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Seafloor Footprint Estimates of Waste Deposition from Potential Finfish Farms in the Wilson Bay area of the Firth of Thames

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NIWA Client Report: HAM2008-125
September 2008

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Executive Summary

Environment Waikato is currently scoping a plan change to allow for the diversification of aquaculture within existing aquaculture management areas in the Region. This plan change may allow for the cultivation of species other than mussels, including finfish. The biggest aquaculture management area in the Region is the Wilson Bay Marine Farming Zone located in the Firth of Thames. Currently, Area A of the Wilson Bay Zone is consented for 470 ha of mussel longlines, and Area B of the Zone, once developed, will comprise an additional 520 ha. In addition to this, 220 ha of older smaller sized farms exist within Wilson Bay (Figure 1).

To provide some background to assist in scoping an aquaculture diversification plan change, this report presents estimates of the scale of expected benthic effects that maybe associated with an individual cage within a fish farm in the Wilson Bay Marine Farming Zone. These estimates are based on the dispersal of waste material (i.e., feed pellets or fish faeces) due to measured currents, bathymetry, a range of realistic fall velocities, best estimates of cage dimensions (cage area and depth) and a range of depths below the cage that could be achieved within Area A.

Data presented in this report show that less than 11% of the waste material from an individual cage may end up being deposited directly beneath a cage. As cages are placed in deeper water less farm waste will be deposited directly beneath the cage, if cages are placed in an area of higher flows less waste material will be deposited directly beneath the cage and if farm waste material has low fall velocity less waste material will be deposited directly beneath the cage.

Results presented in this report give the likely level of deposition (g/m^2/day) for a hypothetical waste load of 1000 g/day from an individual cage. Data from the modelling exercise has shown that in the lateral direction (i.e., in the cross shore direction) there is unlikely to be any cumulative effects between individual cages if cage are placed at least 100 m apart. The modelling has shown that, in the long shore direction, waste material from a cage can be dispersed up to 700 m away from the cage. However, based on a threshold of measurable effects, the longitudinal footprint of an individual cage within a farm will be much smaller than this and may range between 100 and 200 m. Once the actual cage waste loading (based on cage dimensions, stocking rate and feed conversion ratios) is known, it will be possible to determine the actual extent of the cage footprint using the results presented in this report. Once data on the baseline sediment conditions are known the extent of the measurable effect or benthic footprint can be determined.

1. Introduction

Environment Waikato is currently scoping a plan change to allow for the diversification of aquaculture within existing aquaculture management areas in the Region. This plan change will potentially allow for the cultivation of species other than mussels, including finfish. The biggest aquaculture management area in the Region is the Wilson Bay Marine Farming Zone located in the Firth of Thames. Currently, Area A of the Wilson Bay Zone is consented for 470 ha of mussel longlines, and Area B of the Zone, once developed, will comprise an additional 520 ha. In addition to this, 220 ha of older smaller sized farms exist within Wilson Bay (Figure 1).

To provide some background to assist in scoping an aquaculture diversification plan change, this report presents estimates of the scale of expected benthic effects that maybe associated with individual fish farms in the Wilson Bay Marine Farming Zone. The estimates of the benthic footprints are based on the dispersal of waste material (i.e., feed pellets or fish faeces) due to measured currents, a range of realistic fall velocities, best estimates of cage dimensions (cage area and depth) and a range of cage free depths that could be achieved within Area A.

The modelling does not take into account:

- resuspension of material from the seabed;
- time varying fall velocity of farm waste (feed pellets expand with exposure to water);
- dissolution of waste material as it falls through the water column;
- actual farm waste loadings (either from feed pellets, faeces or both).

For the deeper cage sites the results presented in this report in terms of the extent of the cage footprint are likely to be close to those that will actually occur for an individual cage within a farm. Resuspension of bed material (i.e., farm waste and native sediment) by waves in deep water will be very infrequent and will likely lead to only a small change in the extent and shape of the tidally derived footprint. For shallower cage sites resuspension of bed material by waves will still only occur relatively infrequently.

Any resuspension of bed material will result in the mixing of both farm waste and native sediments. The actual degree and effect of this mixing will depend on the length of time since the last bed mobilisation (because farm waste is likely to consolidate with time and therefore become less likely to be mobilised), the depth to which material is reworked (which will be dependent on the duration and intensity of the wind/wave event), the depth of farm waste material on the bed (which will determine how much farm waste and/or native sediment is mobilised and mixed) and the relative concentrations of the native sediments and farm waste (which will determine the final "mixed" concentration of the bed material).

Quantifying the effects of these sediment mixing processes and their effect on the resulting benthic footprint is beyond the scope of this report. Resuspension of bed material will tend to reduce the concentrations along the footprint centreline (due to farm waste and native sediment mixing and the advection of farm waste away from the centreline during resuspension events) and increase the overall size of the footprint during a resuspension event. However, because of the relative infrequency of resuspension events the modelling results presented here will provide a good estimate of the predominant footprint which is important in terms of the long term benthic effects of an individual cage.

The results presented in this report are in terms of a hypothetical load from an individual cage within a farm - actual loadings of specific farm waste (feed pellets, fish faeces, nitrogen etc.) along with estimates of any losses to the water column and the spacing of cages within a farm area can be used later to produce estimates of the actual farm footprint.

By presenting a range of fall velocities the effects of time varying fall velocities can be quantified in terms of the benthic impact.

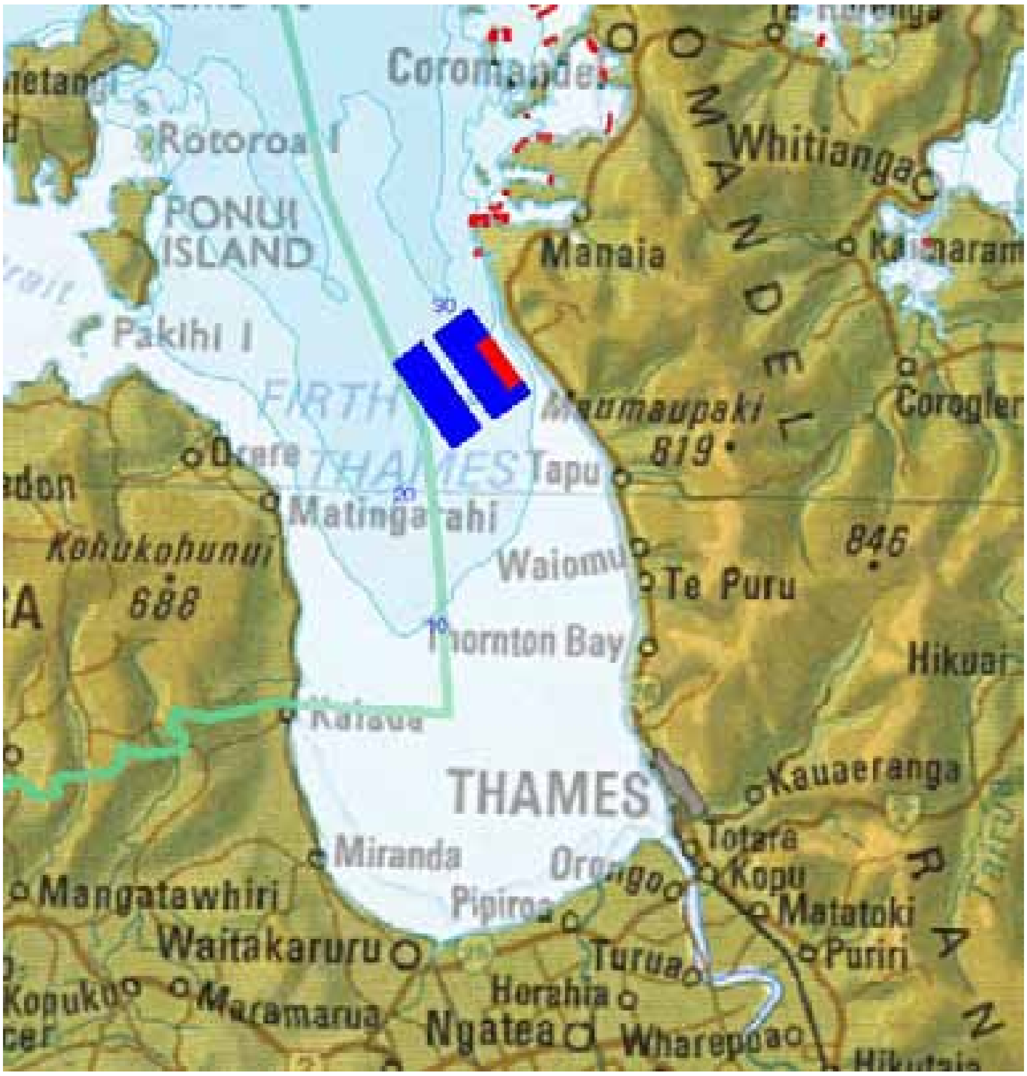

Figure 1: Map of the Firth of Thames showing the original Marine Farms (red), and Areas A and B of the Marine Farm Zone at Wilson Bay (blue). Green line shows Environment Waikato's marine boundary.

2. Methods

2.1 Dispersion modelling

Representative sites at three depths in the vicinity of Area A have been used to establish the effect of cage depth and free water depth (the depth below the cage) on predicted footprint. At each site three representative fall velocities have been used to model the dispersion of farm waste material due to observed currents from the 2002 monitoring programme for Area A (Oldman et al. 2002). The model used was the MIKE21 particle tracking model similar to that used by Oldman and Senior (2000) to quantify the dispersal from aquaculture within the Wilson Bay area. For each cage site particles were randomly released within a 15 m by 15 m area at a random depth between the surface and the bottom of the cage. Predictions of where material may settle on the bed following its release from an individual cage are presented.

2.2 Bathymetry

A bathymetry grid with 5-m horizontal spacing was established using existing bathymetry data in the vicinity of Area A (Figure 2). Three representative cage locations from within the grid were chosen based on probable combinations of water and cage depth for Area A used by Giles (2007):

- water depth = 10 m, cage depth = 5 m, free water depth = 5 m, cage area = 15 m x 15 m;

- water depth = 20 m, cage depth = 10 m, free water depth = 10 m, cage area = 15 m x 15 m;

- water depth = 30 m, cage depth = 15 m free water depth = 15 m, cage area = 15 m x 15 m.

The locations of the individual finfish cages are shown in Figure 2. The cage located in 10 m water depth is inshore of the existing Area A site, the 20 deep m cage is in the middle of Area A and the 30 m deep cage sites just outside Area A to the north of the Area A. By using three different depths, the range of depths where fish farms could be developed within Area A are effectively modelled.

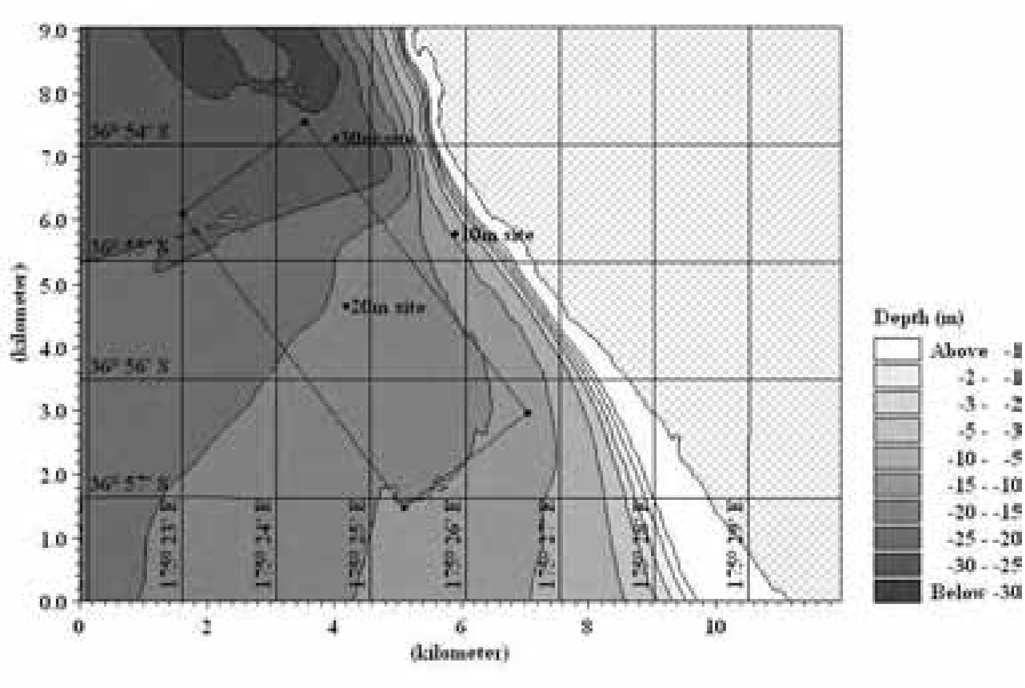

Figure 2: Bathymetric grid and location of the individual cages used for modelling to determine benthic footprint for potential fish farm sites in the Wilson Bay area.

2.3 Currents

Following their release, particles are advected away from the farm site using the recorded currents from the 70 day acoustic doppler current profiler (ADCP) deployment within Area A (Oldman et al. 2002). Every 10-minutes during the deployment period the ADCP recorded the average current within 18 one metre bins through the water column. For each of these 10-minute records the 25th, 50th and 75th percentile current speeds were determined. From the magnitude of the 25th, 50th and 75th percentile north-south and east-west components the mean directions for the 25th, 50th and 75th current speeds were calculated. Figure 3 shows the histogram plots of the resulting current records. The average current speed over the 70 day deployment period for the three percentiles are 0.18 m/s, 0.22 m/s and 0.25 m/s and the maximum currents over the 70 day deployment period range from 0.55 to 0.65 m/s. These values are in good agreement with the current speeds used in the Bayesian analysis of the benthic carrying capacity of finfish in the Firth of Thames (Giles, 2007). The model applies the given time series of currents across the full spatial extent of a bathymetry grid. In reality currents at any given time within Area A will vary. Gall et al. (2003) found that tidal currents at the southern end of Area A were on average 20-25% lower than those measured in the centre of Area A, while for a site to the north of Area A currents were on average 20-25% higher than those measured in the centre of Area A. By using the 25th, 50th and 75th percentile currents from the ADCP site (located in the centre of Area A) the natural variability of currents within Area A is accounted for.

Analysis of the ADCP record indicates that under most conditions the observed vertical variation of current speed can be approximated by a log velocity profile, thus:

$$V_z = \frac{U_f}{\kappa} \ln\left(\frac{h-z}{k_n / 30} \right)$$

Where V_z is the velocity at a depth z m above the bed, U_f is the friction velocity, h the total water depth, k_n the Nikuradse roughness (m) and is the von Karman constant (0.42). The friction velocity is given by:

$$U_f = \left(\frac{v_{mean} . \kappa}{\ln\left(\frac{h}{k_n / 30} \right) - 1} \right)$$

Where v_{mean} is the mean current velocity for the whole water column. A roughness length k_n of 0.05 m was estimated from the near bed ADCP data. This value corresponds to the value used for calibrating the original Firth of Thames model (Oldman and Senior, 2000) and the more recently validated model of the Firth (Oldman et al. 2006).

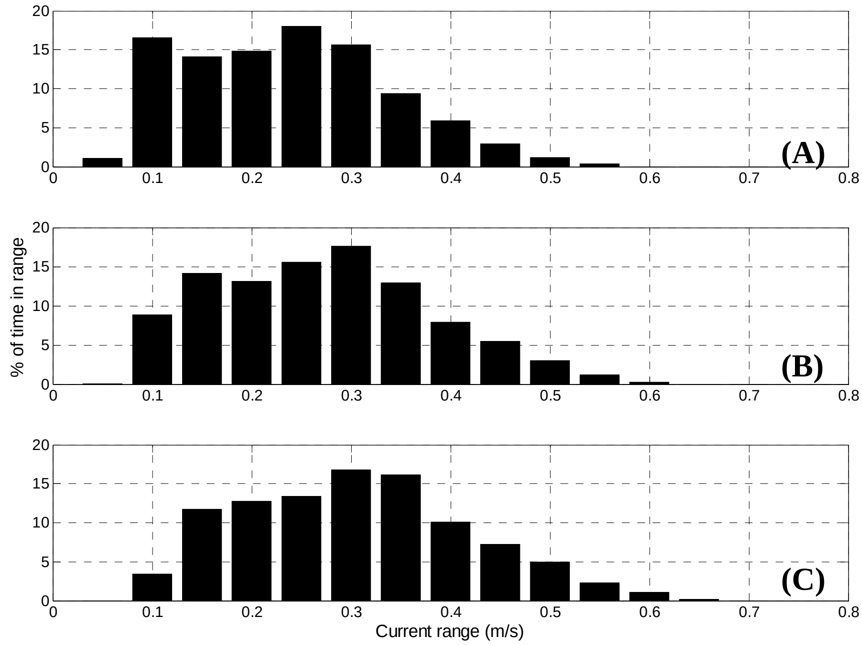

Figure 3: Histogram plots of the (A) 25th, (B) 50th and (C) 75th percentile currents from the current metre deployment within Area A between 24 January 2002 and 4 April 2002.

2.4 Fall velocity

One of the key parameters required for the estimate of the farm footprint is the sinking velocity of waste material (fish faeces and waste feed pellets). Various studies have indicated that sinking velocities vary among species and hence it is imperative to use a realistic range of sinking rates. Vassallo et al. (2006) reported fall velocities for feed pellets ranging from 0.087 m/s for 3 mm pellets through to 0.144 m/s for 5 mm pellets. Chen et al. (1999) measured fall velocities for Atlantic Salmon faeces ranging from 0.053 to 0.066 m/s. Cromey et al. (2002) used fall velocities of 0.18 m/s for feed and 0.032 m/s for faeces to estimate benthic impacts of Scottish marine farms using a particle tracking modelling approach similar to the one used in this study. Elberizon and Kelly (1998) estimated fall velocities for the diet of freshwater salmonid ranging from 0.02 to 0.12 m/s.

Based on these literature values three fall velocities were assigned to the particles:

- 0.02 m/s - representative of the lower range of reported values;

- 0.06 m/s – representative of typical faeces fall velocities;
- 0.14 m/s – representative of larger feed pellet fall velocity.

2.5 Farm loading

Plots of the predicted bed deposition (g/m^2/day) for the hypothetical waste load of 1000 g/day (1 kg/day) are provided. A standard, hypothetical waste load of 1000 g/day was applied in the model because actual loads could vary widely in response to farm production and operational practices. As depositional rates are directly proportional to waste loads, the deposition rates for other loads can be estimated by directly scaling the deposition rates predicted for the standard load.

3. Results

3.1 Deposition beneath individual cages

Firstly, estimates of the average deposition directly beneath each of the modelled cages are given. These values give an indication of the likely level of deposition that may occur directly beneath a cage for the given current speed, fall velocity and cage depth. The predicted mass of material directly beneath the cages (Figure 4) show that between 1.7 and 10.9% of material is deposited directly beneath a 5 m deep cage in 10 m water depth, between 1.0 and 9.3% of material is deposited directly beneath a 10 m deep cage in 20 m water depth and between 0.6 and 6.6% of material is deposited directly beneath a 15 m deep cage in 30 m water depth. The remaining material is exported away from the cage site, dispersed by the currents and deposited beyond the cage margin. For each cage/water depth combination (Table 1) it can be seen that the highest deposition occurs for the largest fall velocity material and as currents decrease more material becomes deposited directly beneath a farm.

Table 1: Percentage of farm waste material deposited directly beneath an individual cage. Based on 15 by 15 m cage for different current strengths and fall velocity.

Modelled scenario	5 m cage in 10 m water depth	10 m cage in 20 m water depth	15 m cage in 30 m water depth
25th currents, 02 cm/s	3.8%	2.3%	1.5%
25th currents, 06 cm/s	7.6%	5.5%	3.7%
25th currents, 14 cm/s	10.9%	9.3%	6.6%
50th currents, 02 cm/s	2.5%	1.5%	1.0%
50th currents, 06 cm/s	5.5%	3.7%	2.4%
50th currents, 14 cm/s	8.4%	6.6%	4.6%
75th currents, 02 cm/s	1.7%	1.0%	0.6%
75th currents, 06 cm/s	3.9%	2.5%	1.6%
75th currents, 14 cm/s	6.2%	4.7%	3.2%

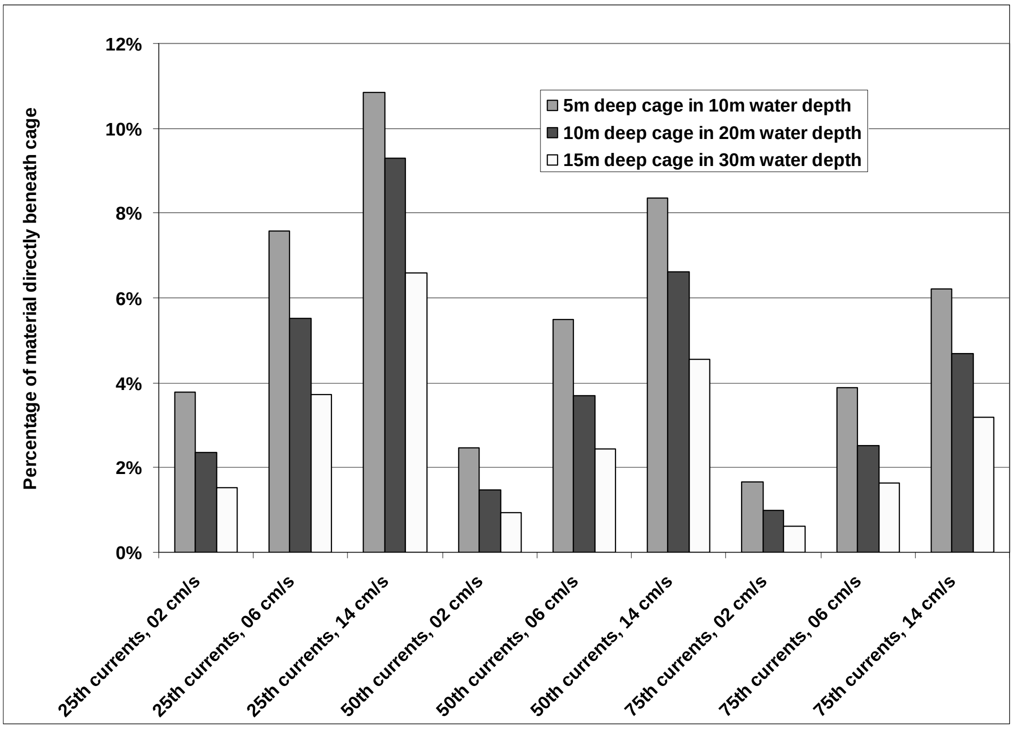

Figure 4: Average mass directly beneath a 15 by 15 m cage (as a percentage of the total mass released), for each combination of cage depth, water depth and fall velocity.

3.2 Far-field estimates of deposition

In addition to establishing the quantity of material that may remain beneath each individual cage the output from the model simulations can also be used to determine the extent of the depositional zone for an individual cage within a farm. Figures 8-34 show the estimated mean deposition rate (g/m^2/day) for the 70-day simulation for a hypothetical waste load of 1000 g/day from an individual cage. Note the scaling of the plots is non-linear so that the detail of the estimates in the immediate vicinity and towards the outer limits of the deposition zone can be seen. The outer band of the footprint is for deposition in the range between 0.001 and 0.002 g/m^2/day which equates to a dilution of greater than 2000-fold[1]. Table 2 shows the predicted length and width of the depositional zone (as defined by the edge of the 0.001 g/m^2/day area) for each of the scenarios modelled.

[1] If all the waste material was to deposit directly beneath the a cage measuring 15 m by 15 m the deposition would be 4.4 g/m^2/day (1000 g/day/15 m/15 m). Therefore 0.001 g/m^2/day is equivalent to a dilution of 4444-fold and a deposition of 0.002 g/m^2/day equals a dilution of 2222-fold.

Data in the table shows that the maximum width of the depositional zone is 75 m which is the same as the gap existing between farm blocks in Area A. This would suggest that even if cages are placed on the outer limits of an individual farm block there is unlikely to be any accumulative effect between individual farm blocks. By placing cages at least 100 m apart in the cross shore direction the combined effect would be no more than an increase in sediment concentration of 0.002 g/m^2/day at the outer limits of deposition, per kg of loading.

For the smallest fall velocity the predicted longitudinal depositional zone extends between 440 m and 700 m of the cage site. For the intermediate fall velocity the predicted longitudinal depositional zone extends between 225 m and 470 m from the cage site. For the largest fall velocity the predicted longitudinal depositional zone extends between 150 m and 300 m from the cage site. In all cases the length of the depositional zone increases as currents increase and as the cage location becomes deeper. These values suggest that if cages are placed near the outer limits of an individual farm block there is potential for a cumulative effect between individual farms in the long shore direction. Likewise within individual farm blocks, if cages are placed within 500-700 m of each other in the long shore direction there will be some degree of cumulative effect.

3.3 Farm footprint estimates

The preceding section gave estimates of the extent of the depositional zone based on a depositional threshold value of 0.001 g/m^2/day (equating to a dilution of more than 4000-fold). It is likely that this level of dilution would result in very little impact at the outer extent of the depositional zone. Recent work carried out for the Ministry of Fisheries (Forrest et al. 2007) indicates that the depositional zone for a fish farm is generally much greater than the zone in which measurable effects can be determined. From page 6 of that report;

"*Farm-derived particulates may disperse further than the footprint of measurable effects, as shown by a recent overseas study detecting farm wastes up to 1 km from the source (Sara et al. 2004). Such findings highlight that the seabed environment beyond the effects footprint may be exposed to farm-derived materials, but has a capacity to assimilate them without exhibiting any measurable ecological changes.*"

Without quantification of the sediment parameters (and their variability), the actual loadings from fish farms (based on stocking density, number of cages, size of cages, farm depth and feed conversion ratios) it is difficult to establish the extent of the benthic footprint where there will be measurable effects due to an individual farm cage. However, the data from this modelling can be used to provide estimates of benthic effects once such data becomes available. Data shown in figures 5-7 shows the predicted average deposition value as a function of distance from the cage for each combination of cage depth, fall velocity and current strength. Variations in current strength have the least influence on the predicted deposition. For each fall velocity modelled (i.e., individual symbol in figures 5-8) the scatter of data is due to the variations in current strengths. Estimates to the right of the scatter of points are for the 75th percentile currents while those to the left are for the 25th percentile currents. Both cage depth and fall velocity have marked effects on the predicted deposition values. With increasing fall velocity more material is deposited directly beneath the cage (distance=0) and the rate at which the predicted deposition changes with distance is greater.

The data in the plots can be used to define the benthic footprint based on a certain deposition threshold – at distances beyond the benthic footprint there would be no measureable benthic impacts. As a example, if a deposition threshold of 0.01 g/m^2/day were to be used to define a benthic footprint, given a waste load of 1000 g per day per cage as used here, the benthic footprint would lie between 110-210 m for 5 m deep cages in 10 m water depth, between 140-210 m for 10 m deep cages in 20 m water depth and between 170-210 m for 15 m deep cages in 30 m water depth. This depositional threshold equates to a dilution of over 400-fold[2]. Because a hypothetical waste load has been used, the plots provided in this report can be scaled for an individual cage once the actual waste loading for an individual cage are known[3].

[2] If all the waste material was to deposit directly beneath a cage measuring 15 m by 15 m the deposition would be 4.4 g/m^2/day (1000 g/day divided by 15 m by 15 m). Therefore 0.01 g/m^2/day is equivalent to a dilution of 444-fold.

[3] Note that a copy of the spreadsheet used to produce these plots (including a scale factor for actual waste loading) will be made available to Environment Waikato staff.

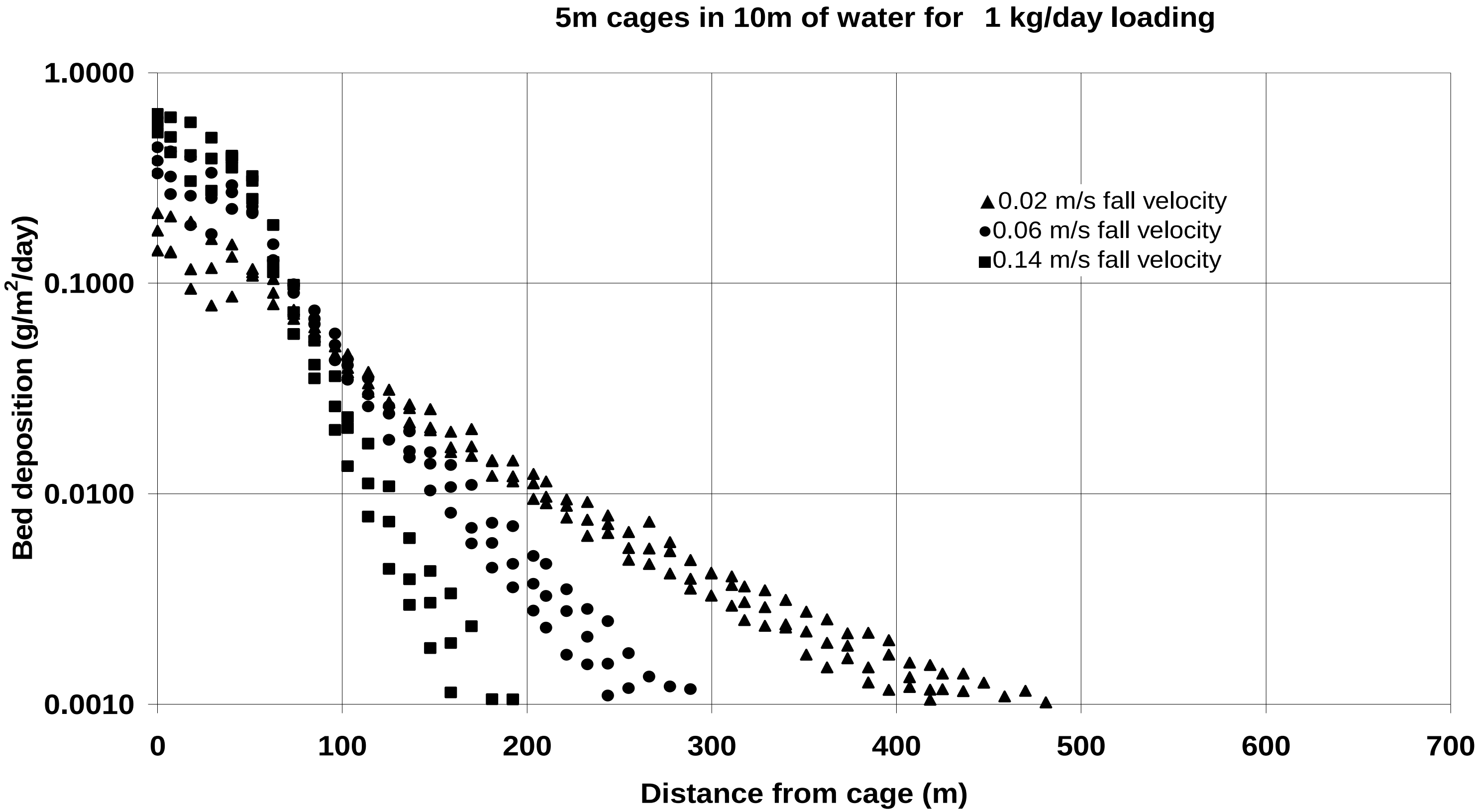

Figure 5: Predicted average deposition rate (g/m^2/day averaged for 70-day simulation) versus distance for an individual 5 m deep, 15 m by 15 m cage in 10 m of water and a waste load of 1 kg/day for each combination of fall velocity and current strength for a 5 m cage in 10 m water depth.

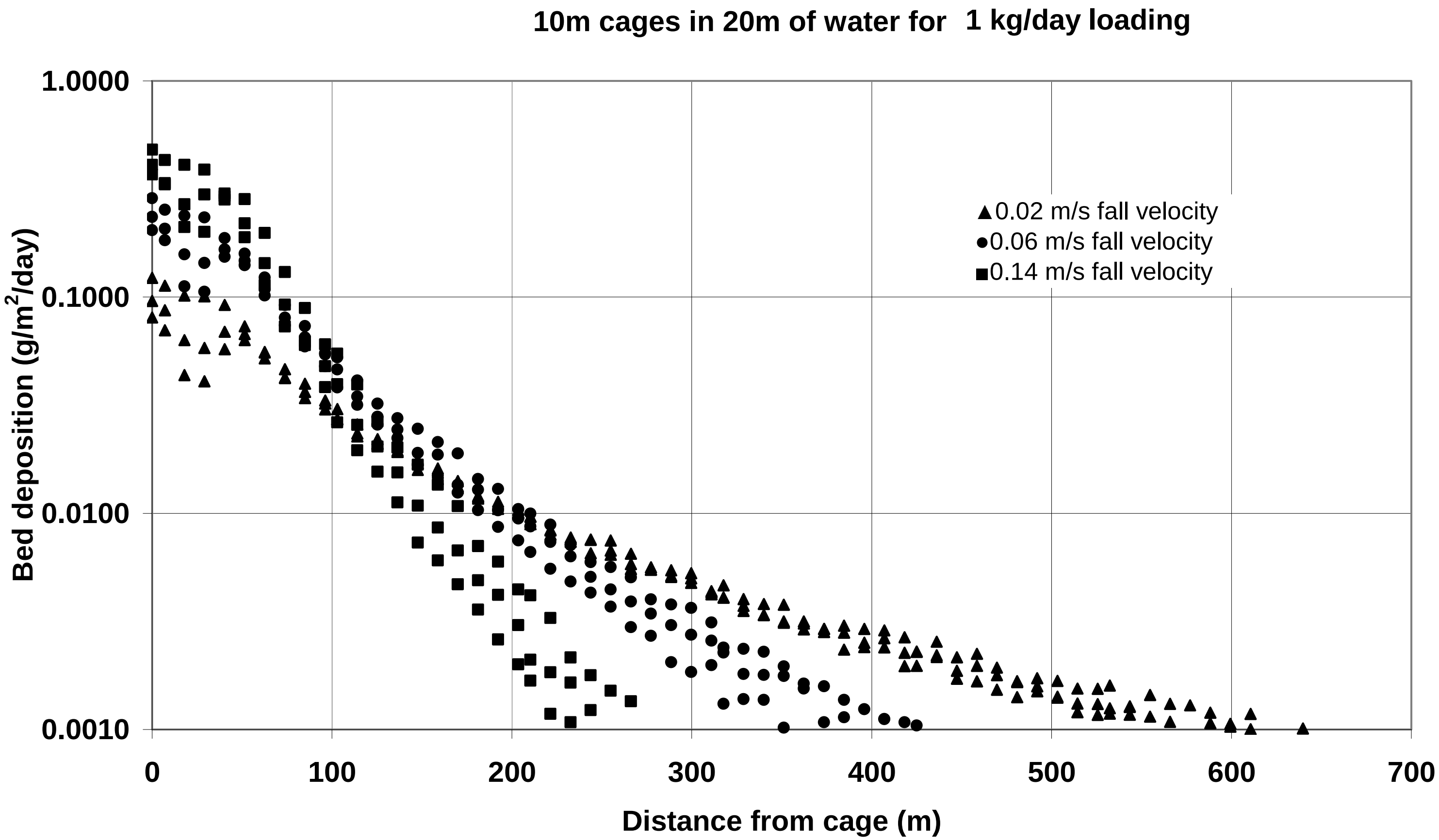

Figure 5: Predicted average deposition rate (g/m^2/day averaged for 70-day simulation) versus distance for an individual 10 m deep, 15 m by 15 m cage in 20 m of water and a waste load of 1 kg/day for each combination of fall velocity and current strength for a 10 m cage in 20 m water depth.

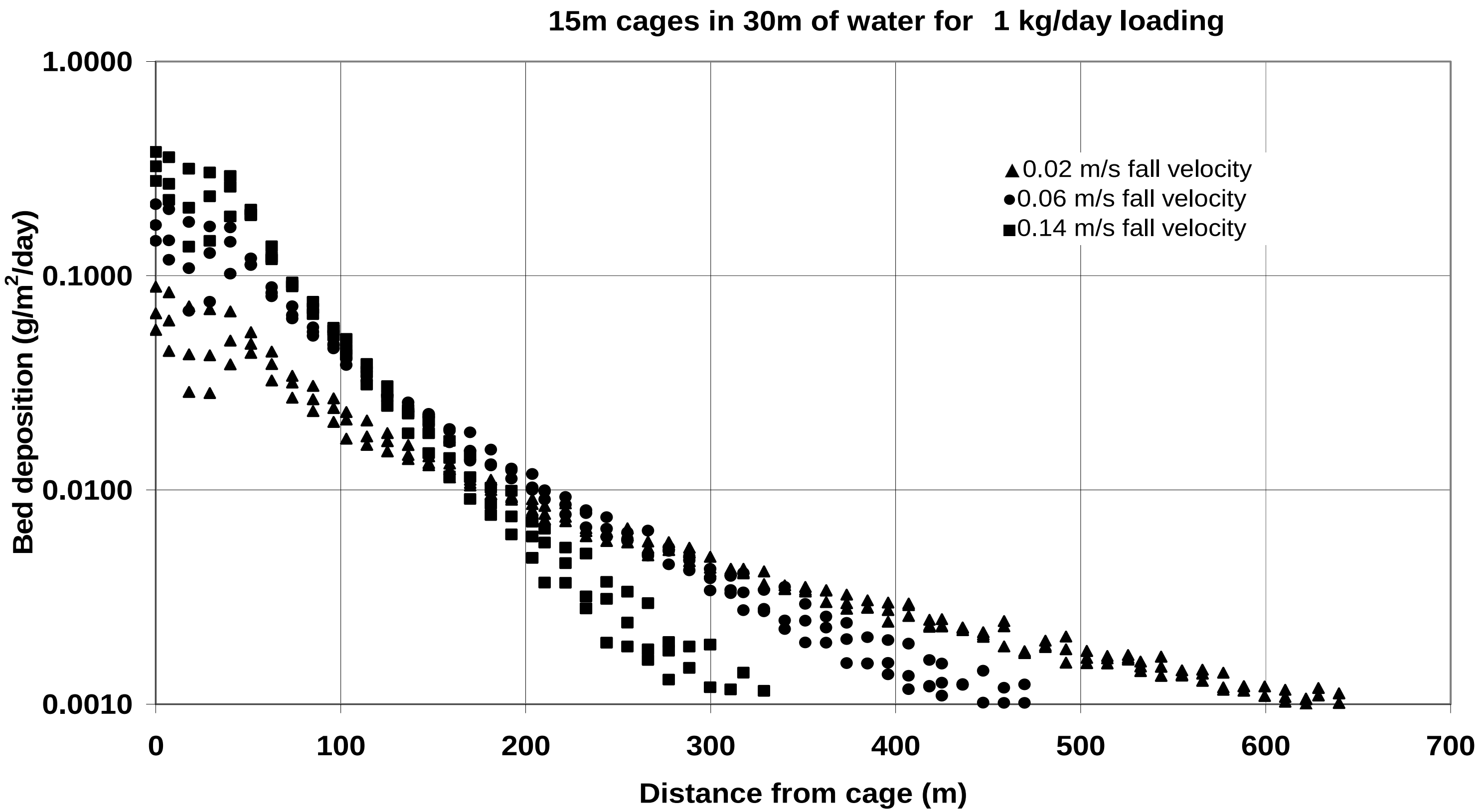

Figure 6: Predicted average deposition rate (g/m^2/day averaged for 70-day simulation) versus distance for an individual 15 m deep, 15 m by 15 m cage in 30 m of water and a waste load of 1 kg/day for each combination of fall velocity and current strength.

4. Conclusions

Based on the measured bathymetry and currents from the Wilson Bay area of the Firth of Thames modelling of the dispersal of fish farm waste (i.e., food pellets and/or fish faeces) has been carried out. The modelling includes a range of fall velocities and current strengths to determine the likely scale of expected benthic effects that maybe associated with fish farms in the Firth of Thames Wilson Bay Marine Farming Zone. Rather than try to define the actual waste loading from an individual cage and then scale this up to the farm level, the modelling used a hypothetical load approach. In this way all results presented in this report can be scaled up once farm loading is known. The farm loading will depend on the stocking density, cage dimensions, cage layout, feed conversion ratios and dissolution of material into the water column is known.

Data in Table 1 gives the percentage of material than is likely to be deposited directly beneath a 15 m by 15 m cage. Given the actual waste loading for the cage the average daily deposition rate (g/m^2/day) beneath the cage can then be calculated. Should cages of other dimensions be considered then the data in Table 1 and the information if Figures 5-7 can be used to make estimates of the likely deposition beneath cages.

Similarly, data presented in figures 5-7 (showing the predicted average daily deposition rate (g/m^2/day) with distance from the cage) can be scaled once the actual cage waste loading is known. Data in these plots can then be used to define the size of the benthic footprint once data on the baseline sediment conditions are known.

Data from the modelling exercise has shown that in the lateral direction (i.e., in the cross shore direction) there is unlikely to be any cumulative effects between individual cages if they are placed at least 100 m apart. The modelling has shown that, in the long shore direction, waste material from a cage can be dispersed up to 700 m away from the cage. Based on any quantifiable threshold of measurable effects, the longitudinal footprint of an individual cage within a farm will be much smaller than this and may range between 100 and 200 m. Given actual waste loadings from individual cages, cage dimensions, water depths, cage layout and baseline sediment data, as well as environmental thresholds denoting acceptable loadings, the actual extent of longitudinal footprint for an individual cage can be determined. By combining results from an individual cage and information on cage layout within a farm estimates of the accumulative effects can also be quantified.

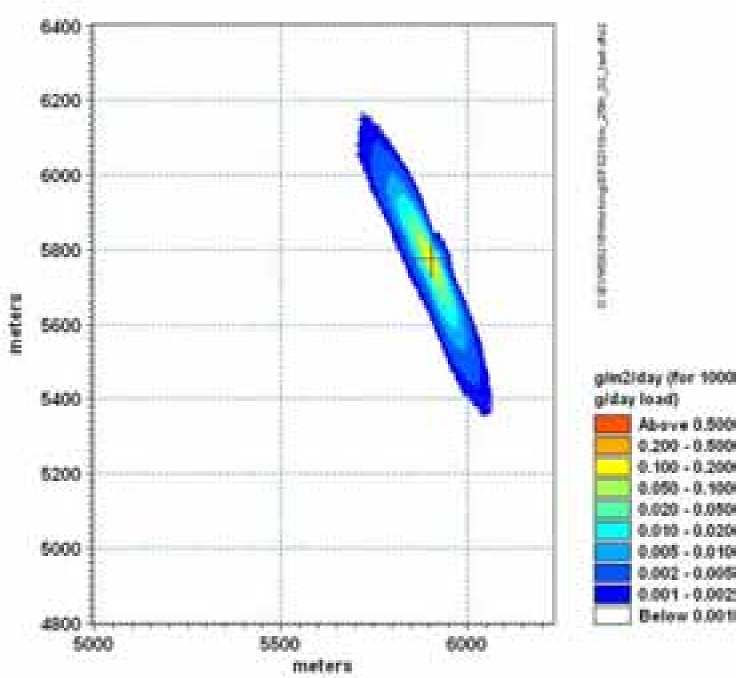

Figure 7: Extent of deposition zone for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 25th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage. Marker shows location of the centre of the cage.

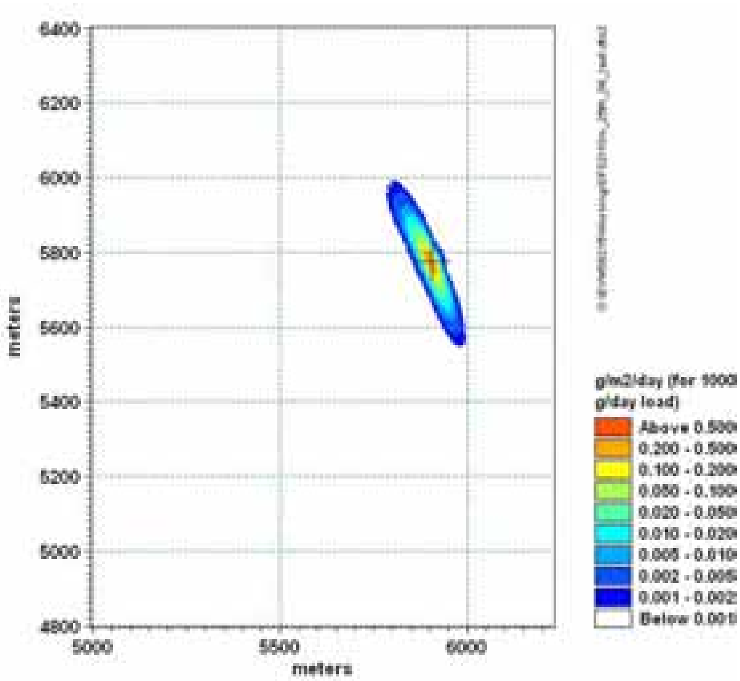

Figure 8: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 25th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

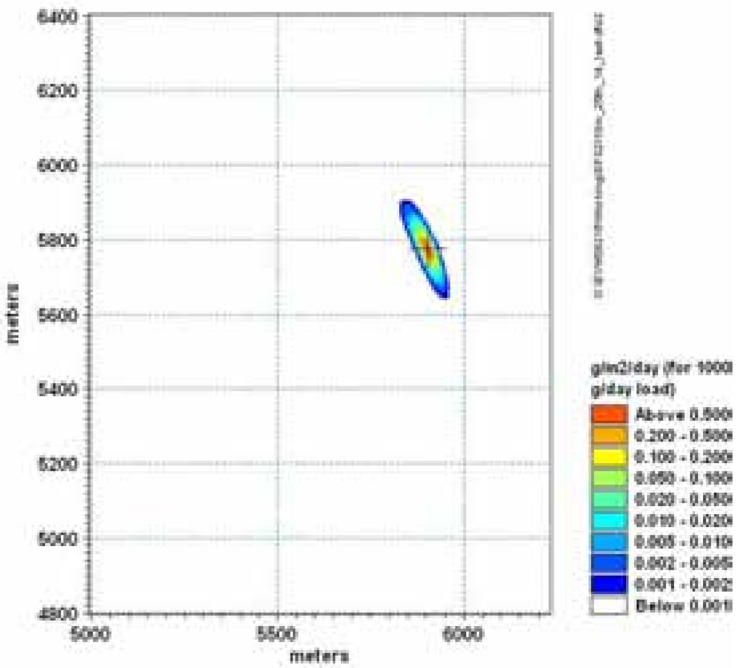

Figure 9: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 25th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

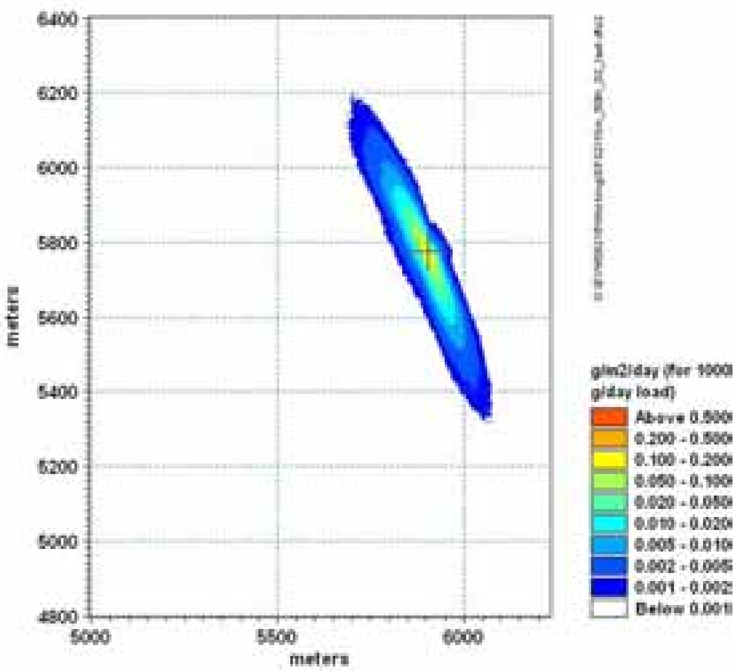

Figure 10: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 50th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

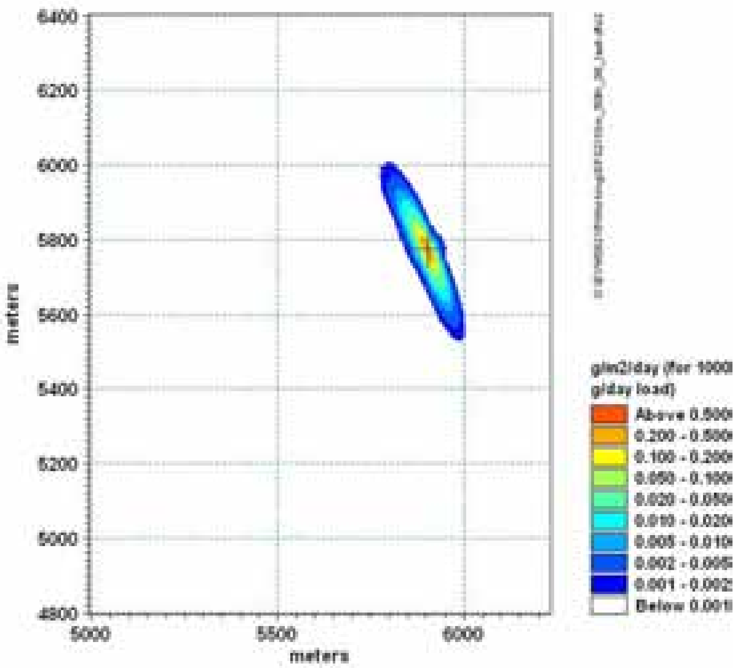

Figure 11: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 50th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

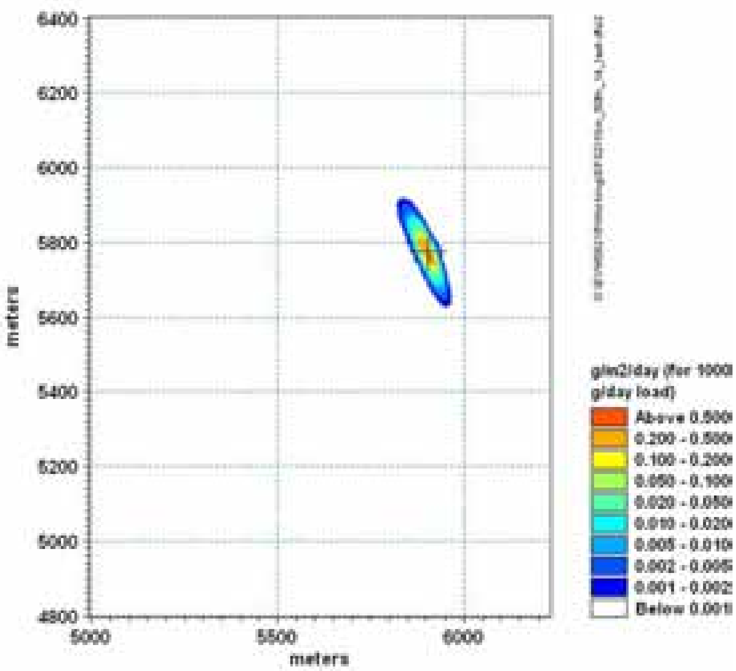

Figure 12: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 50th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

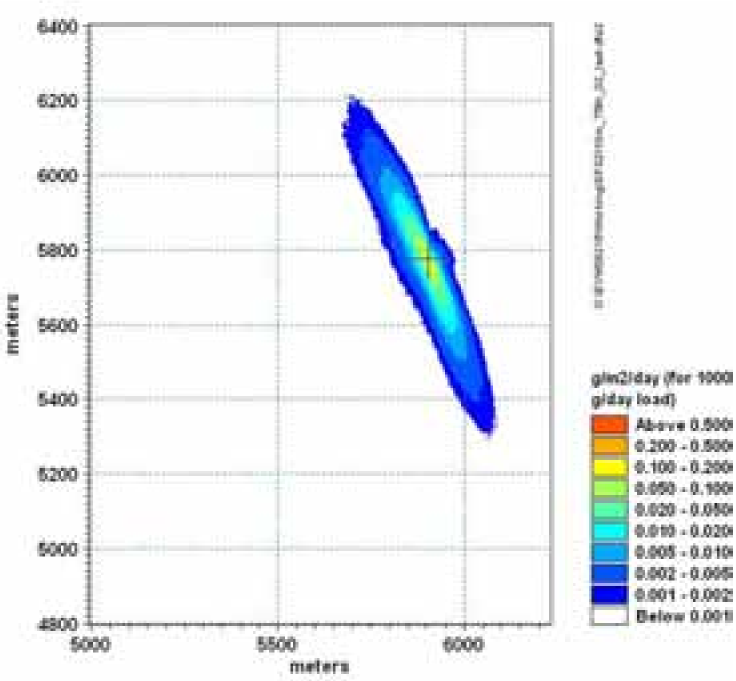

Figure 13: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 75th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

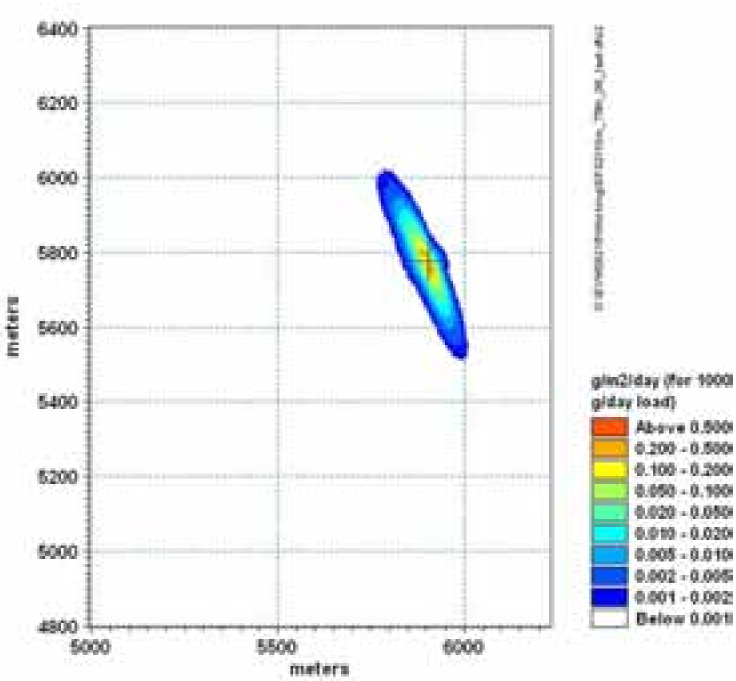

Figure 14: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 75th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

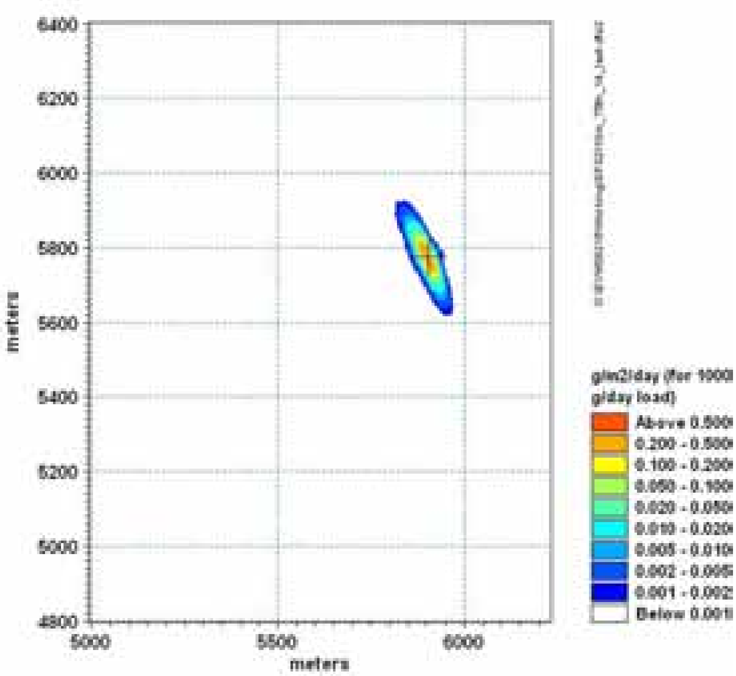

Figure 15: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 5 m deep, 15 m by 15 m cage in 10 m water depth under 75th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

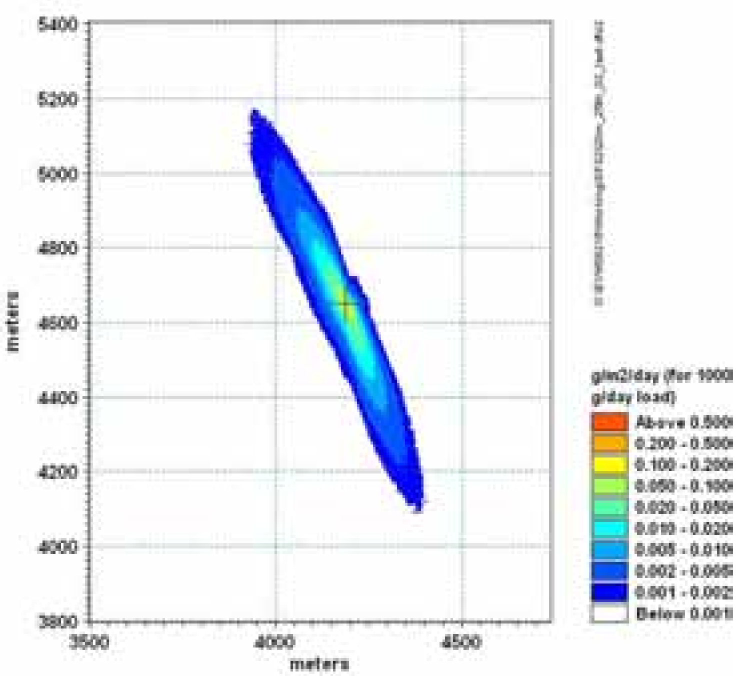

Figure 16: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 25th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

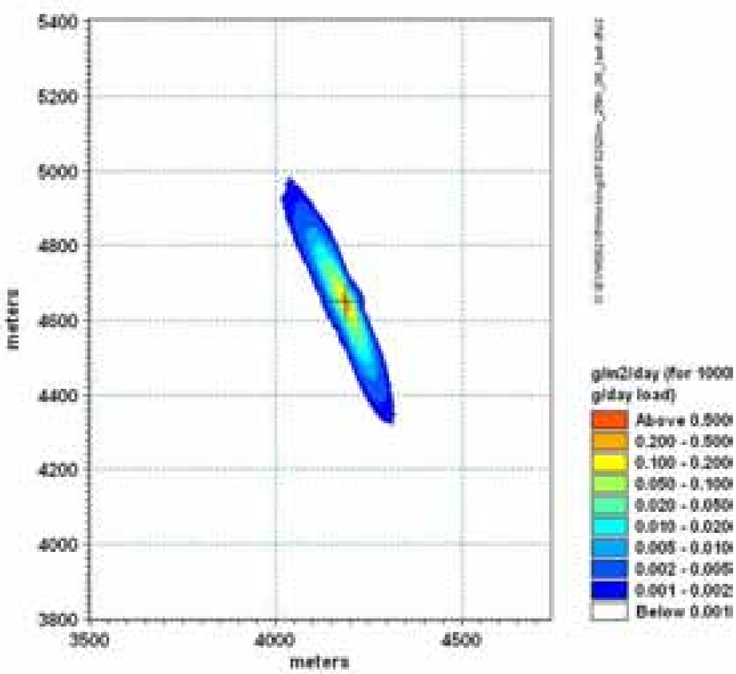

Figure 17: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 25th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

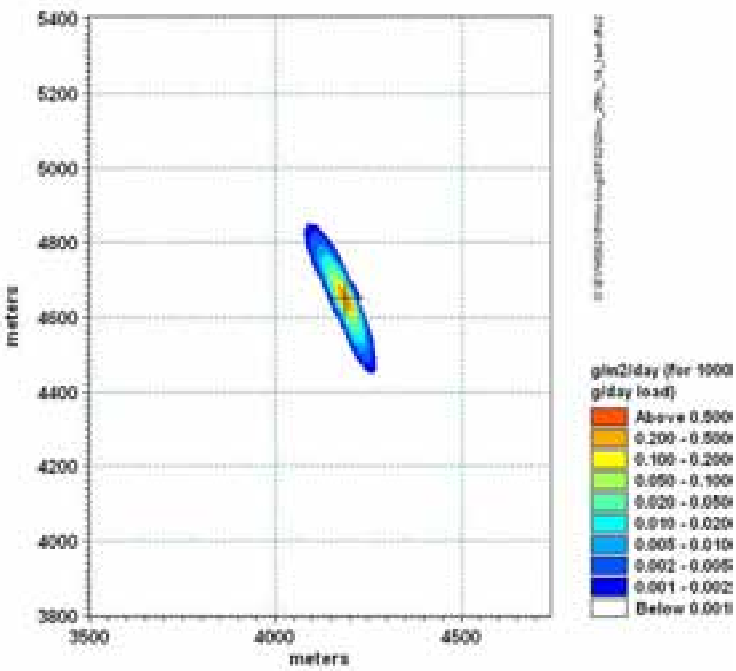

Figure 18: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 25th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

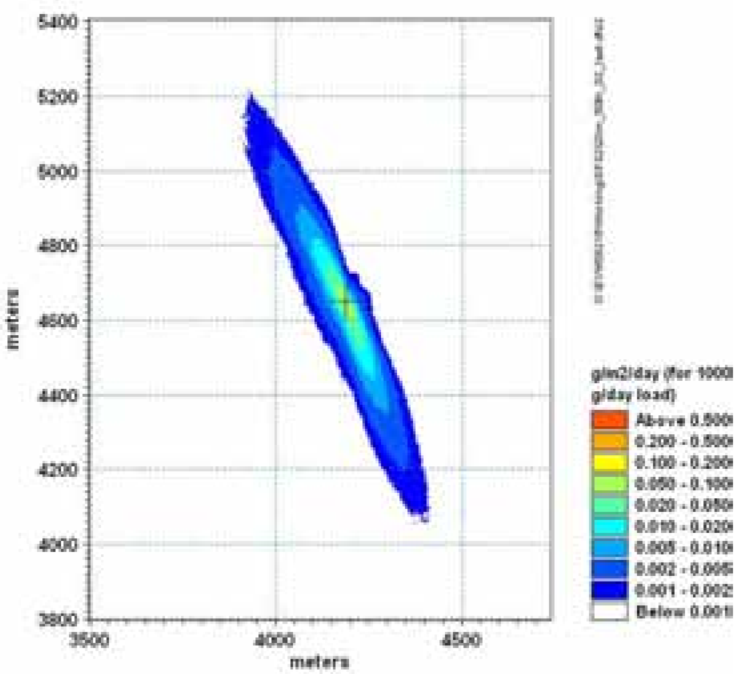

Figure 19: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 50th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

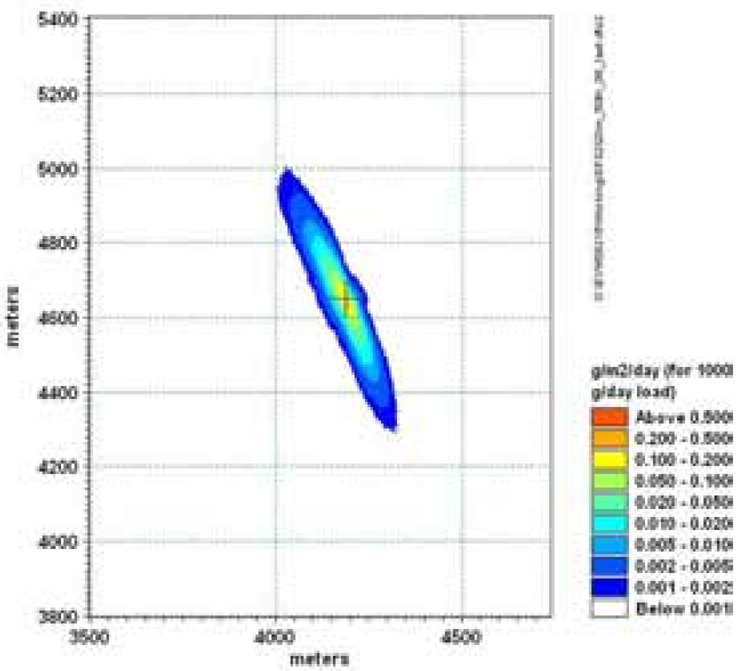

Figure 20: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 50th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

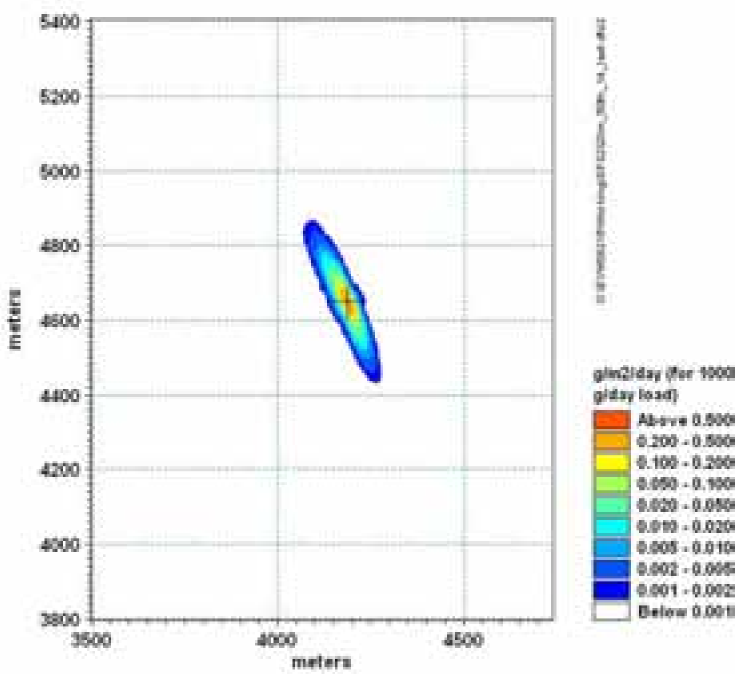

Figure 21: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 50^{th} percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

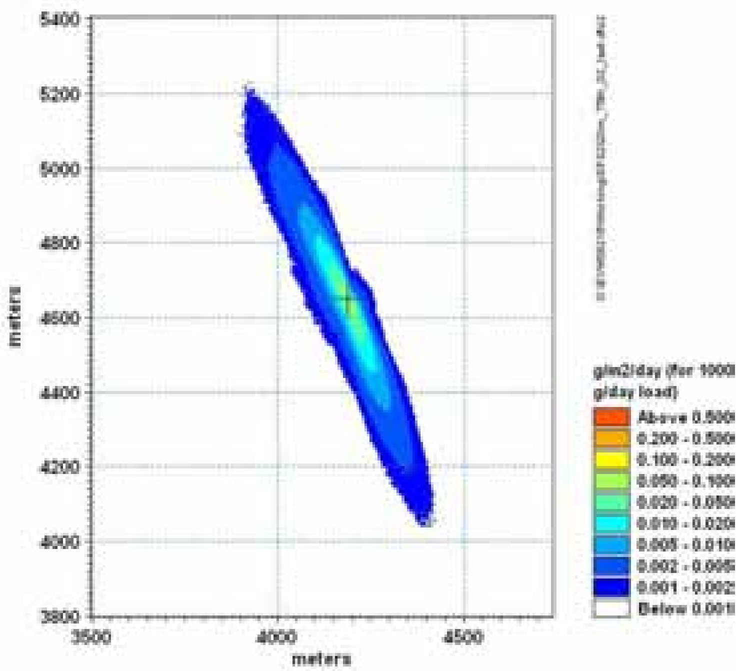

Figure 22: Extent of deposition zone (based on daily deposition limit of 0.001 $g/m^2/day$) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 75^{th} percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

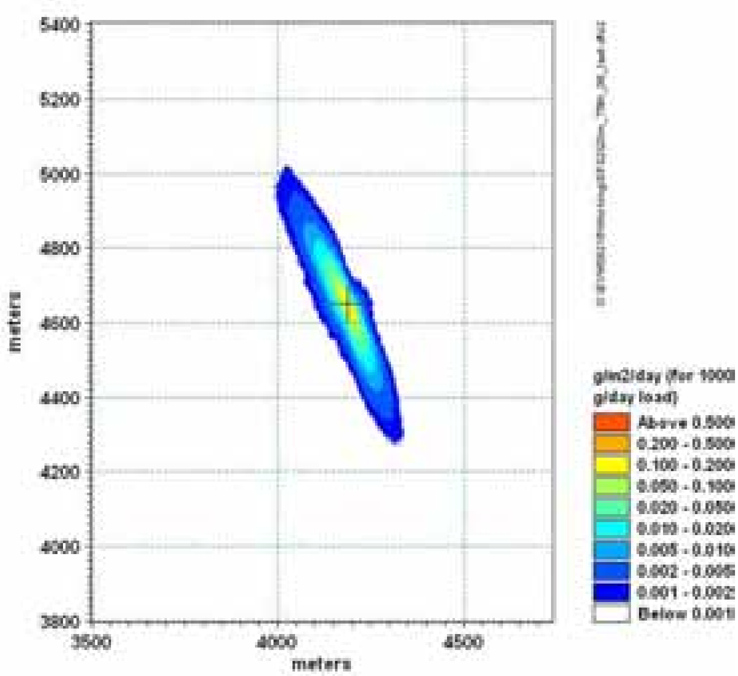

Figure 23: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 75th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

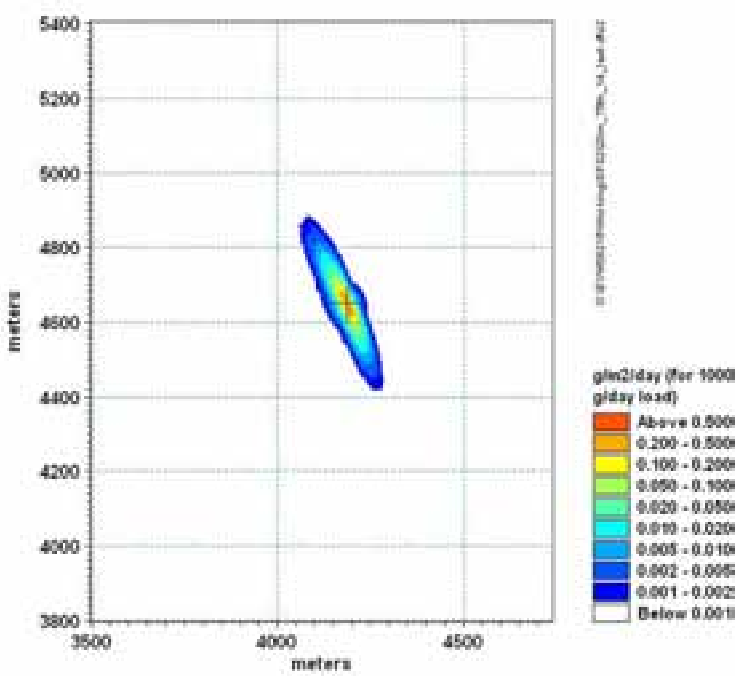

Figure 24: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 10 m deep, 15 m by 15 m cage in 20 m water depth under 75th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

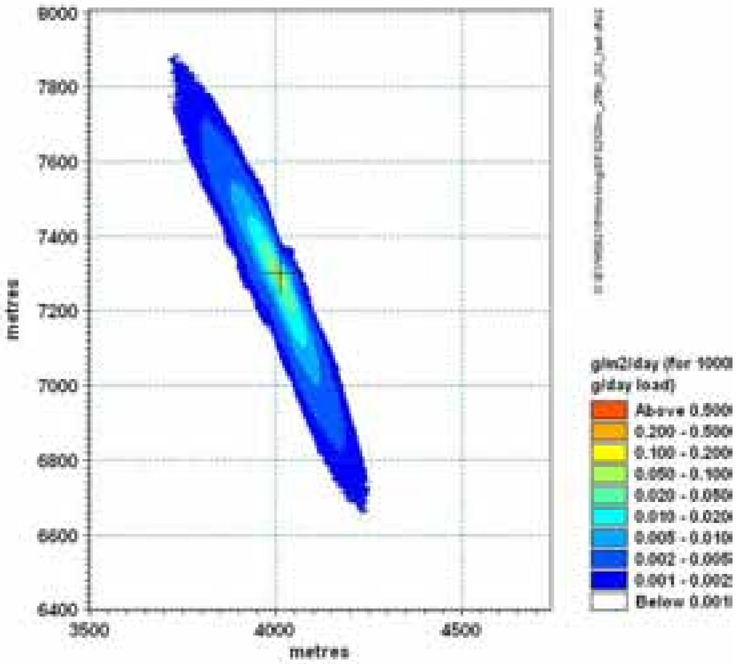

Figure 25: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 25th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

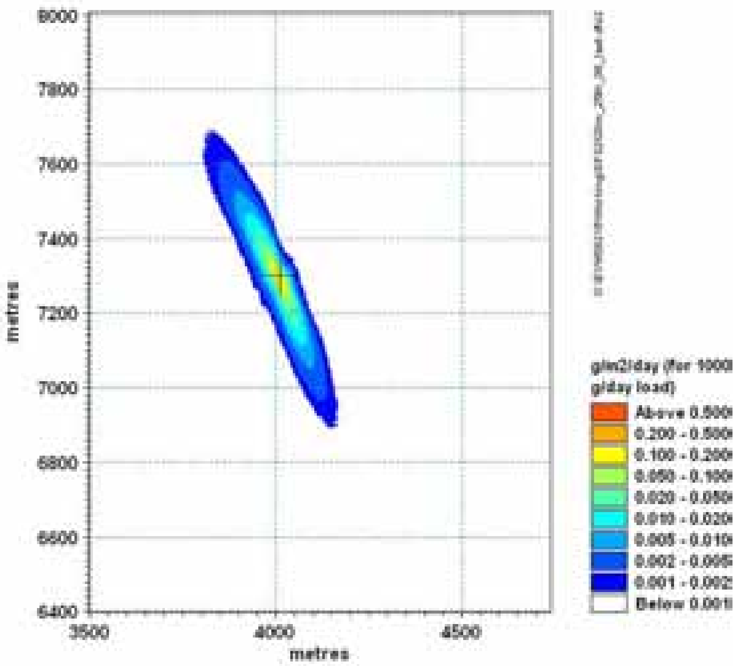

Figure 26: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 25th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

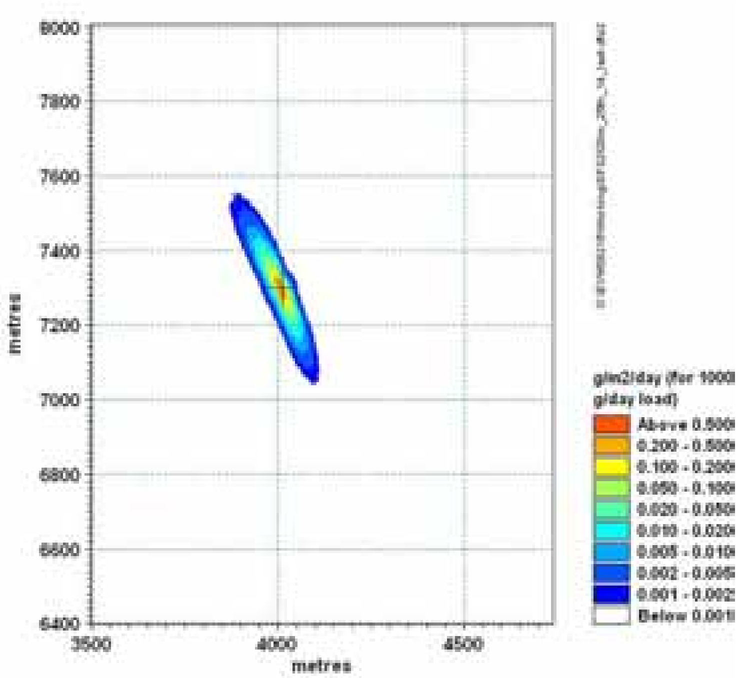

Figure 27: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 25th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

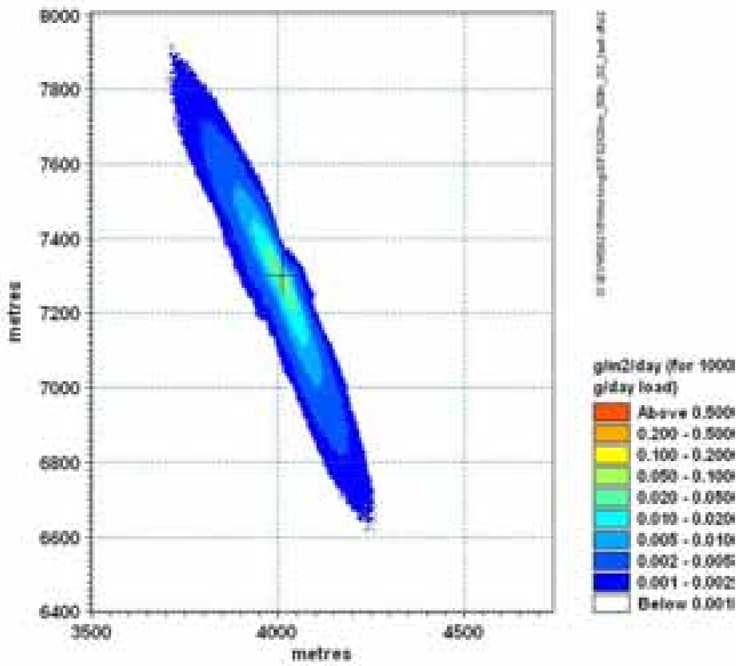

Figure 28: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 50th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

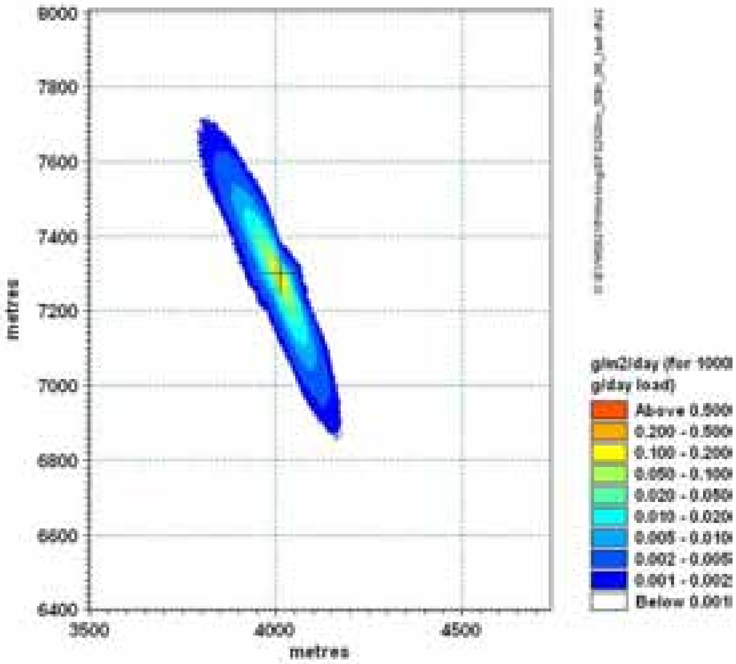

Figure 29: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 50th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

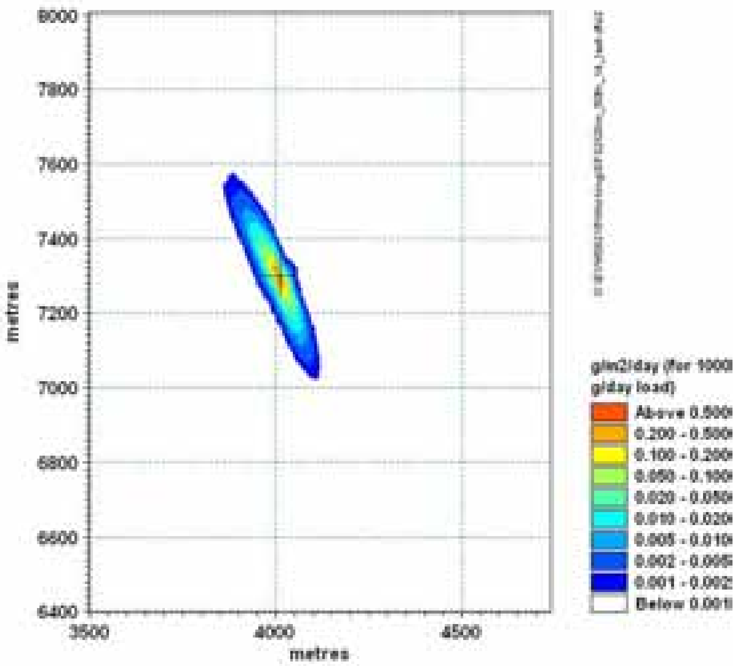

Figure 30: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 50th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

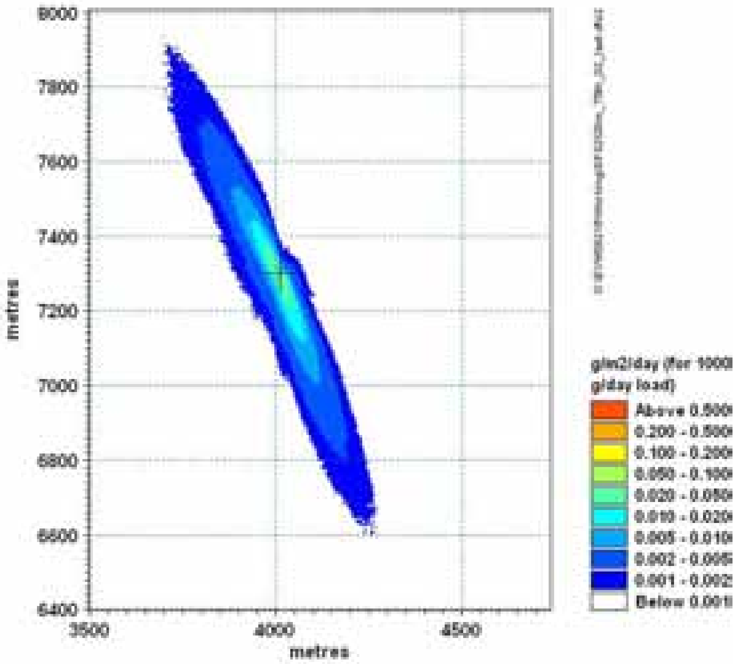

Figure 31: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 75th percentile currents and a fall velocity of 0.03 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

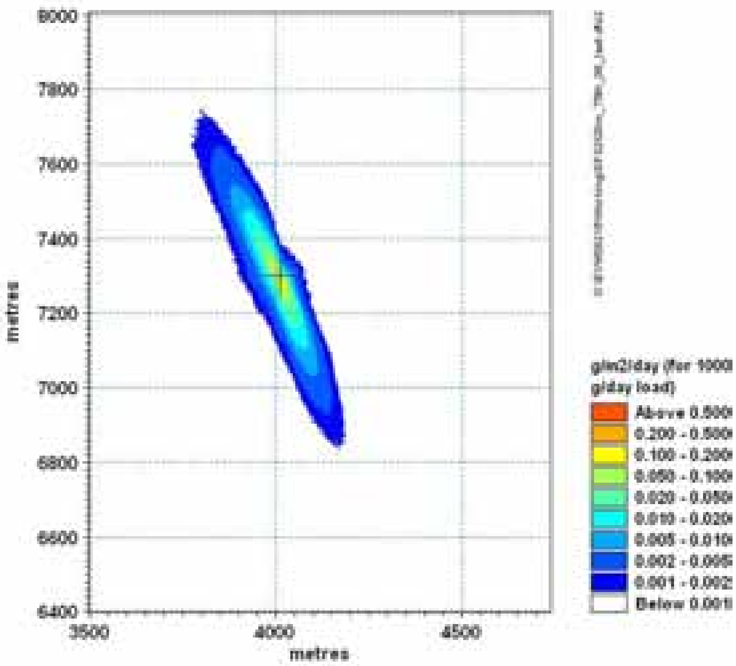

Figure 32: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 75th percentile currents and a fall velocity of 0.06 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

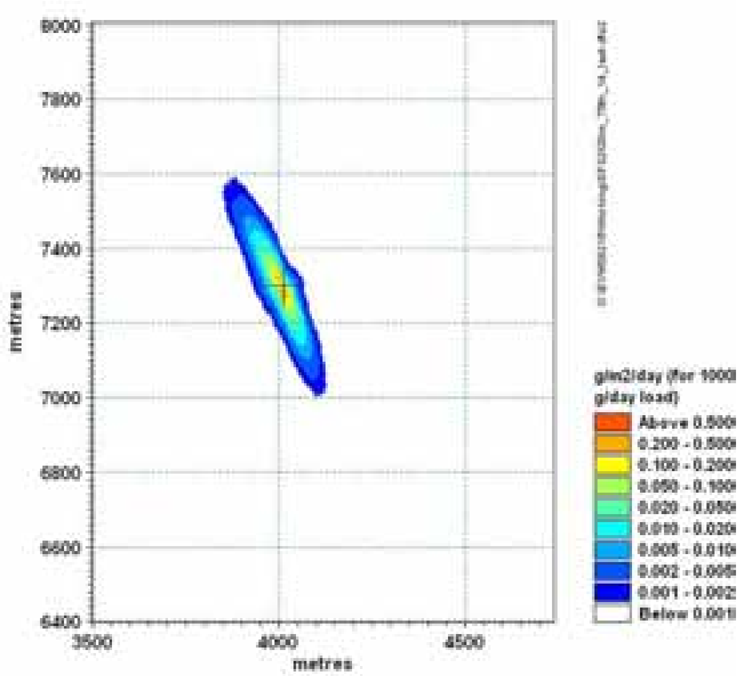

Figure 33: Extent of deposition zone (based on daily deposition limit of 0.001 g/m^2/day) for a 15 m deep, 15 m by 15 m cage in 30 m water depth under 75th percentile currents and a fall velocity of 0.14 m/s for a hypothetical waste load of 1000 g/day. Marker shows location of the centre of the cage.

Table 2: Extent of depositional zone (defined as edge of 0.0001 g/m^2 contour).

Fall velocity (m/s)	Cage depth (m)	Percentile current speed	Longitudinal distance to 0.001 g/m^2/day	Lateral distance to 0.001 g/m^2/day
0.02	10	25	437	58
0.06	10	25	233	42
0.14	10	25	146	29
0.02	10	50	466	58
0.06	10	50	248	44
0.14	10	50	160	29
0.02	10	75	481	73
0.06	10	75	277	51
0.14	10	75	160	36
0.02	20	25	568	58
0.06	20	25	350	44
0.14	20	25	233	44
0.02	20	50	597	73
0.06	20	50	364	58
0.14	20	50	248	44
0.02	20	75	626	73
0.06	20	75	393	58
0.14	20	75	248	44
0.02	30	25	670	73
0.06	30	25	408	58
0.14	30	25	262	44
0.02	30	50	684	73
0.06	30	50	451	73
0.14	30	50	291	44
0.02	30	75	699	73
0.06	30	75	466	73
0.14	30	75	306	58

5. References

Chen, Y.S.; Beveridge M.C.M.; Telfer T.C. (1999). Settling rate characteristics and nutrient content of the faeces of Atlantic salmon, Salmo salar L., and the implications for modelling of solid waste dispersion. *Aquaculture Research 30(5)*: 395-398.

Cromey, C.; Nickell, T. & Black, K. (2002). DEPOMOD-modelling the deposition and the biological effects of wastes solids from marine cage farms. *Aquaculture 214*: 211– 239.

Elberizon, I.R.; Kelly, L.A. (1998). Empirical measurements of parameters critical to modelling benthic impacts of freshwater salmonid cage aquaculture. *Aquaculture Research 29(9)*: 669-677.

Forrest, B.; Keeley, N.; Gillespie, P.; Hopkins, G.; Knight, B.; Govier, D. (2007). Review of the ecological effects of marine finfish aquaculture: final report. Prepared for Ministry of Fisheries. Cawthron Report No. 1285. 71 p.

Gall, M.G.; Image, K.; Zeldis, J.Z. (2003). An assessment of phytoplankton depletion associated with Area A in the Wilson Bay marine farming zone. NIWA Client report CHC2003-08. Prepared for Group A Consortium Wilson Bay.

Giles, H. (2007). Bayesian network analysis exploring the benthic carrying capacity for finfish farming within the Firth of Thames NIWA Client Report: HAM2007-172 prepared for Environment Waikato.

Oldman, J.W.; Hong, J.; Stephens, S.; Broekhuizen, N. (2006). Verification of Firth of Thames hydrodynamic model. NIWA Consultancy Report HAM2005-127 for the Auckland Regional Council.

Oldman, J.W.; Liefting, R.; Green, M.O.; MacDonald, I.T. (2002). Wilson Bay wave and current monitoring. NIWA, Internal Report No. WBG01021/1.

Oldman, J.W.; Senior, A. (2000). Wilson's Bay Marine Farm Dispersal Modelling. NIWA, Internal Report No. EVW01218, 43 p.

Roper, D.S.; Rutherford, J.C.; Pridmore, R.D. (1988). Salmon farming water right studies, Big Glory Bay, Stewart Island. Water Quality Centre. Consultancy Report No. T7074/2.

Sara, G.; Scilipoti, D.; Mazzola, A.; Modica, A. (2004). Effects of fish farming waste to sedimentary and particulate organic matter in a Southern Mediterranean area (Gulf of Castellammare, Sicily): a multiple stable isotope study (δ13C and δ 15N). *Aquaculture 234*: 199-213.

Stewart, A.R.J.; Grant, J. (2002). Disaggregation rates of extruded salmon feed pellets: influence of physical and biological variables. *Aquaculture Research 33(10)*: 799-810.

Vassallo, P.; Doglioli, A.M.; Rinaldi, F.; Beiso, I. (2006). Determination of physical behaviour of feed pellets in Mediterranean water. *Aquaculture Research 37(2)*: 119-126.