Spencer Gulf to 12 m depth (Cameron 1999; Cameron *et al.* 2000). However, the coarser spatial resolution (30 m) of Landsat imagery was shown to limit assessment of the finer detail of seagrass extents; small areas of change/no change and smaller features are not detected (Cameron 1999). Both these aerial photography and Landsat mapping methods, however, determined only 'substrate' and 'seagrass' (a two-class map), as there was insufficient visual separation of seagrass from organic detrital matter, rock, algae and deep water in the imagery. Thus areas mapped as seagrass tended to be a conservative estimate.

Kinhill (1995) conducted a study in Boston Bay to assess the potential of aerial photography for monitoring the impacts of the sea cage tuna farming on macrophyte communities. However, the photography was found to be of limited value, and could only reliably map areas distant from sea cage tuna farms due to imagery problems with artefacts. Hence this particular study was not able to quantify the environmental influences of tuna farming compared with those resulting from significant land-based discharges (Kinhill 1995).

Recent research using high spectral and spatial resolution airborne imagers has shown potential for more accurate mapping of shallow water benthic communities than has been possible with low spectral resolution satellite imagery. These imagers can be flown to acquire geo-registered image strips with resolutions down to 1 metre while recording reflectance in many narrow wavelength channels in the visible and near infrared region of the electromagnetic spectrum. This high spectral resolution potentially allows discrimination of subtly different benthic communities and substrates. Rollings *et al.* (1998) have mapped benthic communities to depths of 12 metres using CASI (Compact Airborne Spectrographic Imager) in Port Phillip Bay, and Dunk and Lewis (2000) discriminated and mapped *Posidonia*, *Zostera* and two sediment types to a maximum depth of 5 m near Port Pirie using HyMap hyperspectral airborne imagery.

In the mapping of South Australian waters adjacent to the South Australian Bolivar Wastewater Treatment Plant, Anstee *et al.* (2000) found that the hyperspectral data provided much higher separability and spectral variation than previous aerial photography demonstrations. Even though aerial photography and hyperspectral imagery quality are very dependent on the weather conditions and mission parameters, hyperspectral imagery offers a significant improvement over aerial photos and allows comparisons of images collected at different times provided that atmospheric corrections are made. However, the high level of accuracy in discriminating between seagrass species could not have been obtained without modeling the atmospheric and in-water radiative transfer, the air-water interface and benthic reflectance as well as robust ground-truthing (Anstee *et al.* 2000).

As with the retrieval of water quality parameters within the water column, the modelling of optics for the benthos needs to be pursued to improve the accuracy of seagrass spectral measurements from remote sensing. Radiative transfer models, such as HydroLight 4.0 [Sequoia Scientific], compute radiance distributions (e.g. water-leaving radiance) and derived quantities for natural water bodies (Sequoia Scientific Inc. 2000), and are an essential step in the calibration of imagery to separate water column and benthic contributions to the measured radiance.

Other remote sensing studies have also addressed this issue. Klonowski *et al.* (2004) had success in mapping a three-component (sand, seagrass and brown algae) benthic habitat (2 m to 15 m depth) with a HydroLight-based Shallow Water Remote Sensing Reflectance Model, derived by Lee *et al* (1998 in Klonowski *et al.* (2004)), which approximates the above-water reflectance spectrum over shallow waters. Holden and LeDrew (2002) similarly modelled water column effects in a coral reef environment. They measured a number of close-range *in situ* hyperspectral reflectance bottom spectra, and used a HydroLight radiative transfer model to predict top-of-the-water column reflectance.

However, accurately mapping and discriminating between benthic communities and seagrass species is of lower importance in assessing the potential effects from finfish aquaculture. Distinguishing between remnant seagrass mat, seafloor seagrass detritus, and the effects of epiphytes still presents a major difficulty because of their spectral similarity.

In addition, the reported studies have mapped benthic communities in shallow 'clear' waters to depths no greater than 15 m. It appears discrimination of features below this depth has yet been unattainable in South Australia. This poses another limitation for aquaculture management as finfish sites are generally situated at depths of 15 m to 25 m (*pers. comm.* Jason Tanner, SARDI, 2005).

2.8 Feasibility Analysis

The suitability of satellite-based sensors to detect and map selected environmental phenomena was tested with a feasibility analysis. The analysis scores the spatial, spectral, temporal and cost attributes of these sensors in relation to a set of spatial, spectral and temporal characteristics and criteria developed for each phenomenon. The criteria were derived from the literature and personal communications with SARDI staff. The satellite and sensor technical information, critical to the analysis, was compiled and listed in Appendix Table 4. Definitions of the sensor attributes are described below:

- **Spatial resolution** refers to pixel size and swath of the sensor and hence determines the minimum size of objects or phenomena that can be discriminated as well as the extent of areas that can be readily mapped;
- **Spectral resolution** refers to the number and position of bands sampling within the electromagnetic spectrum and influences the type and range of materials that may be spectrally discriminated;

- **Temporal resolution** refers to the frequency of repeat image acquisitions, and also considers delivery time and availability;
- **Cost** of the imagery is indicated per scene and also per km^2. Costs are for the supplier most feasible for South Australian users to access.

Algal blooms, water quality, and sea surface temperature were selected as important existing impacts on finfish aquaculture to map and monitor. The feasibility of remotely monitoring the benthos (for potential impacts in the immediate vicinity of the structures as well as in the broader region) was also assessed. The sensors have been scored in relation to the criteria for these environmental phenomena with a three point rating system:

✓✓✓	Highly suitable
✓✓	Moderately suitable
✓	Less suitable

Figure 2.6 presents a simplified summary of the spatial and temporal characteristics of selected phenomena interacting with finfish aquaculture in relation to the spatial and temporal resolutions of common satellite-based imagery. Algal blooms may spatially extend over a few to hundreds of kilometres, and exist for a period of days to months. The spatial characteristics of water quality parameters and sea surface temperature, however, are less definite; measurements can vary with the system under study and may range from point samples to the entire Spencer Gulf area (approx. 20,000 km^2). Water quality and SST measurements may be similar over a period of a week to months. Benthic communities influenced by finfish aquaculture structures are likely to occur on the order of hundreds of meters from the cage margin. However, monitoring up to 1 km^2 would be appropriate for assessing regional impacts. Such communities could show effects over months to years.

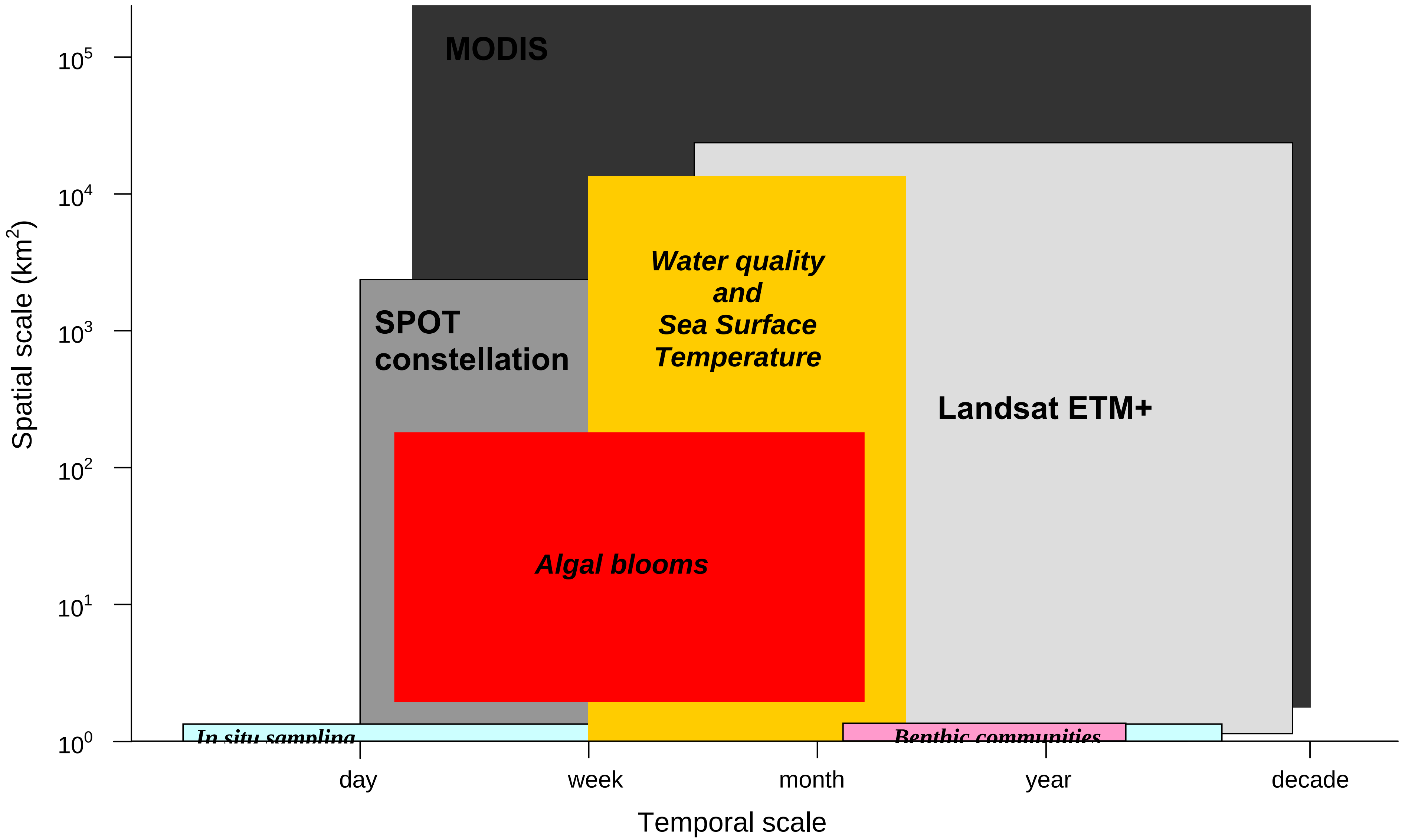

Figure 2.6. Temporal and spatial scales of selected environmental phenomena impacts on aquaculture [algal blooms (red box), water quality and SST (yellow box)], compared to the resolutions of the SPOT, Landsat ETM+ and MODIS sensors (shaded grey boxes), and *in situ* sampling methods (light blue box).

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The SPOT, Landsat ETM+ and MODIS sensors were selected to diagrammatically compare with the phenomena detailed above (

Figure 2.6). In depicting the spatial resolutions of these sensors, the upper limit was determined by sensor image size (i.e. swath width or image tile size). While it is feasible that two or more passes could be acquired and mosaiced together, difficulties exist with image colour balancing, temporal differences, and processing time. The sensors' minimum spatial ranges were depicted as slightly greater than their spatial resolution (Appendix Table 2.4), as it is unlikely they would be able to successfully detect or map phenomena on this threshold. The temporal resolutions are shown as ranging from the sensors' revisit periods, as also detailed in Appendix Table 2.4, to very rough life expectancies of the missions. In comparison, *in situ* sampling can, if necessary, provide point sample measurements several times a day as an ongoing program. The (more detailed) feasibility analyses are presented below.

2.8.1 Algal blooms

Characteristics:

- **Spectral:** algal pigments have distinctive absorption and reflectance characteristics in the visible wavelengths
- **Spatial:** blooms may cover a few to hundreds of km^2 (*pers. comm.* Jason Tanner, SARDI, 2005) though can consist of patches from metres to hundreds of metres in diameter, as indicated in Phinn *et al.* (2005)
- **Temporal:** blooms are dynamic and can form, develop and wane over periods of days to months

	Spatial resolution	Spectral resolution	Temporal resolution	Cost
Landsat	✓✓✓	✓✓✓	✓	✓✓
SPOT	✓✓✓	✓✓✓	✓✓	✓
SeaWiFS	✓	✓✓✓	✓	✓✓✓
Radarsat 1	✓✓✓	✓	✓	✓
MODIS	✓	✓✓✓	✓✓✓	✓✓✓
MERIS	✓✓	✓✓✓	✓	✓✓✓
ASAR	✓✓✓	✓	✓	✓✓✓

The potentially short-lived event of algal blooms means that a high temporal and spectral resolution sensor is required for successful mapping. MODIS fulfils these criteria, although depending on the extent of the bloom, it will likely be limited by its coarser spatial resolution. The spatial and spectral resolution of Landsat and SPOT are perhaps more suited to algal bloom mapping, though these sensors have temporal limitations; given the bloom event may only last days, their temporal frequency of acquisition (Landsat) and data availability (SPOT constellation) may not be fitting. Airborne multispectral or hyperspectral imagery may also be an alternative option suitable for mapping bloom events, provided the aircraft could be deployed on time.

2.8.2 Water quality

Characteristics:

- **Spectral:** distinguished and quantitatively estimated with many bands and smaller bandwidths in the visible wavelengths. Chlorophyll has a distinctive absorption at 675 nm (Carder *et al.* 2004); CDOM at 400nm (Hu *et al.* 2004).

- **Spatial:** can vary over small to large areas; scale is determined somewhat by the system under study and may extend to the entire gulf area (approx. 20,000 km^2)
- **Temporal:** temporally variable, from a week to months

	Spatial resolution	Spectral resolution	Temporal resolution	Cost
Landsat	✓✓✓	✓✓	✓	✓✓
SPOT	✓✓✓	✓	✓✓	✓
SeaWiFS	✓✓	✓✓✓	✓	✓✓✓
Radarsat 1	✓✓✓	✓	✓✓	✓
MODIS	✓✓	✓✓✓	✓✓✓	✓✓✓
MERIS	✓✓	✓✓✓	✓✓	✓✓✓
ASAR	✓✓✓	✓	✓✓	✓✓✓

While the technical specifications of the MERIS sensor place it in reasonably good standing to be suitable for retrieval of water quality parameters, accessibility of the European image data is limited in Australia, reducing its temporal capability. With its high spectral resolution, SeaWiFS may have been another suitable option. However, the recent cessation (Dec 2004) of NASA's distribution contract with OrbImage for SeaWiFS data means that without a research-use licence, recent imagery is difficult to acquire. The MODIS sensor, while potentially limited spatially (depending on the system under study), appears to be the most suitable for monitoring water quality.

Another consideration is the expertise required for retrieving chlorophyll, CDOM and TSS water quality parameters. Accurate retrieval from MODIS imagery is a complex task and requires quantitative image analysis and calibration with field samples (*pers. comm.* Peter Petrusevics, Oceanique Perspectives, 2004).

2.8.3 Sea surface temperature

Characteristics:

- **Spectral:** requires bands in the thermal wavelengths, specifically 3750, 3959, 4050, 11030 and 12020 nm for calculation of temperature from radiance recorded by the sensor (Brown and Minnett 1999)
- **Spatial:** can vary over small to large areas; scale is determined somewhat by the system under study and may extend to the entire gulf area (approx. 20,000 km^2)
- **Temporal:** a week to months

	Spatial resolution	Spectral resolution	Temporal resolution	Cost
Landsat	✓✓✓	✓	✓	✓✓
SPOT	✓✓✓	✓	✓✓	✓
SeaWiFS	✓✓	✓	✓	✓✓✓
Radarsat 1	✓✓✓	✓	✓✓	✓
MODIS	✓✓	✓✓✓	✓✓✓	✓✓✓
MERIS	✓✓✓	✓	✓✓	✓✓✓

ASAR	✓✓✓	✓	✓✓	✓✓✓
AATSR	✓✓	✓✓✓	✓✓	✓✓✓
NOAA	✓✓	✓✓✓	✓✓✓	✓✓✓

MODIS, AATSR and NOAA are spectrally and temporally suitable for retrieving sea surface temperatures (although AATSR data may be difficult to access). However, the coarser spatial resolution of these sensors may be unsuitable for detailed information about smaller area temperature variations. While the MODIS and NOAA AVHRR already-derived SST products are not available for download from the ACRES website, the algorithms are available for the user to perform an extraction (*pers. comm.* James Cameron, DEH/ACRES, 2005). The Algorithm Theoretical Basis Document (Brown and Minnett 1999) provides an overview of the algorithm and image information used for the extraction of SSTs from MODIS imagery.

2.8.4 Benthic communities

Characteristics:

- **Spectral:** requires many sampling bands in the visible wavelengths (Dunk and Lewis 2000) limited by depth of penetration due to light attenuation in water
- **Spatial:** fine scale to 1 km^2 (approx. area of influence around a single tuna cage is 150 m from the cage margin (Cheshire *et al.* 1996))
- **Temporal:** months to years

	Spatial resolution	**Spectral resolution**	**Temporal resolution**	**Cost**
Landsat	✓	✓✓	✓✓✓	✓✓
SPOT	✓✓	✓	✓✓✓	✓
SeaWiFS	✓	✓✓✓	✓	✓✓✓
Radarsat 1	✓	✓	✓✓✓	✓
MODIS	✓	✓✓✓	✓✓✓	✓✓✓
MERIS	✓	✓✓✓	✓✓	✓✓✓
ASAR	✓	✓	✓✓	✓✓✓
Casi	✓✓✓	✓✓✓	✓✓	✓
HyMap	✓✓✓	✓✓✓	✓✓	✓
Hyperion	✓	✓✓✓	✓✓	✓✓

Airborne hyperspectral imagers appear to be spectrally and spatially suitable for mapping the benthos in the vicinity of the aquaculture pontoons. As demonstrated in Anstee *et al.* (2000), hyperspectral imaging techniques have higher separability and spectral variation than previous aerial photography demonstrations. However, airborne imagery needs to be specifically commissioned, and it is often difficult to guarantee rapid and timely acquisition. The procurement is also costly.

Other considerations involved with mapping of the benthos are sensor depth of penetration and capability in distinguishing seagrass mat from detritral seagrass. A review of the literature has revealed most studies have mapped benthic communities in shallow 'clear' waters to depths no greater than 15 m. It appears discrimination of features below this depth has not yet been attainable. While sensors may be spatially, spectrally and temporally suitable, water depth penetration poses a limitation for aquaculture management as finfish sites are generally situated at depths of 15m to 25m. In addition, no reported studies have been located that have distinguished between remnant seagrass matt and derived seagrass features such as seafloor seagrass detritus, and seagrass with epiphytes. This presents a major difficulty because of their close spectral nature. Hence is it problematic to monitor all the potential effects of finfish aquaculture on the benthic community in the vicinity and the broader region of the sea cages.

2.9 Recommendations

A review of the literature found most reported studies have used satellite-based remote sensing systems rather than airborne platforms for detecting and mapping environmental phenomena. While in principle airborne systems suggest high flexibility in terms of targets, time of acquisition, and imaging under cloud, in practice it is often difficult to guarantee rapid and timely acquisition. Airborne imagery needs to be specifically commissioned whereas polar orbiting satellite systems make routine passes over the earth's surface. There appear to be two primary roles for airborne systems:

1. Evaluation of new forms of imagery for research and development. Airborne platforms are a mode for analytically testing sensors that may have increased availability in the future, e.g. airborne hyperspectral systems.
2. Documentation of specific events or target areas, e.g. multispectral cameras/aerial photography acquisition.

Satellite-based imaging systems, on the other hand, have most potential and are already being used to provide repetitive monitoring of marine and terrestrial phenomena at a range of spatial scales.

Using current remote sensing systems and technical expertise available within Australia, several roles for remote sensing can be identified that are relevant to South Australian aquaculture enterprises:

- Increasing understanding of the regional characteristics and dynamics of the surface waters in Spencer Gulf and adjoining southern waters. Better information about the spatial and temporal dynamics of this region would improve understanding of the environmental context of the aquaculture enterprises and enable stronger predictions of influences and events relating to specific locations. The high temporal frequency and spectral capability, as well as low cost of MODIS makes this sensor the obvious choice for further study of the Spencer Gulf waters;
- Detection and mapping of specific events at particular locations (e.g. algal blooms), with acquisition of imagery triggered by other early warning systems. Such mapping might use relatively high resolution imagery, such as SPOT or Landsat, or airborne hyperspectral imagery, to provide detailed documentation and evidence on the distribution and dynamics of a particular event of concern in a limited area;
- Mapping and monitoring of benthic composition in shallow waters. Several airborne and satellite-borne remote sensing systems have the capability to map variations in benthic cover and their imagery could be used to map benthic cover and variations in composition in selected areas of interest. Airborne hyperspectral systems have demonstrated capability in spectral and spatial resolution for this task;
- Analysis of the bio-optical properties of southern Australian coastal waters as a foundation for future analysis and monitoring of water composition using a variety of remote sensing data sources. Such research would enhance capability to exploit current and future remote sensing data for marine monitoring applications.

Based on the literature and the feasibility analysis, identified management needs, as listed in the Terms of Reference (Table 2.1), were reviewed for their current operational potential. Table 2.3 lists these management needs and briefly states the potential (if any) for current operation.

Table 2.3. Current operational potential identified for management needs for South Australian finfish aquaculture

Management need	Current operational potential
Harmful algal blooms - detection, mapping and possible warning system	While there is little scope for using remote sensing as a warning tool, mapping the dynamics of an existing algal bloom is currently feasible. SPOT, Landsat or airborne systems would be suitable for this task. Basic remote sensing skills are required to map and calculate bloom areas.
Water quality – identification and concentration of water constituents	Retrieving water quality parameters from MODIS data is currently feasible. However, accurate retrieval from MODIS imagery is a complex task and requires quantitative image analysis and calibration with field samples. A South Australian company, Oceanique Perspectives, currently extracts these parameters for the Gulf of St. Vincent.
Sea state (SS) for potential effect on access and work operations – identification of high SS periods	A current SAR system such as Radarsat-1 is able to provide information on sea wave height with the assistance of costly extraction software. However, the process is time consuming and the accuracy is uncertain. It is unlikely this would be a cost-effective method of assessing the number of work days on aquaculture operations.
Sea surface temperature (SST) – mapping temperature gradients	At the present time, ACRES does not provide SST products for MODIS and NOAA. However, DEH have the NOAA and MODIS (slightly more complex) algorithms available to users with reasonable remote sensing ability and access to image processing software. As they are adapted from North American algorithms, further calibration would be required before it could be used operationally.
Sea surface salinity - mapping concentrations	There are currently no remote sensing systems available for measuring sea surface salinity. Sensors such as the Soil Moisture and Ocean Salinity instrument (SMOS) (see Appendix Table 4) may be useful in the future.
Oil slicks from sea-cages – detection and mapping of oil slicks	Mapping oil slicks is a currently feasible and well-developed technique. When conditions are favourable, Radarsat-1 could detect slicks from the sea-cages if they were at least approx. 120 m^2. Basic remote sensing skills are required to map and measure slick areas. However, Radarsat-1 imagery (and other radar data) is costly, and therefore it is unlikely that this method would be cost-effective.
Potential farm impacts to benthic communities in vicinity & broader region - mapping of benthos	Accurately mapping potential farm impacts on benthic communities would appear to be unfeasible at the current time. The limitations of sensor water penetration make it difficult to assess the area in the region of the sea-cages situated at 15-25 m. However, there may be scope for mapping any areas of impact in shallower regions closer to shore. Benthos mapping methods are very much in a research phase. Higher resolution imagery would also be needed to detect small losses, and thus allow early intervention, rather than simply documenting large scale loss once it was too late to do anything.

Pontoon locations (coordinates) – monitoring for general management	Locating pontoons should be a straightforward task with a capable sensor. For pontoons of 40 m–50 m diameter, a high-resolution multispectral sensor such as SPOT 5 (10 m multispectral and a 5 m panchromatic band) should be suitable, and has cost and temporal advantages over airborne systems. Pontoons and their coordinates could be fairly quickly and easily identified from the acquired geo-referenced imagery using appropriate (and low/no cost) viewing software.

2.10 Pilot Programs

While this review has evaluated current remote sensing systems for monitoring interactions of finfish aquaculture and environmental phenomena in specific South Australian contexts, pilot programs should be conducted to build understanding of the capability of remote sensing systems and associated analytical requirements for local applications. The following pilot programs are suggested for implementation:

1. Monitoring water quality of Spencer Gulf with MODIS
2. Triggered high-resolution imagery for post event algal bloom mapping
3. Modeling of water quality parameters from field data and hyperspectral imagery

The aims and a brief suggested method are outlined for each recommended study. It is suggested that a framework for coastal environments as detailed in (Phinn *et al.* 2000) be considered to assist with planning for any of these programs.

1. Monitoring water quality of the Spencer Gulf with MODIS

The high temporal and spectral frequency of the MODIS sensor potentially provides an effective means of monitoring water quality in the Spencer Gulf. While the sensor's spatial resolution is not high enough to produce water quality information in the immediate vicinity of the aquaculture structures, it nevertheless places these in context by providing an overall 'picture' of the Gulf's water quality dynamics and patterns (Figure 2.7).

Aims

To evaluate the suitability of MODIS for monitoring water quality at Gulf scale over a two-year period.

Suggested method

Establish a two-year cycle of frequent acquisitions (weekly – monthly; as permitted by cloud cover) and analysis of MODIS imagery for retrieving information on:

- Chlorophyll a
- CDOM
- Total suspended solids
- Temperature
- Other observed phenomena such as algal blooms

Information gathered from *in-situ* sensors would need to be acquired to serve as calibration for imagery-derived variables. SARDI's existing Regional Environmental Sustainability Assessment (RESA) project employs telemetry-based environmental monitoring systems mounted on pontoons to collect information on temperature, salinity, pH, dissolved oxygen, wind speed and direction. Furthermore, the Risk and Response project has recently been commissioned and will continue monitoring until mid 2008. This project will also undertake regular *in situ* monitoring of chlorophyll, turbidity, suspended solids and other parameters. These two *in situ*-based systems would be suitable for using in conjunction with a routine cycle of MODIS image acquisition and analysis.

Figure 2.7. MODIS true colour 1km image acquired 20th February 2004

The Australian Centre for Remote Sensing (ACRES) routinely acquires MODIS overpasses, and the data are free to download for recent acquisitions within the last 7 days. However, as the retrieval of water quality parameters from the imagery requires relatively complex image analysis and interpretation, it is suggested that specialist expertise be employed. Peter Petrusevics of Oceanique Perspectives is an Adelaide-based independent oceanography and coastal zone research provider who acquires daily MODIS images and regularly retrieves information on suspended matter in the water column. He has expressed interest in collaboration on such a project, should it be initiated.

2 Triggered high-resolution multispectral imagery for post event algal bloom mapping

While remote sensing has been shown to have little use in the very early warning or prediction of algal blooms, it has been successful in mapping the extent and temporal dynamics of an existing bloom. High-resolution multispectral imagery such as SPOT 10 m (Spot 5) and 20 m (SPOT 2, 3 and 4) data has the potential to adequately map the dynamics of an established bloom. The constellation of SPOT satellites, and their adjustable viewing angles provides a high temporal resolution with the potential for daily coverage of an area.

There may be some scope for acquiring historic image data on specific algal bloom events. A preliminary search could be undertaken for high-resolution imagery that correspond to a known past event. However, because of the transient nature of the blooms and typical non-routine archiving of high-resolution imagery, there is a low probability that any local events would have been 'captured' on an image.

Operational alert response systems use *in-situ* sensors and other ground-based monitoring to detect alert conditions and then trigger a web-based warning network (Glasgow *et al.* 2004). Acquiring imagery can be a component of this warning system, deployed to monitor, map and record the bloom.

Aims

To assess the value of high-resolution SPOT imagery for mapping algal blooms that have formerly been detected with *in-situ* monitoring.

Suggested method

The Risk and Response project, mentioned in the previous pilot program, presently monitoring water quality of the Spencer Gulf with MODIS, would be an appropriate *in-situ* system to use in monitoring for alert conditions such as increases in turbidity, low dissolved oxygen or high pH (Glasgow *et al.* 2004).

This program would evaluate the use of an alert response from ground-based monitoring to trigger the acquisition of SPOT imagery. It would also test the adequacy of a delivery mechanism. While not in place at the current time, an objective of the Risk and Response project is for further development of a near real-time telemetered environmental observation system with web access. Once operational, this real-time system could improve the delivery mechanism.

It is suggested that this program be run concurrently with program 1 (Monitoring water quality of the Spencer Gulf with MODIS), over a two-year evaluation period. This will also allow for shared resources (e.g. *in situ* sensors) and common environmental information.

3. Modelling of water quality parameters from field data and hyperspectral imagery

In comparison with empirical methods, the modelling approach establishes physical relations between water quality parameters, the underwater light field and the remotely sensed measurements. Proponents of this approach have demonstrated the use of bio-optical radiative transfer models to increase the accuracy and validity of benthic and water column measurements and allow more reliable extrapolation over space and time than is possible with empirical prediction of water quality parameters. High-resolution hyperspectral imagery is an essential part of the research in this area.

Aims

Evaluate the capability of using *in situ* sampling of water quality parameters to calibrate measurements from hyperspectral imagery and build a bio-optical model for Spencer Gulf waters in the regions of importance for aquaculture enterprises.

Suggested method

There is demonstrated scope for use of hyperspectral data for monitoring water quality. For example, previous work by Hoogenboom *et al.* (1998) used the imaging spectrometer AVIRIS to determine water quality parameters in coastal waters. The accuracy depended on accurate atmospheric correction of the airborne hyperspectral imagery and application of an appropriate water quality algorithm.

An essential preliminary component of such a study is the *in-situ* collection of measurements of key water optical properties that are required for modelling the underwater light field in Spencer Gulf. With the assistance of a modelling tool, such as HydroLight, a radiative transfer model could be built from these measurements. The resultant model will act as calibration for the hyperspectral imagery, from which water quality parameters can be retrieved by model inversion. However, this recommendation may be limited by available modelling software and expertise.

However, it is unlikely that this program would be cost effective, or beneficial to the finfish aquaculture industry in the short term. Costly image and field data acquisitions, and the high levels of image analysis required suggest that this program would probably not be feasible at the current time.

2.11 Appendix

2.11.1 Map of Finfish locations

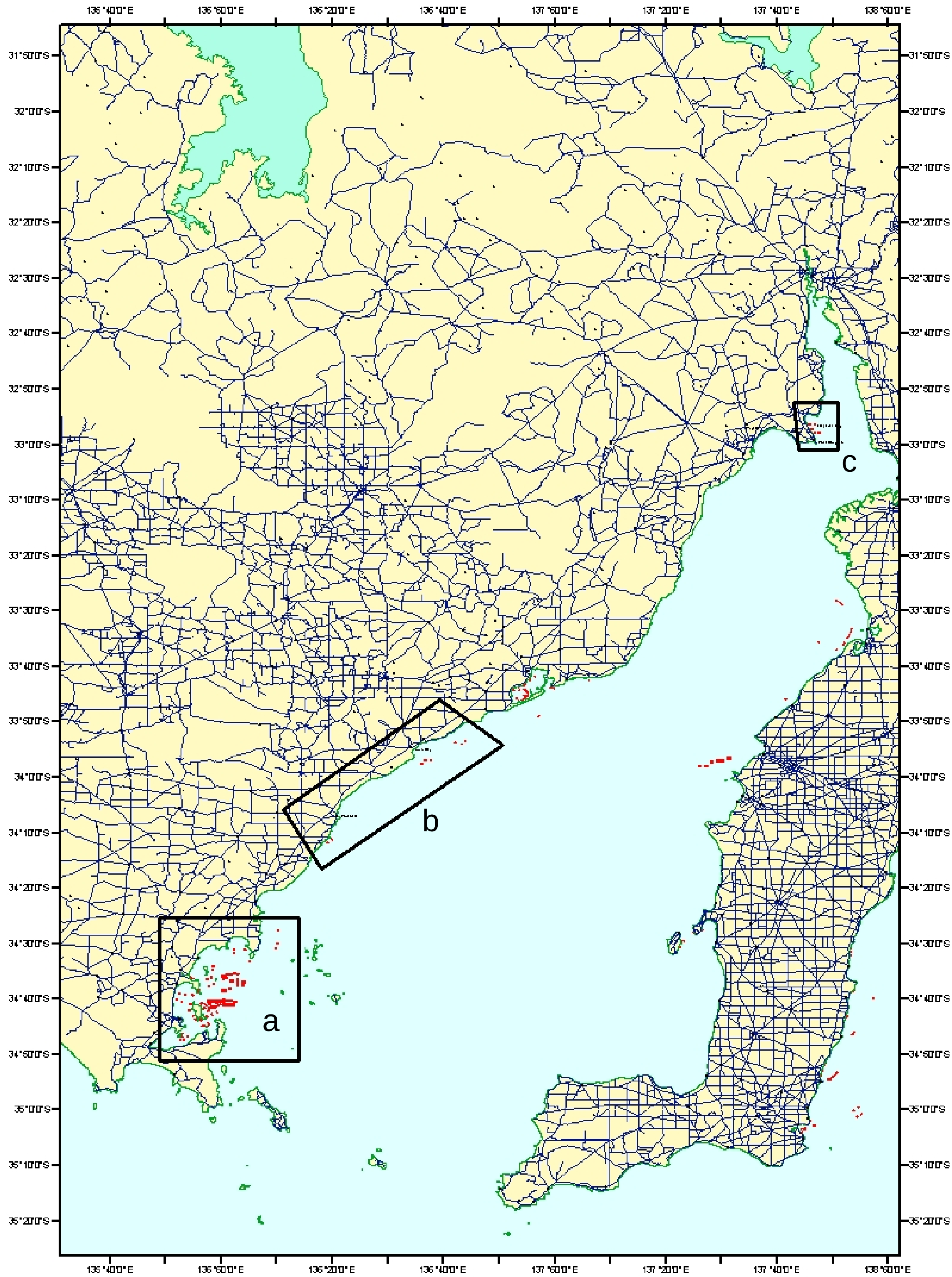
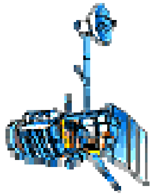
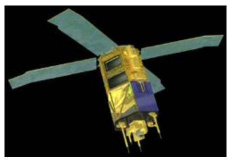
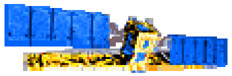


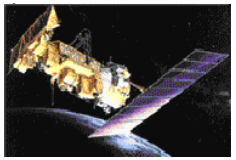
Figure 2.8. Location of southern bluefin tuna (SBT) (*Thunnus maccoyii)* and yellowtail kingfish (YTK) (*Seriola lalandi*) farming areas in Spencer Gulf in 2006: a) Boston Island (SBT & YTK), b) Arno Bay (YTK) and c) Fitzgerald Bay (YTK). Red dots are aquaculture leases (including shellfish).

2.11.2 Catalogue of Sensors

Table 2.4. Technical specifications, availability and cost of selected satellite sensors used for oceanography

Satellite/Mission	Sensor	Spatial resolution (m)	Spectral range (µm)	Revisit period (days)	Swath width (km)	Acquisition time/ data access	Data history	Supplier	Cost*/scene	Approx. cost*/km^2
Landsat 5 and 7 	**ETM+**	30 (Bands 1-7) 60 (Band 6) 15 (Panchromatic)	8 bands: 1: 0.45 – 0.52 2: 0.52 – 0.60 3: 0.63 – 0.69 4: 0.76 – 0.90 5: 1.55 – 1.75 6: 10.40 – 12.50 7: 2.08 – 2.35 Pan: 0.52 – 0.90	16	185	3 days Overpasses routinely acquired by Australian Centre for Remote Sensing (ACRES) [www.ga.gov.au/acres/]	Landsat 5: May 84 - present Landsat 7: Jul 99 - present *(though in SLC-off mode since May 03 due to instrument malfunction)* Comprehensive image archive	ACRES (online delivery)	$1200 (ortho-corrected full scene)	$0.035
SPOT 5 	**HRV-IR**	10 (Bands 1-3) 20 (Band 4) 5 (Panchromatic)	5 bands: 1: 0.50 – 0.59 2: 0.61 – 0.68 3: 0.78 – 0.89 4: 1.58 – 1.75 Pan: 0.51 – 0.73	3 (but daily with entire SPOT constellation)	60	Approx. 1 week (48hrs with $500 priority fee) Pre-order and tasking required from Raytheon [www.raytheon.com.au/]	Jul 02 - present	Raytheon Australia	$4230 (10m colour)	$1.18
Orbview-2 (formerly SeaStar) 	**SeaWiFS**	1130	8 bands: 1: 0.40 – 0.42 2: 0.43 – 0.45 3: 0.48 – 0.50 4: 0.50 – 0.52 5: 0.54 – 0.56 6: 0.66 – 0.68 7: 0.75 – 0.78 8: 0.84 – 0.88	1	2801	3 days Overpasses routinely acquired by Oceanique Perspectives till Dec 04**	Sept 97 – Dec 04 *(NASA contract expired. Currently only available to ORBIMAGE-approved OrbView-2 research users)*	OrbImage/ NASA	$644	negligible

Radarsat 1 	**SAR (Fine beam mode)**	10	SAR C (5.3GHz)	4-6	50	3 days Pre-order and tasking required from ACRES [www.ga.gov.au/acres/]	Jan 96 - present	ACRES (online delivery)	$4710	$1.88
Satellite/Mission	**Sensor**	**Spatial Resolution (m)**	**Spectral Range (µm)**	**Revisit period (days)**	**Swath width (km)**	**Acquisition Time/ data access**	**Data history**	**Supplier**	**Cost*/scene**	**Approx. cost*/km^2**
Aqua and Terra 	**MODIS**	250 (bands 1-2) 500 (bands 3-7) 1000 (bands 8-36)	36 bands Bands 8-16: 0.4 – 0.87 (for ocean colour)	1-2 with both satellites	2330	Available the following morning Overpasses routinely acquired by ACRES [www.ga.gov.au/acres/] and Oceanique Perspectives**	Aug 00 – present Comprehensive image archive	ACRES (online delivery)	Free for recent acquisitions (last 7days) Archive: $150/swath on DVD	$0
ENVISAT 	**MERIS**	300	15 bands 0.39 –1.04 (programmable)	3	1150	Overpasses routinely acquired by ESA Distributed through Eurimage [www.eurimage.com/] *Please note: ordering system awkward as sensor primarily designed for research*	May 02 - present	Eurimage	$483 (334km length)	negligible
	ASAR	30	SAR C (5.3GHz)		400					
	AATSR	1000	7 bands Band centre: 1: 0.555 (green) 2: 0.659 (red) 3: 0.865 (NIR) 4: 1.6 (SWIR) 5: 3.7 (TIR) 6: 10.85 (TIR) 7: 12.0 (TIR)		512					

NOAA 12, 15, 16, & 	**AVHRR**	1100	6 bands: 1: 0.58 – 0.68 2: 0.73 – 0.98 3a: 1.58 – 1.63 3b: 3.54 – 3.87 4: 10.3 – 11.3 5: 11.5 – 12.4	0.5	2399	Available the following morning Overpasses routinely acquired by ACRES [www.ga.gov.au/acres/]	Jul 99 – present Comprehensive image archive	ACRES (online delivery)	Free for recent acquisitions (last 7days) Archive: $150/swath on DVD	$0

* prices accurate as of February 15, 2005 and with current Aud$ exchange rates
** Oceanique Perspectives, contact Peter Petrusevics ph.8365 3995 mob.0418 807 095

2.11.3 Future Sensors:

Satellite/Mission	**Sensor**	**Description**
SMOS 	**MIRAS**	ESA's Soil Moisture and Ocean Salinity (SMOS) mission has been designed to observe soil moisture over the Earth's landmasses and salinity over the oceans for a period of at least three years. Launch date planned for February 2007. An important aspect of this mission is that it will demonstrate a new measuring technique by adopting a completely different approach in the field of observing the Earth from space. A novel instrument called MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) has been developed that is capable of observing both soil moisture and ocean salinity by capturing images of emitted microwave radiation around the frequency of 1.4 GHz (L-band). SMOS will carry the first-ever, polar-orbiting, space-borne, 2-D interferometric radiometer (European Space Agency 2004).
NPOESS 	**VIIRS**	The Visible/Infrared Imager/Radiometer (VIIRS) Suite collects visible/infrared imagery and radiometric data. Data types include atmospheric, clouds, earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean colour, and low light visible imagery. Launch date planned October for 2006 (for NPP). VIIRS will also provide capabilities to produce higher resolution and more accurate measurements of sea surface temperature than currently available from the heritage AVHRR instrument on POES, as well as an operational capability for ocean colour observations and a variety of derived ocean colour products (NPOESS 2004).

2.11.4 Ocean Monitoring Satellites

Table 2.5. A cross-reference between some common ocean variables and respective satellite missions and sensors. Source: Sodemann and Aarup (2004).

Ocean Variable	Mission (Agency)
Significant wave height (SWH)	TOPEX/Poseidon (NASA/CNES), Jason-1 (NASA/CNES), ERS-2 (ESA), ENVISAT (ESA)
Sea surface temperature (SST)	AVHRR (NOAA/NASA), ATSR-2/ERS-2 (ESA), AATSR/ENVISAT (ESA), MODIS/EOS-Terra/Aqua (NASA), AMSR-E/EOS-Aqua (NASA/NASDA), CBERS-2 (INPE), OCTS/ADEOS (NASDA)
Sea surface salinity (SSS)	Aquarius (NASA) launch TBD SMOS (ESA) launch 2007
Ocean Colour	SeaWiFS (NASA), MODIS/EOS-Aqua (NASA), MERIS/ENVISAT (ESA), OCTS/ADEOS (NASDA)

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Chapter 3 SBT telemetry-based environmental monitoring systems

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3.1 Executive Summary

One of the components of this research project was the development of the "SBT Telemetry-based Environmental Monitoring System" with the aim being to apply it to regional environmental monitoring for the tuna aquaculture industry. The processes that led to the development of this system included a review of various systems available both nationally and internationally, followed by a trial of an existing system and finally the development of a customised system.

The trial of the existing system, which was a moored floating buoy, allowed an assessment of some basic water quality parameters in terms of variability and usability. However after a six-month trial, this system was discontinued because of the high maintenance required and limitations of the existing software, which did not allow flexibility and potential expansion.

A South Australian company, Measurement Engineering Australia Pty Ltd (MEA), was chosen to manufacture the customised system as it was cost effective and had the potential to be more flexible in that it could be upgraded with additional sensors as resources allowed. The sea-cage system developed was much more user friendly, allowing real-time access to the data via a software package (MAGPIE) developed by MEA. A second system was subsequently built for another project, where it was used to monitor the effects of fouling assemblages on water exchange.

With increasing interest shown by both industry and researchers, the project worked towards delivery of the data. Initially a real-time delivery system, using a limited-function MAGPIE software was distributed for trial. This software allowed users to dial-up the system directly to obtain real-time data. This direct dial-up was only available to owners of the pontoon where the system was deployed. This work was subsequently expanded to a web-based delivery system in order to make the data more widely available. A website hosted by an external server was set up to deliver near real-time environmental data being collected by the systems to authorized users. The data available included temperature, salinity, dissolved oxygen, wind speed and direction.

The future plan for both of the SBT Telemetry-based Environmental Monitoring Systems is re-deployment in 2006. The Risk and Response Project (Aquafin CRC/FRDC 2005/059) and the Fouling Management Project (Aquafin CRC/FRDC 2003/226) will use the data collected by the systems. In addition, another system with capability to measure current speed and direction, as well as wave characteristics, is being added. This instrumentation will be deployed on a separate buoy, to avoid potential interference in the

readings from a pontoon and is being developed by MEA. The data will be used by the Risk and Response project to help parameterise the models being developed and will also be useful for industry operational purpose.

3.2 Introduction

Regional environmental monitoring for the tuna industry is anticipated to require an approach with two aspects. Firstly, the development of a monitoring programme for the current regional influence of the industry and secondly, the development and parameterisation of large-scale models to understand the environmental implications of expansion into new lease areas and change in management regimes. Consequently, one of the components of this research project was the development of the "SBT telemetry-based environmental monitoring system". The purpose of this component was two-fold; firstly to assess the feasibility of using a range of standard *in situ* water quality monitoring probes linked to a data logger and telemetry system to provide near real-time or actual real-time data to researchers involved in this and possibly other projects, and secondly, successful data collection would provide a data stream to help parameterise ecosystem scale models.

Telemetry-based water quality equipment had previously been trialled at the Tuna Research Farm in Boston Bay (operational in 1996, but no longer) as an alternative to hand-held systems (Clarke *et al.* 1999). Two sondes (Smart Sonde from Greenspan and Hydrolab Minisonde) were trialled for between two to three months and parameters included temperature, dissolved oxygen, turbidity, conductivity, salinity and pH. Summary graphs were given but no assessment report was available (Clarke *et al.* 1999). The report only stated that the monitoring was discontinued after the initial trial because the time and resources required for maintenance of the system was considered excessive and there was also continued logistical problems for servicing the equipment.

In Tasmania, as part of another Aquafin CRC project (4.4 - Development of broad scale environmental monitoring and baseline surveys in relation to sustainable salmon aquaculture in the D'Entrecasteaux Channel region), systems for the continuous monitoring of dissolved oxygen (DO) were deployed. One of the systems was to be a telemetered Ecosan/Greenspan unit. However, after many trials, the Ecoscan unit was still not funtional and the university undertaking the project consequently had to seek legal advice to recoup all monies from the company involved. A comparison of dissolved oxygen data collected from continuous logging, hand-held sonde and standard DO Winkler analysis was conducted under this project. The results indicated that data loggers recorded lower DO values than those measured using Winkler titration, but the difference was generally slight, while the multiparameter sonde had readings that showed increasing differences to the Winkler measurements.

Consequently, in this project, a review of various telemetry-based water quality measurement systems available both nationally and internationally was carried out. In the review, several criteria including the cost, the probable need to eventually have multiple systems, a wide range of sensors and the ability to provide local operational support had to be considered. This was followed by a trial of an existing system while a customised system was being built. This chapter details the various processes that led to the development of the SBT Telemetry-based Environmental Monitoring Systems, which includes a website for delivery of data to authorised users, as well as provide a summary of the data collected.

3.3 Oceanographic buoys

Before assessments concerning the ecologically sustainable development of an offshore aquaculture operation can be undertaken, it is important to understand the dynamics of the system in which the industry operates. The system's key processes, responses and their natural temporal and spatial scales of variation will influence the industry's sustainable development to a large extent. Individual operators on boats using water sample bottles, which are processed later, or direct readings from on-board instrumentation, have traditionally been used to gather this type of information *in situ*. Both methods can provide reasonable spatial resolution of variability, although results derived from the former method are often more expensive to process per sample unit and can take some time to be analysed and collated. Despite this, the principal limitation to both methods is the resolution of temporal variability. The ability to identify change in the marine environment depends on both the duration and frequency of sampling. Characterisation of marine systems is largely dependent on the collection of environmental data with sufficient temporal resolution to map changes at a variety of different time scales. Questions regarding anthropogenic versus natural changes can only be addressed with this type of information. In this regard, the use of telemetry-based automatic monitoring systems (also known as "oceanographic buoys") is an excellent method for gathering information on the system's temporal variability.

3.3.1 History

In the early 1950's, there was a growing awareness of the need for oceanographic exploration and new methods/equipment for marine research. In addition, a growing realisation of the importance of the world's ocean resources drove the development of moored oceanographic buoys. New advances in marine technology that grew from developments made during World War II, particularly in positioning systems, improved the speed and accuracy of the collection of hydrographic and oceanic data. Another motivating element was the need for data on weather systems. Forecasts for civilian and military aviation combined with the need for accurate early warnings of severe weather accelerated the development of global satellite weather watching. Finally, the development of methods for more efficient use of the electromagnetic spectrum for telecommunication purposes played a key role in the discovery of new models of electromagnetic propagation by the ionosphere and the practical use of such new telecommunication techniques. The combination of advances in computer modelling, satellite technology and weather forecasting led to the development of automated, oceanographic buoy observation stations (See http://www.lib.noaa.gov/edocs/noaahistory.html).

By the 1960's, the need for more detailed information on environmental conditions over vast marine areas, which remained largely uncovered except for occasional observations from ships or aircraft of opportunity, oceanographic research expeditions, or the few existing ocean station vessels, was recognised by scientists working in the field. Consequently, a number of US Federal agencies and universities started programs to develop and implement networks of buoys that could routinely and automatically report environmental conditions such as temperature, wind speed and direction. However, these efforts were largely designed to meet individual agency or research needs.

In 1966, a group of US Federal agency representatives was convened by the USA Panel on Ocean Engineering of the Interagency Committee on Oceanography to address the problems and possibilities associated with automated data buoy networks. A national system of ocean data buoys was recommended and the Committee asked the Coast Guard to conduct a feasibility study. The study report made the following conclusions after ten months of work:

- There were extensive requirements for oceanographic and meteorological information to satisfy both operational and research needs in the oceanic and Great Lakes environments.
- Automatic moored buoys were capable of meeting a significant portion of those needs
- An essential element of an overall environmental information and prediction system would be a network of such buoys.

The National Council for Marine Resources and Engineering Development took these conclusions seriously. In November 1967, the Coast Guard was requested by the National Council to accept lead agency responsibility for the research, development, testing and evaluation required to support future decisions on national data buoy systems. The National Data Buoy Development Project was established to do the job. In December 1967, the National Data Buoy Development Project developed a national system of automatic ocean buoys to gather oceanic and atmospheric data. Existing capabilities in a number of disciplines from oceanography to communications were drawn upon and the effort to develop a single, national system capable of providing key observations required to describe conditions in the marine environment was started. The project then became the responsibility and challenge of NOAA (National Oceanic and Atmospheric Administration) and NOAA has since led the development of a consolidated national oceanic and atmospheric research and development program and provided a variety of scientific and technical services to other Federal agencies, private sector interests and the general public (see http://www.lib.noaa.gov/edocs/noaahistory.html).

3.3.2 Uses

There are numerous applications for data collected by oceanographic buoys that complement data collected through other means such as satellites:

- Weather forecasts. Meteorological models routinely assimilate observational data from various sources including satellites, weather balloons, land stations, ships, and data buoys. Most of the models are global and assimilate observational data from all sources around the planet to make their national forecasts. Distribution of meteorological data worldwide is coordinated through the World Weather Watch. Buoy data are crucial for data sparse ocean areas where no other sources of valuable data are available.

- Marine forecast. For similar reasons, buoy data are essential for producing improved marine forecasts.

- Assistance to fisheries. Sea surface temperature is an important tool to find many different species of fish. The buoys provide this information to weather centres daily. These centres, in turn, produce charts of sea surface temperature and distribute them via radio fax broadcasts to fishermen at sea or home office. Knowing where to look for fish saves both fuel and time. Also, using data buoys and other instruments such as sub-surface floats, many advanced oceanographic models now can be used to predict El Niño events and other ocean disturbances. Such information can help fishermen plan their operations in advance.

- Safety at sea. Several nations have successfully used surface wind and ocean current information from the buoys to help locate missing or overdue boats.

- Climate prediction, meteorological and oceanographic research. For example, researchers use the data from the equatorial Pacific moorings to learn how to predict future changes in the world's climate. The buoys were first deployed to learn how to predict the El Niño/Southern Oscillation phenomenon. El Niño events involve disruptions in the ocean surface winds and the upper ocean temperature pattern. These disruptions lead to seasonal climate variations and changes in fish migration patterns in many areas of the world ocean including the tropics.

3.3.3 Types

Drifting and moored data buoys, ice floats, and sub-surface floats are now generally accepted as a very cost-effective means for obtaining meteorological and oceanographic data from remote ocean areas. As such, they form an essential component of marine observing systems established as part of the World Weather Watch (http://www.wmo.ch/), the World Climate Research Programme (http://www.wmo.ch/web/wcrp/wcrp-home.html), the Global Ocean Observing System (http://ioc.unesco.org/goos/), the Global Climate Observing System (http://www.wmo.ch/web/gcos/gcoshome.html), the Joint WMO-IOC technical Commission for Oceanography and Marine Meteorology and other meteorological and oceanographic programmes (http://www.dbcp.noaa.gov/dbcp/0os.html).

3.3.3.1 Drifting

Drifting buoys have a long history of use in oceanography, principally for the measurement of currents by following the motions of floats attached to some form of sea anchor or drogue. Since 1988, over 2500 Lagrangian drifters have been deployed in the world oceans in the context of the Surface Velocity Program (SVP) of the World Ocean Circulation Experiment (WOCE, http://www.soc.soton.ac.uk/OTHERS/woceipo/ipo.htm) and the Tropical Ocean and Global Atmosphere Program (TOGA, http://www.ncdc.noaa.gov/oa/coare/toga.html), and then the Global Drifter Program (http://www.aoml.noaa.gov/phod/dac/gdp.html). These buoys were standardized in 1991, with a small spherical hull and floats, and large Holey-Sock drogue centred at 15 meters below the surface. They are very reliable, with half lifetimes greater than 450 days (with drogue still attached).

In 1993, Lagrangian Drifters with barometer ports, also called SVPB drifters, were tested in the high seas (more than 20 prototypes) and proven reliable. The Lagrangian Barometer Drifter, designed at the Scripps Institution of Oceanography for WOCE, is now commercially available at low cost, and meets both oceanographic requirements (e.g. measurements of sea surface currents) and meteorological requirements (e.g. air pressure).

Most data are encoded and distributed in real time onto the Global Telecommunication System (GTS) and are inserted into numerical weather prediction models at the meteorological centres of many countries.

3.3.3.2 Ice

Ice buoys have been used extensively in Arctic and Antarctic regions to track ice movement and are available commercially for deployment by ships or aircraft. Such buoys are equipped with low temperature electronics and lithium batteries that can operate at temperatures down to -50°C. In addition to the regularly computed Argos (a data collection and relay system used by NOAA) locations, the ice buoys can be equipped with satellite navigation receivers (e.g. Global Positioning System (GPS)), which can compute even more accurate positions for transmission through the Argos system.

3.3.3.3 Sub-surface float

Sub-surface floats are autonomous free-drifting platforms gathering data at mid-depth and surfacing from time to time to transmit via Argos. Argos both locates the float at the surface and collects the data stored in its memory. The two main floats are ALACE (Autonomous Lagrangian Circulation Explorer) and RAFOS (SOFAR spelled backwards which stands for SOund Fixing And Ranging). RAFOS is the reverse concept of SOFAR where signals are emitted from the float and then received at moored buoy sites for location computation (SOFAR floats are no longer used).

ALACEs are autonomous floats that are repeatedly located when they pop up to the surface for satellite location through the Argos system. While they are at the surface their drift gives a measurement of the surface current. The cycling time is adjustable. The instrument is designed for 50 cycles. The basic cycling time used is 36 days, to provide a five-year lifetime.

PALACEs (Profiler ALACE) are special ALACE floats capable of making water temperature and/or water conductivity measurements while popping up or down. They have shorter cycles of 5 to 15 days and a lifetime of about 100 cycles. They can dive as deep as 1500 meters. Some 3000 PALACE floats are planned for deployment in the next few years in the ARGO programme, which is the broad-scale global array of temperature/salinity profiling floats (http://www-argo.ucsd.edu/).

RAFOS floats are drifting listening stations that record the time of arrival of acoustic signals from moored sound sources and at the end of their lives pop up to report the recorded data through Argos. Present recording lifetimes are roughly 2.5 years. MARVOR (sea horse in the Breton language) floats work on the same principle as RAFOS. In addition, they can pop up and down several times during their lifetime and transmit data collected each time they surface.

Sub-surface floats were used in the World Ocean Circulation Experiment (WOCE) to measure the global distribution of current velocity below the high eddy noise region near the surface, to provide an accurate mean velocity. The mean velocity is combined with hydrographic data to compute water mass transport in the major ocean basins. The

WOCE goal is to compute a five-year mean velocity on a 500 x 500 km scale. The requirements translate into the following number of five-year lifetime floats in the oceans: Atlantic: 225, Indian: 180, Pacific: 495, Southern (south of 45°S): 114. Sub-surface float data are not disseminated onto the GTS, principally because the data are not available in real time.

3.3.3.4 Moored

Moored buoys are normally relatively large and expensive platforms. Data are usually collected through geostationary meteorological satellites such as GOES or METEOSAT. If a moored buoy goes adrift it represents a potential loss of costly equipment and a possible hazard to navigation. For these reasons the Argos system has been used for location determination for moored buoys. In addition, some WMO (World Meterological Organisation) member countries use the Argos system for normal transmission of meteorological observations from moored buoys.

About every four to seven years there is a significant disruption of the atmospheric and oceanographic circulation patterns in the equatorial Pacific. These disruptions have complex effects on global scale weather. The two components causing the disruptions, El Niño and its atmospheric component, the Southern Oscillation, were the focus of the international Tropical Ocean and Global Atmosphere (TOGA) program. Through an ambitious program in the equatorial Pacific, TOGA investigated the oceanic and atmospheric dynamics relating to the El Niño/Southern Oscillation phenomenon and its importance in the year-to-year variability of global climate.

As part of the TOGA program, efforts have been made to enhance the real-time ocean observing system in the tropical Pacific Ocean. One element of this improved system is the Tropical Atmosphere Ocean (TAO) array of Autonomous Temperature Line Acquisition System (ATLAS) moorings. The TAO array now supports programmes like the Global Climate Observing System (GCOS), WCRP Climate Variability and Predictability Programme (CLIVAR, http://www.clivar.org/), and the World Weather Watch (WWW, http://www.wmo.ch/web/www/www.html).

The ATLAS mooring, developed at NOAA's Pacific Marine Environmental Laboratory (PMEL) Seattle, WA, in the 1980's, is a taut wire surface mooring with a toroidal float. It is deployed in depths of up to 6000 m. Measurements from the mooring include surface variables (wind, air and sea surface temperature), as well as subsurface temperatures down to a depth of 500 m. These data are transmitted to shore in real time using the Argos System, processed by CLS or Service Argos Inc., and placed on the GTS. Post recovery processing and analysis of the data is performed at PMEL. This array and its planned expansion is the result of international collaboration between scientists from France, Japan, Korea and the USA. The first ATLAS mooring was deployed in December 1984. In 1998 about 70 ATLAS moorings were operational in the equatorial Pacific Ocean.

There are several advantages and disadvantages of moored buoys. Moored, automated oceanographic buoys can be located in very remote ocean areas, far from land. They are also portable and potentially could be used for shorter-term (two- to five-year) studies in one area, and then moved to a new location. This provides greater flexibility, as circumstances change, to reconfigure experiments that track processes continuously over long time periods. It also gives scientists and resource managers the ability to respond in time to observe transient natural events, or even relocate to a new site, as their knowledge of an area increases incrementally over the course of a study. Moored buoys can provide excellent temporal resolution of oceanographic changes. Moored buoys, however, have certain limitations. They require frequent servicing and their data must be constantly monitored to check for drift or irregularities caused by sensor failure or interference (e.g. dddue to fouling). Moored buoys can only deliver as much data as their telemetry system allows. Depending on their sensor array, moored buoys can represent a substantial capital investment that is at risk of loss or damage.

3.3.4 Parameters

There is a wide variety of water quality, hydrodynamic and meteorological variables that can be measured (Table 3.1). Data for each of these parameters can be logged, stored on flash cards and/or transferred by telemetry in real/delayed time to the user. Logging times and frequencies may be modified remotely via the sensor interface.

Table 3.1. The different water quality, hydrodynamic and meteorological variables that can be measured.

Water quality	**Hydrodynamic**	**Meteorological**
Temperature	Wave speed	Air temperature
Salinity	Wave direction	Air pressure
Dissolved oxygen	Wave height	Solar radiation
PH	Current velocity	Wind speed
Turbidity	Current direction	Wind direction
Nitrate		Humidity
Ammonia		
Silicate		
Phytoplankton		
Chlorophyll-a		
Photosynthetic Available Radiation (PAR)		

3.4 Systems Review

For this systems review, various local and international oceanographic buoy manufacturers were contacted. Each supplier was asked to provide a costing on an oceanographic buoy capable of measuring the variables mentioned above (prices quoted here were current as of early 2003). Suppliers were asked to itemise their system costs as much as possible. The manufacturers were chosen based on a search of the World Wide Web and through consultation with various Australian users. Some of the manufacturers supply a turnkey style product, where it would be possible to position the buoy and start collecting data on a large amount of variables almost immediately. These systems represented a considerable capital investment. Two of the manufacturers are based in Adelaide and can deliver a buoy for a fraction of the cost of the overseas manufacturers. However, their systems are much simpler and would provide considerably less information, at least initially.

The manufacturers approached were:

- *EcoScan*® International Pty Ltd for *EcoScan® Maxi Buoy*
- Eco-Sense Ltd for *SmartBuoy*
- Otronix Systems Inc for Coastal Remote Sensing Buoy (*CRSB)*
- Flinders University for School of Informatics and Engineering Oceanographic Buoy (*FUSIEOB*)
- Imbros Pty Ltd for Imbros Buoy
- Measurement Engineering Australia Pty Ltd (MEA) for custom-built system

3.4.1 *EcoScan® Maxi Buoy*

Figure 3.1. EcoScan® Maxi deployed on buoy (source: www.ecoscan.co.uk).

A coastal buoy capable of monitoring up to 6 sensors and transmitting data up to 20 or more kilometres to a base or relay station. Uses analogue UHF receiver to collect data and has battery backup to collect information for up to 24 hours in the event of power failure. The receiver will hold up to 3 months data between each download. The software used will monitor each site and using pre-set alarms automatically phone users when readings reach specified threshold levels. It can send data to other registered users. The buoy is limited to a maximum of 6 sensors from the following list:

- Turbidity
- Dissolved oxygen
- Water temperature
- Salinity/conductivity
- Water level
- Wind speed/direction
- Solar radiation
- Air temperature
- Relative humidity

Cost: $26,538 (for a system with 6 sensors)

3.4.2 Eco-Sense *SmartBuoy*

Figure 3.2. **Eco-Sense Smart Buoy (source: www.eco-sense.co.uk).**

A British-built automated multi-parameter recording moored platform for marine environmental monitoring. Has a GSM (Global System for Mobile communications) telemetry system and is powered by standard alkaline D cells. A solar power supply option was not priced but is available. The package includes:

- Buoy hull, stainless steel frame, all mounting hardware, brackets and fittings
- ESM-2A Buoy controller and data acquisition system
- Power supply (standard alkaline D cells)
- *SmartBuoy* Live Acquire software and local database
- GSM telemetry system
- Cabling system

The *SmartBuoy* system will monitor the following variables:

- Conductivity
- Temperature
- Turbidity
- Chlorophyll-a
- Dissolved oxygen
- PAR x 2 for light extinction depth
- NAS-2EN – a real time Nitrate ($N0_3$) analyser

Cost: $219,362

Additional options

Option 1: Solar Power Supply (cost not available at time of enquiry)
Option 2: WMS-1 water sampler for 500 ml bottles (silicate/ammonium/phytoplankton analysis) = $49,250
Option 3: ESM-1 based meteorological system (wind speed/direction, air temperature, barometric pressure, PAR) = $38,211
Option 4: Wave monitoring system (velocity/amplitude/direction) = $50,948

3.4.3 Otronix Coastal Remote Sensing Buoy (*CRSB*)

Figure 3.3. **Otronix Coastal Remote Sensing Buoy (source: www.otronix.co.kr).**

A Korean company integrating American buoy hull (Ocean Science SeaBuoy) with instruments sourced from a variety of European, Asian and American companies. The system uses CDMA-based telemetry technology and Korean (Otronix) buoy interface controller. Includes the following sensors:

- Wind speed and direction
- Air temperature and humidity
- Barometric pressure
- Water temperature
- Conductivity
- Dissolved oxygen
- pH
- Turbidity
- Chlorophyll-a
- PAR
- Ammonia
- Nitrate
- Current speed and direction
- Wave height/speed/direction

Cost: $257,272

3.4.4 Flinders University School of Informatics and Engineering Oceanographic Buoy (FUSIEOB)


Figure 3.4. **FUSIEOB Oceanographic Buoy.**

A locally manufactured wave-rider buoy using a standard Hydrolab Minisonde 4 for collection of the following water quality variables;

- Temperature
- Dissolved oxygen
- Turbidity
- pH
- Conductivity

The unit is solar powered with backup alkaline batteries. Data are downloaded using GSM-based telemetry on demand.

Cost: $22,106 (total cost of manufacture/replacement)

Or, the unit can be leased at an ongoing cost of $1,500 per month

The buoy platform cannot take meteorological sensors and has a limited number of ports available for additional sensors. Data can be uploaded to a website with access provided to registered users.

3.4.5 Imbros Buoy

Imbros Pty Ltd is a Tasmanian company specialising in the development of remote sensing technologies specific to the marine environment. They are in the process of developing a real-time telemetering buoy for one of the tuna farming companies based in Pt Lincoln (MG Kailis Pty Ltd). This system will record:

- Water temperature
- Salinity
- Dissolved oxygen
- Wind speed/direction

The buoy is completely self-contained with solar power. The system has significant expansion capabilities for future sensors (e.g. turbidity, current speed/direction).

Cost: approximately $30,000

Additional sensors have the following approximate cost:
- Chlorophyll ~ $8,000-9,000
- Nitrate ~ $50,000
- Current profile ~ $18,000
- Wave ~ $50,000
- Phytoplankton (sizing and counting) ~ $60,000

3.4.6 Measurement Engineering Australia (MEA) proposal for cutom-built system

Measurement Engineering Australia is a local Adelaide-based engineering company that designs and builds remote environmental monitoring systems (www.mea.com.au). MEA have experience in installing a radio-linked soil moisture system back to a weather station on SARDI's viticulture research station in the Barossa Valley. They proposed developing a system that would consist of a data logger in an enclosure, powered by solar panel, with the data downloaded using CDMA telemetry on demand for aquaculture applications. The sensors will be mounted on frames suited to a marine environment and linked to the data logger. The system design for this proposed system is given in Appendix I of this chapter.

Cost: $10,230 with every subsequent unit around $6,670

The quote does not include the sensors, as existing sensors (Minisonde 4A Multiprobe) owned by SARDI could be used in the first instance. However, the cost of such a multiprobe with temperature, conductivity, dissolved oxygen and pH sensors cost approximately $6,000 (price quoted in 2004).

3.5 Recommendations from systems review

Clearly, cost was a major factor in determining which system(s) to trial. With limited funds, the large oceanographic units were out of our price range. Just as importantly, the whole concept is for multiple systems to be used by industry, with the expensive systems also not being cost-effective from a commercial perspective. The Flinders University system and the MEA proposed system reviewed fell within our price range, and it was decided that:

- The *FUSIEOB* be trialed for 6 months to provide initial data.
- MEA be engaged to develop the proposed system.

Using the *FUSIEOB* enabled a basic set of water quality parameters to be established and assessed in terms of variability. The *FUSIEOB* represents a buoy with limited capacity to upgrade with additional sensors. However, it did enable data collection and system operation to be commenced while the MEA system was being developed. Operational procedures for data collection, storage and distribution to the industry/other researchers could thus be optimised. The system proposed by MEA can be upgraded with additional sensors as resources allow and for this reason it was also decided to engage them to develop it.

3.6 *FUSIEOB* Trial

The FUSIEOB system was deployed in April 2003. It is a moored floating buoy and was located at 34º 43.069'S and 135º 57.568'E (east of Boston Island), within the lease site of the SARDI Tuna Research Farm (operational in 2003, but no longer).

The FUSIEOB system measured and logged various water quality parameters every 10 minutes and the data were downloaded via a GSM modem on demand. The unit was self-contained, deriving its power from a solar-charged battery system. The water quality parameters were measured using a Hydrolab Minisonde Multiprobe and included water temperature, dissolved oxygen, conductivity, turbidity and pH. An example of the data collected is shown in Figure 3.5.

The trial of this system allowed an assessment of some basic water quality parameters in terms of variability and usability. In addition, SARDI had similar multiprobes, which could also be used with the system.

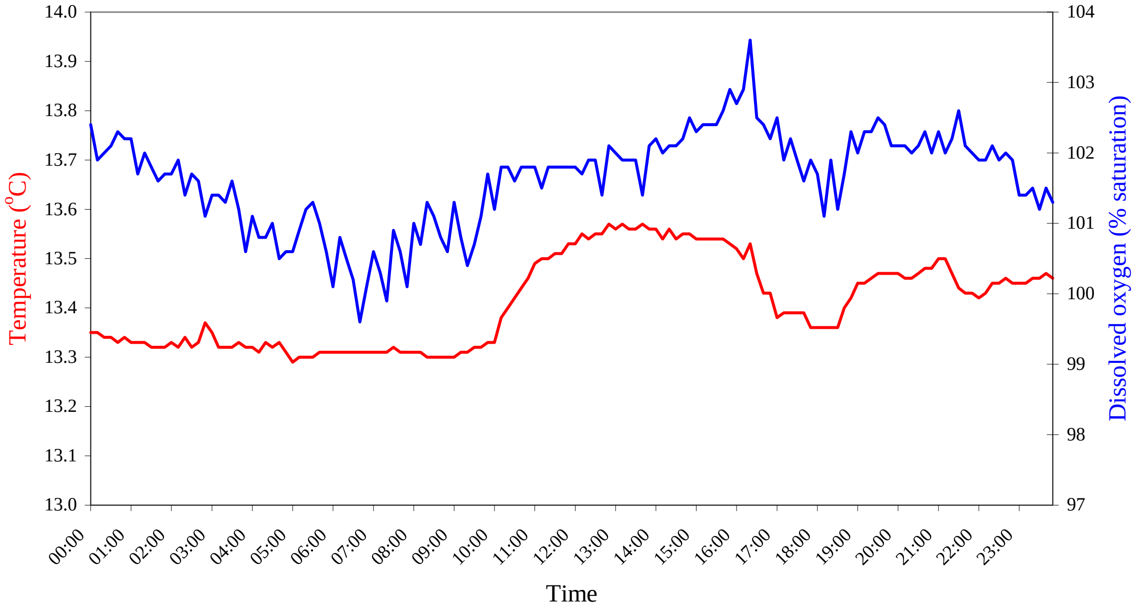


Figure 3.5. **An example of temperature (°C in red) and dissolved oxygen (% saturation in blue) data logged every 10 minutes for one day at 5 m depth (9 September 2003) by the FUSIEOB system.**

After a six-month trial, this system was discontinued because of the limitation of the existing software (dedicated to this system), which did not allow flexibility and potential expansion. During the trial, discussions were regularly held with users and it was recommended that any telemetry system purchased should include wind sensors, which the FUSIEOB system could not accommodate. However, the trial had allowed the researchers to identify various advantages and disadvantages of having a telemetry-based monitoring system. Data from April to September 2003 is available upon request from the author and with approval from Aquafin CRC.

3.7 Custom-built systems by MEA

A custom-built system was first deployed in September 2003 for monitoring water quality in and adjacent to a tuna sea-cage. A South Australian company, Measurement Engineering Australia Pty Ltd (MEA), was chosen to manufacture this system as it was cost effective and had the potential to be flexible in that it could be upgraded with additional sensors as resources allowed. This system was mounted on the stanchion of a sea-cage on the then SARDI Tuna Research Farm (Figure 3.6), and included two Hydrolab Minisonde Multiprobes. Although the sensors used required substantial maintenance, it returned consistent data and SARDI had one such multiprobe that would save some cost for trialling this new system. Consequently, only one Hydrolab Minisonde Multiprobe was purchased with the deployment of one probe to measure water quality parameters within the sea cage at a depth of 5 m, while the other measured similar parameters 5 m on the outside of the sea-cage at a similar depth. The parameters being logged by this system were similar to the *FUSIEOB* buoy system described above, but with the addition of wind speed and wind direction. The MEA system measured and logged the various parameters every 6 minutes and the data were downloaded via a CDMA modem on demand.

Figure 3.6. **The custom-built MEA telemetry-based environmental monitoring system mounted on the stanchion of a tuna sea cage on the SARDI Tuna Research Farm.**

The sea-cage system was much more user friendly and also more flexible, allowing real-time access to the data via a software package (MAGPIE) developed by MEA. The MAGPIE software allows fast and effective methods of obtaining, displaying and reporting data without the need to use a variety of different software. Examples of the water quality data collected by the sea-cage system are shown in Figure 3.7 and 3.8.

A second system was subsequently built for another project (FRDC 2003/226, Aquafin CRC 4.5), "Aquafin CRC-SBT Aquaculture Subprogram-Net Fouling Management to Enhance Water Quality and Southern Bluefin Tuna (*Thunnus maccoyii*) Performance", where it was used to monitor the effects of fouling assemblages on water exchange. For this second system, different probes were trialled, these being an OxyGuard Dissolved Oxygen sensor in combination with a SensorX toroidal EC/WT (conductivity/temperature) sensor. These probes were chosen because they were more cost effective and potentially required less maintenance than the Hydrolab Minisonde Multiprobes.

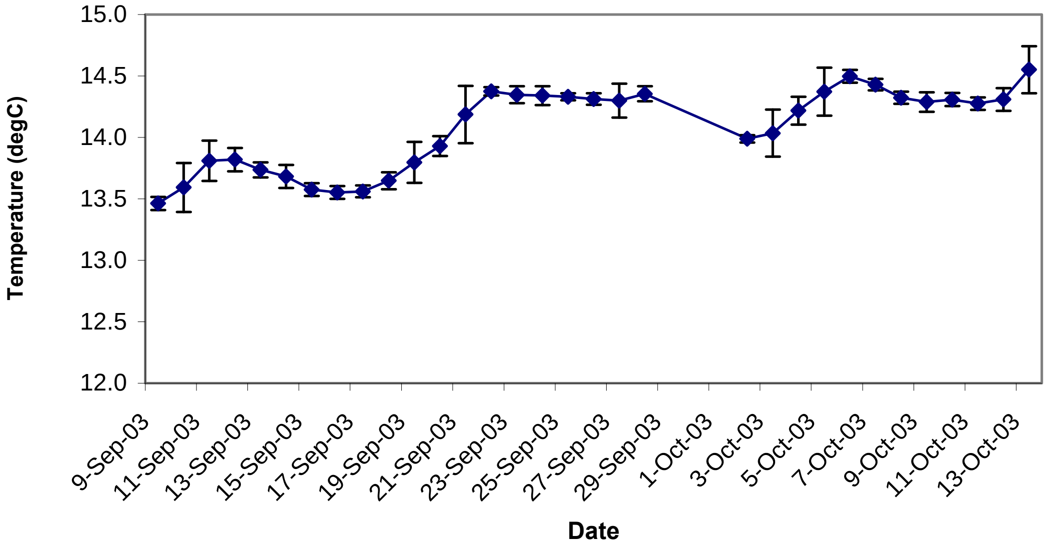


Figure 3.7. **An example of average daily water temperature from 9th September to 13th October 2003 (± standard deviation) collected by the MEA system.**

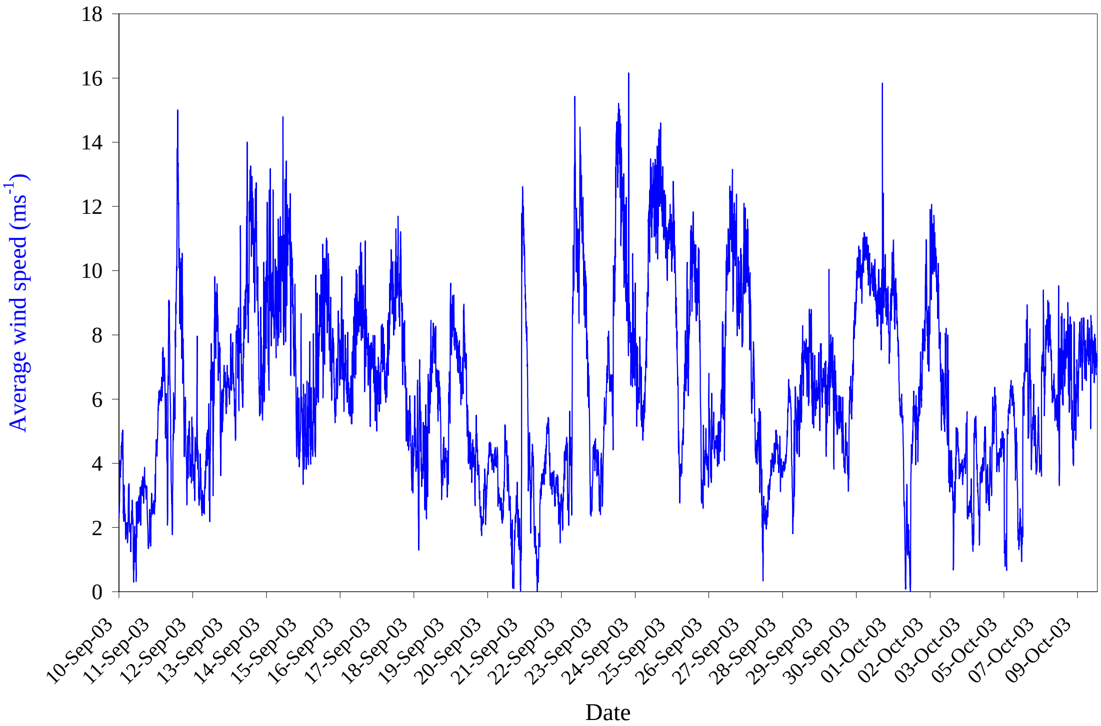


Figure 3.8. **An example of average wind speed (ms^{-1}) from 10th September to 10th October 2003 collected by the MEA system.**

The tuna farming industry showed interest in the data from the initial trials. A request was received for the temperature data from TBOASA, who along with the Australian Quarantine Inspection Service (AQIS), wanted to know when the temperature in the Port Lincoln area fell below 15°C just before winter. This was due to regulations associated with feeding select imported pilchards to tuna. Another potential use was recognised for the wind data, which could provide the industry with more accurate and up-to-date conditions in and around the sea cages for their daily operations. Consequently, the project worked towards real-time or near real-time delivery systems.

3.7.1 Real-time delivery system

A real-time delivery system, using limited-function MAGPIE software was distributed for trial to stakeholders in July 2004. This software allowed users to dial-up the system directly to obtain real-time data (Figure 3.9). This direct dial-up was only available to owners of the pontoon where the system was deployed. The data available through this direct access included temperature, pH, specific conductivity, salinity and dissolved oxygen from the inner sonde (sensor located inside the pontoon) and the outer sonde (sensor located outside the pontoon). Once logged in, the display screen refreshed every six minutes and a reading was logged. There was also access to wind speed and wind direction, which has a faster scan rate of 5 seconds.

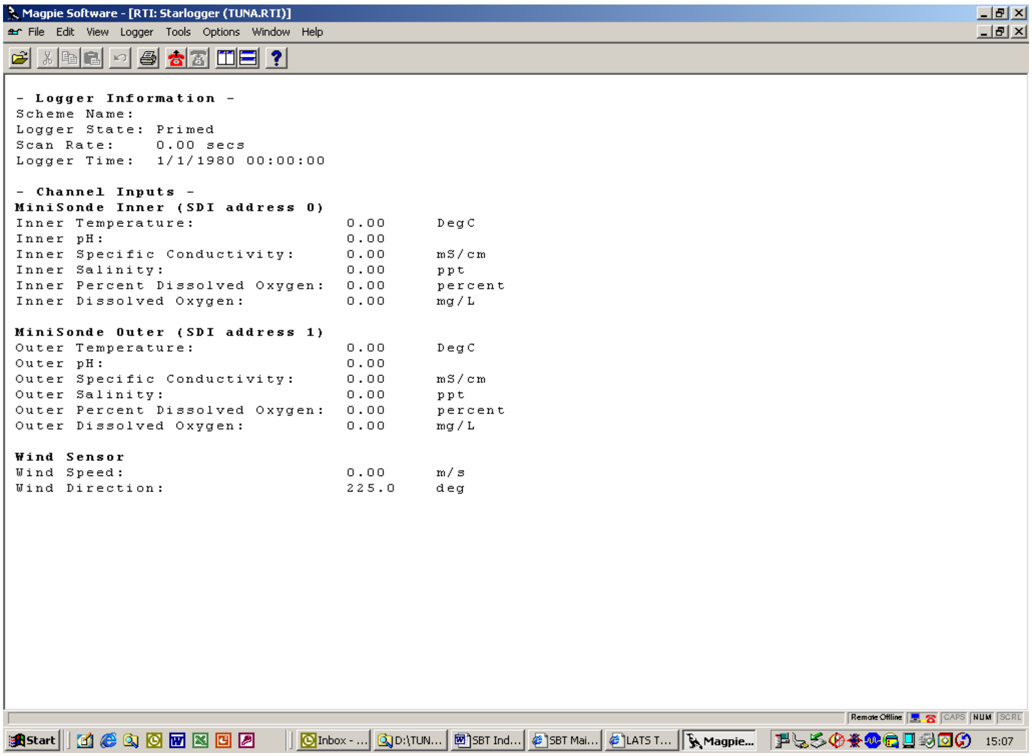


Figure 3.9. **Real-time screen using limited function MAGPIE software showing the various environmental parameters available on direct dial-up to the system.**

3.7.2 Web-based delivery system

Based on the interest expressed by other tuna farming company staff and researchers of other SBT projects, subsequent work was directed towards making the data more widely available. To this end, a web-based delivery system for the environmental monitoring data was set up on a website that is hosted by an external server. Only authorized users have access to these data, which is via a secure user authentication page (Figure 3.10).

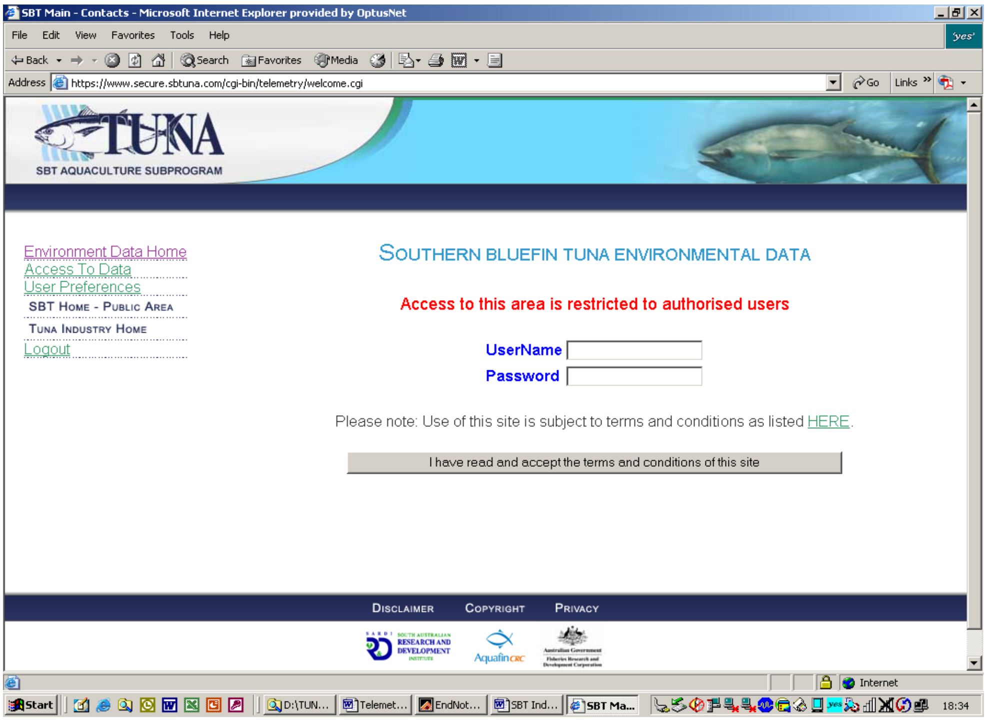


Figure 3.10. **Access to the SBT environmental data web page is via a secure user authentication page.**

Upon accepting the terms and conditions of the site, the next page will take the user to the environmental database page. This page will give a brief summary of what is available in the environmental database (Figure 3.11).

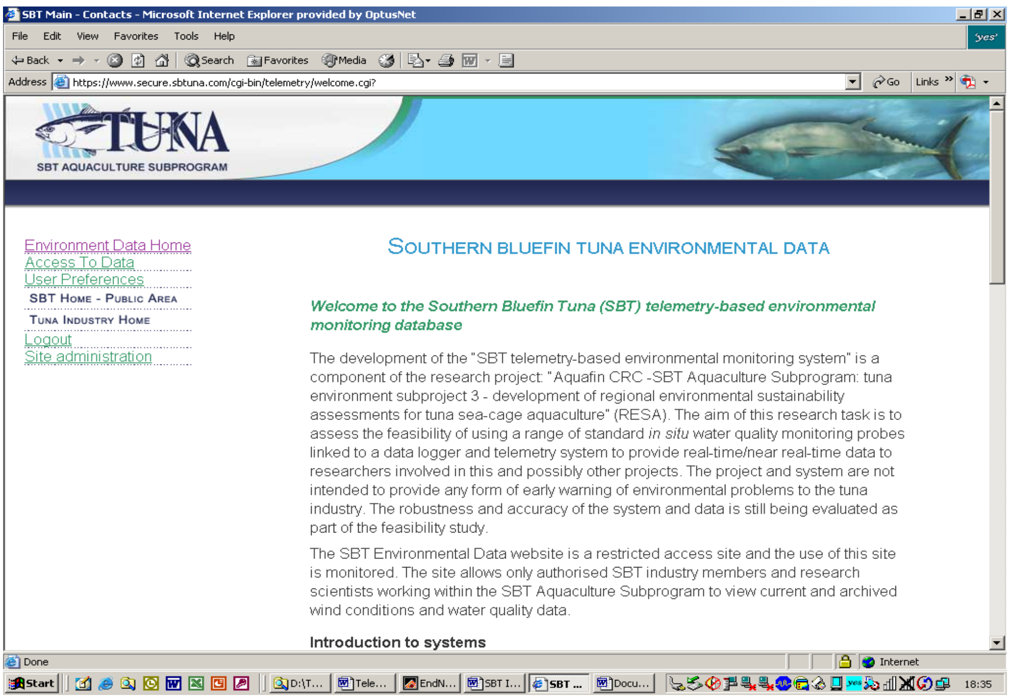


Figure 3.11. **Welcome page for the southern bluefin tuna environmental data web page.**

Selecting "Access to Data" from the menu on the sidebar will then take the user to the SBT Telemetry Data page (Figure 3.12). At this page, the user has the option to select the source of the data. Depending on the user's authorisation, access to the data will vary. For example, users may be authorised to have access to data from the probes within the pontoon and the probe outside the pontoon or just the data from the outside. After selecting the source of data, the user has to select a time period to display (Figure 3.12). This will take the user to a graphical display of the various environmental parameters available and a summary of the data (minimum, maximum and mean) for the specified probe and time period (Figure 3.13).

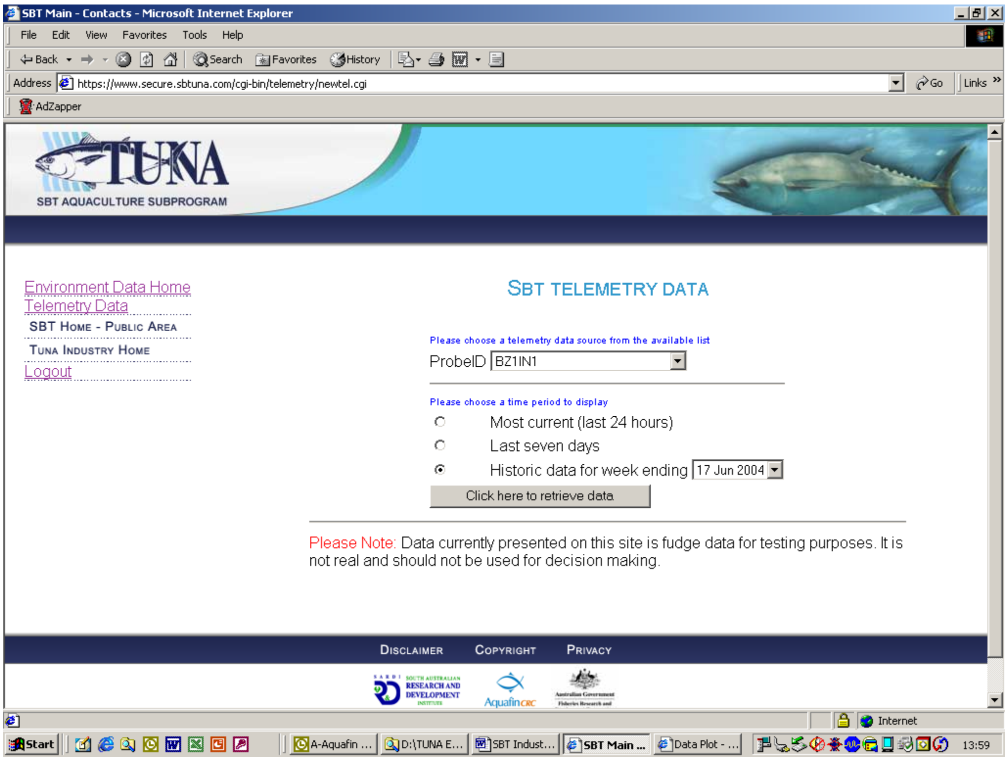


Figure 3.12. **SBT telemetry-based environmental data web page where the user can select the data to view.**

The data available to users includes current data (last 24 hours), last seven days; and archived data. Data from the logger are uploaded onto the website on a regular basis such that the data will be available to users near real-time. This website is still on trial. With continued feedback from users, the site can be upgraded and updated.

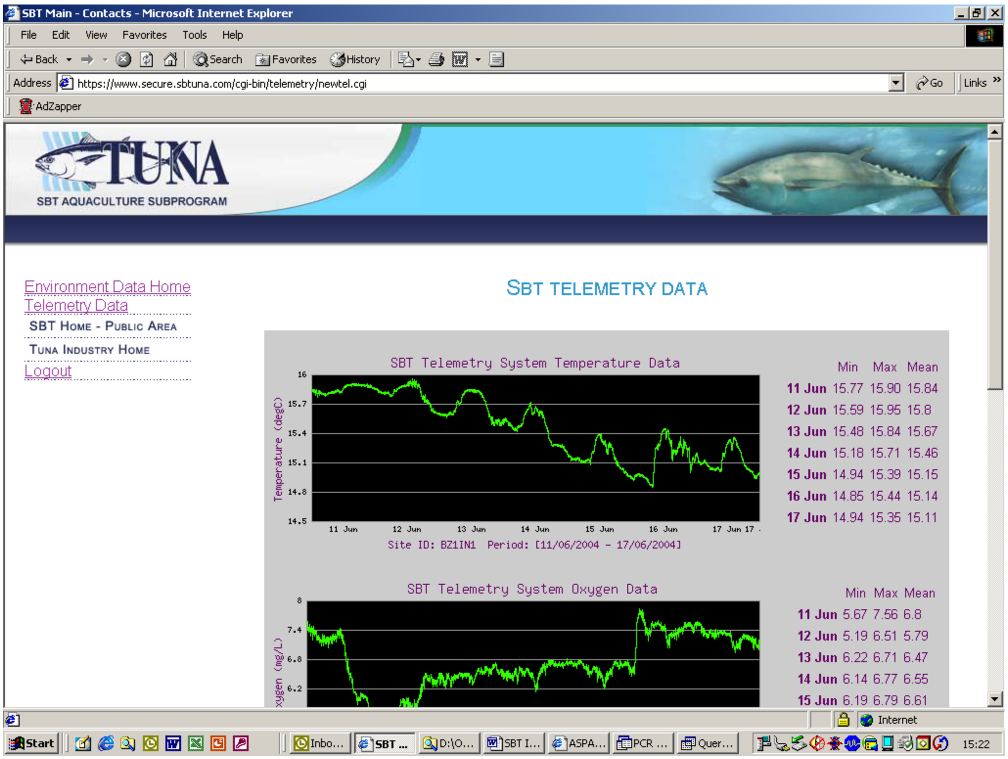


Figure 3.13. **Graphical display and summary (minimum, maximum and mean) of environmental data for the specified probe and time period.**

3.8 Summary of Data

Several datasets are available from the trial of these systems. Below is a summary of the data collected by the SBT telemetry-based environmental monitoring system (custom built by MEA) between March and September 2005. Other data from other years are available on request from author and with approval from Aquafin CRC. The summary below includes water quality data from the outer probe and data from the wind speed and direction sensors. Gaps in the data occurred when the system was removed for maintenance (re-calibration) or repair. Point measurements were taken periodically using handheld meters during maintenance of probes to check that the deployed sensors were reading consistently and accurately. The system returned generally accurate data if the maintenance schedule was kept. Wind data were also checked against the daily weather observations on the Bureau of Meteorology (BOM) website to ensure that readings from the wind sensors were returning correct data. This check usually showed that the sensors on our systems were recording higher wind speeds. This was to be expected as the BOM observations were recorded at North Shields (on land) while our systems were deployed at sea (http://www.bom.gov.au/climate/dwo/IDCJDW5055.latest.shtml).

3.8.1 Monthly summaries of water quality data recorded from the outer probe

March/April 2005

Temperature readings recorded had a downward trend of ~2°C except during 8th to 11th April 2005. Salinity values were constant at ~32 ppt. This average salinity was lower than the data recorded by the inner probe (data not shown here), indicating that there was a calibration problem as data obtained after calibration were within known ranges. Dissolved oxygen showed marked diurnal variation fluctuating generally between 85% and 99% saturation (Figure 3.14).

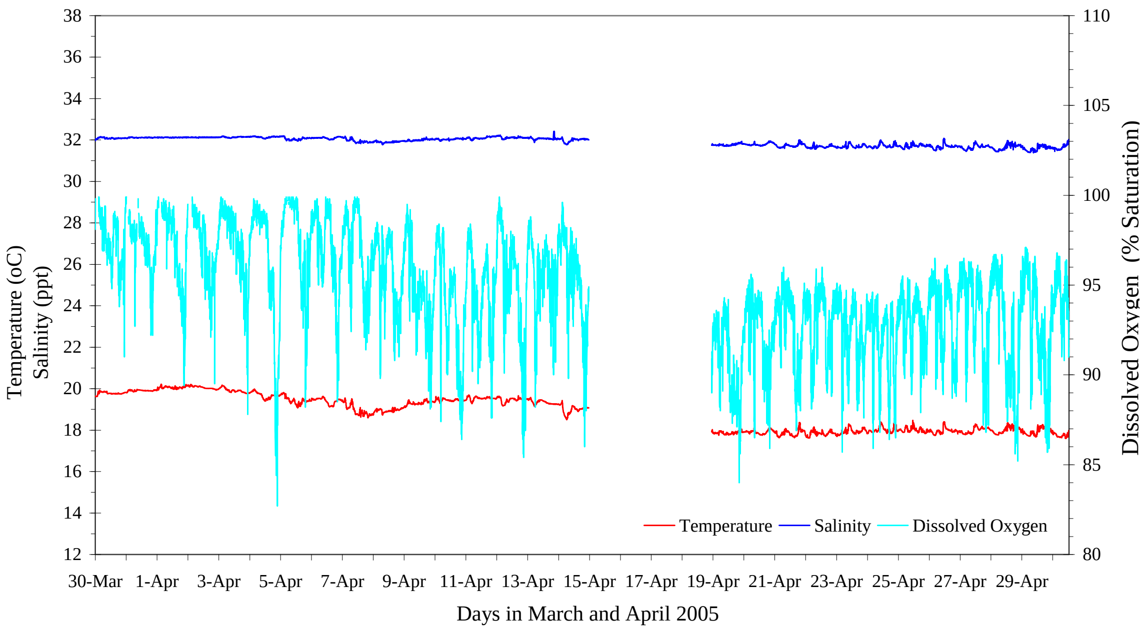


Figure 3.14. **Temperature (°C), salinity (ppt), and dissolved oxygen (% saturation) recorded from 30th March to 29th April 2005.**

May 2005

Data for May 2005 were recorded sporadically as the system was undergoing maintenance and problems were encountered with the power supply. Consequently, no summary of data is provided here.

June 2005

Temperature trended downward and showed some diurnal pattern. Salinity was constant at ~36 ppt. Dissolved oxygen exhibited slightly less diurnal variation but trended upwards to more than 100% saturation (Figure 3.15), although the sudden drop after the probe was returned to the water suggests that this indicates a loss of calibration and may not be a real trend.

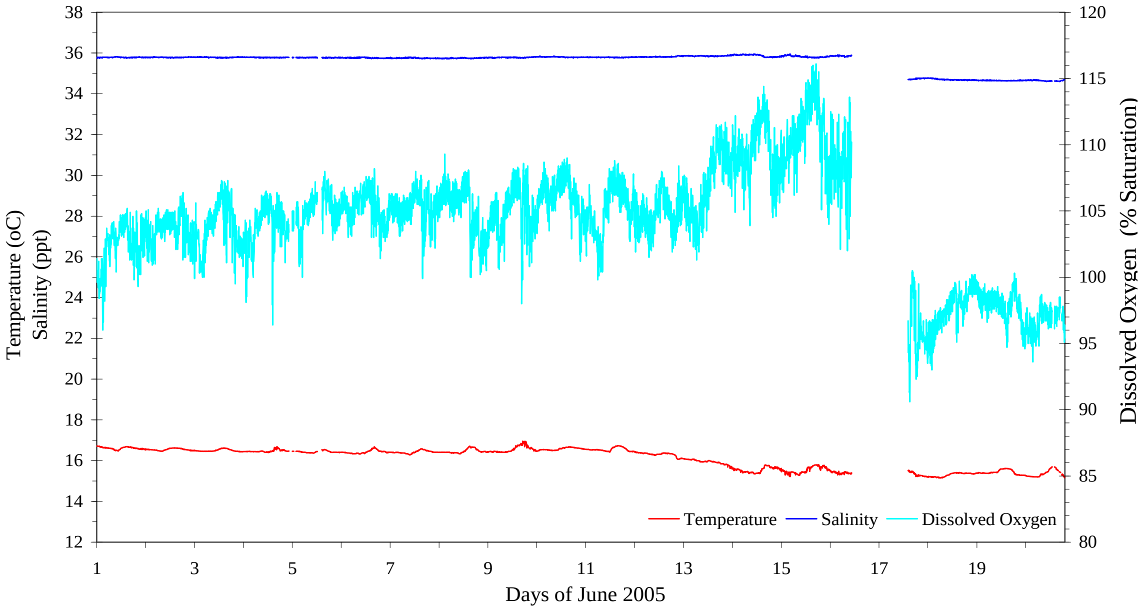


Figure 3.15. **Temperature (°C), salinity (ppt) and dissolved oxygen (% saturation) recorded in June 2005.**

July/August 2005

Water quality data were only available from 22nd July to 12th August 2005 for these two months. Water temperature fell slightly over this period while salinity was fairly constant at ~35 ppt. Dissolved oxygen was high and exhibited a small general upward trend to well above 100% saturation, with some minor diurnal fluctuation (Figure 3.16).

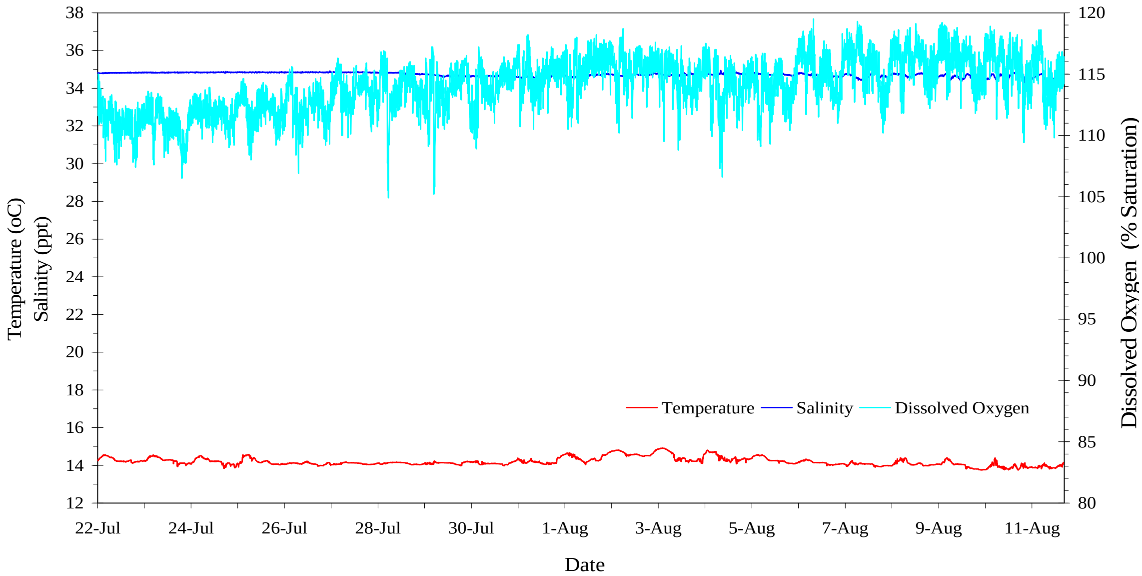
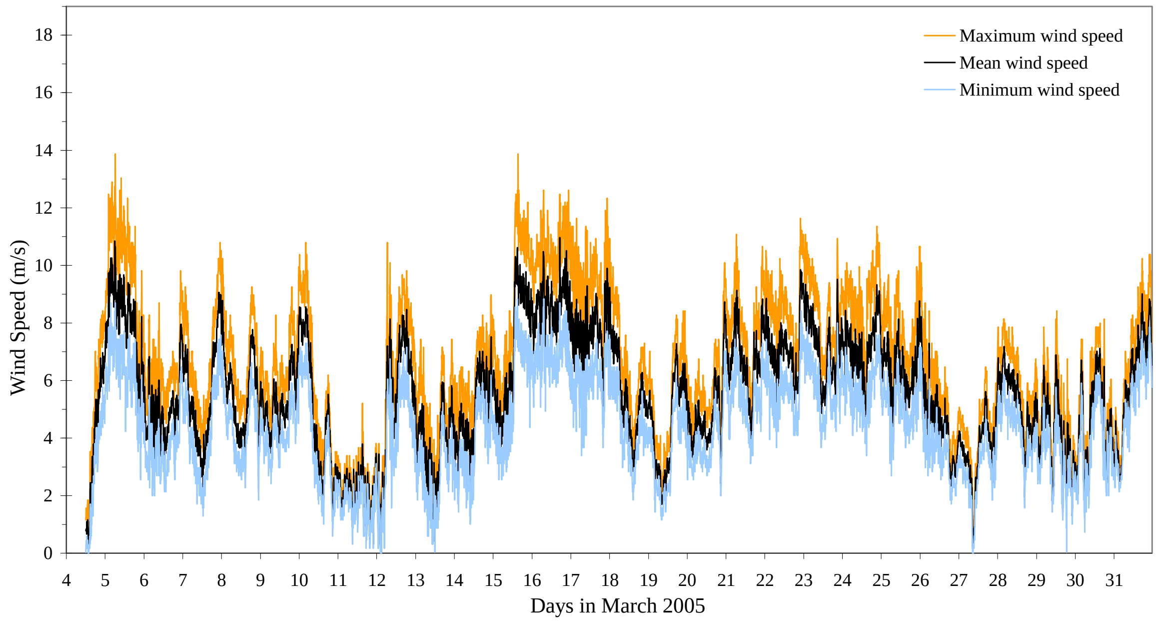


Figure 3.16. **Temperature (°C), salinity (ppt) and dissolved oxygen (% saturation) recorded from 22nd July to 12th August 2005**

3.8.2 Monthly summaries of wind speed and direction recorded

Wind speed was, on average, highest during March, June and August 2005 and most variable during June and August 2005. However, there were only nine and seven days of data recorded for July and September respectively. Wind direction was predominantly from the southeast to south in March, April and May, northwest to northeast in June, northwest in late July, west to north in August and northeast to east in early September.

Wind speed reached a maximum of 13.9 ms^{-1} for March 2005 with wind direction predominantly (39.1%) from the southeast (Figure 3.17). Wind speed reached a maximum of 18.4 ms^{-1} in early April 2005 with wind direction from the southeast 26.6% of the time (Figure 3.18). Wind speed had a maximum of 13.6 ms^{-1} in May 2005 with predominant wind direction similar to March and April, blowing from the southeast (Figure 3.19). Higher wind speeds were recorded in June 2005 with a maximum of 18.6 ms^{-1} in the middle of the month. Wind direction was predominantly northwest to northeast with 22.7% of the time directly from the north (Figure 3.20). Wind speed and direction were recorded only from 22nd to 31st July 2005 as the system was removed for service. Over these nine days, maximum wind speed was 14.3 ms^{-1} with a predominantly northwesterly direction (Figure 3.21). A full month of data was recorded for August with maximum wind speed reaching 18.6 ms^{-1} and wind direction was predominantly from the west to the north (Figure 3.22). Wind data were recorded for the first seven days in September 2005 except for 2nd September. During this time, maximum wind speed reached 11.8 ms^{-1} and wind direction was predominantly from the northeast (Figure 3.23).



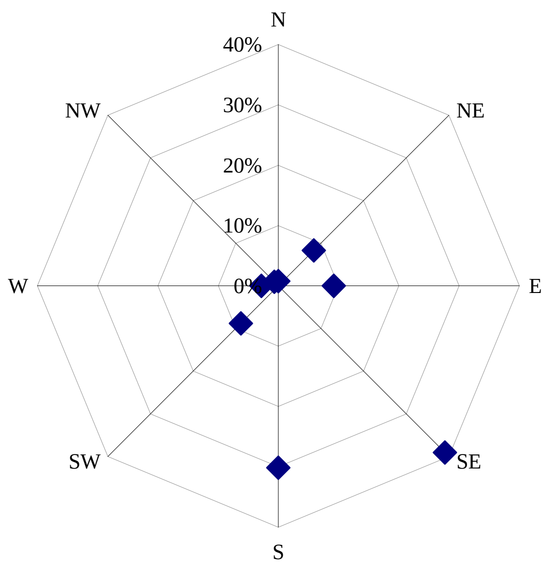


Figure 3.17. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (39% from the southeast) recorded in March 2005.**

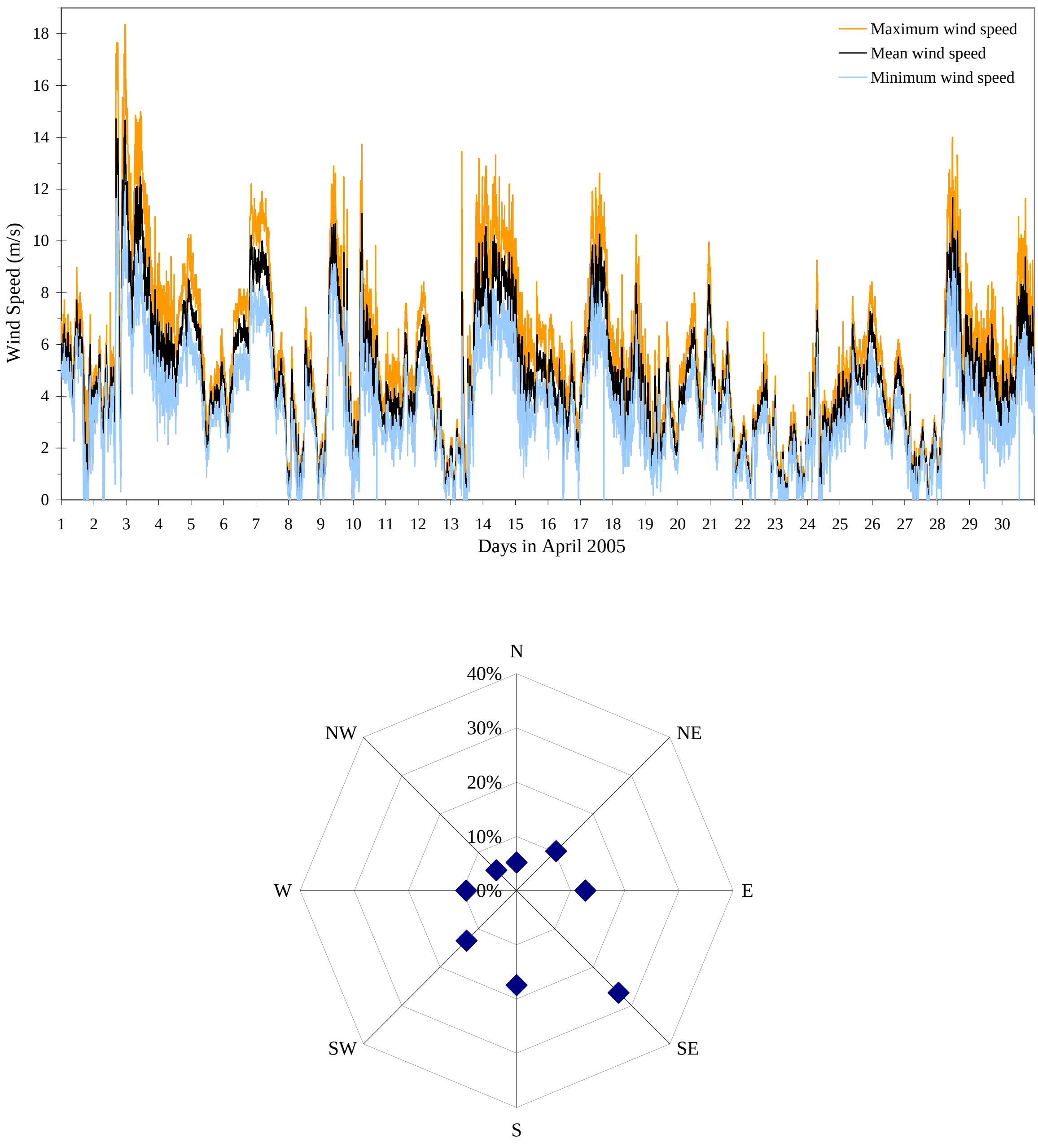
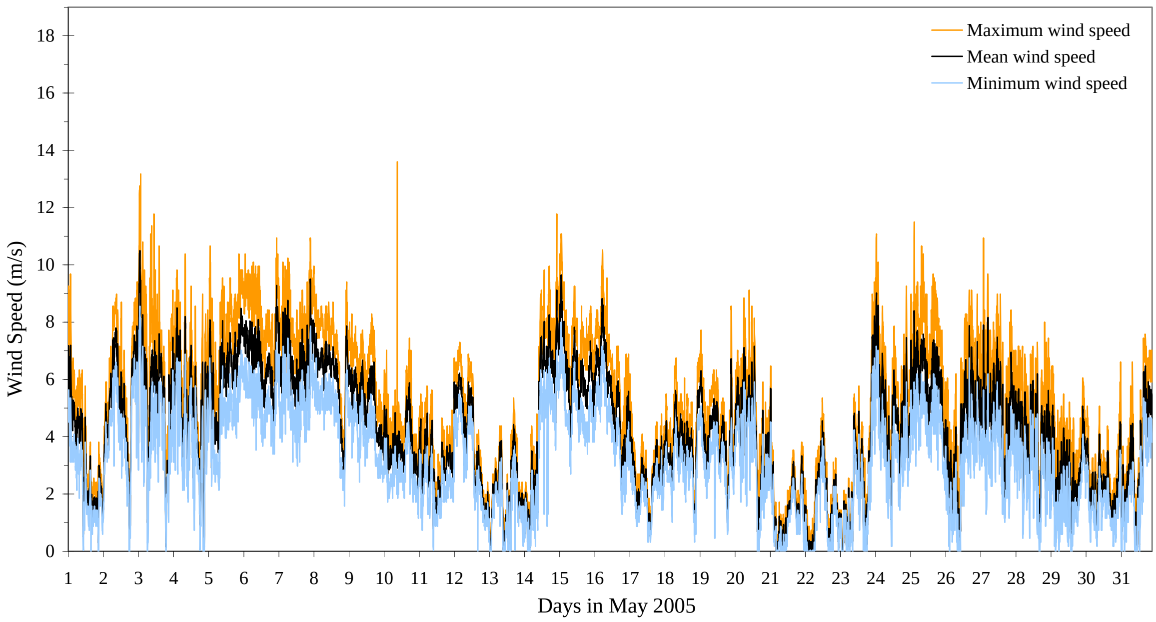


Figure 3.18. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (27% from the southeast) recorded in April 2005.**



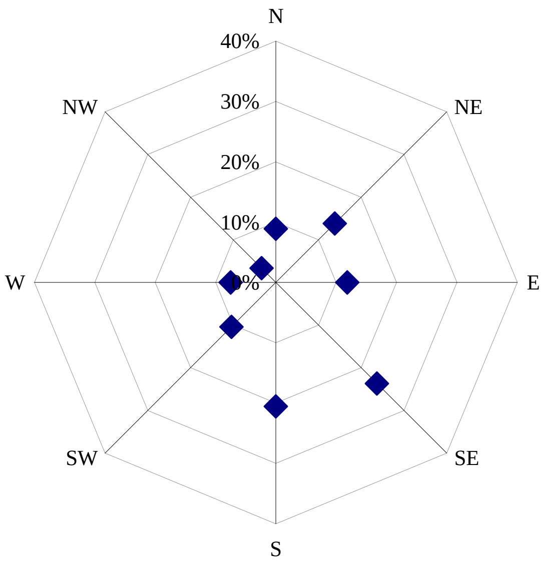
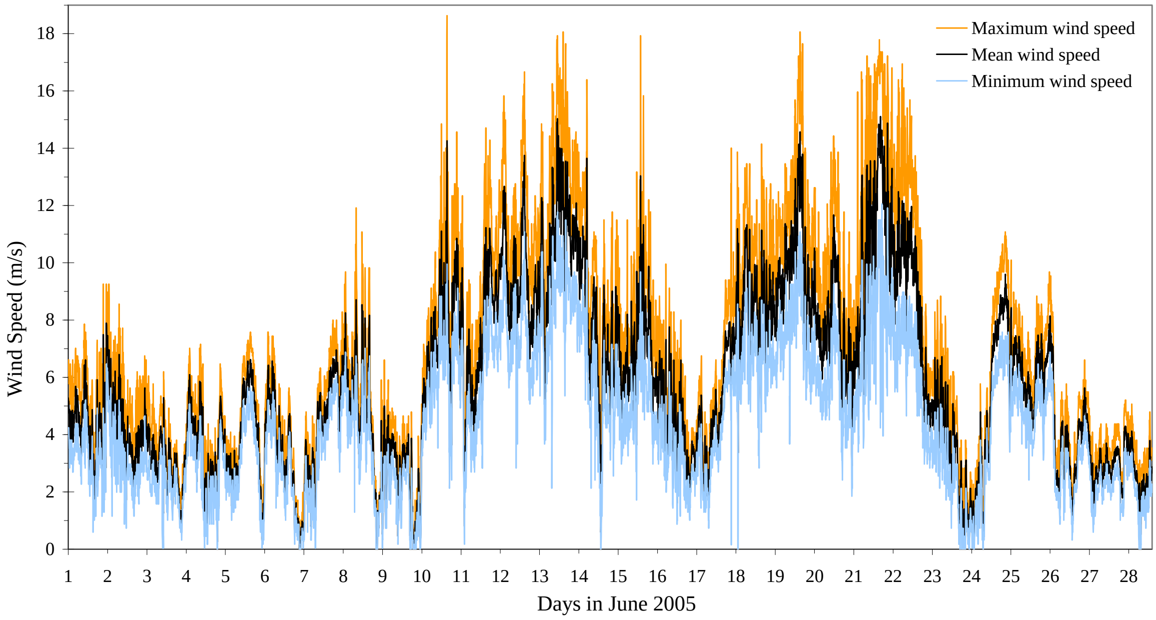


Figure 3.19. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (24% from the southeast) recorded in May 2005.**



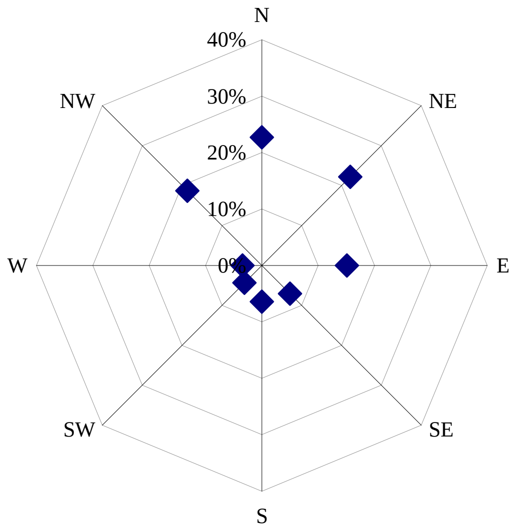
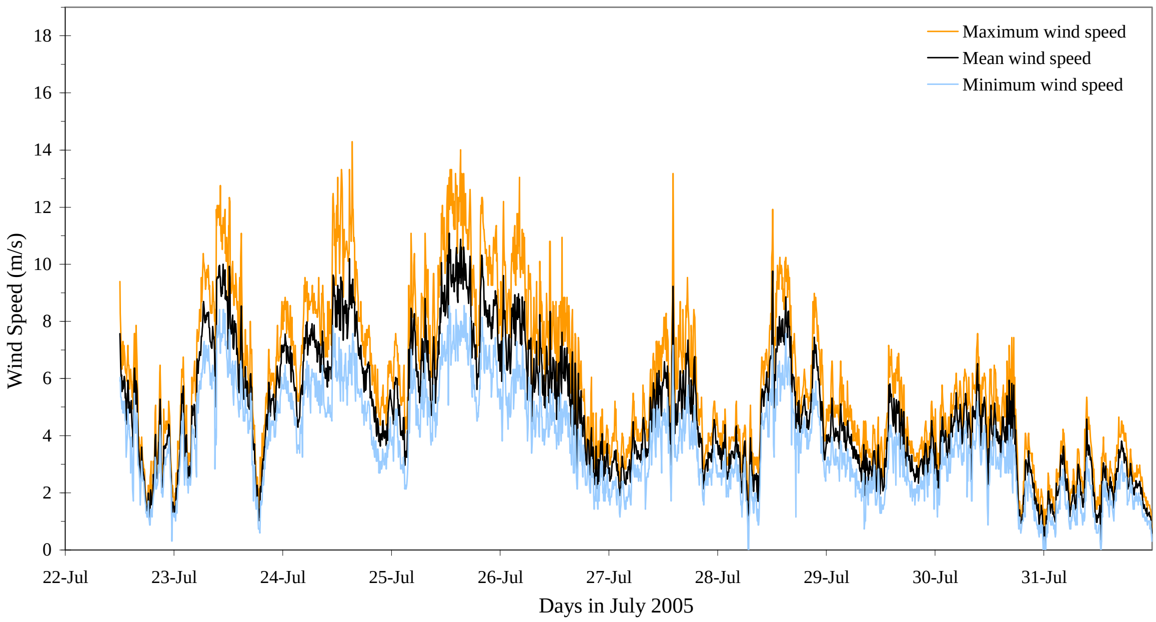


Figure 3.20. **Mean, minimum and maximum wind speed (ms^{-1}) and predominant wind direction (~22% from the north and northeast) recorded in June 2005**.



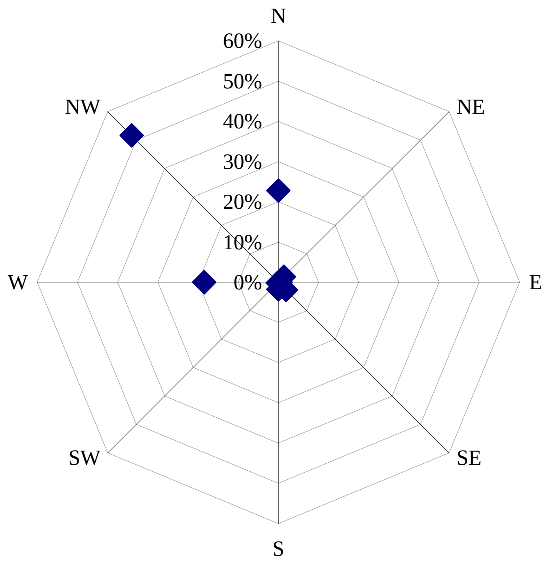
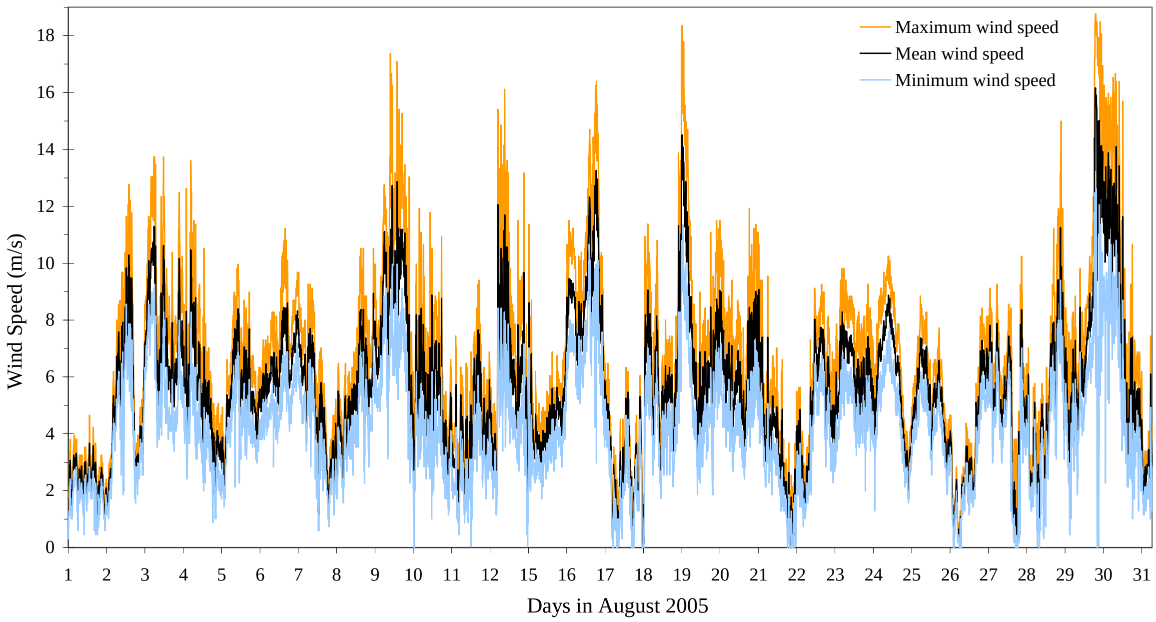


Figure 3.21. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (52% from the northwest) recorded from 22nd to 31st July 2005.**



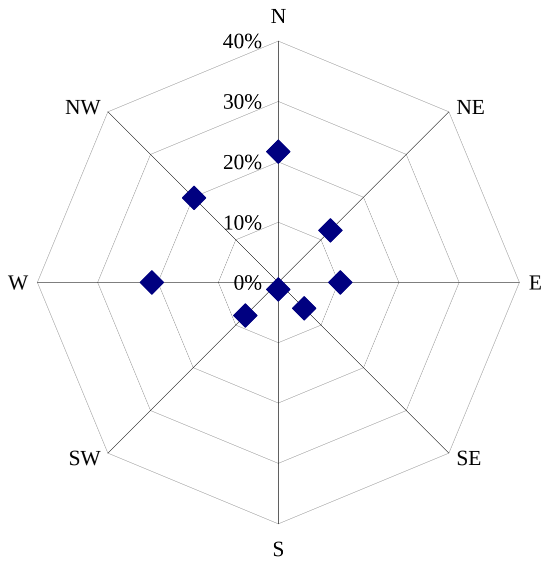
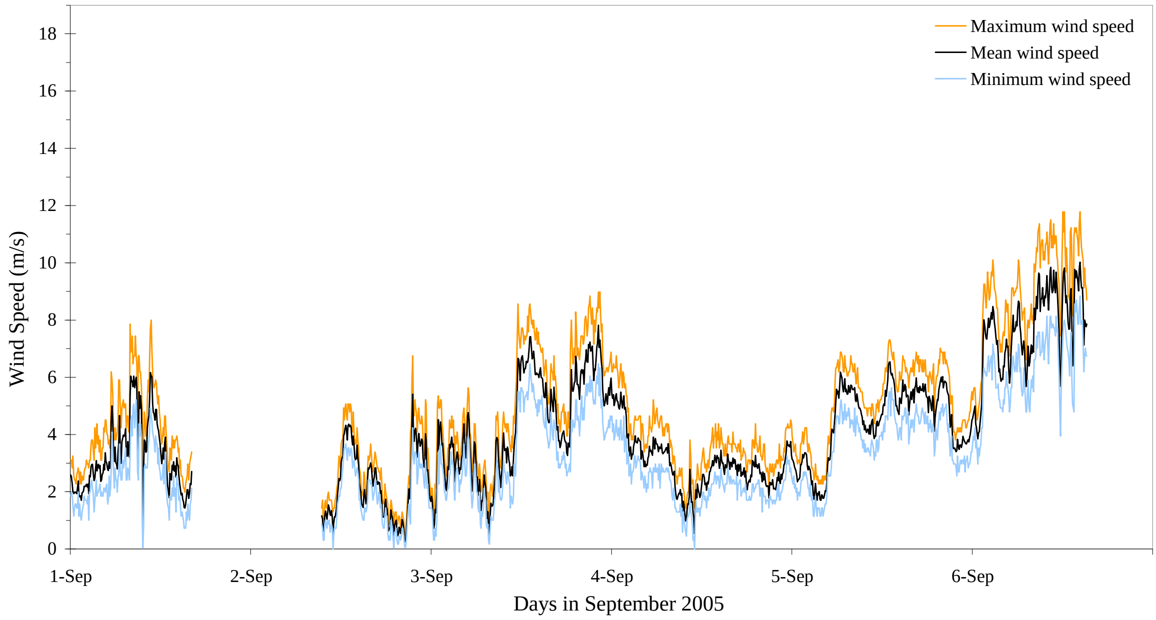


Figure 3.22. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (22% from the north) recorded in August 2005.**



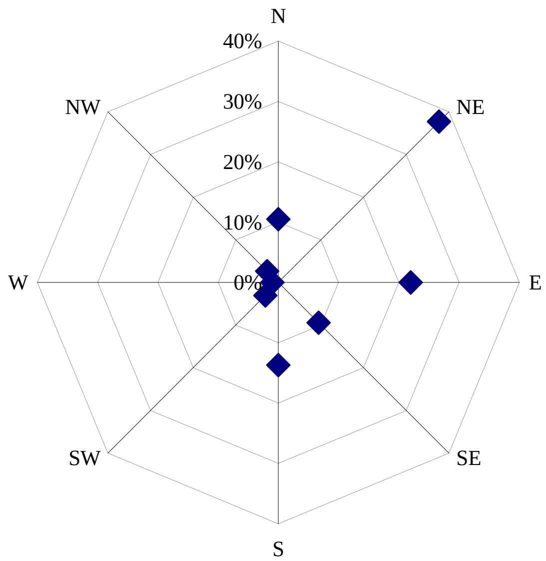


Figure 3.23. **Maximum, mean and minimum wind speed (ms^{-1}) and predominant wind direction (38% from the northeast) recorded in early September 2005.**

3.9 Lessons learnt

The trial of the SBT Telemetry-based Environmental Monitoring Systems had its share of difficulties. There are risks involved when equipment are deployed in the field and left for long periods of time. It is subjected to the elements and the system had to be able to withstand the continuous exposure. Various components of the systems were re-designed during the project for that reason (see section 3.10). Even then, one of the Hydrolab Minisonde was lost during the project, due possibly to entanglement with the sea cage net, which can billow excessively with high wind and tide.

Keeping the SBT Telemetry-based Environmental Monitoring System operational from collection to delivery of data required a substantial maintenance schedule. For the collection of data, the probes had to be regularly serviced and calibrated every two to three weeks because of fouling on the sensors. In particular, the Hydrolab Minisonde, which gets fouled much quicker and needed to be calibrated more frequently than the Oxyguard/SensorX sensors. This process required time and resources.

For the delivery of data on the website, even though download of data from the logger and upload of data to the website were automated, there was still the need for quality assurance which required the daily checking of data to ensure its integrity. However, this may be automated by creating filters in the program.

There were numerous requests for the data by both industry and researchers. Data had been requested by the tuna farming industry, which along with AQIS, wanted to know the temperature in the Port Linocln area for regulations associated with feeding of imported pilchards to tuna. In addition, dissolved oxygen and temperature data had been requested by the industry for insurance purposes. Several students (both Honours and PhDs) working on other Aquafin CRC projects in nutrition or residues also had a use for the data. Even though the time and logistical demands for the maintenance of these systems are high, the advantage of having continuous environmental monitoring may warrant keeping the SBT Telemetry-based Environmental Monitoring System operational. Some of the logistical problems can be overcome, such as the maintenance of the system may be scheduled with the feed boat being on-site if the system was deployed on a working farm and operated by the industry.

3.10 Future directions

The future plan for both of the SBT Telemetry-based Environmental Monitoring Systems is re-deployment in 2006. The Risk and Response Project and the Fouling Management Project will use the data collected by the systems. However, the systems required upgrades and modifications before re-deployment and Measurement Engineering Australia (MEA), who built the systems, was engaged to work in collaboration with SARDI to carry out the upgrades. The changes required included improvements to the power supply, enclosures for logger and battery and housing for sensors, as well as the addition of a chlorophyll (fluorescence) sensor.

Due to the relatively high duty cycles of operation of sensors and communications devices, and possibly environmental factors, the system batteries had not been able to maintain voltage. As such, the solar panels were upgraded from 5 Watt to 10 Watt items, and the battery capacity was increased from 7 to 14 Ah. This constituted a 100% increase in both charge and storage.

Increasing the battery capacity meant that either a larger enclosure or a second battery box was required. It was recommended by MEA that all system components be housed in the one enclosure on the basis of simplicity and reliability. It was noted that one of the existing system enclosures showed signs of mechanical wear. Consequently, a stainless steel enclosure with integral mounting brackets was proposed that would allow for installation in various situations. The box would also be fitted with connector sockets to allow the connection and disconnection of sensor signal cables. The sockets would be covered with a plate to afford protection against impact and high power wave action.

The main enclosure would have two inner enclosures, one containing the logger and modem, the other containing the system batteries. This would allow replacement of batteries if need be, while the logger box remained sealed and undisturbed. This would reduce the possibility of inadvertent water ingress as had been evident from the earlier trials. The enclosure would be large enough to stow spare wind sensor, solar panel and antenna cables. Split conduit will be supplied to afford protection to these cables. This set up would allow free movement of the cables within the confines of the conduit, without over-tightening of securing ties.

The water quality sensors will be deployed in much the same way as presently, with the exception of the chlorophyll sensor on the outer sensor cluster of the second system. However, cable failure in these systems in earlier trials (presumably due to excessive and localised repeated flexure) needed to be addressed. The current method of deployment, where the cable is fully taped to a supporting rope, could be used, but with the cable running inside a flexible conduit. This would allow the cable some freedom to move while still being constrained by the tape and rope.

The chlorophyll sensor would have a connector at the sensor end to allow removal of the sensor for cleaning and maintenance and a connector fitted to the logger end of the cable to facilitate connection and installation. The cable would be run in the same conduit as the EC and DO sensor cables.

A new frame was also proposed for the outside mounted sensors to accommodate the chlorophyll sensor. A downward looking light source and sensor are located on the lower face. This face needs to be kept clean and have an unobscured field of operation to function correctly. A wiper fitted to the bottom face needs to be free to rotate, and must be cleaned regularly. Therefore, this sensor must be exposed and accessible while being protected from impact.

A stainless steel support arrangement would be constructed to house the whole array of EC, DO and chlorophyll sensors. All cabling and support ropes will be bundled with tape, as currently done with the modification of a conduit included in the bundle.

These upgrades and modifications were completed in February 2006 with expected re-deployment in March 2006.

In addition to the above upgrades and modifications of the two existing systems, the capability to measure current speed and direction, as well as wave characteristics, is being added. For operational reasons, this instrumentation will be deployed on a separate buoy, to avoid potential interference in the readings from a pontoon. This buoy will be used to replace one of the existing corner markers of the DI Fishing lease containing the research pontoons, and will provide hourly reports on current and wave conditions at the site. This information is needed for the Risk & Response project to help parameterise the models being developed, and will provide data on an ongoing basis that will help in modelling events outside the time period of data collection for Risk & Response (September 2005 – September 2006). The data will also be useful for industry operational purpose, particularly the wave component. MEA is also developing this system, which will be based around a bottom-mounted Nortek Aquadopp ADCP, and data will be made available on the environmental monitoring web site.

3.11 References

Clarke, S., Cartwright, C., Smith, B., Madigan, S. and Haskard, K. (1999). *Southern Bluefin Tuna Aquaculture Environmental Monitoring Report 1996 - 1998.* South Australian Research and Development Institute, 120 pp.

3.12 Appendix I: System Layout for SBT Telemetry-based Environmental Monitoring System

Provided by Measurement Engineering Australia
12th June 2003

3.12.1 Description

The water quality inside a floating cage of some 40 metres diameter is to be measured and logged, and compared with similar measurements to be taken simultaneously outside the same cage.

Hydrolab Minisondes are to be used at both points, deployed at about five metres below surface level. The outside sonde will be located about five metres outside the cage on a boom. The inside sonde will be located near to the centre of the cage, at the same depth.

Both sensors will be regularly removed for recalibration, and replaced with an alternate pair. A signal will be applied by means of a switch to a spare logger input. This signal will designate a sensor changeover event.

Both sensors, plus a wind instrument will be connected to a Unidata Starlogger housed in a waterproof enclosure attached to one of the stanchions of the cage structure.

A CDMA modem will be fitted inside the logger enclosure. An external antenna will be mounted outside of the enclosure, positioned to ensure adequate signal strength.

A solar panel will be fitted to maintain system battery voltage.

3.12.2 Logger Installation

A framework of hot dip galvanised steel sections will be attached to a stanchion. A galvanised steel pipe section will be inserted horizontally through an existing through hole in the stanchion, and will provide a support and attachment line for enclosure, boom and vertical tubular member. The upper plastic rail, part of the cage flotation and structure, will be used as a second securing line.

The logger and associated equipment will be housed in an IP67 enclosure, which in turn will be housed in a weatherproof enclosure of rating IP66. The outer enclosure will have a hinged front door for easy access to the inner enclosure. This enclosure is made of glass-reinforced polyester, and will withstand the corrosive environment.

Glands fitted to the outer enclosure will allow the transition through to the inner enclosure of sensor cables. This will be done such that the existing Minisonde cables will retain their DB-9 connectors.

A vertical section of 32NB-galvanised pipe will be secured to the cage upper rail and to the lower, horizontal pipe section. This vertical section will carry the solar panel, CDMA modem antenna, and the wind instrument at the top (Figure 3.24).

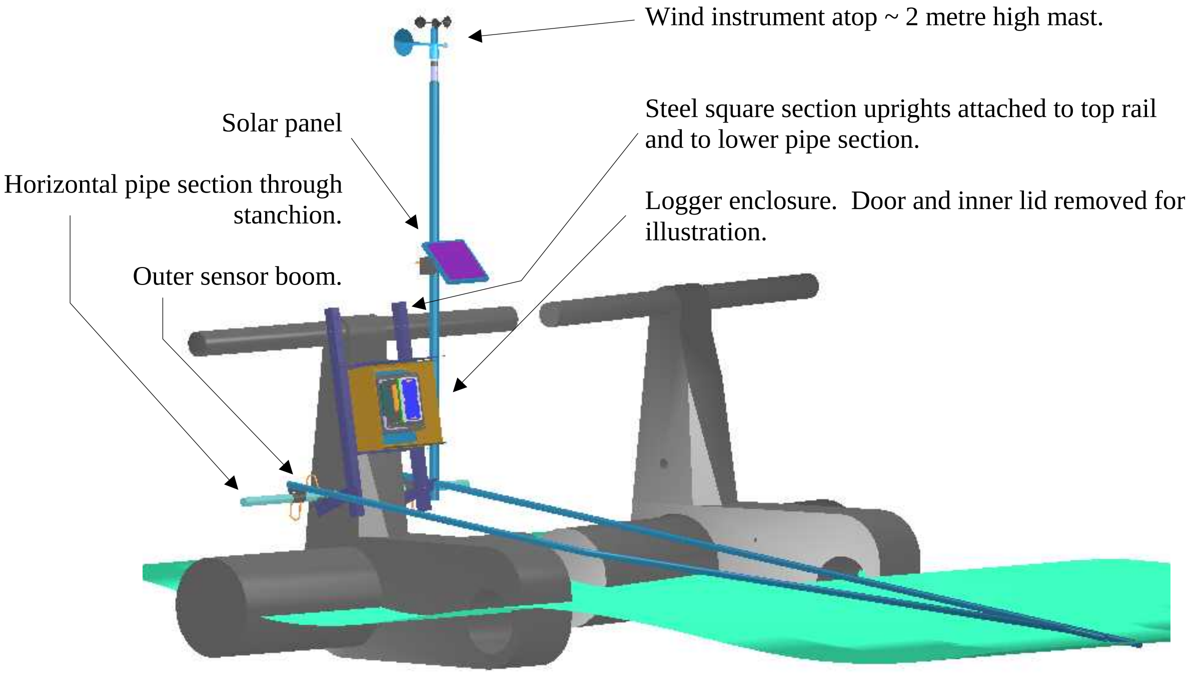


Figure 3.24. **General view of two adjacent stanchions showing logging equipment, solar panel and wind instrument. The outer sonde boom can also be seen. The plastic tubular "rails" are shown as discontinuous and obviously do not reflect the real situation. Similarly, the logger enclosure door has been removed.**

3.12.3 Sensor Deployment

3.12.3.1 Wind Instrument

The wind instrument is simply mounted via an adaptor and plastic insert to the top of the vertical boom. Its cable runs down inside the pipe section, providing some protection. The instrument body has a North alignment index on its body, and this can be easily aligned at installation.

3.12.3.2 Outer Minisonde

A boom made of two 5 m lengths of galvanised water pipe of 25NB will be secured by U-bolts and plastic bushes to the lower horizontal pipe section. The two lengths will be joined at the outer end, and braced near the middle to provide a reasonably rigid outrigger. The use of plastic bushes will allow the boom to rise and fall to compensate for relative movements between surface level and stanchion.

The outer end of the boom will be supported by a flotation device. In calm, flat seas, the boom will angle downward from the stanchion at about 5-10 0. A stainless steel cable will be attached via an eyebolt to the end of the boom. This will support a counterweight or sinker plus the Minisonde itself. The sonde will be located inside PVC tube of 80NB. The remaining space will be filled with a closed cell, water resistant foam (EVA). This will provide a measure of protection to the sonde itself. The sinker may be deployed above the sonde, giving the sonde a degree of freedom of movement that will further protect it from impacts etc (Figure 3.25).

To change sensors over, the boom can be swung upwards to vertical, bringing the sensor within reach of a person standing one the stanchion.

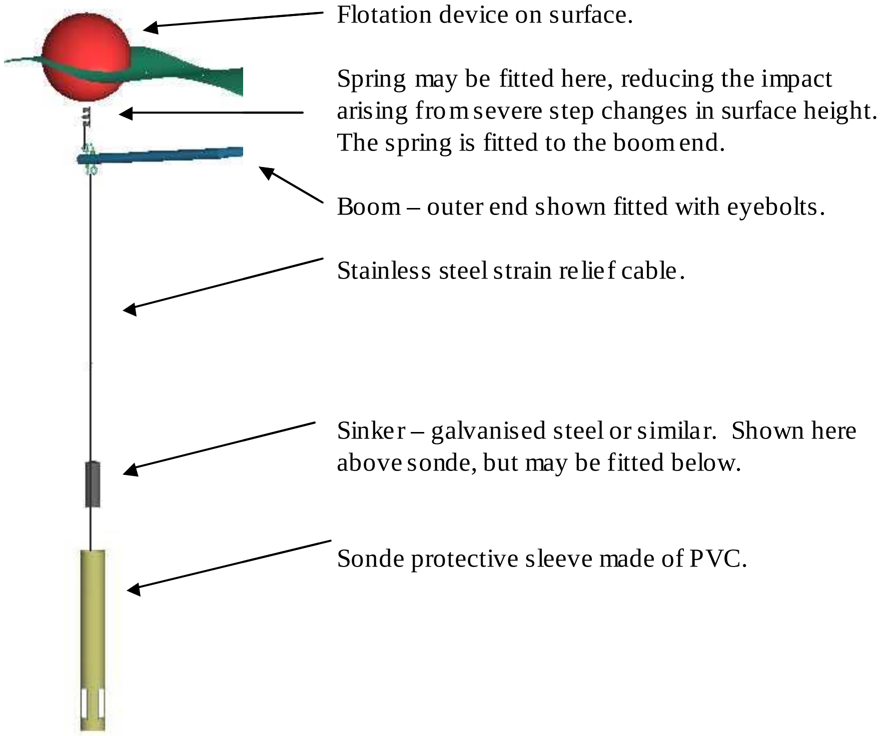


Figure 3.25. **Section showing means of deployment of outer sonde.**

3.12.3.3 Inner Minisonde

The sonde deployed inside the cage will be suspended and housed in a similar fashion to the outer sonde, but will be suspended from one of the radial "spider" ropes. It is envisaged that a clamp will be placed on the rope towards the centre of the cage. The clamp may be a device that can be moved along the rope towards the centre, but cannot be moved back. This will become an anchor point for a pulley. A rope passed over the pulley will have a bracket fixed to it, which supports the sonde and sinker. The rope can be reeled in from the stanchion to retrieve the sonde, and reeled back out to redeploy (Figure 3.26).

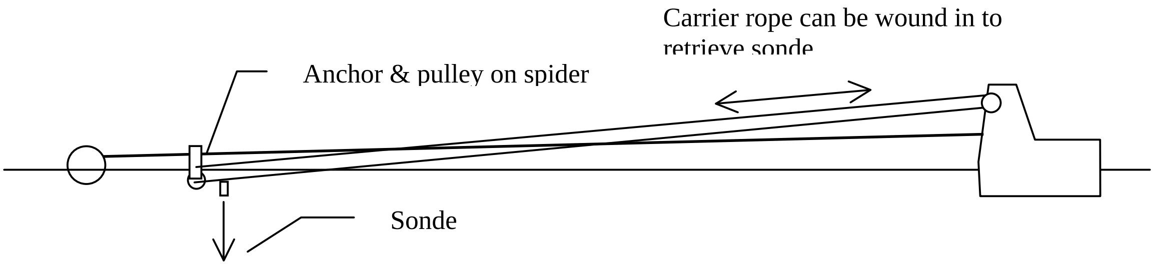


Figure 3.26. **Section showing means of deployment of inner sonde**

Sensor changeover can be logged as an event. This will be achieved by means of a user-operated switch. Various automatic options, such as sensor signal and power consumption changes have been considered as triggers for a sensor changeover flag to be logged, but have been ruled out. At this stage, the most likely method will involve an easily accessed switch to be activated once at the start of the changeover process. This method overcomes false switching or ambiguous signal and power change indicators.

3.12.4 Software

Magpie software will be supplied with a scheme disk containing files specific to this system. All instruments including the SDI-12 Minisondes can be accommodated by both logger and software. The software will also allow the modem to be switched on and off under logger control to conserve power. Notwithstanding this, the modem can be activated to place an SMS call should an alarm event occur. Alarm events are yet to be specified, and can be included in a straightforward manner.

Chapter 4 An integrated analysis of compliance-based environmental monitoring data for benthic infaunal communities from 2001 to 2003

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4.1 Summary

An integrated analysis was carried out using compliance-based environmental monitoring data for the benthic infaunal communities collected during the Tuna Environmental Monitoring Program in 2001, 2002 and 2003. Generally for both groups of control and compliance sites, there was an increase in overall mean abundance from 2001 to 2003 and a decrease in number of taxonomic groups from 2001 to 2002 but an increase in 2003, although the higher number of taxonomic groups collected in 2001 is likely due to the use of different sampling gear (grab versus corer). The results from the multivariate analysis showed that separation of sites was not indicative of impact, but rather reflected the geographical location of each site. This was especially obvious in 2001, but less so in 2002 and 2003. Analysis of all combined data indicated that differences between years were statistically significant. Similarity analyses showed that 2003 was least similar to 2001 and most similar to 2002. The principal taxa contributing to the dissimilarities between years have mostly increased with time. The increase in species more tolerant of organic enrichment, such as some species of Spionidae and Capitellidae, could indicate that changes are occurring in the general environment within the tuna farming zones. However, without samples from control regions, as opposed to control sites within the tuna farming region, it is impossible to determine if these inter-annual changes are only occurring in the tuna farming zone, and hence potentially related to tuna farming, or if they are occurring on a wider scale related to natural variation.

4.2 Introduction

The farming of *Thunnus maccoyii* or Southern Bluefin Tuna (SBT) has expanded almost exponentially since its beginnings in 1990 to be worth $266.9 million in 2002/03 (Knight *et al.* 2004) and $151 million in 2003/04 (Knight *et al.* 2005). Its success can be attributed in part to a significant economic multiplier effect due to its labour intensiveness and infrastructure requirements and the impetus created by the development of other industries and aquaculture sectors (EconSearch 2004). Continued development of the tuna aquaculture industry is fundamentally dependant upon the availability of farming sites, the selection of which requires an understanding of optimal cage spacing (which relates to spatial extent of impacts) and the timescale for seabed recovery after removal of cages (which relates to the total area required on a lease to provide for fallowing). In addition, there is a need to monitor the effect of alternative management approaches or new technologies that may influence the interactions between the tuna industry and the environment and vice versa. Such information would assist in optimising tuna farm productivity and product quality within an ecologically sustainable framework. Achieving these outcomes requires a good understanding of the environmental effects of sea-cage tuna farming operations.

An earlier study (FRDC 1995/091) on the environmental impact of tuna cages focussed on impacts on the benthic flora and fauna of Boston Bay (Cheshire *et al.* 1996a, b), where the tuna industry's initial development occurred. This study demonstrated that as expected there was a localized impact on the seafloor environment; a severe impact within the immediate vicinity of the tuna cages extending to a 20 m distance around each cage with a lesser impact for a further 100 to 150 m from the cages. At a distance of 200 m there was no evidence of an impact relative to control sites situated 1 km away. The nature of the impact was comparable to those described for many sustainable salmonid farm sites in other parts of the world and was generally consistent with those described in the Port Lincoln Aquaculture Management Plan (Bond 1993) for which the then current management strategies were tailored.

Although the work by Cheshire *et al.* (1996a, b) provided some preliminary insights, it became largely irrelevant when tuna farming moved outside Boston Bay into a deeper, high current flow and more wave-exposed region. To address this change of location and an ongoing increase in the size of the industry, an industry-wide tuna environmental monitoring program (TEMP) was initiated in 1996 to characterise the influence of tuna farming on the environment. Initial monitoring focused on a broad regional approach plus a gradient approach using a range of indices indicative of the health of pelagic systems (water quality and phytoplankton community structure) as well as the structure of epibenthic and infaunal communities (Clarke *et al.* 1999, Clarke *et al.* 2000).

In 2001, the form of the TEMP changed to a farm-site compliance-based monitoring program, with the methodology based on a synthesis of recommendations by SARDI (Madigan *et al.* 2001) and subsequent negotiations between the regulators, Primary Industries and Resources South Australia (PIRSA) Aquaculture and the Tuna Boat Owners Association of South Australia (TBOASA), representing the industry. The program adopted by PIRSA Aquaculture as a licence condition for tuna farming consisted of two components, i) Farm Management and ii) Benthic Assessment (PIRSA-Aquaculture 2003). The Benthic Assessment component consists of:

- A qualitative comparison of the biota and the sediment appearance videotaped from transects of the sea floor, from two on-site transects and one off-site transect.
- A quantitative comparison of the characteristics of the benthic infaunal communities at potentially impacted locations (compliance sites located 150 m from the lease boundary) of the licence area being monitored and control locations (located at least 1 km from any lease boundaries).
- A quantitative comparison of particle size of the sediment at potentially impacted locations and control locations.

The quantitative data obtained from the sampling of benthic infaunal communities are analysed and the structure of infaunal communities from each potentially impacted (compliance) site (per licence area) is compared to infaunal communities from eight associated control sites. The two variables used for comparison are total abundance and the number of taxonomic groups for each sample.

PIRSA Aquaculture designated the following conditions as being indicative of an environmental impact:

- A **fourfold or greater increase** in the average abundance of benthic infauna at a potentially impacted (compliance) site relative to the average abundance at a set of control sites; or
- A **twofold or greater decrease** in the number of taxonomic groups of benthic infauna at a potentially impacted (compliance) site relative to the average number of infaunal taxonomic groups at a set of control sites.

The data from the video recordings of the sea floor and particle size of the sediment are summarised and reported as PIRSA Aquaculture do not set criteria for these data.

The Benthic Assessment component of the TEMP was undertaken by SARDI as a consultancy to the TBOASA for three years (2001, 2002 and 2003). As a research task in the Aquafin CRC-Southern Bluefin Tuna Aquaculture Subprogram: tuna environment subproject – development of regional environmental sustainability assessments (RESA), an integrated analysis of data from the macrobenthic infaunal component of TEMP was carried out. Even though the TEMP sampling was not designed for such an analysis, this large dataset presented an opportunity for an integrated analysis to characterise the regional environment in which tuna farming is occurring and to investigate the potential use of TEMP for regional environmental monitoring. This was also recommended in the review by Madigan *et al.* (2001), which was to collate individual licence environmental reports into a single dataset to enable a regional environmental assessment.

4.3 Materials and Methods

4.3.1 Sampling sites and samples used

All the sites sampled under TEMP were located in waters adjacent to Port Lincoln, South Australia. Licence areas were located either in the Boston Island East or Rabbit Island farming zones (Figure 4.1). The compliance sites were located 150 m south (the currents being predominately in a north – south direction (Nielsen and Bennett 1996) of the licence area boundary. Within each farming zone, there were eight control sites, located at least 1 km from any licence area and in water depths similar to the compliance monitoring sites. The number of compliance sites varied each year as compliance monitoring was carried out only on sites with tuna production. In this integrated analysis, only sites located on the eastern side of Boston Island with similar depths (18 to 22 m) were used. One control site in 2001 was not used due to shallower depth and one in 2002 as it was sited on a previous lease site. Consequently, there were 15 control sites for 2001 and 2002 while 2003 had 16 control sites (Table 4.1). The number of compliance sites varied each year with 19 sites in 2001, 18 sites in 2002 and 16 sites in 2003 (Table 4.1).

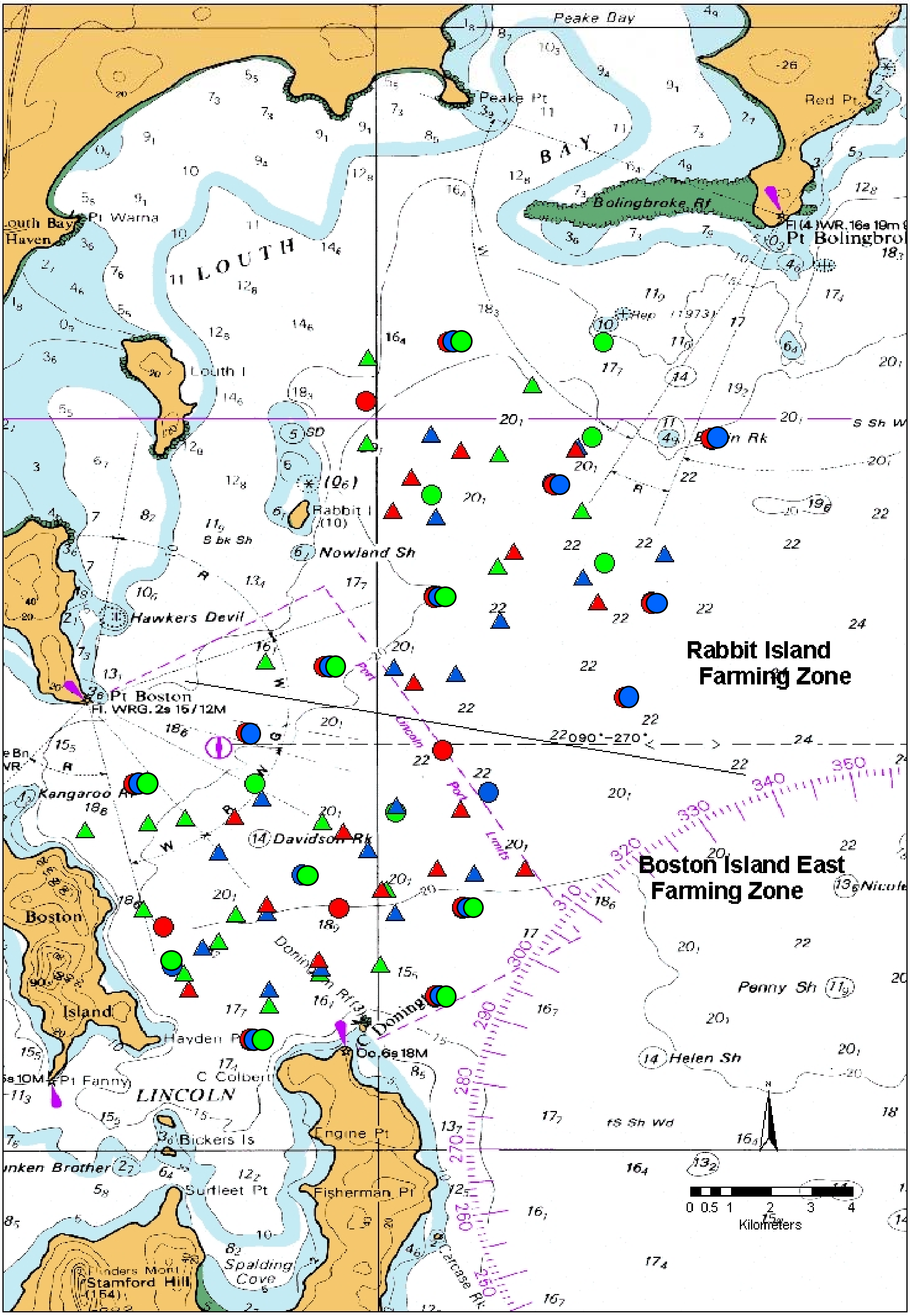

Figure 4.1. Map of the Port Lincoln SBT farming region showing the location of control sites (circles) and compliance sites (triangles) sampled in 2001 (green), 2002 (blue) and 2003 (red) from the Boston Island East Farming Zone and Rabbit Island Farming Zone.

Table 4.1. Number of compliance and control sites for 2001, 2002 and 2003 used in this analysis.

Year	Zone	Number of control sites	Number of compliance sites
2001	Boston	8	12
	Rabbit	7	7
2002	Boston	8	10
	Rabbit	7	8
2003	Boston	8	9
	Rabbit	8	7

4.3.2 Sampling procedures

Samples were collected in October/November of 2001, 2002 and 2003. In 2001, sediment samples were collected using a Shipek grab (200 mm by 200 mm) while in 2002 and 2003, sediment samples were collected using a HAPS Bottom Corer (internal diameter of 67 mm). The sampling for TEMP was designed for compliance monitoring for each lease area and its associated control sites within a farming year. It was not designed to examine any broad temporal or spatial trends in infaunal assemblages. Consequently when the HAPS Bottom Corer, which is a more efficient sampling gear, was purchased, it was used for all subsequent sampling.

At each control and compliance site in 2001, eight replicate grab samples were collected for analyses of benthic infauna; similarly in 2002 and 2003, eight replicate core samples were collected from each site. The samples were preserved in Bennett's solution (a 10 % solution of 1:1 propylene glycol and formaldehyde) in the field and stored until processed.

In the laboratory, the Bennett's solution in the sample jars was decanted before the samples were processed. The samples were gently washed and sieved using 1.0 mm sieves. Animals in the retained sediment were picked out with the aid of a stereomicroscope and identified. The common animals were identified mostly to family level, but it was not practicable to identify the less common taxa to this level, hence these were identified to phyla, sub-phyla, class or order. The animals were then enumerated and preserved in 70% ethanol for storage.

4.3.3 Data analysis

Due to the difference in sampling gear, all abundance data were standardised to number of animals per m^2 before further analysis. The data are summarised by calculating the mean abundance and number of taxonomic groups for each set of control sites (Boston and Rabbit) and their associated compliance sites.

Differences in faunal composition between years, and between control and compliance sites for each year, were examined using Analysis of Similarities (ANOSIM) tests, followed by non-metric Multidimensional Scaling ordination (MDS) to visualise any patterns. A SIMPER (Similarity Percentages) analysis was also performed to examine the taxa contributing to the similarities and dissimilarities in the different years. Multivariate analyses followed the methods described by Clarke 1993) using the PRIMER (Plymouth Routines in Multivariate Ecological Research) software package. The data were square root transformed prior to analysis to decrease the influence of dominant species on the analysis, and Bray-Curtis similarities were used to eliminate the effects of joint absences of taxa.

4.4 Results

The sampling in 2001 yielded a total of 80 taxa with mean abundance per site ranging from 716 to 11,809 individuals/m^2. There were 54 taxa in 2002 with mean abundance per site ranging from 1,276 to 9,714 individuals/m^2. In 2003, 66 taxa were identified with mean abundance per site ranging from 3,261 to 29,928 individuals/m^2.

In general, mean abundances were highest for all groups of control and compliance sites in 2003, while in 2001 and 2002; the mean abundances were less than 6,000 individuals/m^2 for all groups of sites (Figure 4.2). The mean number of taxonomic groups obtained for the groups of control and compliance sites were highest in 2001 with values above 40 while 2002 had the lowest with mean values below 25 (Figure 4.3). However, the higher number of taxonomic groups obtained in 2001 may be due to different sampling gear used for that year (grab versus corer).

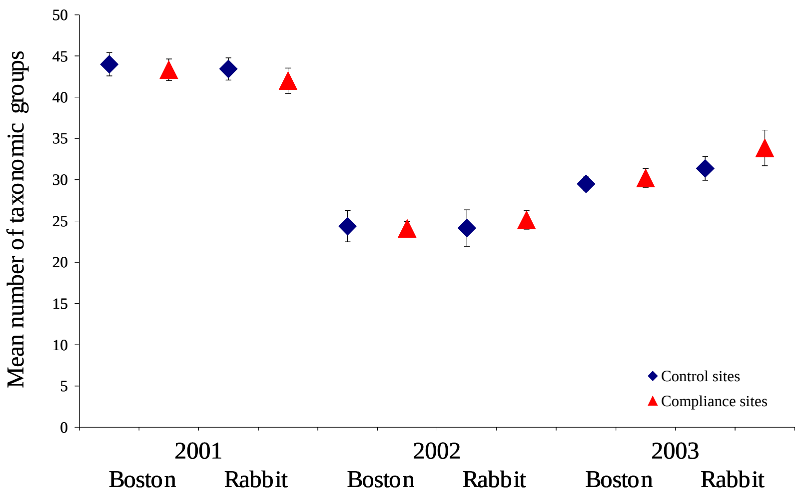

Figure 4.2. **Mean abundance (individuals/m^2 ±SE) for control sites and compliance sites sampled in 2001, 2002 and 2003.**

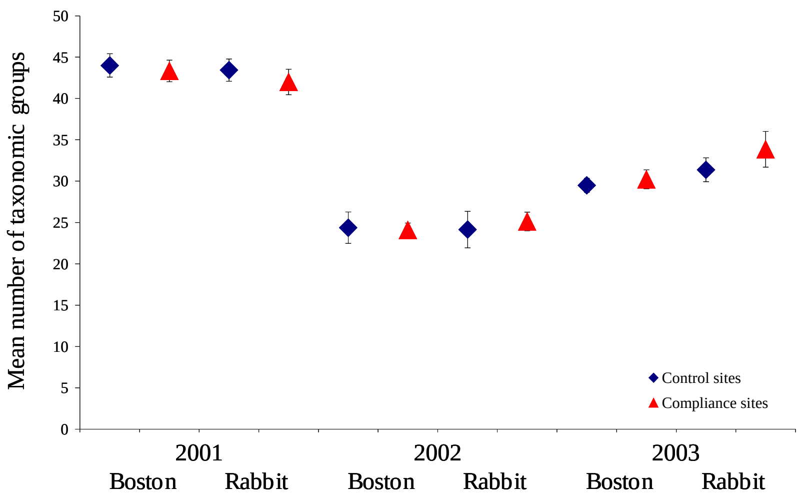

Figure 4.3. **Mean number of taxonomic groups (±SE) for control sites and compliance sites sampled in 2001, 2002 and 2003.**

Multivariate analyses of the benthic infaunal community structure for each year separately indicated that there were no differences between control sites and compliance sites in each zone. The multidimensional scaling (MDS) ordination plots showed no distinction between control or compliance sites or zones (Figure 4.4). For 2001, there was no distinction between control sites or compliance sites from Boston or Rabbit Farming Zones. In 2002, there was slight separation between control sites from Boston Farming Zone and Rabbit Farming Zone, but all the compliance sites were spread across the ordination space. Similarly in 2003, there was slight separation of the control sites from the two farming zones with compliance sites spread across the ordination.

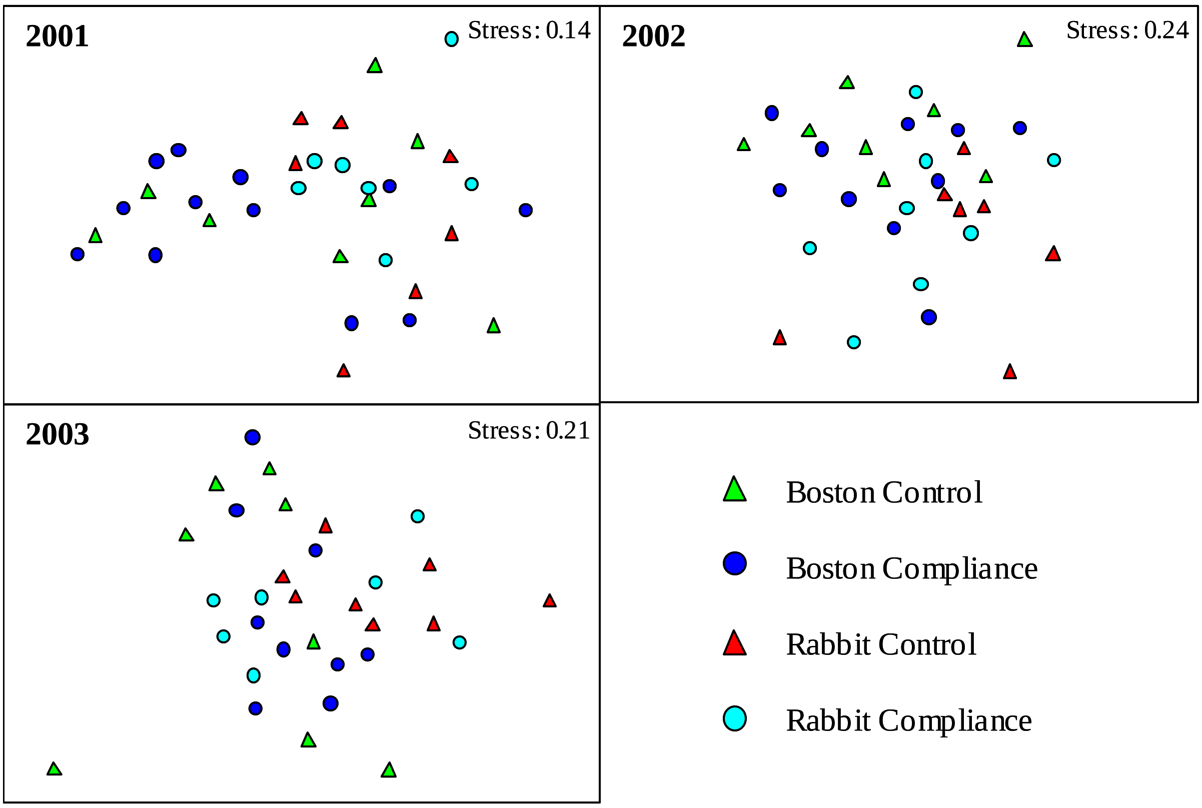

Figure 4.4. Two-dimensional MDS ordination plots of square root transformed abundance data of benthic infaunal communities for the control and compliance sites from Boston farming zone and Rabbit farming zone.

The distribution of the sites appeared to follow the geographical location of each site. This was most obvious in 2001 where sites located less than 3 km from Boston Island were clustered to the left of the ordination plot while sites located greater than 10 km from the island were on the right of the plot (Figure 4.5). This trend was still observed in both 2002 and 2003, but there were fewer < 3 km sites for these two years.

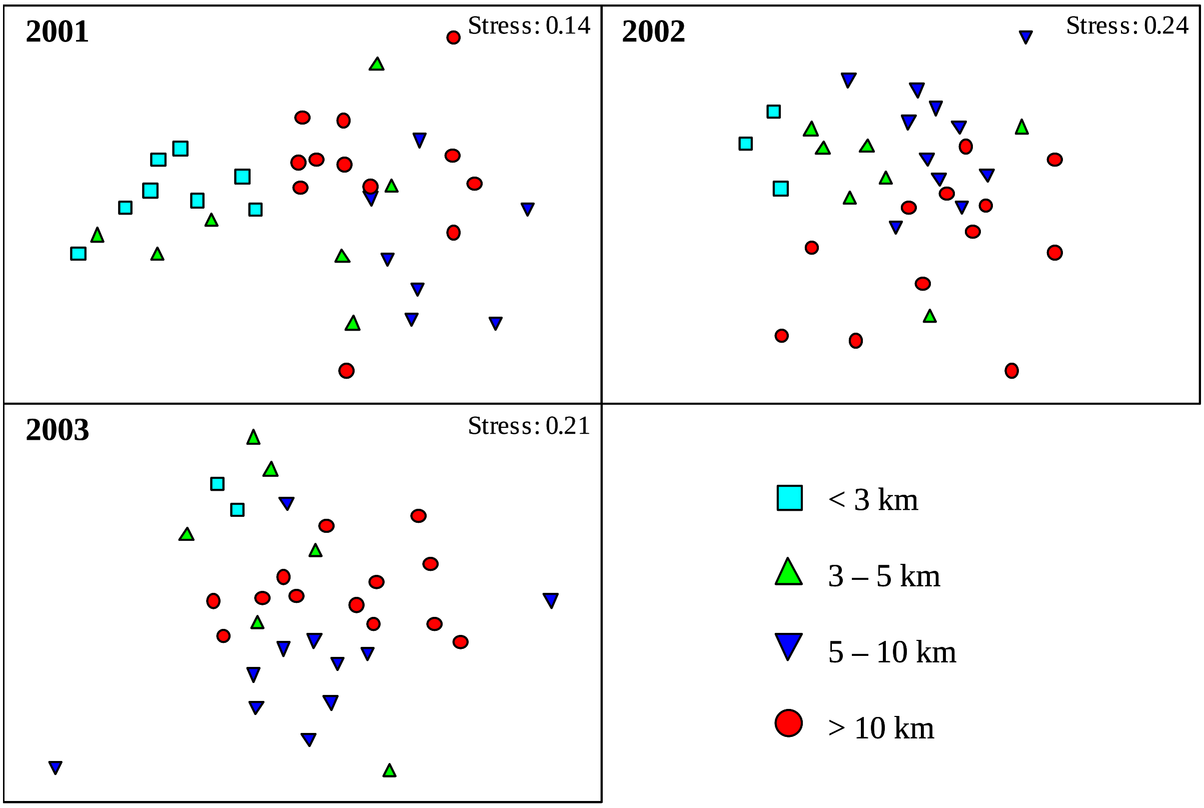

Figure 4.5. Two-dimensional MDS ordination plots of square root transformed abundance data of benthic infaunal communities for all sites in each year with increasing distance from Boston Island. Note: these are the same plots as in Figure 4.4.

The multivariate analysis for all sampling years combined indicated differences between years regardless of control or compliance sites or farming zones. The multidimensional scaling (MDS) ordination plot of the abundance data of the benthic infaunal communities showed the samples from 2001 forming a cluster to the left of the configuration while samples from 2002 were in the middle and the 2003 samples were to the right of the configuration (Figure 4.6). Results from the analysis of similarities (ANOSIM) confirmed significant differences between sampling years (Table 4.2).

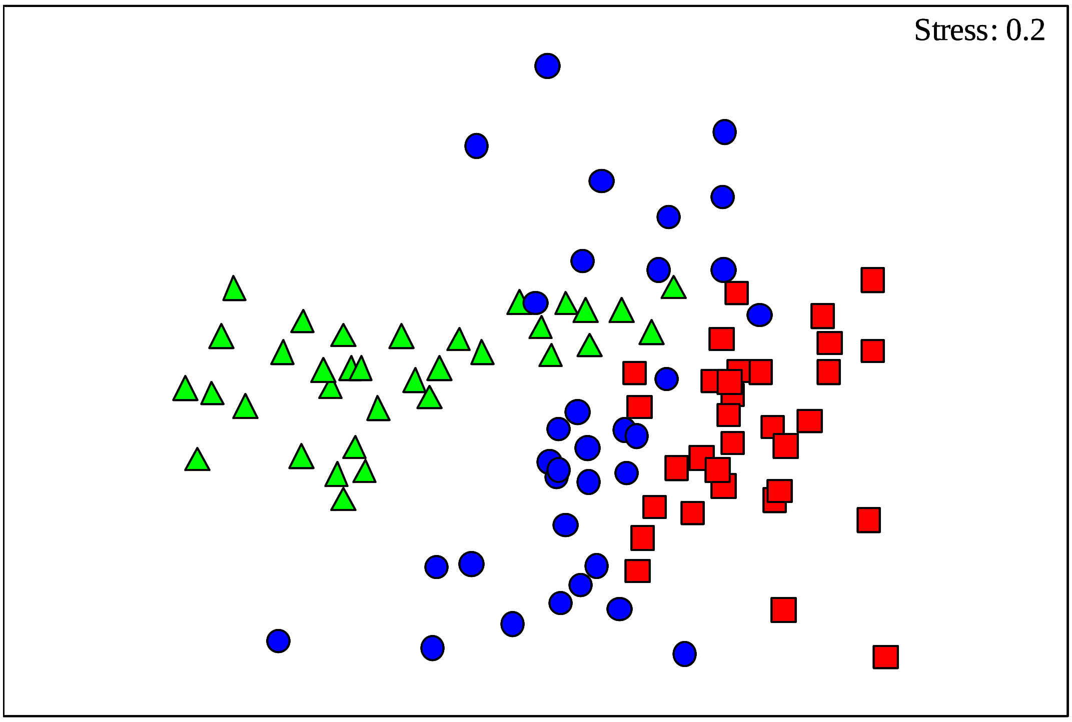

Figure 4.6. Two-dimensional MDS ordination plot (stress=0.2) of square root transformed abundance data of benthic infaunal communities based on samples collected in 2001(▲), 2002 (●) and 2003 (■).

Table 4.2. Analysis of similarities (ANOSIM) for the three sampling years with the R statistic (bold) and the significance level (*italic*) between years. The global R-value was 0.581 at a significant level of 0.1%.

	2001	2002	2003
2001		**0.561**	**0.746**
2002	*0.1%*		**0.382**
2003	*0.1%*	*0.1%*	

The routine SIMPER (Clarke 1993) was run to determine which taxa were primarily responsible for differences between years. This procedure computes the average similarity ($\overline{S_i}$) for all pairs of samples within a year and average dissimilarity ($\overline{\delta_i}$) between all pairs of inter-year samples. The results of this computation give a breakdown of the contributions from each taxa to the average term $\overline{S_i}$ or $\overline{\delta_i}$. The ratio of this average term and the standard deviation give a useful measure of how consistently a taxon contributes to the average similarity or dissimilarity. For within-year similarities, a high ratio will indicate that the taxon typifies that year while for between-year dissimilarities, a high ratio will indicate that the taxon is a good discriminator.

Results from SIMPER analysis showed that all within-year similarities were less than 50%, with 2003 having the highest similarity of 49.60%, followed by 2002 with 49.22% and 2001 with 46.21% (Table 4.3). Within each year, the infaunal assemblages were characterised by similar taxa. Seven taxa variously contributed to approximately 50% of all within year similarities (Table 4.4). Of these, four taxa were common for all years; the polychaete families Lumbrineridae, Spionidae, Nephtyidae and Capitellidae. The addition of gammaridean amphipods to the four polychaete families accounted for 52% of the within year similarity in 2001. 2002 was also dominated by these four polychaete families, while 2003 had two additional polychaete families, Sabellidae and Ampharetidae, which together with the first four families accounted for 52% of the within year similarity (Table 4.4).

Table 4.3. Average similarities (italic) within years and dissimilarities (**bold**) between years. All within year similarities were less than 50% and dissimilarity was highest between 2001 and 2003.

	2001	2002	2003
2001	*46.21*	**60.61**	**67.94**
2002		*49.22*	**57.61**
2003			*49.60*

Table 4.4. Dominant taxa contributing ~50% of within year similarities for 2001, 2002 and 2003 (blank cells indicate that the taxa was not important for that year).

Taxa	**Percentage contribution**		
	2001	**2002**	**2003**
Lumbrineridae	14.62	12.27	6.19
Spionidae	12.61	13.75	19.91
Nephtyidae	12.28	18.19	6.46
Gammaridea	8.86		
Capitellidae	4.58	8.17	6.66
Sabellidae			6.96
Ampharetidae			5.95

The highest dissimilarity was between 2001 and 2003 and the lowest between 2002 and 2003 (Table 4.3). Seven principal taxa (using average contribution to dissimilarity, $\overline{\delta}_i > 2$) contributed to the dissimilarities between the sampling years 2001 and 2002 (Table 4.5). Nine principal taxa contributed to the dissimilarities between sampling years 2001 and 2003 while seven contributed to dissimilarities between 2002 and 2003 (Table 4.6 and Table 4.7). The polychaete family Spionidae had the highest average contribution to the overall dissimilarity for all comparisons ($\overline{\delta}_i > 10.00$). In contrast, all other taxonomic groups contributed less than 10% to the dissimilarities between each year comparison. The ratio indicated that the principal taxa were generally good discriminating taxa.

Table 4.5. Principal taxa contributing to differences between sampling year 2001 and 2002, average abundance across sites within the years 2001 and 2002, and the contribution ($\overline{\delta}_i$) of the ith taxa to the average Bray-Curtis dissimilarity ($\overline{\delta}_i$) between the two years.

Taxa	Average abundance		$\overline{\delta}_i$	Ratio	Cumulative %
	2001	2002			
Spionidae	931.07	875.53	14.93	0.97	24.63
Lumbrineridae	356.99	377.07	5.00	1.51	32.88
Nephtyidae	165.53	391.03	4.32	1.41	40.01
Capitellidae	105.15	230.97	3.00	1.19	44.95
Bivalvia	64.71	246.01	2.99	0.55	49.88
Cirratulidae	66.82	193.37	2.67	1.13	54.29
Eunicidae	92.19	158.99	2.33	1.05	58.15

Table 4.6. Principal taxa contributing to differences between sampling year 2001 and 2003, average abundance across sites within the years 2001 and 2003, and the contribution ($\overline{\delta}_i$) of the ith taxa to the average Bray-Curtis dissimilarity ($\overline{\delta}_i$) between the two years.

Taxa	Average abundance		$\overline{\delta}_i$	Ratio	Cumulative %
	2001	2003			
Spionidae	931.07	2553.58	18.82	1.12	27.70
Sabellidae	55.97	398.82	3.73	1.34	33.19
Lumbrineridae	356.99	428.73	3.53	1.30	38.39
Ampharetidae	41.54	348.97	3.51	1.17	43.55
Gammaridea	116.08	356.73	2.93	0.89	47.87
Phoronida	11.58	291.36	2.75	1.28	51.91
Capitellidae	105.15	331.24	2.67	1.43	55.85
Terebellidae	26.10	289.15	2.63	1.55	59.72
Bivalvia	64.71	238.19	2.03	0.93	62.71

Table 4.7. Principal taxa contributing to differences between sampling year 2002 and 2003, average abundance across sites within the years 2002 and 2003, and the contribution ($\overline{\delta}_i$) of the ith taxa to the average Bray-Curtis dissimilarity ($\overline{\delta}_i$) between the two years.

Taxa	Average abundance		$\overline{\delta}_i$	Ratio	Cumulative %
	2002	2003			
Spionidae	875.53	2553.58	16.07	1.00	27.90
Sabellidae	95.61	398.82	2.88	1.29	32.90
Lumbrineridae	377.07	428.73	2.75	1.31	37.67
Bivalvia	246.01	238.19	2.53	0.78	42.06
Ampharetidae	128.91	348.97	2.51	1.07	46.42
Gammaridea	150.40	356.73	2.47	0.90	50.70
Phoronida	27.93	291.36	2.24	1.26	54.60

4.4 Discussion

The analysis of infaunal assemblages presented here shows that in none of the years studied did tuna farming have a detectable localised impact on the environment 150 m outside of the lease boundaries.

The sampling for TEMP was designed for compliance monitoring for each lease area and its associated control sites within a farming year, however, the large dataset collected over three years from the same region allowed an integrated analysis to potentially examine broad-scale changes in infaunal assemblages. The results from the integrated analyses indicated that the differences observed were most clear between years. The increase in mean abundance for the different compliance and control sites from 2001 to 2003 may be attributed to the shift in community structure with large increases in principle taxa over the three years, as further discussed below. The decrease in mean number of taxonomic groups from 2001 may be due to different sampling gear used (grab in 2001 versus corer in 2002 and 2003). Somerfield and Clarke (1997) showed that different methods of sampling do have biasing effects but significant differences were only detected by multivariate analyses. However, the shift in community structure for each of the methods used did not have a strong or ecologically meaningful explanation. Yet another study (Jensen 1981) showed that a core sampler gave higher abundance and diversity, suggesting that the differences seen in this study over the three years may be real as further discussed below. Unfortunately, it has not been possible to locate other data sets from the area over the same time period that have used a consistent sampling technique. This highlights an important drawback of using data sets collected for other reasons in a meta-analysis – it is not always possible to distinguish differences over time from differences in sampling techniques. However, the comparison between data from 2002 and 2003, where the HAPS Bottom Corer was used, does not have this problem of different sampling gear. Therefore there is more confidence in the comparison of data from 2001 with the other two years.

From the multivariate analysis, the main patterns of variability seen appeared to be related to the geographical location of the sites for each year, which was especially obvious in 2001. This trend was less obvious in 2002 and 2003, possibly due to some inshore farms having moved further offshore, so most of the sites were within the offshore classification.

The significant shift in community structure between the three years sampled as shown by the multivariate analysis could be due to factors such as inter-annual variability. However, it may also be due in part to the movement of the lease sites further offshore, as Figure 4.5 indicates that there is an inshore-offshore gradient in the infaunal assemblage. The principal taxa contributing to the dissimilarities between years have mostly increased with time. The polychaete family Spionidae was the dominant taxa contributing over 20% to dissimilarities between years with a 46% increase in average abundance from 2001 to 2003. The increase in species more tolerant of organic enrichment, such as some species of Spionidae and Capitellidae, could indicate that changes are occurring in the general environment within the tuna farming zones. Without samples from control regions, as opposed to control sites within the tuna farming region, it is impossible to determine if these inter-annual changes are only occurring in the tuna farming zone, and hence potentially related to tuna farming, or if they are occurring on a wider scale related to natural variation. If the TEMP data are to be used for regional-scale environmental monitoring in the future, it is important that these regional controls be added to the sampling program. Care will have to be taken in the selection of regional control sites, however, to ensure that they are far enough from the farming zone not to be impacted by any regional effects, but close enough and in similar habitats to ensure that natural variation in assemblages at these sites is consistent with the natural variation in the farming zone.

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Chapter 5 The interactions between seabirds and tuna farms near Port Lincoln

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Harrison S (2003). The Interactions Between Seabirds and Tuna Farms Near Port Lincoln. Honours thesis, School of Biological Sciences, Flinders University of South Australia.

5.1 Executive Summary

Throughout the world, the interaction between seabirds and humans is often a controversial issue. It is evident that the abundance and distribution of certain seabirds (notably gulls), have markedly increased because of human activities, particularly refuse disposal and fishery discards. Similarly, aquaculture has been considered by some to be a major factor in the increase in some seabirds, despite there being few available data.

This honours project was undertaken in 2003 to develop a preliminary understanding of the nature of the interactions that occur between seabirds and the tuna farms near Port Lincoln, and to try to assess the consequences of these interactions. Three main areas were researched:

1. The economic effect of seabird scavenging on the tuna industry.

2. The effects of aquaculture on seabird populations and breeding biology.

3. Social and ecological implications of seabirds displaced from tuna farms.

It was found that the practices used in 2003 on the study farms to distribute tuna feed resulted in 2.3% of baitfish and 1% of pellet feed being consumed by seabirds. Most baitfish were consumed by silver gulls, but pellets were almost equally consumed by both silver gulls and Pacific gulls. Feeding frozen blocks of baitfish led to the least consumption of baitfish feed by seabirds while pneumatically distributed baitfish were the most consumed. Shovelling baitfish also resulted in a substantial amount of baitfish being consumed by seabirds.

An increased clutch size and a substantially prolonged breeding season in silver gulls has been noted at sites near to Port Lincoln, compared to a control site. This increase in reproductive output has resulted in the number of breeding silver gulls in the Port Lincoln area increasing since 1999. This apparently inflated population leads to social and environmental problems in Port Lincoln when all the tuna have been harvested and the tuna season ends in October each year.

The results suggest that the silver gull population around Port Lincoln has sharply increased, and that it may depend on the large quantity baitfish that are supplied to farmed

tuna. Further research is required to confirm and clarify the links between tuna farming and seagull numbers, and to assess other feeding techniques used on the tuna farms and their effectiveness in reducing scavenging by seabirds. The potential impact of silver gulls on other birds is an important ecological issue that requires further research.

5.2 Commonly Used Abbreviations

ABBBS:	Australian Bat and Bird Banding Scheme
NPWS:	National Parks and Wildlife Service South Australia
SARDI:	South Australian Research and Development Institute
PIRSA:	Primary Industries and Resources South Australia
LMSC:	Lincoln Marine Science Centre, Port Lincoln
SBT:	Southern Bluefin Tuna
Tuna:	Southern Bluefin Tuna
TBOASA:	Tuna Boat Owners Association of South Australia

5.3 General Introduction

5.3.1 Overview

The availability of 'natural' food for many seabirds is spatially and temporally unpredictable (Bertelloti et al., 2001). In contrast, food sources of human origin such as from waste tips, fisheries discards and aquaculture facilities usually offer resources that are relatively abundant and predictable in space and time (Bertellotti et al., 2001; Furness, 1996; Oro, 1999). The availability and abundance of these resources has been associated with an increase in many bird populations that utilise these resources (Bosch et al., 1994).

Human exploitation of marine resources has provided an increasing opportunity for some seabirds to take advantage of resources that would otherwise be unavailable to them (Furness et al., 1988). The aquaculture of fish in ponds and seacages and the thousands of tonnes of fisheries bycatch and offal discarded each year by the fishing industry, provide easily accessible high quality food to many seabirds.

5.3.2 Bird-Aquaculture Interactions

The interactions between birds and aquaculture is a long standing controversial issue. There are three main problem areas associated with this interaction:

- Birds directly predating cultured fish species in ponds, raceways, tanks and seacages.
- Birds interfering with the feeding of cultured fish by scavenging their food or by stressing them so they will not eat.
- Birds may transmit or transport diseases between ponds or farms.

A major concern throughout the world is the widespread, and economically important predation of aquaculture stock by birds (Carss, 1993; Furness, 1996; Galbraith, 1992; Glahn *et al.*, 1999; Price & Nickum, 1995). This is mainly a problem with large inland farms with a high density of stocked fish that are highly visible from the air and hence attractive to birds

(Price & Nickum, 1995). These farms usually culture trout, salmon, baitfish, catfish and crayfish of a variety of sizes which means that appropriately sized prey are potentially available to birds year round (Glahn *et al.*, 1999). Cormorants, egrets, herons and kingfishers, and to some extent grackles and pelicans, are the main problem. These birds can cause major losses ranging from US$10,000 per farm per year (Glahn *et al.*, 1999) to an estimated US$6.6 million per year for the Louisiana crawfish industry (Price & Nickum, 1995). In Europe, damage and losses from birds is estimated at 10-60% of production costs (Price & Nickum, 1995). In many cases, birds take sick fish swimming near the surface and the use of predator nets over the top of the ponds limits bird predation to the moribund fish at the surface (Carss, 1993). In these cases, it is difficult to determine the actual loss because the fish were going to die anyway.

Birds also have an impact on marine aquaculture. At mussel farms the mussels may be taken by eider ducks and scoters (Galbraith, 1992), and salmon are taken from seacages by gulls, herons, osprey and bald eagles (Carss, 1993; Furness, 1996; Price & Nickum 1995). However, bird predation is much greater at inland farms than coastal farms, with, for example, many more salmon being taken by marine mammals than birds (Furness, 1996).

The loss of aquaculture feeds to scavenging birds is well known though little researched. In Europe, swans, coots, and ducks, especially mallards, compete directly for food pellets intended for fish (Price & Nickum, 1995). In Scotland, gulls tear open bags of pellets at salmon farms and feed on the spilled food (Furness, 1996). However, compared to losses through bird predation the loss of pelleted feed is a minor problem, so it is not considered an important part of bird-aquaculture interactions (Furness, 1996).

The interactions of birds with aquaculture at the tuna farms near Port Lincoln are very different from the studies discussed above. Seabirds are not predating the cultured fish but scavenging the fish-feed, which is mainly baitfish, not pellets as in other studies. Therefore, previous research sheds little light on what might occur on tuna farms at Port Lincoln, although studies of seabirds scavenging on fisheries discards may well be relevant.

5.3.3 Seabirds and Fisheries Discards

5.3.3.1 Relevance

Seabirds feed on bycatch and offal discarded from bottom trawlers, purse-seiners, longliners, demersal trawlers and shrimp trawlers all over the world. Some of these fish and invertebrates are too small to be commercially exploited, below the official minimum landing size, a species of no demand, or are caught in excess of the fishing quota and are discarded (Garthe *et al.*, 1996). These discarded fish must be sorted, which takes time, and hence many moribund and damaged fish float around the fishing boats and are taken by seabirds (Walter & Becker, 1997).

5.3.3.2 The Seabirds Involved

The seabirds able to exploit the activities of commercial fishing boats are coastal or pelagic and opportunistic scavengers, many incapable of diving to the seabed. They include many species of gulls, but also skuas, gannets, kittiwakes, terns, cormorants, albatrosses, petrels and fulmars (Blaber *et al.*, 1995; Furness *et al.*, 1988; Garthe *et al.*, 1996; Huppop & Wurm, 2000; Oro, 1996). Gulls are usually the main birds utilizing fisheries discards and are the most dependent on these discards, due to their opportunistic and scavenging nature

(Garthe *et al.*, 1996; Huppop & Wurm, 2000; Martinez-Abrain *et al.*, 2002; Walter & Becker, 1997).

5.3.3.3 What Do Seabirds Consume?

The exploitation of commercial fisheries by scavenging seabirds has been well researched, showing that fish discards are usually the main foraging resource for some seabird populations (Gonzalez-Solis, 1997). The discards from commercial fisheries usually comprise several species of roundfish, flatfish, elasmobranchs, benthic invertebrates and fish offal (Garthe *et al.*, 1996). However, small fish are usually the main discards, being at least 60% of the discards in most fisheries (Martinez-Abrain *et al.*, 2002), and most of these float and are available to birds and other marine animals for up to six hours (Blaber *et al.*, 1995).

The importance of fisheries discards in the diet varies between species and season. The proportion of discards consumed by seabirds ranges from 39% in the North Sea (Garthe *et al.*, 1996) to 72% in the western Mediterranean Sea (Martinez-Abrain *et al.*, 2002). The birds have to compete amongst themselves, as well as with fish and sea mammals also feeding on the discards (Blaber *et al.*, 1995). The proportion of discards in the diet of seabirds can range from 20% for crested terns on the Great Barrier Reef (Blaber *et a*l., 1995) to 73% for Audouin's gull in the western Mediterranean (Oro, 1997), and 100% for some gulls in the North Sea (Huppop & Wurm, 2000). Garthe *et al.* (1996) documented that seabirds consumed 39% of the discards available, with roundfish and offal being taken in the largest proportion. Many other studies have also documented that roundfish are more attractive to seabirds than flatfish and have claimed this is due to the difference in handling time (Bertelloti & Yorio, 2000; Furness *et al.*, 1988; Garthe *et al.*, 1996; Martinez-Abrain *et al.*, 2002). Discard experiments have shown that seabirds select discards according to the length or width of the discard component and therefore how easy they are to handle and swallow (Walter & Becker, 1997). The shorter the handling time, the more attractive the fish, and roundfish were found to require the least handling time for most seabirds (Garthe *et al.*, 1996).

5.3.3.4 Are Inflated Seabird Populations Dependent on Fisheries Discards?

The large amounts of fisheries discards can potentially support extremely large numbers of seabirds, because large proportions of the discards are eaten by seabirds and some birds rely heavily on them due to their abundance and predictability in space and time (Oro *et al.*, 1999). In the British Isles, the numbers of all scavenging seabirds have increased over the last century. This has been attributed to the availability of fisheries discards, and those species that are the most competitive at fishing boats seem to be increasing most rapidly (Furness *et al.*, 1988). Audouin's gull was threatened 22 years ago, with only a few pairs left in the Ebro Delta. These few pairs had increased to 10,000 pairs in 1994 (70% of the worlds population) and this was attributed to the availability of trawler discards for food (Oro *et al*, 1996). These authors suggest that if a current trawling moratorium is continued for many years, this species may once again be threatened. In the North Sea, there are 1.4-3.4 million seabirds in winter and 3-6 million in autumn; scavengers accounting for 66% in summer and 52% in winter (Garthe *et al.*, 1996). In this area, sufficient fisheries waste is available to satisfy the energy demands of all scavenging species and could potentially support 5.9 million birds (Walter & Becker, 1997). The mass of fisheries waste taken by birds in the North Sea area more than equals the 250,000 tonnes of live fish calculated to be consumed by all birds in the North Sea (Garthe *et al.*, 1996).

The availability of fisheries discards can affect scavenging seabird population dynamics through improved breeding success, decreasing mortality and increasing recruitment. An abundance of good quality feed can result in increased clutch size, egg weight and volume, hatching success, chick survival and fledging success (Annett & Pierotti, 1989; 1999). This inevitably results in an increase in population size of opportunistic and scavenging seabirds, such as gulls, which in urban areas can cause management and health problems. These problems include aircraft and traffic strikes, human health issues (through faecal contamination of water), ecological issues (competition for nesting sites, predation and kleptoparasitism) and nuisance issues (defecation on public property, harassment for food etc) (Belant, 1997; Smith, 1995; Smith and Carlile, 1993)

5.4 Relevance to Port Lincoln Tuna Farms

As discussed above, the interactions between seabirds and finfish aquaculture operations near Port Lincoln are unlike most of the reported interactions for birds on aquaculture farms. Firstly, the majority of documented interactions occur on land-based aquaculture farms, whereas tuna are farmed in seacages. Secondly, previously studied birds at inland ponds and seacages feed on the fish cultured in the ponds, while seabirds at the tuna farms consume the tuna feed. Thirdly, the tuna are fed mainly baitfish (one company fed pellets during the course of the study). Finally, there are obvious differences in the species of birds that are problematic. Published results indicate terrestrial and diving birds are the main problem, but gulls are the main problem around Port Lincoln.

The fisheries discards literature is most applicable to tuna farms because in both cases, boats are throwing out large quantities of fish that float or sink slowly, and hence are easily accessible to seabirds and are of a size preferred by seabirds. Seabirds reported to feed and rely on discards are similar to the species found feeding at the finfish seacages in Port Lincoln and some are the same species. Crested terns (*Sterna bergii*) and silver gulls (*Larus novaehollandiae*) have been observed feeding on discards in Australian waters (Blaber *et al.*, 1995; Wood, 1991). The seabirds at the Port Lincoln tuna farms are opportunistic seabirds including gulls, terns and cormorants, but petrels and gannets have also been observed at the seacages (Farlam, unpublished data). However, the silver gull is perceived to be the main problem in terms of consumption of baitfish.

Approximately 50,000 tonnes of baitfish are fed to the tuna per year and they are potentially very attractive as food for seabirds because they are roundfish of a size suitable to many local seabirds. It is unknown what quantity of the baitfish they consume, but it could be high because baitfish, being frozen and often with inflated swim bladders, either float or sink slowly (Brothers, 1995). The seacages are not moved during the tuna season and hence this feed source is highly predictable and within the natural foraging area of local seabirds. Thus seabirds could consume a large amount of tuna feed, which could result in a substantial economic loss to the industry as tuna feed costs about $650-1,800 a tonne, depending on whether it is baitfish or pellets.

The availability of the baitfish fed to the tuna has the potential to have some impact on the population dynamics of the seabirds in the area. The tuna farming season (February-September/October) coincides with most (nearly all) of the silver gull breeding season (April-November), and parts of the breeding season of black-faced, pied and little cormorants, crested terns, Pacific gulls (*Larus Pacificus*) and short-tailed shearwaters (*Puffinus tenuirostris*). Conversations with farm managers indicated that they perceive silver gulls to be the main bird species that consumes baitfish. The availability of much high-quality, high-protein baitfish, before and during most of the silver gull breeding season has the potential to support a large silver gull population and to increase it through increased female body condition, egg size, clutch size, chick size, chick survival and fledging success. Recruitment of individuals from other silver gull colonies around the state could also potentially increase the population, as the feed is available to support them over most of the year.

The silver gull population around Port Lincoln has increased from 3,300 breeding pairs in 1999 to 5,100 in 2000 (Farlam, unpublished data). This population growth could be linked to the availability of tuna feed, among other things, and if so, this population may come to rely on tuna feed as its main food source. This is potentially a major environmental and ecological problem because the tuna feed is only available from February to September/October. By October in most years, the tuna have all been harvested and foraging seabirds (mainly silver gulls) have to either forage for natural food, or move to Port Lincoln in search of other food. There are problems with both these choices. The tuna season ends in spring or early summer when most birds are breeding and silver gulls foraging for natural food are likely to have a considerable impact on eggs and chicks, especially of vulnerable seabirds such as little terns (*Sterna albifrons*). An influx of gulls into Port Lincoln causes management, health and nuisance problems, and is unpopular with the general public.

5.5 Project Aims

5.5.1 General Aims

The objective of this project was to investigate the interactions between seabirds and the southern bluefin tuna farms near Port Lincoln, to identify the problems and their scale, and to suggest potential solutions.

5.5.2 Specific Aims

The specific aims of this project are:

- To determine which species of seabird are of concern.
- To determine the proportion of tuna feed consumed by seabirds.
- To assess any preference by seabirds for baitfish or pellet feed.
- To determine which species of seabird consumed the most feed of each type.
- To assess how different feeding methods influence scavenging and hence find a ‘best practice’ for tuna farmers.
- To determine if there is any seasonal or spatial patterns in either feed consumption or seabird numbers at farms.
- To determine how much tuna feed was consumed by the seabirds at both baitfish and pellet farms.
- To determine whether the reproductive output of silver gulls has increased due to the availability of tuna feed.
- To assess changes in the population size of silver gulls in Port Lincoln over time.

- To determine any differences in the timing of breeding for silver gulls around Port Lincoln and at a reference site away from tuna farms.
- To assess whether the number of silver gulls increased around the town of Port Lincoln during, and near the end of, tuna harvest.

5.6 General Methods

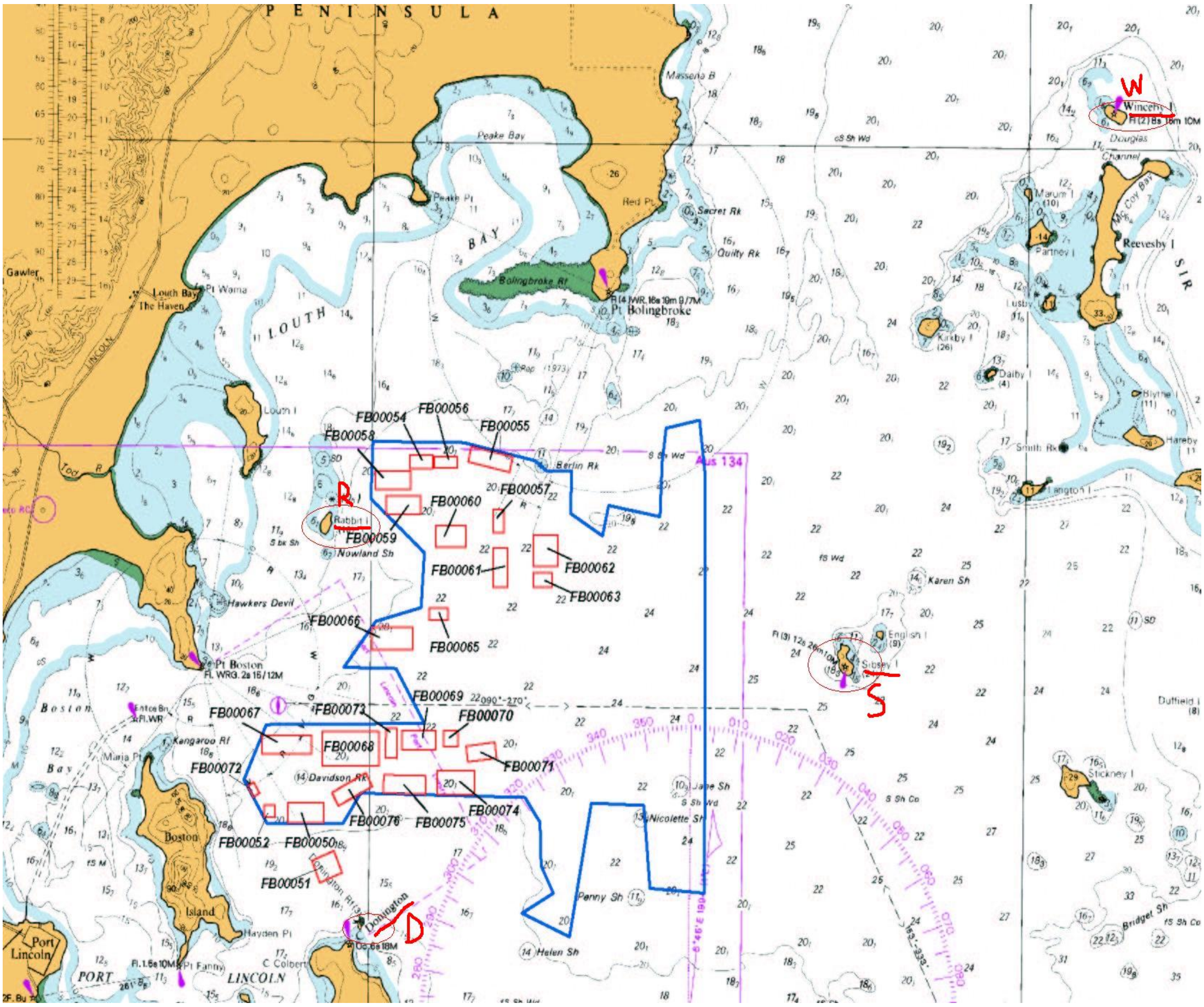

Figure 5.1: **A map of the waters off Port Lincoln where the tuna leases (red rectangles) and the silver gull breeding colonies are situated (red ovals with red letters: R= Rabbit Island, D= Donington Island, S= Sibsey Island and W= Winceby Island) (map obtained from PIRSA Aquaculture).**

5.6.1 Counting The Seabirds

The numbers of each seabird species at the tuna farms, the islands and the mainland was required for each part of the study. Seabird numbers were either directly counted or estimated.

5.6.1.1 Direct Counting

When there were few seabirds present or they were stationary for a prolonged period they were counted using a hand held counter.

5.6.1.2 Estimation

When there were many seabirds (such as at the refuse depot) or they were very mobile (such as feeding at tuna cages) their numbers were estimated. The number of birds in a manageable proportion of the flock was counted and this count could then be extrapolated to the whole flock to obtain a good estimate of the total number. Estimates were checked by counting the number of seabirds in digital photographs and it was found that with practice the estimate was within about 5% of the actual number of birds in the flock.

5.6.2 Bird Banding

Breeding silver gulls (300) were individually banded at the main breeding colony on Sibsey Island on July 1-3, 2003 (Figure 5.1) to assess whether these birds were accessing the study farms and whether they foraged in Port Lincoln after the tuna season had finished.

A clap net or book net (designed by Mike Young ex NPWS; Davis, 1981) was set up near the eastern outer perimeter of the breeding colony. These traps are most effective when the area is pre-baited for several days, but this was not possible because of time and accessibility constraints. The trap consists of a 10m x 4m net powered by shock cords that when released carried the net over birds in the trapping area (Figure 5.2). The trap was released using a 50 m trigger string that was pulled by someone hidden from the birds. Gulls were attracted to the trap area with baitfish and once enough were present, the trap was triggered, trapping the birds (Figure 5.3).

Trapped gulls were retrieved one at a time and handed to a bander. Each gull was permanently marked with a size 8 stainless steel band on the left leg using banding pliers. Gulls were also individually marked with plastic colour bands so they could be identified at a distance. A location code colour was place above the stainless steel band on the left leg to indicate these gulls were banded on Sibsey Island. A combination of the two coloured bands on the right leg individually identified each gull. Thus, each banded gull could be individually identified in the hand by its stainless steel band number and at a distance by its combination of colour bands.

All the information including stainless steel band number, colour combination, life stage (adult or juvenile), and date banded were recorded for each banded gull. The banding was under the supervision of a licensed bander (Jeremy Robertson, ABBBS permit number 2257) with a trapping permit issued by NPWS and ethics approval from Flinders University.

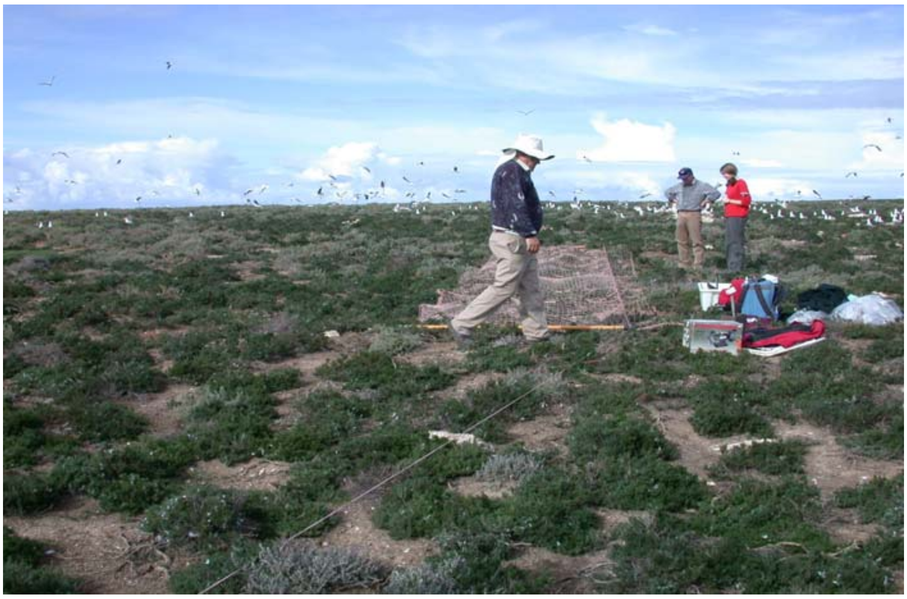

Figure 5.2:**The set book net trap.**

Figure 5.3: **The book net trap after it had been triggered with silver gulls underneath it.**

5.7 Statistical Analysis

Data were analysed with SPSS and Microsoft Excel. All data were examined for homogeneity and normality, and if the data were not found to be either, suitable transformations were made. If the data could not be suitably transformed, a non-parametric test was used. A one-way ANOVA was used for comparisons of the means between several independent groups, and a Mann-Whitney U Test for non-parametric data such as percentages. Bonferroni post hoc tests were performed to analyse multiple comparisons. Two-way ANOVA was used to analyse the multi-factor observational data. Differences between means were considered to be significant at α=0.05. While time of day could have important implications for the number of birds present, it was not considered in the analyses, thus increasing the variability and decreasing the power of the tests.

The boxplots, show the data as box and lines that represent the range. The lower edge of the box represents the lower quartile and the upper edge the upper quartile such that 50% of the data lies in the box, the horizontal line represents the sample median.

5.8 Seabirds at the Tuna Farms

5.8.1 Introduction

Although it is well known that seabirds scavenge feed at aquaculture farms (Furness, 1996; Glahn *et al.,* 1999; Price & Nickum, 1995) this is the first study of their behaviour at tuna farms. It seemed likely that the scavenging behaviour and success rate of the seabirds would vary with the method of delivering feed to the tuna and with the type of food.

5.8.1.1 Methods of Feeding Employed at the study farm

Staff at the study farm fed eight of their seacages with baitfish and six with pellets in 2003. Tuna were fed twice a day and each feed boat distributed either baitfish or pellets, but rarely both. They distributed approximately half of the baitfish into the tuna cages by shovelling (Figure 5.4) and the other half as enclosed floating frozen blocks (~25kg each) that slowly thaw releasing baitfish underwater (Figure 5.5). The pellets were either shovelled or distributed pneumatically, however, my observations only included baitfish and pneumatically distributed pellets. The pellets were placed into a hopper, then sucked from the hopper, through an upright PVC pipe that is moved from side to side to distribute the pellets evenly (Figure 5.6). In addition, in one experimental seacage, tuna were mainly pneumatically fed pellets, but also had a small amount of pneumatically delivered baitfish. Therefore, the pneumatic distribution of baitfish was also observed, though this is not common practice in the tuna industry.

Figure 5.4: **Distributing baitfish by shovelling.**

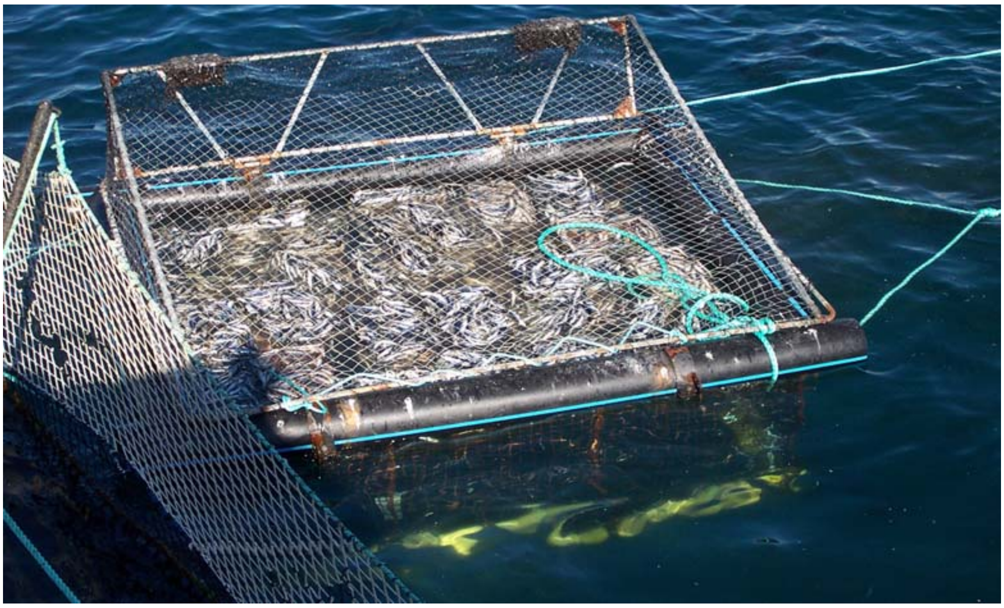

Figure 5.5: **Distributing baitfish by enclosed frozen blocks in a feed cage. Note the blocks are inaccessible from above.**

Figure 5.6: **The PVC pipe that evenly distributes pellets to tuna seacages.**

5.8.2 Materials And Methods

5.8.2.1 Observations

There were two types of observations made on the tuna farms; the number of individual pieces of feed taken by each seabird species (per shovel load or during a one minute observation) and the numbers of each species of seabird present at the farm.

5.8.2.1.1Seabird Numbers

Seabird numbers were recorded each time I visited baitfish and pellet fed seacages. Seabirds were counted inside and outside the seacages, where inside was defined as any bird hovering above the cage, sitting on the water within the cage or swooping and feeding in the seacage. Those counted as outside were defined as any settled seabird within 100-200 m of the seacage.

Feed Method	Date Observed
Shovelled Baitfish	22/5/03, 29/5/03, 19/6/03, 17/7/03, 14/8/03
Frozen Block	29/5/03, 19/6/03, 17/7/03
Pellet	24/6/03, 10/7/03, 14/8/03
Pneumatic Baitfish	24/6/03, 10/7/03

5.8.2.1.2 Amount of Feed Consumed by Seabirds

For shovelled baitfish, the amount consumed by seabirds was estimated by recording the number of baitfish consumed by each species for randomly selected shovelling events. The number of shovel loads required to feed out the total weight of baitfish was recorded for each seacage, as was the weight of shovelled baitfish distributed to the farms. The number of baitfish in a shovel load was also recorded, by randomly collecting a shovel load and counting the number of baitfish per shovel load. This counting of baitfish in shovel loads was performed three to five times for each cage observed during this study. The number of random shovelling events counted per seacage was 30-70 and the average number of baitfish taken per cage was calculated from these observations. Between three and eight cages were observed per day, and each cage was fed between 1 and 3 times per day.

For pneumatically distributed pellets and baitfish, the amount consumed was estimated by recording the number of pellets or baitfish scavenged by each species of seabird for randomly selected one minute intervals. The amount of time it took to feed out the pellets or baitfish and the weight of each feed type distributed to the seacage were also recorded. Approximately 3 one minute intervals were observed per cage, with an average number of baitfish taken per minute calculated from these observations. Three to eight cages were observed per day.

The number of baitfish consumed by seabirds for the frozen block methods was also estimated using the number of baitfish consumed by each seabird species during one minute intervals. The weight of frozen block placed into each cage was also recorded. The number of one minute intervals observed for each cage with this feeding method was one to three. Six to eight cages were observed for 1-3 one-minute intervals, the observations being repeated once per day.

In order to estimate the total weight of either baitfish or pellets that were consumed by seabirds, two samples of 200 pellets and 300 baitfish were weighed, to get an average weight for each feed type. This assumes that these samples are typical of the feed type used throughout the study, which is probably true for manufactured pellets, but may not be for baitfish, which can vary in size and species throughout the farming season.

From these data, the total weight of each feed type consumed for each seacage could be estimated. This could also be compared to the total amount of feed distributed at the seacages to calculate for each feed type the percentage consumed by all seabirds and for each species.

It was necessary to calculate both the weight and percentage of feed consumed by seabirds because tuna require more baitfish than pellets to obtain the same growth (PIRSA, 2000). The weight of feed distributed by each method also differed, so the percentage of the total feed that was consumed was the only common ground.

Data here and in other sections are presented as box and whisker plots. The main box represents 50% of the data values (1st and 3rd quartiles), with the median indicated by a solid line. The whiskers indicate the entire range of the data.

5.8.2.2 Other Seabird Species

Several seabird species other than those described in the results were observed in the study tuna lease. These included black-faced cormorants, pied cormorants, skuas, Australian gannets and giant petrels. However, these species were never observed taking any tuna feed and their numbers were insignificant. Both species of cormorants were occasionally seen inside tuna cages, however, they were never observed consuming tuna feed, though I was unable to observe whether they were feeding underwater.

5.8.2.3 Aims

- To determine how much tuna feed was consumed by the seabirds at both baitfish and pellet farms.
- To assess any preference by seabirds for baitfish or pellet feed.
- To determine what species of seabird consume the most feed of each type.
- To determine the number of seabirds of each species at the tuna seacages.
- To assess different feeding methods and find a 'best practice' for tuna farmers.
- To determine if there is any seasonal or spatial patterns in both feed consumption and seabird numbers at the seacages.
- To determine if there is any variation between cages in both feed consumption or seabird numbers.

5.8.2.4 Hypotheses To Be Tested

- Silver gulls are the most abundant seabirds at the tuna farms.
- More baitfish are consumed than pellets.

- Seabirds will consume fewer baitfish from frozen blocks.
- Silver gulls will consume more tuna feed than other seabirds.

5.8.3 Results

5.8.3.1 Consumption of Feed at Baitfish vs. Pellet Cages

The aim of these surveys was to assess the amount of feed consumed by all seabirds present at seacages feeding tuna with either shovelled baitfish, pneumatically delivered pellets or baitfish, or frozen blocks of baitfish.

Feed consumed by seabirds at tuna seacages was expressed in two ways: (1) the calculated weight consumed (kg) and (2) the percentage of total feed consumed by birds. Both approaches were used because more baitfish were fed to the tuna than pellet feed due to the higher food conversion ratio of baitfish (i.e. baitfish are ~ 70% water, whereas pellets are ~40% water). Table 5.1 summarises the mean percentage of total feed consumed by seabirds and clearly much more baitfish was consumed than pellets. This difference was found to be statistically significant (Figure 5.7).

Table 5.1: **Descriptive statistics for percentage of feed consumed by seabirds at pellet and baitfish fed tuna seacages.**

% of Feed Consumed	Baitfish Cages	Pellet Cages
Mean	2.28	0.97
Median	1.98	0.77
Standard Deviation	1.40	0.73
Maximum	5.12	2.60
Minimum	0.23	0.01
N	21	24

Seabirds also consumed a much higher average weight of baitfish than pellets, which was found to be statistically significant (Figure 5.8).

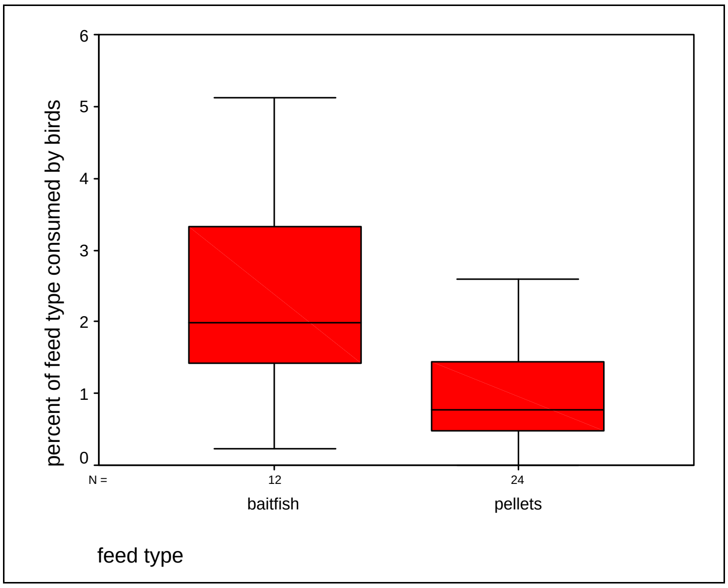

Figure 5.7: **A comparison of average percent of baitfish (50:50 shovelled:frozen) and pellets consumed by all seabirds at the subject tuna seacages ($F_{1, 34}$ = 13.7, p<0.001).**

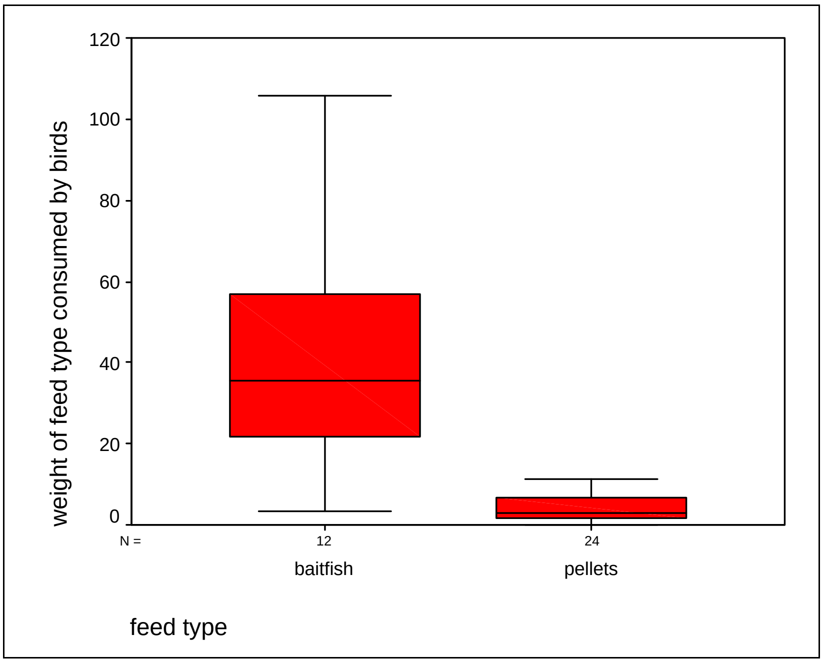

Figure 5.8: **A comparison of the average weight (in kg) of baitfish (50:50 shovelled:frozen) and pellets consumed by all seabirds at the subject tuna seacages ($F_{1, 34}$ = 39.7, $p<0.001$).**

5.8.3.1.1 Consumption of Different Feed Types by Seabirds

The aim of these observations was to determine the proportion of baitfish and pellets consumed by the different species of seabirds. This was examined by determining the amount of feed taken by each bird species for the feed types delivered the most common way (shovelled and frozen baitfish and pneumatically delivered pellets) on the study farms.

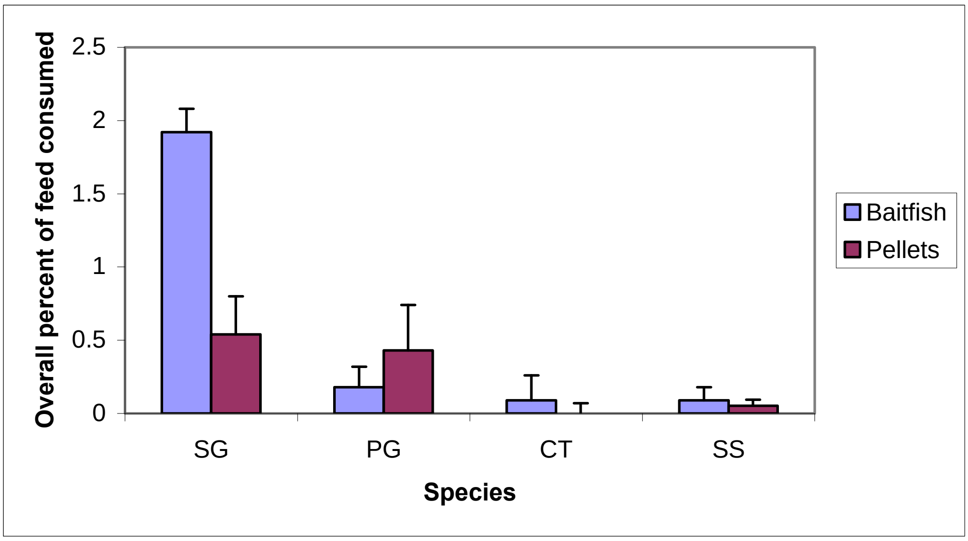

Figure 5.9: **Average percentage (± sd) of baitfish and pellets consumed by each seabird species at the subject tuna seacages over the whole season (SG= silver gull, PG= Pacific gull, CT= crested tern, SS= short-tailed shearwater) (All bird species $F_{1, 23}$ = 3.87, $p<0.05$) (silver gulls only $F_{1, 23}$ = 8.2, $p<0.01$).**

Silver gulls consumed a significantly larger percentage and weight of baitfish than any of the other seabird species (Figure 5.9 and 5.10). They also consumed a significantly larger proportion of baitfish feed than pellet feed. Pacific gulls consumed the second largest amount of tuna feed but they consumed a larger proportion of pellets than baitfish. Short-tailed shearwaters and crested terns consumed a small proportion of baitfish, however, crested terns did not consume any pellet feed and consumed an extremely small proportion of baitfish (Figure 5.9 and 5.10).

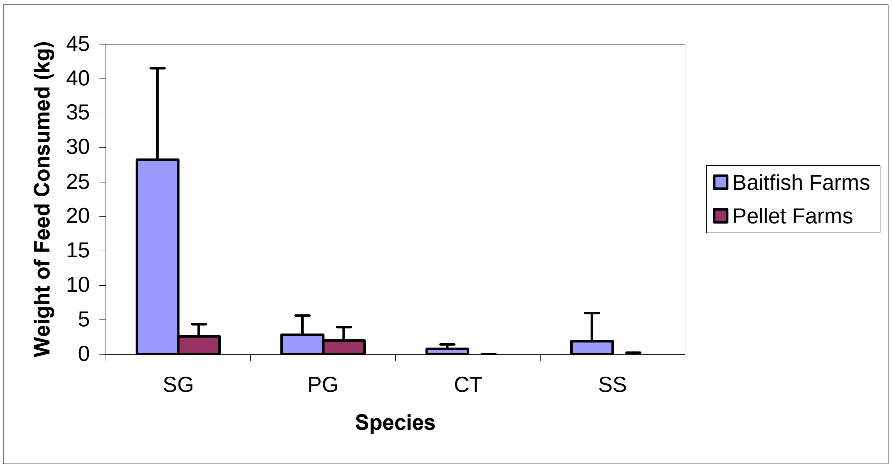

Figure 5.10: **Average (± sd) weight (kg) of baitfish and pellets consumed by seabirds at the subject tuna seacages over the whole season (SG= silver gull, PG= Pacific gull, CT= crested tern, SS= short-tailed shearwater) (All bird species $F_{1, 23}$ = 1.31, NS) (silver gulls only $F_{1, 23}$ = 63.6, p<0.001).**

5.8.3.2 Preference for Baitfish or Pellets

The aim of this comparison was to assess whether the seabirds exhibited a preference for a feed type, when both baitfish and pellets were pneumatically distributed together. The mean percentage of feed distributed of both types that was consumed by the seabirds was much higher for the baitfish than for the pellets (Figure 5.1). These percentage data are the most appropriate data for comparing baitfish and pellets as different amounts of each were fed at the seacage.

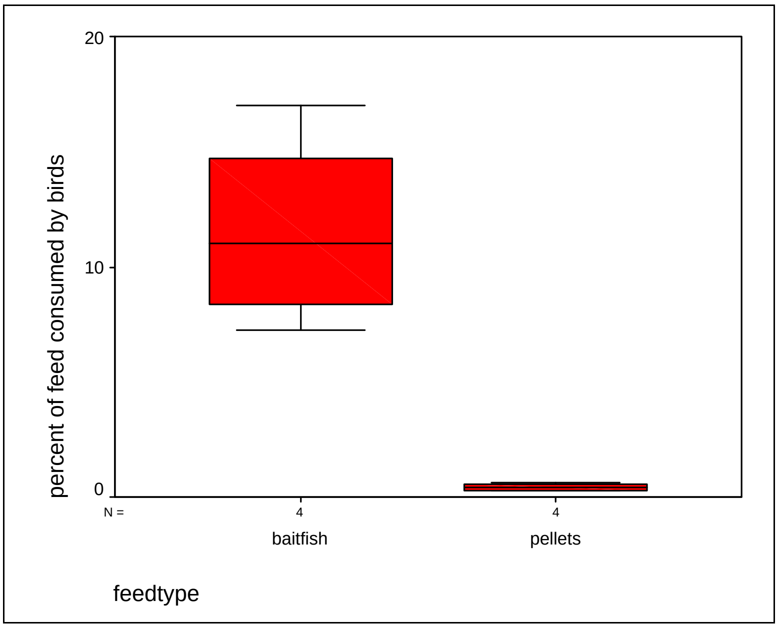

Figure 5.11: **A comparison of the amount of feed (as % of the total) consumed by seabirds when the pneumatic feeding method was used to dispense baitfish and pellets (Mann-Whitney U; $p<0.05$).**

5.8.3.3 Effect of Feed Distribution Method on Consumption by Seabirds

The aim of this comparison was to determine the effect of different feeding methods on the consumption of feed by seabirds. Comparing the different feeding methods will identify the most effective way of reducing or eliminating feed consumption by seabirds.

The percentage of feed consumed by seabirds varied considerably depending on the feeding method, with pneumatically distributed baitfish being the highest (11.56%), and frozen baitfish blocks being the lowest (0%). Shovelling baitfish had the second highest consumption (5.3%), followed by pneumatically distributed pellets (0.97%) (Figure 5.2). No other pellet feeding method was observed, so there is no other technique to compare this to.

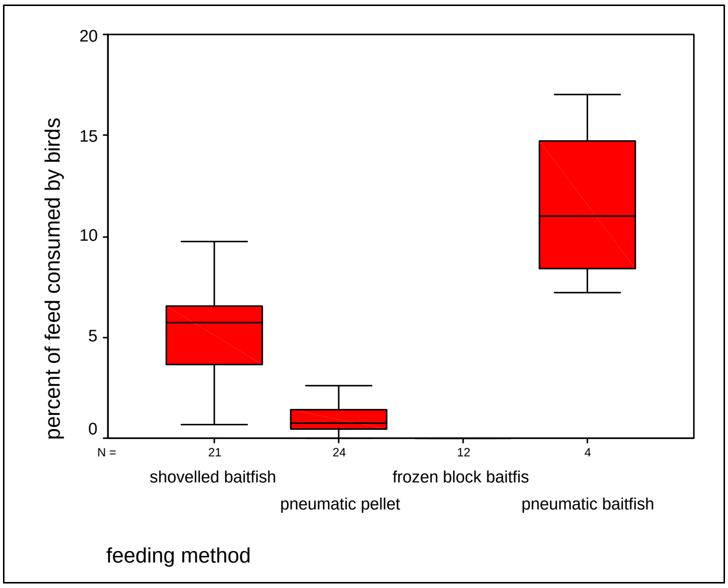

Figure 5.12: **A comparison of the percentage of feed consumed by seabirds for different feeding techniques ($F_{1,57}$ = 92.37, p<0.001).**

5.8.3.4 Seabird Numbers at Baitfish and Pellet Seacages

The aim of this survey was to assess whether there was a difference in seabird numbers at the seacages fed either baitfish or pellets.

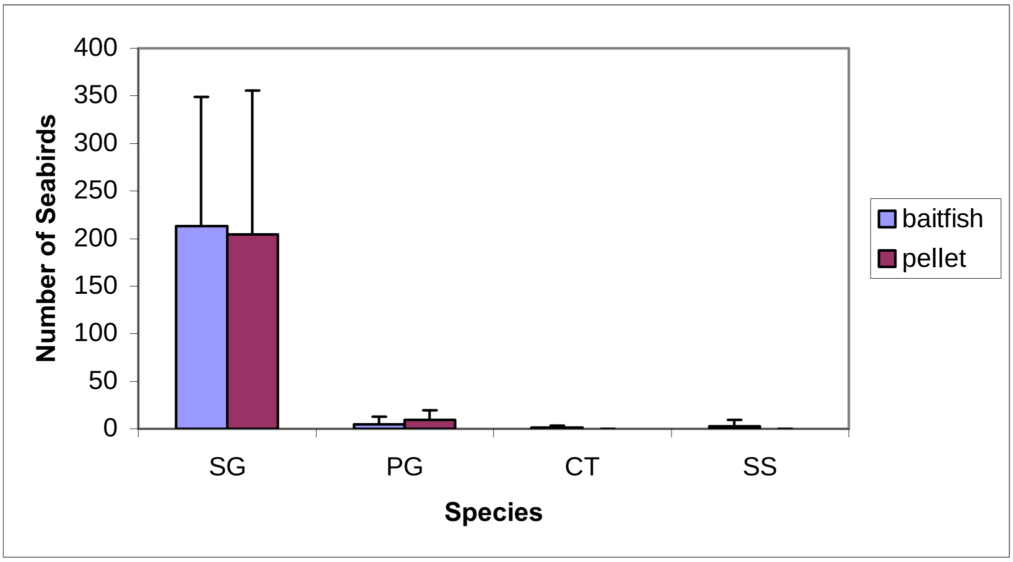

Figure 5.14: **Mean (± sd) seabird numbers feeding at both baitfish and pellet cages for the season. (SG= silver gull, PG= Pacific gull, CT= crested tern, SS= short-tailed shearwater). Effect of feed type ($F_{1,1}$ = 4.2, p <0.05). Effect of species ($F_{1,3}$= 100.9, p <0.001).**

Silver gulls were the most abundant species at both types of seacages, both feeding inside the seacage and outside the seacage (Figure 5.). There was a slightly larger number of silver gulls observed feeding at baitfish seacages compared to pellet seacages (average 213 compared to 204, Figure 5.14). However, silver gulls were more numerous outside pellet fed seacages (average 407) than baitfish-fed seacages (average 252) (Figure 5.15). Pacific gulls were more numerous inside and outside pellet-fed seacages (average 9) than baitfish-fed seacages (average 5). There were significantly more Pacific gulls outside pellet-fed seacages (average 70) than baitfish-fed seacages (average 37). Short-tailed shearwaters were rarely observed inside pellet-fed or baitfish-fed seacages (average 2), however, they were in significantly greater numbers outside both types of seacage (average 60-70). Crested tern numbers were extremely small both inside and outside at baitfish and pellet seacages. There was no statistical analysis on crested terns because of the small numbers.

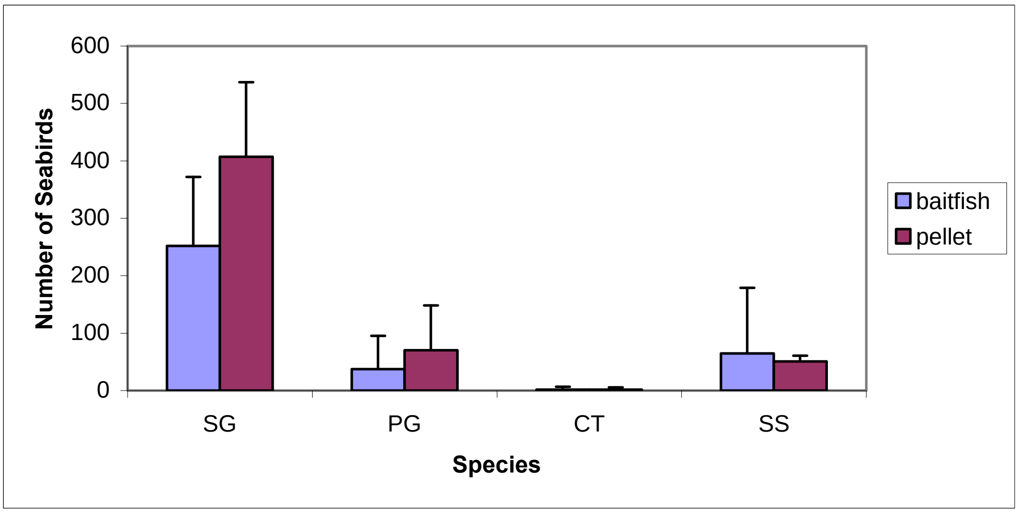

Figure 5.15: **Mean (± sd) seabird numbers outside baitfish and pellet seacages for the season. (SG= silver gull, PG= Pacific gull, CT= crested tern, SS= short-tailed shearwater). Effect of feed type ($F_{1,3}$ = 1.4, p = 0.255, NS).**

5.8.3.5 Seasonal Differences

The aim of these observations was to determine if there was a seasonal pattern in the feed consumption or seabird numbers.

5.8.3.5.1 Feed Consumption – Pellet Seacages

The mean percentage of feed consumed at pellet seacages tended to increase over the tuna season (Figure 5.16), however, the mean weight of feed consumed did not (Figure 5.17). In neither case were the differences statistically significant.

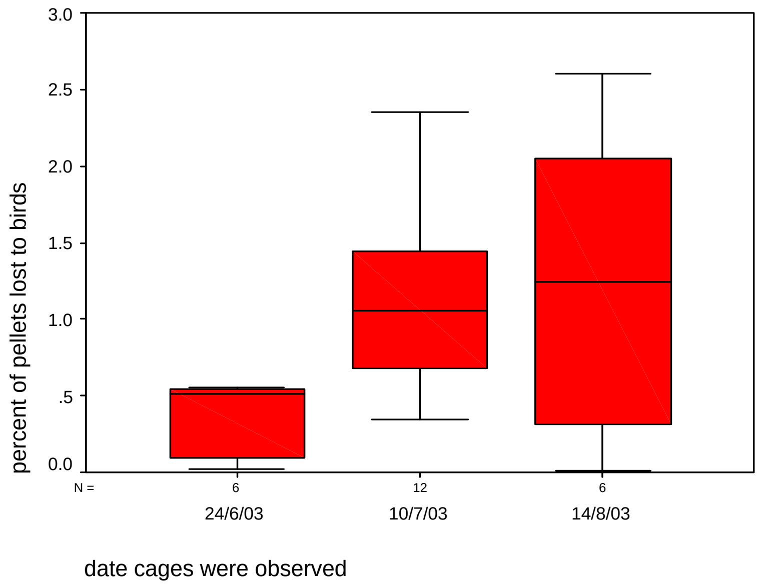

Figure 5.16: **A comparison of the percentage of pellets consumed by seabirds at pellet fed seacages over the tuna season ($F_{2, 21}$ = 3.2, p = 0.060, NS).**

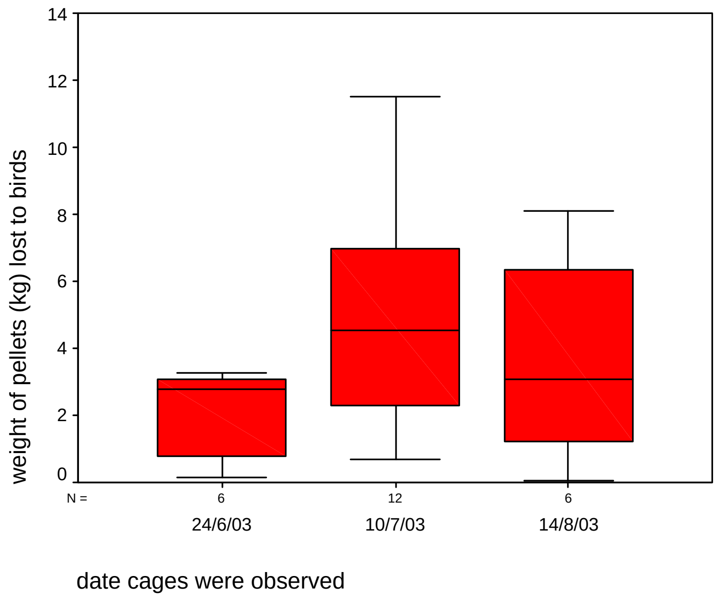

Figure 5.17: **A comparison of the weight of pellets consumed by seabirds at pellet fed seacages over the tuna season ($F_{2, 21}$ = 1.8, p = 0.19, NS).**

5.8.3.5.2 Feed Consumption - Baitfish Seacages

Both the mean percent and weight of feed consumed by seabirds did not change significantly over the season (Figure 5.18 & 5.19).

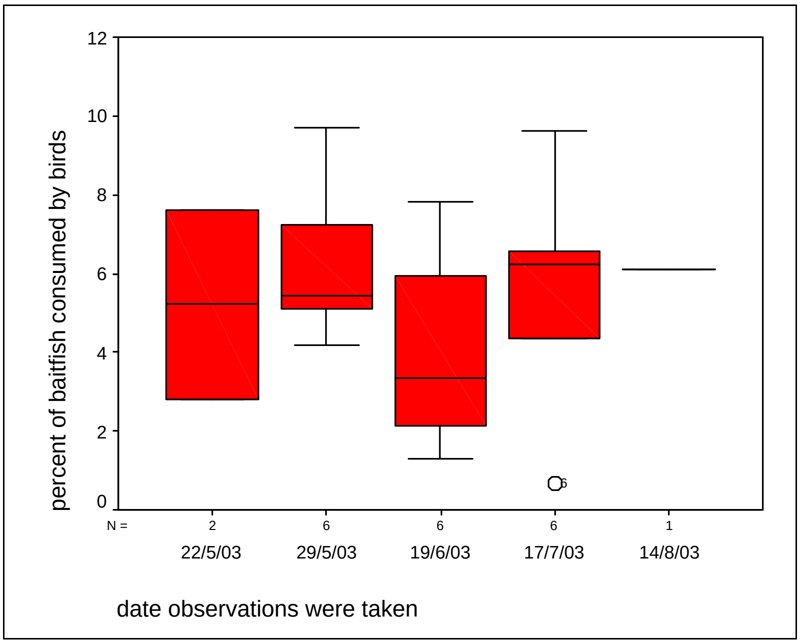

Figure 5.18: **A comparison of the percentage of feed consumed by seabirds at baitfish seacages over the tuna season ($F_{4, 16}$ = 0.62, p = 0.65, NS).**

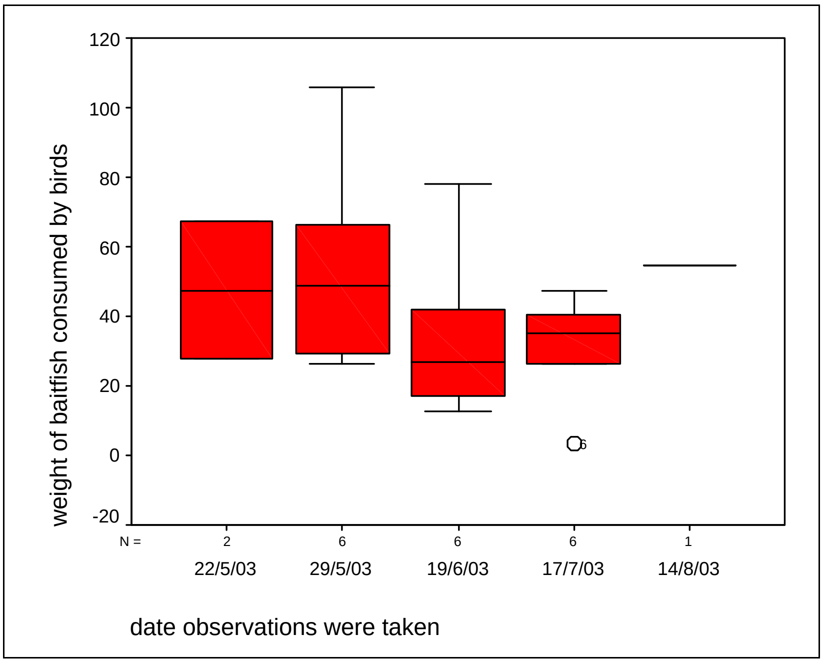

Figure 5.19: **A comparison of the weight of baitfish consumed by seabirds at baitfish fed seacages over the tuna season ($F_{4,16}$ = 0.96, p = 0.46, NS).**

5.8.3.5.3 Number of Seabirds and their Spatial Distribution at the Tuna Seacages

There was a rise in numbers of feeding silver gulls from May to mid-June, followed by a decline at the end of June. The numbers then rose again in mid-July, before decreasing at the end of July and plateauing from the end of July to mid-August. These changes were found to be significant (Figure 5.0). Silver gull numbers outside the cages increased until early July, where they decreased in late July and then slightly increased to August. The numbers of silver gulls inside the cage over the season were significantly less than the numbers outside the cage over the season.

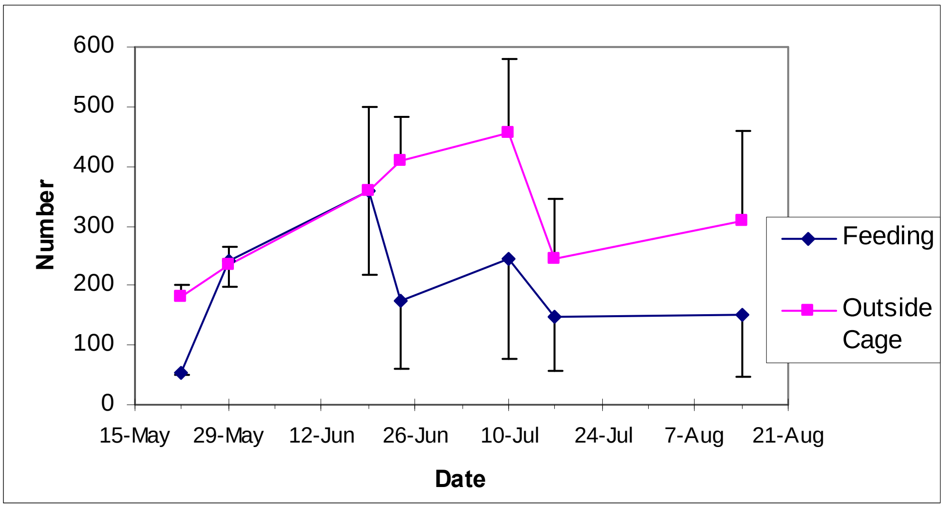

Figure 5.20: **Mean number (± sd) of silver gulls at the tuna seacages over the season. Comparison of feeding and outside gull numbers ($F_{1,1}$ = 16.2, p = <0.001). Effect of date ($F_{1,6}$ = 4.6, p <0.001).**

The number of Pacific gulls feeding inside the tuna seacages was relatively constant over the season (Figure 5.1). Pacific gull numbers outside the cages were highest in late May, then decreased in mid-June and then increased in early July and plateaued from mid-July onwards. There were significantly larger numbers of Pacific gulls outside the cage over the season than inside and feeding.

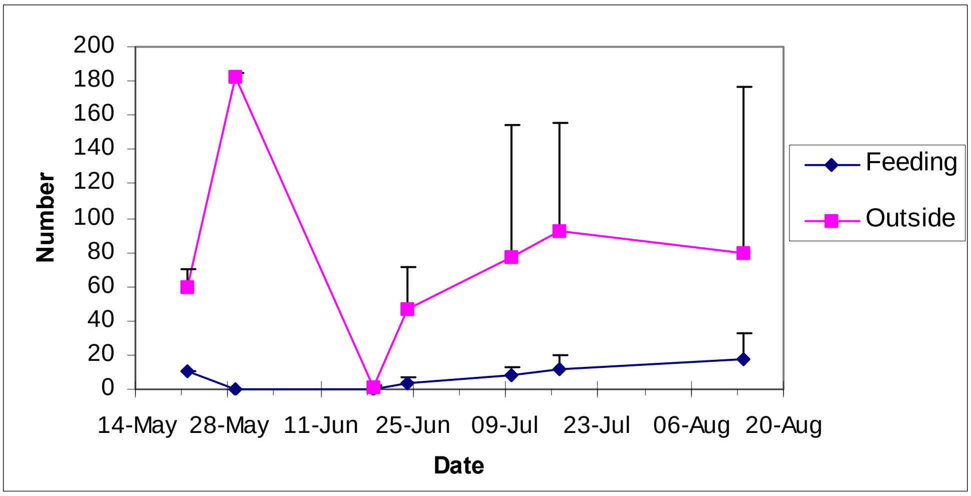

Figure 5.21**: Mean (± sd) number of Pacific gulls at the tuna seacages over the season. Comparison of feeding and outside gull numbers ($F_{1,6}$ = 0.0, p = 1.0, NS). Effect of date ($F_{1,6}$ = 5.05, p <0.001).**

Short-tailed shearwater numbers outside the cage were decreasing in late May, consistently low until mid-July, and then increased from mid-July onwards. They were always in very low numbers inside the cage (Figure 5.22). However, there were insufficient data to analyse the differences statistically.

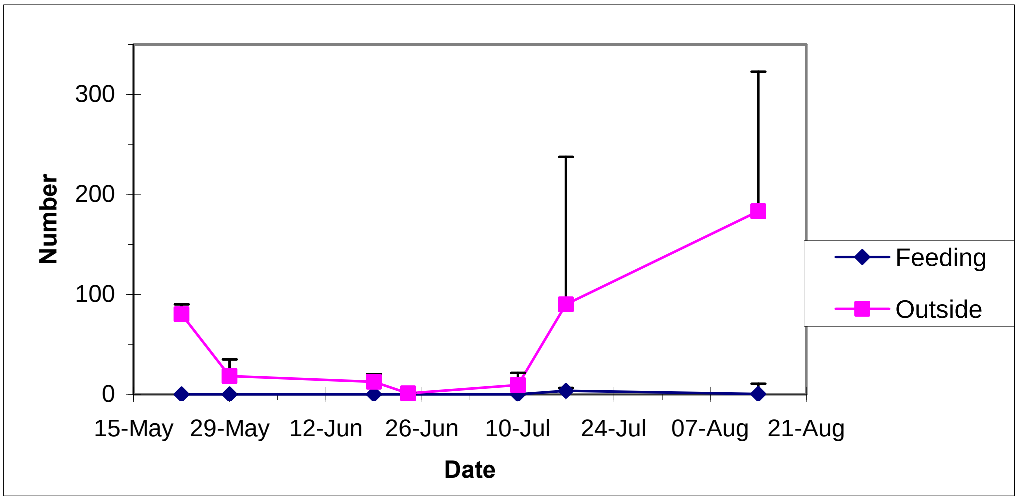

Figure 5.22: **Mean (± sd) number of short-tailed shearwaters at the tuna seacages over the season.**

Crested tern numbers were consistently low both inside and outside the tuna seacages (Figure 5.23). There were insufficient data to analyse them statistically.

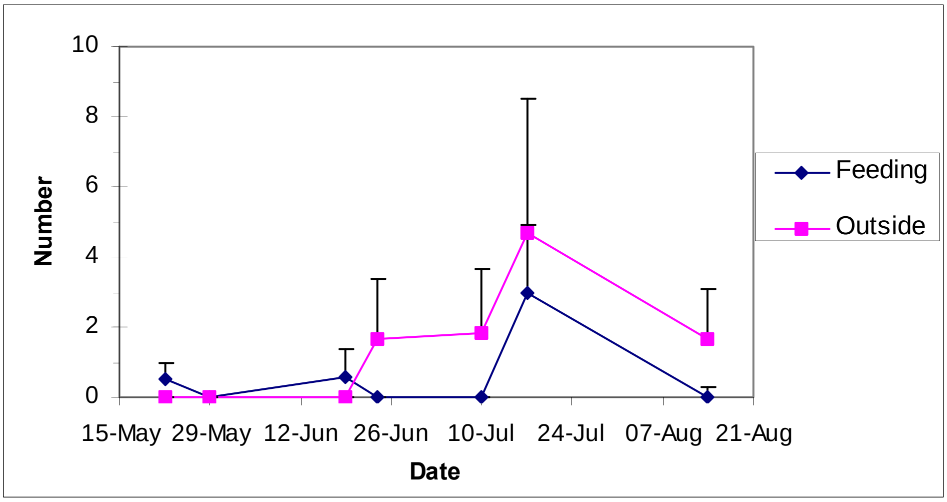

Figure 5.23: **Mean (± sd) number of crested terns at the tuna seacages over the season.**

5.8.3.6 Differences Between Seacages

5.8.3.6.1 Baitfish - Amount of Feed Consumed

Both the mean percent and mean weight of baitfish consumed by seabirds varied by a factor of less than 2 for baitfish fed seacages (Figure 5.24 & 5.25). Therefore, there was no significant spatial difference in feed consumption for baitfish seacages.

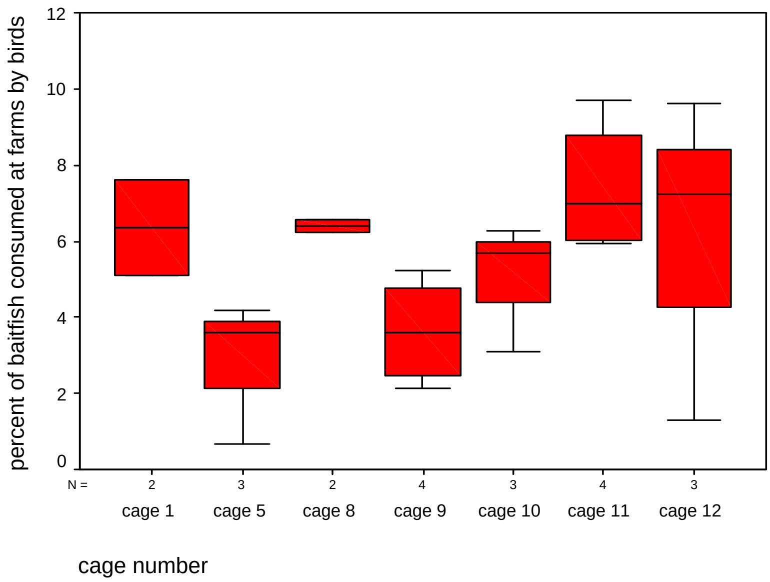

Figure 5.24: **A comparison of the percentage of baitfish consumed by seabirds at each baitfish-fed farm observed ($F_{6, 14}$= 0.161, p = 0.652, NS).**

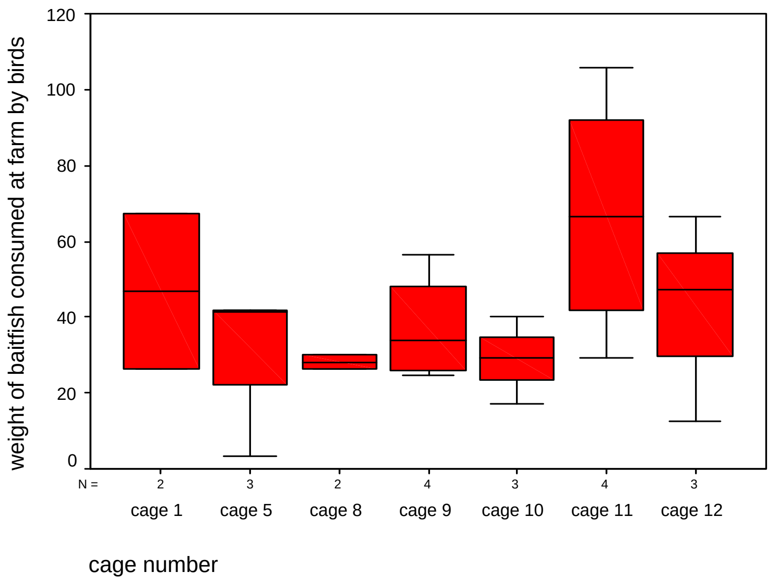

Figure 5.25: **A comparison of the weight of baitfish (kg) consumed by seabirds at each baitfish-fed farm observed ($F_{6, 14}$= 1.3, p= 0.331, NS).**

5.8.3.6.2 Pellets – Amount of Feed Consumed

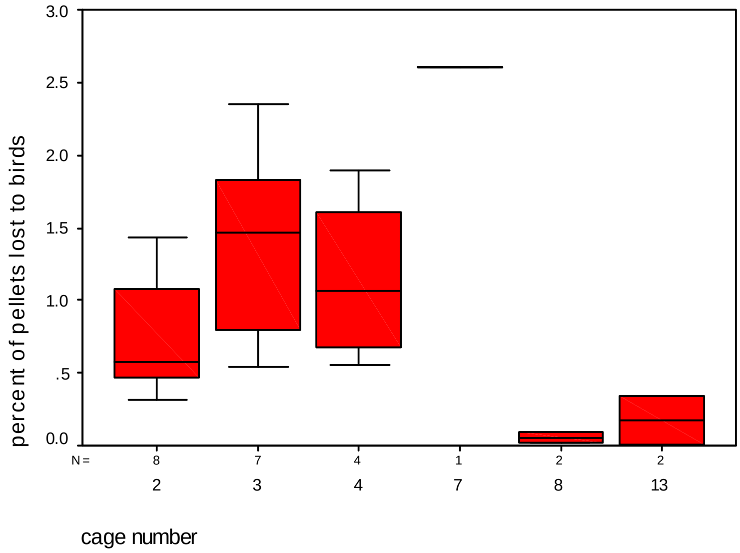

Figure 5.26: **A comparison of the percentage of pellets lost to seabirds at each pellet fed farm observed ($F_{5, 18}$= 5.1, p <0.01).**

The average percentage of pellets consumed by seabirds was significantly different between the six pellet-fed seacages (Figure 5.26). Seacage 7 had the highest feed consumption and seacages 3 and 4 also had a relatively high percentage of feed taken. Seacages 2, 8 and 13 all had a relatively small amount of feed consumed. However, the weight of feed consumed at these seacages was not significantly different (Figure 5.27).

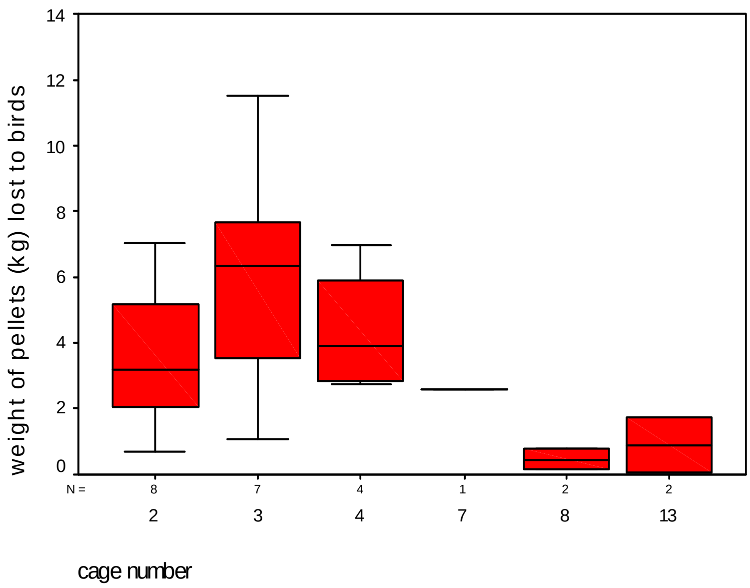

Figure 5.27**: A comparison of the weight of pellets lost to seabirds at each pellet-fed cage observed ($F_{5, 18}$ = 2.1, p = 0.107).**

5.8.3.6.3 Seabird Numbers at Different Seacages

Feeding silver gull numbers were high at seacages 3 (pellet), 5 and 10 (both baitfish). They were moderate at seacages 1, 2, 4, 8, 13 (pellet) and 9, 11, 12 (baitfish) and low at seacage 7 (pellet) (Figure 5.28). Silver gull numbers outside the cage were highest at seacage 4, and also high at seacage 3 (both pellet), and were relatively similar for the rest of the seacages. While the difference in number between seacages and the difference between baitfish and pellet fed seacages was not found to be significantly different, the difference in number between feeding silver gulls and those outside was significant. There was therefore overall a significantly larger number of silver gulls outside the seacages than inside.

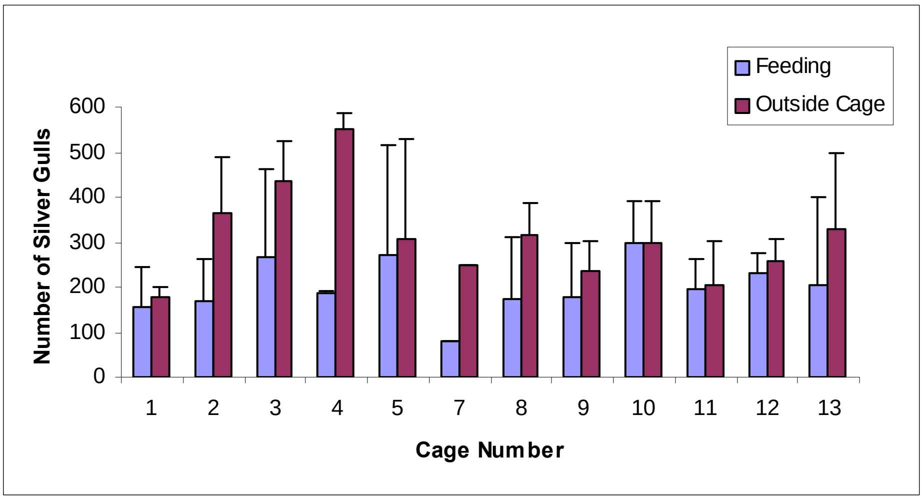

Figure 5.28: **Mean (± sd) number of silver gulls at each tuna seacage in the study lease. (Pellet cages= 1, 2, 3, 4, 7, 8, 13; Baitfish cages= 5, 8, 10, 11, 12, 13). Effect of feed type ($F_{1, 1}$ = 223.6, p = 0.412, NS), effect of location (inside or outside seacage) ($F_{1, 1}$ = 11.07, p < 0.001), effect of cage number ($F_{1, 11}$ = 0.962, p = 0.489, NS).**

Feeding Pacific gull numbers were relatively constant between seacages (Figure 5.29). The numbers outside of the cages were highest at seacages 2, 3, 4, (pellet) and 10 (baitfish), and relatively invariable for other seacages, except seacage 5, where their numbers were very low. While, feed type and cage number were not found to significantly influence the number of Pacific gulls, the location of the Pacific gulls (inside or outside the seacage) did significantly influence their numbers. There was therefore a significantly larger number of Pacific gulls outside the seacage than inside.

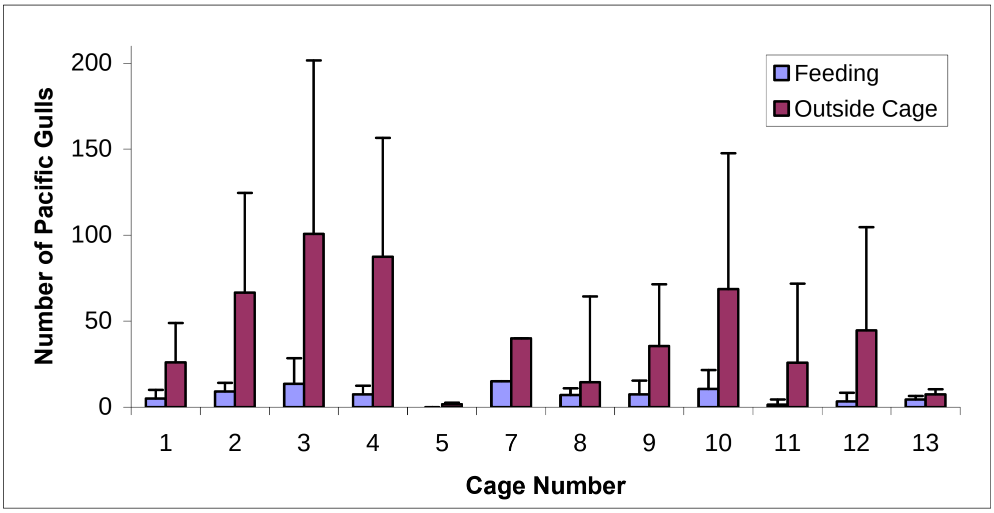

Figure 5.29: **Mean (± sd)number of Pacific gulls at each tuna seacage in the study lease. (Pellet cages= 1, 2, 3, 4, 7, 8, 13; Baitfish cages= 5, 8, 10, 11, 12, 13). Effect of feed type ($F_{1, 1}$=0.755, p = 0.390, NS), effect of location (inside or outside seacage) ($F_{1, 1}$=12.6, p <0.001), effect of cage number ($F_{1, 11}$ = 1.29, p = 0.262, NS).**

Short-tailed shearwaters had large numbers outside the seacages, but they were rarely ever observed inside the cages. There were similar numbers feeding at all seacages (Figure 5.0). Their numbers outside the seacages were highest for cages 5, 7 (pellet), 11 (baitfish) and 13 (baitfish and pellet). However, there were insufficient data to analyse these differences.

Feeding crested tern numbers were highest at the baitfish seacages (9, 10, 11). Their numbers outside the tuna seacages were highest at cage 13 (pellet and baitfish) (Figure 5.1). There were insufficient data to analyse these differences. Nonetheless, the number of crested terns in the tuna lease was very small compared to the other three bird species.

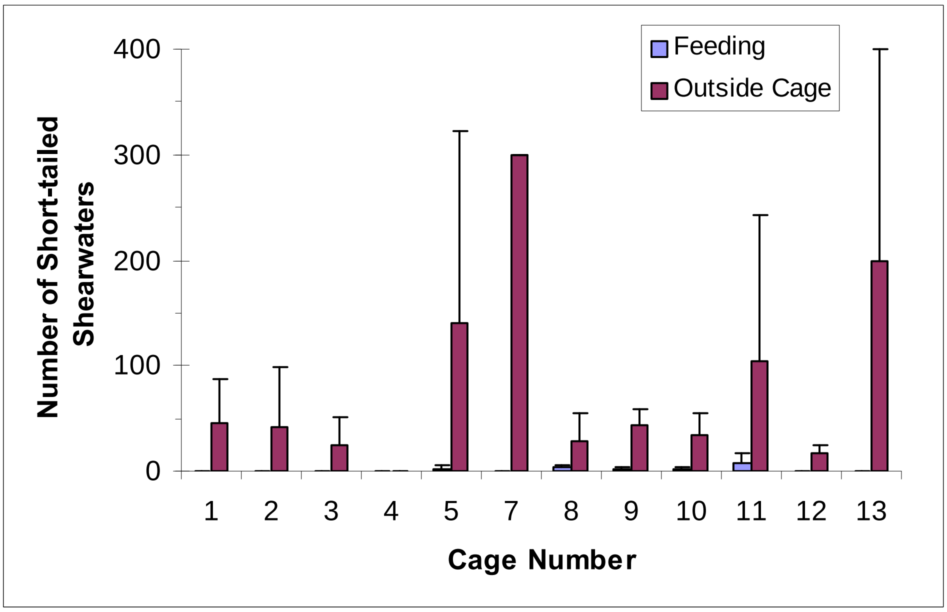

Figure 5.30: **Mean (± sd) number of short-tailed shearwaters at each tuna seacage in the study lease (Pellet cages= 1, 2, 3, 4, 7, 8, 13; Baitfish cages= 5, 8, 10, 11, 12, 13).**

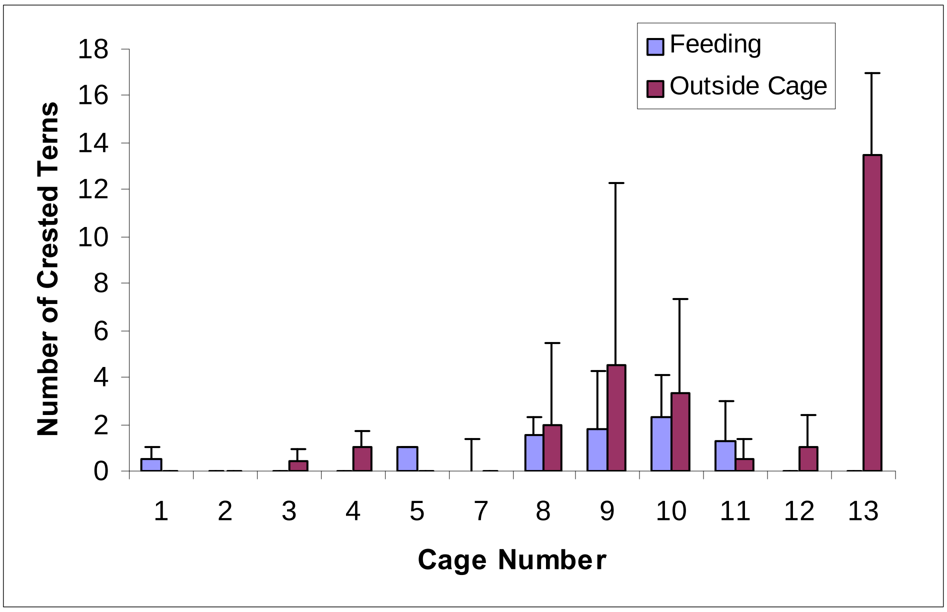

Figure 5.31: **Mean (± sd) number of crested terns at each tuna seacage in the study lease (Pellet cages= 1, 2, 3, 4, 7, 8, 13; Baitfish cages= 5, 8, 10, 11, 12, 13).**

5.8.3.7 Economic Cost to the Industry

The owners of the study farm own approximately 7% (David Ellis TBOASA, pers. comm.) of the tuna quota. They therefore feed out approximately 7% of the 50,000 tonnes of tuna feed (baitfish and pellets), which is approximately 3,500 tonnes. From the data presented here, approximately 2% (assuming 2/3 of the feed is baitfish (2.3% consumed) and 1/3 is pellets (1% consumed)) of this 3,500 tonnes of tuna feed was consumed by seabirds in 2003, which is around 70 tonnes. If it is assumed that tuna feed cost around $1000 a tonne that year, this loss equates to approximately a $70,000 economic loss per year to the owners of the study farm through feed consumption by seabirds.

5.8.4 Discussion

At the study farm, baitfish were fed using three methods and pellets with one. When the different feeding methods were compared, it was obvious that feeding frozen blocks was the best method (of those observed) to reduce feed consumption by seabirds as no feed was lost this way. However, pneumatically distributing baitfish resulted in a greater amount of this feed type being consumed (11.6%). Shovelling baitfish also resulted in a relatively large amount of baitfish being consumed (5.3%), but pneumatically distributing pellets resulted in only a 1% loss to seabirds. Feeding frozen blocks involves placing frozen 25 kg blocks of baitfish into a feed cage, which is inaccessible to the seabirds above. When the blocks thaw, baitfish are released underneath the water. This means that non-diving birds have no access to them, and it is hard for diving birds to see them from above as the feed cage is above the baitfish. Shovelled baitfish is highly visible to seabirds, as is the pneumatically distributed feed. The shovelled baitfish were also easy to access by birds as they usually floated for a short time once they hit the water. Pneumatically distributed baitfish were also easily accessible, but as the baitfish were distributed further across the seacage and they were distributed higher into the air, it probably made them even easier to access than the shovelled baitfish. Pneumatically distributed pellets were also easy to access and visualise by seabirds, however, they were not the preferred feed type by birds.

Overall, baitfish was consumed in a higher percentage and weight than pellets. This may have occurred as there was more baitfish available than pellets. However, when presented with both types of feed fed out by the same method simultaneously, a higher percentage of baitfish was eaten than pellets. Furthermore, assuming that baitfish is 70% water and pellets 40% water, the dry weight of baitfish consumed per farm (12.5 kg (30% of weight eaten)) was still larger than the dry weight of pellets consumed (2.31 kg (60% of what was eaten)). Therefore, baitfish were still consumed in a much larger proportion than pellets. This may be because seabirds prefer baitfish as it is closer to their 'natural' feed. Baitfish is also probably easier to swallow than pellets, being lubricated with the mucous layer that covers the surface of the fishes scales and skin and being about 70% water. On the other hand, pellets are quite large and dry (about 40% water), and are most likely hard to handle and swallow. Therefore, only the bigger birds would be able to successfully handle the pellet (in particular Pacific gulls).

Silver gulls were by far the most prevalent species at both farm types, having similar numbers feeding at seacages of both feed types. However, there were more silver gulls outside pellet-fed cages than baitfish-fed cages. This may have been because Pacific gulls were displacing the silver gulls from the pellet-fed cages, but this is not evident in the data. All species were more abundant outside the cages than feeding inside, probably as there is only limited space inside the seacage. However, short-tailed shearwaters were in unexpectedly high numbers outside the tuna cages and were hardly ever seen inside the seacages. This may be because these shearwaters were feeding on naturally occurring wild fish around the cages, that may have been attracted there due to excess tuna feed in the water. However, shearwaters were not present all the time, suggesting that they are not reliant on tuna farms and do forage for natural feed. They may only use the tuna farms as a feed source if other 'natural' feed is not in abundance.

Silver gulls were also the seabirds at the tuna seacages that consumed the largest amount of both feed types. They consumed approximately 85% of the baitfish and 55% of the pellets scavenged. Pacific gulls consumed approximately 45% of the pellets scavenged and 10% of the baitfish, even though their numbers were significantly smaller than silver gulls. Short-tailed shearwaters and crested terns consumed only small amounts of baitfish, and an even smaller amount of pellets.

There was an average of 400-600 silver gulls at each seacage at the study lease, and although some do follow the feed boat from cage to cage, there is only so much they can eat. There was also a 20-30 silver gull turnover per minute (counted from the study farms, but this also included silver gulls travelling to other tuna farms close by), and with an average feeding event taking around 20 minutes (pers. obsv.) (shovelling baitfish and distributing pellets) and 13 seacages being fed, twice a day, this means that there is around 520 minutes of feeding occurring each day at the study seacages. This equates to approximately 13,000 silver gulls frequenting the study tuna seacages, and nearby seacages, each day.

The results from this study indicate that a large proportion of the Port Lincoln silver gull population frequents the tuna farms and relies on them for a major feed resource. Pacific gulls are also present, but in smaller numbers. However, the amount consumed by these Pacific gulls is likely to have an influence on the reproductive output of these seabirds also. Further research is therefore required to analyse this, as the largest number of Pacific gulls seen at the study tuna seacages was 300. This is a substantial number of Pacific gulls to frequent one feeding place (Coulson & Coulson, 1998). Short-tailed shearwaters and crested terns also occur, but have little influence on the amounts consumed from these farms.

The $70,000 loss per year to scavenging seabirds from the study farm, if typical of the industry, warrants some action by tuna farmers to reduce this loss. If this is extrapolated to the whole industry it would equate to around a $1 million dollar loss to the industry (assuming the study farm was of average size). However, this estimate should be treated with caution, as not all the tuna companies use the same method of baitfish feeding as the study farm. Some companies use a siphoning method, while others use only frozen block. Therefore further research into all the feeding methods used to distribute food in the tuna industry and their effectiveness in reducing seabird consumption is necessary.

The best way for the owners of the study farm to reduce the loss of scavenged feed is to make the feed inaccessible to the seabirds. This could be achieved by erecting bird netting over the seacages, especially the baitfish seacages, as even though it may cost about $5000 to net each seacage, this would pay for itself twice over in the first year, assuming it does not cause other logistical problems. Changing the feeding method of baitfish to frozen block would also significantly reduce the amount taken. However, with this method, diving birds still have some access to the feed

In conclusion, silver gulls are the main seabird species of concern consuming tuna feed at the tuna seacages. Baitfish feed is preferred by seabirds over pellet feed in most cases. The study farm lost about 2.3% of baitfish and 1% of pellets to seabirds with the feeding methods then in use. If they were to use all frozen blocks of baitfish, they would reduce the amount of feed consumed by birds to close to zero.

5.9 The Impacts of Tuna Feed on the Reproductive and Population Dynamics of Silver Gulls

5.9.1 Introduction

The dramatic increase in gull numbers throughout the world over the last century has been associated with an increase in food availability derived from human activity (Bosch *et al.* 1994; Coulson and Coulson, 1998). This is largely human refuse, but also includes fisheries discards, fish processing works, abattoirs and aquaculture facilities (Coulson and Coulson, 1998; Furness, 1996; Oro, 1999). In Australia, silver gull numbers have increased enormously over the past 60 years and this is attributed to their opportunistic use of human derived food (Smith and Carlile, 1993). This increase in population size may be caused by increased reproductive success (increased recruitment), including higher fecundity, increased hatching success and increased chick survival, together with increased body condition and reduced mortality.

It is well known that food supply affects reproduction and population dynamics in seabirds (Oro *et al.* 1999). Fish availability has been found to be a crucial determinant of high reproductive performance in many species of seabirds, including gulls (Bosch *et al.* 1994; Annett and Pierotti, 1989; Annett and Pierotti, 1999). Fish are excellent sources of protein and thus are very important for egg formation (Oro, 1996), particularly the quantity of egg albumen, which is a crucial nutritional factor for developing chick embryos (Wood, 1991). Fish are also vital food for seabird chicks because they can be easily swallowed, unlike most human refuse, and contain the required high levels of digestible calcium and protein (Annett and Pierotti, 1989).

In areas where fish derived from human activity (e.g. fisheries discards, aquaculture), are not readily available, western gulls have been shown to feed on human refuse until the breeding season and then switch to fish they catch themselves (Annett and Pierotti, 1989; Annett and Pierotti, 1999). Similar switches to fish from other foods during the breeding season have been observed in other species of gulls (Annett and Pierotti, 1989). Fish prey are a 'risk-prone' foraging source, with usually a short round trip, but a high variance in trip time compared to human refuse which may have a long round trip, but low variance (Annett and Pierotti, 1989). However, fish are a higher quality feed for chicks than garbage and consequently breeding success, breeding lifespan, clutch size, hatchling production and lifetime fledging production are strongly dependent on the amount of fish caught by breeding pairs (Annett and Pierotti, 1999). Thus western gulls that fed on fish had a higher reproductive output than gulls that continued to feed on garbage and did not switch to fish (Annett and Pierotti, 1999).

A readily available supply of fish through fisheries discards has been shown to significantly influence the timing of egg laying, egg volume and size, clutch size, nest desertion, hatching success and overall breeding success in many species of gulls (Oro, 1996; Oro *et al.* 1995; Oro *et al.* 1996; Oro *et al.* 1999). Where trawling moratoriums have overlapped with egg production and egg laying (not chick rearing), female body condition has been shown to decrease (Oro *et al.* 1999) and this in turn affects the reproductive output of the female. For Audouin's gull and the lesser black-backed gull populations in the Ebro Delta (NE Spain), a trawling moratorium during egg production and laying resulted in a three week delayed laying period (Audouin's Gull only), a decrease in egg size, a decrease in modal clutch size and decreased hatching success and hatchling weight (Oro, 1996; Oro *et al.* 1996). However, these effects were exacerbated if the trawling moratorium overlapped with the chick-rearing period rather than egg production and laying. Chick rearing is probably the most vital stage in determining the breeding success of gulls and it is vital to have a supply of good quality food readily available for breeding success (Oro, 1996; Oro *et al.* 1995; Oro *et al.* 1996). When fisheries discards were not available during chick rearing, the overall breeding success for yellow-legged gulls decreased by 46%, and for Audouin's gull by 48% (Oro *et al.* 1995, 1996). Reproductive success was higher for these gulls in the years when discards were not available during egg production, but were available during chick rearing (Oro, 1996; Oro *et al.* 1996). Therefore, high quality food is more important during chick rearing than egg production, but high quality eggs are also a determining factor in breeding success.

Resource availability during winter can be crucial for over-winter survival of both adult and juvenile seabirds (Martinez-Abrain, 2002). This is also the case for immature birds learning to forage, as they are less successful at gaining food than adults (Garthe *et al.* 1996). A large increase in the populations of crested terns in the south-eastern Gulf of Carpentaria in Australia is thought to be due to the availability of trawl discards when the juveniles are learning to forage (Blaber *et al.* 1995). This 'extra' feed reduces juvenile mortality rates, and therefore increases population size (Blaber *et al.* 1995). Availability of fisheries discards has also been found to affect body condition and recruitment rates of seabirds. When trawl discards were unavailable (trawling moratorium), the body condition of non-breeding black-backed gulls and herring gulls deteriorated, but increased again when trawling resumed (Huppop and Wurm, 2000). The availability of good quality food, such as fisheries discards, supports more seabirds, hence adult recruitment into breeding colonies increases, which further increases reproductive output (Oro *et al.* 1996; Huppop and Wurm, 2000).

At the tuna farm leases near Port Lincoln there are opportunities for seabirds, particularly silver gulls, to forage for high quality baitfish-feed and pellet-feed. The tuna farming season (February-September/October) coincides with most of the silver gull breeding season (April-November) and hence could have a profound effect on their reproductive success. All breeding silver gulls have access to this feed, not just the older, more experienced birds, and hence the reproductive success of the population should be higher than populations with little human-derived food. This research aims to determine whether the consumption of tuna feed by silver gulls effects their reproductive success and population growth.

5.9.1.1 Aims

- Assessing the population size of silver gulls in the Port Lincoln area over the last decade.
- Determining whether the clutch size of silver gulls in the Port Lincoln area is greater than at a reference site, with little human-derived food.
- Determining whether the egg weight of silver gulls in the Port Lincoln area, with access to tuna feed, is different to the egg weight of a reference site, with little human-derived food.
- Determining any differences in the timing of breeding for the silver gulls in these two areas.

5.9.1.2 Hypotheses

- The silver gull population in the Port Lincoln area has increased over time.
- The clutch size of the Port Lincoln silver gulls will be larger than those from a reference site.
- The egg weight of the Port Lincoln silver gulls will be heavier than those from a reference site.
- The breeding season of the Port Lincoln silver gulls will be synchronised with the tuna season and will therefore be different to other breeding gulls in South Australia.

5.9.2 Materials And Methods

5.9.2.1 Locating the Breeding Site

All breeding sites of the silver gull in the vicinity of Port Lincoln and at potential reference sites had to be located. NPWS and SARDI staff knew several islands in the Sir Joseph Banks Group on which silver gulls breed and these and other islands were checked. The only reference site that was sufficiently far from human activities was found in the Coorong National Park.

5.9.2.2 Assessing Clutch Size, Egg Weight and Population Size

Once the breeding sites were located, arrangements were made to visit these islands. The purpose of the visits to each island was to record clutch sizes and egg weights, the number of nests and the size of the population of breeding silver gulls. The breeding sites visited were Winceby Island (23/4/03), Rabbit Island (23/4/03), Donington Island (2/5/03) and Sibsey Island (8/5/03). These islands were all in the vicinity of the tuna farms (Figure 5.1).

Every third nest encountered was marked with a fluorescent pink marker which had the date and nest number recorded on it with black, permanent marker (Figure 5.32), and its location was also recorded with a GPS. For each marked nest, the clutch size was noted and each egg in the nest was weighed. If chicks were present, they were also noted and weighed with a Salter portable electronic balance. Nests with just chicks in them were ignored. Forty nests were selected on Winceby Island, 42 nests were selected on Donington Island and 150 nests were selected on Sibsey Island.

The reference sites for this study were Fat Cattle and Woods Well Islands in the Coorong National Park, visited on 4/9/03. These islands are approximately 45 km from Meningie and hence could be considered a "control" site because there is little chance of the silver gulls accessing human-derived food. The population was small, mainly ate naturally occurring food, and had little reliance on the small local dump and fishing discards (pers. comm. Coorong NPWS). The silver gull populations on these islands were small and hence the clutch size and egg weight of every nest were recorded.

Time and financial constraints meant each site was only visited once, but with generally large sample sizes and at a similar stage in the breeding cycle, it is reasonable to assume that the observed variability in clutch size was an accurate reflection of differential reproductive success at each site.

Figure 5.32: **A marked silver gull nest.**

5.9.2.3 The Breeding Sites in the Vicinity of Tuna Farms

5.9.2.3.1 Winceby Island

Winceby Island is the most northerly island in the Sir Joseph Banks Group of Islands (Robinson *et al.* 1996). It lies approximately 80 km north-east of Port Lincoln and 43 km from the closest tuna farms (Figure 5.1). It is a 30 ha granite island with a calcarenite cap that rises gently to 10 m (Robinson *et al.* 1996). Previously, 24 species of birds were recorded on the island, but not silver gulls which are thus recent newcomers (Robinson *et al.* 1996). Their arrival is important because Winceby Island has been zoned a 'Restricted Access Zone' due to its importance as a seabird breeding area (Robinson *et al.* 1996). In 2003, the silver gull breeding colony was beside a breeding colony of black-faced cormorants and pied cormorants on the north-west of the island. The island was accessed on 23 April during the breeding site survey. Breeding silver gulls and their nests were counted by viewing the colony from the boat.

It was unknown whether the silver gulls on Winceby Island were feeding at the tuna farms, which were a minimum of 43 km away, and hence whether this site could be used as an experimental site. However, regurgitations next to cormorant nests showed signs of pilchards (back bones, heads), which was possibly derived from tuna feed. Thus it was considered an experimental site for this project (silver gulls were also flying a similar distance from Sibsey Island to Port Lincoln).

5.9.2.3.2 Rabbit Island

Rabbit Island lies approximately 29 km north-north-east of Port Lincoln and about 4km from the nearest tuna farm (Figure 5.1). It is a 20 ha, 10 m granite island classed as 'biologically disturbed' because it was mined for guano, is covered in boxthorn and had resident rabbits (Robinson *et al.* 1996). Nevertheless, about 13 species of seabirds live and/or breed on the island, including one of the major breeding colonies of silver gulls since 1996 (Robinson *et al.* 1996; Farlam, unpublished data). However, a survey on 23 April found no nesting silver gulls but there were signs of nesting starting with some eggs and dead chicks.

5.9.2.3.3 Donington Island/Reef

Donington Island/Reef is about 17 km east-north-east of Port Lincoln, 0.5km north-north-east of Cape Donington (Robinson *et al.* 1996) and about 3 km from the nearest tuna farm (Figure 5.1). It is a small, 3m high granite outcrop that provides a roost and nest site for common coastal birds, including silver gulls (Robinson *et al.* 1996). Breeding silver gulls surrounded the island in 2003 and were surveyed on 2 May. As the island was so small, every nest was counted and the number of silver gulls was estimated by circling the island in the boat.

5.9.2.3.4 Sibsey Island

Sibsey Island is about 54 km NE of Port Lincoln and 17 km from the nearest tuna farm (Figure 5.1). It is a 30 ha granite island that rises steeply to 25 m and has about 27 species of seabirds including silver gulls, though in the mid-1990s their breeding colony was small (Robinson *et al.* 1996). In 2003 there was a large breeding colony on the NNW of the island, facing the tuna farms and the mainland.

Sibsey Island was the main study site and the number of nests was estimated by counting all the nests in two representative 250 m^2 areas and extrapolating to the total area of nests that was calculated from GPS readings of the boundaries.

5.9.2.4 Data analysis

The data from the nests studied on the Coorong Islands, Fat Cattle Island and Woods Well Island, were combined, as Woods Well Island only had a sample size of three nests.

5.9.3 Results

5.9.3.1 Timing of Breeding

Surveys in late April and early May found breeding silver gulls on Winceby, Sibsey and Donington Island, where they had been breeding for at least two months, as many nearly fledged chicks were found. In contrast, Rabbit Island had no nesting silver gulls, even though this was the main breeding site for the past five years (Farlam, unpublished data). Attempts in May to find reference breeding sites unaffected by human activities found that the silver gulls were not breeding anywhere else in South Australia. They were not even breeding at Outer Harbour in Adelaide, where a relatively large colony of silver gulls lives and breeds, feeding on refuse from the Wingfield dump. In early July (July 1-3), silver gulls were still breeding on Sibsey Island when a sample of gulls were banded, although the breeding population had decreased. At this time, there were still no silver gulls breeding anywhere else in the state, but they started breeding at Outer Harbour in late July/early August. Reference sites were eventually found in early September at Fat Cattle and Woods Well Islands in the Coorong. These gulls had only been breeding for about a month as there were no chicks present. Interestingly, silver gulls commenced breeding on Rabbit Island at approximately the same time they started breeding elsewhere in the state (July/August).

5.9.3.2 Number of Silver Gulls Around Port Lincoln Over the Last Decade

Sibsey Island was the predominant nesting site for silver gulls, with 7,238 breeding pairs (Table 5.2), which differs from the findings of earlier research that found most silver gulls in the Port Lincoln region bred on Rabbit Island (Figure 5.42). By 2002, the breeding colony covered most of Rabbit Island, but in 2003 the gulls mainly bred on other islands and only started breeding on Rabbit Island in small numbers four months later in late July (Figure 5.33).

Table 5.2: **Numbers of breeding pairs of silver gulls at breeding sites in the Port Lincoln area.**

Breeding Site (Island)	Number of Breeding Pairs
Winceby Island	1000
Donington Island	150
Sibsey Island	7,238
Rabbit Island	2000
Total	**10,388**

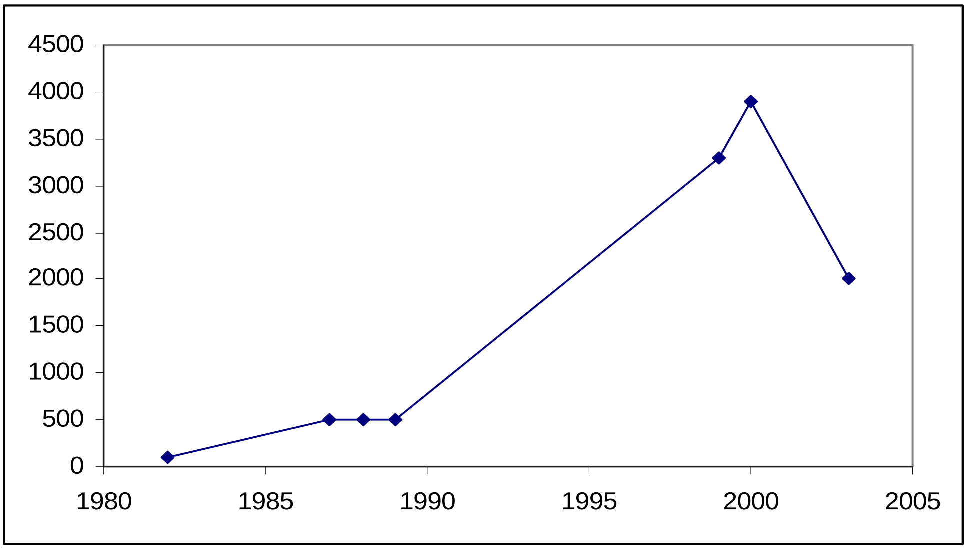

Figure 5.33: **Number of breeding pairs of silver gulls on Rabbit Island 1982-2003. Data from Farlam, (unpublished data) and this study.**

The silver gull population around Port Lincoln has increased substantially since 1999, when the earliest population data were recorded, and the population doubled between 2000 and 2003 (Figure 5.34). The 2003 estimate of the breeding population of silver gulls within 50km of Port Lincoln includes gulls breeding on Rabbit Island, where breeding was delayed for four months. These Rabbit Island gulls were assumed to be a different population because silver gulls are thought to have a high fidelity to their nesting colonies. If this assumption was flawed and the Rabbit Island gulls had bred earlier on other islands the number of breeding pairs in 2003 would fall from 10,388 pairs to 8,388 pairs. The extent of multiple clutching in the silver gulls at Port Lincoln is unknown.

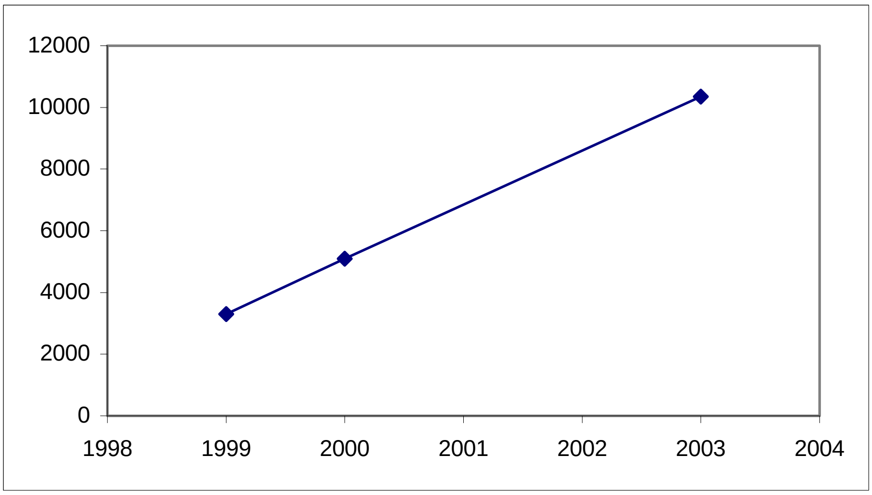

Figure 5.34: **Numbers of breeding pairs of silver gulls in the Port Lincoln area 1999-2003. Data from Farlam (unpublished data) and own research.**

5.9.3.3 Evidence that the Sibsey Island Silver Gulls were Accessing the Tuna Farms

The study tuna farm was the closest farm to Sibsey Island (see Figure 5.1), and the island can be seen from the farm. It was thus possible to count the number of silver gulls moving between Sibsey Island and the farms. This was done by using two hand held counters to count the number of silver gulls flying past the boat 1) from the tuna farms towards Sibsey Island and 2) from Sibsey Island to the tuna farms. This was done for several one minute intervals)(N=13) over 3 days (19/6, 24/6, 10/7). A mean of 30.6 silver gulls/min (SD=16.02) flew from the farms to Sibsey Island and 20.5 gulls/min (SD=14.58) flew to the farms from Sibsey Island. This difference in migration to and from the study farms was because the gulls were also moving to other farm leases.

While measuring clutch size and egg weights on Sibsey Island (Figure 5.44), I noticed that every nest surveyed had many, small fish backbones that appeared to be from sardines; the main baitfish fed to tuna (Figure 5.35). Furthermore, silver gulls banded on Sibsey Island were seen on the study tuna farms and they also frequent the mainland because several banded birds were observed in Port Lincoln.

Figure 5.35: **One of many 'baitfish like' backbones found near the silver gull nests on Sibsey Island.**

5.9.3.4 Clutch Size

The mean and modal clutch size was about one egg greater in the vicinity of tuna farms than at the reference site in the Coorong (Table 5.3), and the difference in mean size was highly significant ($F_{1, 294}$= 85.4, p <0.001).

Table 5.3: **Descriptive statistics for clutch size of silver gulls from the Port Lincoln region (in the vicinity of the tuna farms) and the reference site in the Coorong.**

Clutch Size Data	Reference	Port Lincoln
N	63	233
Mean	1.41	2.35
Median	1	2
Mode	1	3
Standard Deviation	0.61	0.73
Maximum	3	3
Minimum	1	1

Clutch sizes were measured at two islands in the Coorong and three islands in the vicinity of Port Lincoln. However, the 2 Coorong sites were pooled together due to a very small sample size for Woods Well Island (n=3). The largest mean clutch size was on Winceby Island and the smallest was on Fat Cattle Island (Table 5.4). The clutches on Sibsey, Winceby and Donington Islands were significantly larger than the Coorong Islands ($F_{3, 292}$= 30.9, p = <0.001).

Table 5.4: **Descriptive statistics of clutch size for the three breeding sites in the vicinity of Port Lincoln and the reference sites in the Coorong National Park.**

Breeding Island	Clutch Sizes N	Range	Mean	Std.Dev.
Sibsey Island (Port Lincoln area)	151	1-3	2.34	0.7
Donington Island (Port Lincoln area)	42	1-3	2.17	0.82
Winceby Island (Port Lincoln area)	40	1-3	2.55	0.68
Coorong Islands (Fat Cattle and Woods Well)	63	1-3	1.41	0.63

5.9.3.5 Egg Weight

The mean ($F_{1, 571}$= 5.2, p <0.05) and median egg weights were higher at the reference site than at the Port Lincoln islands, but there was no difference in modal egg weights (Table 5.5). However, the mean egg weight for each breeding site was different ($F_{1, 569}$= 9.5, p <0.001), with the heaviest eggs were on Winceby Island near Port Lincoln and the lightest eggs on Sibsey Island (Table 5.6). There was no significant difference between the mean egg weights on Sibsey and Donington Islands. In contrast, the mean egg weights for Winceby Island and the Coorong Islands were significantly different to the mean egg weights at Sibsey and Donington Island.

Table 5.5: **A comparison of egg weights in the vicinity of Port Lincoln and reference sites in the Coorong N.P.**

	Egg Weights (g) Coorong	Port Lincoln
Mean	40.0	38.8
Median	41	39
Mode	40	40
Range	29-50	20-55
St. Dev.	4.03	4.23
N	86	487

Table 5.6: **Descriptive statistics of egg weight for the 3 experimental breeding sites and two reference sites.**

Breeding Island	Egg Weight (g) N	Range	Mean	Std.Dev.
Sibsey Island (Port Lincoln area)	309	27-48	38.23	3.83
Donington Island (Port Lincoln area)	81	20-46	38.87	4.16
Winceby Island (Port Lincoln area)	97	24-55	40.64	5.04
Coorong Islands (Fat Cattle and Woods Well)	86	29-50	39.95	4.03

5.9.4 Discussion

Over the last century, the populations of some opportunistic gulls have rapidly expanded due to their ability to exploit predictable feed derived from human activities such as fisheries discards, refuse, aquaculture facilities, abattoirs and fish factories (Bosch *et al,* 1994; Coulson and Coulson, 1998; Furness, 1996; Oro, 1999). In Australia, silver gulls have increased in numbers dramatically over the last century. This increase is due to the feed availability increasing their reproductive output through better female body condition and increased clutch size, egg weight, hatching success and chick survival (Annett & Pierotti, 1989; Annett & Pierotti, 1999; Oro, 1996; Oro *et al,* 1996).

In Port Lincoln, silver gulls have been increasing for the past decade and the number of breeding birds has doubled from 10,200 in 2000 to 20,776 in 2003. This increase could not occur without high quality feed being available to increase reproductive output and decrease mortality due to starvation. This extra food is potentially the feed used in the southern bluefin tuna farms. The refuse depot was also a feed source for gulls but has recently (January 2003) been privatised and new management practices have been applied to reduce the amount of waste available to birds (Collex, pers. comm.). In any case, the number of silver gulls reportedly observed at the refuse depot by the Collex staff was much smaller before tuna harvest (~ 1000) than during and after harvest (~5500). There was an average of 400-600 silver gulls at each seacage at the study lease, although some do follow the boat from cage to cage. There was also a 20-30 silver gull turnover per minute, so the mean turnover time for all silver gulls at a cage would be about 17 minutes. With an average feeding event (shovelling baitfish and distributing pellets) taking around 20 minutes (pers. obs.) and 13 farms being fed twice a day, there are thus about 520 minutes of feeding occurring each day at the study farms, which equates to approximately 13,000 silver gull visits to the study tuna farms each day.

Fish and fish-derived products have also been shown to increase reproductive success in gulls when compared to gulls that only feed on municipal garbage (Annett & Pierotti, 1989, 1999). Therefore it is unlikely that garbage alone would have had the effect on the silver gull reproductive output that has been observed for the Port Lincoln gulls. This is supported by an increase in breeding gulls on Rabbit Island in 1998, which mirrors the farms moving from inside Boston Island to the outside nearer Rabbit Island in 1997. The farms have recently moved further offshore which may explain why the gulls shifted their main breeding colony from Rabbit Island to Sibsey Island in 2003. Other evidence includes the numerous 'sardine-like' backbones found near most silver gull nests on Sibsey Island. Silver gulls banded on Sibsey Island were also seen on the study tuna farms. Some of these banded gulls have also been observed in Port Lincoln.

The mean, modal and median clutch size of silver gulls breeding near tuna farms were all larger than for gulls breeding at the Coorong reference sites distant from human activities. This indicates that the food supply for the Port Lincoln gulls was ample and of high enough quality for them to be able to increase their mean clutch size by one egg and their modal clutch size by two compared to gulls at the reference site. A diet high in fish has been shown to have similar effects in other species of gulls (Annett and Pierotti, 1989 & 1999). Interestingly, the mean egg weight was less at the breeding sites near the tuna farms than at the reference sites. Perhaps this is because the clutch size was higher and the gulls were expending more energy in producing more eggs, but less energy was expended in each egg. However, the disadvantage of a slightly smaller egg size is likely to be compensated for by the more readily available food during the chick rearing period. At the reference site, the mean clutch size was one egg less and apparently more resources were expended on each egg produced. Other factors that influence breeding success, such as hatching rate, chick survival and fledging success, need to be studied to determine whether egg weight is critical in determining the breeding success of the silver gulls.

Further evidence that the availability of tuna feed was influencing reproduction in silver gulls was that in 2003, breeding near Port Lincoln started 4-5 months earlier than at any site in South Australia. Breeding probably started in early March, as when the Port Lincoln islands were visited in late April there were many nearly fledged chicks. Other breeding colonies in the state, including those that also have access to artificial feed, did not start breeding until late July or early August. This was later than usual as they generally start breeding in May or June (Higgins & Davies, 1996). This delay may have been caused by numerous factors such as the current drought or El Nino. Whatever the cause, it clearly had no effect on the breeding season near Port Lincoln. This suggests the breeding gulls are consuming high quality food, of fish or products containing fish (such as pellets), because gulls are known to delay their laying period if fish is not available (Higgins & Davies, 1996).

The silver gulls near Port Lincoln have also lengthened their breeding season. The breeding season was from May to September in 1987-89 and extended to April-November in 2000, and possibly started earlier (Farlam, unpublished data). The same breeding season was observed in 2003. Farlam, (unpublished data) hypothesised that this lengthened breeding season was influenced by the tuna farming season, which runs from February to September/October each year. This hypothesis is clearly supported by the results of the present study.

The primary breeding site of the Port Lincoln silver gulls shifted from Rabbit Island to Sibsey Island in 2003. This shift may be due to numerous factors or a combination of factors. The move may be due to the tuna farms moving further offshore, however, this is probably unlikely because there are still tuna farms within 4 km of Rabbit Island. The move may be due to the fact that the breeding colony outgrew Rabbit Island. It is only a small island and in 2002, silver gulls nested over most of the island (Farlam, unpublished data) and consequently they may have moved to a larger island closer to the tuna farms. There also may have been some unidentified disturbance that resulted in the silver gulls abandoning their nests which would explain the abandoned eggs and dead chicks found on Rabbit Island in late April. It appeared that the gulls had started to breed but then abandoned the island. Silver gulls did not start breeding again on Rabbit Island until late July or early August, which is about the same time as gulls started breeding elsewhere in the state. The gulls that started breeding late on Rabbit Island may have been the gulls that failed early in the year. Alternatively, they may be younger inexperienced birds as they are known to start breeding later than older, more experienced birds (Smith, 1995; Smith and Carlile, 1992). These gulls may have been unable to establish a preferred site on Sibsey Island, though this is unlikely on such a large island. All this speculation emphasises how little is known about the breeding dynamics of the silver gull and the need for further research on marked populations.

In conclusion, the availability of a large amount of high quality food at the tuna farms has potentially enabled the silver gull population of Port Lincoln to increase their reproductive output to the extent that they have doubled their population from 10,200 breeding birds in 2000 to 20,776 breeding birds in 2003. The combined effects of a large initial population, larger clutch sizes and a prolonged breeding season means that the population will further increase provided the gulls can continue to scavenge enough food from the tuna farms.

5.10 Social Impacts of Increased Scavenging Seabird Numbers

5.10.1 Introduction

The rise in gull populations close to human centres associated with the increase in food availability derived from human activities has engendered a range of management and ecological problems. The populations of silver gulls in Australia have increased enormously over the last 60 years (Smith and Carlile, 1993) to the extent that they have been classed as a pest by the NSW National Parks and Wildlife Service (Smith, 1995). A number of concerns have arisen as a result of enlarged populations of silver gulls due to anthropogenic food sources Australia wide (Smith, 1995). These concerns include silver gulls becoming a pest and a nuisance, their effects on other native species, and human health and safety (Smith, 1995).

Gulls have been associated with the spread of bacteria that cause enteric human diseases such as *Escherichia coli* and *Salmonella* spp. (Belant, 1997). Contamination of public water supplies by gull faeces has been considered a major source of disease transmission, but gulls disperse pathogens rather than being the primary source (Belant, 1997). Gulls may transport bacteria and other pathogens from refuse dumps and/or sewage works to water reservoirs. Gull faeces have also been implicated in accelerated nutrient loading, which may also lead to growth of bacteria and other pathogens (Smith, 1992).

Gulls are frequently considered a general nuisance because of their noise, defecation and harassment of people (Belant, 1997). They foul picnic and restaurant tables, pavements, park benches, cars and fountains (Smith, 1995). They may harass tourists, steal food from patrons at outdoor eating establishments, nest on roofs and compete for food with farm and zoo animals (Belant, 1997).

Silver gulls steal food, eggs and chicks from other birds and hence large numbers of gulls may have localised adverse effects on other species of birds, through competition for nesting space, kleptoparasitism or predation (Coulson and Coulson, 1988; Smith, 1992). In Queensland, gulls raid tern colonies for food and affect breeding success; particularly since gull numbers have increased due to tourism (Smith, 1992). In Sydney, gulls congregate near little tern colonies and consume the contents of the nest (Smith, 1995). In South Australia, gulls steal eggs from banded stilts breeding in Lake Torrens (Smith, 1995) and Lake Eyre, thereby significantly reducing breeding success.

Silver gulls can also cause severe habitat changes for other species (Smith, 1992, 1995). For example, at the Five Islands near Sydney, Kikuyu grass may have been introduced by gulls as nesting material, and Big Island, the largest in this group, is now almost entirely covered by this grass (Smith, 1992, 1995). The thick runners make an almost impenetrable barrier for burrowing species that nest there such as the short-tailed shearwater (*Puffinus tenuirostris*), wedge-tailed shearwaters (*Puffinus Pacificus*) and little penguins (*Eudyptula minor*) and shearwaters are often found entangled in grass runners at the entrance to their burrows (Smith, 1992, 1995).

Gulls can pose a serious threat to aviation and in the USA alone may cause about US$40 million damage annually to civilian aircraft through damage by air strikes (Belant, 1997). Historically, most gull problems within Australia have been at airports, where collisions with aircraft can cause serious damage or crashes (Smith, 1995). Gulls are mainly a problem to aviation when the airport is in close proximity to waste depots (Smith, 1992) and gull flight paths cross the runway (Smith, 1995).

All these problems may be intensified at Port Lincoln from October to February because seagulls congregate around the town outside the tuna season (February to September/October). The tuna are all harvested by October, apart for some broodstock, and thus there is little tuna feed until the following February. Thus, large numbers of gulls no longer have a food source and must forage elsewhere. This may lead to a large influx of silver gulls into Port Lincoln searching for alternative food sources. It is known that gulls rapidly react to changing food sources. For example, herring gulls and greater black-backed gulls migrate within days of their regular food sources disappearing during a month-long Christmas break in North Sea fishing, but they rapidly return when fishing resumes (Huppop & Wurm 2000).

Silver gulls in Port Lincoln may search for food at the local dump, or harass tourists or people eating outside as well as raiding rubbish bins. They may steal the food of farm animals or pelleted feed at abalone and kingfish farms. They may also feed on the eggs and chicks of other birds and this can have serious ecological consequences because the tuna harvest occurs in spring and the gulls are thus seeking new food sources when many birds are nesting. This is particularly important for the Port Lincoln area where there are many important breeding colonies of vulnerable seabirds such as little terns and crested terns. Despite all these speculations, very little is known about where the silver gulls disperse at the end of the tuna season and in particular whether there is an influx of gulls into Port Lincoln.

5.10.1.1 Aims
The aim of this study was to assess whether the numbers of silver gulls increased around Port Lincoln after the tuna harvest.

5.10.1.2 Hypothesis
The numbers of scavenging silver gulls will increase in Port Lincoln following the end of the tuna harvest.

5.10.2 Materials And Methods

During the tuna season and near the end of the tuna harvest the numbers of silver gulls were monitored from the following places around Port Lincoln:

1. the town foreshore
2. the town refuse depot
3. the town wharf
4. the marina loading berth
5. oil wharf beach
6. fish factories near the town

Where possible, counts for each site were done on the same day. However there was a disproportionate number of counts done for each site, and this is why a monthly average was taken for each site.

5.10.2.1 The Port Lincoln Foreshore

The Port Lincoln foreshore is the main beach in Port Lincoln and is adjacent to the main shopping precinct. It is about 3 km long and is a popular area for picnics, beach activities and is adjacent to many pubs, cafés and eateries all with alfresco dining to enjoy the view. The town jetty is on this beach and it is popular for recreational fishing. Thus, there is much artificial food available all along the beach.

Seabirds were counted with a hand held counter by walking along the entire length of the foreshore which took 20-25 minutes. This was done from July to October, with 2-4 counts performed for each month (total 13 counts) (with an average calculated for each month). It was not possible for each count to be at exactly the same time. Over the 4 months of observations six counts were made at about 7:30 am, three about 10-11 am and four between 2 pm and 6 pm.

5.10.2.2 The Refuse Depot

The refuse depot is open every day except Sundays and public holidays, and household refuse is delivered on weekdays. Port Lincoln has a population of about 13,500 and hence this site is a large source of human refuse. Seabirds were counted by walking around the site which took about 10 minutes. A total of four counts were done (2 for September, 2 for October) with one count for each month made between 10 am and 1 pm and one count for each month made between 3 pm and 5 pm. The counts were averaged for each month to get a monthly average.

5.10.2.3 The Town Wharf

The town wharf is a loading wharf and berth for many of the tuna and fishing boats in the area and it is used for loading grain and fertilizer boats. It is also popular for recreational fishing. There is usually some spilt grain, fish and bait available as food for gulls. Seabirds were counted by walking the length of the wharf and the surrounding area which took 5-10 minutes. A total of four counts were performed (1 for August, 2 for September and 1 for October). Of these counts, two counts were made between 7 am and 9 am and another two between 3 pm and 5 pm.

5.10.2.4 The Marina Loading Berth

The Marina loading berth is also used for loading and unloading tuna and fishing boats, especially the smaller boats. It is also popular for recreational fishing and there is usually some fish and bait available as food for gulls. Seabirds were counted a total of five times (2 for August, 2 for September, 1 for October) between 2 pm and 6 pm by walking along the loading berth which took about two minutes.

5.10.2.5 Oil Wharf Beach

This beach is next to the oil loading/unloading wharf, which is about one kilometre from the town wharf. There is a large rubbish bin at this beach, which is usually overflowing and people usually park in the car park to eat and drink. Seabirds were counted by walking along the beach, and also counting the number of seabirds on the jetty, which took five minutes. A total of 5 counts were performed (1 for August, 2 for September, 2 for October0. Of these counts, two of the observations were made between 7 am and 9 am and three were made between 2 pm and 5 pm.

5.10.2.6 Fish Factories

The fish factories are on the road leading to the refuse depot. They process tuna, abalone and wild-caught fish. There are also a few fertilizer factories that use the fish waste to make fertilizer. There is potentially fish waste available to gulls from all of these operations. Seabirds were counted while driving to the refuse depot and took about two minutes. A total of four counts were performed (2 for September, 2 for October). Of these, two counts were made between 10 am and 1 pm and two were made between 3 pm and 5 pm.

	Dates Observed			
	July	August	September	October
Foreshore	14th, 16th	19th, 22nd, 25th, 29th	12th, 16th, 22nd	1st, 5th, 9th, 12th
Dump	-	-	16th, 24th	5th, 22nd
Wharf	-	26th	12th, 17th	9th
Marina Loading Berth	-	14th, 27th	12th, 24th	12th
Oil Wharf Beach	-	25th	17th, 24th	3rd, 14th
Fish Factories	-	-	16th, 24th	5th, 22nd

5.10.3 Results

5.10.3.1 Seabird numbers

The number of silver gulls in Port Lincoln increased during the study period at most sites, especially where artificial feed was readily available, such as at the refuse depot, the foreshore and the fish factories (Figure 5.36). The biggest increase in numbers was seen at the refuse depot near the end of tuna harvest in September and October (Figure 5.37).

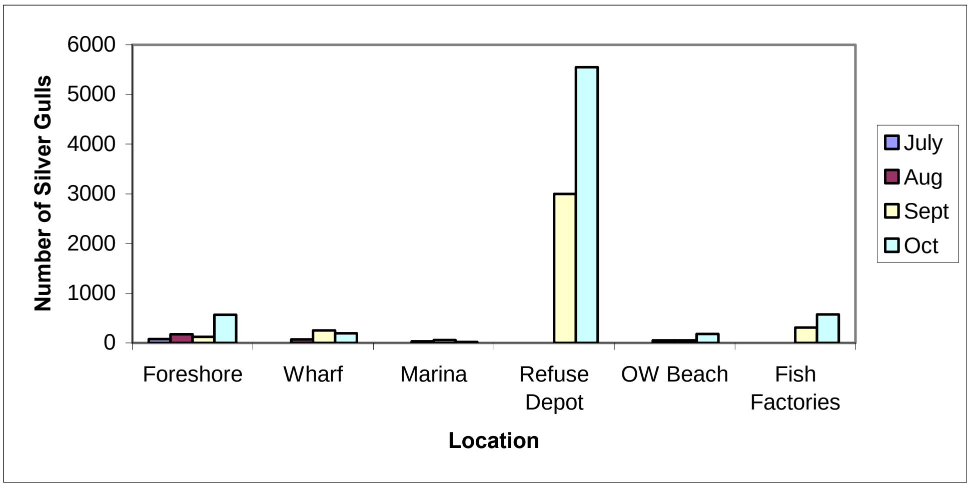

Figure 5.36: **Silver gull numbers at sites around Port Lincoln from July to October.**

Figure 5.37: **Silver gulls at the refuse depot.**

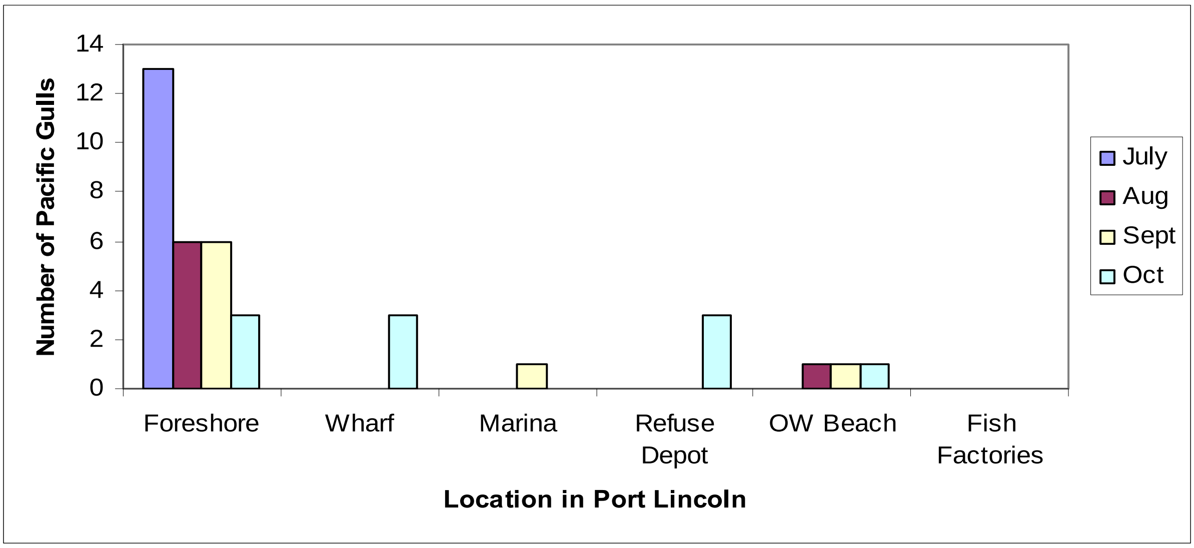

Figure 5.38**: Pacific gull numbers at sites around Port Lincoln from July to October.**

Pacific gull numbers differed between sites in the town (Figure 5.38). They decreased at the foreshore from July to August. They were constant at Oil Wharf beach and increased at the Wharf and the refuse depot near the end of tuna harvest. However, their numbers were not large at any of the sites.

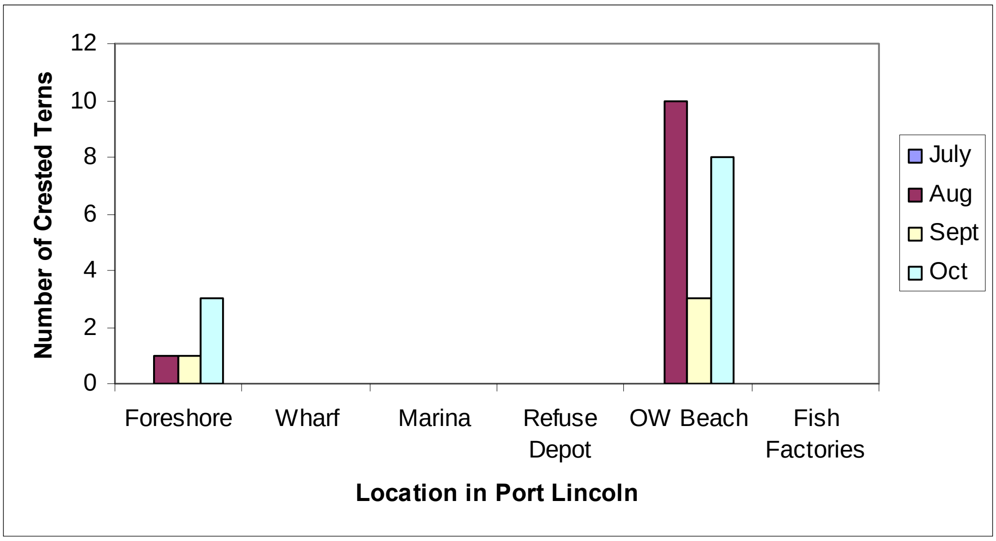

Figure 5.39: **Crested tern numbers at sites around Port Lincoln from July to October.**

Crested tern numbers were either very small or non-existent at sites around the town. They were only observed at the two beaches, the foreshore and oil wharf beach (Figure 5.39). Their numbers increased slightly at the foreshore near the end of tuna harvest, but decreased in September at oil wharf beach and then increased again in October.

Short-tailed shearwaters were not observed anywhere in the town. Both black-faced cormorants and pied cormorants were observed at the sites near water. Pelicans were observed at the refuse depot.

5.10.3.2 Observed Problems with the Influx of Silver Gulls into Port Lincoln

On all counts performed at the foreshore, silver gulls were observed scavenging for scraps when people were eating. Up to 200 gulls have been observed surrounding some people at the foreshore on numerous occasions. They harassed people for food and defecated on park benches, footpaths, cars and roofs. They fed on scraps on the road in front of approaching cars and consequently many have been run over and there have been near accidents (I have observed three) when drivers stop suddenly to avoid them. Further traffic disturbances were caused by silver gulls scavenging freshly caught pilchards in brine from open bins on a truck transporting them from the boat to a freezer. When the truck started at traffic lights pilchards were spilt onto the road and gulls swooped onto them and would not move for cars (this has been seen on two occasions).

There was an extremely large number of silver gulls observed at the refuse depot. These birds are likely to forage in other parts of the town and therefore are potential vectors for enteric diseases.

There have also been reports in the past of silver gulls scavenging pelleted feed from domestic animals around Port Lincoln especially expensive pelleted horse feed. They have also been reported to scavenge pelleted feed at abalone farms.

These large numbers of silver gulls are also likely to be causing accelerated nutrient loading to the marine systems with their faeces.

5.10.3.3 Other Problems

Silvers gulls were observed pecking the head of a cape barren goose chick that had wandered from its nest into the silver gull breeding colony on Sibsey Island. The chick subsequently died (Figure 5.0). Silvers gulls are likely to attack other birds, pushing them out of their nesting area, and to eat the eggs and chicks of other birds.

Figure 5.40: **Cape Barren Goose chick that was pecked to death by silver gulls on Sibsey Island.**

5.10.4 Discussion

Over the last century, expanding gull numbers in urban areas have caused a variety of management and ecological problems. Silver gulls have increased exponentially all over Australia and have caused many concerns about their potential impacts (Smith, 1992, 1995). In Port Lincoln, silver gulls have access to large artificial sources of food, and have rapidly multiplied, causing many problems.

The number of gulls in the town increases markedly after the tuna harvest starts, when less feed is being fed to the tuna. When the tuna feed becomes less abundant and eventually unavailable, the gulls must find an alternate food source. This decline in tuna feed usually occurs in September/October, but during the year studied, low tuna prices prolonged the harvest and hence many gulls could continue feeding at the tuna leases and did not need to move to the town. Nevertheless, there was an influx of gulls in spring especially at the refuse depot where about 5,500 gulls were foraging in October. The number of silver gulls also increased at other sites around town where anthropogenic food sources were available such as the town foreshore where people go for picnics and ‘fish ‘n chips on the beach’. From the numbers of silver gulls observed in the town in October (near the end of tuna harvest for this year), there was probably about 7,000 to 8,000 silver gulls in the town of Port Lincoln at any one time.

A potentially large environmental problem around Port Lincoln is the impact of hungry silver gulls preying on the eggs and chicks of other birds. Unfortunately, the end of the tuna harvest coincides with spring and early summer, when other seabirds such as little terns and crested terns are starting to breed, and their eggs and nestlings are a likely target for hungry gulls. More research is needed to ascertain the impact of this predation on local populations of birds and to determine if it is more of a problem near seasonal tuna leases than in areas with artificially large gull populations that have less seasonal food supplies.

In conclusion, my research indicates there is a seasonal influx of silver gulls into Port Lincoln, particularly to places where artificial feed is readily available such as the refuse depot and the foreshore. This increase in scavenging gulls brings with it management, health, safety and ecological problems the scale of which requires further research.

5.11 General Discussion and Future Research

5.11.1 General Discussion

5.11.1.1 Implications of Scavenging Seabirds to the Industry

Seabirds scavenged approximately 2.3% of the baitfish and 1% of the pellets fed to the tuna on the study farms. As the owners of the study farms own about 7% of the tuna quota, in 2003 they lost approximately 70 tonnes of tuna feed a year to seabirds at an expense of about $70,000. If this is extrapolated to the whole industry it would equate to around a $1 million dollar loss to the industry. However, this assumption is unwise as not all the tuna companies use the same method of baitfish feeding as is used on the study farms.

Silver gulls consumed the majority of tuna feed scavenged by seabirds. They consumed approximately 85% of the baitfish and 55% of the pellets taken by birds. After silver gulls, Pacific gulls were the seabird that consumed the second largest quantity of tuna feed. However, they consumed more pellets than baitfish, consuming only around 8% of the baitfish and 45% of the pellets consumed. Short-tailed shearwaters and crested terns together consumed around 7% of the baitfish taken and less than 1% of pellets. Thus, most seabirds preferred baitfish over pellets, not just because baitfish was more abundant, but for other reasons. These are most likely that the baitfish more closely matches the natural feed of these seabirds and is easier to swallow as it is lubricated. In contrast the pellets are dry, large (~4 cm long x 3 cm diameter) and would be hard to handle and swallow.

This study indicates that shovelling and pneumatically distributing baitfish results in a relatively large proportion of this feed type being scavenged by seabirds. In contrast, feeding frozen blocks of baitfish resulted in no observed losses to seabirds (however, the losses to diving birds, such as cormorants, could not be established) and pneumatically distributing pellets resulted in a small loss (section 5.3.3.4). These results indicate that the best feeding methods to reduce the amount of feed scavenged by seabirds is to feed frozen blocks of baitfish or pneumatically feed pellets. However, the same number of problematic scavenging birds was observed at pellet farms as at baitfish farms. If the industry was to switch to pneumatically distributing pellets, or if the baitfish was distributed in a way that made it unavailable, it is likely that these birds would adapt to feeding on pellets and therefore more would be consumed. Due to the opportunistic nature of the silver gull, and the fact that they have been observed switching between feed types when others become unavailable (for example, it was reported that silver gulls switch to earthworms when refuse became unavailable (Coulson & Coulson, 1998; Smith, 1992; 1995; Smith & Carlile, 1993)), it is likely they would adapt to pellets. Although it was not significant, there was an increase in percentage of pellets consumed over the three months pellet feeding was observed (near the end of the season) (section 5.3.3.6.1), when baitfish was becoming less available, which may indicate that this adaptation is possible. Other feeding methods such as shovelling pellets and siphoning baitfish need to be analysed to fully understand how much feed is scavenged by seabirds over the whole industry.

As seabirds may adapt to feeding on pellets, and because frozen blocks could still be accessed by diving birds and some baitfish may be required to be shovelled to induce the tuna to feed, then making the feed unavailable to the seabirds is vital to reduce the amount of feed scavenged by seabirds. This could be achieved by erecting bird netting over the farms, especially the baitfish farms, as even though it may cost about $5000 to net each seacage, this would pay for itself twice over in the first year. There may, however, be other issues with such an approach, such as entanglements or restriction of operator access to the cages.

5.11.1.2 Effect of the Feed Source on the Reproductive Output and Population Dynamics of Silver Gulls

Banded silver gulls were observed at the tuna farms during their breeding season and pilchard frames were observed near every nest observed on the main silver gull breeding colony near these farms. Silver gulls were also found to be breeding 4-5 months earlier at Port Lincoln than any other breeding site in S.A. The other silver gulls in South Australia did have a delayed breeding season this year, possibly caused by the drought, a colder winter or El Nino, but whatever affected these gulls, it appeared to have no effect on the Port Lincoln gulls. These gulls appear to have synchronised their breeding season with the tuna season and have moved their breeding colonies accordingly (Farlam, unpublished data). All of this circumstantial evidence, coupled with the fact that approximately 70 tonnes of tuna feed is consumed by seabirds on the study farms, of which about 60 tonnes is consumed by silver gulls, suggests that the Port Lincoln silver gulls rely heavily on the tuna farms as a feed source. This large availability of feed is likely to influence the reproductive output of these silver gulls and this is what the second part of this research endeavoured to find out.

As predicted, the favourable conditions around Port Lincoln have had a large impact on the reproductive output of the silver gulls. On average, the Port Lincoln gulls had one more egg than gulls breeding at the reference site at the Coorong, which is ecologically significant. However, the mean egg weight of the Port Lincoln gulls was less than those at the reference site. This is probably because the extra energy for the Port Lincoln gulls is put into clutch size, not egg weight. In any case, the disadvantage of a slightly smaller egg weight would most likely be compensated for by the readily available food during the chick rearing stage, which is the most important stage in terms of overall breeding success (Oro, 1996; Oro *et al.* 1995, 1996). This increased reproductive output is evident from the linear increase in silver gull numbers over the last five years. The numbers of breeding pairs have substantially increased from nearly 3,500 in 1999 to nearly 10,500 in 2003. The number of non-breeding silver gulls is unknown, but is likely to be high as it includes chicks, fledglings and immature birds.

A similar, but scaled down, effect could be occurring for the other seabirds in the Port Lincoln area that have been observed feeding at the tuna seacages. Pacific gulls start breeding in about August, near the end of the tuna season, but the availability of high quality food during egg production may influence female body condition and therefore clutch size, egg size, hatching success and hatchling size. They may also have synchronised their breeding season with the tuna season as a substantial number of Pacific gulls were observed at the tuna farms. Short-tailed shearwaters and cormorant chicks are just hatching when the tuna season starts (February), so the availability of high quality food may influence chick survival, fledging success and juvenile mortality. Crested terns may breed either from September to December, when the lack of tuna farms means they could not influence the breeding birds, except for perhaps egg production; or they breed from March to June when tuna feed could affect the entire breeding cycle in the same way as silver gulls (pers. comm. NPWS; Trounsen & Trounsen, 1989). However, the specific breeding seasons for these seabirds around Port Lincoln is unknown, as is the effect of tuna feed on their reproductive output and population dynamics.

5.11.1.3 Potential Methods for Controlling the Problem

This research has shown there is an inflated population of silver gulls around Port Lincoln that are of economic concern to the tuna industry, a social problem in Port Lincoln, and a potential ecological problem for other birds. These problems are likely to increase without management and control strategies. There is no quick fix. Culling the gulls may decrease the population in the short term, but if the food is still readily available, they will eventually increase to pre-cull numbers. If the tuna farmers were to feed all their baitfish as frozen blocks, it would effectively prevent all the feed scavenging by silver gulls, but many gulls might starve. This might be considered unacceptable by the public, but could be offset by an effective publicity campaign showing the negative environmental, social and economic impacts of the exponential increase in gulls. To avoid exacerbating these problems would require careful management and timing, so that the food supply of scavenging gulls was gradually reduced until the population reached a sustainable equilibrium. Otherwise, thousands of gulls would have to find other food sources in and around Port Lincoln. Thus, the problem needs a collaborative and well-planned strategy in which the tuna industry gradually change their feeding methods while NPWS vigorously cull gulls until the population is reduced to the few thousand pairs that occurred before tuna farming.

On Rabbit Island in June 1999, all silver gull eggs were made unviable by egg pricking in a joint effort by NPWS and TBOASA, however, there was no follow up data on its effectiveness in reducing the population size (Farlam, unpublished data). In any case, the number of breeding gulls increased from 1999 to 2000 (section 5.4.3.2). Pricking eggs is probably not effective because the egg contents leak and smell, which gulls may detect and respond to by laying another egg (Smith, 1995; Smith & Carlile; 1993). Any culling method needs to be repeated for many seasons to be effective (Belant, 1997). Clearly further research is required to assess the most effective management strategies, feeding regimes at tuna farms, and culling regimes.

5.11.1.4 Do Scavenging Seabirds Search for Other Sources of Artificial Feed When Tuna Feed is Unavailable?

Silver gulls reliant on tuna feed become a problem during and after the tuna harvest. Their main feed source is diminished and then disappears completely so they have two choices; they can either forage for natural feed or invade the town, seeking out artificial feed. It was hypothesised, that due to the opportunistic and scavenging nature of these gulls there would be an influx into town. Although there were limitations in our data because the birds were not counted at regular times at each site and there were few observations, there is nonetheless an evident trend. Near the end of tuna harvest, the number of gulls increased in Port Lincoln, particularly at sites where artificial feed was evident such as the refuse depot and the foreshore. Unsurprisingly, the largest numbers of silver gulls were observed at the refuse depot, but there were probably only 7,000 to 8,000 silver gulls in the town of

Port Lincoln at any one time, which is not even half of the estimated breeding population of silver gulls in the Port Lincoln area. Therefore, where do the majority of these silver gulls go after tuna harvest? The dispersal routes and summertime feeding locations of these silver gulls is unknown. These birds may be foraging for natural feed, such as fish, but could also be preying upon other bird species.

The October efflux of large numbers of hungry silver gulls coincides with the main breeding season of most birds, both seabirds and terrestrial birds, some of them endangered or threatened (such as the banded stilt, fairy tern, little tern and crested tern). Silver gulls are notoriously brazen and aggressive consumers – usually scavenging carrion, but quite capable of taking the eggs and live chicks of other bird species. There have been numerous reports of the detrimental impact of silver gulls on other bird species, consuming the eggs and chicks of endangered species such as the Little Tern (Egan, 1990; Smith, 1995; Smith & Carlile, 1993). They can substantially decrease the breeding success of these species, which is of a great ecological concern.

This ecological impact may not just be localised to Port Lincoln, with 95% of banded silver gulls from South Australian breeding colonies travelling up to 460 km from the banding/breeding colony (Ottaway *et al.,* 1985). Therefore, these silver gulls may travel quite a distance to their summertime feeding sites, and may even travel to ecologically significant breeding sites such as Lake Eyre, where they have been observed to consume banded stilt eggs and chicks (Robinson & Minton, 1989).

5.11.2 Future Research

Further research into the interactions between seabirds and tuna farms could include:

- Assessing the population sizes and reproductive output of Pacific gulls, cormorants, crested terns and short-tailed shearwaters in the Port Lincoln area.
- Determining the ecological impact of the enlarged silver gull population on other birds, especially vulnerable or threatened species.
- Fitting radio tracking devices to silver gulls to assess
    i. dispersal routes and summertime feeding locations.
    ii. whether they breed more than once per season.
    iii. whether they return to Port Lincoln in successive seasons.
- Assessing the nuisance-value of the silver gull in affecting human activities.
- Assessing the amount of feed consumed by seabirds for other feed-delivery methods.
- Using underwater cameras to assess if cormorants take any of the defrosting fish fed as frozen blocks of baitfish.

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Chapter 6 Oceanographic conditions in the offshore southern bluefin tuna farming zone, near Port Lincoln SA

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6.1 Executive Summary

While it is unavoidable that intensive open sea-cage aquaculture operations will release wastes into the surrounding environment, it is the fate of these wastes, and the ability of the environment to assimilate them, that is of importance. Locations with better flushing will allow for the distribution of wastes over a larger area, while sheltered locations may result in an accumulation of wastes. Such an accumulation may increase concentrations of nutrients in the water column and can lead to eutrophication or growth of phytoplankton, which can lead to detrimental effects for the captive fish and the surrounding environment.

The aim of this report was to assess the oceanographic conditions in and around the SBT farming zone near Port Lincoln in Spencer Gulf. This involved determining whether there was any significant difference in oceanographic conditions, nutrients and phytoplankton between near the beginning and near the end of the farming season. A further aim was to observe whether the pens and the presence of fish could result in any changes to the nutrients or phytoplankton and to find out if the farming process is resulting in an accumulation of nutrients.

It was observed that in winter the waters of the offshore SBT farming zone were cooler, fresher and denser than they were in summer. This is a signature of the wintertime density driven exchange circulation across the mouth of Spencer Gulf, which includes inflow of low salinity ocean water on the western side of Spencer Gulf. Concentrations of chlorophyll-*a* were seen to increase in areas where the greatest number of pens were located both before fish were present inside the pens and while there were fish in the pens, indicating that the structures alone may contribute to a localised increase in primary productivity by providing a framework to which photosynthetic organisms may attach. However, there was no significant increase in average chlorophyll-*a* concentrations through the season, hence the high number of fish in the area apparently does not result in an increase in primary productivity on a regional scale. Similarly the nutrient concentrations do not increase despite the presence of fish and the associated farming processes. These results suggest the region is well flushed and this is likely to be driven by the gulf-scale circulation that develops in May each year. There was little evidence of stratification in the water column in either summer or winter, suggesting that the waters are well mixed, and that the system is oceanographically dynamic.

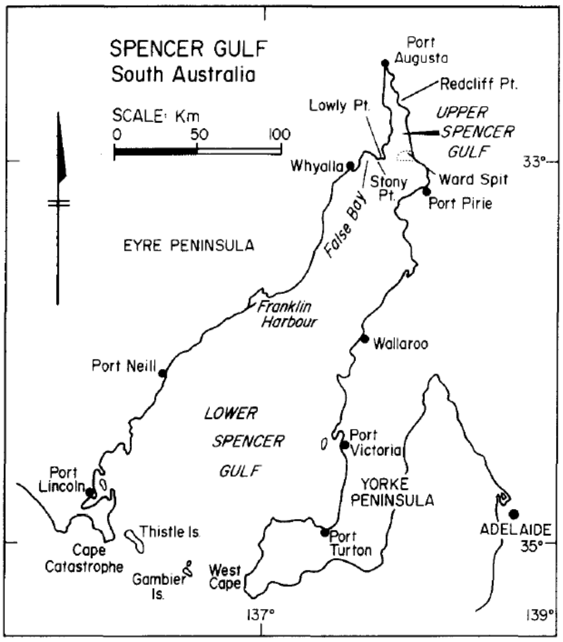
6.2 Background

6.2.1 Spencer Gulf

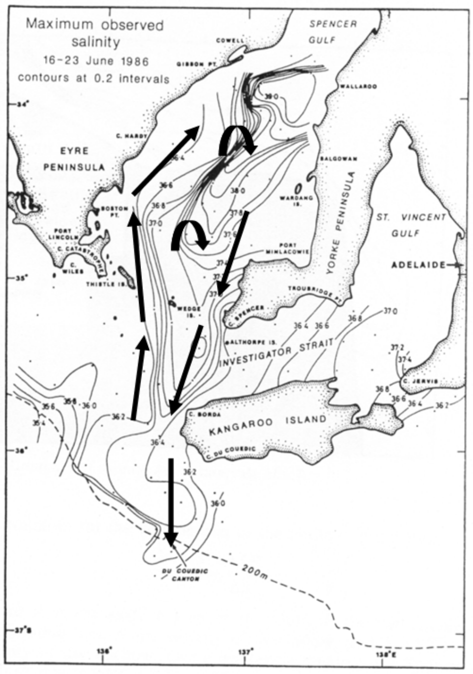
The farming of SBT takes place in the waters offshore from Boston Island, near the township of Port Lincoln, in the lower Spencer Gulf of South Australia. Spencer Gulf is a triangular shaped negative (inverse) estuary located between approximately 33-35ºS and 136-137ºE (Figure 6.1a). The triangular shaped gulf is closed in the north, but open to the continental shelf in the south. Bounded by Eyre Peninsula to the west and Yorke Peninsula to the east, Spencer Gulf experiences only limited connection to the shelf waters. The gulf is 325 km long from the head to the entrance with a mean width of 60 km and a width at the entrance of 80 km (Nunes Vas *et al* 1990). The mean water depth is 22 m but reaches a maximum of 50 m at the mouth. The semi-arid Mediterranean climate of hot-dry summers and cool-wet winters combined with the lack of fresh water input from rivers and the negative precipitation – evaporation balance leads to a salinity in the gulf that is greater than on the shelf. The salinity maximum is located at the head and can be as high as 49 ppt in late summer, but drops to 43 ppt in late winter (Nunes Vas *et al* 1990). Salinity decreases with distance from the head and drops to 36-37 ppt near the shelf. Maximum salinities occur in summer due to high evaporation and low fresh water input. Water temperature also varies between seasons. In summer the mean water temperatures are in the order of 24ºC, while in winter it drops to 12ºC (Nunes Vas *et al* 1990). The gulf waters experience a greater seasonal temperature variation than the shelf due to the shallow water depth, warmer than the shelf in summer but cooler than the shelf in winter. The high evaporation leads to a loss of fresh water but there is no year to year salinity increase, hence there must be processes acting to remove saline water from the gulf and replace it with fresher shelf water.

In late summer both the salinity and temperature within the gulf are high, but in autumn the water temperature decreases whilst the salinity remains high. The cooler saline water becomes denser and a density gradient develops between the water in the gulf and on the shelf. This instability enables the gulf water to flow out of the gulf along the seafloor under an inflow of fresher shelf water (Lennon *et al* 1987) (Figure 6.1b). The current flows out along the central channel within the gulf where the depth is greater, but exits the gulf on the eastern side due to the Coriolis Effect. Once out of the gulf the current crosses over Investigator Strait and flows down the west coast of Kangaroo Island. It flows down the shelf in the Du Couedic canyon to a depth of 250 m, where it finds its own density level (Lennon *et al* 1987). At the mouth of the gulf, the current is 50 km wide but narrows to 20 km near Cape Border on Kangaroo Island (Lennon *et al* 1987). The average speed of this flow has been estimated at 0.1 m s^{-1} and hence the current would take 3 months to remove the salt accumulated over summer (Lennon *et al* 1987). Accompanying this outflow of high salinity water on the eastern side of Spencer Gulf must be an inflow of lower salinity ocean water on the western side of the gulf to conserve volume. This circulation does not begin until winter, when the sea surface temperature (SST) front that exists across the mouth in summer breaks down.

The SST front that limits the communication between the shelf and the gulf forms in November each year and persists until May. The maximum temperature gradient that occurs is 0.8 ºC/km producing a temperature difference of 4ºC between the gulf and the shelf, with the gulf warmer than the shelf in summer (Petrusevics 1993). A density minimum at the front suggests the presence of a convergence zone with mixing between the gulf water and shelf water and between shelf water and ocean water, but no direct mixing between gulf and ocean water (Petrusevics 1993). Hence the SST front prevents the large scale circulation in Spencer Gulf until the breakdown of the front in May.



(a)



(b)

Figure 6.1: (a) M**ap of Spencer Gulf, South Australia (Noye 1984) and (b) the outflow of the high salinity water during winter that generates the gulf scale circulation (Lennon *et al* 1987).**

6.2.2 Boston Bay

In the south west of Spencer Gulf, near to the mouth, is Boston Bay. This shallow bay is approximately 15 km long, 6 km wide and up to 15 m deep. It is bounded by lower Eyre Peninsula with the township of Port Lincoln to the west and Boston Island to the east. Boston Island is 5 km long and 2 km wide and limits exchange to the bay to the 4 km wide channels to the north and south of the island. For the majority of the time the winds in the region are gentle breezes of less than 10 knots (~5 m s^{-1}) mostly from the southeast in summer and from the west in winter (Bond 1992). The region rarely experiences gale force winds, 34 – 40 knots, but when they do occur they are predominantly from the northwest and occur during spring (Bond 1992). Within the bay currents are relatively weak, less than 5 cm s^{-1} for the majority of the time and slightly weaker in the west, close to the coast, than in the east near the island. The currents are greatest in the south channel entrance to the bay, but still less than 12.5 cm s^{-1} for the majority of the time (Bond 1992). Waters within the bay are well mixed with surface to bottom variations of less than 0.5 ºC and 0.05 ppt (Bond 1992). The exchange periods for the bay have been calculated, using actual wind and tide data, to be 29 days in summer but just 4 to 5 days in winter (Bond 1992). This dissimilarity may be attributed to the seasonal variations within the entire Spencer Gulf limiting exchange during summer.

6.3 Aims and Objectives

The purpose of this report is to assess the oceanographic conditions in and around the SBT farming zone, offshore from Boston Island, that influence nutrient dispersal.

Comparisons between the conditions in summer, before the SBT farming season, and winter, during the season, will show what affect, if any, the aquaculture activities have on the nutrient regime. Comparisons between measurements taken throughout the region and measurements taken nearby to a pen will give an indication of the effect of these structures and the fish within. Measurements of temperature, salinity and density will give an indication of stratification or mixing throughout the water column. Turbidity measurements along with current speed and direction will indicate whether sediment resuspension may be occurring. Measurements of chlorophyll-*a* will show the significance of primary productivity and whether it is being altered by the presence of the aquaculture operations, while nutrient concentrations will show whether nutrients are accumulating in the water column or being dispersed by the currents.

Some of the questions that this report will attempt to address include:

- Is there a significant difference in the oceanographic conditions between summer and winter?
- Are there any changes in nutrient regimes and primary productivity between the two seasons?
- Do the pens and the presence of fish within these pens affect the nutrients and primary productivity?
- Is there any accumulation of nutrients within the water column or are currents sufficient to disperse wastes?

6.4 Methods

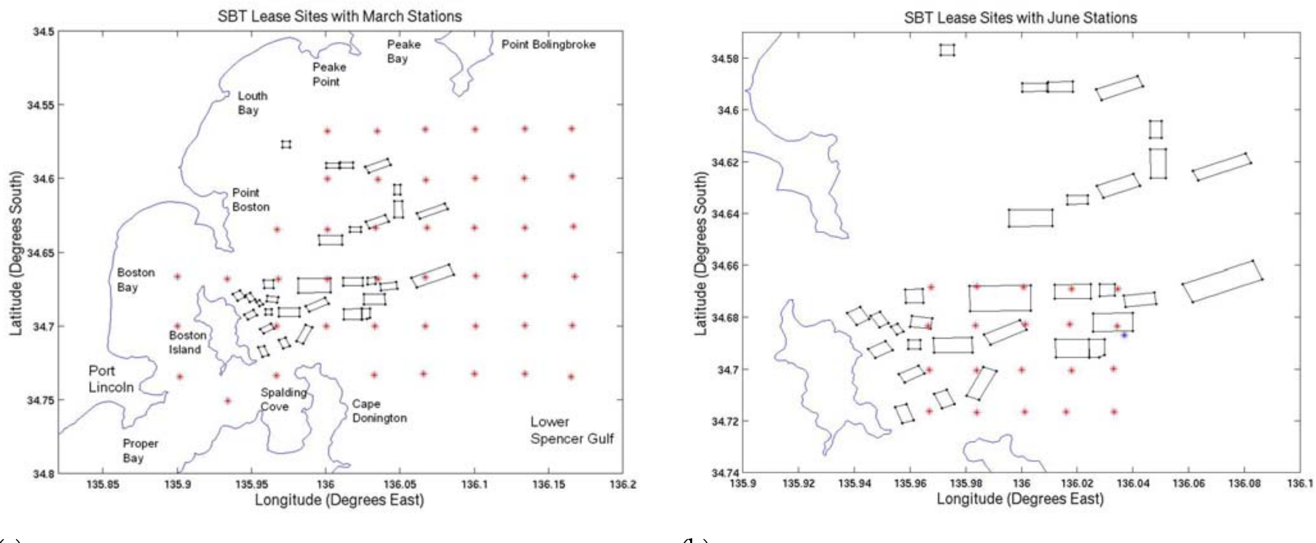
6.4.1 Site Description

The majority of SBT leases are currently located directly east from Boston Island, with some further north offshore from Point Boston. They are spread over an area that extends from 34º 34.2`S to 34º 43.2`S and from 135º 56.2`E to 136º 4.8`E. Hence the study area includes this and the surrounding waters (Figure 6.2). The coastline to the west of the study area, or the eastern side of Eyre Peninsula, is varied consisting of numerous bays and points incorporating both sandy beaches and rocky shores with a number of small islands spread throughout the region. From the north of the area following the coast southward exists Point Bolingbroke, Peake Bay, Peake Point, Louth Bay, Louth Island, Rabbit Island, Point Boston, Boston Bay, Boston Island, Proper Bay, Spalding Cove and Cape Donington. The east of the study area is the lower Spencer Gulf and the Sir Joseph Banks group of islands, which includes more than 17 individual islands. Water depths in the area range from 18 m up to 24 m with the greatest depths towards the south east.

6.4.2 Field Work

In order to assess the oceanographic properties of the region it was necessary to obtain *in situ* measurements of temperature, salinity, current speed and current direction. To obtain a background summertime description of the area, a large grid was established consisting of 44 stations starting in Boston Bay and extending from Cape Donington in the south to Point Bolingbroke in the north and as far east as Sibsey Island (Figure 6.2a). The main section of this grid consisted of equally spaced stations separated by 2 minutes of longitude and 2 minutes of latitude, ~ 3.05 km in the east/west direction and ~ 3.71 km in the north/south direction, covering a total area of 340 km^2. To assess the conditions during winter, a smaller grid was established immediately east of Boston Island where the majority of lease sites are located (Figure 6.2b). This grid consisted of 20 equally spaced stations separated by 1 minute of longitude and 1 minute of latitude, ~ 1.53 km in the east/west direction and ~ 1.86 km in the north/south direction, covering an area of 34 km^2. The large grid was surveyed at the beginning of the SBT farming season, between the 7th and the 11th of March 2005, whilst the small grid was surveyed towards the end of the farming season, between the 28th of June and the 1st of July 2005. Also in both March and June additional stations were sampled over a small area surrounding a single pen, which in March contained no fish.

At each station, water samples were collected from both the surface, using an open bucket, and near the seafloor, with a Nansen bottle, and 250 mL of this water was filtered through 0.45 μm filter paper using a hand pump to remove all organic matter from the sample for the determination of chlorophyll-*a*. The filtered water was transferred to a 250 mL black sample bottle and kept on ice until the return to land, while the filters were folded in half and wrapped in foil and also iced. Once back on shore, within 8 hours of collecting the samples, the bottles were frozen at -20ºC and the filters at -80ºC. Measurements of temperature, conductivity, pressure, turbidity, current speed and current direction were obtained at different depths between the surface and the seafloor using a recording current meter. The first measurement was taken 1 m below the surface, with subsequent measurements taken at approximately 2 m intervals, with the actual depth determined from measurements of the pressure. Along with these measurements, recordings of the precise location of the boat were taken to later correct for any drift of the boat during sampling.



(a) (b)

Figure 6.2: **(a) The location of sampling stations in reference to the coastline and the SBT leases in March and (b) the sampling stations in June. The positions of the moorings are indicated by the blue star in (b).**

6.4.3 Chlorophyll-*a* Analysis

The abundance of phytoplankton and hence the primary productivity within a body of water can be estimated using the concentration of chlorophyll-*a* [C_a]. Chlorophyll-*a* is a nitrogen containing plant pigment that is a necessary part of the conversion of sunlight into energy in photosynthesis. High concentrations of chlorophyll-*a* will indicate high primary productivity and a large presence of phytoplankton, thus possibly indicating an algal bloom.

Determining [C_a] involved measuring the fluorescence of the C_a pigments at 665 nm due to stimulation at 440 nm using a fluorometer. Initially the filters were dissolved in 5 mL of 90% acetone in a 10 mL centrifuge tube using a vortexer for ~ 2 minutes. Tubes were placed in a bucket of ice and stored in a freezer for 24 hours. After this time the centrifuge tubes were removed from the ice and the vortexer was again used to evenly mix the solution. The tubes were placed in the centrifuge and centrifuged for 10 minutes at 2000 rpm to remove solid particles from the solution that may interfere with the fluorescence. After allowing the fluorometer to warm up for ~ 10 to 15 minutes, a blank solution, consisting of a clean filter dissolved in acetone, was placed in the clear cuvette and placed inside the fluorometer. The reading from this test was subtracted from the results of the samples. Samples were pipetted into the cuvette, which was placed in the fluorometer for a few minutes until a stable reading was observed. Between each sample the cuvette was rinsed with 90% acetone and the outside was cleaned with a tissue. At regular intervals another blank was tested to record the offset for the readings. After all the samples were tested the blank was subtracted, then the fluorescence readings were converted into concentrations of C_a. This was done using the equation $[C_a] = \left(\frac{F}{S}\right) * \left(\frac{V_E}{V_S}\right) * SF$ (μg L^{-1}), where F is the fluorometer reading, S is the slope (2.1457 when the fluorometer is set to a very high range, 0.2625 for high range and 0.05385 for medium range), V_E is the extracted volume (0.005 L), V_S is the sample volume (0.250 L) and SF is the scaling factor (1.088, based on a stock solution).

6.4.4 Nutrient Analysis

Nutrients present in the water column are utilised by phytoplankton and are necessary for growth. Often when concentrations of a nutrient are low, the growth of phytoplankton is limited by that nutrient, usually nitrogen in the marine environment. When the availability of the limiting nutrient is increased this may lead to an increased growth of phytoplankton, and possibly an algal bloom. Thus it is necessary to monitor the concentrations of nutrients available in the water.

Water samples collected and filtered on the boat were stored in black sample bottles and frozen until they could be analysed using a μchem MP nutrient analyser by Systea. This automatic chemical analyser tested the water samples for ammonia (NH_3), phosphate (PO_4), nitrite (NO_2) and nitrate (NO_3). Samples were removed from the freezer and allowed to thaw at room temperature. Once defrosted, the water was transferred from the black sample bottle to a 100 mL sample bottles in the automatic sampler. The analyser drew ~25 mL of the sample from the sample bottle into the cell where it mixed with the reagents. After the reactions took place the optical density, OD, was measured using a monochromatic light source and a silicon detector. The OD of a pure water solution, or blank, was subtracted and the result converted into a concentration in μg L^{-1}.

The test for ammonia follows Berthelot's reaction, where ammonia and phenol in the presence of chlorine react to form indophenol blue (Lau *et al* 2003). Trisodium citrate and EDTA are added to the reaction to avoid the precipitation of alkaline hydroxides, while nitroprusside acts as a catalyst. The indophenol is then measured using a wavelength of 630 nm. In the test for phosphate, the orthophosphate present in the sample water reacts with molybdate in an acid medium to form phosphomolybdate. This intermediate product then reacts with ascorbic acid, with an antimony catalyst, to form molybdenum blue which is measured at 880 nm. Nitrite present in the sample reacts with sulphanilamide and N-(1-naphtyl) ethylendiamine in acid medium to give diazonium salt, which is measured at 550 nm. Finally nitrates present in the sample are reduced to nitrite in a copper cadmium column, in a buffered medium, and then tested as nitrites (SYSTEA μchem MP user manual).

Various problems occurred with the analysis of these nutrients. After the March water samples were collected, but before they could be analysed, the freezer broke down causing all the samples to defrost. The samples remained in a fridge at 1 – 2 ºC for a period of ~2 days. As the instrument for testing the samples was unavailable for use at this time, the samples were refrozen. It is unknown what effect this problem had on the nutrient concentrations within the water. The processes used by the analyser rely upon prepared reagents, a calibration solution and a buffer solution for the reactions. Though due care was taken in the preparation of these solutions and readings were blanked and calibrated every time a solution was changed it is still possible that this also impacted upon the concentrations. A number of unexplained anomalies resulted in concentration values that were well beyond reasonable values and hence these were excluded from the results. This explains the low number of nutrient concentrations compared to the number of samples taken.

6.4.5 CTD Analysis

Oceanographic properties such as current speed, current direction, temperature, conductivity, pressure and turbidity were measured using an RCM-9 Mk II, a recording current meter by Aanderaa. The range, resolution and accuracy of these parameters are given in Table 6.1.

Table 6.1: **The range, resolution and accuracy of the parameters measured by the RCM-9 Mk II (Aanderaa Instruments 2000).**

Parameter	Sensor Type	Range	Resolution	Accuracy
Current Speed	Doppler Current Sensor	0 – 300 cm s^{-1}	0.3 cm s^{-1}	± 0.15 cm s^{-1}
Current Direction	Magnetic Compass	0 – 360 º	0.35 º	± 5 º to ± 7.5 º
Temperature	Thermistor	9.81 – 36.66 ºC	0.1 % of range	± 0.05 ºC
Conductivity	Inductive cell	0 – 74 mS cm^{-1}	0.1 % of range	± 0.8 % of range
Pressure	Silicon piezoresistive bridge	0 – 700 kPa	0.1 % of range	± 0.25 % of range
Turbidity	Optical Back-scatter sensor	0 – 100 NTU	0.1 % of full scale	± 2 % of full scale

From the range of conductivities, the salinity range was calculated to be 0.01 – 57.42 ppt (at 20ºC and 10 kPa) with an accuracy of ± 0.08 ppt and a resolution of 0.043 ppt. The range for density values was found to be between 993.5 and 1044.3 kg m^{-3}, from the extremes of the temperature and salinity range.

The measurements of conductivity were recorded in mS cm^{-1} and converted into salinity in ppt using the temperature and pressure following the method given in Fofonoff & Millard (1983). Densities were calculated from the salinity, temperature and pressure using SEAWATER version 3.0 in MATLAB. The actual depths of the measurements were calculated from the pressure measures using the equation $Depth = \frac{P - P_0}{\rho . g}$ (m), where P is the pressure in Pascals, ρ is the density in kg m^{-3}, g is the acceleration due to gravity (~9.8 m s^{-2}) and P_0 is the atmospheric pressure. As the atmospheric pressure at the time of measurements was not known with sufficient precision, P_0 was calculated by assuming the first measurements of each profile occurred at 1 m below the surface.

Current speeds were recorded in cm s^{-1} and the direction was recorded in degrees from magnetic north. The motion of the boat affected these measurements, and to correct for this, the current speed and direction firstly had to be broken down into the north/south and east/west components. This was done using the relationships *v = V*COS(a)* and *u = V*SIN(a)*, where *v* is positive in the northward direction and *u* is positive in the eastward direction. The GPS coordinates of the boat's location were recorded at the start and end of the profile, in degrees and minutes to 3 decimal places, and the displacement of the boat in the north/south and east/west directions were determined from these coordinates. The displacement of the boat in each direction was converted from minutes of latitude and longitude into centimetres using the relationship that 1 minute of latitude equals ~1.86 km and 1 minute of longitude (at ~34° 40`S) equals ~1.53 km. The displacement was converted into a speed, in cm s^{-1}, using the period of time over which measurements were collected. These *u* and *v* components of the boat's motion were added to the components of current speed to get the actual current speed components. Finally the actual current speed was calculated as the square root of the sum of these corrected components squared, $V = \sqrt{u^2 + v^2}$, and the actual current direction was calculated using the inverse tangent function of the ratio of the corrected *u* component to the corrected *v* component.

This process of correcting for the drift of the boat assumed that the boat was moving at a constant speed and in the same direction over the period of the profile.

6.4.6 Moorings

To measure variation in the currents within the SBT farming zone over a period of time, two moorings were deployed and measurements of current speed and direction were recorded between late June and early August. The construction of both moorings was similar, consisting of two 30 kg bottom weights connected by a 40 m ground line. The instrument was connected to a buoy attached to one weight to hold the instrument 1 m above the seafloor. The second weight was connected to a surface buoy used to retrieve the mooring. One instrument used was an RCM-9 Mk II; the same as the instrument used in the CTD profiles. This mooring recorded current speed, current direction, temperature, conductivity and turbidity every 5 minutes for a period of 42 days from June 29th to August 9th 2005. The second instrument was the S4, which measured current speed and direction every half second for a period of 5 minutes once every 6 hours between the 1st of July and the 6th of August 2005. The moorings were located approximately 370 m apart within the SBT farming zone at approximately 34° 40.928 S and 136° 02.026 E (Figure 6.2b). Problems were encounted with the salinity and turbidity measurements from the RCM-9 as a result of fouling. The fouling of the sensors resulted in an increase in turbidity measurements over time accompanied by a decrease in salinity measurements.

6.5 Results & Discussion

6.5.1 March

6.5.2 Temperature

In March, measurements of water temperature were recorded from the sea surface and seafloor and at various depths in between. All of the temperature measurements fell between 19.5 °C and 21.0 °C with an average value of 20.1 °C. This small range indicates that the water temperatures in the region during this time of year were uniform. The surface water was slightly warmer than near the seafloor as a result of contact with the atmosphere. Figure 6.3 shows how the surface and seafloor temperatures varied with location indicating that there was very little spatial variation with only small areas where temperatures were slightly warmer or cooler. Figure 6.4 shows an example of a typical vertical profile and the distribution of the depth-averaged temperature measurements for the large grid. The majority of the temperature profiles show an almost constant temperature with depth, while a smaller number of locations show slight increases in temperature at the very surface or bottom of the profile, but these resulted in temperature to bottom differences of no more than 0.5ºC.

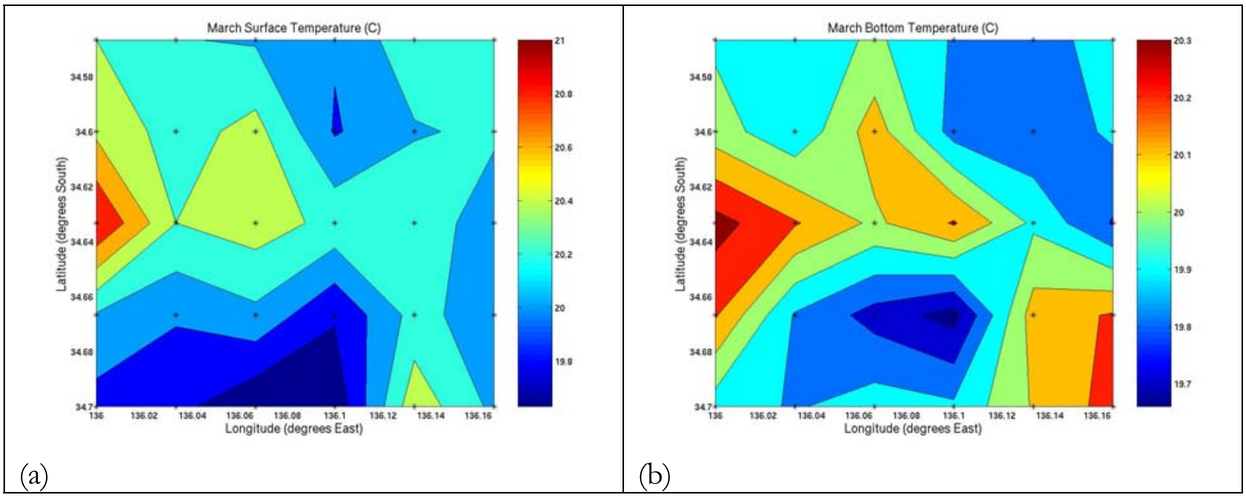


Figure 6.3: (a) Surface and (b) bottom temperature (ºC) variations in March 2005.

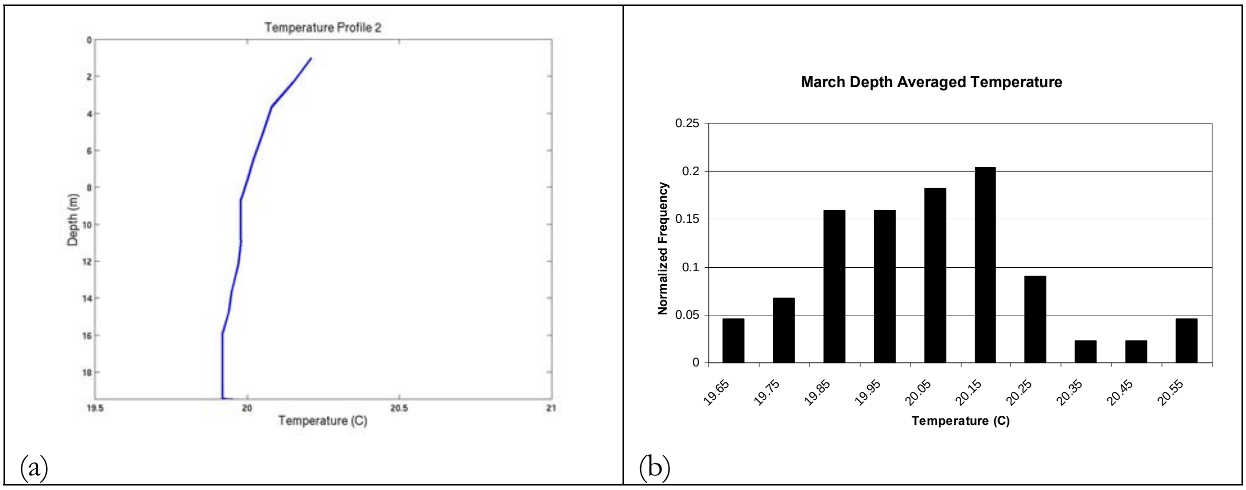


Figure 6.4: (a) **A typical temperature profile showing the small variation between the surface and seafloor and (b) the distribution of depth-averaged temperature measurements.**

6.5.3 Salinity

Salinities observed during March range from 36.63 ppt to 37.22 ppt with an average value of 36.89 ppt. Salinity measurements show spatial variation near both the surface and the seafloor, with an increase in salinity towards the south-east where the depth of water is greatest. This variation is more evident near the seafloor where salinity in the south-east is 0.2 ppt greater than average. The majority of profiles of salinity with depth show no difference in salinity between the surface and the seafloor. Figure 6.5 shows the spatial variation in surface and bottom salinity, while Figure 6.6 shows an example of the near uniform salinity profiles and the distribution of depth-averaged salinity measurements.

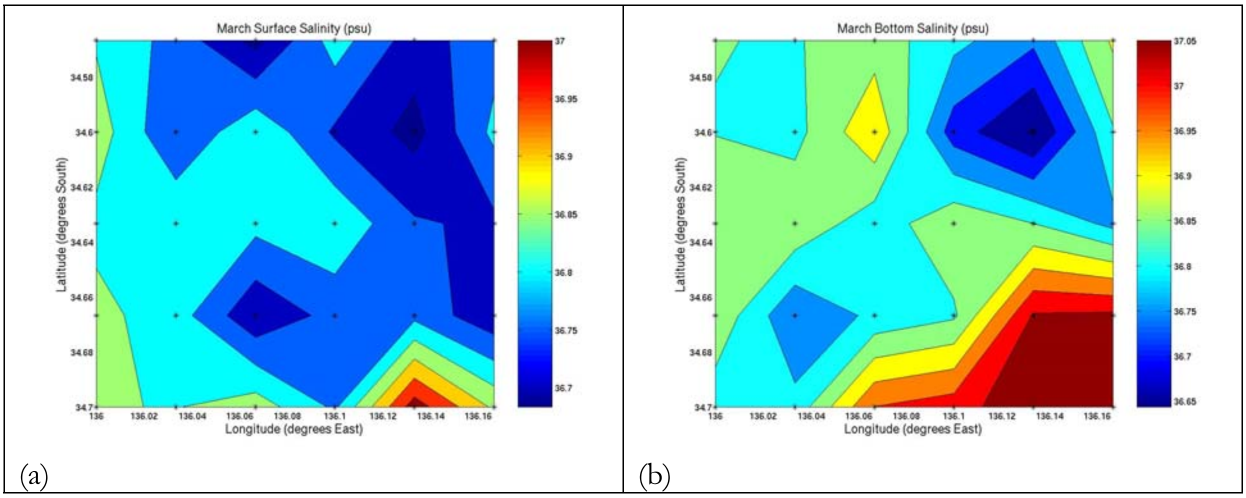


Figure 6.5: **(a) Surface and (b) bottom salinity variations in March 2005. 1 psu = 1 ppt.**

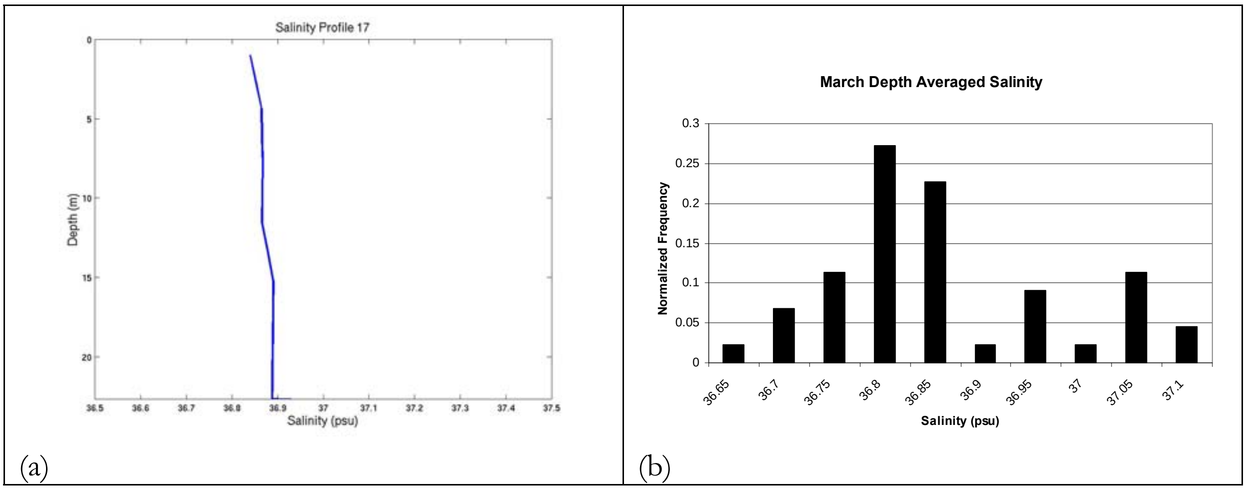


Figure 6.6: **(a) An example of a near uniform salinity profile and (b) the distribution of depth-averaged salinity measurements. 1 psu = 1 ppt.**

6.5.4 Density

Density measurements were calculated from the temperature and salinity data. Densities ranged between 1025.8 kg m^{-3} and 1026.5 kg m^{-3} with an average value of 1026.2 kg m^{-3}. The lateral variations in density are similar to those in salinity, with the denser water located in the south east where the water is deepest and the salinity greatest. This is as expected with salinity a controlling factor in the density structure when temperatures are nearly constant. Like the temperature and salinity, density shows very little variation through the profiles with only a slight increase towards the seafloor, indicating a well mixed body of water. Figure 6.7 shows the surface and bottom density plots showing only minor increases in density towards the south of the study area. Figure 6.8 shows an example of a density profile showing only a minimal surface to bottom density increase and the distribution of depth-averaged density measurements.

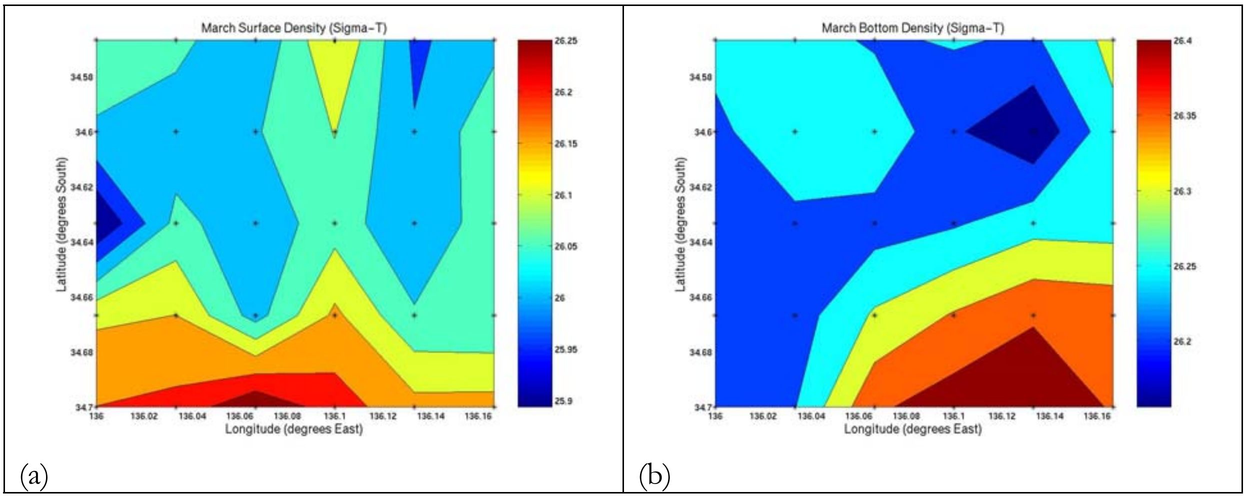


Figure 6.7: **(a) Surface and (b) bottom density variations in March 2005. Units are variations from 1000kg m^{-3}.**

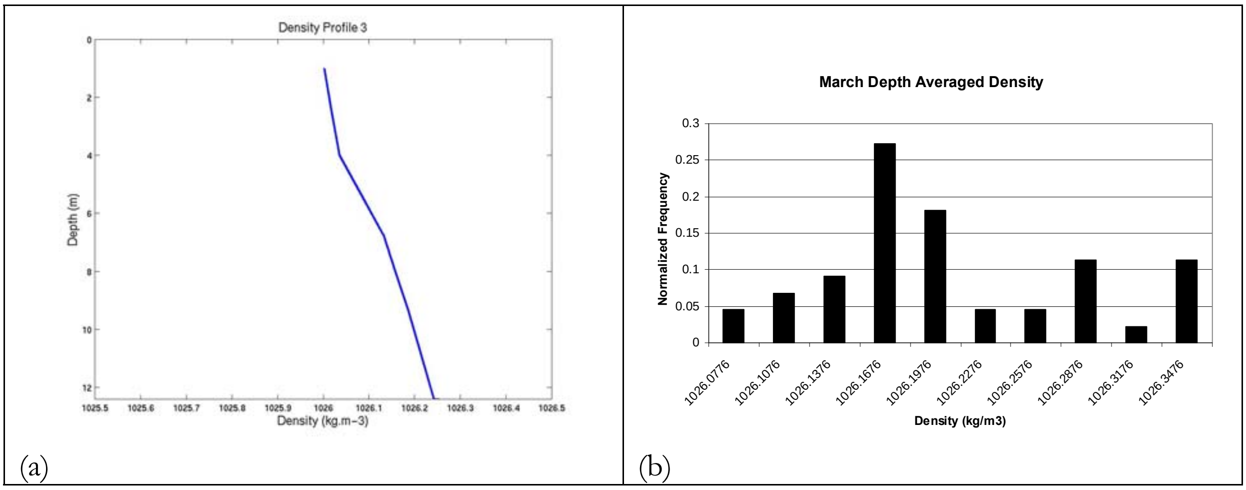


Figure 6.8: **(a) A typical density profile and (b) the distribution of depth-averaged density measurements in March 2005.**

6.5.5 Current Speed & Direction

Measurements of current speed and direction were taken at the same locations as the other variables. The current speeds observed range between 0.30 cm s^{-1} and 33.7 cm s^{-1} with an average speed of 12.7 cm s^{-1}. The distribution of speed measurements is such that the majority of data points are located at the lower end of the range, as indicated by the positive skewness value of 0.50. The current direction varied through the full 360º.

Measurements of current speed with depth were made both within and just outside an unstocked pen. These measurements indicate only a minor reduction of speed within the pen compared with outside, from a depth-averaged speed of 10.6 cm s^{-1} outside to 9.97 cm s^{-1} inside.

The majority of current speed profiles show an almost constant speed with depth, with only small variations of up to 10 cm s^{-1} within the profile as a result of turbulence and mixing. When considering the current speed near the surface and near the seafloor separately, it can be seen that surface currents are on average slightly greater than currents near the seafloor, an average of 12.2 cm s^{-1} compared to 9.98 cm s^{-1}. The current direction remains constant with depth for the majority of locations also. Figure 6.6 shows a typical current speed profile and current direction profile.

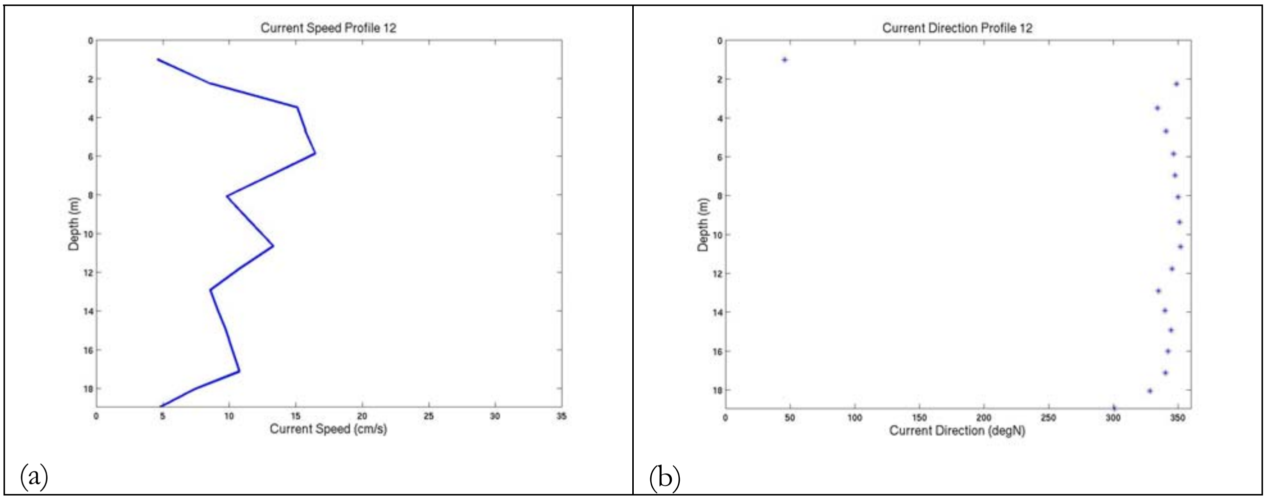


Figure 6.9: **(a) A typical current speed profile and (b) current direction profile observed during March 2005.**

6.5.6 Turbidity

Turbidity measurements during March ranged between a minimum turbidity of 0 NTU and a maximum turbidity of 4 NTU, with an average value around 0.8 NTU. Surface turbidity values were very low averaging 0.6 NTU, while bottom turbidity values were only slightly higher with an average of 1.2 NTU. Both surface and bottom turbidity values are greatest in the west, but this observation is more evident in the surface values. No correlation could be observed between turbidity values and water depth, nor could a relationship be observed between the turbidity near the seafloor and the current speed at that depth. Figure 6.10 shows the increase of surface turbidity towards the coastline and the increase in turbidity towards the seafloor. Average turbidity near the seafloor around the selected unstocked pen was slightly greater, 1.34 NTU, compared with the average turbidity near the seafloor over the large grid, 1.10 NTU. Figure 6.11 shows the distribution of the depth-averaged turbidity measurements in March and the distribution of surface and seafloor turbidity indicating the difference in the range of measurements between the surface and seafloor.

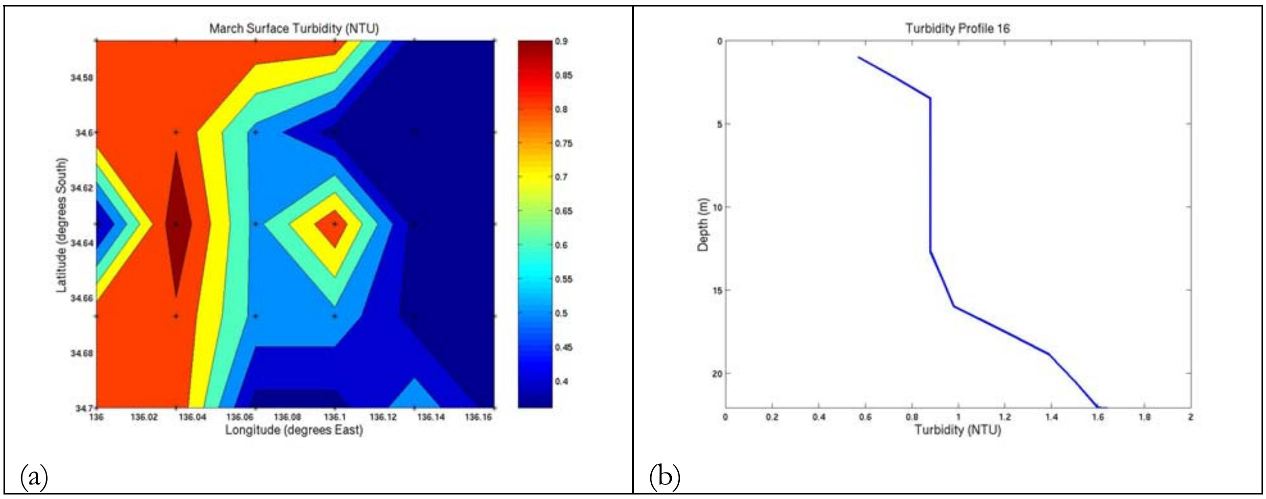


Figure 6.10: **(a) The variation in surface turbidity with location and (b) the increase in turbidity with depth in March 2005.**

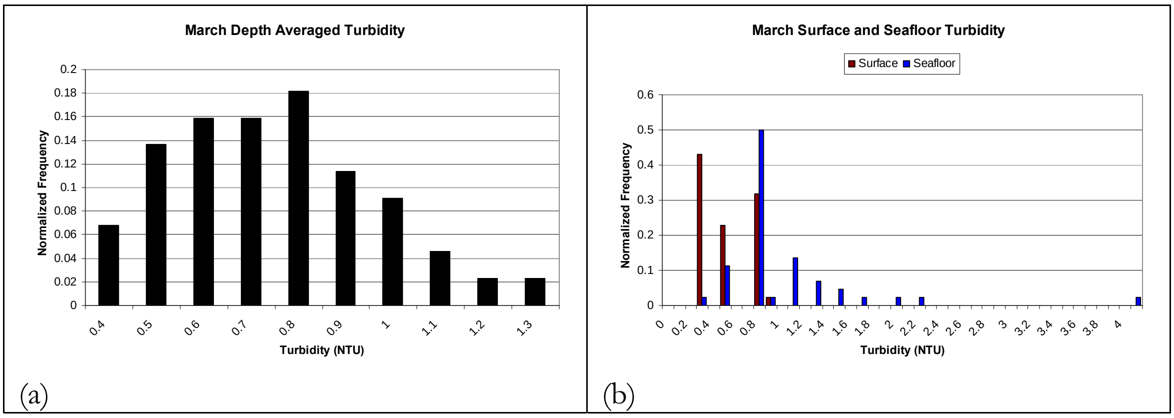


Figure 6.11: **(a) The distribution of depth-averaged turbidity measurements and (b) of surface and seafloor turbidity, in March 2005.**

6.5.7 Chlorophyll-*a*

Measurements of chlorophyll-*a* concentrations during March ranged from 0.23 μg L^{-1} up to 1.94 μg L^{-1}, with an average value of 0.73 μg L^{-1}. Although the range of values was very similar for the surface and near-seafloor measurements, the average concentration at the surface was greater than near the seafloor; 0.85 μg L^{-1} compared to 0.59 μg L^{-1}. There was an increased concentration of chlorophyll-*a* towards the south west of the study area (Figure 6.12). This corresponds to water directly offshore from Boston Island where the majority of SBT leases are located. Two main factors could lead to higher chlorophyll-*a* in this area: proximity to land and proximity to SBT pens. These aquaculture structures may slow water flow and create conditions more favourable to plankton growth, although the minimal decrease in current speed measured inside the pen suggests that this is unlikely, especially given that phytoplankton doubling times are on the order of 1 day in favourable conditions.

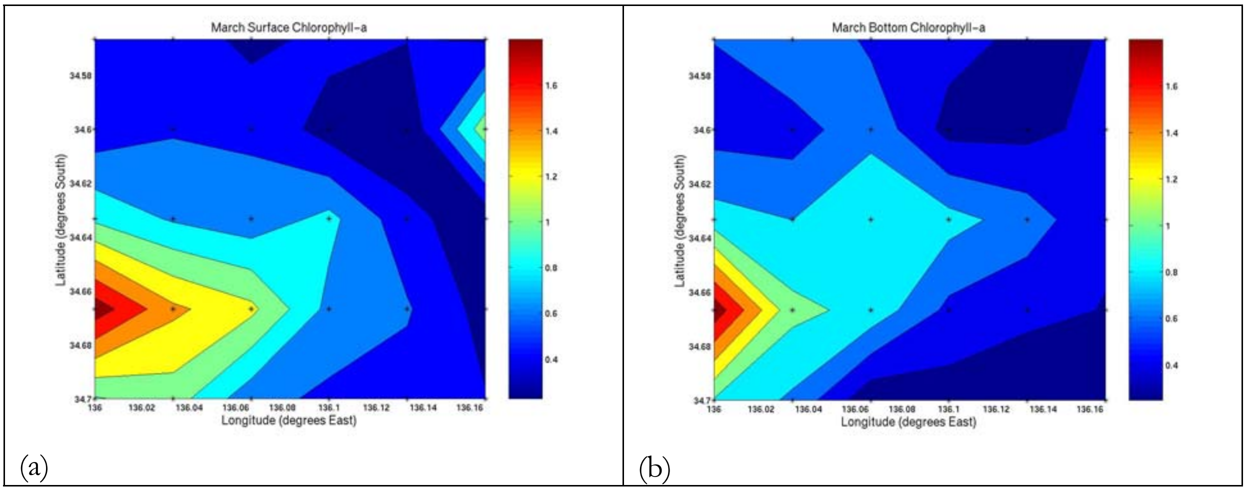


Figure 6.12: (a) **The surface and (b) near seafloor chlorophyll-a concentrations (μg L^{-1}) in March 2005.**

A number of chlorophyll-*a* concentrations were determined over a small scale surrounding the selected unstocked pen. It was observed that the concentrations around the pen lie within a smaller range than those from the large grid, but have an average that is greater at

0.92 μg L^{-1} compared to 0.63 μg L^{-1} of the other stations. Also a greater surface to seafloor variation is observed around the pen. Surface and near seafloor averages near the pen are 1.20 μg L^{-1} and 0.52 μg L^{-1}, while over the other stations of the grid the surface and seafloor averages are 0.65 μg L^{-1} and 0.60 μg L^{-1}, respectively. Figure 6.13 shows the distribution of chlorophyll-*a* concentrations determined in March. It shows the concentrations determined over the large grid and from around the pen. It can be seen that the surface and seafloor values for the grid lie over the same range, but the surface and seafloor values from around the pen form two distinct peaks showing the variation between the surface and the seafloor. The higher chlorophyll-*a* concentrations nearby to the pen suggests that these structures might influence chlorophyll-*a* levels, despite being empty at this time of year, by fouling of photosynthetic organisms upon the structures. However, it is also likely that these results are due to the sampled pen being situated in more nutrient rich waters close to shore.

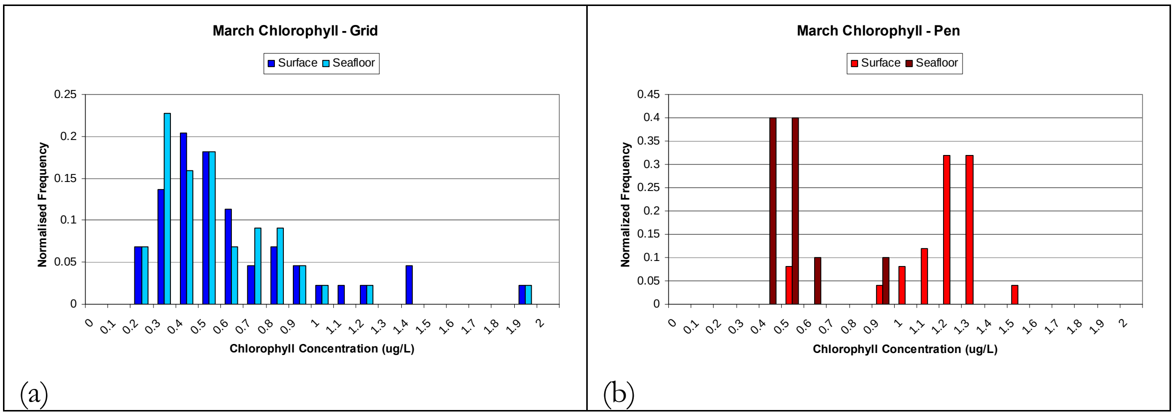


Figure 6.13: (a) **The distribution of chlorophyll-*a* concentrations from the surface and near the seafloor from across the grid in March and (b) near the pen.**

6.5.8 Nutrients

In March, measurements of ammonia, phosphate, nitrite and nitrate were made at the sea surface and near the seafloor. It was seen that the average ammonia at the surface was slightly lower than the average ammonia at the seafloor; 17 μg L^{-1}compared to 21 μg L^{-1}. The phosphate, nitrite and nitrate showed no variation between the sea surface and seafloor, with mean concentrations of approximately 14, 4 and 25 μg L^{-1} respectively. Both ammonia and nitrate show large ranges of values (Figure 6.14), but the low number of measurements at the higher end of the scale indicates that these values may be outliers as a result of problems encountered in the analysis process and may not be representative of actual conditions in the system. The range of phosphate and nitrite is less (Figure 6.14) and phosphate values form a distribution that is close to normal while the nitrite shows the greatest number of values close to zero with a decreasing number of values at higher concentrations. Figure 6.14 shows the distribution of surface and bottom ammonia, phosphate, nitrite and nitrate. No patterns can be observed for the spatial variation of ammonia, nitrite and nitrate, but phosphate appears to be greatest on the perimeter of the study area with minimum values in the centre. As mentioned, a number of errors occurred in determining nutrient concentrations which places much uncertainty in the results presented here.

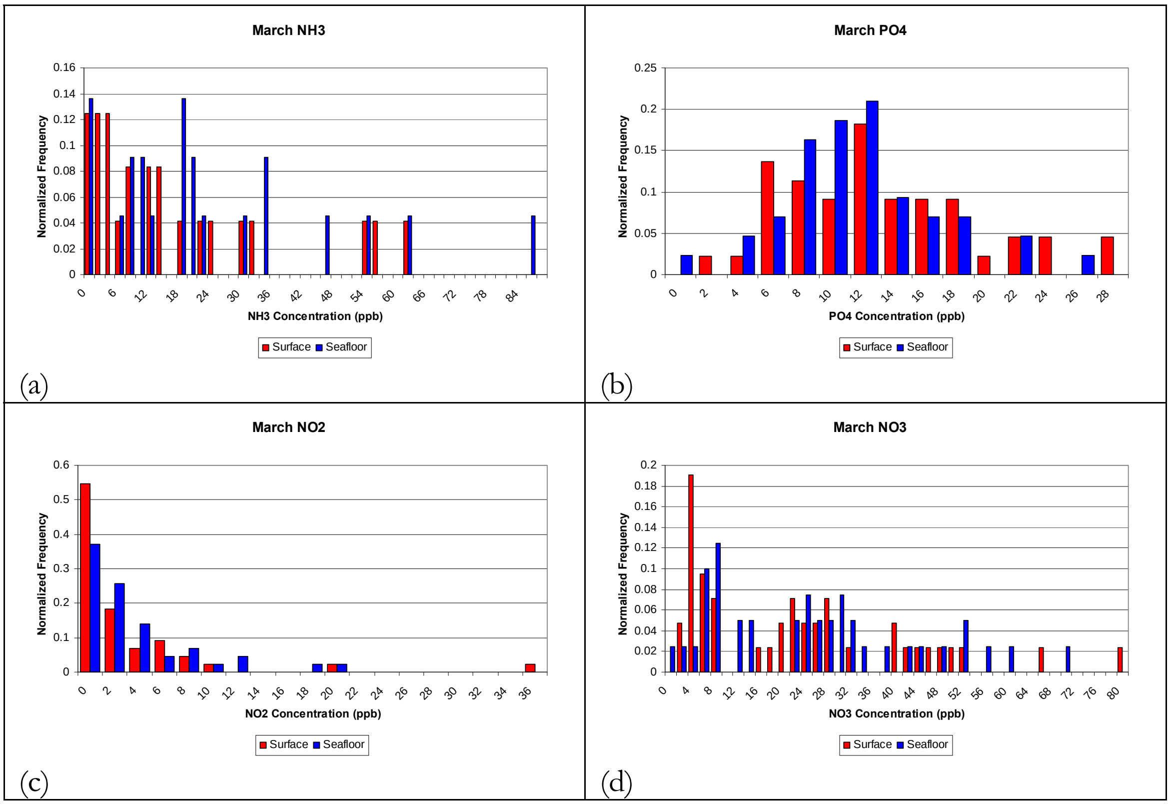


Figure 6.14: **The distribution of nutrient concentrations in March 2005: (a) ammonia, (b) phosphate, (c) nitrite and (d) nitrate. 1 ppb = 1µg L^{-1}.**

6.5.9 June

6.5.10 Temperature

Water temperatures observed during June ranged from 13.9 °C to 15.4 °C with an average value of 15.1 °C. The majority of measurements fell towards the warmer end of the range with fewer measurements occurring closer to the minimum value, as shown by the negative skewness of -2.02. Surface temperatures were slightly warmer than at the bottom with an average of 15.2 °C compared to 14.7 °C. Figure 6.15 shows the surface and bottom variations in temperature, while Figure 6.16 shows a temperature profile from a station located near the centre of the grid and the distribution of depth-averaged temperature values. The profile shows the difference between surface and bottom temperatures evident in the centre of the grid. Other profiles in shallower waters further to the east show almost no drop in temperature. The contour plots show a clear increase in temperature with distance from the coast, probably due to shallower water depths towards the south east of the smaller area monitored in June.

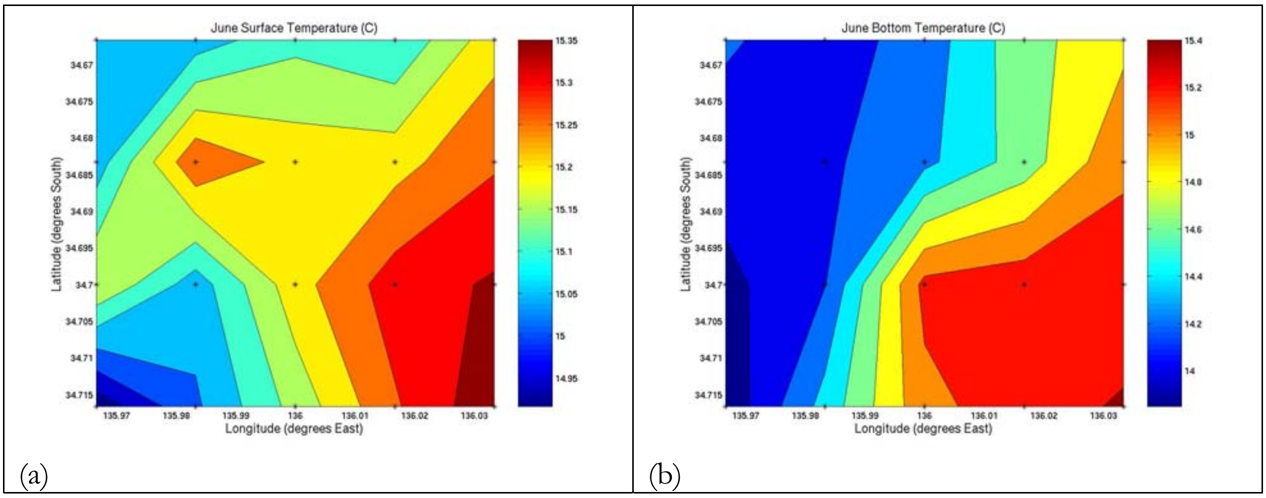


Figure 6.15: (a) S**urface and (b) near seafloor temperature variations observed in June 2005.**

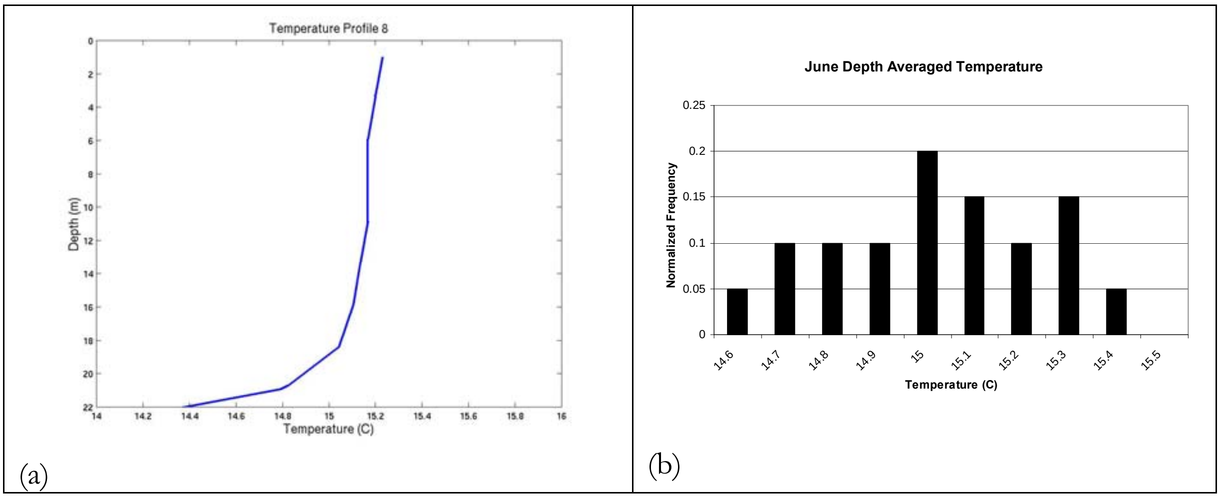


Figure 6.16: **(a) A typical temperature profile and (b) the distribution of depth-averaged temperature measurements from June 2005.**

6.5.11 Salinity

Salinity measurements in June ranged from 35.62 ppt to 36.18 ppt with an average salinity of 36.03 ppt. Average surface salinity was 36.08 ppt, which is very similar to the average bottom salinity of 36.03 ppt. Figure 6.17 shows the spatial distribution of salinity near the surface and seafloor and Figure 6.18 shows one of the salinity profiles and the distribution of depth-averaged salinity values. There is very little variation in salinity on the surface, on the bottom or at any depth down the profile.

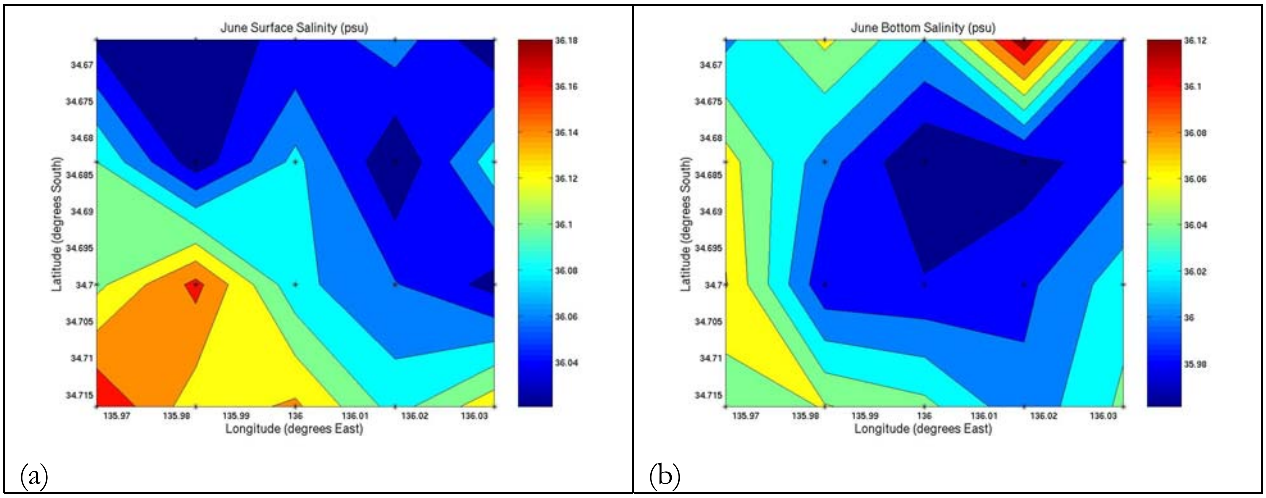


Figure 6.17: **(a) Surface and (b) bottom salinity variations in June 2005. 1 psu = 1 ppt.**

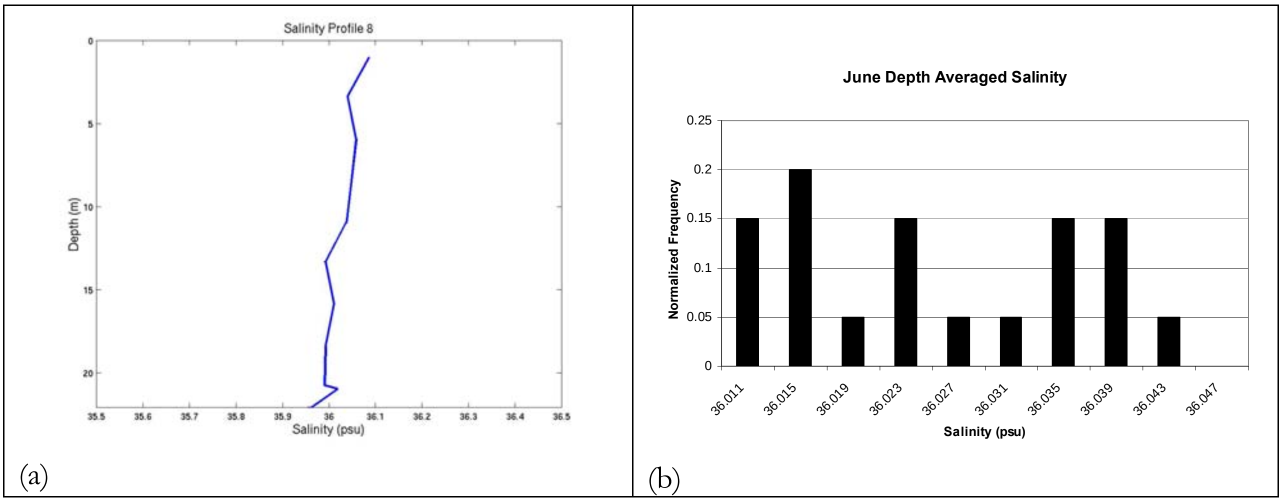


Figure 6.18: **(a) A typical salinity profile and (b) the distribution of depth-averaged salinity values in June 2005. 1 psu = 1 ppt.**

6.5.12 Density

Density values observed in June range between 1026.6 and 1027.2 kg m^{-3} with an average of 1026.9 kg m^{-3}. As expected, the surface density average was slightly less than the average bottom density; 1026.8 kg m^{-3} compared with 1027.0 kg m^{-3}. Figure 6.19 shows the density variations observed in June and Figure 6.20 shows a density profile and the distribution of depth-averaged density. Very little spatial variation was seen in the surface densities with only a minor increase towards the south-west, but the bottom density appears to decrease towards the south-east. This is a result of decreased water depth and the increase in water temperature that results from this. The profiles show the slight increase in density between the surface and the bottom, but this difference is again very small, indicating that the water body is well mixed.

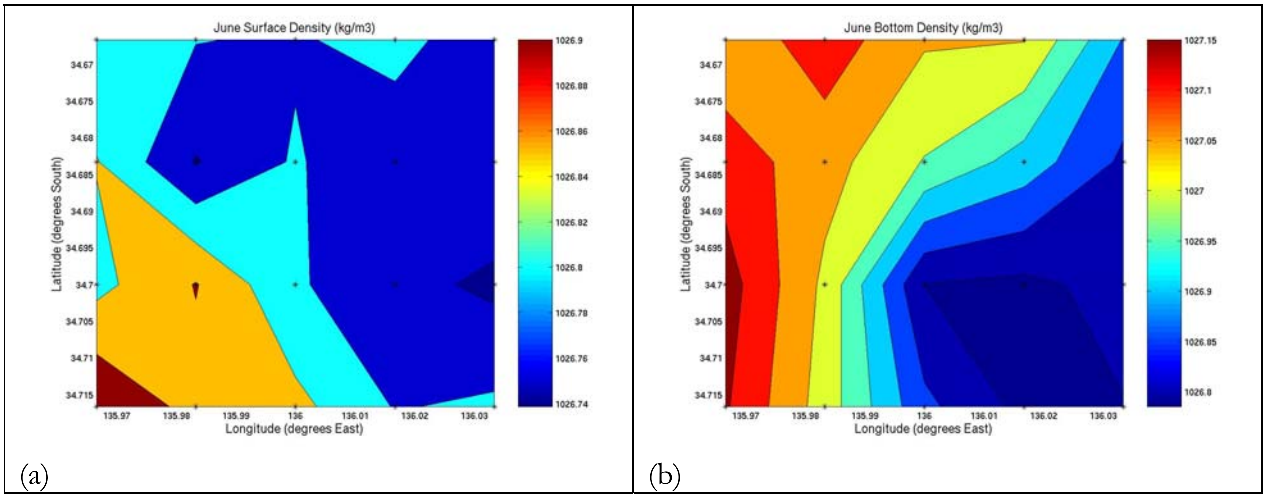


Figure 6.19: (a) S**urface and (b) seafloor density variation in June 2005.**

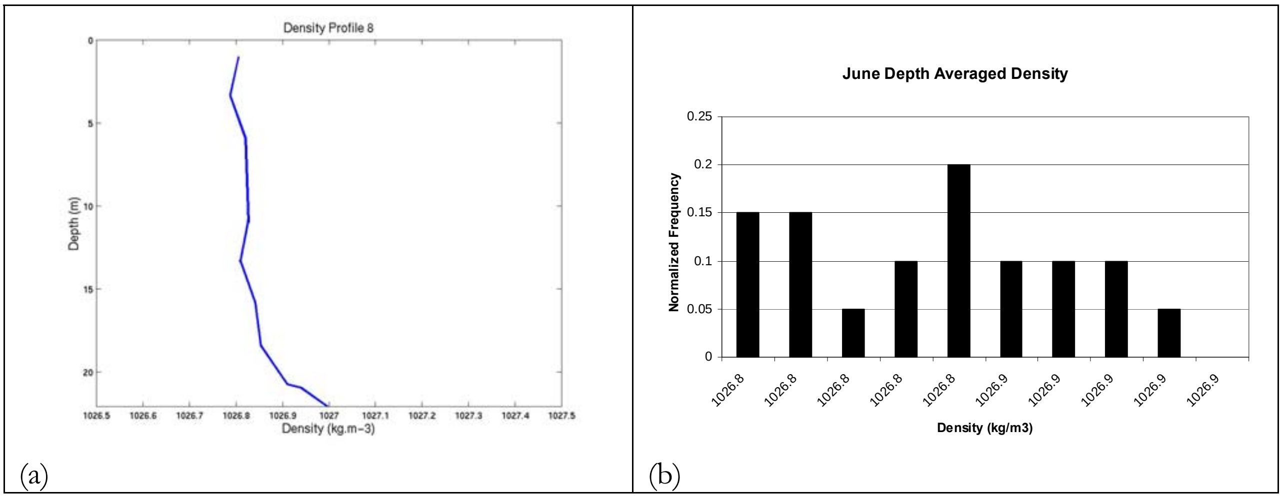


Figure 6.20**: (a) A typical density profile and (b) the distribution of depth-averaged density measurements from June 2005.**

6.5.13 Current Speed & Direction

Current speeds experienced during June range from a minimum value of 0.22 cm s^{-1} up to a maximum speed of 22.3 cm s^{-1}, with an average of 5.97 cm s^{-1}. The distribution of current speed measurements was skewed such that the majority of values occurred towards the slower end of the range, as indicated by the positive skewness value of 1.38. The direction of the currents varied throughout the possible range of 0 – 360º.

Current speed profiles show an almost constant speed with depth, only varying by up to 10 cm s^{-1} in any given profile. Average current speeds near the surface were greater than near the seafloor; 11.6 cm s^{-1} compared to 4.80 cm s^{-1}. The majority of current direction profiles show a large variation in current direction with depth. The direction of the currents varies across the entire range of 0 – 360º with no pattern that can be observed.

6.5.14 Turbidity

The turbidity of the water in June ranged from 0 NTU up to 4 NTU, with an average of 0.5 NTU. The turbidity at the sea surface over the grid was low averaging just 0.46 NTU, whilst the turbidity near the seafloor was slightly higher at 1.02 NTU. A few outliers above 1 NTU occurred, but there was no correlation between the turbidity measurements and current speeds near the seafloor. Both the surface and bottom average turbidity measurements from near the stocked pen were lower than the average over the larger grid, with surface and near seafloor values of 0.36 and 0.49 NTU respectively. Also the increase in turbidity towards the seafloor was less evident in the profiles nearby to the pen than it was during March.

6.5.15 Chlorophyll-*a*

Chlorophyll-*a* values for June ranged between 0.44 and 2.40 μg L^{-1} with an average value of 0.88 μg L^{-1}. Again, chlorophyll-*a* at the sea surface was greater than near the sea floor with an average value of 1.07 μg L^{-1} compared to 0.70 μg L^{-1}. The average chlorophyll-*a* concentrations from around the stocked pen were almost identical with the average concentrations from the rest of the area. However, the average surface concentration near the pen was actually slightly less than the average for the rest of the surface measurements, while the average bottom concentration was slightly greater than the average for the rest of the bottom measurements. Figure 6.21 shows the surface and near seafloor variations in chlorophyll-*a* concentration in June. It can be seen that there is a slight increase towards the north of the study area in both the surface and seafloor measurements. Again this area of greater chlorophyll-*a* concentration corresponds to where the greatest number of pens are located, but whether this is due to influences of the pens, proximity to land, or other factors, is debateable at this stage. Figure 6.22 shows the distribution of chlorophyll-*a* measurements from over the large grid and around the pen. It shows the difference in surface and seafloor chlorophyll-*a* variations between the grid and the stocked pen.

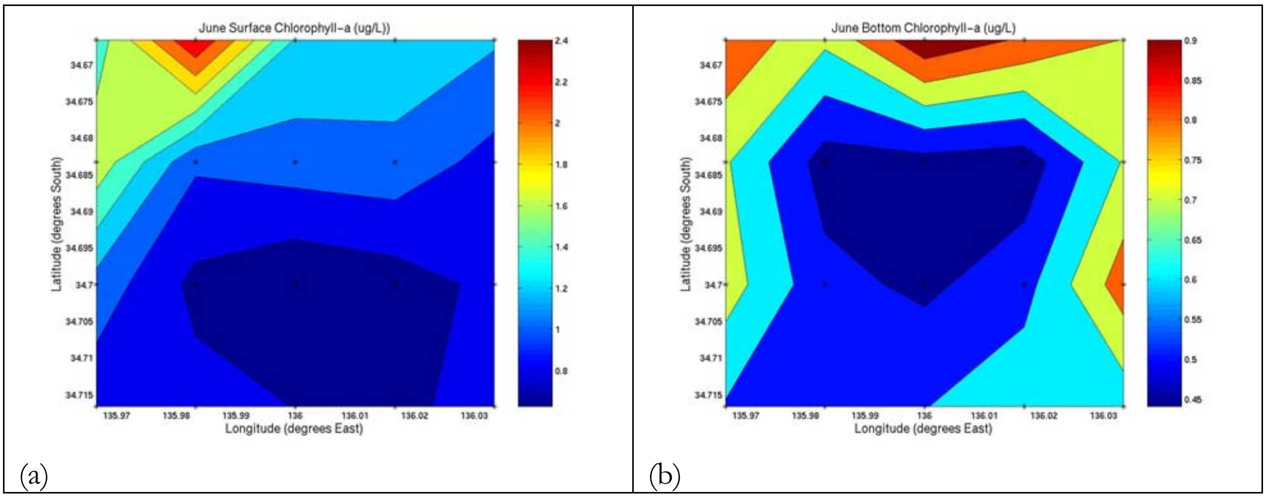


Figure 6.21: **(a) Surface and (b) seafloor chlorophyll-a variations in June 2005.**

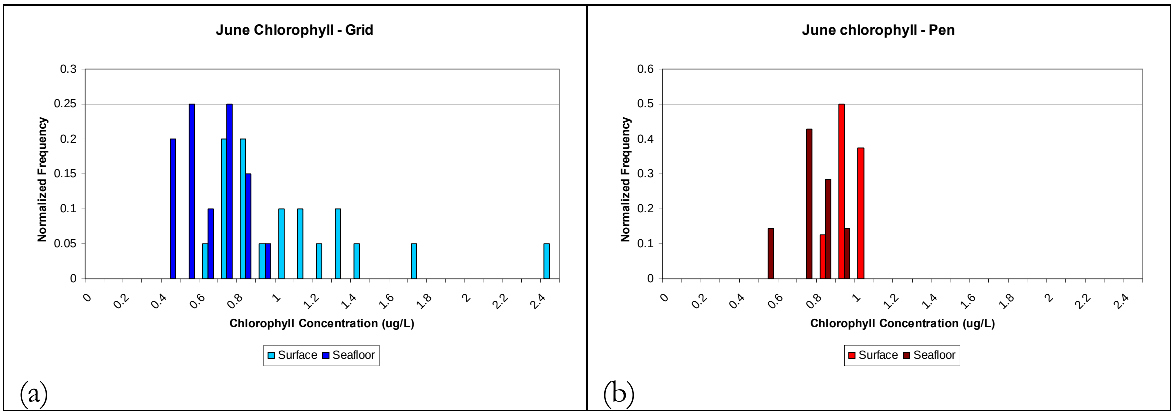


Figure 6.22: (a) **The distribution of chlorophyll-a concentrations from the surface and seafloor for the grid and (b) near the stocked pen, in June 2005.**

6.5.16 Nutrients

Measurements of ammonia, phosphate, nitrite and nitrate in June showed no observable variations from the sea surface to the seafloor. Average concentrations during June for ammonia, phosphate, nitrite and nitrate were 9, 15, 5 and 4 μg L^{-1}, respectively. Insufficient data were available to indicate any patterns of spatial variation in ammonia, nitrite or nitrate, but phosphate measurements did indicate an increase in concentration towards the north both at the surface and near the seafloor as shown in Figure 6.23. Figure 6.22 shows the distribution of the surface and seafloor concentrations of ammonia, phosphate, nitrite and nitrate. The low number of values is due to problems associated with determining nutrient concentrations mentioned earlier. Despite this, it can be seen that no significant difference exists in the ranges between the surface and the seafloor and that no dominant concentration exists for either nutrient.

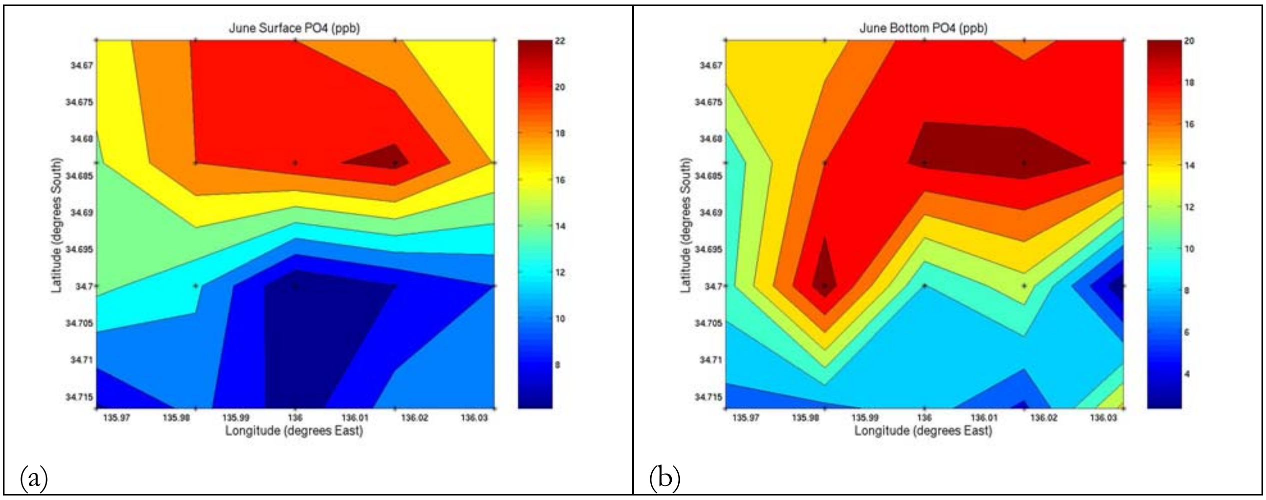


Figure 6.23: **(a) Spatial variation of phosphate on the surface and (b) near the seafloor in June 2005.**

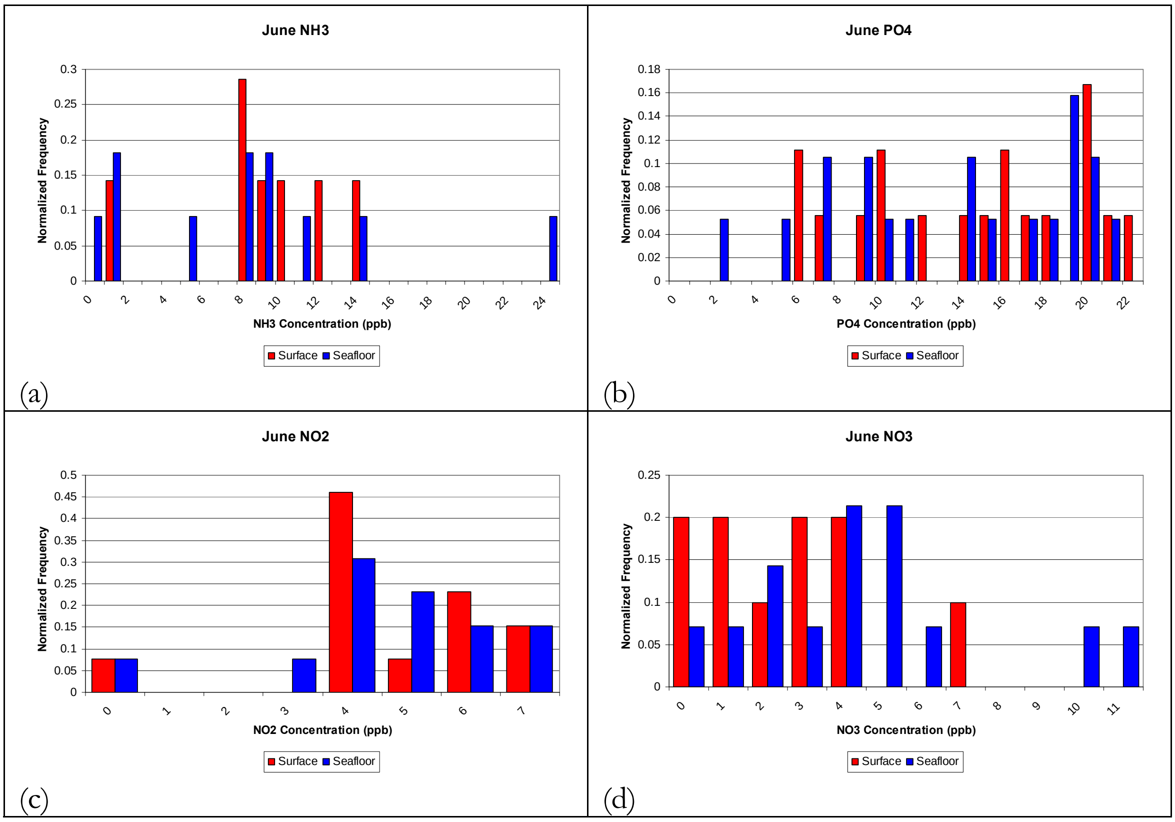


Figure 6.24: **Distribution of nutrients at the surface and on the seafloor in June 2005: (a) ammonia, (b) phosphate, (c) nitrite and (d) nitrate. 1 ppb = 1 μg L^{-1}.**

6.5.17 March – June Comparisons

The main difference that can be observed between the measurements of temperature, salinity and density taken in March and in June is the magnitude of the values. On average the water within the SBT farming zone in June was cooler by 5.03 °C, fresher by 0.86 ppt and hence denser by 0.62 kg m^{-3}. This difference is highlighted in Figure 6.25; a TS diagram displaying all temperature and salinity measurements from March and June. It is the decrease in salinity in winter that provides evidence of the effects of the gulf scale circulation in the region.

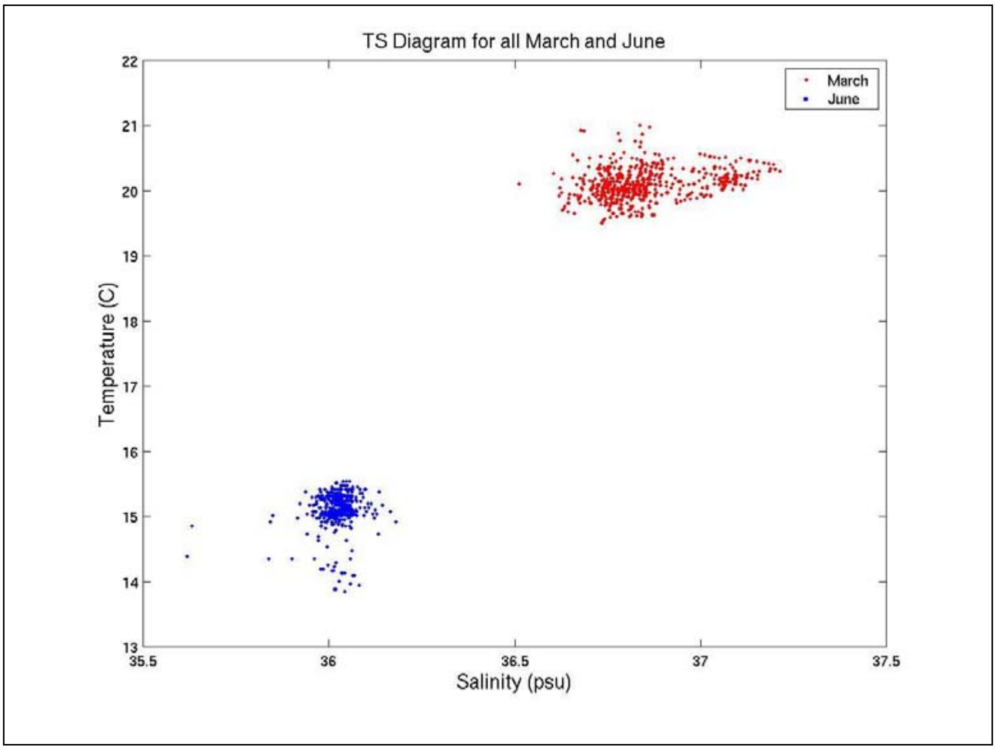


Figure 6.25: **TS diagram of all measurements from March and June.**

Six of the twenty stations surveyed in June were at the same location as a station surveyed in March. This enabled comparisons of the same locations between seasons to be made. Profiles of temperature, salinity and density at these locations are similar between the months, with the only difference being the decrease in temperature and salinity and the increase in density.

There is an increase in chlorophyll-*a* concentrations of 0.16 µg L^{-1} on average from March to June, although this is likely to be due to the June sampling locations being in the area with highest concentrations in March. The average surface concentration increased by 0.22 µg L^{-1} while the average bottom concentration increased by 0.11 µg L^{-1}. Overall, the seasonal increase in chlorophyll-*a* is small, and stocking of the pens and the farming processes appear not to have a significant effect on these levels. If the 6 sampling stations that coincide are considered, an inverse trend is observed. It is seen that 5 of the 6 locations show a decrease in surface chlorophyll-*a* from March to June and 4 of the 6 show a decrease in bottom chlorophyll-*a* also. The measurements taken around the pen show a decrease in surface chlorophyll-*a*, but a slight increase in chlorophyll-*a* near the seafloor.

Concentrations of phosphate, ammonia, nitrite and nitrate do not increase from the beginning to the end of the farming season, when all the pens were stocked to full capacity therefore possibly resulting in large amounts of waste being produced. The average concentrations of ammonia and nitrate decrease from the beginning to the end of the farming season while phosphate and nitrate remain almost the same. Although a small regional effect was observed in phosphate concentrations in June, the average concentration does not increase during the season indicating that there is no accumulation of nutrients as a result of the farming practices on a regional scale.

6.5.18 Moorings

Current speeds as measured by the RCM-9 current meter ranged from 0 to 24.6 cm s^{-1} with an average speed over the 42 day period of 8.17 cm s^{-1}. The components of the current indicate an average northward component of 0.89 cm s^{-1} and an average eastward component of 0.43 cm s^{-1}. These averaged components together result in an average current direction of 25.8º. By combining the two average components we have a net current of 0.99 cm s^{-1}. Multiplying this value by the period of just over 41 days it is seen that there is an overall displacement of 35.5 km towards NNE. This current is equivalent to a water transport of 855 m day^{-1}, and results in a flushing time for the SBT farming zone of approximately 17 days. It is possibly this flushing that explains why both nutrient and chlorophyll-*a* concentrations do not increase throughout the season despite some possible localized effects being observed near the pens. This northwards flow along with the lower salinity values in winter, corroborates the presence of the gulf scale circulation in winter. Figure 6.26 shows the current speeds measured and the predicted displacement of a parcel of water over the period of almost 42 days from late June to early August.

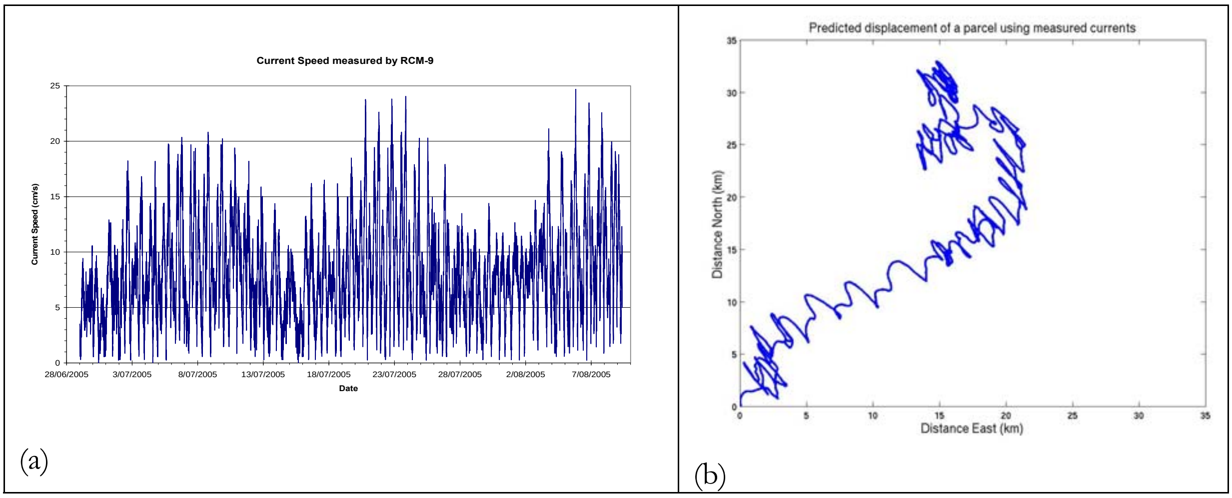


Figure 6.26: (a) **The current speeds measured and (b) the net displacement for the mooring location calculated for the 42 day period.**

The RCM-9 current meter also measured temperature, salinity and turbidity over the same period. Temperatures between 13.6 ºC and 15.3 ºC were recorded with an average of 14.5 ºC. Salinity ranged between 34.8 and 36.4 ppt, with an average of 35.9 ppt. Turbidity ranged from 0 up to 25 NTU, with an average value of 2.95 NTU. The turbidity measurements are shown in Figure 6.27 for the first 18 days of July. Also shown is the current speed measured by the S4 current meter over the same period. It can be seen that there are 3 intervals where the turbidity appears to be elevated above average levels. These are between the 2nd and 7th of July, between the 11th and 14th of July and 17th to 18th of July. Interestingly, these high turbidity values appear to bracket a period of high current speed, when they would be expected to coincide with it if currents act to stir up the seabed and resuspend sediments.

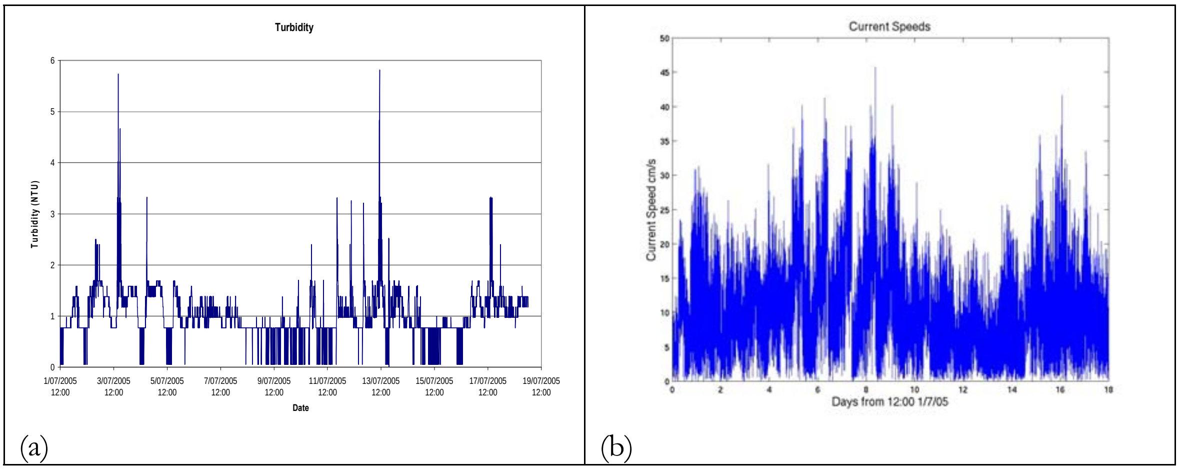


Figure 6.27: **(a) Turbidity measured by the RCM-9 current meter in the first 19 days of measurements and (b) current speeds measured over the same period by the S4 current meter.**

Both turbidity and salinity show a significant anomaly on the 19/7/2005 with a sudden drop in salinity and rise in turbidity. For a period of approximately 6 hours on the 19th the salinity was 0.86 ppt lower than the average. At the same time that salinity suddenly increased back up to and even slightly higher than its average value, the turbidity increased significantly for a period of just 20 minutes, indicating possible interference by marine organisms on the sensors.

Figure 6.28 shows the temperature and salinity measured by the RCM-9 current meter for the first 17 days of July. Temperature over this period shows the daily cycle of heating and cooling, but it also shows a slight decrease over the time period, but this is as expected for the time of year with cooling of the atmosphere. The salinity over the same period shows a decrease with time; a drop of over 0.2 ppt over the 17 days. The decrease in salinity is expected with the wintertime flushing of the gulf, however fouling of the sensors could have also contributed to this pattern.

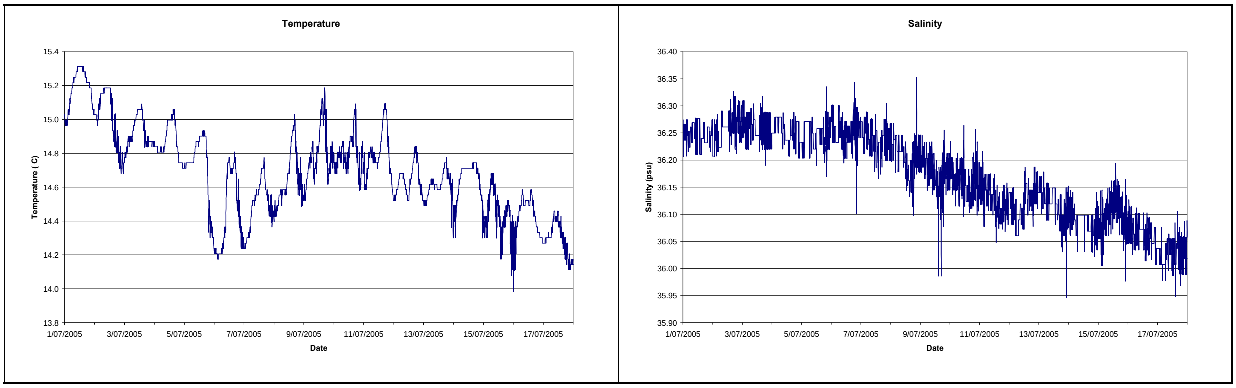


Figure 6.28: T**emperature and salinity between 1st to 18th of July 2005 as recorded by the RCM-9 current meter. 1 psu = 1 ppt.**

6.6 Conclusion

The purpose of this report was to assess the oceanographic conditions in and around the SBT farming zone, offshore from Boston Island, and to understand the distribution of nutrients and primary productivity of the region. This was done by observing the changes in temperature, salinity, density, turbidity, chlorophyll-a and nutrients throughout the region and between the seasons. By doing so, we hoped to be able to understand whether there are any significant changes in oceanographic conditions between March and June, whether there are any changes to the nutrients and primary productivity of the region between the two seasons, and whether there is any accumulation of nutrients or increase in primary productivity as a result of the aquaculture operations or whether flushing in the area is sufficient to disperse this potential hazard.

In June, the water within the SBT farming zone was cooler, fresher and denser than it was during March. This is a signature of the wintertime density-driven exchange circulation across the mouth of Spencer Gulf, which includes inflow of lower-salinity ocean water on the west side of Spencer Gulf in response to the outflow of high salinity water on the eastern side of the gulf. The inflow current had a flow speed of 1 cm s^{-1} and result in a displacement of almost 1 km per day towards the north.

Concentrations of chlorophyll-*a* at the beginning of the farming season were seen to increase near the coastline around the area where the greatest number of pens were located. These higher levels of chlorophyll-*a* could result from a series of factors, including land runoff, shallower waters or the presence of SBT pens. Also, measurements taken towards the end of the farming season show greatest concentrations where the greatest number of pens are located. The average concentration does not increase significantly during the season though, suggesting that the high number of fish in the area have at most a localized impact that does not result in any increase in primary productivity on a regional scale.

A similar pattern is observed for the availability of nutrients, with no detectable increase during the farming season. It should however be noted that nutrient measurements were inconclusive as a result of complications in the analysis process. It does appear unlikely, however, that nutrients increased between March and June despite the presence of fish and the associated farming processes, such as the input of feed, that undoubtedly results in waste products. Phosphate concentrations are seen to be higher in areas where pens are located but the average concentration for the region is no higher than before the farming season began.

Since there is no significant increase in primary productivity or accumulation of nutrients throughout the season, this suggests that the region is well flushed. This is likely to be driven by the gulf-scale circulation that develops after May each year following the breakdown of the SST front across the mouth of Spencer Gulf.

The farming season begins before the breakdown of the SST front and hence before the large scale circulation that is responsible for flushing the region. It is possible that accumulation of nutrients does occur in the period between March and May and future studies will need to focus on taking regular measurements of nutrient concentrations during this period to better understand the system.

Note that there was no attempt here to take into account any accumulation of waste in the sediments or release of nutrients from the sediments. To give a complete description of nutrients and primary production in the SBT aquaculture zone it would be necessary to understand seasonal and spatial changes in the sediments also.

6.7 Appendix

Table 6.2: **Summary of the temperature, salinity, density, turbidity, chlorophyll-*a*, ammonia, phosphate, nitrite, nitrate and current speed measured in both March and in June and the current speed, temperature, salinity and turbidity measured over 41 days from late June to early August 2005.**

Parameter	Month	Location of Measurements	Number of measurements	Average	Min	Max	Standard Deviation	Skewness	Kurtosis
Temperature (ºC)	March	All Grid	732	21.01	19.51	21.01	0.23	0.32	0.69
		Surface	44	20.22	19.63	21.01	0.30	0.71	1.33
		Seafloor	44	20.05	19.51	20.50	0.23	-0.04	-0.21
	June	All Grid	358	15.05	13.85	15.42	0.31	-2.02	4.06
		Surface	20	15.19	14.92	15.39	0.12	-0.30	-0.43
		Seafloor	20	14.65	13.85	15.42	0.54	0.11	-1.64
Salinity (ppt)	March	All Grid	732	36.89	36.63	37.21	0.13	0.61	-0.62
		Surface	44	36.85	36.68	37.20	0.12	1.07	0.99
		Seafloor	44	36.92	36.64	37.19	0.13	0.37	-0.79
	June	All Grid	358	36.10	35.72	36.26	0.04	-3.60	30.81
		Surface	20	36.12	36.06	36.22	0.05	0.41	-0.85
		Seafloor	20	36.14	36.08	36.26	0.04	1.09	1.28
Density (kg m^{-3})	March	All Grid	732	1026.2	1025.8	1026.5	0.10	-0.05	0.10
		Surface	44	1026.1	1025.8	1026.4	0.12	-0.14	0.08
		Seafloor	44	1026.3	1026.1	1026.5	0.08	0.41	-0.80
	June	All Grid	358	1026.9	1026.7	1027.3	0.01	1.72	3.22
		Surface	20	1026.9	1026.8	1027.0	0.05	0.87	0.66
		Seafloor	20	1027.1	1026.9	1027.3	0.14	-0.137	-1.55
Turbidity (NTU)	March	All Grid	732	0.78	4.17	0.36	0.31	2.53	21.28
		Grid Surface	44	0.59	0.98	0.36	0.23	0.36	-1.62
		Grid Seafloor	44	1.10	0.36	4.17	0.61	3.33	15.05
		All Pen	366	0.79	0.36	2.42	0.31	1.25	2.87
		Pen Surface	22	0.46	0.36	0.88	0.16	1.60	1.95
		Pen Seafloor	22	1.34	0.57	2.42	0.45	0.43	0.16
Parameter	**Month**	**Location of Measurements**	**Number of measurements**	**Average**	**Min**	**Max**	**Standard Deviation**	**Skewness**	**Kurtosis**
Turbidity (NTU)	June	All Grid	358	0.56	0.36	4.38	0.34	4.58	45.62
		Grid Surface	20	0.46	0.36	0.88	0.21	1.62	0.70
		Grid Seafloor	20	1.02	0.36	4.38	0.87	3.30	12.89
		All Pen	152	0.43	0.36	0.98	0.18	2.13	2.59
		Pen Surface	0.36	0.36	0.36	0.36	0.00		
		Pen Seafloor	0.49	0.36	0.88	0.24	0.49	1.44	0.00

Chlorophyll-*a* (µg L^{-1})	March	All	133	0.72	0.23	1.94	0.37	0.97	0.23
		All Surface	69	0.85	0.23	1.92	0.41	0.27	-1.08
		All Seafloor	64	0.59	0.25	1.94	0.27	2.36	8.80
		All Grid	88	0.63	0.23	1.94	0.34	1.80	4.06
		Surface Grid	44	0.56	0.23	1.92	0.36	1.58	2.80
		Seafloor Grid	44	0.60	0.25	1.94	0.31	2.14	6.81
		All Pen	45	0.92	0.44	1.52	0.37	-0.04	-1.77
		Surface Pen	25	1.20	0.50	1.52	0.23	-1.89	3.97
		Seafloor Pen	20	0.57	0.44	0.98	0.15	2.10	4.10
	June	All	55	0.88	0.44	2.40	0.34	2.09	7.25
		All Surface	28	1.07	0.63	2.40	0.36	2.20	6.44
		All Seafloor	27	0.69	0.44	0.98	0.16	-0.07	-1.13
		All Grid	40	0.88	0.44	2.40	0.38	1.97	5.47
		Surface Grid	20	1.10	0.63	2.40	0.42	1.76	3.84
		Seafloor Grid	20	0.66	0.44	0.98	0.16	0.35	-.89
		All Pen	15	0.89	0.55	1.10	0.14	-0.81	1.14
		Surface Pen	8	0.99	0.89	1.10	0.08	0.39	-1.18
		Seafloor Pen	7	0.79	0.55	0.95	0.13	-1.01	2.01
NH_3 (ppb)	March	Surface	24	17	0	62	18.50	1.41	1.10
		Seafloor	22	21	0	64	22.42	1.37	1.78
	June	Surface	7	9	1	14	4.11	-1.07	1.93
		Seafloor	11	9	1	25	6.88	1.16	2.13

Parameter	**Month**	**Location of Measurements**	**Number of measurements**	**Average**	**Min**	**Max**	**Standard Deviation**	**Skewness**	**Kurtosis**
PO_4 (ppb)	March	Surface	44	14	3	30	6.35	0.61	0.10
		Seafloor	43	13	1	27	5.09	0.50	0.78
	June	Surface	18	15	6	23	5.24	-0.29	-1.20
		Seafloor	19	14	2	21	5.87	-0.42	-1.07
NO_2 (ppb)	March	Surface	44	4	0	38	6.74	3.56	15.29
		Seafloor	43	4	0	21	5.03	1.68	2.72
	June	Surface	13	5	0	8	1.91	-1.21	3.89
		Seafloor	13	5	0	8	2.07	-1.09	1.90
NO_3 (ppb)	March	Surface	42	24	4	82	19.15	1.04	0.80
		Seafloor	40	26	1	72	17.80	0.66	-0.21
	June	Surface	10	3	1	7	2.06	1.10	1.30
		Seafloor	14	5	0	11	3.00	0.80	0.70

Current Speed ($cm\ s^{-1}$)	March	All Grid Surface Seafloor	732 44 44	12.67 12.21 9.97	0.30 2.19 0.75	33.67 21.20 19.65	7.07 6.78 4.79	0.50 0.55 0.01	-0.41 -0.45 -0.16
	June	All Grid Surface Seafloor	358 20 20	5.97 11.60 4.80	0.21 3.12 2.18	22.29 22.29 9.62	3.63 5.34 2.19	1.37 0.51 0.64	2.56 -0.47 -0.51
Moorings									
Current Speed ($cm\ s^{-1}$)	June-August	RCM-9 S4 – 5 min avg. S4 – All	11912 144 36937	8.16 10.07 10.10	0 4.82 0	24.63 23.24 45.80	4.40 3.91 6.09	0.63 1.26 0.92	8.17E-05 1.36 0.81
Temperature (ºC)	June-August	RCM-9	11911	14.50	13.63	16.31	0.33	0.38	-0.50
Salinity (ppt)	June-August	RCM-9	11911	36.94	34.80	36.35	0.40	-1.15	-0.33
Turbidity (NTU)	June-August	RCM-9	11911	2.95	0.05	25.20	3.82	2.17	3.93

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Chapter 7 Carrying capacity modelling

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Note: The models described here were originally developed as part of a project for PIRSA Aquaculture, and subsequently further developed for SBT through funding from Aquafin CRC.

7.1 Executive Summary

To help predict the pattern of benthic impacts around a tuna pontoon, and in particular to examine the potential for impacts of neighbouring pontoons to overlap, as well as broader scale pelagic impacts, two models of what can loosely be termed 'carrying capacity' were developed. While the models have not been fully calibrated and validated, and therefore cannot provide an absolute estimate of deposition loads, they do provide a useful qualitative picture of the pattern of carbon deposition and nutrient inputs which are likely to occur based on stocking densities, feeding rates and current flows. In the short term, this information can be used by farm operators to examine the likely consequences of different pontoon arrangements within a lease, and it can help structure monitoring programs as it predicts the positions of maximal impact, even if the numeric estimate of loading is not currently verified. They can also be used to guide increases in production in an adaptive management framework. In the longer term, the models will provide a framework to direct future research and assist in the integration and synthesis of field results and the identification of gaps in current knowledge.

Model 1 predicts the increase in dissolved nutrients and is based on the mass balance models provided by Beveridge (1987). The model relies on the knowledge of the level of input of nutrients, the geometry of the aquaculture area and the flushing regime of the area. Predictions are provided at the scale of entire zones (i.e. an area of several leases). By comparison with published guidelines for water quality (in this case the ANZECC/ARMCANZ (2000) water quality guidelines), it is possible to suggest the amount of production that may be supported without breaching these levels.

Model 2, "*Farmér*", is a simulation of the increased carbon loading to the seabed caused by finfish farming. From estimates of feeding rates and chemical composition of food and fish, the path of carbon in both faecal material and uneaten food is simulated to the seafloor to estimate the pattern of organic deposition on the seabed. This involves two components of movement in the water column– a current induced movement (advection) and diffusion independent of water motion (dispersion). The magnitude of both effects is determined, at least in part, by the time taken to sink to the seafloor. Once deposited, the carbon can either accumulate over the period of the simulation, or it can be utilised at least in part by the benthos, depending on the options selected. The resultant output is a two dimensional surface plot of loading across the area of the seabed covered by the waste materials. Currently, the model is set up to operate at the lease scale, although a single pontoon can also be simulated, as could interactions between 2 neighbouring leases.

7.2 Introduction

"Carrying capacity" has multiple definitions in the ecological literature. In terms of traditional population ecology, it refers to the number of organisms of a given species that can be supported by the level of resources available (Fernandes *et al.* 2001). This definition does not take into account detrimental effects to the environment, except insomuch as they negatively feed back on the organisms of interest. Aquaculture operations necessarily involve a waste stream that has the potential to impact on the surrounding environment (Gowen *et al.* 1994). These changes to the surrounding environment may result in conditions that are deleterious to the fish being raised or have an unacceptable effect on the natural biota (Pearson and Black 2001; Read *et al.* 2001). Thus the "environmental carrying capacity", also known as assimilative capacity, represents the level of production that can be maintained without a loss of habitat quality that is unacceptable because of an effect on stock or other biota (Fernandes *et al.* 2001).

Carrying capacity is not determined by a single variable, but rather by any one of a suite of potential factors operating at different scales (Silvert 1992). At the most localised of scales, the stocking rate of the fish within a pontoon will have ramifications on oxygen levels in the immediate water column (Silvert and Cromey 2001) and the likelihood of disease transmission. At a larger, but still quite local scale, organic deposition, of either uneaten food or faecal material, can have a profound influence on the benthos (Findlay and Watling 1994; Silvert and Sowles 1996). At the regional scale, the release of soluble nutrients becomes a more important issue (Silvert 1992, Silvert and Cromey 2001).

7.2.1 The overall modelling approach

The modelling strategy used here investigates carrying capacity in terms of organic deposition (a near-field effect) and the release of soluble nutrients (a far-field effect). It is important to note that while other issues, (e.g. oxygen stress, disease transmission, physiological response to environmental conditions such as temperature and salinity, behavioural issues etc) may act to limit productivity, these effects are not within the scope of the models detailed here. Such issues should be dealt with based on the cumulative experience of industry.

Two models have been created to simulate aspects of the impact of finfish farming on the environment. In the first, the focus is on levels of dissolved inorganic nutrients and in the second, carbon deposition to the seafloor is modelled. The nutrient model is used to provide an estimate of the extent to which a set increase in production would increase nutrient levels in the water column. This model is designed to be used at the scale of the farming region. The nutrient model can also be used at the scale of an individual lease, although this requires the assumption that nutrients from nearby leases are not dispersed into the lease. The carbon deposition model simulates the deposition of carbon onto the seafloor around an individual pontoon or a small group of pontoons. This model is designed primarily to be used at the lease scale, allowing an examination of how deposition from neighbouring pontoons may overlap, but it could also be used to examine interactions between two neighbouring leases or deposition around a single pontoon. The carbon deposition model cannot be used at the scale of the entire farming region in its current implementation. While there are no theoretical restrictions to running the model at this larger scale, the computational effort required would be excessive, and unless wastes disperse large distances before settling out, little would be gained. Both models are based on the best available data, but our understanding of many processes, particularly hydrodynamics, in the Port Lincoln area is incomplete, and thus neither model has been fully calibrated or validated. Thus, while the patterns they predict are likely to be reasonably accurate, the absolute values of the predictions should be treated with caution. In the short term, this information can be used to help structure monitoring programs as it predicts the positions of maximal impact, even if the numeric estimate of loading is not currently verified. In the longer term, the model will provide a framework to direct future research and assist in the integration and synthesis of field results and the identification of gaps in current knowledge.

In the case of dissolved nutrients, a standard mass balance model (Beveridge 1987) was developed to predict how increased inputs from aquaculture would increase nutrient levels within the water column. Predicted nutrient levels can then be compared to a set of trigger values, such as those provided by ANZECC / ARMCANZ (2000), to estimate the carrying capacity. Due to the uncertainties in some of the parameters of this model, it is important that production be increased incrementally, with the subsequent effects on nutrient levels being compared to model predictions to determine how well the model performs.

Carbon deposition is modelled using a Gowen type model (see Gowen *et al.* 1994) developed by SARDI. This allows a prediction of the pattern of organic deposition around each pontoon. Again, due to uncertainties in some parameters, the model is more useful as a predictor of the qualitative pattern of carbon deposition and of the *relative* impact on different sites than it is as an indicator of the absolute rates of deposition. This model cannot be used to predict the carrying capacity of a region, but can be used to assess likely consequences of different stocking rates and pontoon arrangements at the lease scale.

7.3 Model 1: Predicting the build-up of dissolved nutrients

A mass balance model of the type devised by Beveridge (1987) was utilised to predict the change in dissolved nutrient concentrations in the water body represented by the aquaculture zone. This model was the principal tool utilised to make quantitative predictions of how great a nutrient increase could be expected to be associated with any given level of production, an approach used previously in studies of finfish aquaculture potential in South Australian waters (e.g. Petrusevics 1998).

The dissolved nutrients that were investigated in this model were nitrogen (both as nitrate and ammonia) and phosphorus (as phosphate). The simulations detailed below were parameterised for southern bluefin tuna (*Thunnus maccoyii*). The model can also be applied to other finfish species including yellowtail kingfish and snapper. Each run of the model requires the operator to develop a specific set of parameters that are applicable to the individual site, species being farmed, and stage of growth.

The central equation of this model is:

$$\Delta N = \frac{L \text{ x } (1 - R_s)}{V \text{ x } F} \tag{7.1}$$

Where: ΔN = the change in dissolved nutrient concentration (kg/m^3)
L = total amount of nutrient released to the environment (kg)
R_s = proportion of nutrient retained by the sediments (denied to water column) (%)
V = volume of water in the proposed zone (m^3)
F = the number of water body changes occurring across the period of interest

Note: R_s can be estimated as a function of flushing rate, whereby

$$R_s = \frac{1}{1 + 0.747 \text{ x } F^{0.507}} \tag{7.2}$$

By adding the present level of the dissolved nutrient to the calculated change (ΔN), a level can be predicted for any given amount of farmed fish growth. These levels can then be compared with appropriate trigger values.

The amount of nutrient lost to the environment is calculated from the amount of nitrogen added in the food (in this case it is assumed tuna are fed entirely on Australian sardine – *Sardinops neopilchardus*, although results for other baitfish are likely to be similar), and the amount assimilated in the growth of the fish. The difference between the two represents loss to the environment. This is a very simplified first order approach, as it does not take into account any feed wastage, and it assumes that all wastes are in a dissolved form. Box 1 demonstrates a worked example of such a calculation.

The flushing rate is calculated from results on particle retention from a hydrodynamic model. The flushing time was taken (conservatively) as the time required for 100% of particles to be flushed, assuming a linear decay rate. This calculation makes the critical assumption that the water body is properly exchanged in this tidal movement, and ignores the possibility of "plug" movement, whereby the nutrients are moved out on an outgoing tide, and then straight back in again on the incoming tide. Without knowledge of the nature of the water exchange, it is not possible to quantify this effect. However, it is worth noting that in this respect, the model is NOT conservative, and thus underestimates accumulation. It assumes full exchange and no "plug" movement. To run the model conservatively, taking this into account effectively reduces the flushing rate to zero, and consequently, carrying capacity would be reduced substantially. Such sensitivity is a clear indication that the estimates must be treated with extreme caution. Alternatively, particle tracking within a hydrodynamic model can be used to calculate flushing rates. This provides a much more accurate picture of what is happening, but requires access to a fully calibrated hydrodynamic model of the area of interest. Such a model is being developed for Risk & Response (FRDC 2005/059), and the results of this could be used to improve the current model once available.

General parameters used in this model are (as % of wet weight)**:**
Baitfish nitrogen content: 3.248% (*S. neopilchardus* is 20.3% protein (Ellis & Rough 2005), which is assumed to be 16% N)
Baitfish phosphorus content: 0.456% (Ellis & Rough 2005)
Baitfish & SBT water content: 71% (Ellis & Rough 2005 for SBT, baitfish was assumed to be the same)
SBT nitrogen content: 3.584% (22.4% protein (Ellis & Rough 2005), which is assumed to be 16% N)
SBT phosphorus content: 0.56% (Ellis & Rough 2005)
Food Conversion Ratio (wet weight) 1: 12 (based on 50,000 tonnes of baitfish fed annually for an increase in total fish weight of 4,300 tonnes)
Growout period of 8 months

Other required site-specific parameters are:
Average depth (20 m)
Flushing Rate (21 turnovers/yr = 14 turnovers/8 month season, Chapter 6)
Current level of dissolved N as ammonium (11.5 $\mu g\ N\ l^{-1}$, calculated from Bierman – Chapter 6)
Current level of dissolved N as nitrate (3.6 $\mu g\ N\ l^{-1}$, calculated from Chapter 6)
Current level of dissolved phosphorus (4.7 $\mu g\ P\ l^{-1}$, calculated from Chapter 6)
Zone area (172 km^2)

These nutrient levels lie within the range of previously reported results for the area by Petrusevics and others (in SKM 2001), and Fernandes et al. (2007).

1. Calculate the increase in loading associated with 1kg of production
   -1kg of production requires 12kg of food (FCR=12)
2. This 12kg represents 12kg x 3.248% = 389.8g of Nitrogen
3. Of this, some is retained in the form of fish growth: 1kg of growth x 3.584% = 35.8g
4. This leaves 398.8g – 35.8g as lost to the environment = 354g
5. Of this, a proportion is retained by sediments and not released
   $= 1/(1+ 0.747 \times 14^{.507}) = .2599$ (or 25.99%)
6. So the amount which *is* released = (1-0.2599)*354000mg =261995mg
7. This amount is divided by the total volume of water that it can be released into (i.e. the standing volume x the number of flushes/growout season) So: 261995mg / $(172000000 \times 20m^3 \times 14) = 5.44 \times 10^{-6}$mg m^{-3} or $5.44 \times 10^{-6} \mu g\ l^{-1}$
8. The above figure represents the increase in nutrient concentration for every kg of production. If (for example) 100 tonnes (100,000kg) of production is proposed then there will be an increase of $10^5 \times 0.544 \times 10^{-5} \mu g\ l^{-1}$ or $\underline{0.544 \mu g\ l^{-1}}$.

This increase can be calculated for any proposed level of increase in production, and added to the existing level to predict the new level under that operational regime.

Box 1: Example calculation of the increased load caused by aquaculture production in a 172 km^2 area of average depth 20 m, flushing rate of 21 yr^{-1}, and an 8 month growout season.

7.3.1 Model Assumptions

As with any model, a number of assumptions have had to be made:

- The area is modelled as an individual entity, and is not under the influence of any adjacent area, nor are any other inputs, other than ambient nutrients, considered. It is assumed that the background nutrient concentrations used take into account all other activities in the area, including existing production, and thus the results show the effects of any increase in aquaculture production.

- The proportion of nitrogen in both the feed and the fish was equal to 16% of gross protein. This assumption is routinely made when calculating nitrogen content.

- All baitfish fed to the fish were ingested.

- All nitrogen and phosphorus lost to the environment was lost in soluble form. This is not entirely correct as several sources (Skretting Australia dietary fact sheet; Cho *et al.* 1991) would suggest that up to 20% of the waste nitrogen is in solid form and would therefore not add to the dissolved nitrogen load. However, nitrogen in the solid form is taken up, used by the benthic ecosystem, and utilised within the sediment, resulting in some proportion of this being re-released. Without knowledge of this figure, it was necessary to assume that eventually all of the waste nitrogen was converted to the soluble form in order to produce a conservative result. Similar arguments would apply to phosphorus.

- The lack of detailed knowledge concerning the nitrogen cycle and the processes of nitrification, denitrification and ammonification also led to the need to make assumptions about the species of nitrogen being dealt with. Although marine fish release ammonium (and associated species, e.g. urea) rather than nitrate, the processes indicated above will convert some proportion of this to nitrate. Without knowledge of what this figure is, it was necessary to assume that all nitrogen released was released as ammonium when basing predictions on ammonium, and all as nitrate when nitrate was the limiting factor.

- It is assumed that the tidal movement of the water body results in flushing with complete exchange, rather than a "plug" movement of nutrients as they slosh out of the area and then straight back in again.

7.3.2 Results

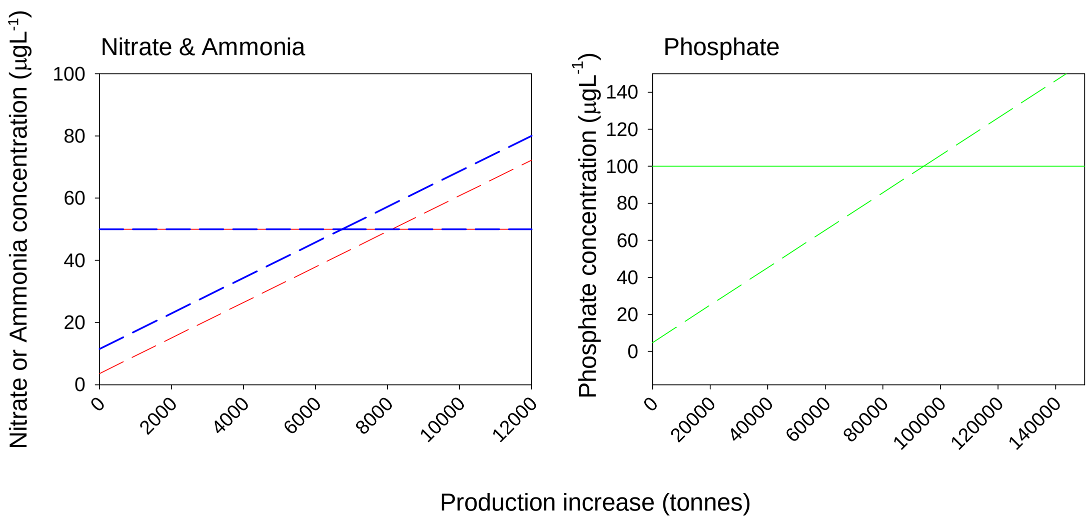

Figure 7.1: **Example of the predicted concentration of ammonia, nitrate and phosphate dissolved in the water column as a function of production in the Port Lincoln tuna farming zone. Blue represents ammonia, red nitrate. Horizontal lines indicate threshold values for South Australian waters as per ANZECC / ARMCANZ (2000).**

For SBT fed on Australian sardines at Port Lincoln, the model predicts that a production increase of 1000 tonnes per annum would result in an increase in water-column ammonia of 5.71 $\mu gL^{-1}N$ (50%), nitrate of 5.71 $\mu gL^{-1}N$ (159%) and phosphate of 1.01 $\mu gL^{-1}P$ (21%) (Figure 7.1). Alternatively, a 10% increase in ammonia levels would result from a 200 tonne increase in production, a 10% increase in nitrate from a 63 tonne increase in production and a 10% increase in phosphate from a 476 tonne increase in production, assuming that none of these released nutrients are utilised by other components of the ecosystem.

Given that existing production is around 4300 tonnes per annum, and that there are numerous other sources of nutrients in the area, these model predictions do not seem realistic. Even if all the dissolved nitrogen currently present resulted from current production, it is difficult to envision increases in nitrogen levels of 50% and 159% respectively for ammonia and nitrate if an extra 1000 tonnes is produced. This indicates that there are problems with the model formulation, with the most likely errors relating either to chemical and biological cycling of nutrients or hydrodynamics. Our knowledge of both areas is currently being extended as a part of the Risk & Response project (FRDC 2005/059), and thus this model has not been pursued further here. However, using a similar model, Petrusevics (in SKM 2001), calculated that carrying capacity for the region was ~17,000-19,000 tonnes based on nitrate, which is not much higher than our estimate of 12,500 tonnes. If we use the same flushing rate as Petrusevics, our calculated carrying capacity is 17,800 tonnes, virtually identical to that of Petrusevics.

7.4 Model 2: Farmér – predicting carbon loading to the seafloor

One of the principal factors to be considered in assessing the waste stream generated by a marine pontoon aquaculture system is the deposition of carbon to the seabed (Ervik *et al.* 1997; Bergheim *et al.* 1991; Panchang *et al.* 1997). The deposition of organic material, either in the form of uneaten food or faeces, creates a biological oxygen demand, and this may lead to a level of deoxygenation in the overlying water column which is detrimental to the health of both the farmed fish and any natural biota. The fact that this material is particulate rather than dissolved dictates that this problem is a near field, or local issue, in contrast to the issue of dissolved nutrients, which is a far field issue (Silvert 1994a). Thus, the output of the Farmér model is restricted to the area of seafloor in close proximity to an individual lease. The assumption is made that leases are separated by a great enough distance that the carbon deposition of a given lease is not going to interact appreciably with that of any other lease.

Farmér is a composite model that performs mass balance calculations on the carbon flow through the system, and then applies diffusion and current displacement functions to the carbon loads represented by faecal matter and uneaten food. These two components are modelled separately as they are likely to have very different sinking rates. However, they are treated in a similar manner.

Food is assumed to be evenly distributed across the surface of the pontoon, as are faeces. Both components are subject to two separate influences that affect the pattern of deposition. The first is a current induced movement that is defined by current speed and direction and the time taken to sink to the seafloor. The second influence is a natural diffusion that occurs independent of the current, and in still water results in inputs from a point source being deposited in a circular area centred on the point of input (Figure 7.2). The combination of these two provides a pattern of deposition for a given time period over which the current is assumed to be uniform.

The time step used in the model is hourly across the course of a year. Note that the fall time is calculated from the *bottom* of the pontoon rather than the top, as the presence of the pontoon walls is claimed by some sources to substantially restrict water movement. The assumption is thus that no material is dispersed through the sides of the pontoons, and that it all falls through the bottom. While this claim may be an oversimplification, this produces the most conservative estimates as decreasing fall time results in a smaller area over which material diffuses and therefore a greater loading to the benthos.

7.4.1 Step 1: Mass Balance Calculations

These calculations are based around the carbon waste stream for a single pontoon for one day.

- $\mathbf{Weight_{fish}}$ = stocking rate (g m^{-3}) x area of pontoon (m^2) x depth (m)
- $\mathbf{Weight_{food}}$ = Feeding Rate (% body weight per day) x $Weight_{fish}$ (g)
- $\mathbf{Carbon_{input}}$ = $Weight_{food}$ (g) x $\%Carbon_{food}$
- $\mathbf{Carbon_{uneaten\ food}}$ = $Carbon_{input}$ (g) x %Food uneaten
- $\mathbf{Carbon_{respired}}$ = O_2 consumption rate (mg O_2 kg^{-1} hr^{-1}) x $Weight_{fish}$ (g) x 16/32 x 24 (hr day^{-1})

- **$WeightGain_{fish}$** = $Weight_{food}$ (g)/ FCR
- **$CarbonGain_{fish}$** = $WeightGain_{fish}$ (g) x %$Carbon_{fish}$
- **$Carbon_{faeces}$** = $Carbon_{input}$ (g) - $Carbon_{uneaten\ food}$ (g) - $Carbon_{respired}$ (g) - $CarbonGain_{fish}$ (g)

The important end products of this process are $Carbon_{uneaten\ food}$ and $Carbon_{faeces}$. These values are then converted to hourly figures by dividing by 24.

7.4.2 Step 2: Translocation of Carbon Load to Benthos

The diffusion and current-aided transport of the carbon loads associated with the faeces and uneaten food are modelled from the bottom of the pontoon to the seafloor. The two carbon loads are treated separately as they have different sinking rates, which results in them taking different times to reach the seafloor, and subsequently different amounts of time for the actions of diffusion and current movement. For similar reasons, when sinking speeds are represented by a distribution of different speeds (the model will allow particles from each waste stream to be allocated to as many as 10 different sinking rates on a percentage basis) rather than a single average, the fall of each of these components and its distribution on the seafloor is simulated separately. When all components of uneaten food and faeces have been distributed, these loadings are summed to produce an overall distribution. This process is iterated on an hourly basis to take into account the effects of the changing currents. After each hourly iteration, the new distribution is mapped onto the existing one.

The carbon load of the pontoon is uniformly distributed across the area of the pontoon. Diffusion is modelled via the use of a diffusion coefficient that determines the circular area across which the load from a point source will be distributed. Within this circle of diffusion, a truncated normal distribution is used, with 99% of the load being distributed according to a normal distribution centred on the point of discharge (see Figure 7.2). The 1% that falls further away (i.e. more than 2.58 standard deviations away (Zar 1984)) is, for computational reasons assumed to fall without diffusion. By superimposing the identical patterns of distribution for every point within the pontoon, an overall pattern of distribution of the pontoon could be determined. Essentially this looks like a normal curve flattened toward the centre of the pontoon, as all points in the central area had similar loading, and tailing off some distance outside the area of the pontoon. How flat and how far away the tailing off occurred was dependent on the coefficient of diffusion.

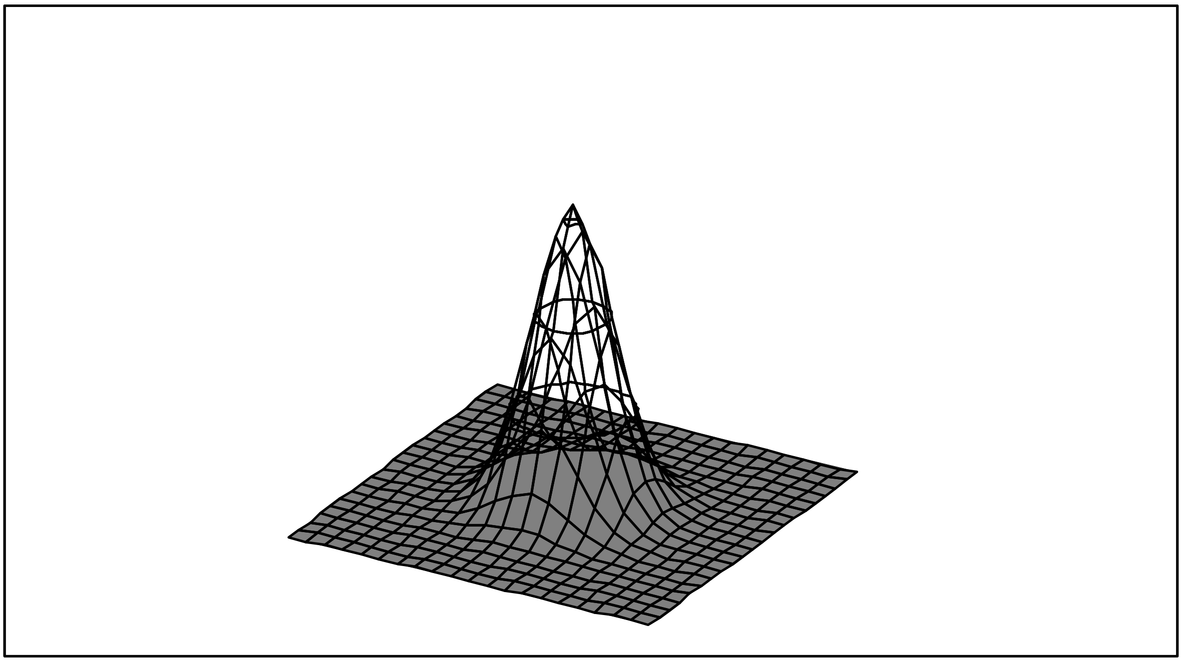

Figure 7.2 : **Distribution of carbon released from a single point. The width of the circle, and therefore the height, is determined by a diffusion coefficient. The largest proportion of the particles fall directly down, with increasingly smaller proportions falling at distances further from the release point.**

Once the diffusion matrix has been calculated for the pontoon, the effects of currents are introduced. Current data were obtained from Bierman (Chapter 6), with the first 28 days of data used to represent a full spring-neap tidal cycle, and then replicated across the entire year. This procedure was necessary as there are no current data for a full year available from the area, although this is being rectified at the time of writing, and future versions of the model will be able to incorporate monthly variation in currents. The 5 min current data collected by Bierman (Chapter 6) were vector averaged to produce a single current speed and direction for each hour. While other short sets of current data are available for the area, it was considered better to use a single data set and multiply up, rather than splicing together multiple data sets from different years and locations, and then filling in the gaps by multiplying some of these up.

The effect of the currents was to displace the calculated diffusion matrix away from the pontoon by an amount and direction determined by the current magnitude and direction. This was repeated on an hourly basis across the growout period and the buildup of carbon was recorded as a surface map of the lease area and any additional area that the material diffused or was moved into. A picture of the situation at the end of the growout period was then provided.

7.4.3 Parameterisation

7.4.3.1 Operational Data:

SBT were fed on a diet of baitfish.
The percentage of food *not* ingested was 3% (Fernandes et al. 2007 – Chapter 4)
Food Conversion Ratio (wet weight): 12:1 (based on 50,000 tonnes of baitfish fed annually for an increase in total fish weight of 4,300 tonnes)

Proportion of Carbon in Food (wet weight basis): 11.6% (40% of DW Fernandes et al. 2007 – Chapter 9)
Proportion of Water in Food: 71% (Fernandes et al. 2007 – Chapter 4)
Proportion of Carbon in Fish (wet weight basis): 8% (Silvert 1994b)
Fish Respiration rate: 600 mg O_2 kg^{-1} hr^{-1} (resting metabolic rate for SBT – Q. Fitzgibbon pers. com.).
Stocking Rate: 2.7 kg/m^3 (based on 2000 17 kg fish in a 40 m diameter, 10 m deep pontoon). For simplicity, this was assumed to be constant over time and thus will overestimate stocking density early in the season and underestimate it late in the season.
Feeding Rate: 7% of body weight per day.
Sinking Rate of feed and faeces: Table 7.1

The model was run across a 243 day period, beginning January 1, with fish being stocked until August 30.

Table 7.1: **Sinking rates for feed and faeces used in the carbon deposition model (obtained from Fernandes et al. 2007 – Chapter 4).**

Food		Faeces	
Settling rate ($m\ sec^{-1}$)	**% settling**	**Settling rate ($m\ sec^{-1}$)**	**% settling**
0.05	27	0.005	62
0.08	73	0.009	8
		0.013	16
		0.05	14

7.4.3.2 Assumptions

Like the model dealing with dissolved nutrients, the carbon deposition model relies on several assumptions, and further work is necessary to ascertain their validity.

- The lease is modelled as an individual entity, and is not under the influence of any adjacent lease. With a minimum lease separation of 1 km, and assuming a water depth of 20 m and a net height of 10 m, a particle would need to be advected 100 m for every 1 m it sank through the water column to reach an adjacent lease. Assuming a high current speed of 20 cm sec^{-1} (see Figure 6.9), this would require particle settling rates <0.2 cm sec^{-1}, which is extremely slow, and 40% of the minimum settling rate assumed in the model. However, it is not unrealistic that some fine material is transported this distance (see Fernandes et al. 2007, Chapter 4), and with bidirectional currents, it is likely that areas of deposition would overlap if leases are placed directly in line with each other, as material from each lease would then only have to be advected 500 m.
- All carbon contained in both faecal matter and uneaten feed is assumed to be in the solid rather than the dissolved form. Any carbon in the latter state would clearly not add to the loading of the seafloor. Thus the assumption that all the carbon is solid is a conservative one as it produces the highest values of deposition.
- The nets surrounding the pontoon, any fouling on these and the presence of the fish themselves act to reduce currents within the pontoon quite markedly (Cronin 1995). This would act to restrict carbon within the pontoon, rather than allowing it to disperse through the nets. For this reason it was assumed that the distance over which diffusion and current movement could occur was the distance between the bottom of the pontoon and the seafloor, rather than from the surface of the water.

This would lead to a decreased area of dispersion and therefore increased density of deposition, so it is an assumption that provides a more conservative estimate of seabed souring.

- It is assumed that carbon is released uniformly on a temporal basis, i.e. each hour, 1/24th of the daily load is released. While there is anecdotal evidence that evacuation from the fish occurs less uniformly, without either verification or quantification, it is difficult to model this satisfactorily. Feed can be input either as a single daily pulse, or evenly over 24 hours.
- Post depositional changes, whereby the sediments and benthic community recycle the organic matter are not taken into consideration. Other models such as that of Fox (1990) (cited by Gowen *et al.* 1994) have modules that deal with this aspect. Although our model does itself have a capacity for introducing the removal of carbon through benthic respiration, it is not well enough calibrated at present to use it for predictive purposes.
- The sea floor is assumed to be a uniform depth, equal to the average depth of the lease. While this may be unrealistic in some areas, leases in the current tuna farming zone are unlikely to vary by more than a few meters in depth.
- Current speeds and directions are calculated on a depth-averaged basis (i.e. are assumed constant throughout the water column) rather than at different levels within the water column. This is likely to be less of a problem in these open coastal situations than in the fjordic systems of some other countries (Silvert and Cromey 2001).
- The diffusion coefficient used has assumed that a sinking time of 400 seconds would result in 99% of the particulate matter falling in a normal distribution within a circle of diameter 80 metres. This figure requires empirical validation.
- No effects of temperature on fish physiology are integrated within the model.
- Lack of quantification of the effects of scavenging of carbon by the natural biota dictates that this factor, whilst available in the model, has not been taken into account. Again, this follows the precautionary principal required when our data are poor.
- Fish respiration rates were obtained from ongoing experimental studies of metabolism of free swimming SBT (Q. Fitzgibbon pers. com.)

All parameters detailed above are subject to change through further measurements and research as well as changes in the operation of leases and food technology.

7.4.3.3 Output

Output from the model is in the form of a surface plot of carbon loading. A record is also made of total loading and the point on the map where maximum loading occurs along with the value of that load. The output in all cases reflects the *additional* load imposed by the aquaculture operation. It does not take into account background rates of deposition. Figure 7.3 represents an example output from the model, and demonstrates how carbon deposition changes on a monthly basis through an 8 month farming season.

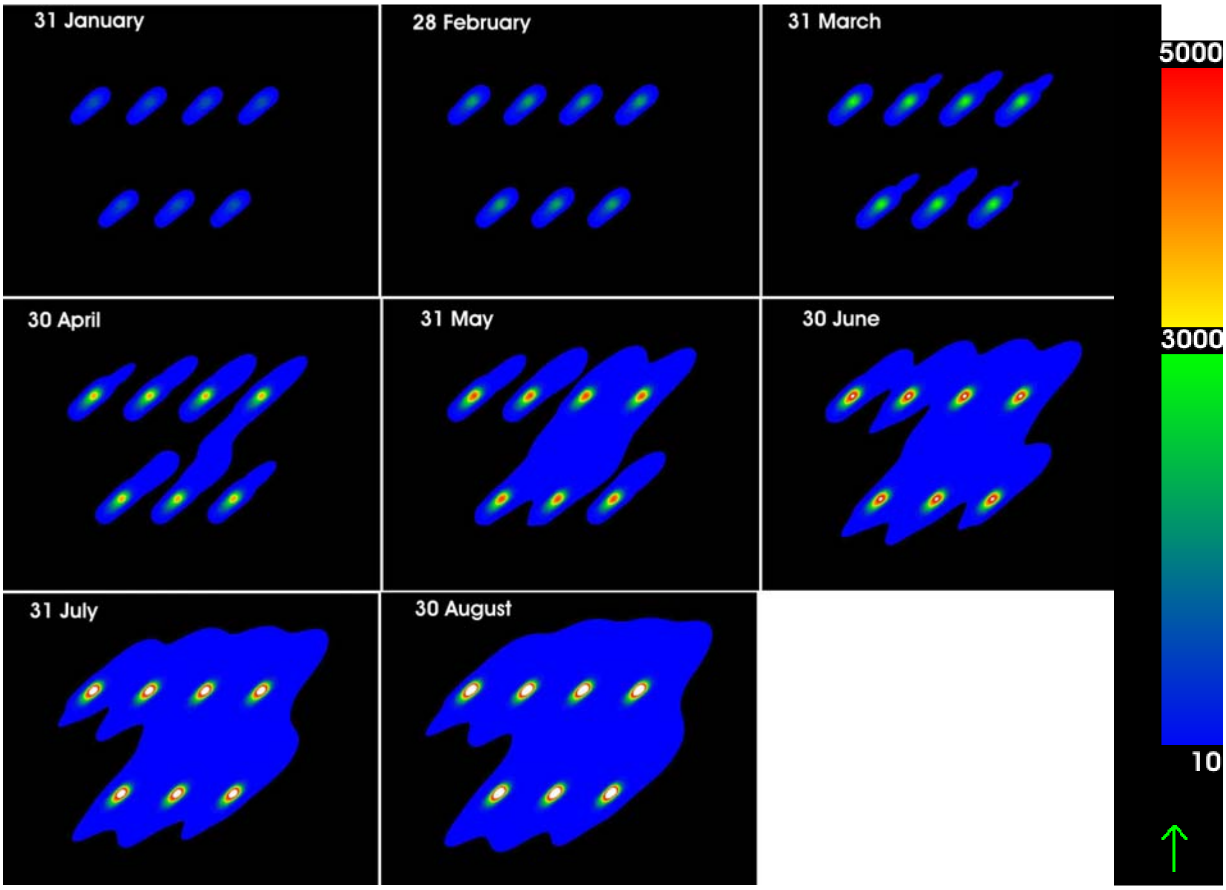

Figure 7.3: **An example output from the Farmér (carbon deposition) model, showing development of carbon deposition over time (note: there are no removal processes operating in this simulation). Scale bar shows total deposition over time in g m^{-2}.**

7.4.4 Finfish Carbon Deposition Model – Sensitivity Analysis

A sensitivity analysis was performed on the finfish carbon deposition model (Farmér) to test the sensitivity of the model predictions of maximum carbon loading and the pattern of spread from finfish aquaculture pontoons to respiration rate, food conversion ratio (FCR), and feeding rate. This analysis shows how carbon deposition changes with changes in these parameters. Similar sensitivity analyses could be conducted for any other parameter desired, although the other parameters that have high uncertainty (sinking rates and currents) are complex and are not just introduced into the model as a single parameter. Thus a sensitivity analysis would have to be based on comparing different scenarios, rather than simply stepping through different values of a parameter.

7.4.4.1 Respiration rate sensitivity analysis

The initial model simulations of carbon deposition were based on a tuna resting respiration rate of 600 mg O_2 kg^{-1} hr^{-1}, although rates immediately post feeding of 1200 mg O_2 kg^{-1} hr^{-1} have been recorded (Q. Fitzgibbon pers. com.). The sensitivity analysis involved repeated simulations of the carbon deposition model using a range of respiration rates. The respiration rates used for the sensitivity analysis were 300, 600, 750, 900, 1050 & 1200 mg O_2 kg^{-1} hr^{-1}, hence, a total of 6 simulation runs were performed.

7.4.4.2 Food Conversion Ratio (FCR) sensitivity analysis

The food conversion ratio (FCR) is the amount of food fed per kg to achieve a 1 kg increase in fish body weight (Jover *et al*, 1999). Within the current model, an FCR value of 12 is used. This value is calculated on the basis that approximately 50,000 tonnes of baitfish are fed to produce a 4,300 tonne increase in the weight of tuna. Repeated model runs were conducted with FCRs ranging from 9 to 25, in steps of 2 (i.e. 9 separate runs).

7.4.4.3 Feeding rate sensitivity analysis

To examine the effects of varying feeding rate, a sensitivity analysis was conducted of this parameter also. Fernandes et al. (2007 – Chapter 4) quotes feeding rates of 1-15% of body weight per day, although in initial model runs we found that values at the lower end of this range were insufficient for fish to maintain their basal respiration rate. The sensitivity analysis involved model runs with feeding rate varying from 4 to 16% of body weight, in 2% increments (7 model runs).

7.4.5 Results and Discussion

7.4.5.1 Respiration

The model output is sensitive to the value of respiration rate chosen (Figure 7.4). It is obvious that as respiration rate increase, the amount of carbon deposited on the seafloor decreases if the other parameters remain constant. This decrease is due to increased amounts of carbon being respired as carbon dioxide. Assuming an FCR of 12 (wet weight), and a feeding rate of 7% of body weight per day, respiration rates above 846 mg O_2 kg^{-1} hr^{-1} produce a carbon deficit (i.e. the fish would lose mass if respiration rates greater than this were maintained). The pattern of carbon deposition around a series of pontoons is very similar at the different respiration rates (Figure 7.5), although obviously the area of high deposition decreases as respiration increase, and disappears when respiration is set at 800 mg O_2 kg^{-1} hr^{-1}.

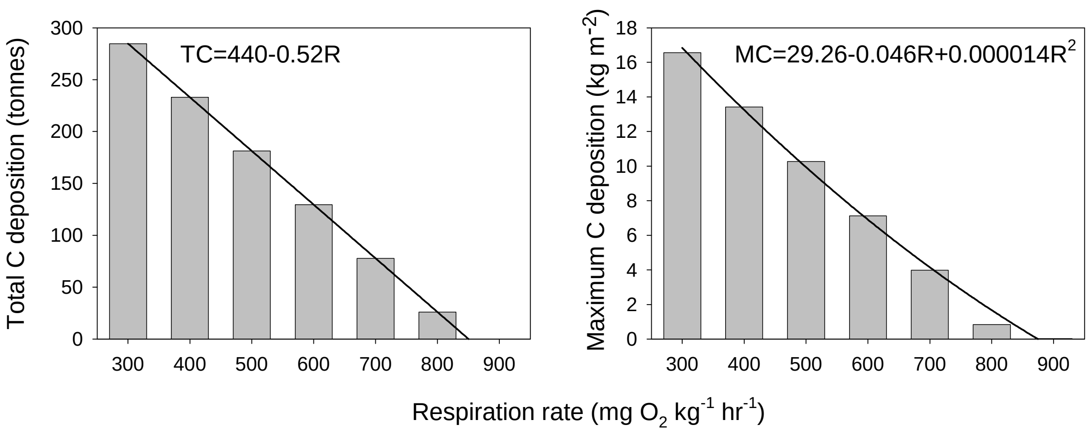

Figure 7.4: **Sensitivity analysis of respiration rate on total and maximum carbon deposition (FCR=12, feeding rate = 7%). The linear fit for total carbon deposited has r^2=1, while the quadratic fit for maximum carbon loading at a point has r^2 of 0.99.**

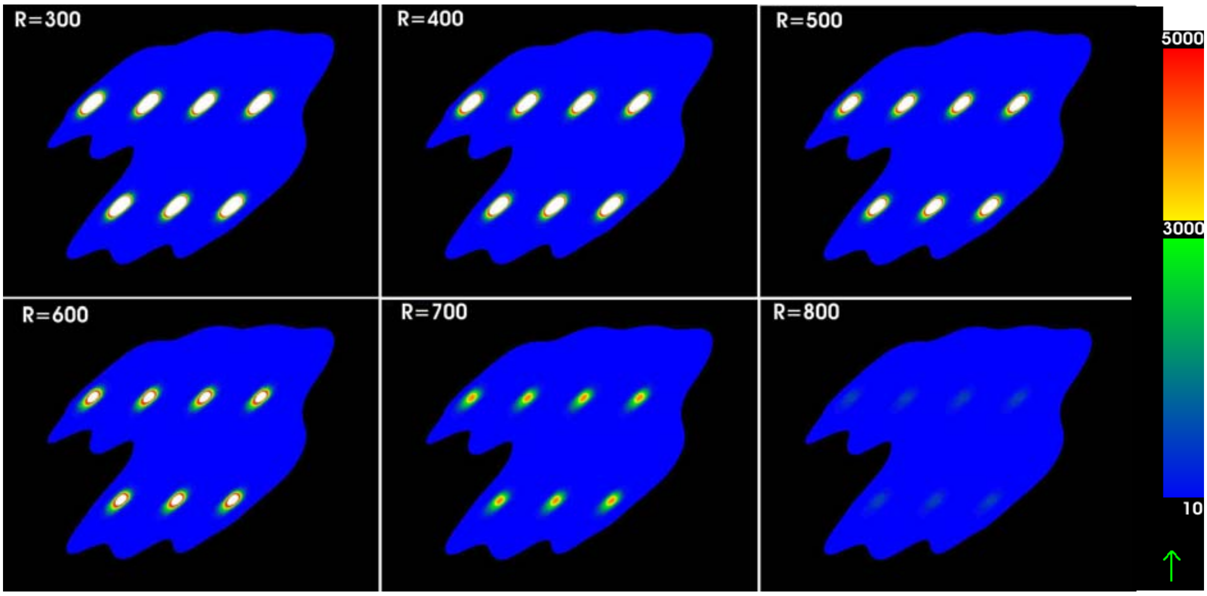

Figure 7.5: **Sensitivity analysis of respiration rate (varying from 300-800 mg O_2 kg^{-1} hr^{-1}) on carbon deposition pattern (note: there are no removal processes operating in this simulation). Scale bar shows total deposition over time in g m^{-2}.**

7.4.5.2 Food Conversion Ratio

The model was much less sensitive to FCR than it was to respiration rate (Figure 7.6). As the FCR improves (gets lower), the amount of carbon assimilated by the fish increases, and obviously the amount deposited on the seafloor decreases. At a respiration rate of 600 mg O_2 kg^{-1} hr^{-1}, and feeding rate of 7% of body weight per day, none of the FCRs tested resulted in carbon demand of the fish being greater than supply. Again, FCR appeared to have little effect on the actual pattern of carbon deposition (Figure 7.7).

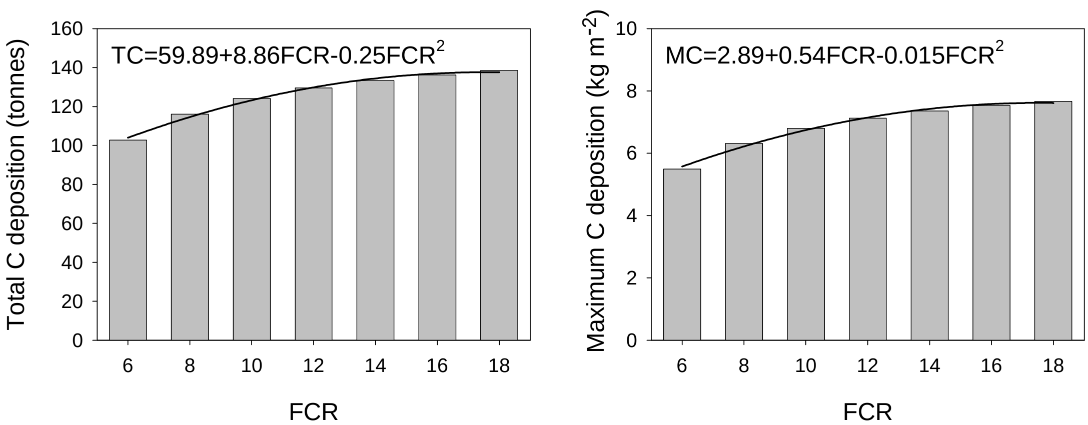

Figure 7.6**: Sensitivity analysis of FCR on total and maximum carbon deposition (respiration rate =600 mg O_2 kg^{-1} hr^{-1}, feeding rate = 7%). The quadratic fits for both total carbon deposited maximum carbon loading at a point have r^2 of 0.99.**

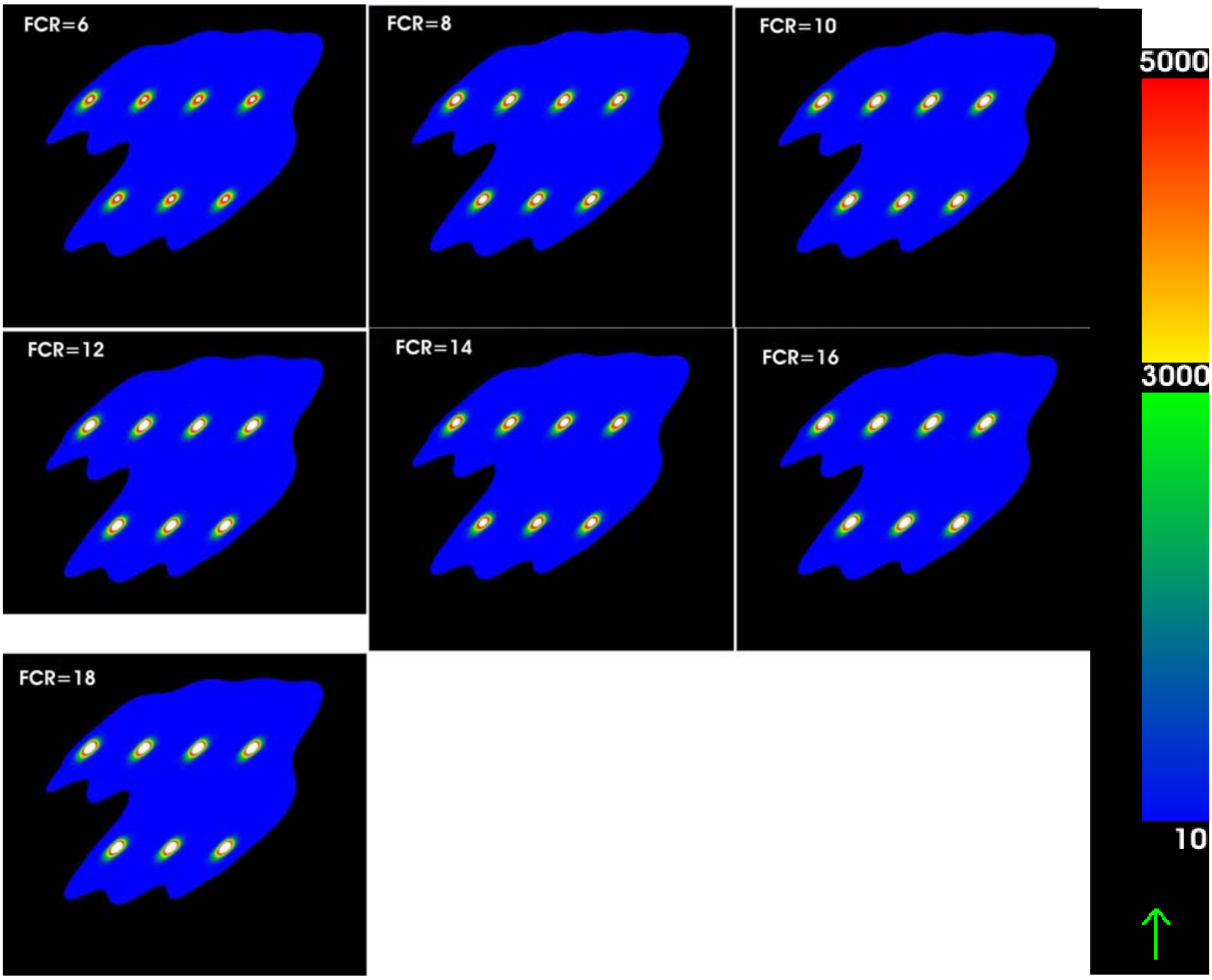

Figure 7.7: **Sensitivity analysis of FCR (varying from 6-18) on carbon deposition pattern (note: there are no removal processes operating in this simulation). Scale bar shows total deposition over time in g m^{-2}.**

7.4.5.3 Feeding Rate

The model displayed similar sensitivity to feeding rate as it did to respiration rate (Figure 7.8). Obviously, lower feeding rates led to lower carbon deposition. Carbon demand by the fish equalled carbon supply at a feeding rate of 4.94% of fish body weight per day. That is, this feeding rate supplied just enough carbon to the fish for it to maintain its basal respiration, without any carbon being deposited as faecal material, and without any scope for fish growth. At low feeding rates, the carbon spread is less than at high feeding rates (Figure 7.9).

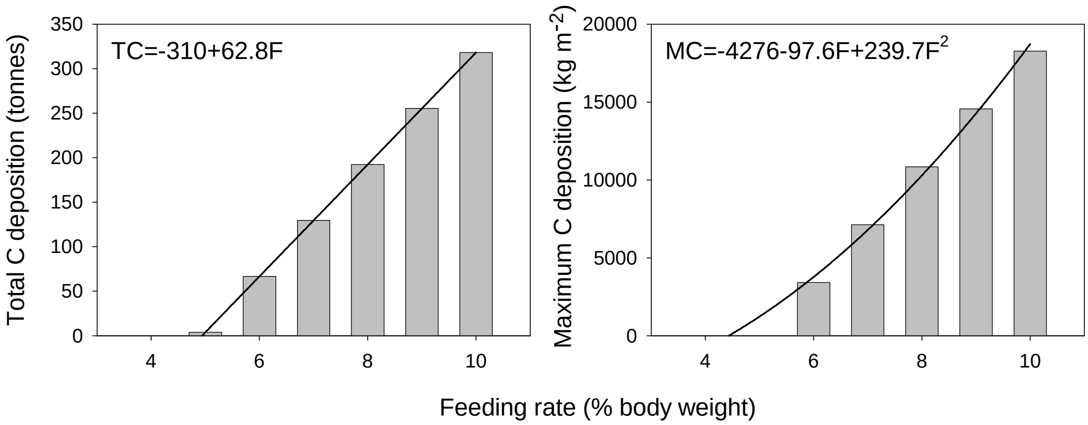

Figure 7.8: **Sensitivity analysis of feeding rate on total and maximum carbon deposition (respiration rate =600 mg O_2 kg^{-1} hr^{-1}, FCR=12). The linear fit for total carbon deposited has r^2=1, while the quadratic fit for maximum carbon loading at a point has r^2 of 0.99.**

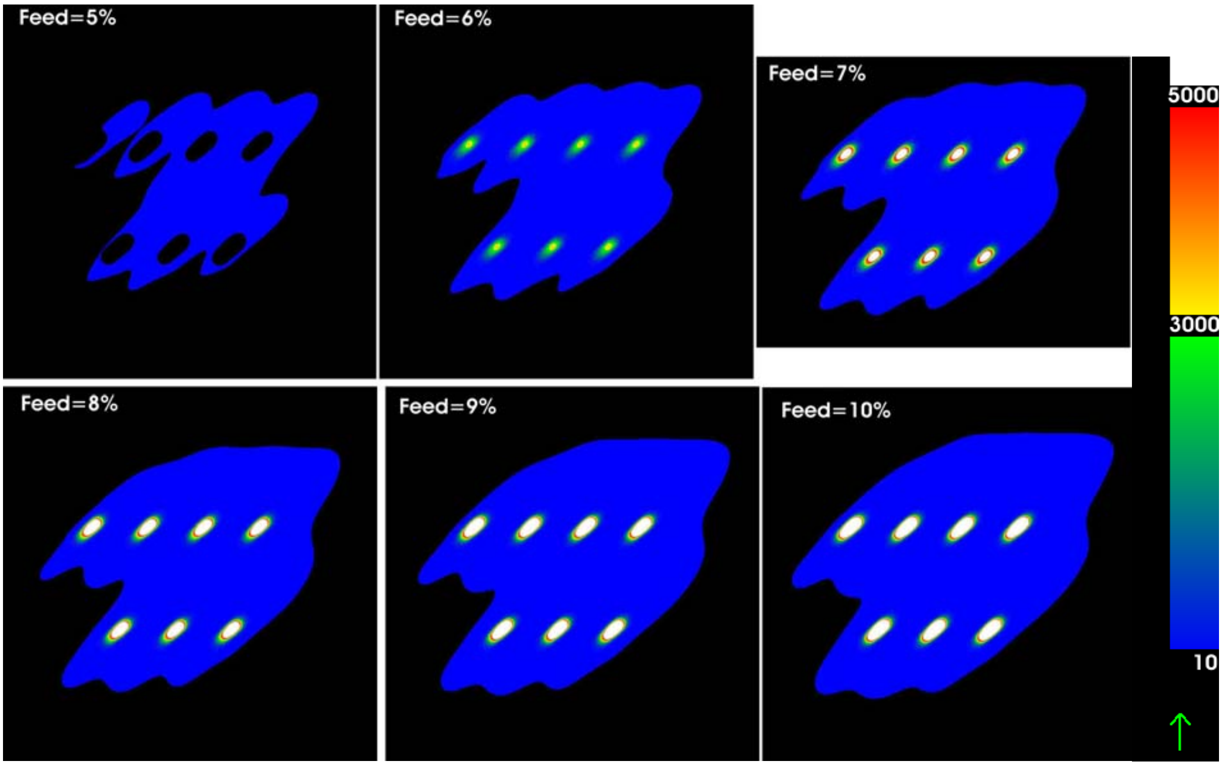

Figure 7.9: **Sensitivity analysis of feeding rate (varying from 5-10% of body weight) on carbon deposition pattern (note: there are no removal processes operating in this simulation). Scale bar shows total deposition over time in g m^{-2}.**

The results from this simple sensitivity analysis have shown that the respiration rate and feeding rate must be accurately measured or estimated to yield conclusive and confident model predictions. Exact knowledge of the FCR is considerably less important. The respiration rate used in the model of 600 mg O_2 kg^{-1} hr^{-1} is that for a swimming tuna between 10 and 25 hours after feeding (Q. Fitzgibbon pers. com.).

7.4.6 Model validation

The results of the carbon deposition model can be compared to data on sedimentation rates to determine how valid the model outputs are. Ideally, this would involve measuring sedimentation at a series of points whose location is known precisely in relation to the position of pontoons, at a time when conditions are calm and there is no or minimal turbulence, and during a period for which current measurements in the vicinity of the pontoon(s) being monitored are available. While sedimentation data are available, they unfortunately do not meet these criteria, and thus the model can only be validated fairly coarsely.

Fernandes et al. (2007 – Fig 5.15), show that sedimentation immediately adjacent to a pontoon can be between 0 and 60 g DW m^{-2} day^{-1} higher than at control sites. Assuming that the additional material is all faeces, and that faeces are 30% carbon (based on the figure for yellowtail kingfish used by Tanner et al. 2006, as no values for SBT are available), then this equates to 0-4.4 kg C m^{-2} 8 $months^{-1}$. The base model (Fig 7.3), predicts that maximum carbon deposition will be 7.1 kg C m^{-2} 8 $months^{-1}$, although this will only occur in a very small area immediately under the cage and downcurrent of it. If we increase the respiration rate from the 600 mg O_2 kg^{-1} hr^{-1} used in the base model, to 700 mg O_2 kg^{-1} hr^{-1}, then maximum carbon deposition decreases to 4 kg C m^{-2} 8 $months^{-1}$ (Fig 7.4). Thus, the modelled and measured carbon deposition rates match to within the known uncertainties of the model and the field data.

7.5 Implications of the results

The parallel application of the two models described above has allowed a range of useful outcomes. A quantification of the likely effects of differing levels of finfish aquaculture on dissolved nutrient concentrations is provided by model 1, although it is acknowledged that some of the processes being modelled are poorly understood, and hence the model results are unrealistic in terms of absolute values. The model can, however, still be used to get an idea of the relative consequences of different management actions. Farmér, whilst not used directly for the enumeration of carrying capacity, has provided useful information on likely patterns of carbon deposition, and with future calibration efforts and research on the environmental effects of different levels of deposition, is likely to become an even more useful tool.

While the consequences of different cage placement within a lease have not been investigated here, one of the potential uses of Farmér is to study this question. Thus, farm managers could run a series of simulations to determine how best to space cages to minimise overlap of their deposition zones, thus avoiding having areas of extremely high impact within their lease. The model could also be used to assess potential interactions between 2 closely neighbouring leases. From a regulatory perspective, the model could be used to determine the location of the area of highest impact outside the lease if it was desired to monitor this point to detect any breaches of licensing conditions.

Where possible, these models have been designed and parameterised with the precautionary principle in mind, i.e. where uncertainty exists, parameters are chosen to produce the worst possible outcome. Areas which require particular attention are the issue of water exchange when flushing rates are used, the ambient concentration of nutrients in the water across a farming season, and the sinking rates and diffusion coefficients of uneaten food and faeces. While some data are available on these factors, they are not comprehensive. The sensitivity analysis of the carbon deposition model also indicates that it is important to have good estimates of respiration and feeding rate, while FCR is less important in predicting carbon outputs. Both models also track total inputs, assuming that these inputs remain in the system, and are not processed by other components such as scavengers and phytoplankton.

It is important to recognize the boundaries of this modelling process. Predictions of carrying capacity have been made on the basis of dissolved nutrient levels, with useful indicators of the patterns of carbon deposition also being produced. However, other factors may act to dictate a carrying capacity lower than that indicated, such as microalgal levels or disease transmission rates. The models used here represent the commonest issues impinging on the environmental carrying capacity. However, an appreciation of other factors that may change the situation is necessary (Henderson *et al.* 2001).

Also beyond the scope of these models, but worth considering, is the eventual fate of material flushed “out” of the system. While the model sees this material as removed, this is because an artificial boundary has been imposed in the form of the zone. In reality the material is moved to another region, where it could potentially cause problems if the ecosystem is sensitive to nutrient enrichment. The aquaculture zone has been modelled, but the potential effects beyond this zone, while they may be important, have not been investigated. Similarly, it is assumed that no other aquaculture zones export nutrients into the tuna farming zone, or that if they do, these nutrients are included in the background levels used, and there is no simultaneous increase in production in these zones.

The results of these models should be seen, not as an endpoint of the process, but as a part of a cycle of improvement (Read *et al.* 2001; Henderson *et al.* 2001). Adaptive management is the principle that makes use of models to make preliminary predictions that are then adopted along with a careful monitoring strategy. The object of this monitoring is essentially to test the predictions of the model. In doing this, it serves two purposes – it acts to safeguard stock, and importantly, it is used to improve the model. Thus it becomes a recursive process, with the model becoming increasingly accurate and the monitoring acting to test the model and indicate further areas for improvement.

The immediate benefits of the creation of this modelling system are preliminary estimates of the environmental carrying capacity of the Port Lincoln tuna farming zone, and indications of the likely pattern of carbon loading around the lease area. However, there are other benefits of the creation of an "in-house" model that will be realised with time. Unlike proprietary models such as DEPOMOD (Cromey *et al.* 2000), we have developed a flexible system that can be continually re-engineered to reflect a system that we understand increasingly well. This model is in place, being used for preliminary predictions, and is deployed in an environment that is eager to monitor its results, recalibrate and continually improve its output, both in terms of accuracy and function.

Future directions already identified involve better estimation of sinking rates and the development of a new model for better estimating the flux of nutrients from the water body in question. Such an approach involves the use of decay curves that describe the rate at which particles are lost to the system over a tidal cycle. The nutrients introduced each day then disappear from the system at a varying rate defined by the decay curve.

7.6 Future directions for the finfish carrying capacity models

7.6.1 Model 1: Predicting the build-up of dissolved nutrients

There are several factors that need to be addressed and improved to develop a better estimate of likely production based on the build-up of dissolved nutrients around finfish pontoons. A few important points are outlined below:

1. The current nutrient levels in the water column are based on field measurements made at two points in time, although it does fall in the range of values obtained from previous studies. The Risk & Response project (FRDC 2005/059) is currently collecting data on nutrient levels along a transect across the farming zone on a monthly basis, which will allow seasonal variation to be incorporated into future versions of the model.

2. All nitrogen lost to the environment was lost in soluble form. This is not entirely correct as several sources (Skretting Australia dietary fact sheet; Cho *et al.* 1991) would suggest that up to 20% of the waste nitrogen is in solid form and would therefore not

add to the dissolved nitrogen load. However, nitrogen in the solid form is taken up, used by the benthic ecosystem, and utilised within the sediment, resulting in some proportion of this being re-released. Without knowledge of this figure, it was necessary to assume that standard equations (eqn 7.2) could be used to predict how much waste ended up in dissolved form versus particulate. Since this modelling was conducted, Fernandes et al (2007 – Fig 9.1) has produced a nitrogen budget for tuna farming, which indicates that 67-76% of N is eventually released in soluble form. This figure compares favourably with the calculation used here, which suggested that 74% would be released in dissolved form.

3. The lack of detailed knowledge concerning the nitrogen cycle and the processes of nitrification, denitrification and ammonification also led to the need to make assumptions about the chemical species of nitrogen being dealt with. Although marine fish release ammonium (and associated compounds such as urea) rather than nitrate, the processes indicated above will convert some proportion of this to nitrate. Without knowledge of what this figure is, it was necessary to assume that all nitrogen released was released as ammonium when basing predictions on ammonium, and all as nitrate when nitrate was the limiting factor. This is an area that needs to be further investigated.

4. A better understanding of water movement in the tuna farming zone is needed to allow an improved estimate of flushing rate. Currently it is assumed that any nutrients moved out of the zone do not return, whereas this assumption is unlikely to be correct. The development of a proper hydrodynamic model for the area will allow particles movements to eb traced and accurate flushing times to be estimated. This is currently being done as a part of the Risk & Response project (FRDC 2005/059).

7.6.2 Model 2: Farmér – predicting carbon loading to the seafloor

There are many factors that need to be considered in the refining of the carbon deposition model. Important areas of improvements are listed below:

7.6.2.1 The speeding up of model simulations

Currently the speed of simulations is relatively fast if the simulation results are not regularly plotted while the simulation is running. If the pattern of deposition over time is being plotted on screen, however, the simulations can be fairly slow. The most likely avenue for speeding up the model is in the way the effects of the currents are handled. Currently, at each iteration, the relevant current vector is applied to every point in the model domain. Amalgamating currents beforehand and multiplying by a matrix of current movements, skipping those that are zero, may provide faster simulations whilst retaining the ability to see the pattern of spread developing over time. This is being investigated as a part of developing a user-friendly version for industry use.

7.6.2.2 Improvements to Program Function

Future directions already identified involve better estimation of sinking rates and the development of a new model for better estimating the flux of nutrients from the water body in question. Such an approach involves the use of decay curves that describe the rate at which particles are lost to the system over a tidal cycle. The nutrients introduced each day then disappear from the system at a varying rate defined by the decay curve.

Also, it would be beneficial to develop the simulation output as a 3-D view of the contour map showing the concentration of carbon loading.

7.6.2.3 Improvements to Calibration

Adequate calibration of the model has not currently been achieved and this is probably the most important issue to be considered at this stage of development. There are several factors that need either a more complete data set to give better predictions, or more information and knowledge is needed to further build the model structure to make the simulations more realistic.

The empirical measurements of falling rates of food and faeces need to be improved. Currently, there are two settling rates for uneaten feed and four for faeces, and these need to be resolved in finer detail. Use of a broader range of particle sizes is likely to result in a more even distribution than that indicated. More importantly, field/laboratory measurements of diffusion distance for each particle size/type need to be included. The diffusion coefficient used has assumed that a sinking time of 400 seconds would result in 99% of the particulate matter falling in a normal distribution within a circle of diameter 80metres. This figure requires empirical validation, although this will be difficult to achieve. Additionally, the model does not take into account turbulent mixing associated with wave action, which has the potential to increase the dispersion of wastes.

At this stage of the model development temperature has not been incorporated within the structure. This is an area that needs to be revised and parameterised accordingly. Temperature is likely to influence respiration rate, which the sensitivity analysis indicates is important for the carbon deposition model.

Finally, the results need to be validated against long-term field measurements. This is a very important consideration in the model's development. If the model predictions can be compared to long-term field situations, then a greater understanding and confidence in model predictions can be achieved.

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Chapter 8 Collation of data relevant to regional oceanography in the mouth of the Spencer Gulf

Sam McClatchie

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8.1 Overview of the datasets

- Bathymetry data at two resolutions (1 km and 250 m) for the region are available under a data agreement with Geoscience Australia.
- A wealth of water mass analyses, current observations, tidal analyses and seasonal variation in temperature and salinity at the mouth of Spencer Gulf is available in the PhD thesis of Hahn (1986), but the data are not readily available.
- More recent hydrographic data from well-calibrated CTD are available for several of the annual SARDI pilchard surveys (2001, 2002 and 2005).
- Operational time-series tidal data (sea-level) and meteorological (wind data) for discrete locations are available since 1995-1996 in digital format. Analogue data from 1962 to 1995 may be available depending on location. Tidal data are available at SARDI for 6 locations and meteorological data from 5 locations.
- Wave height data since 1998 are available from a wave-rider buoy off Cape du Couedic (south-west tip of Kangaroo Island).
- Water column and sediment nutrient data are available for the area between Boston Island, Point Bolingbroke and Cape Donington. Recent (2005) nutrient data are also available from 50 stations between Port Lincoln and Sibsey Island.
- Infaunal and epifaunal data are available for the tuna lease areas from 1996 to 2004. Sediment grainsize, morphology and chemistry are available for the same area for 2002.
- Time-series data from Telemetry-based Environmental Monitoring systems located off Port Lincoln east of Boston Island collected wind speed and wind direction, water temperature, conductivity/salinity and dissolved oxygen for specific periods in 2004 and 2005.
- There are large numbers of fragmentary datasets from localised regions and times, many of which are qualitative, and some of which are of dubious quality. These are not included in the collation.
- Potentially useful, more comprehensive datasets have been tabulated.

8.2 Introduction

This chapter presents an overview of the oceanographic data available from the Port Lincoln region and surrounding areas, as well as details of how the original data may be obtained (if available). The primary purpose of this collation is to provide a starting point for developing a linked hydrodynamic, biogeochemical and sediment model of the farming zone. Developing this model will require an intensive data collection effort, and with limited resources, there is a clear need to develop an understanding of the existing data available before commencing collection of new data. The modelling exercise is being undertaken as a part of a new Aquafin CRC project "Risk & Response: Understanding the tuna farming environment", that started in July 2005.

8.3 General observations

The data that have been collected in the mouth of Spencer Gulf are substantial but their usefulness is limited by being disparate in both space and time. Most of the data have been collected for projects that are not closely linked to the goals of the current project, and so the sampling regimes are not ideal for current purposes. Because the data have been compiled over a wide range of years, using various methods, and with varying quality, it would not be advisable to carry out a meta-analysis that aggregates the data.

The most comprehensive, integrated oceanographic dataset for the region is the thesis by Hahn (1986). The annual sardine ichthyoplankton surveys conducted by SARDI also provide a comprehensive and standardized dataset, which includes oceanographic measurements and overlaps with the region of interest, although caution should be exercised. The conductivity, temperature, depth (CTD) calibrations for these surveys were adequate for precise oceanographic measurement in the region of interest only for 2001, 2002, and 2005.

8.4 Gap analysis

Although there are some seasonal datasets (most notably in Hahn 1986), there are more data from the summer than from the winter. The data available for any season are limited to physical oceanographic and weather data, sediments, nutrients and phytoplankton. The absence of any zooplankton data or particle size spectra data is notable. Species data for the phytoplankton as well as the zooplankton are few, although these can be critical for interpreting impacts in the water column and for understanding sedimentation to the benthos. Current velocity records are also limited to a few sites and years. There is an absence of any comprehensive monitoring program for the aquaculture sites and surrounding areas that extends over a useful time frame for detecting interannual variability. If this were available for even half a dozen key locations on a decadal time plan, it would be extremely valuable. Although they are readily available from Distributed Active Archive Centres there is currently no compilation of satellite imagery for the region of interest for any variables (sea surface temperature, SST), ocean colour, sediment, or sea surface roughness) on appropriate time scales (composites) at any of the available resolutions. There is no comprehensive effort to collect ground-truth data for satellite imagery, particularly with regard to interpreting nearshore ocean colour information, and this limits the interpretation of the imagery in nearshore regions.

8.5 Bathymetry

One-minute resolution bathymetry purchased from Geoscience Australia bathymetry and topography grid (January 2002, GeoCat no. 38713) (Figure 8.1) is held at SARDI Aquatic Sciences. Data were re-grided using GMT (Wessel 1998) and contours plotted at 10 m intervals to 200 m, and 100 m intervals to 1000 m. A higher resolution dataset obtained by the Adelaide University School of Petroleum will soon be available to SARDI under a data agreement (it may be used in reports, but cannot be re-distributed).

Contact
Dr. John Middleton
SARDI Aquatic Sciences
middleton.john@saugov.sa.gov.au

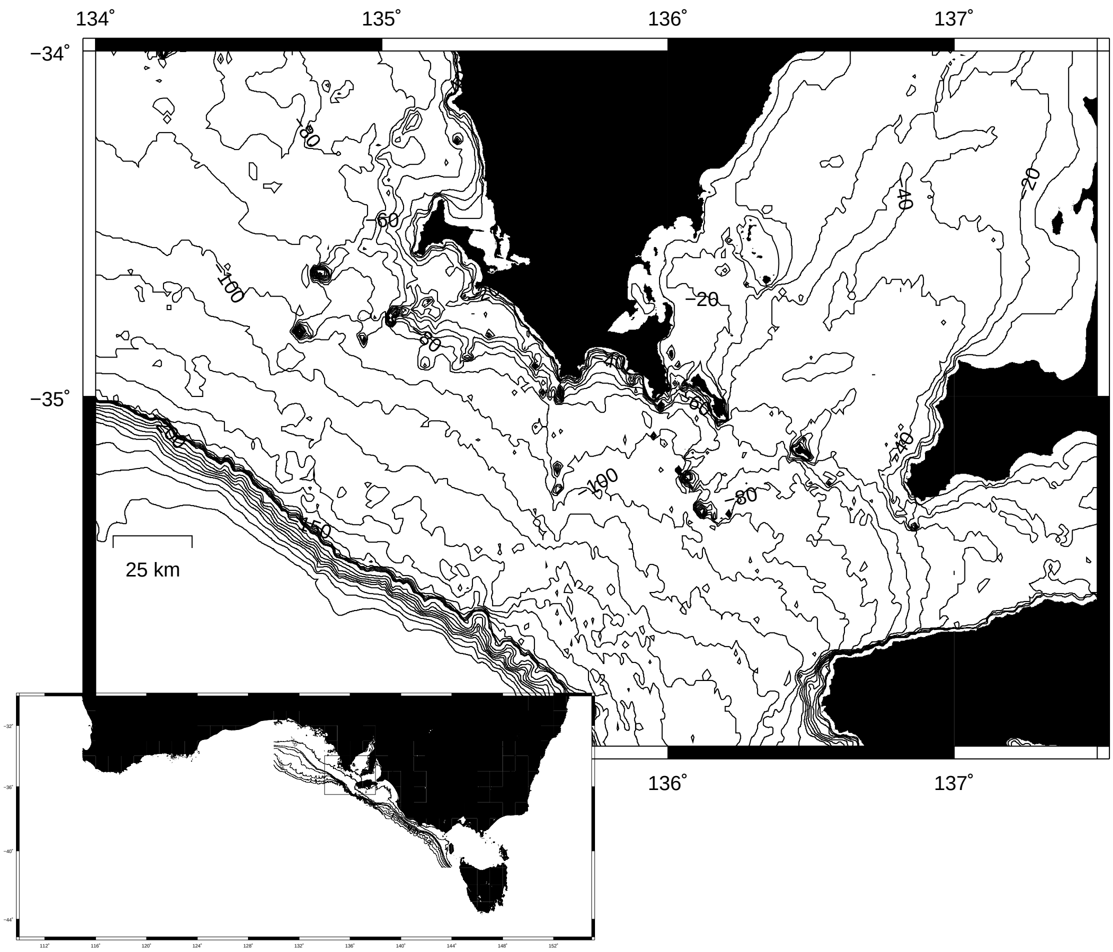

Figure 8.1: **The area of interest extends from 134°E to 137 30'E, bounded to the south by the shelf edge (200 m contour) and to the north by latitude 34°S. Bathymetry shown here is contoured from 1 km resolution dataset.**

8.6 Descriptive hydrography

8.6.1 CTD survey and mooring results in Hahn (1986)

Hahn's (1986) thesis results provide a rich source of information in the form of graphs and tables, but the data are not readily accessible. Physical oceanographic data collected prior to the arrival of Dr. Matt Tomczak to Flinders University in 1992 were not properly archived, and these data are thought to have resided on unreadable magnetic tapes, that have subsequently been lost (M. Tomczak, personal communication). The only possibility is that they may have been entered into the National Oceanographic Data Centre database (M. Tomczak, personal communication), but we have not pursued this. The most relevant parts of Hahn's (1986) data come from a 5-station CTD transect across the mouth of Spencer Gulf, and an 8-station CTD transect normal to the first extending along the axis of the Gulf out onto the shelf to a mooring station in ~140 m water. Numerous CTD surveys were run between 1980 and 1982, with the rather complicated sampling described in Section 3.2.3 of the thesis (Hahn 1986). Seasonal sections of temperature, salinity and density from the two CTD transects mentioned above are graphed in Figures 9-21 and described in Section 5.2 of the thesis (Hahn 1986). These data are used in the water mass analysis.

Data were collected at the mooring from January 1981 to June 1983 in a complicated set of thermistor chain and current meter deployments, tabulated in Figure 7 of the thesis. Chapter 6 of the thesis describes seasonal variability of currents, presents a frequency analysis of currents and estimates the annual mean currents. This is followed by analysis of the main tidal components. The variation in temperature and salinity and the seasonal formation, deepening and destruction of the thermocline are described in Chapter 7. Short-term variations in the depth of the thermocline in relation to tidal forcing are described and the possible influence of internal waves is discussed.

Hahn's thesis is the most comprehensive presentation of the descriptive regional physical oceanography of the area that we have encountered.

Contacts

Dr. Matt Tomczak,
School of Chemistry, Physics and
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Flinders University
GPO Box 2100
Adelaide SA 5001
Matthias.Tomczak@flinders.edu.au

Dr. S.D. Hahn
National Fisheries Research and
Development Institute
Korea

8.6.2 SARDI annual sardine surveys: CTD data

Data are available to describe the regional water masses and hydrographic structure near the southern tip of Eyre Peninsula and the mouth of Spencer Gulf. Calibrated CTD profiles were collected in the region of interest in February/March of 2001, 2002 and 2005 as part of the annual sardine surveys in the eastern GAB.

An example of the dataset is presented here for 2001. Profile data were collected along transects normal to the coast, at stations spaced ~9 km apart (Figure 8.2 - 8.7). At each station, a vertical profile was obtained by lowering a calibrated Sea-Bird 19plus SEACAT Conductivity-Temperature-Depth profiler and fluorescence sensor. Additional sensors for dissolved oxygen, turbidity, and irradiance were available in 2005. The profiler was lowered to a depth of 70 m, or to 10 m from the bottom in waters less than 80 m deep. Profiles were analysed with Ocean Data View (Schlitzer 2003). Data shallower than 5 m and questionable points based on inspection of profiles were excluded. Two zonal and one meridional section of temperature, salinity, density and fluorescence were plotted to show the water column structure. Water masses were distinguished using a temperature-salinity-fluorescence plot (Figure 8.6).

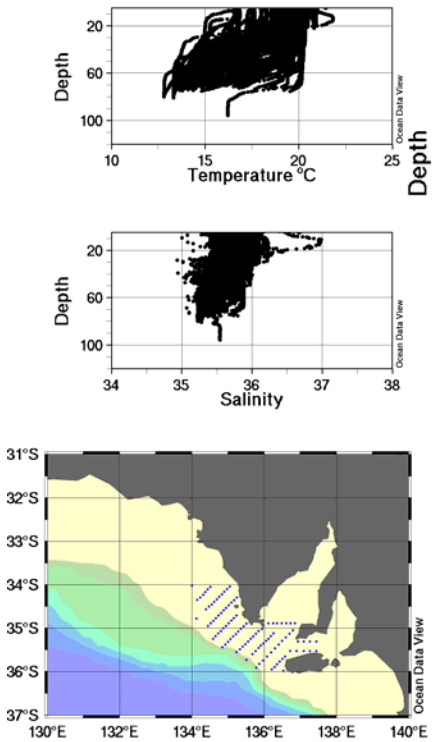

Figure 8.2: **Summary of the CTD profiles from the 2001 pilchard survey in the region of interest (see Figure 8.1). The profiles show data from individual CTD casts at each station marked by the blue dots on the map.**

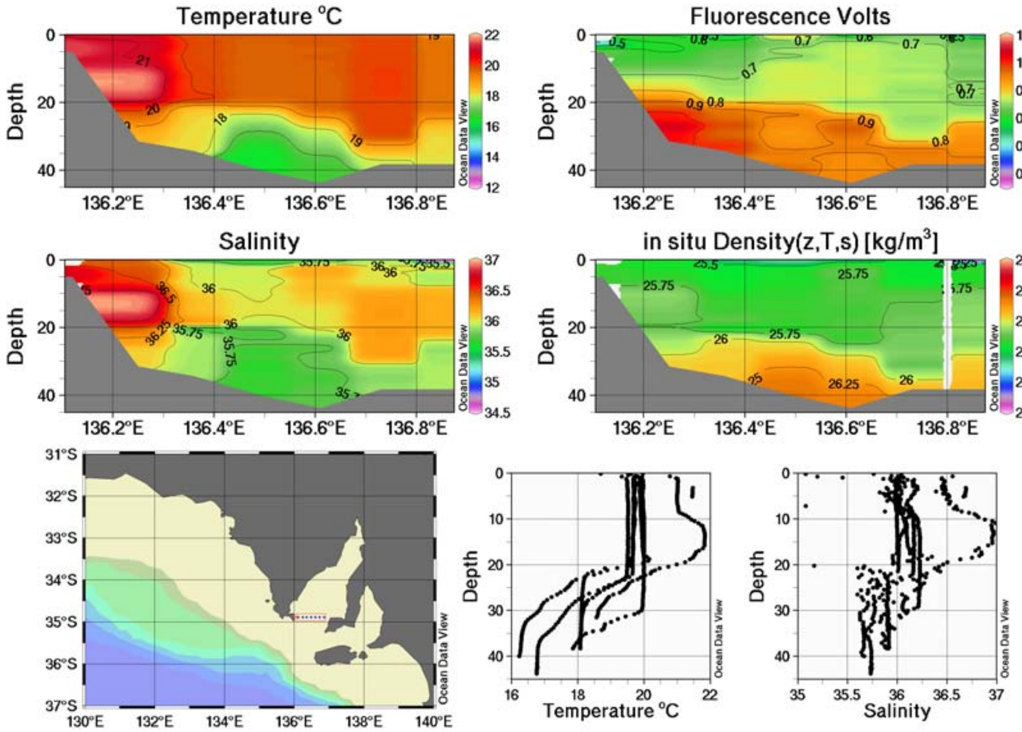

Figure 8.3: **Section along transect "g" of the 2001 pilchard survey. Data collected 28/2/01. The four upper panels show the contoured sections derived from temperature, salinity, fluorescence and density profiles along the transect enclosed by the red box on the map. The profiles at bottom right show data from individual CTD casts at each station marked by the blue dots on the map.**

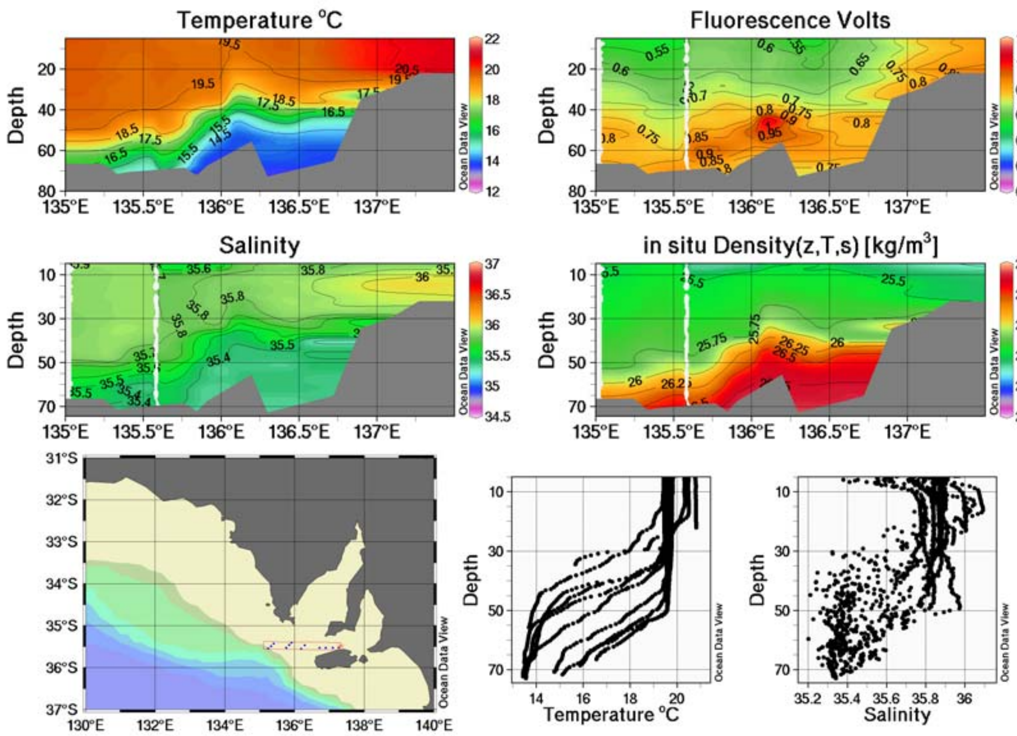

Figure 8.4: **Section along transect "sgc" of the 2001 pilchard survey. Data collected 28/2/01. The four upper panels show the contoured sections derived from temperature, salinity, fluorescence and density profiles along the transect enclosed by the red box on the**

map. The profiles at bottom right show data from individual CTD casts at each station marked by the blue dots on the map.

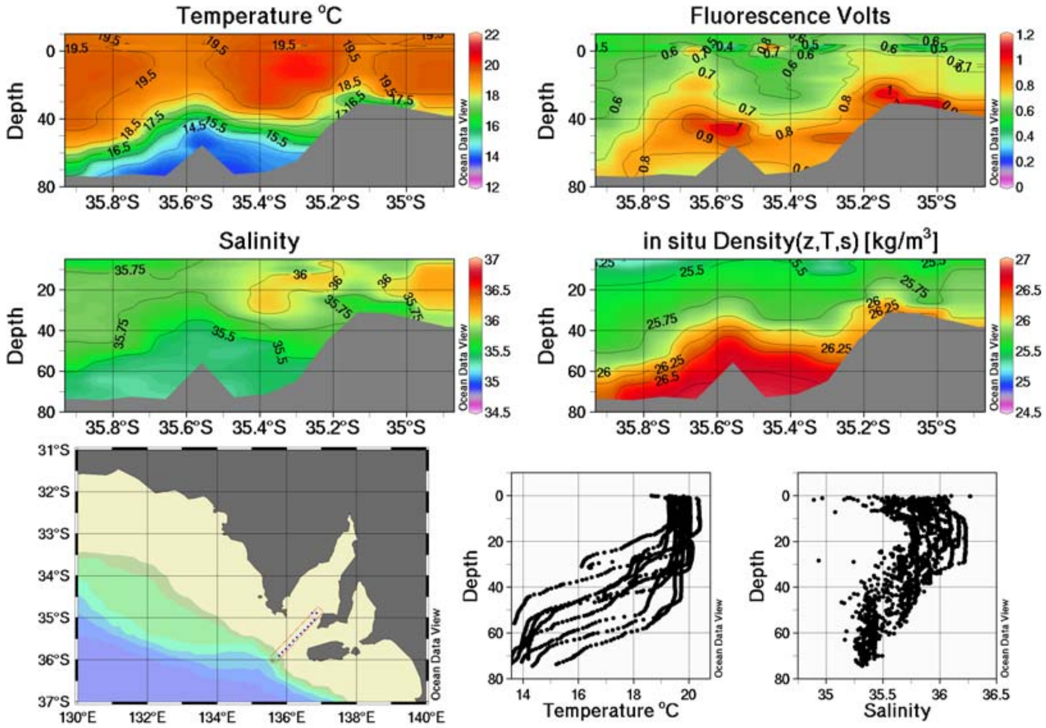

Figure 8.5: **Section parallel to transect "sgc" of the 2001 pilchard survey. Data collected 27/2/01-1/3/01. The four upper panels show the contoured sections derived from temperature, salinity, fluorescence and density profiles along the transect enclosed by the red box on the map. The profiles at bottom right show data from individual CTD casts at each station marked by the blue dots on the map.**

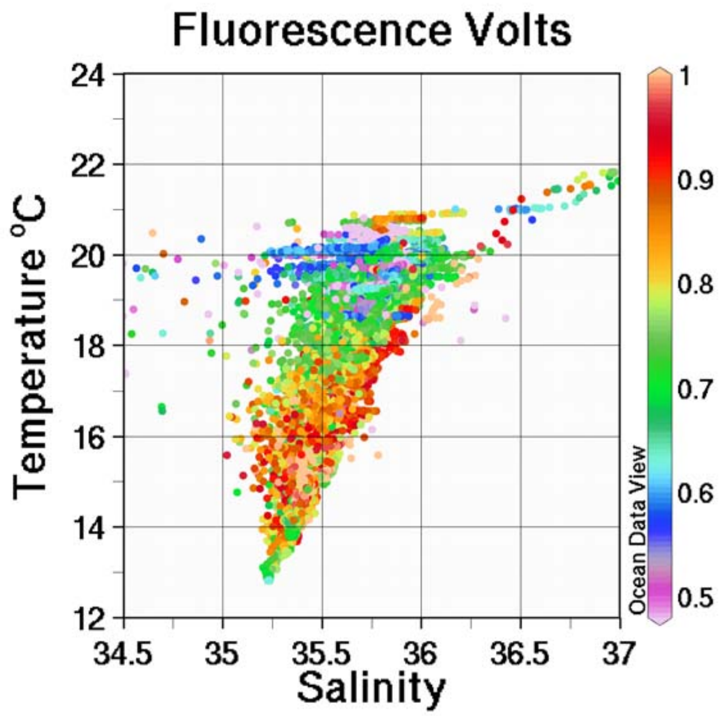

Figure 8.6: **Temperature-salinity plot of the 2001 pilchard survey for the region of interest compiled from all CTD profiles for the region of interest. Colour coding indicates levels of phytoplankton (as fluorescence). Data collected 26/2/01-18/3/01.**

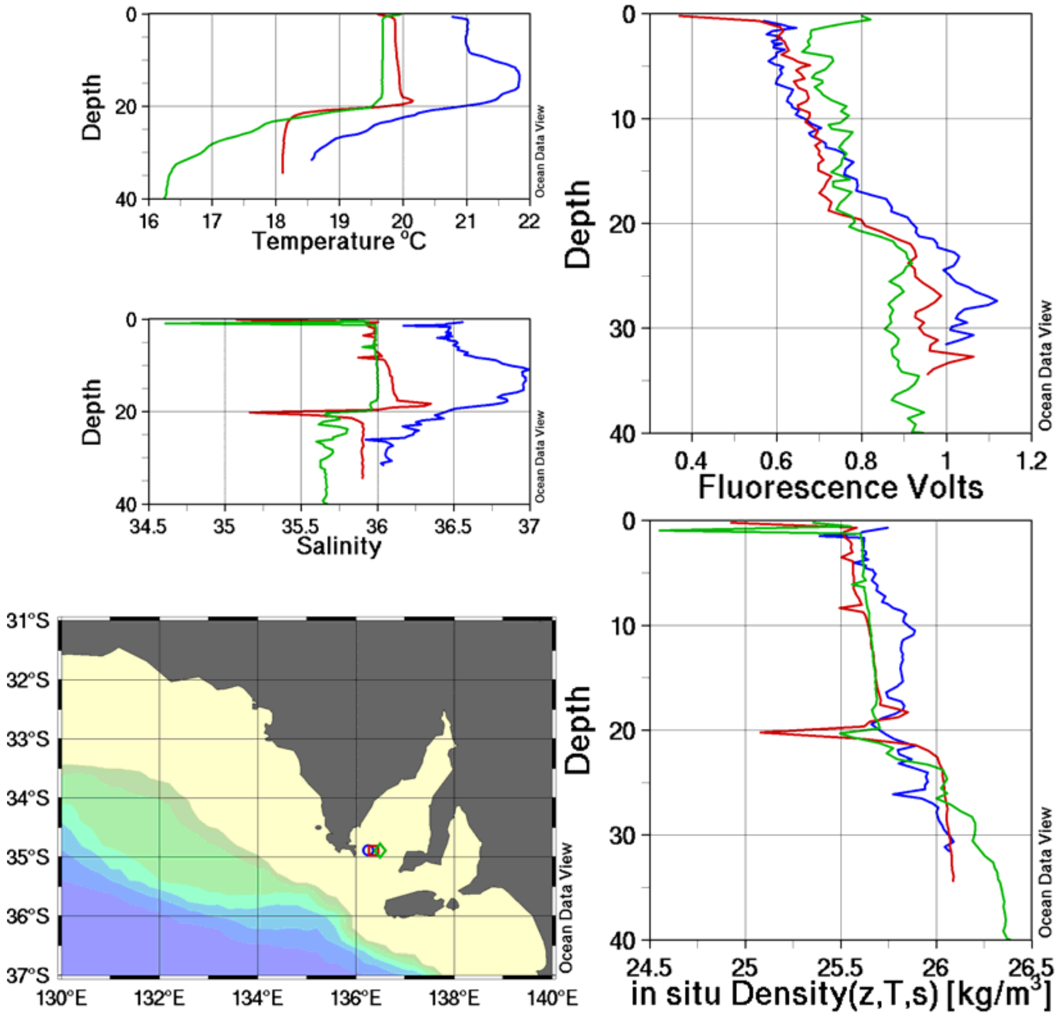

Figure 8.7: **CTD profiles of temperature, salinity, and density for the 3 westernmost stations of the "g" transect (see Figure 8.4, close to Port Lincoln. Data collected 28/2/01. The coloured lines for each profile correspond to the data for a CTD drop at the station marked with the same colour symbol on the map.**

Contact

Dr. Tim Ward

SARDI Aquatic Sciences

ward.tim@saugov.sa.gov.au

8.6.3 Tides (sea level)

Available data

SARDI Aquatic Sciences holds sea level data from 1/1/1996 to 1/1/2001 for the locations Port Lincoln, Whyalla, Wallaroo, Thevenard, Pt Pirie and Pt Giles.

Contact: Dr Jason Tanner,
SARDI Aquatic Sciences
(tanner.jason@saugov.sa.gov.au).

Later data are available from the National Tidal Facility – see contact details below.

Historical

A tide gauge located in Port Lincoln has been measuring sea level heights in digital format every five minutes since 5-Aug-1996, apart from some periods when the tide gauge was malfunctioning. Analogue data are available from 1962-1996. Some earlier records prior to 1962 exist.

Costs
One year of data will cost $396, 5 years will cost $883 and the full dataset will cost $1090, all include GST.

Contact

<table>
<tr>
<td>The National Tidal Facility (NTF) can supply the 5-minute sea levels, hourly means or monthly means with permission from the Flinders Ports Corporation (FPC) who own the gauge. NTF Contact:
Paul Davill
Data Manager/Analyst
National Tidal Centre
Bureau of Meteorology
PO Box 421
Kent Town 5071
South Australia
Tel: 08 8366 2713
Fax: 08 8366 2651
E-mail: tides@bom.gov.au
URL:
http://www.bom.gov.au/oceanography</td>
<td>FPC Contact
Greg Pearce
HydroSurvey Australia
(Flinders Ports Pty Ltd)
296 St Vincent St (PO Box 19)
Port Adelaide
South Australia 5015
Phone +61 8 8447 0657
Fax +61 8 8447 0606
Mobile 0408 842 254
E-mail pearce.greg@hydrosurvey.com.au
Web http://www.hydrosurvey.com.au</td>
</tr>
</table>

Predicted

Tidal predictions for Port Lincoln (primary port) are available from the Australian Hydrographic Service.

Costs

Predicted tide heights prices available on application (approx $55 per annum).

Grzechnik (2000) presents a model of tide and storm surge prediction for the Boston Bay region of South Australia using wind data obtained from the Bureau of Meteorology, tide records from Pt Lincoln and current meter data from three sites in Boston Bay for the period 10/8/1992 to 16/9/1992.

Contact
hydro.licensing@defence.gov.au
http://www.hydro.gov.au/prodserv/tides/tidal_products/tidal_products.htm

8.7 Meteorological Data

SARDI held data

Hourly of average wind speed and direction over 10 min prior to report time (starts reporting half hourly but changes to hourly).

Station ID	Location	Years Available
18115	Neptune Is	1995-2005
18191	Coles Pt	1992-2005
22049	Stenhouse Bay	1996-2005
22801	Cape Borda	2002-2005
18192	North Shields(Pt Lincoln)	1992-2005

Contact: Dr Jason Tanner,
SARDI Aquatic Sciences
(tanner.jason@saugov.sa.gov.au).

Later data, and data from other stations, are available from the Bureau of Meteorology – see contact details below.

Costs

The approx cost of the extraction of these data and the preparation of five files in csv format is $30.

Contact

Peter Clemett
Technical Officer
Climate & Consultative Services
Bureau of Meteorology
Adelaide S.A.
climate.sa@bom.gov.au
http://www.bom.gov.au

Additional sources

Flinders Ports has been recording wind speed and direction from a beacon in the middle of the Port Lincoln harbour.

Costs

The records can be supplied in most formats (e.g. excel, text comma delimited). The cost depends on data required. One year of data will cost $396, 5 years will cost $883 and the full dataset will cost $1090, all include GST.

Contact

Greg Pearce (FPC). Contact details as in previous (Tidal) section.

8.8 Wave Height

Available data

The Waverider buoy uses electrical sensors to measure the vertical movement each time a wave passes beneath it, relaying the data to a ground station where the information is used by the Bureau of Meteorology.

An important calculation from the observed data is the "significant wave height", which is the average height of the highest one-third of the waves observed. This value relates mathematically to what an experienced fisherman standing on his vessel would judge wave height to be, given that human observers apparently often note only the bigger waves when making an estimation of wave height.

Wave periods in seconds are also recorded.

The only buoy in the southern Spencer Gulf area of interest is at Cape du Couedic (south-west tip of Kangaroo Island), which has been in operation since 1998.

Costs

Costs for preparation of data on application.

Contact

Paul Lainio
Manager Public, Marine and Special Weather Services
Bureau of Meteorology, Adelaide
Telephone : (08) 8366 2640
Facsimile : (08) 8366 2651
p.lainio@bom.gov.au

Additional source

The waverider buoy is partly funded by the SA Dept of Environment and Heritage (DEH), Coastal Protection Section. Dr. Murray Townsend (from DEH) has been supplied with some waverider data. Non-SA government staff will be charged for data.

Contact:

Townsend.Murray@saugov.sa.gov.au

8.9 Water column/ sediment nutrients and other data

Available data - Coverage

The offshore tuna farming zone (roughly the area between Boston Island, Point Bolingbroke and Cape Donington).

Water column:	Sediments:
• **dissolved organic carbon** • **ammonia** • **oxidized nitrogen (nitrate/nitrite)** • **total nitrogen and phosphate** • **suspended matter** • **particulate organic carbon and phosphorus** • **plankton abundance, diversity and planktonic pigments** • **dry matter/carbon/nitrogen sedimentation rates.** Water column data are available for March, May, July and November 2004	• **inorganic and organic carbon** • **nitrogen and their stable isotopes** • **total phosphorus** • **mineral grain size** • **extractable ammonia** • **planktonic pigments** • **infaunal biomass and abundance** • **ammonia and phosphate in sediment porewaters** • **ammonia, nitrate/nitrite and phosphate fluxes from the sediments as well as oxygen consumption.** **2002 (October), 2003 (January, May, July and November) and 2004 (March, May, July and November):** **Infaunal biomass and abundance, mineral grain size** **2002 (October), 2003 (January) and 2004 (March, May, July and November): Inorganic and organic carbon, nitrogen and their stable isotopes** **2004 (March, May, July and November):** **Extractable ammonia, planktonic pigments, ammonia and total phosphorus in sediment porewaters, ammonia, nitrate/nitrite and phosphate fluxes from the sediments as well as oxygen consumption.**

More recent data (as of 17 March 2005)

A grid of roughly 50 stations (Figure 8.8) was covered between Port Lincoln and Sibsey Island and data collected on ammonia, nitrate and phosphate in surface and bottom waters, as well as current speeds and direction, temperature, salinity and turbidity (water column profiles).

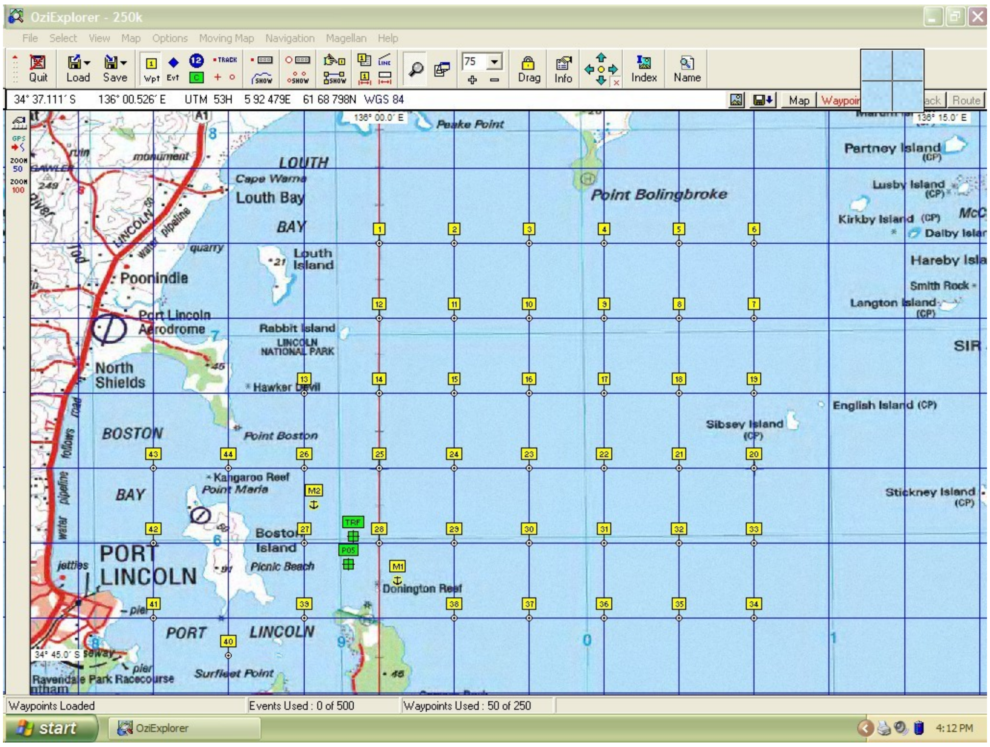

Figure 8.8: **Station locations for sampling of nutrients at surface and bottom, current speed and direction, and profiles of temperature, salinity and turbidity.**

Contact
Dr. Milena Fernandes (Aquatic Sciences)
PO Box 120
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SA 5022
Fernandes.milena@saugov.sa.gov.au

8.10 Additional SARDI-held data.

8.10.1 Telemetry based environmental monitoring

The development of the "SBT telemetry-based environmental monitoring system" is a component of the present research project and report: The aim of this research task is to assess the feasibility of using a range of standard *in situ* water quality monitoring probes linked to a data logger and telemetry system to provide real-time/near real-time data to researchers involved in this and possibly other projects. The project and system are not intended to provide any form of early warning of environmental problems to the tuna industry. The robustness and accuracy of the system and data is still being evaluated as part of the feasibility study.

The SBT Environmental Data website is a restricted access site and the use of this site is monitored. The site allows only authorised SBT industry members and research scientists working within the SBT Aquaculture Subprogram to view current and archived wind conditions and water quality data.

Introduction to systems

Each SBT telemetry-based environmental monitoring system consists of wind monitoring equipment and two multi-parameter water quality probes, connected to a data logger and telemetry system.

- Wind data parameters include wind speed and direction.
- Water quality parameters include water temperature, dissolved oxygen and salinity.

Location of systems

In 2005 there were two telemetry systems, both situated within the SBT aquaculture-farming zone off Pt Lincoln, South Australia.

- SBTE System was located at (34° 39.566'S, 136° 05.705'E) in the Eastern section of the tuna farming zone
- SBTW System was located at (34° 41.986'S, 135° 59.462'E) in the Western section of the tuna farming zone.

Available data

- Data from SBTW – from June to August 2004, and then from March to September 2005
- Data from SBTE – wind data from May to September 2005 and water quality data from June to July 2005

Contact

Dr Maylene Loo (Aquatic Sciences)
PO Box 120
Henley Beach
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loo.maylene@saugov.sa.gov.au

8.10.2 Tuna Environmental Monitoring Program

Clarke et al. (1999) reports on sites located at or near the tuna farms in Boston Bay, Pt Lincoln between 1996 and 1998. Area includes Boston Bay, Port Lincoln and the area east of Boston Island from Rabbit Island in the north to Taylor Island in the south. 15 parameters were measured on a 6 weekly basis at 12 sites over 4 regions.

1. Water quality monitoring of nutrient and physical parameters including silica, nitrite, nitrate, ammonia, total Kjeldahl nitrogen, filtered reactive phosphorus, total phosphate, chlorophyll-a, chlorophyll-b, conductivity, turbidity, suspended solids and total dissolved solids.
2. Phytoplankton composition and abundance monitoring from water samples collected as for the water quality analyses.
3. Benthic monitoring of sediment particle size, sediment organic content, infauna, waste feed, undulations and organic detritus with increasing distance from the pontoons, as well as at sites more remote from farming activities.

Clarke et al. (2000) is a follow on report to Clarke et al. (1999), and includes further reporting of environmental parameters in 1999/ 2000.

1. Concentrations of ammonia, total Kjeldahl nitrogen, total phosphorus and filtered reactive phosphorus at 39 sites in Boston Bay
2. Concentrations of chlorophyll-*a* and *b* and dominant phytoplankton taxa were identified.
3. Water temperatures, dissolved oxygen, pH levels, salinity and turbidity were measured at all 39 sites.
4. Benthic monitoring of sediment particle size and colour, sediment organic content, infauna, waste feed, undulations and organic detritus with increasing distance from the pontoons.

Contact

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Table 8-1: **Summary of the available data by type, region, and date with contacts for access.**

Type	Locations	Dates	Source	Accessibility	Contact
Bathymetry 1 km resolution	SG & Shelf	composited	GeoScience Australia	SARDI	Sam McClatchie
Bathymetry 250 m resolution	SG & Shelf	composited	GeoScience Australia	Uni. Adelaide/ SARDI	Sam McClatchie
Tidal sea level	6 Spencer Gulf ports	Jan 1996-Jan 2001	National tidal Facility	SARDI	Jason Tanner
Tidal sea level	6 Spencer Gulf ports	-	National tidal Facility	commercial	Hydrosurvey Australia
Predicted tidal sea level	Port Lincoln	-	Australian Hydrographic Service	commercial	Australian Hydrographic Service
Wave height	Cape de Coudic, Kangaroo Is.	1998- present	Wave rider buoy	Commercial	Bureau of Meteorology
Meteorological	5 Spencer Gulf and Kangaroo Is. locations	-	Bureau of Meteorology	Commercial	Bureau of Meteorology
CTD, fluorescence CTD, fluorescence CTD, fluor, oxygen	SG & Shelf	Feb/ Mar 2001 Feb/ Mar 2002 Feb/ Mar 2005	Ward et al.	SARDI database	Tim Ward
CTD Thermistor chain Current meter	Mouth SG, onto shelf 140 m outside SG 140 m outside SG	Seasonal 1980-82 Jan 1981- June 83 Jan 1981- June 83	Hahn 1986	Inaccessible	Matt Tomczak
Tides (sealevel)	Port Lincoln, Whyalla, Wallaroo, Thevenard, Pt Pirie and Pt Giles	1/1/1996 to 1/1/2001	National Tidal Facility	SARDI files	Jason Tanner
Nutrients, currents, temperature, salinity, turbidity	Tuna farming zones Port Lincoln to Sibsey Is.	March 2005 to present	Unpublished	SARDI files	Milena Fernandes
Surface winds, temperature, salinity dissolved oxygen	easternTuna farming zone	June - August 2004March to September 2005	Loo & Cheshire 2003	SARDI files	Maylene Loo
Surface winds, temperature, salinity dissolved oxygen	westernTuna farming zone	May to September 2005 and water quality data from June to July 2005		SARDI files	Maylene Loo
Water quality, phytoplankton, sediment, epifaunal, infaunal	Port Lincoln area (TEMP program)	1996-1998	Clarke et al. 1999, Clarke et al. 2000 *8.3.1.2*	SARDI files	1996-2000 Steven Clarke, 2001-present Maylene Loo

Table 8-1 continued: Summary of the available data by type, region, and date with contacts for access.

Epibenthic, infaunal	Port Lincoln area (TEMP program)	2001-2004	Madigan et al. 2002/3, Loo et al. 2004/5	SARDI files	**Steven Clarke**
Sediment grainsize, morphology, chemistry	Tuna farming zone	2002	Fernandes et al. 2006	SARDI files	**Milena Fernandes**
Current velocity, sediment and water quality, (qualitative benthic flora and fauna)	Rabbit, Boston, & Taylor Islands	Post May 1996	Hone et al. 1997a	SARDI files	**Steven Clarke**
Current speed and direction, sea level height, temperature	Taylor & Rabbit Is.	21 Oct-26 Nov 1996	Nielsen & Bennet 1997	Flinders University	**Matt Tomczak**
Water quality, Chlorophyll *a*, phytoplankton composition & abundance	Boston Bay	1995	Paxinos et al. 1996, and in prep	SARDI files	**Rosemary Paxinos**
Winds, waves, swell, currents, water quality	Potential aquaculture sites	1998	Petrusevics et al. 1998	Oceanique Perspectives	**Peter Petrusevics**

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Chapter 9 . Conclusions

9.1 Benefits and Adoption

The most tangible direct benefit to the tuna industry of this project to date has been the provision of near real-time environmental information from the farming zone, which is used by some operators to help plan their operations. This information has also been useful for other projects, including the Aquafin projects 2003/226 "Net fouling management to enhance water quality and southern bluefin tuna performance" and 2005/059 "Risk and response - understanding the tuna farming environment".

At the November 2005 SBT steering committee meeting, it was requested that the waste deposition model be made available to industry in a user friendly form to allow operators to examine the potential consequences of pen locations. The software is currently being modified to allow this, and will be provided to interested industry members at a short workshop to introduce them to the application of the model and teach them how to use it. The models were also the basis of a subsequent FRDC/PIRSA Aquaculture project 2003/222: "Innovative solutions for aquaculture: Spatial impacts and carrying capacity – further developing, refining and validating exisiting models of environmental effects of finfish farming". The refined models are used by PIRSA Aquaculture to help establish initial maximum stocking levels for aquaculture zones as they are developed and/or revised.

In a broader context, the tuna industry will benefit from this work in a number of ways. The risk assessment exercise has documented the major perceived environmental concerns associated with the industry, and has provided a literature review of the major issues identified, which will assist industry in either addressing real concerns, or refuting spurious concerns. The remote sensing report has identified a number of options for the use of remote sensing in management, as well as highlighting several potentially useful systems that are expected to come on-line in the next few years. This report has formed the starting point of a current PhD project to use remote sensing to assess spatial and temporal variation in water quality around the farming zone. The work on seabirds has highlighted ways in which industry can reduce their feed losses, which could be substantial for some operators, and the chapter on oceanography highlights that the tuna industry is not causing elevated nutrient or chlorophyll levels on a regional scale. The regional analysis of the Tuna Environmental Monitoring Program data also indicates that there are no broad benthic impacts occurring in the region, although the analysis is sensitive enough to pick up subtle natural gradients in infaunal composition. While there is an indication of a broad scale change over time in this analysis, without control sites at extended distances from the tuna farming zone, these changes cannot be reliably ascribed to tuna farming.

The original application identified that 90% of the benefits of this project would be to the commercial sector in South Australia, with the remaining 10% being to non-fisheries beneficiaries for such things as ecotourism and aesthetic enjoyment. This is likely to be a fairly accurate representation of the actual flow of benefits. While the primary beneficiary in the commercial sector will be the tuna industry, the results of the work also have the potential to be useful for other marine finfish sectors in South Australia, as well as Australia more broadly.

9.2 Further Development

From a research perspective, the further development of the work presented here will be largely addressed by the new Aquafin project 2005/059 "Risk and response - understanding the tuna farming environment". This project will develop an integrated hydrodynamic, biogeochemical and sediment model, which will greatly aid our understanding of how tuna farming and the environment interact. Risk & Response will directly address issues raised in most of the chapters of this report, with the exception of that on seabirds, which are currently being addressed as part of a Flinders University PhD project, which has been adopted by the Aquafin CRC.

As noted above, the waste deposition model is currently being further developed, primarily through the inclusion of a user-friendly interface, to allow industry members to use it to assess the likely consequences of pen spacing within their leases.

9.3 Planned Outcomes

This project has contributed to a number of the outcomes in the Aquafin CRC's Commonwealth agreement, as follows:

- An ability to predict the environmental impact of cage aquaculture at the system-wide (eg. estuary) scale

The modeling described in chapter 7 provides preliminary predictive ability in relation to region-wide increases in nutrients associated with tuna farming. While the model seems to produce high estimates of nutrient loads, from a management perpective this produces conservative results if it is used for setting maximum stocking levels. In being conservative, however, it still allows for industry expansion from the current situation. Perhaps more importantly, the project has helped set the scene for the current project 2005/059 "Risk and Response - understanding the tuna farming environment", which should provide much greater predictive ability, and allow for scenario analyses to be conducted.

- Improved monitoring of the environmental performance of cage aquaculture operations

The integrated analysis of the tuna environmental monitoring program data indicates that the current monitoring is capable of detecting relatively subtle changes in infaunal assemblages related to natural changes in sediment composition. This result gives us confidence that this monitoring program is also adequate to detect subtle effects of aquaculture on the benthic environment at the compliance points. Given that it has not done so, we can be confident that such effects are at most minimal. This result also indicates that the current monitoring program does not need to be altered to improve its ability to detect impacts.

In addition, the planned outcomes for the project have all been met as described below.

1. **A system for quantitatively assessing and/or modelling the impact of tuna farming activities at regional scales will provide greater certainty in planning and thereby help to secure tenure for aquaculture industries in marine environments. It will also allow for impacts related to aquaculture to be placed in context with other environmental impacts (sewage outfalls, stormwater etc).**

This project has demonstrated that a multivariate analysis of the data currently being collected for license-based monitoring of the tuna industry can be used successfully to detect regional-scale variations in the benthos. While no effects due to tuna farming were distinguished in this analysis, there were clear geographic differences related to natural variations in sediment composition and hydrodynamics. That these variations can be detected gives confidence to the assertion that farming has not affected the benthos at this scale. Further confirmation of this result would require sampling at regional control sites, well away from the tuna farming zone. Sampling of water quality and chlorophyll levels throughout the tuna farming zone has also indicated that there are no obvious changes associated with the onset of the farming season.

2. **Regional monitoring and modelling will assist in determining the carrying capacity of farm environments by indicating the most appropriate number of farms that a region can accommodate. This will reduce risks associated with environmental decline and thus enhance the health, survivorship and quality of farmed stock.**

As discussed above, the regional scale analysis of the Tuna Environmental Monitoring Program (TEMP) data, as well as the water quality sampling conducted, suggest that the current stocking levels and practises are sustainable, as no signal of tuna farming could be seen in infaunal assemblage structure, water quality, or chlorophyll levels within the zone. Given the well known sensitivity of infauna to organic loading to the benthos, the ability of the multivariate analysis of the TEMP data to detect natural geographic variation in assemblage structure indicates that this information can be usefully utilised as a core component of a regional scale monitoring program. The project has also provided an important lead-in to the Aquafin project 2005/059 "Risk and response - understanding the tuna farming environment", which will deliver an integrated hydrodynamic, biogeochemical and sediment model that will allow a much greater understanding of where nutrient inputs from farming go, and how they cycle through the environment.

3. **Knowledge of the regional scale impacts of the tuna industry will assist in the protection of sensitive ecosystems such as seagrass beds and macroalgal communities. This will ensure the continuation of natural fish stocks that are reliant on these systems for food and shelter.**

While seagrass and macroalgal assemblages were not investigated as a part of this project, the lack of a detectable regional-scale effect on infauna and phytoplankton (the latter measured as water column chlorophyll *a*) suggests that there would be little effect on these groups. Seagrasses and macroalgae only occur further from tuna farms than do the sites studied for water quality and infauna, and hence would be subject to lower levels of disturbance from tuna farming due to the dilution of waste inputs from the farms. In addition, the oceanographic component of the project indicates relatively high current movement in the area, which would lead to the rapid dispersal of dissolved nutrient inputs over a large area, reducing the potential for them to impact negatively on these components of the ecosystem.

4. **A wide range of other users of coastal waters benefit from a sustainable approach to tuna aquaculture. Benefits also flow through tourism related not only to SBT aquaculture but also to the wider region including recreational fishing and diving.**

The results presented in this report will help the tuna industry promote its environmental credentials in the short-term, and in the longer term help it to improve environmental performance even further. This will then flow on to other users as their perceptions of the effects of tuna farming improve, and they become more willing to undertake other activities in the area.

9.4 Conclusions

The project successfully delivered on four of the original five objectives, and has provided some valuable outcomes for industry, as well as an important lead in to the current Risk & Response project, which is aimed at developing an integrated hydrodynamic and biogeochemical model of the tuna farming environment to aid a better understanding of how farming and the environment interact. The third of the original objectives was dropped from the project early on, after problems were identified with what had been proposed.

1. Establish a steering committee of stakeholders and hold a Steering Committee for Fisheries and Aquaculture Environmental Sustainable Development reporting workshop to develop a set of operational parameters for regional scale environmental sustainable development (ESD) assessment.

While a workshop using the SCFA ESD framework was conducted in December 2002, this was the first time that this approach had been taken with an aquaculture industry, and a number of problems were identified. The first issue was that at the time, the reporting framework had not been adapted for aquaculture, and instead was designed for wild fisheries. While many of the issues are similar, there are a number that relate to only one sector or another. It was easy to drop issues that were not applicable during the workshop, but more difficult to ensure that all the aquaculture-specific issues were identified. This issue with the framework has since been resolved, as it has been modified specifically for aquaculture, partly on the basis of the experience gained from the SBT workshop. The second issue related to ensuring that workshop participants represented a broad range of groups, and that all had up-to-date and relevant information available. The workshop conducted was dominated by a few groups with particular interests, and as a result the discussion and resultant risk rankings focused on these issues. It was also obvious that many participants nominated risk ranking based on perception rather than data. As a consequence of this, considerable time was spent after the workshop reviewing the literature and data available on the key issues identified, and refining the risk rankings to produce a more balanced view of what the real risks are likely to be. It was as a result of these issues that the original objective 3 (using knowledge gained through this process and in consultation with stakeholders develop target levels for key parameters as a basis for effecting management responses) was dropped from the project.

2. Develop a set of methodologies for measuring and evaluating each of the parameters in order to provide an ESD assessment.

While the risk assessment process unexpectedly identified issues relating to higher vertebrates as being the main issues, there were also concerns addressed about water quality. As a consequence of this, some work was done on seabirds, to assess their role in removing tuna feed, and their potential impacts on other species. While seals and dolphins were also identified as an issue, their interactions with aquaculture are being studied under other projects funded outside Aqufin, and so these issues were not pursued here. In addition, a set of methodologies were developed and used for assessing broader-scale impacts on water quality and the benthos. Analysis of existing data on infaunal assemblages from the tuna environmental monitoring program clearly showed an apparent lack of regional scale effects on the benthos, but still showed clear geographic patterns. While there were changes over time, these cannot be ascribed to tuna farming with any certainty. The potential for the use of remote sensing for monitoring water quality was assessed, and has led to the appointment of a PhD student in this area as part of the Risk & Response project. A successful telemetred water-quality monitoring system has also been developed, and its operation will be continued and expanded as part of Risk & Response. This system is used enthusiastically by some industry members for planning their farming operations.

3. In collaboration with researchers involved in the development of ecosystem scale models for salmon farming, identify the key information/data required to parameterise and validate these models for the tuna industry.

To assist in identifying the data required for parameterising future ecosystem scale models of the tuna industry, two simpler models were developed. The first of these predicts the expected increase in nutrient concentrations that would be expected with a given increase in production. While a number of substantial simplifications are made in this model and its performance remains to be calibrated, it suggests that production could be increased from current levels by approximately 6000 tonnes before water quality guidelines are breached (based on ammonia levels, see Fig 7.1). The second model predicts carbon deposition on the seafloor around a group of cages, such as would occur on an individual lease, or possibly two neighbouring leases. It can be used to examine the likely consequences for the benthos of different cage layouts, and has identified that it is important to know about fish respiration and feeding rates to predict environmental consequences. This exercise has set the scene for transfer of the more comprehensive modelling approach that has been adapted for salmon farming to the tuna farming zone as part of the current Aquafin project 2005/059 "Risk and response - understanding the tuna farming environment"

4. Integrate the field and remote data collection systems necessary to provide the data required for the parameterisation of these ecosystem scale models, into the regional ESD assessments.

The development of the water-quality monitoring system, and the initiation of a PhD on remote sensing both contribute to the provision of data for the ecosystem models. In addition, the final chapter of this report documents what data are available on physical and chemical processes and parameters in and around the farming zone, and that could be of use in parameterising and validating these models. Given the issues that were identified in the risk assessment process undertaken, and discussed in chapter 1, it was decided not to continue with the integration of these data collection methodologies into regional ESD assessments, although they could be used for this purpose in the future.

Appendix 1: Intellectual Property.

This report will be made freely available to the public via the Aquafin CRC, FRDC and SARDI.

The carbon deposition model (Farmér) is jointly owned by SARDI and Aquafin CRC.

Appendix 2: Project Staff.

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