Predicting the dispersion of nutrients from aquaculture cages

Honours thesis for a Bachelor of Engineering in the field of Applied Ocean Science

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“If you train and direct your mind along paths you want it to travel, you will achieve great happiness.”

The Dhammapada 3. Thoughts, Verses 35 & 36

To all my family and friends, thank-you for your support.
To my grand-father, Papa, who has always been my inspiration in science,
your belief in me gave me the strength to get this far
and to be determined to take it a lot further,
thank-you.
Abstract

Aquaculture is the growing of aquatic organisms. Cage culture is predominantly used for the culture of finfish and involves a floating or submerged cage situated in a natural water body. The cage requires constant inputs of feed as the stocking density means food demand is greater than the natural feed available. A proportion of the feed is uneaten and is deposited to the sea floor. The amount of food consumed can be manipulated in a mass balance to determine the amount of solid and dissolved wastes being excreted from the animals.

Cage culture makes use of natural currents around the cages to disperse the nutrients. If the currents are insufficient, there may be an accumulation of C, N and P in the sediments, which can potentially turn the receiving sediments anoxic. The dissolved waste discharges can possibly cause nuisance algal blooms. It is therefore important to predict how far nutrients will disperse from the cages during a production cycle and the amount of loading associated with the discharges.

The solid dispersion modelling is performed with a program developed in MATLAB. The program also outputs the dissolved nutrient loadings, which can potentially be used to predict the dissolved transport. A number of potential scenarios are modelled to gain an estimate of dispersion in a range of farm sites. The different scenarios enabled the author to determine the effects of strong, weak, uniform and oscillating currents on dispersion, as well the effect of changing the site depth, cage width or stocking density. Generally, there are regions around each farm that show localised increases in sediment C levels.
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1.0 Introduction

Aquaculture has been growing at a rate of 13% per annum since 1991 in Australia, with production expected to increase from nearly $700 million in 99/00 to over $2.5 billion by 2010 (Caton & McLoughlin 2000). Aquaculture is a broad term that can be used for the culture of aquatic plants and animals (Pillay 1993). Within aquaculture, further classification can be made according to the culture techniques used (eg. ponds, raceways, recirculating systems, cages or pen culture), the type of organism cultured (eg. finfish, oyster, mussel and seaweed culture), the type of environment cultured in (eg. fresh water, brackish water and mariculture), or due to a specific characteristic of the environment (eg. inland, estuarine, coastal and offshore) (Pillay 1993).

With such a large increase in aquaculture production, it is not surprising that Western Australia’s industry is also growing, and that we would expect similar environmental impacts as seen overseas when the local industry is not managed properly.

Environmental impacts range from shifts in the benthic community, changes in the reduction potential of sediments, shifts in the trophic state of the system and increased algal blooms due to eutrophication. Water quality has been described as the single most important factor that governs the success of aquaculture ventures, which means a comprehensive site evaluation is needed before projects begin (Makaira 1997). As aquaculture activities directly affect their surroundings, an analysis of their effect on water and sediment quality is also needed during operations.

The fish raised in Australia are generally carnivores, which require regular feeding. This ultimately produces wastes that are treated, flushed or disposed of. Cage culture requires flushing of the nutrients and solids away from the cages by the currents and tides. Determining the physical characteristics of the wastes is therefore important and is also looked at in this report.

Waste dispersion models in aquaculture generally rely on coupling feed to waste models with dispersion models. There are many forms of feed to waste models available that are based on conserving energy and mass. These are then coupled with dispersion models to predict the spatial and temporal extent of the wastes. It has been
noted that many of these dispersion models lack consideration of the physical characteristics of the feed and faeces (Chen, Beveridge & Telfer 1999). The model being manipulated contained data on the total mass of nutrients exported but not on the settling characteristics of discharges. As the benthic accumulation of solid wastes is important, trials were carried out to determine the settling velocities of wastes.

“Although a number of models have been developed to predict waste outputs, dispersal and impacts from aquaculture ventures in Europe, Canada and the USA, no easy-to-use model is presently available for use by individuals, companies or agencies from the aquaculture industry in WA. This is despite the fact that the aquaculture industry, Fisheries WA and the Department of Environmental Protection urgently need such information.” [Kolkovski 2000]. The eventual outcomes of this model will benefit a number of groups. Apart from the environmental uses, due to the ultimate success of an aquaculture facility depending on the physical and biological characteristics of the site (Makaira 1997), the future results will potentially be used by the industry as a management tool.

The Department of Fisheries, Western Australia developed the web based feed to waste model in a collaborated effort with the Centre for Water Research and the National Centre for Mariculture in Israel. The web-based development was viewed in the project proposal as “a first step in the development of a fully coupled three-dimensional ecological model to assess the effects of aquaculture on the surrounding water column and sediments…based on the CWR model ELCOM” [Kolkovski 2000]. This project hopes to adapt the feed conversion program into an aquaculture discharge model capable of predicting the plumes and benthic accumulation.
Finally, the aims of the project are to:

_ To re-write the bioenergetic equations necessary for modelling feed to waste in Matlab.

_ To determine the settling velocities of feeds and fish wastes from Pink Snapper.

_ To develop a user-friendly framework that predicts waste outputs.

_ To determine the distribution of aquaculture solid discharges using a model developed in MATLAB and a theoretical site.

_ To determine the distribution of the dissolved wastes from the theoretical site.
2.0 Background

2.1 Aquaculture Growth Worldwide

Aquaculture is defined by the United Nation’s Food and Agricultural Organisation as “the farming of aquatic organisms, including fish, molluscs, crustacea and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate ownership of the stock being cultured. For statistical purposes, aquatic organisms that are harvested by an individual or corporate body who has owned them throughout their rearing period contribute to aquaculture, while aquatic organisms that are exploitable by the public as a common property resource, with or without appropriate licences, are the harvest of fisheries.” [p17 Lee & Nel 2001].

2.1.1 World Fish Stocks

Fishing was developed back in the days of hunting and gathering. As civilisations evolved, however, the majority held the notion that to increase food supplies, people needed to farm more animals on land, and in fisheries, had to improve their catch methods and find new resources (Pillay 1993). The fish stocks were seen as a resource that could sustain being heavily exploited but improved methods of capture led to the deterioration of a number of the worlds fish stocks (Kaufmann et al. 1999). The maximum sustainable yield of fisheries is around 60 million metric tonnes, which is where the annual catches have stalled since reaching those levels in 1969.

Worldwide concern has since been generated at the ability of traditional fisheries to meet sustainable objectives (Kaufmann et al. 1999). Some of the management options used are restrictions on fishing gear, restrictions on the size and sex of fish caught, seasonal fishing and by setting quotas (Kaufmann et al. 1999). However, there are flaws in most of the methods such as limits being breached due to the inability to accurately monitor all catches taken by recreational and commercial fishermen.
The world human population also went through an exponential rate of growth during the past century, with a current reduction in the rate of increase. The larger population means that we will need to continue to develop farming methods that are more efficient and that make the most of our resources. In Australia, there is a large push for ecologically sustainable development (ESD), which is based on the sustainable use of our resources on an ecological level. Aquaculture has the ability to meet these objectives.

2.1.2 Aquaculture Produce

The supply of aquaculture produce to world markets has increased steadily in the past few decades. Worldwide aquaculture production was valued at US$16 billion in 1986 and US$23 billion in 1989 (Hatch & Kinnucan 1993). However, by 1996 the total production of aquatic species reached 34.12 million metric tonnes, worth over US$46 billion (Lee & Nel 2001). The increase in aquatic products was greater than increases in livestock meat production [Table 1].

<table>
<thead>
<tr>
<th>Food Source</th>
<th>Annual Increase</th>
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<td>Aquaculture</td>
<td>10%</td>
</tr>
<tr>
<td>Wild Fish</td>
<td>1.6%</td>
</tr>
<tr>
<td>Livestock Meat</td>
<td>3%</td>
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[Source: Lee & Nel 2001].

As aquatic production has increased, aquaculture produce has taken a larger percent of the seafood market, which has also been expanding. Finfish and shellfish reared in aquaculture settings increased from 13% of the market in 1990 to 22% in 1996, with more than 25% of the fish being consumed as human food coming from aquaculture (Lee & Nel 2001).

Aquaculture is growing in a number of environments. In 1996, there were 15 million tonnes of freshwater produce, 10 million tonnes of produce from marine environments, 1.6 million tonnes from brackish-water environments, and nearly 8 million tonnes of aquatic plants produced (FAO 1998). Further needs for increases in
the production of food supplies will see aquaculture continue to develop. Fish supply essential proteins. With fisheries at maximum sustainable yields and agricultural land becoming limiting, aquaculture is a current and future answer to food shortages.

Australia is slightly above most of the world in current increases in aquaculture production. This is largely due to the Australian industry forming after overseas industries. Current production has been increasing in Australia at around 15% per annum, due to improved technologies, increased markets and more investment interest (Caton & McLoughlin 2000). Predictions quoted for Australia at Aquaculture Beyond 2000 are for aquaculture sales to reach $2.5 billion by 2010, a fourfold increase on 98/99 production (Lee & Nel 2001). At present, silver lipped pearl oysters are the main species of aquaculture production in Western Australia, although other activities are being investigated (FWA 2000a).

The potential for aquaculture to assist rural and isolated communities will lead to even greater increases in aquaculture production (Pillay 1993). Currently inland aquaculture is based on yabby, marron, trout and barramundi (Paust 1999). However, there is potential for the culture of Australian bass, black bream, mulloway, greenback flounder, pink snapper, silver perch, whiting, mullet, mangrove jack, estuary cod and others (Jenkins 1999). A number of these species will be reared in cages in inland dams or man-made ponds.

Aquaculture has been slow to develop as a science due to the complexity of aquaculture systems (Piedrahita 1988). There are, however, scientific principles that weigh in the favour of aquaculture. Aquaculture is seen as a more efficient way of producing animal proteins than for swine, sheep and steers, and equal or higher to poultry (Pillay 1993). Aquaculture can make use of the information collected on species by fisheries organisations like the Department of Fisheries in Western Australia. Many of these organisations are branching into the aquaculture field and now collecting the data needed specifically for aquaculture. This provides information as to the energy requirements of the fish and how nutrients and energy are consumed or stored. This can be translated to achieve optimum diets for growth, conditioning, profits and effluent content. Research is also needed into the systems, with large amounts of work still to be done on the design of cages in high wave and submerged
environments. This is more structural information regarding to the strength of the cage, moorings and attachments in the face of wave, current, tidal and wind induced stresses. Offshore cage designs will increase the productivity from cage culture in regions with limited coastal sites.

2.2 Fish Growth

2.2.1 Fish Growth
Like all heterotrophic organisms, fish consume organic matter and break it down to gain energy for growth and maintenance. This results in the formation of wastes. Fish growth and bioenergetics has been studied for many years. A bioenergetic flow graph can be used to relate the fish growth and environmental factors (Cacho 1993). Fish growth primarily relates to the fish’s age, weight, body composition and the water temperature (Cacho 1993). The balance between food intake and energy expanded in maintenance, food processing and locomotion are determining factors in the weight and composition of the fish (Cacho 1993). The main nutrients used as sources of energy for growth and maintenance are proteins, lipids and carbohydrates, while the fish body is composed of water, protein, fat, carbohydrates and ash (Cacho 1993). The amount of carbohydrates and ash remain fairly constant as a percentage of body weight, however, the percentage of water, protein and fat vary depending on the food intake and diet composition (Cacho 1993).

Aquatic species are sensitive to temperature, dissolved oxygen concentrations, ammonia levels, salinity and the pH (Hatch & Kinnucan 1993). When these parameters vary, responses seen in the fish may be from reduced feeding rates to death and so optimum growth conditions and the site characteristics must be known if the greatest growth rates and profitability are to be achieved.
2.2.2 **Fish Wastes**

The wastes produced in the culturing of fish affects the quality of the water and, without proper management, can be detrimental to the fish health (Boyd 1982). The major wastes are uneaten feed and excreta. The amount of nutrient retention in the fish inversely relates to the amount of nutrients in the waste. Nutrient retention can be improved by altering the constituents of the feed (Fornshell 2001).

Proteins are one of the main sources of energy for fish growth and maintenance. To utilize the energy though, nitrogen must be extracted from the proteins, which results in the formation of ammonia (Cacho 1993). The ammonia is excreted into the surrounding environment and this can lead to adverse effects on the cultured animals if it accumulates. Closed systems make use of biological filters to perform denitrification, whereas open systems rely on natural dispersion. This results in plumes often forming downstream from the cages. Other metabolic wastes coming from the cages include carbon dioxide, phosphorous and other plant stimulating nutrients (Boyd 1982). Carbon dioxide concentrations can have an effect on the pH, although the observed effects would depend on the buffering of the system. Negligible effects may be expected in well-buffered water bodies like most marine systems, but some lakes with potential for cage culture may not be well buffered and increases in the pH will be seen.

A proportion of the daily feed fed to the fish goes out of the cages as solid wastes that have not been chewed by the fish. The characteristics of the pellets will help determine the distribution. As pellet manufacturers use different techniques to form the pellets, the characteristics depend on how the feed is manufactured (De Silva & Anderson 1995). The most common pellets used in WA are of the extruded pellet type, in contrast to the compressed pellets. Extruded pellets can be made to be floating or slow-sinking by adjusting the ingredient combinations and through the cooking conditions (De Silva & Anderson 1995). Fish bite and then spit out some of the feed pellets, which reduces the size of the particles and a further percentage of the feed is expelled in a dissolved form through the fish gills [Figure 1].
2.2.3 Fish Diets

The majority of fish that are farmed are carnivorous or omnivores that require a certain level of proteins and fats that can most easily be derived from other fish. Like other agricultural industries, aquaculture uses fishmeal coming from the by-catches of the fishing industry (Costa-Pierce 2001). However, with a number of integrated systems being designed that utilise farm wastes to form feeds or commercial products, aquaculture may become a supplier of fishmeal to other industries. But as wastes from cages are flushed straight into the ocean, caged fish will require continual inputs of fishmeal or protein sources. Therefore, to keep in line with ESD principles, aquaculture producers in the caged sector may wish to support the development of farm-produced fishmeal in their diets.

Figure 1 Nutrient and energy partitioning and utilization by a fish. Example of a 5 gm to 500 gm barramundi on a 45% protein diet.

[From http://www.cwr.uwa.edu.au/cwr/fishmodel.index2.html]
Food consumption ratios (FCRs) are an area undergoing much research around the world. FCRs are defined as

\[
FCR = \frac{\text{FoodEaten}}{\text{WeightIncrease}} \quad \text{Equation 1}
\]

With many species around the world, FCRs have dropped from greater than 2:1 to 1:1, although it is a dry to wet weight ratio, which means the fish still eat more food than they increase in weight (Fornshell 2001). This is somewhat inevitable, with fish having energy requirements for maintenance and movement. On a 1:1 basis, a diet using 50% fishmeal requires 2.5kg of dry fish to get 1kg of dry fish product (Costa-Pierce 2001). The environmental benefit of lowering FCRs is that less effluent will be released from the cages (Fornshell 2001). This is why feed characteristics and FCRs must be an integral part of any cage-modelling program.

Diets used in aquaculture vary depending on the fish species, fish age and due to the financial situation of the farm. Thus, diets vary in their composition, size and way of manufacture. Smaller fish have a higher demand for protein and eat a higher percent of their body weight per day than larger fish. As feeds are directly dispersed to the ocean floor, their composition helps determine where the uneaten feeds will fall. Also, as the excreted wastes come from the food the fish eats, the composition of the diet will also affect the composition and settling velocities of the wastes.

The quality of a feed is a function of how well it meets the nutritional requirements of a species. Apart from the absolute amounts of protein and energy available, it is more useful in knowing the amount of digestible protein or energy as these are the proportions that may be consumed by the fish. The remaining proportion will be passed through the fish undigested.

Fish use proteins and carbohydrates in their diets. The amount of protein in many snapper diets is 450 grams of protein per kilogram of dry matter and 220 grams of carbohydrate per kilogram of dry feed. This type of diet would be referred to as a 45:22 diet. Smaller fish on a weaning diet may be given a higher protein 51:16 diet until they reach 30 grams.
The specific weight of proteins and carbohydrates varies and so diets with more protein and less fat should be heavier and sink faster, but other feed constituents and the manufacture process also affect the density of the pellet and so it is only a generalisation.

2.3 Cage Culture

Cages, ponds and enclosures are not identical, although they are all regarded as open systems (Lee & Nel 2001). A cage is an offshore culture unit that has mesh sides and bottom. A pond or enclosure has one or more sides formed by a natural body. As the natural bottom is used for a number of ponds, the sediment chemistry is very important, and generally stocking densities are lower in ponds and enclosures compared with cages. Cages are seen as a cheap form of culturing fish due to the low set-up costs. Cage culturalists make use of natural water flows to flush and disperse the untreated wastes from their cages. If there is adequate flushing, wastes will be diluted to an acceptable level for the fish and surrounding organisms.

The cages may float on the surface or be completely submerged. This allows for the exploitation of lakes, rivers, canals, estuaries and seas for aquaculture (Midlen & Redding 1998). The survival of the organisms within the cage is dependent on the inputs into that system, which affects the biological and physical characteristics of the water (Piedrahita 1988). It is ironic that environmental groups worry about the waste problems. One of the biggest threats of poor water quality is for the farmers themselves, and so water quality is something any long-term farmer will need to ensure for optimum growth in their farm.

2.3.1 Current Usage of Cages

Cages have predominantly been used for the culture of finfish but recent uses also include shellfish (Lee & Nel 2001). Cage design is in a developing stage in many environments. Cages that float on the surface have been the most successful and have been used more extensively in the past, although they are generally used in areas with low wave energy. These cages can be seen in the large coastal grow-out areas of Norway, Tasmania and South Australia. The salmon farming in Huon Estuary,
Tasmania, uses cages up to 40 metres in diameter, and the production value has now reached A$60 million (Caton & McLoughlin 2000). A similar industry was set up at Eyre Peninsula in South Australia to fatten southern bluefin tuna. Tuna caught in local waters are placed inside the cages and fed until reaching a larger size. The result has been that over 90% of Australia’s southern bluefin tuna quota was being fattened in cages and exported to Japan (Caton & McLoughlin 2000). There is also a barramundi sea cage trial underway in the Northern Territory (Lee & Nel 2001).

Many of the sites currently used for cages are relatively protected, but these protected sites without user conflicts are limited, which is forcing producers to move further offshore (Braginton-Smith 2001). The environmental impacts should be minimized due to the stronger currents and greater depths (Beveridge 1996). The move offshore has presented new engineering challenges in the design of the structures, with much larger forces encountered offshore compared to the protected bays where many floating cages are situated. In Hawaii, with high wave environments persisting, aquaculturalists have trialled the use of submerged cages (Helsley 2001). These cages have the benefit of remaining below the region of highest wave energy.

Cages are also being used in lakes, some with high levels of sediment chemistry. As the cages allow producers to keep the population in the surface layer of the lake, they remain isolated from the toxic chemicals. The risks involved in this sort of culture include mixing of the water column or an overturning of the system. In a cage trial in a lake in Florida, a passing cold front had reduced surface temperatures from 31 °C to 25 °C overnight, and the lake overturned and released hydrogen sulfide, which poisoned the fish (Benetti et al. 2001). This leads to the possibility of using coal voids for fish culture if the water body can be adequately managed.

### 2.4 Problems of Cage Culture

Aquaculture developments have altered coastal areas through physically modifications to natural habitats and by increased nutrient inputs that have caused subsequent eutrophication (FWA 2000). The nutrients inputs affect both the water column and sediment. Other problems include disease control, genetic impacts, exotic introductions, toxicants, anti-biotic usage, marine mammal impacts, noise pollution
and aesthetics (Sylvia & Anderson 1993). The section below looks predominantly at the problems associated with wastes from cage culture.

2.4.1 Waste Accumulation

Waste and feeds dropping out of the cages is an environmental concern, as it deposits as benthic effluent (Sylvia & Anderson 1993). These wastes are spread spatially due to the water currents (Dominguez et al. 2001). However, the cages act as a barrier to water flow and reduces the currents, which makes larger particles sink even closer to the cages (Dominguez et al. 2001). To reduce self-pollution problems cages are now set in areas where the current velocity and depth allow adequate dispersion (Sylvia & Anderson 1993).

Previous studies suggest that cage aquaculture can have a negative effect on the marine community surrounding and down-stream of the cages. As the wastes and uneaten feed accumulates, the capacity of the sediments to transform the wastes is reduced, and if the capacity is exceeded, metabolic by-products will be released including toxins like hydrogen sulfide, ammonia and methane (Beveridge 1996). The chances of these releases is reduced if the amount of waste coming from the farm is reduced. This can be done by managing the feeding regime and diet quality and by considering the cage size, stocking densities and the site selection (Sylvia & Anderson 1993). If the organic loading to the benthos is too high, a fallowing period may be necessary for the remediation of the area around the cages to return the sediments to their previous state (Sylvia & Anderson 1993).

2.4.2 Inadequate Flushing

Cages rely on the currents surrounding them to disperse the wastes. Flushing rates and current speeds are therefore critical components influencing the waste distribution. The loss of nutrients occurs quickly after feeding, and the feed not consumed decomposes, potentially lowering the dissolved oxygen in the water to critical levels (Hatch & Kinnuacan 1993). Lower DO levels lead to reduced appetites and increased risks of mortalities (Hatch & Kinnucan 1993). So flushing in an area must remain adequate for maximum fish growth and to minimise adverse environmental impacts and so it is preferred to go to areas with strong currents. However, for non-
environmental reasons cage placement is often recommended in low current areas. Current speeds greater than 20 cms\(^{-1}\) lead to higher energy expenditure for the fish that can cause decreased growth and mortalities, and currents in excess of 60 cms\(^{-1}\) cause damage to the nets and cages (Beveridge 1996). A mid-point needs to be found that allows for adequate dispersion without imposing too large energy requirements on the fish.

The waste products and decomposing foods can fuel algal growth. Nitrogen, phosphorus and organic matter are added to the system, which are among the major limiting nutrients for plant growth in waterways. As these nutrients become available, it allows for greater phytoplankton populations. The phytoplankton populations then affect the dissolved oxygen concentrations in the water (Cacho 1993). This can have adverse affects on the fish and other aquatic species by lowering DO to critical levels for fish survival, or by toxins flowing through the cages, which get released when the sediments become anoxic.

2.4.3 **Other Problems**

Many fish that are farmed are bred from farmed stocks and so have a select genotype. The risk of fish escaping through damaged nets is extremely high, with these fish having the potential to alter the genetic structure of a natural population if the natural population is small. Inarguably, the risk factor is exaggerated by using exotic or genetically engineered breeds.

The use of antibiotics in fish culture can enhance the levels of environmental impacts. The antibiotics, if reaching the sediments, kill the microbial populations that are breaking down the wastes from the farm. This limits the destruction of wastes and so they will accumulate at a much faster level. If treatments are not used, the stock will be vulnerable to disease outbreaks.

Cages can also interfere with the ability of other ocean users to access areas. Groups that may be affected by cage industries include sailors, divers and recreational fisherman.
2.4.4 Previous Studies into Environmental Impacts

There have been a number of studies into the environmental impacts of cage culture in Australia and around the world. Various degrees of impacts can be seen due to cage culture, from minimal to long-term impacts. Some studies like at Jurien are based on data collected from farms in place, while the review for Lake Argyle was performed before asking for tenders for the lake.

2.4.4.1 Finfish Culture in Jurien Bay, Western Australia

Black bream have been successfully grown-out at Jurien Bay from 1995, with a number of other species including Pink Snapper also being stocked (Gardner 1998). The impacts have been monitored in a number of studies with the first running from 1995 to 1998, which reported slight increases in the sediment concentrations of nitrogen and phosphorous (Gardner 1998).

The results of Gardner’s study were more evident, with elevated levels seen in nutrient concentrations in the sediments and water column after 5 months (Gardner 1998). There was also a reduction in the species richness and abundance in the surrounding benthos. For the dissolved component, a noticeable plume of nitrogen was detected updrift, which could potentially cause algal problems.

2.4.4.2 Tuna Fattening at Port Lincoln, South Australia

The Eyre Peninsula in South Australia is home to agricultural, tourism, fishing and aquacultural activities (Anon 1997). The tuna-fattening industry is becoming a large industry and is discussed earlier.

Reports state that the solid wastes are confined to within 50 m of the cages (Anon 1997). This is presumably due to the shallowness of the sites, as the report states that the cages drag on the bottom at some of the sites. When looking at the dispersion graphs for 10 m sites in Figure 9, it is seen that all size classes of waste are expected to fall within 50 m of the cages. The localised nature of the waste distribution will mean that the sites will have a short life-span for production if waste loadings are not minimized.
2.4.4.3 Lake Argyle Barramundi Production

A detailed review was undertaken to determine the viability of a 2000 tonne per annum barramundi aquaculture fishery in Lake Argyle (EPA 1999). The review was wisely undertaken before the industry was established. The review found that issues affecting the RAMSAR wetlands, the maintenance of genetic diversity of wild stocks and aesthetics were all manageable, but water quality issues would need further work (EPA 1999).

The recommended work included collecting meteorological data, CTD and DO profiles, nutrient and oxygen concentrations in the major layers, sediment oxygen demand, nutrient content and fluxes in oxic and anoxic conditions and the temperature, volumes and nutrient concentrations of the inflows (EPA 1999). This data will then be used to model the cage impacts using a program like DYRESM. A 3-D model is recommended to be used for simulations around 3 months, with the results used to run 10 to 20 year simulations in the 1-D model (EPA 1999).

2.5 EXCEL Based Waste Output Model

The Department of Fisheries Western Australia provided 3 feed to waste models in an EXCEL format for barramundi (*Lates calcarifer*), snapper (*Pagrus auratus*) and trout (*Oncorhynchus mykiss*). These three species have high aquaculture potential in Western Australia. Each EXCEL model contained the information for one of the species.

The model is based on a mass and energy balance between the amount fed, the amount consumed, the amount of retention and the amounts of solid and faecal waste. This method can be was shown in Figure 1. The general nutritional assumption made is that the energy requirement of a growing fish is the sum of its needs for maintenance and growth. Maintenance is dependent on body size while the energy requirement for growth is only dependent on the amount and composition of the weight gain. The equations for growth are shown in Table 2.

Example cage used to determine inputs to model;
10 m x 10 m x 7 m deep cage with 14 000 snapper with an initial weight of 50 grams and grown for 201 days to reach a final weight of 221 days. The initial stocking density is thus 1 kg/m³ and the final stocking density will be 5 kg/m³.

2.5.1 Production Page

<table>
<thead>
<tr>
<th>Initial fish weight (g)</th>
<th>50.0</th>
<th>User enters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of growth (days)</td>
<td>221</td>
<td>*</td>
</tr>
<tr>
<td>Temperature</td>
<td>18.0</td>
<td>*</td>
</tr>
<tr>
<td>Number of fish</td>
<td>14000</td>
<td>*</td>
</tr>
<tr>
<td>Final fish weight (g)</td>
<td>250.7</td>
<td></td>
</tr>
<tr>
<td>Biomass gained (kg)</td>
<td>2810</td>
<td></td>
</tr>
<tr>
<td>Total feed (kg)</td>
<td>4300</td>
<td></td>
</tr>
<tr>
<td>FCR</td>
<td>1.53</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 An example of the production page

The main production page consists of input and calculated values. The user inputs the initial weight of the fish (in grams) and the number of days of interest. The time was modified in the example until a weight of 250 grams was reached, which corresponds to a stocking density of 5 kg/m³ for a cage with the cage dimensions outlined earlier. Apart from the final weight, the production page gives the user values on the total biomass gained, the total amount fed and the average food consumption ratios.
2.5.2 Feed Composition Page

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Value (g/kg)</th>
<th>Digestibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter g/kg</td>
<td>929</td>
<td>*</td>
</tr>
<tr>
<td>Protein g/kg</td>
<td>450</td>
<td>*</td>
</tr>
<tr>
<td>Lipid g/kg</td>
<td>200</td>
<td>*</td>
</tr>
<tr>
<td>Ash g/kg</td>
<td>120</td>
<td>*</td>
</tr>
<tr>
<td>Phosphorus g/kg</td>
<td>15</td>
<td>*</td>
</tr>
<tr>
<td>Carbohydrate g/kg</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>Gross energy MJ/kg</td>
<td>20.00</td>
<td>*</td>
</tr>
</tbody>
</table>

**Digestible values**

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Value (g/kg)</th>
<th>Digestibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein g/kg</td>
<td>405.0</td>
<td>*</td>
</tr>
<tr>
<td>Digestible energy MJ/kg</td>
<td>17</td>
<td>*</td>
</tr>
</tbody>
</table>

Figure 3 An example of the feed composition page

If the user wishes to use a diet other than that specified, the user may have to alter the feed composition page. Different diets have varying properties and so the properties need to be entered here. These should be available from the feed manufacturers and include the amount of dry matter, protein, lipid, ash, phosphorous, gross energy and digestible protein and energy per kilogram of feed. The amount of carbohydrates is the difference between the dry matter and the sum of the other ingredients.
### 2.5.3 Daily Energy Requirement Chart for snapper

<table>
<thead>
<tr>
<th>Weightgain</th>
<th>Daily</th>
<th>DE/day</th>
<th>maint</th>
<th>growth</th>
<th>DE/kg gain</th>
<th>Feed/day</th>
<th>Feed</th>
<th>FCR</th>
<th>(days)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.00</td>
<td>0.593</td>
<td>11.96</td>
<td>4.21</td>
<td>7.75</td>
<td>20.2</td>
<td>0.70</td>
<td>0.00</td>
<td>1.19</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>55.36</td>
<td>0.620</td>
<td>12.82</td>
<td>4.58</td>
<td>8.24</td>
<td>20.7</td>
<td>0.75</td>
<td>6.44</td>
<td>1.22</td>
<td>8.8</td>
<td>8.84</td>
</tr>
<tr>
<td>60.96</td>
<td>0.647</td>
<td>13.68</td>
<td>4.96</td>
<td>8.72</td>
<td>21.2</td>
<td>0.80</td>
<td>13.33</td>
<td>1.24</td>
<td>17.7</td>
<td>8.84</td>
</tr>
<tr>
<td>66.79</td>
<td>0.673</td>
<td>14.56</td>
<td>5.35</td>
<td>9.21</td>
<td>21.6</td>
<td>0.86</td>
<td>20.67</td>
<td>1.27</td>
<td>26.5</td>
<td>8.84</td>
</tr>
<tr>
<td>72.86</td>
<td>0.699</td>
<td>15.45</td>
<td>5.75</td>
<td>9.69</td>
<td>22.1</td>
<td>0.91</td>
<td>28.46</td>
<td>1.30</td>
<td>35.4</td>
<td>8.84</td>
</tr>
<tr>
<td>79.15</td>
<td>0.725</td>
<td>16.35</td>
<td>6.16</td>
<td>10.18</td>
<td>22.5</td>
<td>0.96</td>
<td>36.73</td>
<td>1.33</td>
<td>44.2</td>
<td>8.84</td>
</tr>
<tr>
<td>85.68</td>
<td>0.751</td>
<td>17.25</td>
<td>6.58</td>
<td>10.67</td>
<td>23.0</td>
<td>1.01</td>
<td>45.46</td>
<td>1.35</td>
<td>53.0</td>
<td>8.84</td>
</tr>
<tr>
<td>92.43</td>
<td>0.777</td>
<td>18.17</td>
<td>7.01</td>
<td>11.16</td>
<td>23.4</td>
<td>1.07</td>
<td>54.67</td>
<td>1.38</td>
<td>61.9</td>
<td>8.84</td>
</tr>
<tr>
<td>99.41</td>
<td>0.802</td>
<td>19.10</td>
<td>7.45</td>
<td>11.66</td>
<td>23.8</td>
<td>1.12</td>
<td>64.36</td>
<td>1.40</td>
<td>70.7</td>
<td>8.84</td>
</tr>
<tr>
<td>106.61</td>
<td>0.827</td>
<td>20.04</td>
<td>7.89</td>
<td>12.15</td>
<td>24.2</td>
<td>1.18</td>
<td>74.53</td>
<td>1.43</td>
<td>79.6</td>
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</tr>
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<td>8.35</td>
<td>12.64</td>
<td>24.6</td>
<td>1.23</td>
<td>85.20</td>
<td>1.45</td>
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<td>8.81</td>
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<td>25.0</td>
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<td>1.47</td>
<td>97.2</td>
<td>8.84</td>
</tr>
<tr>
<td>129.52</td>
<td>0.901</td>
<td>22.91</td>
<td>9.28</td>
<td>13.64</td>
<td>25.4</td>
<td>1.35</td>
<td>108.02</td>
<td>1.50</td>
<td>106.1</td>
<td>8.84</td>
</tr>
<tr>
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<td>23.89</td>
<td>9.75</td>
<td>14.13</td>
<td>25.8</td>
<td>1.41</td>
<td>120.18</td>
<td>1.52</td>
<td>114.9</td>
<td>8.84</td>
</tr>
<tr>
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<td>0.949</td>
<td>24.87</td>
<td>10.24</td>
<td>14.63</td>
<td>26.2</td>
<td>1.46</td>
<td>132.85</td>
<td>1.54</td>
<td>123.8</td>
<td>8.84</td>
</tr>
<tr>
<td>154.38</td>
<td>0.973</td>
<td>25.86</td>
<td>10.73</td>
<td>15.13</td>
<td>26.6</td>
<td>1.52</td>
<td>146.04</td>
<td>1.56</td>
<td>132.6</td>
<td>8.84</td>
</tr>
<tr>
<td>163.08</td>
<td>0.997</td>
<td>26.86</td>
<td>11.23</td>
<td>15.63</td>
<td>26.9</td>
<td>1.58</td>
<td>159.75</td>
<td>1.58</td>
<td>141.4</td>
<td>8.84</td>
</tr>
<tr>
<td>172.00</td>
<td>1.021</td>
<td>27.87</td>
<td>11.74</td>
<td>16.13</td>
<td>27.3</td>
<td>1.64</td>
<td>173.98</td>
<td>1.61</td>
<td>150.3</td>
<td>8.84</td>
</tr>
</tbody>
</table>

Figure 4  An example of the energy requirement chart

This chart entails the growth of the fish, using constants that have been determined by Fisheries scientists and by using the inputs from the production page for initial and final weight as well as temperature. The equations in Table 2 and constants in Table 3 are used to fill in the sheet.
2.5.4 Body Composition and Nutrient Retention

Nitrogen g/kg live weight  26.7
Phosphorus g/kg live weight  7.4
Carbon g/kg live weight  91.3*(g) ^0.153
Energy MJ/kg live weight  4.04 * (g) ^ 0.153

Initial Nitrogen per biomass(kg)  18.69
Initial Phosphorus of biomass (kg)  5.180
Initial Carbon of biomass (kg)  116.282
Initial Energy per biomass MJ  5145.4

Final Nitrogen of biomass (kg)  93.73
Final Phosphorus of biomass (kg)  25.98
Final Carbon of biomass (kg)  746.3
Final Energy per biomass MJ  33023

Total Nitrogen gained (kg)  75.04
Total Phosphorus gained (kg)  20.80
Total Carbon gained (kg)  630.0
total Energy gained MJ  27877

Total feed fed (kg)  4300
Total Nitrogen fed (kg)  310
Total Phosphorus fed (kg)  64
Total Carbon fed (kg)  1939
Total Energy fed MJ  85991

Nitrogen retained %  24.24
Phosphorus retained %  32.25
Carbon retained %  32.49
Energy retained %  32.42

leftover solid
Nitrogen in feces  30.96  17.46  56.4
Phosphorus in feces  33.67  28.48  84.6
Carbon in feces  387.82  225.71  58.2
Particulate matter in feces  1582.23  1018.96  64.4

digestibility
protein  90  10
energy  85  15
phosphorus  47.8  52.2
carbon  80  20

Figure 5 An example of the body composition chart
This page details the composition of the fish and uses this to calculate the wastes that will be coming from the cages. Mass balance is used. All of the above had to be included into the MATLAB model.

### 2.5.5 Feeding Table

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Gain G/day/fish</th>
<th>Feed g/day/fish</th>
<th>Feed % / day</th>
<th>FCR</th>
<th>Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>0.59</td>
<td>0.70</td>
<td>1.41</td>
<td>1.19</td>
<td>0</td>
</tr>
<tr>
<td>55.4</td>
<td>0.62</td>
<td>0.75</td>
<td>1.36</td>
<td>1.22</td>
<td>9</td>
</tr>
<tr>
<td>61.0</td>
<td>0.65</td>
<td>0.80</td>
<td>1.32</td>
<td>1.24</td>
<td>18</td>
</tr>
<tr>
<td>66.8</td>
<td>0.67</td>
<td>0.86</td>
<td>1.28</td>
<td>1.27</td>
<td>27</td>
</tr>
<tr>
<td>72.9</td>
<td>0.70</td>
<td>0.91</td>
<td>1.25</td>
<td>1.30</td>
<td>35</td>
</tr>
<tr>
<td>79.2</td>
<td>0.73</td>
<td>0.96</td>
<td>1.21</td>
<td>1.33</td>
<td>44</td>
</tr>
<tr>
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<td>0.75</td>
<td>1.01</td>
<td>1.18</td>
<td>1.35</td>
<td>53</td>
</tr>
<tr>
<td>92.4</td>
<td>0.78</td>
<td>1.07</td>
<td>1.16</td>
<td>1.38</td>
<td>62</td>
</tr>
<tr>
<td>99.4</td>
<td>0.80</td>
<td>1.12</td>
<td>1.13</td>
<td>1.40</td>
<td>71</td>
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<td>0.83</td>
<td>1.18</td>
<td>1.11</td>
<td>1.43</td>
<td>80</td>
</tr>
<tr>
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<td>0.85</td>
<td>1.23</td>
<td>1.08</td>
<td>1.45</td>
<td>88</td>
</tr>
<tr>
<td>121.7</td>
<td>0.88</td>
<td>1.29</td>
<td>1.06</td>
<td>1.47</td>
<td>97</td>
</tr>
<tr>
<td>129.5</td>
<td>0.90</td>
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<td>1.04</td>
<td>1.50</td>
<td>106</td>
</tr>
<tr>
<td>137.6</td>
<td>0.93</td>
<td>1.41</td>
<td>1.02</td>
<td>1.52</td>
<td>115</td>
</tr>
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<td>145.9</td>
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<td>1.54</td>
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<tr>
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<td>0.97</td>
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<td>141</td>
</tr>
<tr>
<td>172.0</td>
<td>1.02</td>
<td>1.64</td>
<td>0.95</td>
<td>1.61</td>
<td>150</td>
</tr>
<tr>
<td>181.1</td>
<td>1.04</td>
<td>1.70</td>
<td>0.94</td>
<td>1.63</td>
<td>159</td>
</tr>
</tbody>
</table>

![Figure 6](image-url) An example of the feeding chart

A feeding table is outputted from the program. It is essential that the producers follow the feeding table outputted or the anticipated results will not reflect the scenario. A different feeding regime will mean more mass enters the system and so the mass balance will not be correct.
2.5.6 Waste Output

<table>
<thead>
<tr>
<th>Input (kg/t fish produced)</th>
<th>Total Input (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed 1529.9</td>
<td>Feed 4300</td>
</tr>
<tr>
<td>Carbon 690.0</td>
<td>Carbon 1939</td>
</tr>
<tr>
<td>Nitrogen 110.2</td>
<td>Nitrogen 310</td>
</tr>
<tr>
<td>Phosphorus 22.9</td>
<td>Phosphorus 64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Retention (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon 224.2</td>
</tr>
<tr>
<td>Nitrogen 26.7</td>
</tr>
<tr>
<td>Phosphorus 7.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>solid (kg)</td>
</tr>
<tr>
<td>solid (kg)</td>
</tr>
<tr>
<td>dissolved (kg)</td>
</tr>
<tr>
<td>dissolved (kg)</td>
</tr>
<tr>
<td>80.3 Carbon 385.5</td>
</tr>
<tr>
<td>6.2 Nitrogen 77.2</td>
</tr>
<tr>
<td>10.1 Phosphorus 5.4</td>
</tr>
</tbody>
</table>

Figure 7 An example of the waste output page

The waste output page gives the waste in two versions. The first version is based on a per tonne of fish production. This gives a standardized rate that is best for comparing between different runs. However, for a farm that has been decided, they will want to know how much waste comes from a production cycle. The per tonne production will also be useful for determining the amount of waste associated with increasing production. For example if I want to increase production from 20 to 100 tonne and I have already calculated the per tonne value, it is easiest to multiply this number by 100 tonnes. As stated earlier though, the total output is not useful for predicting the dispersion on a daily basis.

The current project uses the same scientific equations and constants as used in the Excel based model. The main difference in this project changes output time step for waste and the visualization capabilities. The project changed the nutrient load calculation to a daily time step, so the nutrient loads and dispersion can be modelled
on a daily basis. The EXCEL model has limited forms of visualization as shown and so this was another area that was noted as needing improvement in the new model.

### 2.6 Nutrient Transport

The main concern is how far can the impacts of the farm be felt. This has implications for environmentalists and for farm managers. A farm manager needs to have the cages set far enough apart to ensure they do not have negative impacts on each other, although the current model only caters for a single cage. Wastes will be distributed by diffusion, settling and flushing. These processes must be accurately modelled. Water currents within the vicinity of cages are the main source of flushing in the area. The effects can be simplified into a two-dimensional situation. The main outputs are solid wastes and dissolved wastes in the forms of food and excreta.

#### 2.6.1 Solids Transport

The pellet properties determine whether the pellets are heavy enough to sink, or whether they will remain in the water column. Past results on feed report that pellet settling velocities for Atlantic salmon diets range from 5.6 cm/s (2mm pellet) to 13.9 cm/s (10mm pellet) for 20-40% fat pellets (Chen, Beveridge & Telfer 1999). The settling rates were significantly larger for larger pellets but were not significantly affected by immersion times in water. Significant differences were seen in settling velocity for all diets with an increase in salinity from 20psu to 30psu, but only some of the diets showed significant differences with temperature changes (Chen, Beveridge & Telfer 1999). As the settling velocity is affected by the density difference, changing the salinity should have a larger effect on velocities than temperature will, due to the larger effect of salinity on density.

Past tests on faecal matter have collected faeces in a number of forms, such as, with nets, by anaesthetizing the fish and stripping them and by dissecting the fish and removing the contents (Chen, Beveridge & Telfer 1999a). The results from these tests were that no significant differences were attributed to faecal size, but that settling velocities ranged from 4-6cm/s at 33psu (Chen, Beveridge & Telfer 1999a). Settling velocities varied with salinity, and therefore density of water.
Equation 1 is a basic dispersion equation that can be used to determine the horizontal distribution, d, of wastes from the cages in an area of depth D, current velocity, Uc, and particle settling velocity, Us. The settling velocity, current velocity and the water depth can be used to gain an estimate of where the cage wastes will fall [Figure 8]. However, the currents, average particle diameter and associated settling velocities, as well as the depths change on temporal and spatial scales around farms.

Settling velocities of feed pellets is between 4-14 cms\(^{-1}\) and between 4-6 cms\(^{-1}\) for faecel wastes (Chen et al. 1999; Chen et al. 1999a). Due to limitations from cage designs and for ease of operations, current speeds at sites are generally less than 60
Higher current speeds tear nets and break cages. By using the equation in Figure 8 and the range of settling velocities of waste, the following contours for predicted dispersion was developed.

![Contour plot](image)

**Figure 9**  Contours for solid waste dispersion in a 10 m deep site

Stratification impacts the dispersion of the solid wastes as the water properties vary and the current profiles differ. The above equation has been found to be good for predicting dispersion in mixed or weakly-stratified sites where the currents are uniform. Alternatively, if strong stratification persists and current velocities reduce with depth, the dispersion can be given by this equation;

\[
d = \frac{U_c^* (D - mP)}{U_s}
\]

Equation 2

where \( m \) is an exponent in the range between 0.15-0.20 and \( P \) is the depth of the pycnocline (Beveridge 1996). The affect of this equation is an ‘effective’ depth, that is proportional to the decrease in distance traveled due to a smaller velocity acting in the lower layer. However, this equation was not used in the model as it was
determined that applying Equation 1 with different velocities throughout the vertical would give the same result and actually reduces the current in the lower layer, rather than setting an ‘effective’ depth.

2.6.1.1 Discrete Settling

For discrete, non-flocculating particles in a dilute suspension, the settling velocity is a function of the fluid properties and the characteristics of the particle (Jorgensen). The particle is acted upon by gravity, buoyancy and frictional forces as it travels through the water column. After an initial accelerating period, the particles reach a constant velocity described by,

\[
U_s = \sqrt{\frac{2g \left( \rho - \rho_f \right) \cdot V}{Cd \cdot \rho_f \cdot A}}
\]

Equation 3

where
- \( g \) is gravity = 9.807 ms\(^{-1}\),
- \( \rho \) is the particle density,
- \( \rho_f \) is the fluid density,
- \( V \) is the volume of the particle,
- \( Cd \) is Newton’s Drag Co-efficient,
- \( A \) is the projected area in the direction of travel.

Newton’s drag coefficient is a function of Reynolds number and the particle shape. For Reynolds Numbers less than 1, \( Cd = 24/Re \). For Reynolds values greater than 1000, the \( Cd \) value conforms to a set value depending on shape.
Reynolds number = \( u \cdot d / \text{viscosity} \); Natural water bodies are often turbulent and so values of constant \( C_d \) will be reached. \( C_d \) values calculated will need to be close to this value and so the Reynolds Number is calculated for each pellet in the experiment. By viewing the past results, for sinking feeds;

\[
\text{Re} = 0.056 \times 0.002 / 10^{-6} = 112
\]
\[
= 0.14 \times 0.1 / 10^{-6} = 14000
\]

These results show that if \( C_d \) is calculated for the pellets in a settling tube, they may not be characteristic of turbulent conditions. This will only be true for the smaller pellets, and \( C_d \) calculated for larger pellets may be applicable under a range of conditions.

Settling velocities depend on the particle and fluid characteristics. In aquaculture, these characteristics will vary depending on the composition and size of the diet used, the size of the fish, the fish species and the environmental conditions at the site. Not surprisingly, significant differences have been noted in settling velocities for a number of feed diets depending on the feed type, feed size, water temperature and salinity (Chen, Beveridge & Telfer).
2.6.2 Dispersion

Dispersion forces act upon dissolved substances that enter aquatic ecosystems. Without dispersion, the ammonia excreted by fish in the seas would reach critical levels. In areas where the dispersion is limited, the nutrient levels can rise enough to promote excessive algal growth (Lewis 1997). These are natural processes that are not limited to areas with cages. However, with increasing nutrient loads coming from human sources ending up in coastal estuaries and waterways, it is appropriate to gain an understanding of how these will be dispersed and if the levels will reach levels which will change the state of the system.

Diffusion is the process of mixing and dilution of a substance. The volume that the substance is distributed over increases and the concentration of the substance in the fluid is reduced. Diffusive transport occurs between two sections of a liquid when there is a concentration gradient and the ability for molecules to be transported in both directions. The molecular diffusion can be described as;

\[ Q_{mol} = -\eta A \frac{dC}{dy} \]  

Equation 4

The mass transported, Qmol, is dependent on the molecular diffusion co-efficient, \( \eta \), the cross-sectional area, A and the concentration gradient, \( \frac{dC}{dy} \). The molecular diffusion co-efficient is a fluid property and is constant with fixed temperatures (Lewis 1997). The negative sign means that transport will be from high to low concentrated regions. The diffusion also takes place by turbulent motions in the liquid, with the diffusion due to the turbulent motions being much faster. Ink put in water would take a few hours to diffuse to the same levels, as turbulent diffusion would achieve in a number of seconds (Lewis 1997). Turbulent diffusion is given by;

\[ Q_{turb} = -K_y A \frac{dC}{dy} \]  

Equation 5

The mass transported by turbulent diffusion is dependent on the turbulent diffusion co-efficient, which varies depending on the size and strength of the eddies in the fluid (Lewis 1997). The turbulent diffusion co-efficient is hard to measure but values are
generally around 1000 times large than the molecular diffusion co-efficient. Also, due to the concentration gradients in turbulent flows not being steady, an average value needs to be determined and used.

The dispersion of substance in laminar and turbulent water bodies varies. The two flow types have a number of characteristics that differ. The particles in laminar flow follow paths that are parallel to each other. In turbulent flows, the paths of the particles are of random orientation. Generally, many natural water bodies are turbulent systems. Cages will be set up in estuaries and coastal areas where the hydrodynamic regimes are complex. Flows vary in magnitude and direction with the tides, which makes it hard to use basic equations for modelling. However, with respect to turbulence, the tidal actions mean that the systems remain in a turbulent state for most of the time (Lewis 1997).

Stratification also affects the amount of dispersion as the fluid properties vary in the different regions and the stratification acts as a barrier to transport. Stratification may be caused through a combination of solar heating, light winds, fresh water inflows and other forces. The stratification limits the size of eddies that can be formed, which effects the diffusion co-efficient and the amount of mass transported through turbulent diffusion (Lewis 1997). Some of the substance can be transported across the layer if instabilities occur.

Substances are also diluted through shear dispersion. Shear dispersion is due to the fluctuating forces acting on different parts of the substance, which distorts the shape of the substance. The shearing effect will depend on the magnitude of forces acting on the substance.

Example of diffusion of ammonia in a channel (Modified from Lewis 1997)
Assume the ammonia input is 1.7 kg/d for 14000 fish at 250 grams. The area of the channel where the cage is placed is 200 m² and the depth is 10 m. The current speed is 0.3 ms⁻¹ and so the flow rate is 60m³/s. Ky is 0.05 m² s⁻¹ and the monitoring point is 50m downstream.

Time to get to monitoring point= monitoring point / U = 166 s
W = 5.7(Ky^{0.5})*(t^{0.5}), width of plume = 16.45 m
A(t) = W^*D = 164.5 m^2
C = \frac{Q_{\text{input}}}{uA(t)} = 0.4 \text{ mgm}^{-3}

This example has some assumptions that lead to differences from calculated to observed results. For instance, if the velocity is not constant along the river, it is difficult to determine the time of travel needed to reach the concerned spot (Lewis 1997). There are also variations in the flow across the channel due to the shape of the bottom and sides. This means that complications soon arise when the dispersion of substances is tried in marine or estuarine systems where flows are spatially and temporally variable.

2.6.3 Matlab
Matlab stands for matrix laboratory and it is a powerful computer program that is based on C-programming with a number of complex mathematical routines built in. The program has more mathematical solving power than programs like EXCEL. Matlab allows program files to be created and run. Matlab was used due to the mathematical power and the ability to give the user choices. This allowed the combination of the different Excel programs into one model that could be used for a number of situations by changing the user-defined inputs.

2.6.4 ELCOM
ELCOM (Estuary and Lake Computer Model) is a numerical modeling tool that applies hydrodynamic and thermodynamic models to simulate the temporal behavior of stratified water bodies with environmental forcing. ELCOM is used to determine the distribution of dissolved wastes. The hydrodynamic simulation method solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure.

Modelled and simulated processes include baroclinic and barotropic responses, rotational effects, tidal forcing, wind stresses, surface thermal forcing, inflows, outflows, and transport of salt, heat and passive scalars. Through coupling with the
CAEDYM (Computational Aquatic Ecosystem DYnamics Model), ELCOM can be used to simulate three-dimensional transport and interactions of flow physics, biology and chemistry. The hydrodynamic algorithms in ELCOM are based on the Euler-Lagrange method for advection of momentum with a conjugate-gradient solution for the free-surface height (Casulli and Cheng, 1992). Passive and active scalars (i.e. tracers, salinity and temperature) are advected using a conservative ultimate quickest discretization.

3.0 Potential for cage culture in Western Australia

The potential for cage culture in Western Australia is limited by the amount of available coastal waters, and the species that can be grown there. This section summarises some facts about the species that can be chosen in the model, which all have potential for aquaculture in WA. The potential areas for cage culture can be viewed as highlighting the regions that need to be modelled.

3.1 Potential Species for Cage Culture in Western Australia

There are a number of species with potential for cage culture production in Western Australia. The Department of Fisheries and the Fremantle Maritime Centre have worked on joint projects on the developments of marine finfish (FWA 2000a). These include species such as Pink Snapper (*Pagrus auratus*), Rainbow Trout (*Oncorhynchus mykiss*), Brown Trout (*Salmo trutta*), Barramundi (*Lates calcarifer*), Black Bream (*Acanthopagrus butcheri*), Silver Perch (*Bidyanus bidyanus*) and Dhufish.

The potential for each of the species needs to be determined in terms of biology, bioenergetics, hatchery and growout conditions. Species with adequate research done on the controlling factors can be used for commercial efforts. Due to the model currently using only pink snapper, rainbow trout (often referred to as Sea Trout when raised in marine cages) and barramundi, they will be the only species discussed in the following section.
3.1.1 Pink Snapper, *Pagrus auratus*

Pink Snapper is a long-lived, slow growing species sold on domestic and export markets (Kaufmann, Geen & Sen 1999). It is common throughout Japan and Australasia with independent and reproductively isolated populations occurring throughout the region (FWA 1995).

In Western Australia, snapper occur from the Dampier Archipelago to the South Australian border with adult fish concentrated at Shark Bay, the Abrolhos Islands and in Cockburn Sound, with juveniles found in the embayments and estuaries along the coast (FWA 1995).

The optimum temperature range for rearing snapper is 20°C to 28°C, although growth can be continued in waters down to 13°C (FWA 1995).

Below 10°C the snapper stop feeding (FWA 1995). Snapper also need the salinity to maintain above 16ppt for successful culture, and for dissolved oxygen levels to remain above 3ppm (FWA 1995).

Pink snapper are carnivores and so require a high protein diet. In the wild, they consume crustaceans, molluscs, worms and fish (FWA 1995). The dietary needs have been researched so that a number of artificial diets are available for both juvenile and adult snapper (FWA 1995). Captive snapper have shown increased growth rates compared to wild fish in Australia, with captive snapper reaching market size of 250 mm within two years compared to four or five for wild fish (FWA 1995).

Catches of pink snapper are restricted not only by regulations but also through the market supply (FWA 1995), which may restrict aquaculture production if aquaculturalists cannot compete with prices of wild-caught fish. However, the success
of commercially farming snapper in Japan since the 1960’s, after it was first reared successfully near the beginning of last century (FWA 1995), gives hope to aquaculturalists. In Japan, snapper are called Red Sea Bream and 1988 production was three times greater than wild catches in that country (FWA 1995). Snapper has also been cultured in other parts of the world, with saline lakes being used in Egypt (FWA 1995).

Research and experimental cultures have been developed in Western Australia, South Australia, New South Wales and New Zealand (FWA 1995). Many of these are at a commercialization stage. This could bring benefits to a number of groups, including inland farmers stricken by salinity. There is potential for *Pagrus auratus* to be stocked in cages in inland ponds where the groundwater is saline.

### 3.1.2 Rainbow Trout, *Oncorhynchus mykiss*

Due to the native catfish being the only large freshwater species in the southern region, rainbow trout were introduced into West Australian waters in 1942 to provide food and for recreational fishing (FWA 1999). Trout have been farmed since the 1800’s and are considered domestic (FWA 1999), and have been successfully reared in cages (Lee & Nel 2001). When the cages are placed in the marine environment, the trout are called sea trout. The global production of rainbow trout reached 360,000 tonnes in 1995 (FWA 1999).

Trout have a high demand for high quality water, which is a limiting factor for trout production in WA (FWA 1999). The preferred growth temperature of trout is reported to be between 10 and 15degC, with high mortalities recorded in temperatures above 25degC. However, at the South West Freshwater Research and Aquaculture Centre (SWFRAC) in Pemberton, where they have bred trout for over 40 years, the stock has a higher temperature tolerance and feeds up to 23degC (FWA 1999). Selective breeding may further raise the temperature tolerance to increase prospects in Western Australia, and is being looked at by FisheriesWA (FWA 1999).
Trout have an ability to withstand a range of salinities, which can be seen in the natural migration of juveniles from rivers to the sea and the return to the rivers by adult fish to spawn (FWA 1999). The tolerance to salinity depends on the age, the rate of acclimatisation and the water temperature (FWA 1999). If the trout are acclimatised to salt water between 6 months to 2 years of age, they will be able to be reared in sea-cages (FWA 1999).

3.1.3 Barramundi, *Lates calcarifer*

Barramundi occurs throughout the South-East Asian region, including northern Australia (FWA 1999a). Research has been carried out into barramundi culture in Australia since the 1980s and commercial farms have been developed in numerous states.

Being euryhaline, barramundi naturally move between fresh and salt-water throughout their life cycle. The mature barramundi live in estuaries and coastal areas. Eggs and larvae need salinities of at least 22 ppt to survive and so the larvae are only found in the coastal waterways. The adjacent mangrove swamps and brackish waterways adjoining the estuaries provide ideal protection for the juvenile barramundi (FWA 1999a). The older barramundi are found in the upper reaches of the rivers (FWA 1999a).

Barramundi become sexually mature at 2-3 years of age, and in the wild the fish spend 1 or 2 spawning seasons as males. Once the fish are greater than 100 cm, the fish undergo a sexual change and become female although earlier changes have been reported in captive fish (FWA 1999a).

The practices used to induce barramundi to spawn in the eastern states have had limited success in WA and modifications will need to be made to the techniques to increase successes. A number of larval rearing techniques are available including clean and green water methods. Grow-out techniques, apart from cage culture, include extensive pond culture and tank culture.
3.2 Regions for cage culture in Western Australia

Studies have been done to access the suitability of aquaculture in various regions of Western Australia. This section summarises the outcomes of those studies in relation to the cage culture of species. It include offshore, coastal and inland regions. Presently, due to the dry continent, over 95% of current aquaculture in Australia comes from estuarine or coastal waters (Caton & McLoughlin 2000).

Salinity levels in the groundwater is viewed as a negative for numerous agricultural activities, however, these levels may be a positive for inland saline aquaculture (Smith 1999). If the composition of the groundwater is suitable, then numerous endemic, euryhaline species, or local species capable of a range of salinities, will be able to be cultured in inland areas (Jenkins 1999).

3.2.1 Coastal and offshore locations

There are a number of potential sites for cage aquaculture in coastal and offshore areas of Western Australia. In the north of the state at Broome, production trials for barramundi were undertaken by the local TAFE (FWA 2000a). This has led to speculation that sea-cage grow-out of barramundi has potential in the northern region, although sites will need to be determined.

Coming down the coast, you find protected areas in Shark Bay that may have potential, especially for local species of pink snapper that thrive in the hypersaline conditions. Further south, the Houtman Abrolhos Islands have been recognized for their potential for aquaculture in the Aquaculture Plan for the Houtman Abrolhos Islands; prepared and available from the Department of Fisheries, Western Australia. The archipelago consists of 122 low-lying islands about 60km off the Geraldton Coast (FWA 2000b). A number of possible cage culture areas are highlighted in the Plan.

Generally, the estuaries and rivers in the southwest region are too shallow for cage culture. Also, remediation has been taken for many of these areas to negate eutrophication and nuisance blooms, such as in the Swan and Peel systems. Cages would increase the nutrient loads and further the degradation and so it is highly unlikely that cages would be allowed in these areas. Production within the protection
of Rottnest and Garden Island will be most likely limited by other industries and recreations using the waters but there will probably be some small operations.

The southern aquaculture region extends around from the Capes and to the South Australian border. The majority of aquaculture is at Albany, although this doesn’t include finfish (FWA 2000a). Aquaculture in the Esperance region will follow the principles in the Aquaculture Plan for the Recherche Archipelago where a number of potential cage sites are highlighted (FWA 2000a).

### 3.2.2 Inland aquaculture

Cages vary in size and so have potential to be placed in small dams to large lakes. Lake Argyle is seen as having the largest potential for aquaculture in inland waters (FWA 2000a). A review was undertaken to establish the environmental impacts of producing 2000 tonnes per annum of barramundi in Lake Argyle (EPA 1999). The results were promising, with water quality being the main issue that would need monitoring. The environmental impacts should be minimised by the water depth, current velocities and feeding regime. However, the initial phase will have a 500 tonne per annum limit until adequate 3-D modelling can be applied (EPA 1999).

Freshwater and saline fish have potential in the southern inland region. Trout have been available for a number of years from the SWFRAC at Pemberton (FWA 2000a). Black bream have been successfully reared at Fremantle and stocked in dams throughout the state, and juvenile snapper have been trialled in cages in salt lakes north of Perth (Jenkins 1999).

There is also potential for cage-culture in flooded coal mine pits. Coal mines leave behind large deep holes that are filled with water. The sediments are deficient in organic matter, which means toxins are easily released into the water column. Fish farming can allow for increased rates of organic loading, to levels that may not be acceptable in other aquatic environments. However, stratification will need to be maintained in the water to separate the lower and upper levels of the lake, which will keep any toxins away from the stock.
3.3 Aquaculture Legislation

Aquaculture developments in the past have altered coastal habitats through physical alteration, nutrient inputs and subsequent eutrophication (FWA 2000). This is the reason all applications are assessed on a cage-by-cage basis (FWA 2000).

In Australia, the government plays a significant role in the provision and funding of fisheries management. This is done by forming legislation at the state and federal level, which often sets up and then delegates authority to organisations (Kaufmann, Geen & Sen 1999). All of the states issue permits and licenses conditional on ecologically sustainable development, and through requirements set out under the relevant environmental legislation (Caton & McLoughlin 2000).

3.3.1 Federal Legislation

Federal Acts and regulations relating to fisheries are the ‘Fisheries Administration Act 1991’ and the ‘Fisheries Management Act 1991’

The FMA1991 replaced the Commonwealth’s Fisheries Act 1952. The new act repeats that one of the primary objectives is for ecologically sustainable development and for regards to be taken on the impact of fishing and related industries on non-target species and the marine environment (Bates 1995). A set of regulations to support these acts was also passed, titled the ‘Fisheries Management Regulations 1991’. The acts and regulations work together to deliver the goals of the act.

Aquaculturalists planning to go outside state waters should take note of the ‘Environmental Protection and Biodiversity Act 1999’. The EPBA1999 has effect on all waters outside of state boundaries (>3nm) (FWA 2000). As cage culturalists may have to go far offshore to reach areas of adequate flushing and reduced conflicts, this Act will come into applications. Australia’s Ocean Policy is also important to note, as it relates to the ecologically sustainable development of our oceans (FWA 2000).
3.3.2 State Legislation

Fish Resources Management Act 1994

The FRMA1994 relates to the management of fish resources administered by the Department of Fisheries. Part 8 provides the legal and administrative framework for the Minister for Fisheries and for the Department of Fisheries to manage aquaculture in Western Australia (Anon 1998). It includes provisions for the governing of the culture and propagation of aquatic species (FWA 2000).

Environmental Protection Act 1986

The EPA1986 details the Environmental Impact Assessment procedures to be followed when developing a project. Many aquaculture projects will be referred to the DEP and possibly the Environmental Protection Agency for reviews. EIA’s should be a definite part of any aquaculture project that releases untreated effluent into the surrounding system like cages do.

3.3.3 The Licence and Lease Procedures

Under the FRMA1994, the Executive Director of the Department of Fisheries and the Minister for Fisheries perform many functions relating to aquaculture (FWA 1998). Section 97 allows the Minister to grant leases for aquaculture, up to 21 years, for areas vested in the Minister’s authority (Anon 1998). Section 93 allows aquaculturalists to hold a general licence, with annual rights of renewal set out in section 94, which is based on the good behavior characteristics set out in Section 143 (Anon 1998). Licenses are assessed in accordance with Ministerial Policy Guideline No 8.

All applicants for new licenses and leases will be required to provide detail to the Department of Environmental Protection to assess the environmental impacts, and if appropriate, to determine an appropriate monitoring program (Anon 1998). A security bond will also be required so that if proper clean-up isn’t done, money is available for remediation (Anon, 1998). This money may potentially be used to monitor sediments during fallowing and to remove materials left on site.
4.0 Method

The method outlined below is based on converting a feed to waste program into a feed to waste dispersal program. The model supplied was based in EXCEL and so the first step was to rewrite the program in MATLAB. The next step involved adding the components to the program so waste dispersion can be modelled. The changes ranged from switching the output time step to including a waste dispersion grid.

4.1 Growth Equations and Waste Output

The model is designed to give the user choices on the species to be grown, the size of fish to be grown, the feed to be used and the time of growth. The background science is written outside of the user’s view and includes the equations and constants for the different species and feeds as well as the code to perform the solid dispersion. The entire program works on the assumption that the feeding strategy recommended is used. The amount needing to be fed should be outputted, printed and adhered to.

The original feed to waste program involved a number of input pages and charts that are shown in the background section. The equations used for growth are shown in Table 2. The parameters used in the models, Table 3, have been developed in a joint effort between FisheriesWA and the National Centre for Mariculture, Israel. Their experiments determined the percentage composition of nutrients in each species and their energy requirements for growth and maintenance. The parameters supplied were accepted as being correct and no modifications were made to these. From this information and a mass balance, the amount of waste coming from the fish can be determined on a daily basis. This is the same principle as the initial program but is based on a daily time step rather than the period of growth. This was an essential change to determine the daily waste loadings.
Table 2 Growth and Energy Equations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight(t)</td>
<td>grams</td>
<td>(initial weight$^a + b \cdot \exp(cT)t)^d$</td>
</tr>
<tr>
<td>weightgaindaily(t)</td>
<td>grams</td>
<td>$f \cdot \weight(t) \cdot \exp(cT)$</td>
</tr>
<tr>
<td>DEperday(t)</td>
<td>kJ/day</td>
<td>maint(t) + growth(t)</td>
</tr>
<tr>
<td>Maintenance (t)</td>
<td>kJ/day</td>
<td>$h \cdot \exp(iT) \cdot \weight(t)/1000^j$</td>
</tr>
<tr>
<td>Maintenance (t) only</td>
<td>kJ/day</td>
<td>$m \cdot (-1.04 + 3.26T - 0.05T^2) \cdot \weight(t)/1000^j$</td>
</tr>
<tr>
<td>growth(t)</td>
<td>kJ/day</td>
<td>weightgaindaily(t) $\cdot k \cdot \weight(t)/1000^j$</td>
</tr>
<tr>
<td>DEperkggain(t)</td>
<td>kJ/(kg*day)</td>
<td>DEperday(t)/weightgaindaily(t)</td>
</tr>
<tr>
<td>feedperday(t)</td>
<td>grams</td>
<td>DEperday(t)/digestible_energy</td>
</tr>
<tr>
<td>accumfeed(t)</td>
<td>Kg</td>
<td></td>
</tr>
<tr>
<td>FCR</td>
<td>unitless</td>
<td>feedperday(t)/weightgaindaily(t)</td>
</tr>
</tbody>
</table>

Table 3 Growth Constants

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>Snapper</th>
<th>Barramundi</th>
<th>Trout</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.56</td>
<td>0.474</td>
<td>0.36</td>
</tr>
<tr>
<td>b</td>
<td>0.01624</td>
<td>0.001</td>
<td>0.00688</td>
</tr>
<tr>
<td>c</td>
<td>0.072</td>
<td>0.162</td>
<td>0.115</td>
</tr>
<tr>
<td>d</td>
<td>1.7857</td>
<td>2.11</td>
<td>2.786</td>
</tr>
<tr>
<td>f</td>
<td>0.029</td>
<td>0.00211</td>
<td>0.0192</td>
</tr>
<tr>
<td>g</td>
<td>0.44</td>
<td>0.526</td>
<td>0.641</td>
</tr>
<tr>
<td>h</td>
<td>35.3</td>
<td>14.55</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>0.02</td>
<td>0.045</td>
<td></td>
</tr>
<tr>
<td>j</td>
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<td>0.83</td>
<td>0.824</td>
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<td>3.37</td>
</tr>
<tr>
<td>L</td>
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<td>0.099</td>
<td>0.211</td>
</tr>
<tr>
<td>m</td>
<td>1.78</td>
<td>1.5</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Further equations that are involved in determining the waste conversion can be viewed in the MATLAB script. All the outputs from the initial model were built into the updated model, although the forms of visualization are slightly different. The outputs include but are not limited to the daily growth, the total biomass gained, energy requirements, a feeding table and the total and daily waste produced.
It should be noted that the EXCEL model can be used to determine the daily waste discharges, and this method was used to get comparisons with the outputs from the MATLAB program while being developed. The EXCEL model determines the total waste over a period, so if the time is slowly incremented, the waste values can be viewed and entered into a spreadsheet for each day. The daily discharges can be determined by subtracting the difference between days in the spreadsheet. This is an arduous task and it is recommended to save time that the time increment be increased by 5 days for each row of the spreadsheet. This method is still a slow task, but fortunately the MATLAB program gives daily results at a much faster time scale.

The model in MATLAB is written to give the amount of carbon, nitrogen and phosphorous coming from the cages in a solid and dispersed form on a daily basis. The amount of waste coming from the cages per day was determined using the equations in the supplied model. However, there are no characteristics implied in the EXCEL model as to the settling velocities or characteristics of the solid particles. Therefore the choice had to be made between using settling velocities that have been determined for other species, diets and water densities or to run trials and determine the settling velocities for species in the model. The choice was made to run trials but due to the time involved, settling velocities were only determined for wastes from pink snapper fed on various sized pellets of the 45:22 diet. This is the most common diet used for snapper grow-out.

4.2 Site Selection and Dispersion

The dispersion of nutrients from the cages will depend on the environmental conditions around the site. In a 2-D situation, the key factors for the solids dispersion are the current speed, settling velocity and depth. These factors need to be included into the model if it is to be used for prediction.

The user is able to choose the water depth at the site, which is currently a fixed value for the whole domain. The user then enters whether the site has uniform or oscillating currents. The uniform currents assume a constant current over the domain, which remains constant over the entire growth period. The oscillating currents take the form
of a sine curve. The period was set to model the current field changing on a daily basis throughout the growth period. Currently, the feed and faecal waste are dispersed at the same time although there is a definite time lapse while food is digested. This is discussed in the recommendations for future work.

The settling velocity is dependent on the solid characteristics as well as the water characteristics. When the water density changes, the settling velocities change. This is why the user is given a choice of a stratified or a non-stratified site. The model assumes that the density in each layer is constant, with the settling velocities being a function of the difference in density between the water and solids. The distance the particles travel is the sum of the horizontal distance travelled in each layer. Apart from affecting solid dispersion by affecting the settling velocity, stratified sites also show varying currents, often decreasing with depth. The model imposes a 50% reduction on the current speed in the lower layer to model decreasing currents with depth.

4.3 Determining the Solid Settling Velocities

The aim of this section was to determine the settling velocities of fish wastes and uneaten feed pellets. The trials also enabled the determination of Newton Drag co-effecients for feed and faecal pellets.

4.3.1 Feed Pellet Velocities

3 feed pellets were tested for their settling velocities. These were a 45:22 3 mm pellet, a 45:22 4 mm pellet and a 51:16 3 mm pellet. The first two pellets were commercial pellets and the third was a trial pellet. Different size pellets were used to determine the effect of size on the settling velocity, and the 51:16 diet enabled a comparison of pellet composition. The $C_d$ co-efficients were calculated for all pellets and averaged.

30 random pellets were taken from each of the batches. The pellets were weighed using scales (prec. 0.1mg) and the maximum length and diameter was measured using digital calipers (prec. 0.1mm). From these values the maximum volume, assuming cylindrical shape, the maximum area and the density were calculated. The pellets
were then placed in a 1.8 m perspex tube, which had a 5 cm mark from the top and marks every 50 cm below this. Longer tubes have been used to determine the velocity, but no statistical differences have been detected between different sections of the column (Chen, Beveridge & Telfer 1999). Tweezers were used to insert the pellets below the surface and to remove any air bubbles.

The pellets were then released and the time taken to fall the first 50 cm and 1 m were recorded. It is recommended not to include the bottom 20 cm of the tube in the sampling region due to the particles feeling the presence of the bottom when they reach that depth (Chen, Beveridge & Telfer 1999). Taking two measurements for each pellet reduced the chances of getting no result for the drop. Times when no results occurred is when the stop-watch was not stopped or started or if the pellets were prematurely dropped, however, as two measurements were made at least 1 time was recorded for each of the pellets. In the sections where the pellets hit the sides, the times were disregarded. As a number of the pellets did hit the sides in at least one section, covering two lengths of the tube meant measurements could still be taken from that pellet’s descent. The time taken to fall the set distances were converted to velocities by calculating the time to fall 1 m and inverting this number. The temperature and salinity of the column was recorded and used to determine the fluid density and viscosity. Drag co-efficients were determined using the settling velocity and other parameters calculated or measured.

Further data on the settling velocities of 45:22 5 mm pellets was determined by Malene Felsing 2001.
4.3.2 Faecal Pellet Velocities

The faecal pellet trials were run with the assistance of the Department of Fisheries, utilizing tanks that were built to gather faecal material. The trial layout is shown in Figure 11. Two size classes of fish were used, a 40 gram class and a 140 gram class.

![Figure 11 The experimental set-up to collect faecal waste](image)

<table>
<thead>
<tr>
<th>Tank 1</th>
<th>Tank 2</th>
<th>Tank 3</th>
<th>Tank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight ave=36.2 gms</td>
<td>Weight ave=39.7 gms</td>
<td>Weight ave=170.9 gms</td>
<td>Weight ave=178.3 gms</td>
</tr>
<tr>
<td>20 fish</td>
<td>20 fish</td>
<td>10 fish</td>
<td>10 fish</td>
</tr>
<tr>
<td>45:22 (3mm)</td>
<td>45:22 (4 mm)</td>
<td>45:22 (4 mm)</td>
<td>45:22 (5 mm)</td>
</tr>
</tbody>
</table>

4 160 L tanks on a flow-through system were used for the trial. Each size class was split into 2 groups, with one group per tank. For the 40 gram class, 20 fish were placed in each tank. For the 160 gram class, 10 fish were placed in each tank. The composition of all feeds was the same, with each size class being fed two sizes of pellets. The 40 gram fish were fed a 3 mm and a 4 mm pellet. The larger class was fed a 4 mm and a 5 mm pellet.

Fish were fed twice a day until no vigorous feeding was observed. From the model it was determined the smaller class needed to be fed 1.4 % of their body weight per day and the larger class needed to be fed 1.0% of their body weight per day. This means that approximately 15 grams per day will be consumed by each tank of fish.

4.3.2.1 Waste Collection

To determine settling velocities required collecting wastes from tanks. The water and waste flows out the bottom of the tank and into the collectors. The solids get trapped in the bottom and the water flows out the side. Faecal matter is expelled around 6
hours after feeding. For experimental tanks, a small settling chamber may be used to collect waste and this can be used to determine the settling velocity for the species in the tanks at various stages of the growth cycle. The amount of waste expelled will depend on the amount fed, the age of the fish and the diet type and the number of fish. So a higher stocking density, larger tank size or having repetitions of the tanks will shorten the collection period as there will be a larger biomass producing waste.

On the first day, the collected waste was sieved for 3 minutes in an electronic sieve. The sample was separated into a 1000, 500, 250, 125 and 63 microns samples. Excess moisture was removed using paper towel and the samples were weighed. This was a rough estimate to gain an understanding of the percent distribution of size classes of faeces.

Settled wastes were sieved to remove the fraction smaller than 360 microns. The solids were then placed in the settling column and the times recorded for the pellets to fall. Due to the composition of the wastes, faecal pellets were not weighed and measured like the feed pellets, but just sieved in size. Sieving the faeces probably affects the velocities observed.

4.3.3 The solid waste grid

From the growth equations the amount of daily C, N and P discharged is determined. Settling velocities are written into the script and these are used with the equation in Figure 8 to determine the distance dispersed on a daily basis. The outputs are visible as a line graph, as is the loading amounts. The solid waste grid is set up using the distance and the daily waste amount matrixes and is used to show the loading of carbon to the surrounding benthic community. The daily waste matrix shows the amount of waste per metre of cage per day. Both matrices have the number of columns equal to the cage width +1. In the final column of the daily waste matrix is the amount of waste feed per day, while the other columns are the amount of faecal waste per metre of cage. The values in the daily waste, except for the final column, have been divided by the cagewidth to determine the loading per metre. The number of rows is equal to the number of days. The daily faecal amounts are divided by the cage width as it is assumed faecal matter will be distributed evenly across the width of
the cages. The feed waste, however, is modelled as coming from just one metre of the cage; as feeding occurs at set points and not across the width of the cage.

The distance matrix is the same size as the waste matrix, but has an integer value corresponding to each waste amount, which is equal to the distance that amount of waste will be dispersed. For the rows up to $i=cagewidth$, the distance matrix has values of the distance dispersed plus $i$, this allows for a band of solid waste the size of the cage to be modelled, rather than just a single source. The final column relates to the amount of uneaten feed.

Two new matrices are formed as solid waste grids using the above two matrices. The first column contains every metre from the minimum to the maximum distance dispersed. The second column contains the amount of waste at that distance on that day. These matrices are formed for a one month period. The first is a plot of the daily loading and where it will land. The second plot is an accumulation of the total carbon deposited to the area in the month. These plots are then visualized to determine where solids may accumulate in different scenarios and if loading at any particular points will be of a concern.

### 4.4 Dissolved wastes

The dissolved waste amounts are determined from the MATLAB program. ELCOM is then used to predict the nutrient dispersion by using tracers. This approach assumes that the dissolved nutrients will not react and their dispersion will be due to the water movement only. This will possibly lead to an over-estimate of concentrations downstream as there will be some diffusive dispersion as well as reactions after the discharges. A basic canal style ELCOM set-up is used with a constant depth across the range. The canal has an inflow at one end and an outflow at the other. The velocities are constant across the canal, with the ability to change between uniform and oscillating currents, as with the solids dispersion. Much further work can be done on modeling the dissolved wastes than was attempted in this project.
4.5 Trial Runs

A number of trial runs are carried out which cover a range of theoretical farm sites, although all the situations shown use snapper as the farmed species. The aim is to determine the effect of factors such as the current speed and type, the stocking density, cage width, stratification and amount of grazing from wild fish on the distribution and loading of the solid wastes. A smaller number of trials are performed to determine the effect of a number of these factors on the dissolved transport.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Cage width (m)</th>
<th>Grazing</th>
<th>Depth (m)</th>
<th>Current type</th>
<th>Max. current (m/s)</th>
<th>Initial Stocking Density (kg/m³)</th>
<th>Final Stocking Density (kg/m³)</th>
<th>No of fish</th>
<th>Days of Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0.9</td>
<td>10</td>
<td>uniform</td>
<td>0.4</td>
<td>1</td>
<td>5</td>
<td>14000</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.9</td>
<td>10</td>
<td>uniform</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>14000</td>
<td>220</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.9</td>
<td>10</td>
<td>uniform</td>
<td>0.1</td>
<td>5</td>
<td>25</td>
<td>70000</td>
<td>220</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.9</td>
<td>20</td>
<td>uniform</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>14000</td>
<td>220</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.9</td>
<td>20</td>
<td>oscillating</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>14000</td>
<td>220</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>0.9</td>
<td>20</td>
<td>oscillating</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>70000</td>
<td>220</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>0.5</td>
<td>20</td>
<td>oscillating</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>70000</td>
<td>220</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>0.9</td>
<td>20</td>
<td>stratified 2 m</td>
<td>oscillating</td>
<td>0.1</td>
<td>1</td>
<td>5</td>
<td>70000</td>
</tr>
</tbody>
</table>

Table 4 shows the characteristics entered for each trial run. Trial 1 is a shallow site with uniform currents. This site may represent a cage in an estuary with constant, strong discharges to the oceans, or an area where the winds are constant and strong, imposing uniform currents in one direction. Trial 2 is a similar site but has either a smaller discharge or is much more protected, and hence has a lower current speed. Trial 3 is the same site as trial 2 but with a stocking density 5 times greater than the previous example.

Trial 4 is used to compare against trial 2 to determine the effect of depth. Trial 4 versus 5 allows for a comparison of current type, either oscillating or constant. Trial 6 allows for the effects of cage width to be seen, trial 7 for the effect of grazing and trial 8 the effect of stratification.
5.0 Results

5.1 Fish Growth and Maintenance

An example of the output results for fish growth and maintenance is shown in this section. For this example, snapper are grown for 200 days in a water temperature of 18 °C on a 45:22 diet. Other site conditions are not relevant until the dispersion is looked at. The growth chart shows the expected weight of the fish over the growth period (Figure 12).

![Growth Curve](image)

Figure 12  An example of the growth curve output

The graph is for individual fish and shows the expected weight for each day of the trial. Variations were seen when different species and temperatures were picked as inputs, which was also reflected in the amount of wastes coming from the cages. The initial and final weights seen on the growth page in EXCEL are seen in the updated model in a visual output. From the above figure, the initial weight is 50 gms, time of growth is 200 days and the final weight is approximately 226 gms. These values were compared to the Excel outputs to verify the Matlab results for a number of scenarios. The results are also available in a matrix form but it is generally easier to interpret the results from a graphical representation. The above graph can also be used to determine the period of growth needed to reach market size. Figure 12 shows that the
snapper will not reach the plate size of 250 gm that many aquaculturalists desire. An extended run to 250 days showed that the desired weight was reached after 220 days of growth.

Figure 13 Plots of the total biomass and the total biomass gained for trial 1

The next output by the program gives visual results of the biomass, another integer output of the growth page in Excel. Two plots are shown, the total biomass and the biomass gained (Figure 13). This graph provides easily derived information. The difference between the two lines is the initial biomass; that is the number of fish multiplied by the initial weight. The total biomass or the biomass gained is easily determined for any time of the growth period. For example, in Figure 13 the initial biomass is 700 kg, the final biomass is 3150 kg and the biomass gained is 2450 kg. The biomass plots may also be used for economic considerations. If a farmer knows that they need a minimum amount of produce, the inputs can be manipulated to achieve the desired amount of biomass and the associated waste loadings can be determined for this regime.
The daily growth and amount fed per fish are also important factors. Fish grow over 170 grams in 200 days and so the average daily growth rate is slightly above 0.85 gms/day/fish. The daily amount fed increases as the fish grow. However, the daily growth figure is a total amount and does not easily show that the fish have lower percentage growth of their body weight with age. Simply, the fish begin growing at 0.6 gms/day when they weigh 50 gms. At day 200, the fish are growing near 1.2 gms/day and weigh 226 gms. The growth has only increased by 2 times while the fish weight has increased by 4.5 times.

The daily amount fed also increases with time but decreases as a percentage of total body weight. As mentioned above, the smaller fish have the highest percentage growth rates and so they are fed more as a total percent of their body weight. It may also be seen that the amount fed increases greater than the growth. As the fish get older, the FCRs in the program increase, thus more feed is needed to gain the same

Figure 14 The daily growth per fish, daily amount fed per fish and the associated food conversion ratios (FCRs) for trial 1
proportion of fish weight. This accounts for the amount fed increasing at a faster rate than daily growth in Figure 14.

![Daily Energy Requirements](image)

Figure 15 Daily energy requirements: total, for growth, for maintenance

The daily energy requirements are shown in Figure 15. The total energy requirements are the sum of the energy needed for maintenance and growth. Energy for maintenance is less than the amount for growth as maintenance assumes zero growth and so no energy is expended in this form. The amount of energy needed directly relates to the water temperature as fish are cold-blooded and are heated by their environment. With temperatures outside the optimum range, more energy is needed, which increases feed costs or decreases growth. Either way, the profits from the farm will be reduced and the waste loadings will increase.

### 5.2 Feed Pellet Velocities

The feed pellets showed variability in the size, weights and density within each size class of pellet. The 45:22 3 mm pellet varied in size from a maximum length, diameter and weight of 2.6 mm, 2.7 mm and 0.0216 grams to 6.5 mm, 3.5 mm and 0.0712 grams. The calculated densities varied from 1037 to 1452 kg/m$^3$, and the timed settling velocities ranged from 7.0 to 10.0 cm/s. The values meant that the drag
co-efficients calculated ranged from 0.17 to 2.8, with a mean of 1.5 and standard deviation of 0.72. A summary of the feed pellet velocities is given in Table 5.

<table>
<thead>
<tr>
<th>Feed Type</th>
<th>Lmax (mm)</th>
<th>Dmax (mm)</th>
<th>Weight (grams)</th>
<th>Density (kg/m³)</th>
<th>Fluid Density (kg/m³)</th>
<th>Settling Velocity (m/s)</th>
<th>Cd</th>
<th>Reynolds Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pivot 45:22 3 mm</td>
<td>3.8</td>
<td>3.1</td>
<td>0.037</td>
<td>1253</td>
<td>1024</td>
<td>0.081</td>
<td>1.58</td>
<td>216</td>
</tr>
<tr>
<td>Pivot 45:22 4 mm</td>
<td>6.4</td>
<td>4.0</td>
<td>0.097</td>
<td>1185</td>
<td>1024</td>
<td>0.081</td>
<td>1.48</td>
<td>279</td>
</tr>
<tr>
<td>Pivot 45:22 5 mm</td>
<td>6.9</td>
<td>5.3</td>
<td>0.160</td>
<td>1052</td>
<td>1025</td>
<td>0.070</td>
<td>0.43</td>
<td>319</td>
</tr>
<tr>
<td>Pivot 45:22 5 mm</td>
<td>6.6</td>
<td>5.2</td>
<td>0.148</td>
<td>1056</td>
<td>1024</td>
<td>0.072</td>
<td>0.48</td>
<td>322</td>
</tr>
<tr>
<td>Pivot 45:22 5 mm</td>
<td>6.5</td>
<td>5.2</td>
<td>0.147</td>
<td>1065</td>
<td>1022</td>
<td>0.068</td>
<td>0.73</td>
<td>304</td>
</tr>
<tr>
<td>Pivot 45:22 5 mm</td>
<td>6.9</td>
<td>5.2</td>
<td>0.156</td>
<td>1065</td>
<td>1010</td>
<td>0.081</td>
<td>0.67</td>
<td>358</td>
</tr>
<tr>
<td>GF 42:8 5 mm</td>
<td>7</td>
<td>4.4</td>
<td>0.119</td>
<td>1119</td>
<td>1025</td>
<td>0.071</td>
<td>1.21</td>
<td>269</td>
</tr>
<tr>
<td>GF 42:8 5 mm</td>
<td>7.4</td>
<td>4.3</td>
<td>0.118</td>
<td>1099</td>
<td>1024</td>
<td>0.091</td>
<td>0.58</td>
<td>334</td>
</tr>
<tr>
<td>GF 42:8 5 mm</td>
<td>7.3</td>
<td>4.3</td>
<td>0.120</td>
<td>1133</td>
<td>1022</td>
<td>0.100</td>
<td>0.72</td>
<td>368</td>
</tr>
<tr>
<td>GF 42:8 5 mm</td>
<td>7.3</td>
<td>4.3</td>
<td>0.120</td>
<td>1133</td>
<td>1010</td>
<td>0.100</td>
<td>0.80</td>
<td>368</td>
</tr>
<tr>
<td>Exp. 51:16 3 mm</td>
<td>8.2</td>
<td>3.1</td>
<td>0.059</td>
<td>957</td>
<td>1024</td>
<td>0.033</td>
<td>-7.77</td>
<td>88</td>
</tr>
</tbody>
</table>

* Pivot is a commercially available aquaculture feed, as is Glen Forrest (GF).
# Results were supplied by Malene Felsing of the Department of Fisheries, WA.

It can be observed that the velocities were in the same range as for salmon diets tested in similar water densities. It may be noted that the settling velocities for the 3, 4 and 5 mm Pivot pellets do not increase with size. This is assumably due to the higher densities of the smaller Pivot pellets, which were felt to be harder than the larger pellets. The settling velocity at 1010 kg/m³ was 0.081 m/s while at 1024 kg/m³ the velocity decreased to 0.072 m/s. The Glen Forrest pellets also show a decrease in velocity with an increase in density, although the velocity seems to be a little high at a density of 1022 kg/m³.

It was expected that the drag co-efficients, C_d, would be slightly above 1, and this was seen in a number of the trials. But some of the trials had average values less than 1. It should be noted when looking at the co-efficients that the maximum volume and area
were used in the calculations, as well as being used to determine the density. The final diet shown in Table 5 reveals strange trends due to strong variations in the pellet behavior, with a number of the pellets floating. Although the floating pellets were discarded, the high variability in pellets led to the negative drag co-efficients when results were averaged.
5.3 Faecal Pellet Velocities

There was some difficulty in collecting the faecal pellets intact, however, the results were that the faecal waste put in the settling column had settling velocities between 0.6-2.8 cm/s. This was below expected values of between 4-6 cm/s recorded for Atlantic Salmon (Chen, Beveridge & Telfer 1999), and possible reasons for this are put forward in the discussion.

<table>
<thead>
<tr>
<th>Tank</th>
<th>Waste Density (kg/m³)</th>
<th>Feed type</th>
<th>Waste Velocity (m/s)</th>
<th>Std Dev. (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1353</td>
<td>45:22 3 mm</td>
<td>0.019</td>
<td>0.009</td>
</tr>
<tr>
<td>2</td>
<td>1222</td>
<td>45:22 4 mm</td>
<td>0.019</td>
<td>0.009</td>
</tr>
<tr>
<td>3</td>
<td>1121</td>
<td>45:22 4 mm</td>
<td>0.020</td>
<td>0.008</td>
</tr>
<tr>
<td>4</td>
<td>1301</td>
<td>45:22 5 mm</td>
<td>0.014</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Faecal sizes and weights were not recorded before placing in the settling column due to the difficulties in performing this. Sieving of the some samples showed the faecal matter collected had low uniformity and there were many size classes present. This led to large standard deviations in the results that led to insignificant differences between the tanks. The collected waste would also flocculate together and these would fall at a rate at least twice as fast as the other particles depending on the particle size. The flocculating particles had settling velocities close to those reported in past papers.

Due to the lack of confidence in the results for faecal matter velocities, these were not used in the program. Settling velocities from the lower end of reported velocities were used in the program instead. However, if the lower values observed here are further verified, they will be included in the program at a later date.
5.4 Solid Dispersion

The solid dispersion output can be viewed in a number of forms; either as matrix outputs from the model, by comparing a number of line graphs (Figure 16) or by visualizing the colour grids. The colour grids are the easiest form of visualization, especially with oscillating currents. With the other methods, the user has to mentally manipulate the loading amounts with the daily distances dispersed, which makes it difficult to determine where problem spots may occur due to accumulation. The following outputs are from performing the snapper trials outlined in the method in water temperatures of 18 °C for a growth period of 220 days, although the colour plots only show one month of the data.

Figure 16 Plots of the solid faecal waste, solid feed wastes and distances dispersed

The plots in Figure 16 show the amount of C,N, and P leaving the cages as solid feed and faecal waste per day. It can be seen that the amount of wastes increase through
the growth period, with the highest loadings at day 220 (Figure 16). An idealised situation of varying currents is shown in the third plot, which relates to run 5 in the trial runs. The colour plots for trial 5 are shown later (Figures 24 & 25). The colour plots show the distance and the loading of C per metre for the first month of growth.

![Daily waste loading grid](image)

**Figure 17 Daily loading and dispersion of C for trial 1**
( uniform currents of 0.4 m/s at a 10 m site with 14000 fish in a 10 m wide cage)

Cages in areas with uniform currents will have the nutrients dispersed to the same area each day as is seen in Figure 17. The amount of leftover food and faeces dispersed slowly increases over the period due to more feed being needed and more waste coming from the farms. The feed waste is heavier and will fall at around 50 m from the cages at a rate of 0.05 kg/m/day. The faecal matter is lighter and travels 100 m before reaching the bottom. The loading rates are slightly more for the faecal wastes than for feed wastes as the wild fish population is consuming 90 % of the unconsumed food.
Figure 18  Cumulative loading and dispersion of C for trial 1
( uniform currents of 0.4 m/s at a 10 m site with 14000 fish in a 10 m wide cage)

The cumulative loading shows that there will be an accumulation of wastes at set
distances from the cage. As was shown in Figure 17, the faecal waste falls between
100-110 m each day. As the waste falls at the same point, there is an accumulation of
C at these sites to over 1.5 kg/m in the first month at the worst affected spots. The
feed waste accumulates at 50 m and the faecal waste, which is lighter, accumulates
from 100-110 m down current from the cages.
The plot for trial 2 is similar to trial 1 except the effect of a lower current speed can be observed (Figure 19). The distances dispersed have been reduced to 12 and 25 m from the cage points, as opposed to 25 and 100 m previously. Nutrients are dispersed up to 35 m on the grid due to the positioning of the axis with respect to the cage, which means some nutrients travel the distance dispersed plus the cage width. The distances dispersed are four times larger as the current was reduced by 75%. The loading values are the same in the two trials as the same amount of fish are being fed and there is the same discharge per metre.
Figure 20 Cumulative loading and dispersion of C for trial 2.

( uniform currents of 0.1 m/s at a 10 m site with 14000 fish in a 10 m wide cage)

The pattern seen in the cumulative loading is as expected and can quite easily be derived from looking at Figure 19. Once again, there is an accumulation of carbon at 2 distances from the cages, which is due to the different settling characteristics of faecal and feed wastes. The amount of loading is the same as in Figure 18 but at positions closer to the cage.
Stocking density has a large effect on the waste loadings coming from farms, with a linear relationship between density and waste loadings. The distances dispersed that are seen in Figure 21 are the same as for trial 2. The loading amounts are 5 times larger though as the stocking density has increased from an initial density of 1 kg/m³ to 5 kg/m³, which also means that feed inputs are increased 5 fold. From a comparison of Figures 21 and 19, it can be seen that the program reflects a change in the stocking density in the loadings it predicts. Although a somewhat straightforward observation, it was a result that had to be verified from the model to prove the models usefulness.
Figure 22 Cumulative loading and dispersion of C in trial 3
(uniform currents of 0.1 m/s at a 10 m site with 70000 fish in a 10 m wide cage)

The plot for C in Figure 22 shows that over 7 kg/m of C is being deposited from the cages per day to the surrounding marine community. This is expected due to the high numbers of fish, the low current speeds and the shallow depth. Generally, the stocking densities for cages is limited due to the environmental risks. Organic loading of 7 kg in a month per metre will cause problems in many marine environments. It should be observed that the final loading values are 5 times higher than for trial 2, which had 5 times less fish.
The daily plot for trial 4 is not shown, as it is quite similar to previous daily plots. However, the linear relationship between distance dispersed and depth is evident in Figure 23 of the cumulative waste. The depth was doubled from the 10 m used in trial 3 and the distances dispersed doubled. The loading pattern per metre remained the same. The comparison between Figure 23 and 22 shows that wastes will be dispersed further away from cages at deeper sites, but these effects are irrelevant to the loadings at sites with uniform currents, where the wastes will accumulate at the same spot each day.
Figure 24 Daily loading and dispersion of carbon in trial 5.
( oscillating current to 0.1 m/s at a 20 m site with 14000 fish in a 10 m wide cage)

Figure 24 is the first example of a trial under oscillating currents. Once again it can be seen that the loadings each day slightly increase over the period. It can also be seen that the wastes are dispersed to different regions on different days, which relates to the changing current speeds at feeding throughout the growth cycle. The width of the band coming from the cages each day is the same as before, but the positioning of the wastes changes each day. When looking at this figure, it may be difficult to determine where the maximum accumulation will occur.
Figure 25 Cumulative loading and dispersion of carbon in trial 5. (oscillating current to 0.1 m/s at a 20 m site with 14000 fish in a 10 m wide cage)

Figure 25 identifies the regions where the organic loading is likely to accumulate quickest around the cages. A region of intense loading can be seen at 52 m from the cages, due to the overlapping of the daily dispersion. An extra region of intensity is also found where the feed and faecal wastes overlap. This can be found at around 23 m from the cages. A significant difference between Figure 25 and earlier plots is that the majority of sediments around the farm feel the extent of the wastes to some degree, however, the most intense loadings seen are smaller with oscillating currents than uniform currents as the waste is dispersed over a wider region.
Comparing trials 5 and 6 shows the effect of the cage width on nutrient loadings. The band of nutrients coming from the cages has increased from 10 m wide to 40 m (Figure 26). This means a larger area of sediments will be affected. The stocking density is the same and so the faecal matter per metre of cage is the same as in Figure 24. However, the amount of feed being added to the cages is not the same and has increased. It is possible that the assumption of a single feeding source may not be true for larger cages in which case the program will need to be modified to include multiple feeding points. This will reduce the loading of the feed wastes per metre and increase the number of lines seen on the daily plot in Figure 26.
Figure 27 Cumulative loading and dispersion of carbon for trial 6
(oscillating current to 0.1 m/s at a 20 m site with 70000 fish in a 40 m wide cage)

Once again there is an accumulation of carbon at two regions from the cages. The
most intense region is near 60 m. Although the faecal wastes in the previous plot
showed relatively small loadings compared to the feed amounts, the effect of the
overlapping faecal matter is seen in Figure 27. As the band of faecal waste overlaps
itself each day, the cumulative amounts increase significantly. Using a wider cage but
with the same stocking density is similar to having a number of smaller cages side by
side.

The C loading is most intense around 50 –60 m from the cages. The more accurate
ability to determine trouble areas from the cumulative plots highlights why they are
preferred for viewing. If someone views Figure 26 alone, they may believe the feed
waste would cause the most problems and not look for cumulative problems at 50 - 60
m away.
Figure 28 Daily loading and dispersion of C for trial 7
(oscillating current to 0.1 m/s at a 20 m site with 70000 fish in a 40 m wide cage with grazing reduced to 0.5)

Figure 28 highlights one of the assumptions that is made in the program relating to the start point of the feed and faecal wastes. It was assumed the faecal waste is evenly distributed from the width of the cages, and that the feed only exits from a single metre of the cage. This has implications on the colour plots for large cages as the width reduces the loadings to an amount much smaller than the feed waste and so the faecal wastes are hardly visible on a daily plot.
The cumulative diagram shows the extent of the faecal matter much clearer and shows that there will still be a significant accumulation of C due to the faecal wastes, although the area with the greatest interaction with the feed waste has the highest loading per metre. This shows the significance that leftover feed can have on the nutrient dispersion from cages.
It was assumed that stratification affects the waste by decreasing the current speed and settling velocity. The currents were reduced by 50% in the lower layer for the above run and the settling velocity was reduced by approximately 5% from the surface layer. The resultant is that wastes will fall closer to the cages, as the current speed has been reduced by a larger factor than the settling velocity in the above case. However, if the current velocities are similar between layers and the change in settling velocity is significantly lower due to denser water, the solids will be dispersed further away.
5.5 Dissolved nutrient dispersion

The extent of determining the dissolved dispersion of nutrients from the cages is minimal. However, the program was structured to determine the amounts of dissolved wastes coming from the cages per day as C, N and P, with this data plotted as an output as well as being saved in a “.dat” file for each nutrient. This structure was set so that the outputs determined from the program for dissolved nutrients can be imported and modelled in a hydrodynamic driver like ELCOM.

![Graph of accumulated dissolved nutrients](image)

![Graph of daily dissolved nutrients](image)

Figure 31 Plots of the accumulated dissolved nutrients from run 1 and daily discharges to the environment in kg of C, N and P for a 700 m³ cage from day 0 to 220.
The currents going through the cages will disperse the dissolved wastes. Proper analysis using these numbers was not possible, as there was insufficient time after the Matlab model had been completed to get ELCOM working sufficiently. An example calculation as shown in the background section will be repeated here for the outputted results.

The cross-sectional area of the cages to the currents is assumed to be 70 m and the current speed is 0.4 m/s. The channel is assumed to be 200 m long, 100 m wide and 20 m deep. The flow rate can be determined from the velocity and area to be 28 m³/s. A $K_y$ value of 0.05 m²/s is assumed (Lewis 1997). Concentrations at 50 m and 100 m downstream are approximated:

\[
t = \text{distance travelled} / \text{velocity}, \quad \text{(time to get to monitoring point)}
\]
\[
t(50 \text{ m}) = 50 / 0.4 = 125 \text{ s}
\]
\[
t(100 \text{ m}) = 100 / 0.4 = 250 \text{ s}
\]

\[
W = 5.7(K_y^{0.5})(t^{0.5}), \quad \text{(width of plume)}
\]
\[
W(125 \text{ s}) = 14.25 \text{ m}
\]
\[
W(250 \text{ s}) = 20.15 \text{ m}
\]

\[
A(t) = \text{width} \times \text{depth}
\]
\[
A(125 \text{ s}) = 285 \text{ m}^2
\]
\[
A(250 \text{ s}) = 403 \text{ m}^2
\]

\[
C(t) = \frac{Q_{\text{input}}}{\text{velocity} \times A(t)}, \quad \text{(concentration downstream after traveling time t)}
\]

It is seen that the concentrations are near 1.8 kg/day at the end of the production cycle, $Q_{\text{input}} = 1.8 \text{ kg/day} = 0.02083 \text{ gm/s}$.

\[
C(125 \text{ s}) = 0.18 \text{ mg/m}^3
\]
\[
C(250 \text{ s}) = 0.13 \text{ mg/m}^3
\]

This example shows that concentrations decrease as the currents disperse the nutrients downstream. A lower velocity will result in a longer time to reach the same monitoring point, which will cause a larger width of plume. However, the time factor
in the width equation is to a function of 0.5, which reduces the increasing effect of the plume. The dominance of the smaller velocity in the concentration equation means that higher concentrations are seen at the same distance from cages at lower current speeds. If the current speed is reduced from 0.4 m/s to 0.1 m/s, the concentration at 50 m increases from 0.18 gm/m³ to 0.36 gm/m³.

The results from using a tracer in ELCOM were very preliminary and are not worth showing although they did highlight the possibility of using ELCOM for this purpose. Further verification of this will need to be performed.
6.0 Discussion

6.1 Fish Growth
The model has a number of benefits compared to the Excel model when looking at fish growth. The ability of the program to automatically produce charts for a range of factors on a daily basis may be taken for granted until the Excel model is used. Plots of daily growth can be made from the Excel charts but these are not automatic, and a number of the plots shown from Matlab can not be calculated in Excel because it does not have values over the entire period.

Another use of the growth outputs is to determine the time of growth or number of fish to reach a set level. The benefits of this program are that graphs for extended runs can be produced and the day that the prescribed value is reached can be recorded and then used for the model runs. The Excel model can be used for similar purposes, although, the user would have to keep changing the numbers until the desired result was achieved. This other method is not considered as simple as looking at a graph to determine the optimum time of growth and other factors.

The visualization of the biomass gained in such a graphical form may be able to be used to determine when the stock should be harvested. If the stock should be harvested at 2500 kg of biomass, this time can be determined from the graphs. An extension of this idea may overlap a profit curve based on input and output costs at different times of the growth period. This would probably involve the inclusion of economic considerations into the program.

6.2 Settling Velocities
The results obtained from the feed pellet velocities were as expected and consistent with other results. There is still a lack of proper classification of feed pellet properties to predict velocities, partly due the variability in the pellet shapes and sizes within each batch and the lack of testing across the range of pellet types. Further trials in a wider range of water densities may also give a better idea of pellet characteristics such as drag co-efficients.
The faecal matter was somewhat more difficult to determine velocities for. The first difficulty was in determining the correct way to collect the faecal waste. Due to the time restriction of waiting around the tanks to collect freshly evacuated faeces and the need to kill fish to gather waste from the guts, collecting waste from sedimentation was the only method used.

The waste was collected overnight in a tube beneath the cages. It was assumed that the microbes had broken down the waste into smaller particles while they were in the collection tube, which would range in time periods up to 16 hours. This was due to the fish consuming the largest proportion of the feed in the afternoon feeding period, which meant the majority of wastes were excreted in the middle of the night. Due to the fish needing about 6 hours to pass the food, most food was probably in the tube for 10 hours or less, which would still be sufficient for microbial activity. Further degradation of particles occurred during collection from the tube. As the wastes were in water, a sieve was used for collection. The pressure of the water during sieving and the draining of excess water affected the particles. Future tests may attempt to collect the waste while keeping it immersed, and then scooping faecal pellets from the water sample containing the faeces and putting them directly into the settling column.

Another possible reason for the lower velocities may be due to the fish species being used. Snapper have characteristically small mouths compared to many of the fish in the northern hemisphere for which faecal settling velocities have been calculated. This and other biological differences may impact on the size of faecal pellets being expelled from the fish. It has been seen that different fish show varying composition in their solid waste excretions, with some species having waste that is less solid (Felsing pers. comm.).
6.3 Waste Discharge, Dispersal and Loading

It can be viewed by the outputs of the trial runs that the model is working accurately within its current assumptions. When the current or depth was reduced, the distance dispersed was less. When there were more fish, there were more wastes. These results were anticipated and hence verify the framework constructed. There is definitely a number of areas where there can be some additional improvements. Apart from the carbon, the loading of solid nitrogen and phosphorous to the sediments can also be put into colour plots.

The distribution of faecal waste will be greater in the real environment then predicted. This will be due to the range of sizes seen in the faecal matter coming from fish and the fact that only one size class is currently modelled in the program. An accurate description of the relative percent and sizes of faecal waste will lead to the wastes occurring over a larger area.

The current velocities in the model are not straight-forward. Rather, the current velocities in the matrix are only for the time of feeding. As stated earlier, the trial runs used an idealised situation. To model real currents, the current speeds will need to be determined for each time of feeding. This may be done by taking the current velocities for each hour for the entire period and taking out the data relating to the time of feeding each day.

Is it better to grow the same amount of fish in a larger cage at a smaller density or to use a smaller cage and a higher density? The results show that increasing the density will increase the organic loading to the sediments and does not change the extent of distribution. However, larger cages mean that the waste will be dispersed over a larger distance and the loading will be reduced per metre. To decide which option is better a criteria needs to be established. The criteria chosen to determine the better method was that the better method would have less chance of having surrounding sediments turn anoxic. Obviously, if the same amounts of fish are raised then a larger cage will disperse the wastes over a larger distance and the loading will be less per metre. Therefore, there will be less chance of sediments turning anoxic and so it is author’s
views that lightly stocked, larger cages will be more environmentally friendly than smaller, heavily stocked cages.

6.4 Dissolved nutrients
It was important to determine the dissolved carbon, nitrogen and phosphorous. The relative importance of each of these nutrients on aquatic ecosystems depends on the type of system being considered. Considering snapper will be grown in marine environments, nitrogen may be considered the most critical for minimizing environmental impacts, as marine environments are often nitrogen limited. For trout production using cages in freshwater lakes or ponds, carbon and phosphorous may be more important.

The dissolved dispersion needs the greatest amount of work to be performed, as the dissolved results do not tell us much at the moment. The consideration of the dissolved nutrients will be much more important in semi-enclosed and enclosed areas than open areas. The retention time of particles in enclosed areas and the reactions they undergo will play a significant part.

6.5 Recommendations for future work
It is acceptable to model the feed dispersion using the currents at the time of feeding, but the lag between feed consumption and waste excretion may lead to a change in the currents before faeces are expelled. A modification needs to be made to allow for this time lag, which is approximately 6 hours, although it will vary depending on a number of factors. If the currents are constant, then the modification will be irrelevant as the currents do not change. To perform the modifications, the user may wish to add an additional current speed column that shows the expected currents at the time of faecal expulsion. As the faecal wastes and their distribution are determined before being entered into the grid and in a separate column this modification will not be difficult.
The model does not accurately reflect the vertical current profiles that affect the solid wastes. As many water bodies show large variation in vertical currents, the vertical profile is an important factor to include in the model to determine the true distribution of wastes. It should be possible to take the approach used for the two layered, stratified system and to increase the number of layers enough to reflect the current profile. Once again, this modification will only see minor alterations to the program.

The model could be adapted to include the bathymetry of sites, instead of using the average depth. Deeper holes or shallower regions will influence the distribution of solid and dissolved wastes. The solids will sink until they hit a physical barrier or an area of equal density. Objects in the water will also affect the water flows and hence the dissolved nutrient dispersion. How this will be performed with the current framework is unsure. If it cannot be modelled, the structure of the output data may need to be changed to include this. Hopefully the addition will be possible to the current framework being used in the model.

Another possible inclusion is the addition of an extra dimension into the solid waste grid and having currents that change in the x and y directions. An approach to this may include the proponent of the current in each direction with the distance travelled by the waste in each direction recorded in separate matrices and then combined to determine the position within the plane. The grid formation will be altered to build a colour plot for each day in a 2-D format. The results for each day can then be used to form a movie of the solid waste dispersion over the period.

The resuspension of sediments is quite a major factor in the settled solid distribution. Shearing effects lift the particles from the bed or carry them along as bed load. These effects should not be ignored although they have been up to this stage.

A future step is to identify and include the remaining factors that affect the nutrient dispersion that have not been listed above. These include factors such as phytoplankton uptake, respiration, denitrification and other marine and freshwater processes. Many of these processes are particularly important to dissolved concentrations. The main focus of this project has been on the solid wastes, as these
are of most concern in open marine environments. But the role of the dissolved nutrients will have a greater affect in enclosed areas or lakes. In these areas the effects of the dissolved nutrients may need to be modelled as they may stimulate algal blooms. To determine the possibility of this will need coupling of ELCOM and CAEDYM and the use field trip data collected from around the sites to calibrate the models.

7.0 Conclusions

Aquaculture is a growing industry with a need for scientific models to assess the environmental and economic benefits of aquaculture developments. This was an initial attempt to develop a model to give estimates of the waste loading and dispersion for aquaculture cage ventures in Western Australia. With aquaculture expected to be worth $600 million in this State by 2010, it probably will not be the last attempt. Key components of any such model will be diet, species and site specifications.

This initial model is not yet at a stage that could accurately predict dispersion in a 3-D situation where the currents change in the x, y and z directions, but the model can be used in situations where the site is simplified to 2 dimensions and the associated assumptions are recognised when viewing the outputs. If the model is used like this it should give the relative distances the wastes will fall but will not distribute the wastes radially around the cages. This will lead to an over-estimate of loading amounts per metre in the model as in the field there may be a circle of waste at 50 m, which would cover an area of the circumference. The 2-D situation will only put the wastes at ±50 m and the concentration will be at a level 0.5*circumference higher at these points compared to having a circular band of waste around the cages. By looking at the site currents, an analysis could be made to determine how much of a circumference your wastes are going to be spread over in the real world and this amount could be factored back into your results to correct for going from a 2-D to a 3-D situation. The lack of transformations from the solid to other forms in the program will also lead to an over-prediction of the solid waste loading.
It is the author’s view that an over-prediction in determining the environmental loads has benefits. If the farm designs are based on an over-prediction of wastes, there will be less chance of environmental damage. If the model is used to determine the maximum size of cages and number of fish while staying under a set limit of carbon deposition around the cages, the program will predict smaller cages and less fish will achieve the levels than what may actually be possible.

There is still more work that needs to be performed, as outlined in the discussion. This work includes determining the feed and faecal pellet settling velocities and drag coefficients. Preferably, settling velocities for each size class of the feed pellet types will be calculated. Trials will then need to be run using the different diets for each species, with the waste collected and faecal matter velocities determined. The current study only determined the faecal velocities from 2 size classes of pink snapper fed a 45:22 diet with 3 different sized pellets and the results were not that good. The other diets will need to be tested with the snapper, and all the diets tested for barramundi and trout. If more species are to be added to the model, faecal settling velocities will also need to be collected for the new species.

As stated in various locations of this report, the results from this program have the potential to be used by a number of people in slightly different ways. The most obvious use is for determining the loading for potential sites recognised by the aquaculture industry. The model shows that there can be considerable accumulation of wastes around cages, although it is probably an over-predictor. However, if the model is further refined and verified it can potentially be used against the cage industry. If the C loadings are compared with accurate C turnover rates in an area, it may be shown that cage culture to densities that meet economic merit are not environmentally feasible. As cage aquaculture is the most polluting and potentially carries more ecological threats such as fish escapes than from other forms of aquaculture, limiting cage production may be a positive step and welcomed by other aquaculturalists who use better, but more costly, systems that limit their waste discharges to natural environments.

The model may also have positive uses. The model developed from this project will potentially be used in management strategies for the rehabilitation of coal-mines or
areas lacking organic material. If suitable growing conditions can be achieved in the coal-mines, rapid organic loading can be achieved. The possibilities of this can be seen in the program. The stocking densities modelled earlier are similar to what the industry would attempt in a natural environment. However, the densities that would be used in a rehabilitation project would be considerably higher, although this will require aeration devices near the cages to keep the water saturated with oxygen. The organic rich solid wastes from the cages will be dispersed to the bottom. The dissolved nutrients may also stimulate algal blooms, which is an important mechanism of converting the dissolved wastes to solids. When the population crashes, there will be further organic loading to the sediments.

In conclusion, the program has fair potential for commercial use, considering it is the only model of its kind presently being used in this state. The author plans to perform some of the modifications to the program in the coming months whilst undertaking a review of the local industries need for such a tool. After this period, the extent that the model will be further developed by the author will be known.
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