A comparison of suspended particle size and sediment loading produced by artificial and seaweed diets in integrated flow-through and re-circulating aquaculture systems on a commercial South African abalone farm.

Applied Marine Science Course-work Masters Degree: Mini - Thesis.
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1. Abstract

The future of abalone farming in South Africa may provide benefits by the integration of abalone-seaweed re-circulation systems. This is a new system design of abalone fed on a kelp diet integrating seaweed culture facilitated by a re-circulation system. This kind of culture has the potential to increase abalone growth through increased water temperature, minimizing pumping costs while also incorporating production of on-farm seaweed resources. It has, however, the potential disadvantage to increase the suspended particulate concentration in the tank environment, with subsequent negative effects on abalone health.

This study ties in with an existing Swedish-South African joint project the results of this study will be used as inputs when trying to model a complete commercial re-circulated abalone farm. Divided into two experiments this study records suspended particulate matter, particle size range and water nutrient concentrations (phosphate, ammonium and nitrite). The first experiment investigates abalone tank water of three different diets (Abfeed™, Kelp, Mixed algal diet) fed to abalone in a flow-through tank system as compared to a 25% re-circulation system (abalone fed a kelp diet). The second experiment compares the build up of suspended particulate matter and nutrient concentrations over a 7 day cleaning cycle in a 25% re-circulation system verses a flow-through system. The first study tests the hypothesis that if Abfeed™ or a mixed diet (Kelp, Gracilaria and Ulva) should generate more suspended particulate matter and nutrients compared to a kelp diet, as well as the hypothesis that re-circulation system increases suspended particulate matter and sedimentation in the abalone tanks. The second study test the hypothesis that total particulate loading from abalone farms are significant and that this is, compared to dissolved nutrient release, the main effluent from abalone farming. Suspended particulate matter may impact negatively on abalone growth, both farmed and wild, either directly or through the stimulation of the parasitic sabellid occurrence by increased particles within the sabellid feeding range. Past research concludes that abalone diet is important in influencing infestation level and size of the sabellid worm. This study showed that an Abfeed™ diet produces a high particle load in the water column, with the largest proportion consisting of 20-30μm particle *sizes while a mixed diet produces particles of 30-40µm size. Since the sabellid feeds on particles smaller than 35 µm it would suggest that an Abfeed™ or mixed diet produces the ideal particle size range for the sabellid worm, and the mixed diet as well as the Abfeed™ increase sediment loading in the tank compared to the kelp feed. There was a significant difference in the phosphate concentration of the three diets. Mixed diet was significantly lower compared to Abfeed™ diet and the re-circulation system. There was no significant difference in the nutrient concetrations of the re-circulation and flow-through system. There was also no significant difference in the particle concentrations between the flow-through system and the re-circulation system. The daily build up of particle concentration in the flow through system was not significantly different from the re-circulation, but the re-circulation system showed a significant difference over the seven day cleaning cycle from day to day. This study provides abalone farmers with useful data in terms of potential pollution problems from abalone effluent waters. This study also provides evidence to show that a shift from a flow-through culture system to an integrated 25% re-circulation system farm will not result in deterioration of tank water quality. Future studies should focus on how seasonality affects the build up of sediments and particulate concentration in the water column of the tank system.*

2. Introduction

Global Aquaculture

The global aquaculture industry contributes 30% to the total food fish production (36 million tons, net value of US $ 52 billion, 1998) (AASA, 2004). Over the past two decades there has been an increase of more than 40% in world aquaculture production with the increase in demand and stagnant supplies from capture fisheries (FAO, 2004). Africa contributes 6% (570 000 tons) of total world catch while South Africa contributes 9% of the 6% to Africa and 0.5% to total world catch. Aquaculture plays an important role in the future supply of food as most of the world's fishing areas have reached their maximal potential (Naylor *et al*, 2000; Troell *et al*, 2003). In light of the continued growing world population the need to expand aquaculture production is further stressed, as the demand for seafood continues to increase. Today 90% of aquaculture is practiced in developing countries. For marine environments, 44% is seaweed production, 46%

molluscs, 8.7% fin-fish farming and 1% is farming of crustaceans (FAO, 2004). Although abalone cultivation only contributes a small proportion of world aquaculture, it generates high export earnings due to its high commercial value (AASA, 2004). The export markets include Asian countries such as China, Japan and Korea, where it forms part of traditional cuisine (Sales & Britz, 2000; 2001).

Aquaculture in South Africa

South Africa's aquaculture production has shown a marked increase over the past decade. Total production and value has increased from 3 000 tons (R51 million) in 1997 to 4 030 tons (R146 million) in 2000. This reflects an increase of 31% in weight and 35% in value from 1997 to 2000 (AASA, 2004).

The South African commercial abalone species, *Haliotis midae* (Donovan), is found naturally along the rocky shore coastline from Cape Columbine to Quoin Point (Tarr, 1989). The over-harvesting of wild abalone and high market value has resulted in the rapid development of farming in the late 1980's. A study by Genade *et al,* (1988) showed that abalone growth rates and food conversion efficiencies were sufficient enough to make farming profitable. When compared to other aquaculture species, abalone have less potential for damaging the ocean and coastal resources (Naylor *et al,* 2000). Since abalone are herbivores they do not depend on fishmeal and fish oil inputs, and this results in less nutrients being discharged into the local environment. Today there are 22 commercial abalone farms in South Africa (D. Robertson-Andersson pers.com; AASA, 2004), which feed the abalone kelp and an artificial diet. These farms have an estimated investment of R346.5 million, with productions of 527 tons in 2003 and 700 tons in 2004 (D. Robertson-Andersson pers.com). Due to over fishing of natural stocks and illegal poaching the demand for abalone has risen. In 1997 the authorities attempted to curb the exploitation by implementing Total Allowable Catches (TAC) (Cook, 1998). All farmed abalone are exported mainly to Japan. Producers sell their abalone at sizes between 80-100mm which is smaller than the minimum legal harvestable size of 11.43cm (Cook, 1998). Since December 2004 the recreational abalone season has been closed till further notice (DEAT, 2004). The export ensures that there is less illegal harvesting of under sized abalone, as there is a constant reliable supply of cocktail abalone which cannot be guaranteed by the illegal harvest. A farm takes 5 years to become established by which time it reaches full production. Adult abalone brood stock is caught in the wild and maintained in conditioned tanks. After spawning the larvae settle on plastic plates (a method adopted from the Japanese) and are fed a benthic diatom diet (Matthews & Cook, 1995). After 7 – 12 months they are fed an artificial diet to help with the transition to a kelp diet. After 5 years they reach 100mm of shell length (Sales & Britz, 2001).

Artificial Diets

Development of artificial diets are an active area of research in South Africa. Although most of the South African farms are situated on the southwestern coast where there is an abundant supply of kelp, the abalones' natural and preferred diet. However, artificial diets are becoming more popular. Formulated fish feeds provide a secure and guaranteed nutritional value (Britz, 1996; Britz & Hecht, 1997; Cook, 1998; Sales and Britz, 2001). This has the disadvantage to the farmer of being dependent on external fish production. Although there is an abundant supply on the southwestern coast, the demand for kelp in abalone farming is rapidly increasing. Anderson (2003) showed that seaweed Concession Area Six (SCA6) reached its maximum sustainable harvest (MSY) in 2002, and other areas are also approaching their MSY. An alternative to kelp harvesting is the cultivation of seaweeds such as *Gracilaria* and *Ulva* on the abalone farm, and this has proved to be successful on a smaller scale at the Irvine & Johnson Mariculture farm, in Gansbaai (Evans & Langdon, 2000; Robertson-Andersson, 2003).

Formulated feeds when compared to natural sources offer convenience and cost benefits to farm management (Britz *et al*, 1994). The requirements of abalone feed maintain that the water soluble nutrients remain in the feed and that the food particles remain bound together for at least 2 days (Flemming *et al*, 1996). A starch-bound dry pellet was developed in the early 1990's (Britz et al, 1994) and leaching of this pellet was 5% over 24hrs (Britz & Clayden, 1996). This was more cost effective than previous feeds, and it was shown that formulated diets produced a significantly better increase in shell length and weight in juvenile (5.00-8.54mm shell length) *H. midae* than gels (Knauer *et al*, 1995).

Integrated Aquaculture systems

Methods for using seaweeds for treating effluents from enclosed land-based mariculture systems were introduced in the mid 1970's (Haines, 1975). Waste nutrients are considered in integrated aquaculture as a resource for the auxiliary culture of plants (Chamberlane & Rosenthal, 1995). Edwards *et al,* (1988) defined integrated farming as where 'an output from one subsystem in an integrated farming system, which otherwise may have been wasted, becomes an input to another subsystem resulting in a greater efficiency of output of desired products from the land/water area under a farmer's control'. Closed re-circulation systems with bacterial filter units are being used on some abalone farms in South Africa. The disadvantages of such a system are that they are costly and rather complex. *Ulva* and *Gracilaria* are some of the most commonly used biofiltration organisms in South Africa for the purposes of integration (Robertson-Andersson, 2003). They are safe for human consumption and are used as feed for macroalgivores such as abalone and sea urchins (Neori *et al,* 2004). These seaweeds have high nutrient uptake capacities and industrial culture technologies for their production are well known (Martinez-Aragon *et al*, 2002). The integration of abalone-seaweed re-circulation systems could bring many benefits for the abalone industry in South Africa. Preliminary results from small-scale re-circulation experiments, carried out on some South African farms, show promising results (Anderson, 2003). An experimental system to test the efficacy of re-circulation is in use at the Irvine & Johnson Mariculture farm in Gansbaai.

The potential benefits of these re-circulation systems include the following:

- They allow the farm to be less dependent on continual seawater input,
- They are less vulnerable to other coastal environmental factors such as HAB:s or oil spills,
- Pumping coast are decreased,
- Re-circulated water is of higher temperature which has a positive effect on the growth of abalone and seaweeds, and
- These systems release fewer nutrients into coastal waters.

The system employed at I & J farm is a new system design of abalone fed on kelp diet integrating seaweed culture facilitated by a re-circulation system. This kind of culture has however the disadvantage to potentially increase the particulate concentration, with subsequent negative effects on abalone health.

The future of abalone farming in South Africa is very promising and of crucial importance. Re-circulated farms with low external inputs can provide a high value product to a demanding market, employment for local people with a sustainable and economically sound alternative to exploitation of wild stocks.

Problems experienced on South African farms

Toxic algal blooms occur frequently on the south African west coast and it affects many organisms negatively, especially filter feeders like bivalves. Although abalone are not filter feeders, in hatcheries where the water has not been filtered sufficiently, they have experienced mortalities due to toxic algae (Cook, 1998). The toxins attach to epipodia and render the abalone unsellable in live form but may be sold at a lower price in canned form (Joyce *et al*, 2005; Botes *et al*, 2003).

The parasitic sabellid worm (*Terebrasabella heterouncinata*) has been known to cause problems in Californian farms as well as in South Africa. It is widespread in South Africa and infests a range of host gastropods, which lead Cook & Ruck (1998) to believe that it was endemic to South Africa. The worm was accidentally introduced to California by abalone farmers intending to experiment with cultivating the South African abalone species *H. midae* (Kuris & Culver, 1999). The sabellid is associated with high stocking densities and poor water quality in aquaculture farms (Chalmers, 2002). An improvement in water quality conditions of these farms has decreased the occurrences of infestations. But as this worm occurs naturally in most mollusc species it will never be completely eradicated. However, research has shown that good farm design and animal husbandry can reduce these infestations and keep the infestation levels low (Chalmers, 2002).

Farmers have noted higher infestation rates on Abfeed™-fed abalone and it is suggested that the diet could be an important factor causing these high infestation levels (Chalmers, 2002). High stocking densities have also been identified as factors influencing infestation rates (Oaks & Fields, 1996). To investigate the feeding behavior of this parasitic worm, particle size class experiments from abalone diets have been investigated. Particle size distribution of suspended solids present in kelp-fed and

Abfeed™-fed abalone raceways show that sabellid feeding follows no structured behavioral pattern for both diets (Chalmers, 2002). The sabellid worm is a filter feeder and sorts particles according to size distribution (Fitzsimons, 1965; Bock & Miller, 1997), and *T. heterouncinata* may be capable of changing its feeding pattern in response to changes in particulate composition and size (Chalmers, 2002). Chalmers (2002) showed that the quantity of suspended solids was greater in kelp raceways than in Abfeed™ raceways. However the protein and energy levels in the suspended solids were found to be higher in Abfeed™ raceways, with higher infestation levels of the worm. Sorokin (1973) suggests that sabellids concentrate on filtering small size range of particles which contain bacteria and small phytoplankton which constitute a greater portion of the planktonic biomass. Farmers have noted that Abfeed™ decomposes faster than kelp, and Chalmers (2002) speculates that the bacteria colonize the Abfeed™ and so provide a rich food source for the worm.

The first experiment investigates abalone tank water of three different diets (Abfeed™, Kelp, Mixed algal diet) fed to abalone in a flow through tank system as compared to a 25% re-circulation system (abalone fed a kelp diet). The second experiment compares the build up of suspended particulate matter and nutrient concentrations over a 7 day cleaning cycle in a 25% re-circulation system verses a flow-through system. The first study tests the hypothesis that if Abfeed™ or a mixed diet (Kelp, Gracilaria and Ulva) should generate more suspended particulate matter and nutrients compared to a kelp diet, as well as the hypothesis that re-circulation system increases suspended particulate matter and sedimentation in the abalone tanks. The second study test the hypothesis that total particulate loading from abalone farms are significant and that this is, compared to dissolved nutrient release, the main effluent from abalone farming. Suspended particulate matter may impact negatively on abalone growth, both farmed and wild, either directly or through the stimulation of the parasitic sabellid occurrence by increased particles within the sabellid feeding range.

3. Materials & Methods

To investigate how abalone will influence water quality in closed systems this study quantifies dissolved and particulate excretion. This study ties in with an existing Swedish-South African joint project (Bredberg, 2003; Robertson-Andersson, 2003), the results will be used as inputs when trying to model a complete commercial re-circulated abalone farm. This study contains two experiments. The first experiment, Part A, investigates the particle size range and water nutrient concentrations present in flow-through tanks containing abalone fed on three different diets (a). Abfeed™, (b). Kelp and (c). Mixed diet (kelp for three weeks and in the fourth week they are fed farm-grown *Gracilaria* and *Ulva*). Part B. compares sediments in a flow-through system (kelp-fed abalone) with a 25% re-circulation system (kelp-fed abalone). The second experiment investigates total sediment build up and daily water nutrient concentrations over a seven day culture cycle in a 25% re-circulation system (kelp-fed abalone) as compared to a flow-through system (kelp-fed abalone). The control for both these studies is the kelp-fed abalone. The system design is illustrated in Fig. 1. Each of these treatments in both experiments consists of 3 replicates of each treatment i.e. there are three Abfeed™- fed abalone tanks, three Kelp fed abalone tanks, three Mixed diet fed abalone tanks and three kelp fed abalone tanks in a 25% re-circulation system.

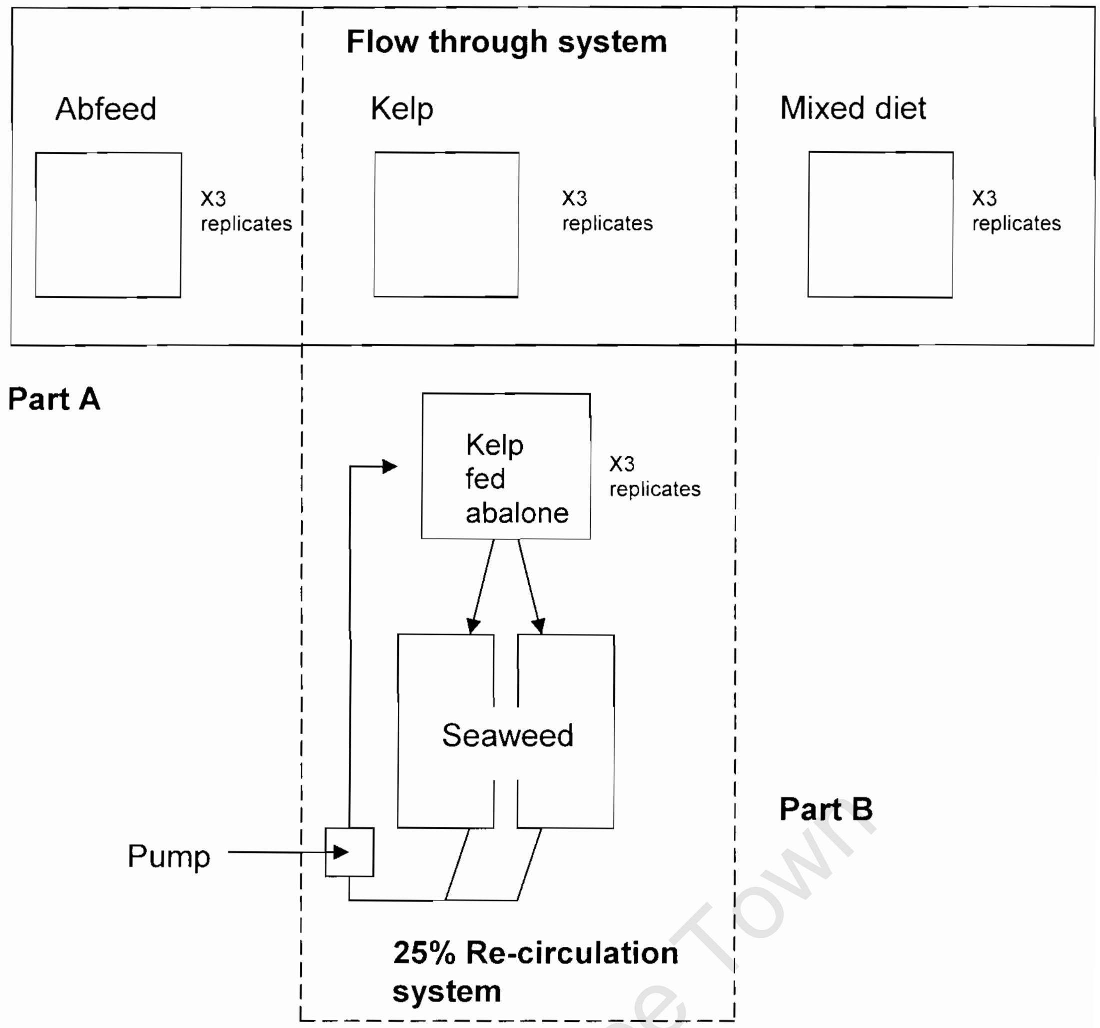

Figure 1: Set up of study. Experiment 1 consists of two parts part A and B, experiment 2 consists of essentially Part B run over a 7 day cleaning cycle. Note that the control for both experiments is the abalone fed on a kelp diet (total n=12).

The study was conducted at Irvine & Johnson Mariculture farm at Danger Point, 140km east of Cape Town. The farm opened in 1994 and research studies carried out by the University of Cape Town have been ongoing since 2000. The land based rows of abalone tanks line the coast, and are supplied with filtered seawater through a system of pumps. The most commonly used tank dimensions were as follows: 6.6 m (length) X 2.08 m (width) X 0.88 m (depth) = 12 000 l(volume), these concrete tanks undergo 4 volume exchanges per day and the bottom of the tank is v-shaped. The abalone are maintained on a diet of wild harvested kelp (*Ecklonia maxima*), but formulated pellets and on-farm cultivated seaweeds such as *Gracilaria* and *Ulva* are utilized as well. The abalone are exported live to Asian countries when reaching 70 g in weight. The farm exports about 120 tons of abalone per annum, at a value of US$35 per kilogram. The abalone in the treatments were 60-65mm is size, weighing 45-55g, with approximately 550 abalone in a basket. Thus there was around 660 kg biomass per tank. The Abfeed treatments were fed every Monday, Wednesday and Friday with 5 % feed ratio by body weight. This is approximately 33kg of Abfeed™ a week. The kelp treatments were fed every Monday with 60kg and each Friday with a top up feed of 30kg. The mixed diet treatments are fed 60kg of Kelp on Monday and 30kg of *Ulva* and *Gracilaria* on Friday.

Experiment 1:

Part A involves comparing the size distribution of suspended particulate matter from three different diets fed to abalone (Abfeed ™, Kelp and a Mixed diet), as well as the total sediment concentration (wet weight). Tanks were sampled over a four day period, and samples were taken from three locations in the tank; incoming water; water column (30cm from the surface) and bottom sediment samples. Samples for suspended particulate fractions and total suspended particulate matter were sub sampled from a 10L volume siphoned from the tanks. Whatman G/F Filter papers (25mm) of 1.0μ mwere used for syringe filtering and the larger (110mm) filter papers were used when filtering the particulate fraction samples. Filters were pre-ashed for 2 hours at 400°C and weighed. A volume of 5L was filtered through a series of mesh filters; 50, 40, 30, 20μm. The filtrate was then transferred to pre-weighed filters paper using de-ionized water. It was assumed that the use of distilled water did not decrease the filtrate and that is was necessary for removing salt. Three sub samples of 100ml were taken from the 10L sample and then syringe-filtered through 25mm Whatman Fiber Glass filter paper for analysis of total particle concentration. Samples were taken over a four day period. The cleaning cycle of the three different tanks had been displaced in time to facilitate for sampling three tanks per day (see Table 1).

Table 1: Sampling schedule

Tank	Number of tanks sampled	Experiment	Day cleaned	Day sampled
Abfeed	Three tanks	Experiment 1: week 1	Monday, 13 September 2004	Monday, 20 September 2004
Kelp	Three tanks	Experiment 1: week 1	Tuesday, 14 September 2004	Tuesday, 21 September 2004
Mixed	Three tanks	Experiment 1: week 1	Wednesday,15 September 2004	Wednesday, 22 September 2004
Recirculation	Three tanks	Experiment 1: week 1	Thursday, 16 September 2004	Thursday, 23 September 2004
Kelp & Recirculation	Six tanks	Experiment 2: week 2	Friday, 24 September 2004	Monday, 27 September 2004
Kelp & Recirculation	Six tanks	Experiment 2: week 2	No cleaning	Tuesday, 28 September 2004
Kelp & Recirculation	Six tanks	Experiment 2: week 2	No cleaning	Wednesday, 29 September 2004
Kelp & Recirculation	Six tanks	Experiment 2: week 2	No cleaning	Thursday, 30 September 2004
Kelp & Recirculation	Six tanks	Experiment 2: week 2	No cleaning	Friday, 1 October 2004

To be able to capture the sediment in a tank the water level was lowered by letting out only the top water layer. This was achieved by attaching a short drainage pipe in the outlet hole (at the bottom). This prevented the bottom water from leaving the tank. After reaching the height of the drainage pipe this was prolonged some centimeters by adding a shorter extension on top. This facilitated for capturing an additional water volume when the tank walls and baskets were cleaned using brushes and a high pressure hose. The remaining water volume after cleaning was about 400L. This water was then pumped into a large container, and from this three 20 ml sub-samples and a 5L sample were after vigorous mixing taken and handled as described for the water column samples. Outflow during the cleaning process was also quantified by taking samples during pipe exchanges and after draining (this process is explained above). As the tanks are drained of their water, the pipes are exchanged. During this process some water is lost, therefore 10L bucket samples were taken and sub-sampled to quantify this loss of sediment. . These samples were added to the total particulate loading from the tanks (see Fig. 2). Suspended particulate matter which was collected on the filters was dried in the oven at 60°C for 24hrs, and re-weighed until weights were constant. This work was carried out at the laboratory facilities at the Department of Botany, University of Cape Town.

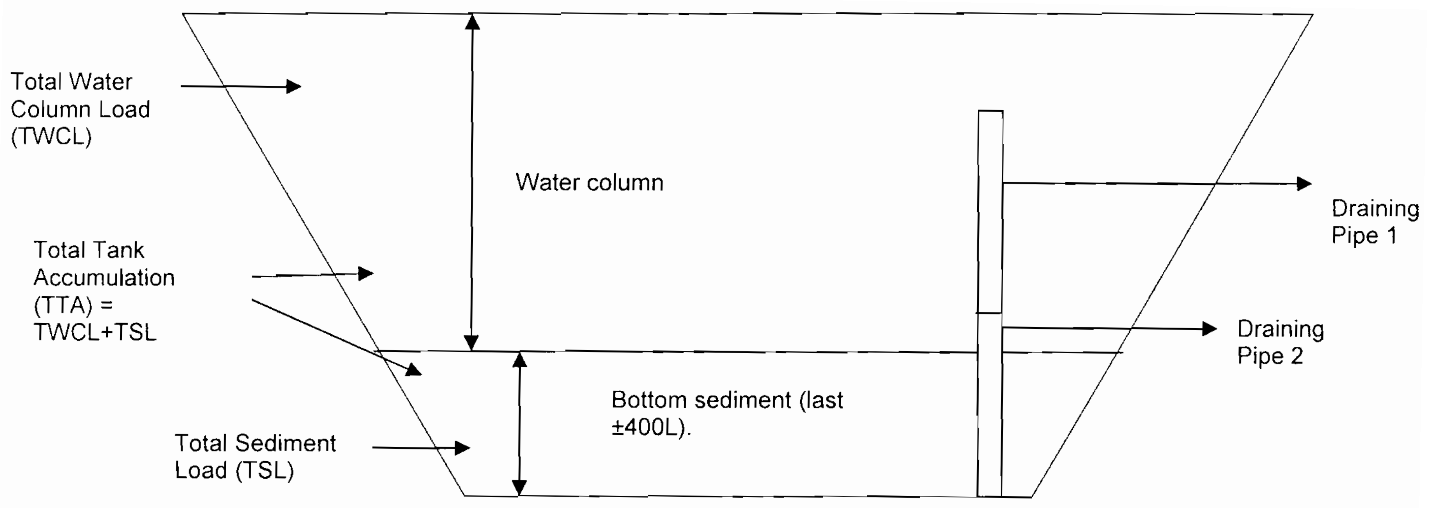

Figure 2: Tank set up illustrating the sampling locations within the tank. Note that there were two pipe exchanges the large pipe was exchanged with a smaller pipe as the water level decreased in the tank.

Samples for determination of phosphate, ammonium and nitrites were taken from the water column in all treatments were analyzed at the Sea Point Marine Research Aquarium. Water samples were syringe filtered through Whatman G/F filters, and 100ml was collected in bottles which were placed in a freezer immediately for later analysis. . Samples for nitrate were also taken but have not been analyzed.

The nutrient analysis was as follows:

- For the determination of inorganic phosphate in sea water effluent, the Acid Molybdate method described by Grasshoff *et. al* (1999) was used. Samples were run in triplicate and were modified to 5ml. Ascorbic acid and mixed reagent (ammonium heptomolybdate tetrahydrate and potassium antimony tartrate) were added to each sample Absorbance's were measured at 880nm within 10-30 minutes. This method is based on reactions with an acidified molybdate reagent to yield a phosphomolybdate heteropoly acid, which is then reduced to a highly coloured blue compound (Grasshoff *et. al* 1999). This method yields the amount of dissolved inorganic phosphate ions in true solution and probably also includes a small fraction of those ions that are absorbed onto particles and subsequently dissolved by the acid in the mixed reagent (Grasshoff *et. al* 1999).

- Chemical analyses for ammonium were performed in triplicate according to the Indophenol method described by Grasshoff *et. al* (1999) modified for the use of 5 ml samples. Citrate, phenol and hypochlorite (Trione) reagents were added to the samples, which were covered and left at room temperature in the dark overnight. The absorbance's of the samples were measured at 630nm using a Cecil CE 1020 spectrophotometer equipped with a digital readout. Grasshoff *et. al* (1999) states that ammonia reacts in moderately alkaline solution with hypochlorite to give monochloramine which, in the presence of phenol, catalytic amounts of nitroprusside ions and excess of hypochlorite, gives indophenol blue. The reaction mechanism is complex and cannot be fully explained Grasshoff *et. al* (1999).
- The method used for the analysis of nitrite was based on the formation of azo-dye with sulphanilamide and NED – N- (1-naphthyl) – ethylenediamine dihydrochloride (for colour development). Sulphanilamide and NED were added to each sample and absorbances were measured at a wavelength of 540nm within the hour. Nitrite reacts with aromatic amine, sulphanilamide hydrochloride to produce diazonium ions. These are then coupled with NED to form a bright pink complex. Grasshoff *et. al*. (1999) states that the molar absorptivity of the azo-dye at 540nm is very high (~ 46 000) making the determination of nitrite one of the most sensitive spectrophotometric methods.

Part B investigates a comparison of suspended particulate matter in a flow-through system as compared to a re-circulation system. The sampling procedures were exactly the same as for Part A (see Table 2). The recirculation tanks were sampled in the same manner as the three different diet treatments and these results were compared to the kelp tank which was the control for both experiments.

Table 2: Shows a break down of the two experiments and the sampling procedure in each.

<table>
<tr><th colspan="4">Experiment 1: Comparison of particulate matter between three different diets.</th></tr>
<tr><td>Part A & B</td><td>Sampling type</td><td>Amount of water filtered</td><td>Location of sample water</td></tr>
<tr><td></td><td>Suspended particle load</td><td>100ml</td><td>Incoming sea water & water column samples.</td></tr>
<tr><td></td><td>Suspended particulate fraction</td><td>5L</td><td>Incoming sea water, water column & bottom sediment samples.</td></tr>
<tr><td></td><td>Total tank accumulation</td><td>20ml</td><td>Bottom sediments i.e. last 400L sediments in tank.</td></tr>
<tr><td></td><td>Water nutrients</td><td>100ml</td><td>Incoming sea water, water column samples</td></tr>
<tr><th colspan="4">Experiment 2: Comparison of total sediment build up in the water column over a 7 day cleaning cycle between a flow-through system and a 25% recirculation system.</th></tr>
<tr><td></td><td>Sampling type</td><td>Amount of water filtered</td><td>Location of sample water</td></tr>
<tr><td></td><td>Suspended particle load build up</td><td>100ml</td><td>Incoming sea water, water column samples in kelp and recirculation tanks.</td></tr>
<tr><td></td><td>Suspended particulate fraction</td><td>5L</td><td>Incoming sea water, water column samples in kelp and recirculation tanks.</td></tr>
<tr><td></td><td>Water nutrients</td><td>100ml</td><td>Incoming sea water, water column samples in flow-through and re-circulation tanks.</td></tr>
</table>

Experiment 2:

The second experiment measured suspended particulate fraction, build up of total suspended particulate matter and water nutrient concentrations recorded over a 7 day cleaning cycle. A 25% re-circulation system was compared with the flow-through system. The abalone in both systems were both fed a kelp diet. The sampling procedures were as for the first experiment (see Table 2).

Statistical Analysis

Analysis of variance (Kruskal Wallis - ANOVA) was used to test if there were significant differences between the mean particle sizes and particle loads of the different treatments. Leven's test was used to check homogeneity of variance and normality was checked by plotting data on a normal probability plot. The null hypothesis was rejected at $p < 0.05$. Particle fractionation was analyzed using factorial ANOVA.

4. Results

Suspended particle matter in incoming seawater showed high variability (Table 3). One sample per day was therefore increased to four samples per day during the second week for experiment two.

There was a significant difference in mean incoming suspended particle matter between the two weeks ($p<0.001$), but no significant difference between daily readings in week 2 (Table 3, 4, & 5).

Incoming suspended particle matter was low compared to within the tank. Incoming seawater, however, could not be subtracted from the surface particulate fraction samples as this gave negative values due to the variability in particles as these particles settled out in the tanks. There was no significant difference in the particulate fractions of incoming seawater between the two weeks (Table 4 & 5).

In week 1 the average particulate fraction at a particle size of 50μm was 3.5 ± 3.7mgl^{-1} and in week 2 it decreases to 1.6 ± 1.4 mgl^{-1} in the same size class (Table 4 & 5).

Table 3: Particle concentration of incoming sea water recorded over the two week experimental period.

Suspended particulate matter (mgl^{-1})	Day 1	Day 2	Day 3	Day 4	Day 5	Average
Week 1	38.0	105.0	103.0	99.0	--------------	86.3
Week 2	102.3	94.7	86.3	91.7	92.7	93.5

Table 4: Particulate fraction of incoming sea water recorded in week 1.

Suspended particulate fraction size, daily dry weights in mgl^{-1}	Day 1	Day 2	Day 3	Day 4	Average	Std Dev. / wk
50 < µm	4.8	8.1	0.4	0.5	3.5	3.7
40 – 50 µm	3.5	2.0	0.1	0.1	1.4	1.7
30 – 40 µm	4.9	4.0	0.2	2.8	2.9	2.1
20 – 30 µm	2.9	2.1	0.3	0.5	1.4	1.2

Table 5: Particle fractionation of incoming sea water recorded in week 2.

Suspended particulate fraction size, daily dry weights in mgl^{-1}	Day 1	Day 2	Day 3	Day 4	Day 5	Average	Std Dev. / wk
50 <	0.9	0.6	0.8	0.3	2.6	1.6	1.4
40 – 50	0.1	0.2	0.3	0.1	0.7	0.3	0.3
30 - 40	0.1	0.4	1.1	0.1	0.2	1.2	1.8
20 - 30	0.2	0.2	0.6	0.2	2.2	0.7	0.8

Experiment 1:

PART A: Comparison of suspended particulate matter in tank water from three different diets.

Suspended particle matter did not differ significantly between the three diets. Kelp had the highest concentration (105.3 ± 2.3 mgl^{-1}) while the mixed diet the lowest (103.0 ± 0.4 mgl^{-1}) (Fig.3). The surface suspended particulate fractions were also not significantly different between the diets. While an Abfeed™ diet contained more of the 20-30µm particle size (7.1 ± 21.0 mgl^{-1}), kelp diet contained more of 40-50µm particles (4.6 ± 14.3 mgl^{-1}), and the mixed diet contained more 30-40µm surface suspended particles (5.6 ± 44.0 mgl^{-1}) (Fig. 4). The bottom particulate fractions differed significantly between the three diets (p=0.001, F=6.10). Particles greater than 50µm dominated the sediment in all three diets. Abfeed™ had the largest amount of particles below 30-20µm (Fig. 5). As the sediment had been diluted during cleaning of the walls and baskets, these concentrations can not be compared with the concentration in the water column. A significant difference was found in total particulate accumulations between the three diets ($p<0.01$ H=10.91). A mixed diet of kelp, *Gracilaria* and *Ulva* resulted in the highest tank accumulation (594.8 ± 32.4 mgl^{-1}) while a kelp diet resulted in the lowest (274.7 ± 28.2 mgl^{-1}). These values translate to 0.062 tons/tank/yr for a mixed diet, 0.052 tons/tank/yr for a kelp diet and 0.057 tons/tank/yr for the Abfeed diet™ (Table 6). These values were obtained by taking into account the volume of water they occupy in the tank as a whole (i. e. the samples obtained in bottom 400L were multiplied up accordingly to represent the true concentration for that volume).

Table 6: Total tank accumulation of particulate matter in the three different diets.

Diet	TTA (mg / tank of 8880L / wk)	Std Error	Kg / tank / wk	Tons / tank /yr	Tons/yr/farm of 500 tanks
Abfeed	1078877.2	152.870	1.1	0.057	28.6
Kelp	1043596.1	16.995	1.0	0.052	26.0
Mixed diet	1153561.2	15.341	1.2	0.062	31.2

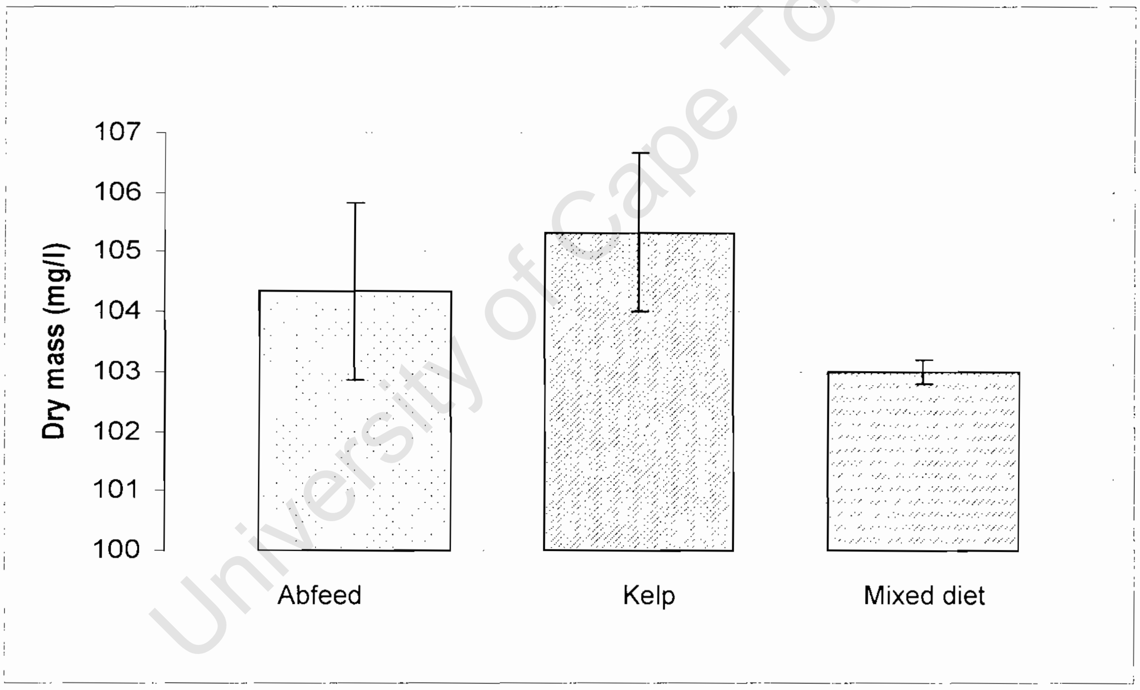

Figure 3: Suspended particle matter in tanks when using three different diets fed to abalone (n=9). Standard error bars are represented.

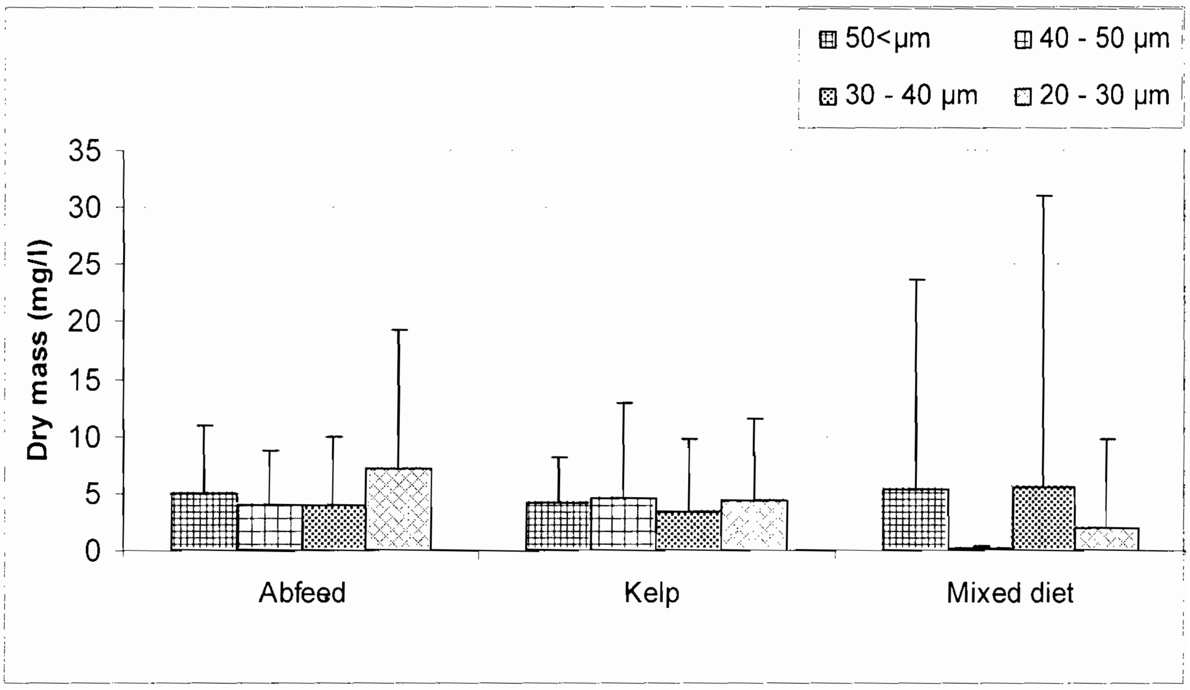

Figure 4: Surface suspended particulate fraction comparison between three different diets fed to abalone (n=9). Standard error bars are represented.

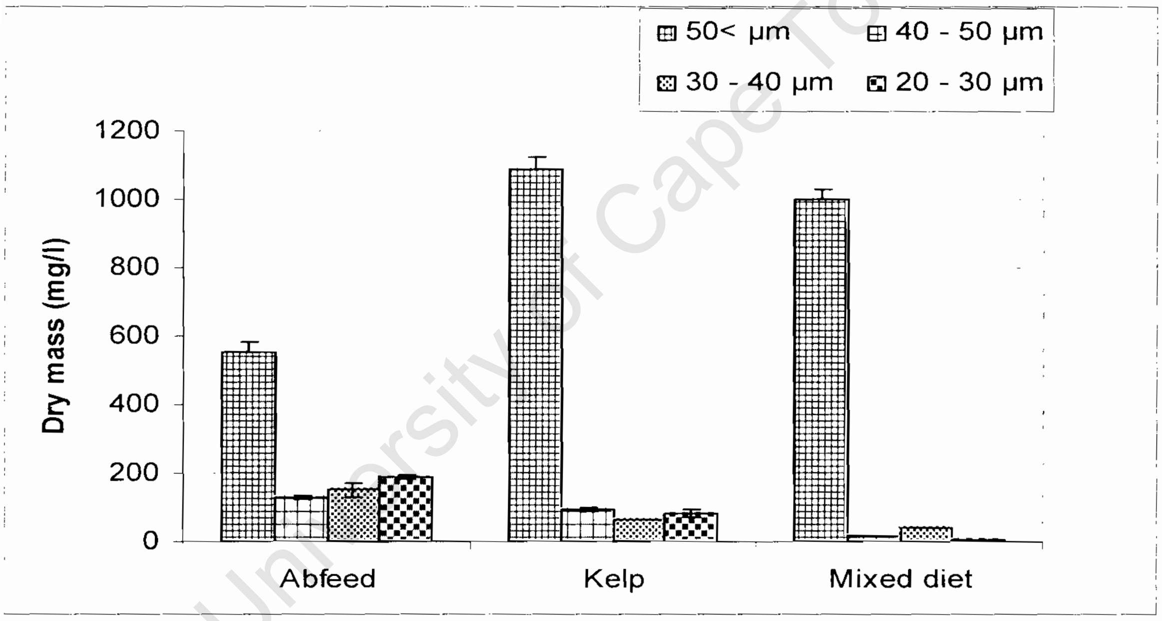

Figure 5: Bottom particulate fraction comparison between a three different diets fed to abalone (n=9). Standard error bars are represented.

Experiment 1: Nutrient values for the three diets

There was a significant difference in water column phosphate concentration between the different diets (H=10.9, p=0.02, d.f =3) (Fig. 6), but no significant difference for ammonia and nitrites (Fig. 7 & 8 respectively). The mixed diet produced the highest concentration of phosphates (2.2 ± 0.5 μmol P l^{-1}), while an Abfeed™ diet produced the lowest concentration (1.3 ± 0.2 μmol P l^{-1}).

Abalone fed on an Abfeed™ diet produced the highest concentration of ammonia (4.1 ± 0.8 μmol N l^{-1}) (Fig. 7) and nitrites (0.2 ± 0.03 μmol N l^{-1}) (Fig. 8), through feed derived waste. While abalone fed on a kelp or mixed diet produced roughly the same amount of ammonia (2.3± 0.8μmol N l^{-1} & 2.7 ± 1.1 μmol N l^{-1} respectively) and nitrite concentrations remained the same (0.1± 0.8 μmol N l^{-1} for both diets). The Abfeed™ treatment shows a significant difference in ammonia concentration when compared to the kelp diet (p=0.02, t=3.605), as well as when compared to the mixed diet (p=0.007, t=-4.913).

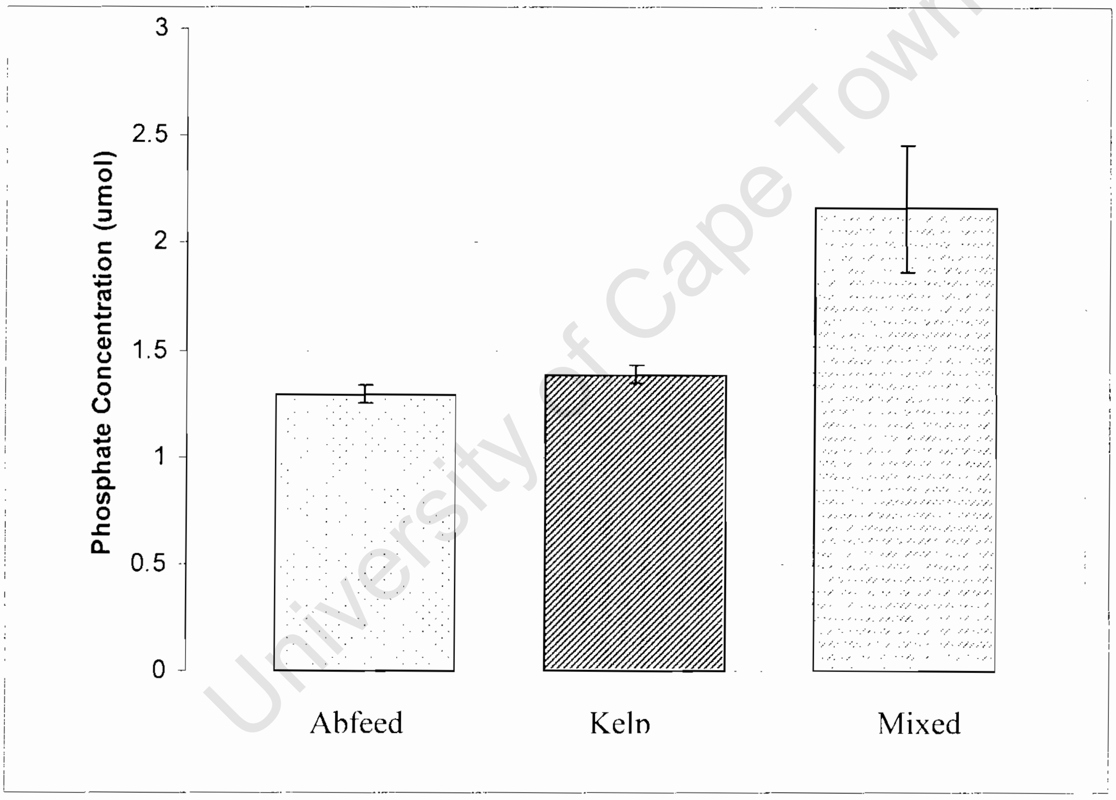

Figure 6: Phosphate concentrations (μmol) compared between the three different treatments. (n= 12). Standard error bars are represented.

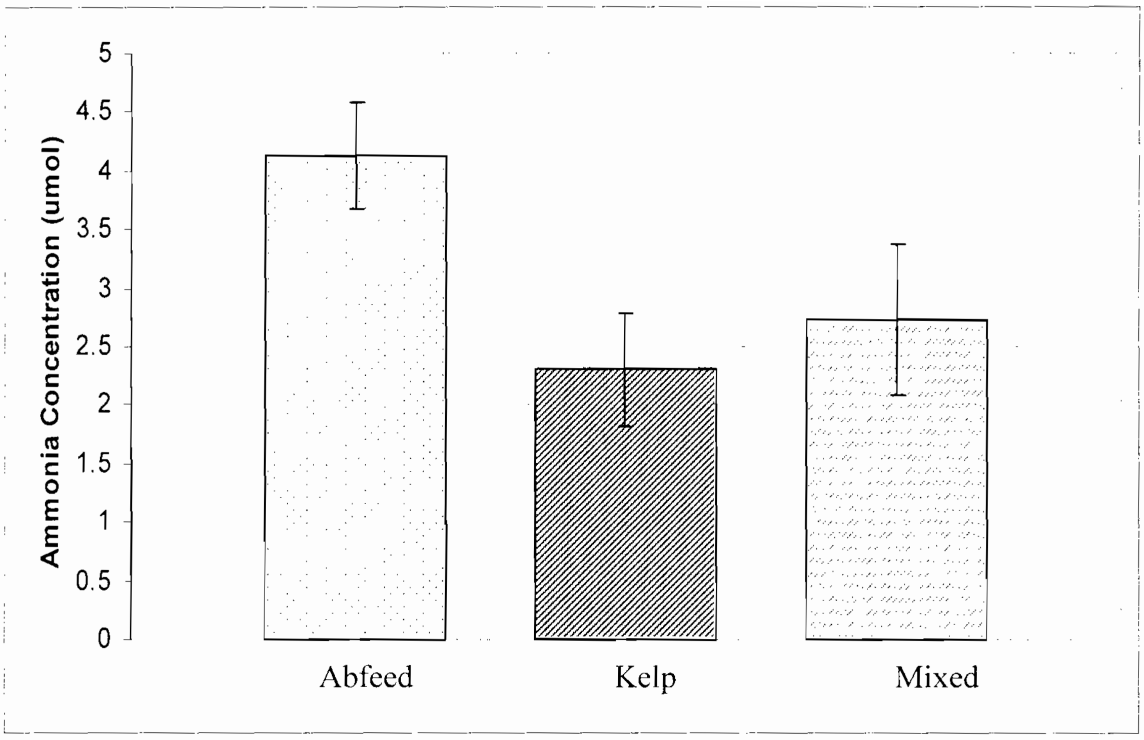

Figure 7: Ammonia concentrations (μmol) compared between the three different treatments. (n= 12). Standard error bars are represented.

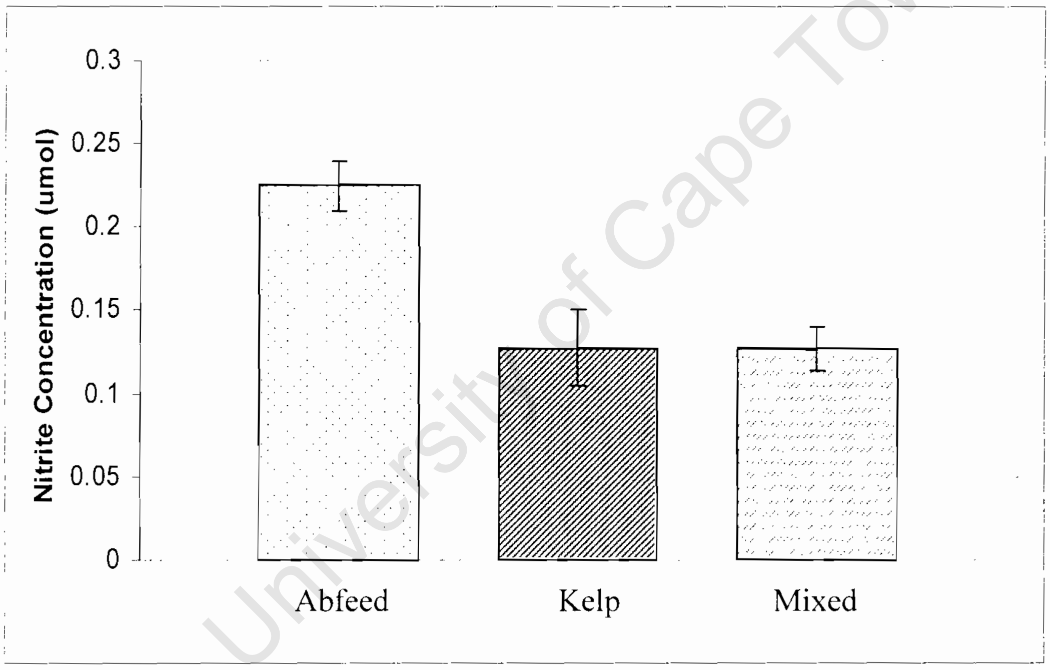

Figure 8: Nitrite concentrations (μmol) compared between the three different treatments. (n= 12). Standard error bars are represented.

PART B: Comparison of suspended particulate matter build-up in two different systems

The surface suspended particulate fraction between the two systems showed that there was no significant difference (Fig. 9), whereas the bottom particulate fraction difference was highly significant ($p<0.001$, $F=16.96$) between the two systems (Fig. 10). The flow-through system had a higher proportion of the larger particles (50 < µm:1085.3 ± 61.1mgl^{-1}) but both systems contained more of the larger particles. The re-circulation system had more of the 30-40µm (110.0 ± 35.8 mgl^{-1}) but less of the 20-30µm particles (35.3 ± 8.0 mgl^{-1}) (Fig.9). The total tank accumulation of particulate matter for the two systems was not significantly different. When these values are multiplied up the flow-through systems produced 0.052 tons/tank/yr and the re-circulation system produced 0.047 tons/tank/yr (Table 7).

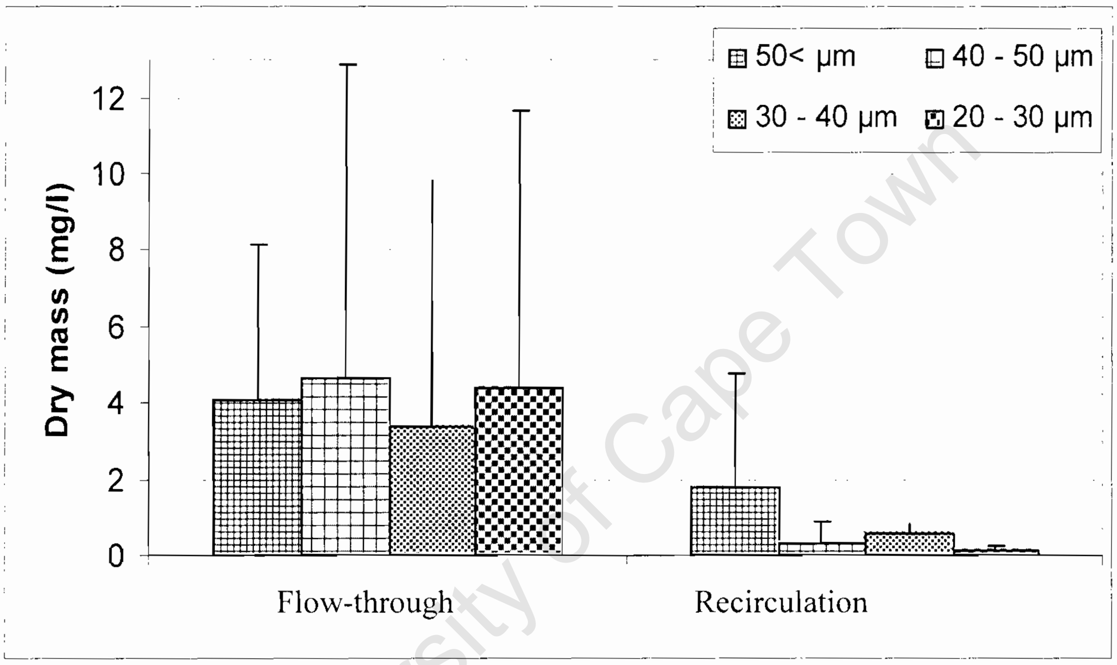

Figure 9: Surface suspended particulate fraction comparison between a flow-through system and a 25% re-circulation system (n=9). Standard error bars are represented.

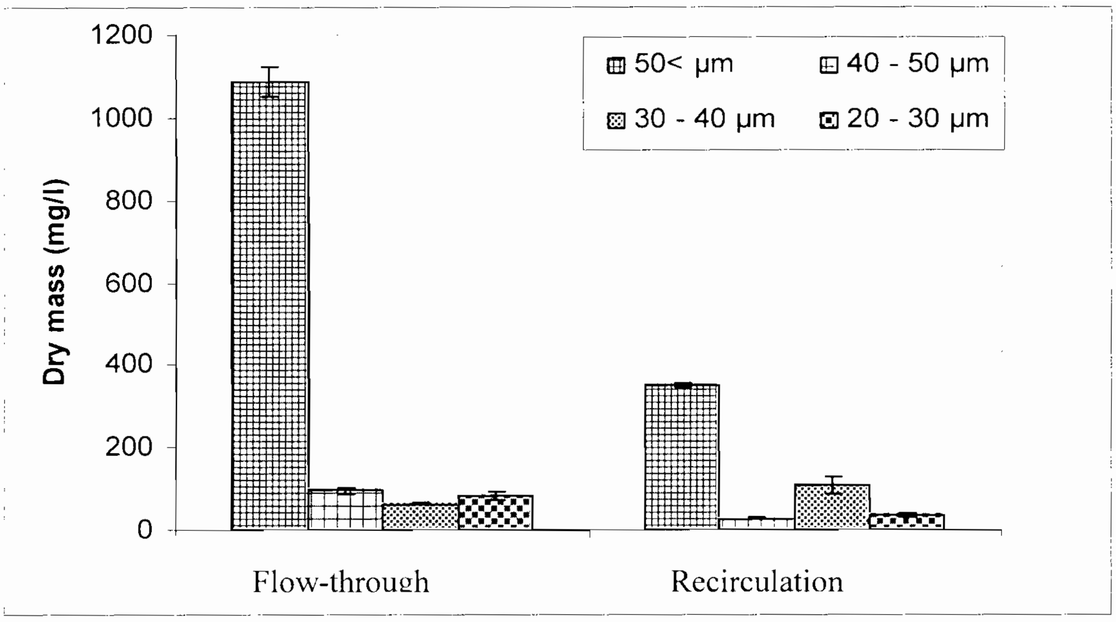

Figure 10: Bottom particulate fraction comparison between a flow-through system and a 25% recirculation system (n=9). Standard error bars are represented.

Table 7: Total tank accumulation of particulate matter in the two different systems.

System type	TTA (mg / tank of 8880L / wk)	Std Error	Kg / tank / wk	Tons / tank /yr	Tons/yr/farm of 500 tanks
Flow-through	1043596.1	16.995	1.0	0.052	26.0
Recirculation	920765.4	878.802	0.9	0.047	23.4

There was no significant difference in any of the nutrient concentrations tested between the re-circulation system and the flow-through system (see Table 8 below).

Table 8: Nutrient concentrations of the re-circulation system and the flow-through system.

	Phosphate (PO_4)	Std error (PO_4)	Ammonium (NH_4)	Std error (NH_4)	Nitrite (NO_2)	Std error (NO_2)
Re-circulation system	1.98 µmol P l^{-1}	0.15	2.13µmol N l^{-1}	0.12	0.12µmol N l^{-1}	0.05
Flow-through system	1.38µmol P l^{-1}	0.04	2.30µmol N l^{-1}	0.49	0.12µmol N l^{-1}	0.02

Experiment 2: Comparison of particulate concentration build up in the water column over a 7 day cleaning cycle between a flow-through system and a 25% re-circulation system.

The concentration of suspended particulate matter in the water column was not significantly different between the two systems ($p > 0.10$). There was also no significant difference in the daily suspended particulate fraction build-up in the kelp diet, but there was a significant difference in the re-circulation build-up over the cleaning cycle ($p<0.05$, $H=9.75$) (Fig. 11). Water column particulate concentration in the re-circulation system remained constant during the experimental period (Fig.11), whereas no pattern was found in the flow-through system. Note on days 1 & 2 samples were not taken to enable a build up of particles to accumulate. Regression showed that there was no significant difference ($p=0.75$, $R=0.149$) between the flow-through and re-circulation particulate concentrations over time, and thus the concentration was fairly constant. The particulate fraction build up in the flow-through system and the re-circulation system showed no significant difference (samples were not taken on days 1 & 2). The suspended particulate fraction in the kelp tanks showed that particles greater than 50μm particle remain high throughout the week while particles of the smaller sizes remain low. The 20-30μm particle size occurred at low concentration in the beginning of the week but peak on the 6th day (1.4 ± 0.5 mgl^{-1}) and drop the following day (1.2 ± 0.3 mgl^{-1}). (Fig.12). The particulate fraction in the re-circulation tanks showed that the particles greater than 50μm remain high but peak on the 5th day (1.9 ± 4.5 mgl^{-1}), while the smaller particles remain low throughout the week (Fig. 13).

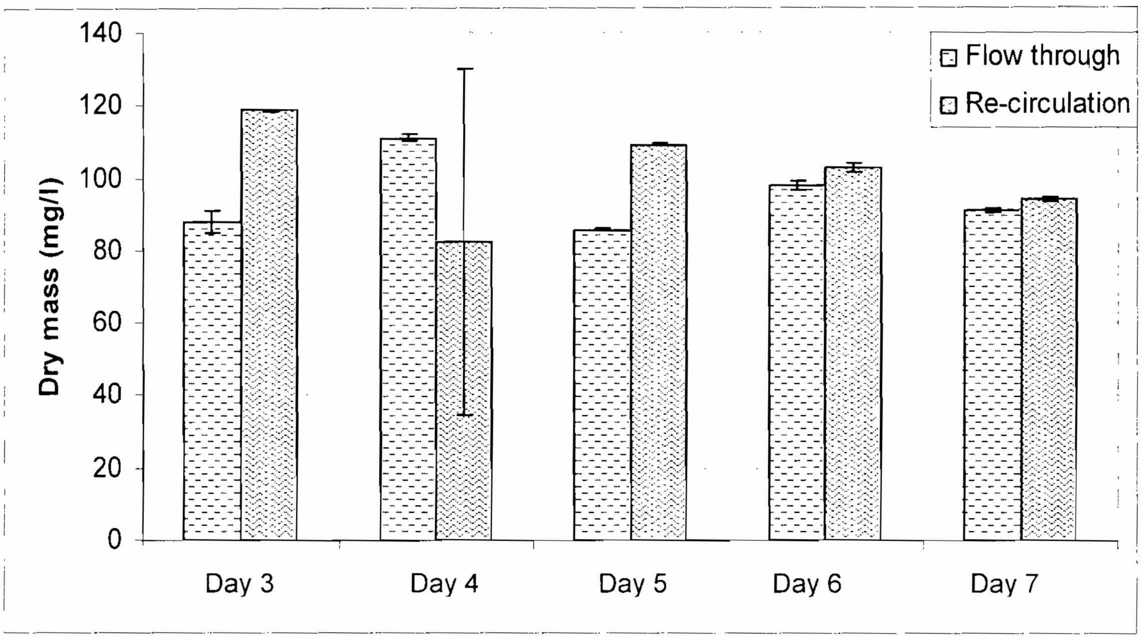

Figure 11: Daily suspended particle concentration over a 7 day cleaning cycle between flow-through system and a 25% re-circulation system in the water column (n=6). Standard error bars are represented.

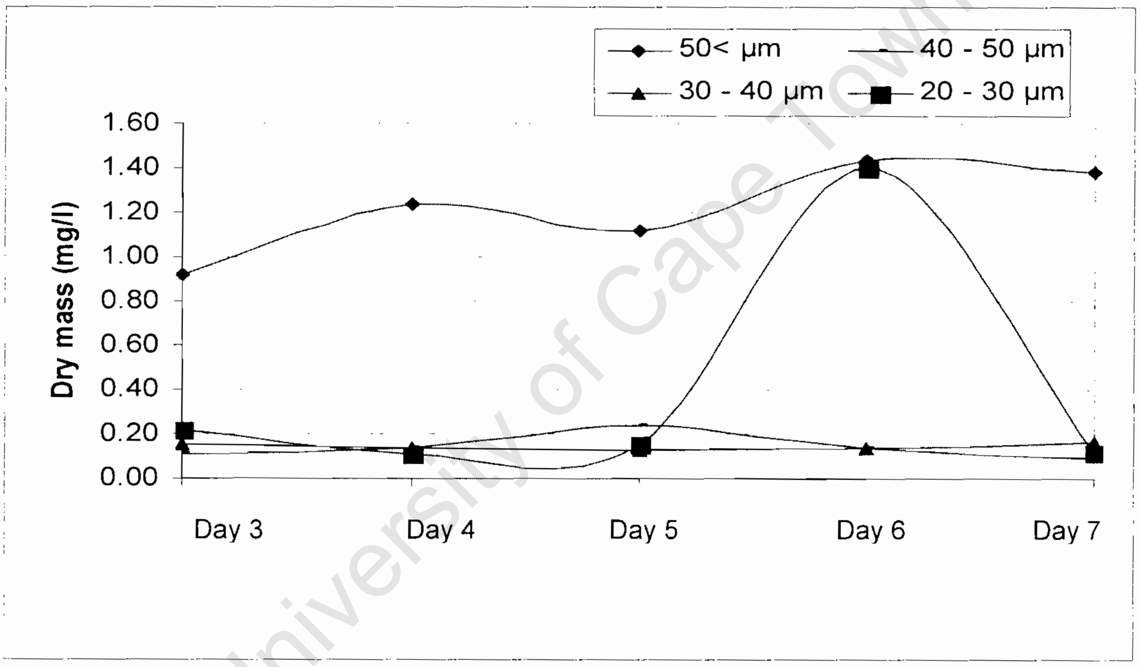

Figure 12: Daily suspended particulate fraction over a 7 day cleaning cycle in a flow-through system of which the abalone are fed a diet of kelp (n=6).

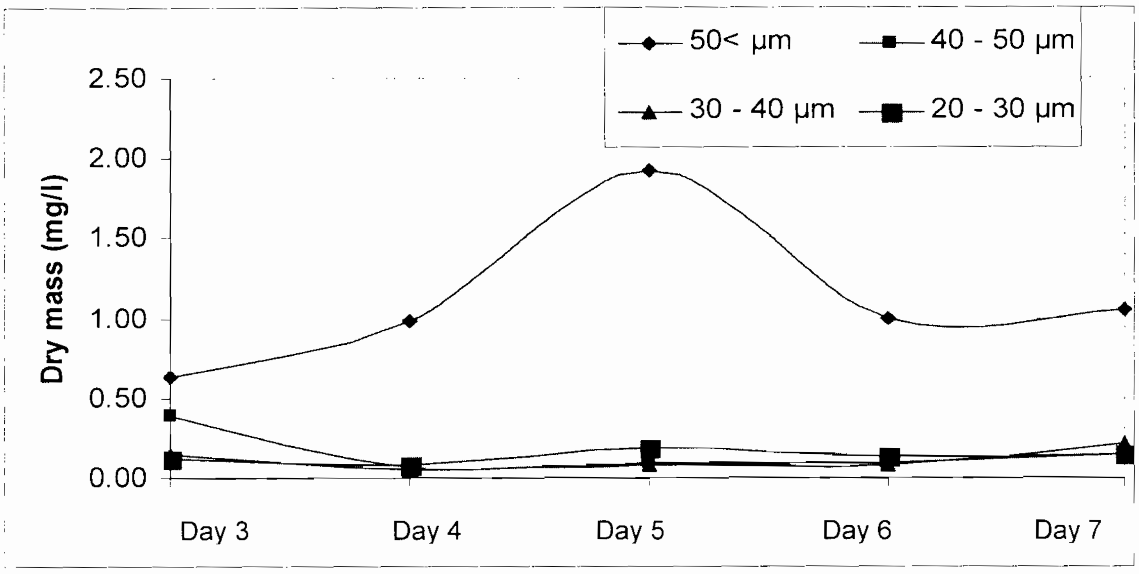

Figure 13: Daily suspended particulate fraction over a 7 day cleaning cycle in a 25% re-circulation system of which the abalone are fed a diet of kelp(n=6) .

Over the 7 day cleaning cycle there was a clear oscillation in all three nutrient levels of the flow-through and re-circulation system. There was no significant difference in the three nutrients (PO_4, NH_4, & NO_2) (Fig. 14, 15 & 16). Ammonia concentrations were highly variable and show no synchronization between the two systems (see Fig. 15), while the nitrite concentrations of the flow-through and re-circulation system seem to be synchronized with each other (see Fig.16). The seawater nutrient concentration follows the same pattern as the flow through system (see Figs14, 15 & 16).

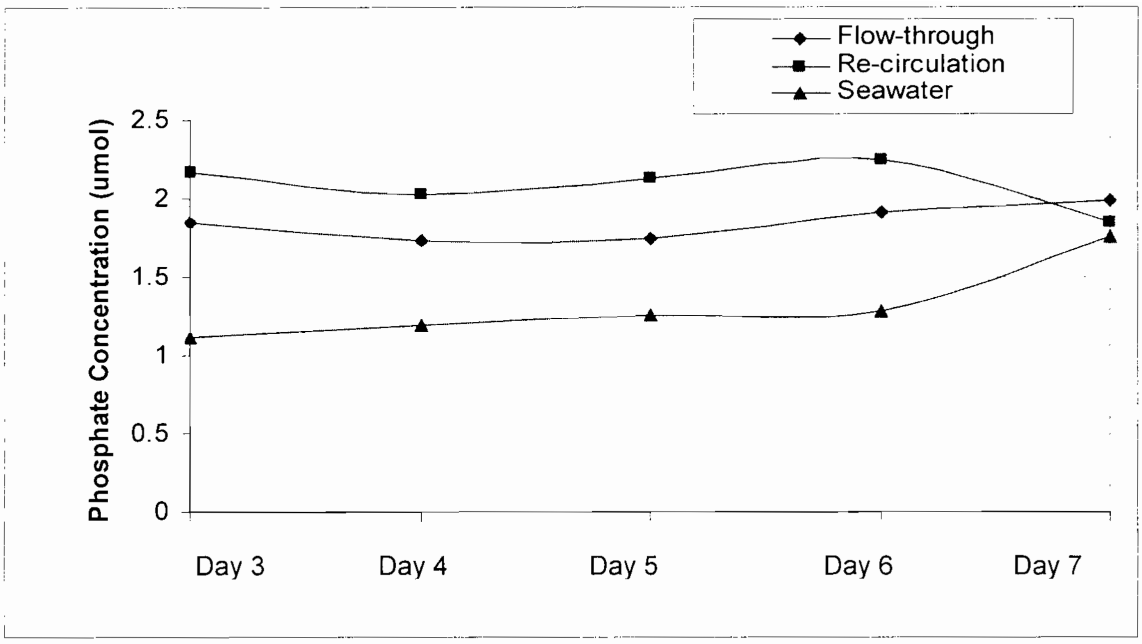

Figure 14: Phosphate concentration recorded over the a 7 day cleaning cycle in a 25% re-circulation system (abalone fed on a kelp diet) and a flow-through system(abalone fed on a kelp diet). (n= 28).

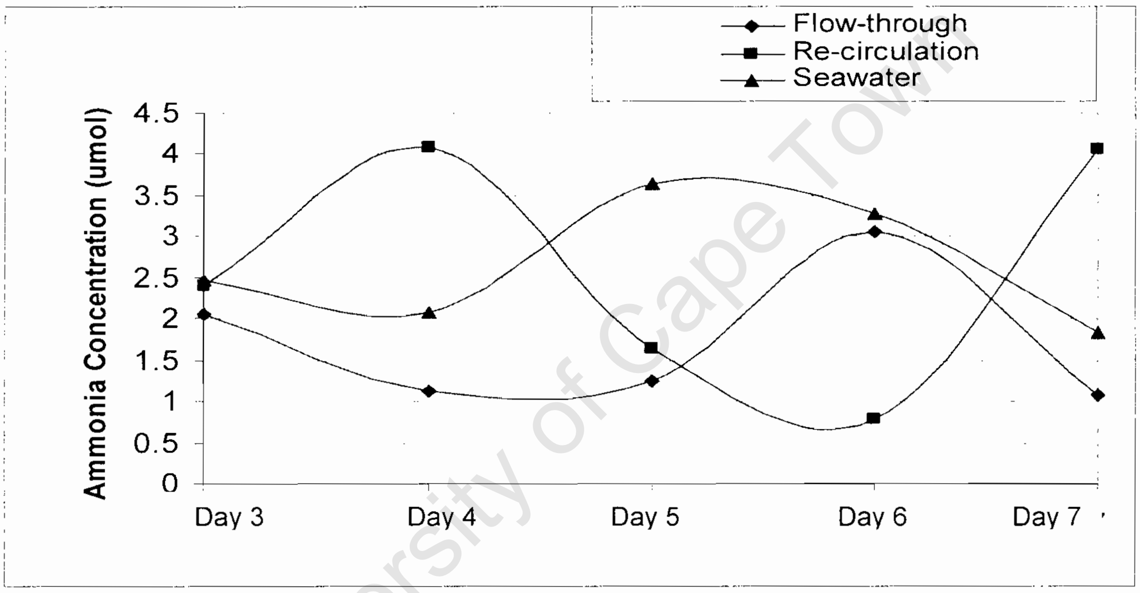

Figure 15: Ammonia concentration recorded over the a 7 day cleaning cycle in a 25% re-circulation system (abalone fed on a kelp diet) and a flow-through system(abalone fed on a kelp diet). (n= 28).

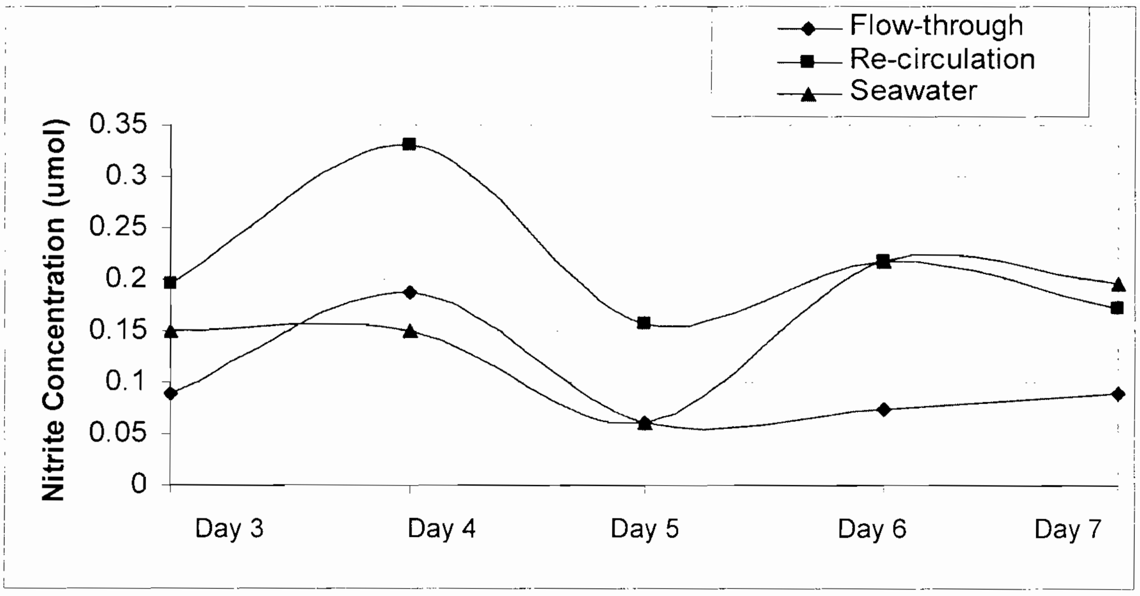

Figure 16: Nitrite concentration recorded over the a 7 day cleaning cycle in a 25% re-circulation system (abalone fed on a kelp diet) and a flow-through system(abalone fed on a kelp diet). (n= 28).

5. Discussion

Suspended particulate concentration of incoming seawater is something that will vary from farm to farm and will also show temporal/seasonal variation.

It can be noted that the inconsistency between the total suspended particulate concentration and the size fractionated material of the sea water may be due to different methodology used in each sample type. The total suspended particulate concentration was measured by syringe filtering 100ml of sample water through 25mm Whatman G/F filter paper of 1.0μm mesh size. This method filtered out all of the particles under pressure. The size fractionated material was measured by filtering 5L of water through a series of mesh filters drawn down by the force of gravity, the filtrate was then transferred to the large (110mm) pre-weighed filter papers using de-ionized water (see Fig. 17). During the process of transferring the filtrate, I believe that some of the particles were lost either remaining behind in the mesh container or particles may not have transferred to the relevant mesh size (see Fig. 17).

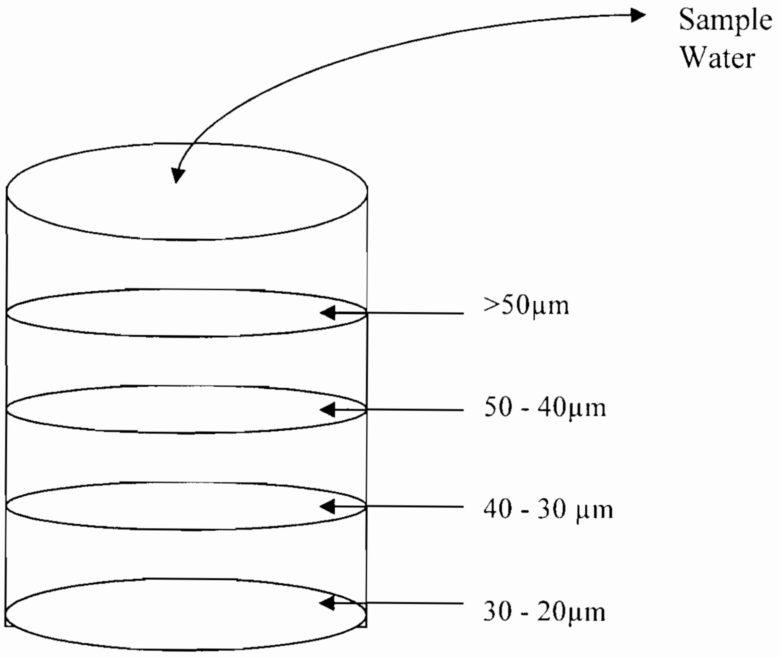

Fig.17: Series of mesh filters (20, 30, 40, 50µm).

Another option is that there might be more particles in the <20 µm size range which were not collected by the fractionation method, but were collected in the syringe filtering method. It is my opinion that the samples contained particles of 100mg/l rather than 10mg/l, and therefore the syringe filtering method is most accurate. Future studies should find a better method to separate the different particle sizes from each other. This inconsistency was then repeated throughout the study as the same methods were used in measuring total suspended particles and size fractionated material of the other treatments.

This study showed that the variability in incoming seawater was high even on a weekly basis. In the first week one sample of each was measured while in the second week triplicate samples were taken for a better average. In table 5 the particulate concentrations are much lower than in Table 4, this is attributed to triplicate samples being measured in the second week while in the first week only one sample was taken. The suspended particulate concentrations are higher in incoming seawater than are usually recorded i.e. in this study values were close to 100mg/l whereas in other studies these values are tightly bound in the range 0.5 to 10 parts per million by volume. The reason for these high readings is due to the inlet pipe for seawater being located close to a kelp bed. *Eklonia maxima* and *Laminaria pallida* both undergo fragmentation from the tip and thus release structural components as particulate matter and a dissolved fraction as well as cell contents into the water column (Newell *et al*, 1980), therefore accounting for the high particulate concentration of the incoming seawater.

There have been several studies completed on the feed formulation and digestibility in abalone (Britz, 1995; Shipton 1999; Sales 2001) but little work on suspended particle concentrations in abalone tanks resulting from feed derived wastes. Chalmers (2002) showed that the average weight and particle size composition in the tank water column differed significantly between abalone being fed kelp and artificial feeds. The findings from this study supports' Chalmers finding in that particle concentration differed between the three diets and bottom particulate fraction size differed significantly between the three diets.

Detritus is a major source of food for many polychaete worms including *T. heterouncinata* (Fauchald & Jumars, 1979). *Terebrasabella heterouncinata* a member of the Sabellidae family subfamily sabellinae which are sessile suspension feeders inhabiting tubes. Fauchald & Jumars (1979) suggest that sabellids select particles exclusively on size but there is no evidence for selection based on other characteristics. However, Kiørboe *et al*, (1980) and Bacon *et al,* (1998) have shown that particle selection is based on organic quality. Chalmers (2002) also showed that protein and energy levels of particles differ between kelp and Abfeed™ abalone raceways, and that this explained feeding selection between the two diets. Kelp particles are lower in protein and energy, compared to Abfeed™ particles (Chalmers, 2002). The increased protein and energy levels of artificial feeds increase the growth rates of abalone but this diet may be producing beneficial conditions for the growth and infestation of the sabellid worms. Although when utilizing a mixed diet the seaweed is fertilized but protein levels are not as high as with an Abfeed™ diet (Robertson-Andersson, 2003).Abalone farmers have noted that Abfeed™ decomposes faster than kelp. The small nutritious particles could be attractive for bacterial colonization, resulting in a richer food source to the sabellid. This is an area for further research. Shields *et al,* (1998) and Ruck (2000) showed that microcapsules ranging between 3 – 30 μm, and particles up to 35 μm, were found in the gut of the sabellid. It suggests that the preferred feeding size range of the sabellid is smaller than 40 μm although it may ingest larger particles (Chalmers, 2002), and debris of abalone aquaculture systems usually comprise of this particle size range (Ruck, 2000).

The present study indicated that abalone fed on a kelp diet produced slightly more surface suspended particles of 40 – 50 µm and that the Abfeed™ diet produced slightly more surface suspended particles in the size range of 20 – 30 µm. The mixed diet generated the lowest surface suspended particulate concentration mainly within the size range of 30 - 40µm particle size. Thus the Abfeed™ or mixed diet generates the ideal particle size range for the sabellid worm. The mean surface suspended particulate fraction between the three different diets is not significantly different from each other, this indicates that the three diets do not contain large amounts of particles in one or more the four fractionated size ranges within the water column. But in the bottom sediment there was a highly significantly difference between the three diets and this indicates that particles in the bottom sediment contain large amounts of one or more of the four different size fractions. All treatments had the largest proportion made up of the greater than 50 µm particles. These large particles (50µm<) sink to the bottom of all treatments and may be attributed to the abalones' feeding behaviour. Abalone grazing on a kelp diet break off larger particles when feeding which may be lost to the bottom sediments and comprises the greater than 50µm particle size range. Abalone bulldoze the Abfeed™ (pelleted feed) off the feeding plate which may fall to the bottom sediment, these particles were not digested and remain in the greater than 50µm size range. The structure of *Gracilaria* is such that when the abalone break a section off, whole strands of the seaweed may be lost to the bottom sediments, these stands are not digested and fall into the greater than 50µm size range. Thus it is not surprising that all treatments show a large portion of the bottom sediment containing greater than 50µm particle size.

The suspended particulate matter concentration in the water column showed little difference between the three diets but the amount of sediment building up in the tanks differed significantly. This shows that the water column has reached loading capacity and it is highly unlikely that there will be more loading. The aeration within the tank was exactly the same for all tanks and therefore the water motion within the tanks (velocity) was also the same. The water column only hold so many particles at a certain velocity, adding more feed or abalone will not affect particle load within the water column. The total sediment build up gives an indication of the potential pollution levels of the particular diet and the potential amount of bacteria build up. Due to the high energy waves of the South African coast, together with low abundance of abalone farms the particle loading (as the tanks are cleaned) probably only cause localized effects. Farms located on the west coast are subject to the more energetic Benguela system which would facilitate more rapid dispersion of particles.

A farm consisting of 500 tanks with a yearly production of 330 tons releases 31.2 tones/yr if all abalone are fed a mixed diet feed, 28.6 tones/yr if all abalone are fed an Abfeed™ diet, and 26.0 tones/yr if fed a kelp diet. In a study done by Samsukal (2004), suspended matter greater than 63 μm was released in relatively large concentrations during the cleaning process and this is cause for concern. In the current study the particulate concentrations were lower than those recorded in Samsukal's (2004) study thus there is little cause for concern. The highest total tank accumulation is recorded with a mixed diet and *Gracilaria* contributes more to this value due to the feeding behavior of the abalone as described previously.

Aquaculture systems produce a lot of food-derived waste with the potential to effect the environment negatively (Cripps, 1995; Tovar *et al,* 2000). Eutrophication can be defined as a natural process whereby there is a gradual accumulation of nutrients and organic biomass accompanied by increased levels of production (Laws, 1993). Cultural eutrophication is simply the anthropogeninc acceleration of this process. The accumulation of these sediments in the local waters has the potential to alter the particle concentration of the water, this may change the composition of the benthic communities, and may affect the higher trophic levels. However, these changes will occur over long time periods, owing to the lower turnover times associated with larger body size.

In a flow-through system (the system used in all three diets of this study) the critical components of effluent consist of phosphorus, nitrogen, suspended solids and pathogens (Cripps, 1995). Studies have shown that nutrients released from aquaculture species are suitable for seaweed growth as the nitrogen released is the preferred nitrogen source (NH_3) for seaweed (Lobban & Harrison, 1994). The dissolved release of phosphorus is also beneficial for the growth of seaweed. The higher concentration of phosphates in the mixed diet may be due to the additional artificial fertilization of the seaweed tanks. The nutrient enriched Abfeed™ diet consists of an artificial fish protein therefore waste water will accumulate higher ammonia and nitrite levels. Abfeed™ is higher in protein than the other diets and de-animating of the protein supports the higher significant difference of ammonia in comparison to the other treatments. The analysis of the nutrient concentrations follow the same methods used by Samsukal (2004), her study was conducted on the I & J Farm as well as the surrounding farms. The values recorded in this study were consistent with values recorded in Samsukal's study (2004), and therefore the analytical methods were satisfactory.

The west coast average for phosphorus is 1.71 μmol P l^{-1} (DWAF, 1996), and the values recorded in this study are below this level except for the mixed diet which is above this level. This is due to the artificial fertilization of the seaweed tanks as described previously. Ammonium is regarded as toxic because it is uncharged and lipid soluble. Unpolluted waters do not exceed 5 μmol N l^{-1} (DWAF, 1996), in this study none of the treatments exceed this limit. Nitrite occurs in seawater as an intermediate compound in the microbial reduction of nitrate or in the oxidation of ammonia. There is little record of natural occurrences of nitrites in the open-ocean, but means values such as 0.3 μmol N l^{-1} have been recorded. The nitrite concentrations recorded in this study were all below this mean.

The total tank accumulations of the flow through and re-circulation systems were not significantly different from each other. This is a highly significant result because it provides evidence to dismiss the notion that the re-circulation system accumulates particles to a higher degree than the flow-through system as previously thought. In this study only 25% of the tank water was re-circulated which was sufficient for flushing the excess solids, a 75% re-circulation system would therefore flush the system even more efficiently, and this requires further research.

Suspended solids management is thus a key factor in determining the success of re-circulation systems (Chen *et al,* 1993). Chen *et al,* (1993) states that suspended solids concentration should not exceed 15mgl^{-1} for re-circulating systems. In this study the surface particle concentration was 90 mgl^{-1}, which is 6 times the limit but there is no need for concern. In Chen *et al.*'s study the system relies on a gravel bed filter which draws water downwards and becomes clogged causing there to be pockets of anoxic air trapped beneath the gravel at high particulate concentrations. Whereas in this study the system is not a gravel bed system therefore the higher particulate concentration was no cause for concern. The most effective way to decrease the nutrient loading is to improve the feed and feeding (Makinen *et al,* 1988), and ways to minimize re-suspension of particulate matter is through designing the aeration systems properly. Besides the choice of feed, farm management feeding schedules and cleaning processes play an important role for controlling the concentration of particles. The findings in this study show that there is no significant difference between particle concentrations in the flow-through system verses the re-circulation system. This may indicate the particles effectively get trapped in the sediment, either in the abalone tank or the re-circulation unit (seaweed tanks). Particle concentrations in size classes in the surface waters were not significantly different between the flow through and the re-circulation systems. The re-circulation system contained more of the larger particles in the size classes of 30-40 μm.

The daily build up of particle concentration in the flow-through system was not significantly different but in the re-circulation system the build up of particle concentration was a significant different. This is very interesting because with the re-circulation system one would expect there to be a build up in particles but the results show that particulate matter remains constant.

The aquaculture industry requires fast growth rates and this may be achieved by increasing the nutrient content of the food fed to abalone, and these are often in excess amounts (Wiesmann *et al,* 1988). Not only are these high levels of nutritional rich suspended solids ideal for filter feeders like sabellids but the sediment accumulation may also increase bacterial densities and ammonium concentrations. The nutrient concentrations of the two systems did not differ significantly and these values were very low. This indicates that the re-circulation system would not accumulate an excess of nutrients and thus is a viable option when considering a large scale commercial re-circulated abalone farm.

6. Conclusion

This study provides abalone farmers with useful data in terms potential pollution problems from abalone effluent waters. It shows that an Abfeed™ diet or mixed diet provides greater particles in the size range preferred by sabellids, this could become a problem for abalone farmers who feed only one or other diet. The re-circulation system does not increases particle concentration and sedimentation in the abalone tanks. The total particulate loading from the farm, would suggest that abalone farming does not have serious environmental impacts on the dynamic west coast of South Africa. This study only focuses on a 25% re-circulation system but future studies should investigate a 75% re-circulation system. These findings indicate that a shift from a flow-through culture system to an integrated 25% re-circulation system farm will not result in deterioration of tank water quality.

The current study only covered a limited time period of the year and it is therefore difficult to generalize. To be able to say something about the effects of different feeds on particulate concentrations or sediment loading from a farm other seasons need to be studied further.

7. Acknowledgements

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8. References

Anderson, R. – 2003. Seaweed. *In:* Research highlights 2001-2002. Department of Environmental Affairs and Tourism and Marine and Coastal Management. Cape Town. Pp.31-32.

AASA - 2004. Aquaculture Association of Southern Africa's homepage: www.sun.ac.za.

Bacon, G. S. MacDonald, B. A. & J. E. Ward – 1998. Physiological responses of infaunal (*Mya arenaria*) and epifaunal (*Placopecten magellanicus*) bivalves to variations in the concentration and quality of suspended particles. 1: Feeding activity and selection. *J. Exp. Mar. Biol. Ecol.* **219**: 105-125.

Bredberg, C. - 2003. Comparison of nutrient release from South African abalone *Haliotus midae* (Mollusca, Haliotidae) fed on three seaweeds: *Gracilaria*, *Ulva*, and *Ecklonia*. MSc. Thesis. Department of Systems Ecology. Stockholm University, Sweden.

Bock, M. J. & D. C. Miller – 1997. Particle-bound organic matter as a cue for suspension feeding in tentaculate polychaetes. *J. Exp. Mar. Biol. Ecol.* **215**: 65-80.

Botes, L., Smit, A. J. & P. A. Cook – 2003. The potential threat of algal blooms to the abalone (*Haliotis midae*) mariculture industry situated around the South African coast. *Harmful Algae*. **2** (4): 247-259.

Britz, P. J., T. Hecht, J. Knauer, &M. G. Dixon – 1994. The development of an artificial feed for abalone farming. *S.A. J. Sci.* **90:** 7-8.

Britz, P. J. – 1995. The nutritional requirements of *Haliotis midae* and development of a practical diet for abalone aquaculture. Ph.D. thesis, Rhodes University, Grahamstown, Pp. 150.

Britz, P. J. – 1996. Effects of dietary protein level on growth performance of South African abalone, *Haliotis midae*, fed on fishmeal based semi-purified diets. *Aquaculture* **140**: 55-61.

Britz, P. J. & C. Clayden – 1996. Evaluation of the growth rate and feed conversion ratios of *Haliotis midae* fed formulated practical diets. *Proc. Aquacult. Assoc. S. Afr*. **5:** 68-73.

Britz, P. J. & T. Hecht – 1997. Effect of dietary protein and energy level on growth and body composition of the South Africa abalone, *Haliotis midae*. *Aquaculture*. **140**: 63-73.

Chalmers, R. - 2002. An investigation into the feeding biology and factors influencing the population dynamics of *Terebrasabella heterouncinata* (Polychaeta: Sabellidae), a problematic tube welling polychaete in farmed abalone in South Africa. MSc Thesis. Rhodes University. South Africa.

Chamberlane, G. & H. Rosenthal – 1995. Aquaculture in the next century: opportunities for growth, challenges for stability. *World Aquac. Soc. Mag*. **26** (1): 21-25.

Chen, S., Timmons, M. B., Aneshansley, D. J. & J. J. Bisogni - 1993. Suspended solids characteristics from re-circulating aquacultural systems and design implications. *Aquaculture*. **112**: 143-155.

Cook, P. - 1998. The current status of abalone farming in South Africa. *J. Shell. Res.* **17:** (3) 601-602.

Cripps, S. J. - 1995. Serial particle size fractionation and characterization of an aquaculture effluent. *Aquaculture*. **133**: 323-339.

DEAT – 2004. Department of Environmental Affairs and Tourism. Recreational Fishing Information Brochure, December 2004.

DWAF: Department of Water Affairs and Forestry – 1996. South African Water Quality Guidelines for Coastal Marine Waters. **1**: Natural Environment.

Edwards, P., Pullin, R. S. V. & J. A Gartner - 1988. research and education for the development of integrated crop-livestock-fish farming systems in the tropics. ICLARM Studies and Reviews, vol 16. International Centre for Living Aquatic Resources Management Manila, Pp. 53.

Evans, F& C. J. Langdon - 2000. Co-culture of dulse *Palmaria mollis* and abalone *Haliotis rufescens* under limited flow conditions. *Aquaculture.* **185**:137-158.

Fauchald, K. & P. A. Jamars - 1979. The Diet of Worms: A study of polychaete feeding guilds. *Oceanogr. Mar. Biol. Ann. Rev*. **17:** 193-284.

Fitzsimons, G. - 1965. Feeding and tube-building in *Sabellastarte magnifica* (Shaw) (Sabellidae: Polychaeta). *Bul. Mar. Sci*. **15**: 642-671.

Flemming, A. E., R. J. Van Barneveld & P. W. Hone – 1996. The development of artificial diets for abalone: a review and future directions. *Aquaculture* **140** 5-53.

FAO - 2004. Food and Agriculture Organization of the United Nation's homepage: wwwfao.org

Genade, A. B., Hirst, A. L. & C. J. Smit - 1988. Observations on the spawning, development and rearing of the South African abalone *Haliotis midae* Linn. *South Afri. J. Mar. Sci.* **6:** 3-12

Grasshoff, K. ; Ehrhardt, M. and Kremling, K. 1999. Methods of Seawater Analysis: Chapter 10. Pp.159-228

Haines, K. C. - 1975. Growth of the carrageenan-producing tropical seaweed *Hypnea musciformis* in surface water, 870m deep water, effluent from a clam mariculture system, and deep water enriched with artificial fertilizers or domestic sewage. 10th

European Symposium on Marine Biology, Ostend, Belgium, 17-23 Sept., vol. 1, Pp. 207-220.

Joyce L.B., G.C. Pitcher, A. du Randt & P.M.S. Monteiro - 2005 Dinoflagellate cysts from surface sediments of Saldanha Bay, South Africa: an indication of the potential risk of harmful algal blooms *Harmful Algae*: **4** (2): 309-318

Knauer, J., T. Hecht & J. R. Duncan – 1995. A note on the feeding behaviour and growth of juvenile South African abalone, *Haliotis midae*, fed on an artificial weaning diet. *S.A. J. Sci.* **91**: 91-93.

Kiørboe, T., Mohlenberg, F. & O. Nohr - 1980. Feeding particle selection and carbon absorption in *Mytilus edulis* in different mixtures of algae and re-suspended bottom material. *Ophelia*. **19**: 193-205.

Kuris, A. M. & C. S. Culver - 1999. An introduced sabellid polychaete pest infesting cultured abalones and its potential spread to other California gastropods. *Invert. Biol.* **118**: (4): 391-403.

Laws, E.A. - 1993. Aquatic Pollution. An Introductory Text. Second Edition. John Wiley and Sons, NY.

Lobban, C. S. & P. J. Harrison - 1994. Seaweed Ecology and Physiology. Cambridge University. Press, Cambridge, Pp. 366.

Martinez-Aragon, J. F., Hermandez, I., Perez-Llorens, J. L., Vazquez, R. & J. J. Vergara - 2002. Biofiltering efficiency in removal of dissolved nutrients by three species of estuarine macroalgae cultivated with sea bass (*Dicenntrachus labrax*) waste waters: 1. Phosphate. *J. Appl. Phycol.* **14**: 365-374.

Matthews, I, & P. A. Cook - 1995. Diatom diet of abalone post-larvae (*Haliotis midae*) and the effect of pre-grazing the diatom overstorey. *Marine and Freshwater Research.* **46**: 545-548.

Mäkinen, T., Lindgren, S. & P. Eskelinen - 1988. Sieving as an effluent treatment method for aquaculture. *Aqucutlure. Eng.* **7**: 367-377.

Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C. M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & M. Troell - 2000. Effects of aquaculture on world fish supplies. *Nature*. **405**: 1017-1024.

Neori, A., Chopin, T., Troell, M., Buschmann, A. H., Kraemer, G. P., Halling, C., Shipigel, M. & C. Yarish - 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*. **231**: 361-391.

Newell, R. C., Lucas, M. I., Velimirov, B., & L. J. Seider – 1980. Quantitative significance of dissolved organic loses following fragmentation of kelp, (*Eklonia maxima & Laminaria pallida*). *Marine Ecology Progress Series*. **2**: 45-59.

Oakes, F. R. & R. C. Fields - 1996. Infestations of *Haliotis rufescens* shells by a sabellid polychaete. *Aquaculture.* **140**: 139-143.

Robertson-Andersson, D. - 2003. The cultivation of *Ulva lactaca* (Chlorophyta) in aquaculture effluent for the purpose of abalone feed and bioremediation. M.Sc. Thesis University of Cape Town.

Ruck, K. R. & P. A. Cook - 1998. Sabellid infestations in the shells of South African mollusks: Implications for abalone mariculture. *J. Shellfish Res.* **17**: (3): 693-700.

Ruck, K. R. - 2000. A new sabellid which infests the shells of mollusks and the implications for abalone mariculture. M.Sc. thesis, University of Cape Town, Pp. 90.

Sales, J. & P. J. Britz - 2000. South African abalone culture succeeds through collaboration. *World aquaculture.* **31:** (3)44-61.

Sales, J. - 2001. Nutrient digestibility in South African abalone (*Haliotis midae* L.). Ph.D. thesis, Rhodes University, Grahamstown, Pp. 171.

Sales, J. & P. J. Britz - 2001. Review; Research on abalone (*Haliotis midae* L.) cultivation in South Africa. *Aquaculture Res.* **32:** 863-874.

Samsukal, P – 2004. A preliminary study of effluent water quality of land based abalone farms in South Africa. M. Sc. Thesis. The Norwegian College of Fisheries Science, Norway, Tromsø Pp 69.

Sheilds, J. D., Buchal, M. M. & C. S. Friedman - 1998. Microencapsulation as a potential control technique against sabellid worms in abalone culture. *J. Shellfish. Res.* **17**(1):79-83.

Shipton, T. A. - 1999. The protein requirements of the South African abalone, *Haliotis midae*. Ph.D. thesis, Rhodes University, Grahmstown, Pp. 146.

Sorokin, Y. I. - 1973. Microbiological aspects of the productivity of coral reefs. *In:* Biology and geology of coral reefs, Vol II., Biology 1. O.A. Jones & R. Endeon (Eds.) Academic Press, New York, Pp 17-45, 480.

Tarr, R. J. Q. - 1989. Abalone. *In* Oceans of Life off Southern Africa. EdA. I. L. Payne & R. J. M. Crawford. Vlaeberg Publishers, South Africa. Pp. 62-69.

Tovar, A., Moreno, C., Manuel-Vez, M. P. & M. Garcia-Vargas - 2000. Environmental impacts of intensive aquaculture in marine waters. *Water Res.* **34** (1): 334-342.

Troell, M., Halling, C., Neori, A., Buschmann, A. H., Chopin, T., Yarish, C. & N. Kautsky - 2003. Integrated Mariculture: Asking The Right Questions. *Aquaculture*. **226**: 69-90.

Wiesmann, D., Scheid, H. & E. Pfeffer - 1988. Water pollution with phosphorus of dietary origin by intensively fed rainbow trout (Salmo gairdeneri Rich.) *Aquaculture*. **69**: 263-270.