A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites.

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ABSTRACT

Modern Geographical Information Systems (GIS) offer a powerful modelling environment capable of handling large databases. They are a very suitable environment in which to develop a suite of tools designed for environmental management of aquaculture sites, including carrying capacity prediction, land-water interactions and multi-site effects. One such tool, presented here, is a fully integrated and validated particulate fish waste dispersion module which uses mass balance to estimate waste input and takes account of variable bathymetry and variable settling velocity for feed and faecal components. The model also incorporates the effect of cage movement on waste dispersion, the first such model to do so. When tidal range was low (1.67m), the maximum movement of a 22m diameter circular cage was 10.1m and 7.7m easting and northing respectively. Highest deposition from particulate fish waste is under the cage and incorporation of cage movement increased the effective area under a cage by 72%. This reduced peak deposition measurements by up to 32% and reduced the average modelled feed and faecal settlement at the cage centre by 23% and 11% respectively. The model was validated by comparing model predictions with observed deposition measured using sediment traps during three 2-week field trips at a fish farm on the west coast of Scotland. The mean ratio of observed to predicted waste deposition at 5 – 25m from the cage centre ranged from 0.9 to 1.06, whilst under the cage the model over-predicts deposition (observed/predicted = 2.21). Although far-field data was seen to be comparable the near-field discrepancies resulted in variable overall accuracy in the model. The overall accuracy based on August 2001 data was ± 50.9%, on February 2002 ± 72.8% and on April 2002 ± 50.6%. Summarizing the data resulted in an overall average predictive accuracy of ± 58.1%.

INTRODUCTION

The effects of waste deposition from fish farm cages have been well studied, in particular for temperate species such as Atlantic salmon (Salmo salar). Studies include changes in sediment chemistry (Gowen and Bradbury, 1987; Weston, 1990; Silvert, 1992; Black et al, 1996 Davies et al, 1996; Findlay and Watling, 1997; Kempf et al, 2002), oxygen availability (Enell and Löf, 1983; Hall et al, 1990) and changes in the number and diversity of benthic species (Brown et al, 1987; Gowen and Bradbury, 1987; Weston, 1990; Henderson and Ross, 1995; Kempf et al, 2002). The extent to which the seabed is affected depends on the type and quantity of particulate material being released from the cage site and the local physical conditions, such as bathymetry and prevailing water currents, both of which can be incorporated into dispersion models.

Particulate waste dispersion models can give a cost-effective method to evaluate outcomes in site selection and biomass limits in terms of local environmental capacity, to set quality standards and aid decision-making for environmental regulation and management, by testing a variety of pre-production scenarios for given environmental conditions. Across Europe the extent to which such models are used for this purpose varies widely (Henderson et al, 2001). In Scotland, DEPOMOD (Cromey et al, 2002) is now widely used for Environmental Impact Assessments and to estimate the likely seabed deposition of in-feed sea-lice treatments (SEPA, 2001).

Many deposition models of fish cage waste in use are based on an original concept presented by Gowen et al (1989), who used simple mass balance calculations to estimate waste levels and dispersion equations in combination with hydrographic data to assess the downward and lateral movement of particles. Subsequent dispersion models include fish growth sub-models to more accurately predict waste quantities (Silvert, 1992; 1994), bathymetry variation (Hevia et al, 1996), settling velocities for feed and faecal components (Chen et al, 1999a,b; Cromey et al, 2002) and the use of GIS technology (Perez et al, 2002). The primary purpose of GIS was for the storage, analysis and display of geographic data. Modern GIS goes well beyond this, however, and includes a range of powerful spatial modelling and decision making tools which can be used on a wide range of applications.

GIS has been established as an excellent tool for facility site selection (Church, 2002) using spatial analytical approaches with the overlay of thematic data layers, relating to land function and use, to form an image or graphical output that identifies appropriate sites. This technology is now widely used in aquaculture site selection (Ross, 1998; Nath et al, 2000) and is equally relevant for the siting of a range of aquaculture products and structures such as fish, bivalves, ponds or cages (Congleton et al 1999; Arnold et al, 2000).

This paper extends the modelling work of Perez et al (2002), who used a combination of spreadsheet and GIS to estimate the distribution of fish farm derived particulate carbon waste. This paper describes a validated particulate waste distribution model fully integrated into the GIS software by development of a specific programme module. Such integration in to a GIS-based package is important because it ensures there is no data loss when integrating data from various sources and the outputs from the waste dispersion module become one of a number of layers within an integrated Coastal Zone Management (ICZM) approach to aquaculture site management. As part of their fieldwork for model validation Cromey et al (2002) suggest that cage movement may have accounted for some of the variation in their sediment trap collections, although the amount was not quantified. The effects of cage movement are explored and the model is validated by comparison with data collected in the field.

MODELLING PROCEDURE

The dispersion module was developed in the IDRISI32 GIS environment (Clark Labs, Massachusetts, USA), which has been especially designed to allow user extension of its capabilities. The required code was developed using DELPHI 3 (Borland Software, California, USA) and the resulting executable was integrated into the IDRISI32 software using the IDRISI Application Programming Interface (API). The architecture for the modelling process is shown in Figure 1, which shows the elements developed within the model and the links between model components, with the general logic of the model presented below.

Data for cage block generation, dispersal parameters and mass balance calculations, are entered into IDRISI32 via two easy to follow dialogue boxes within a waste dispersion module. Cages may be either square or circular, as part of a block or separate within a cage array, with the relative layout identified through distance measures (in m) between cages in a row, between rows and orientation (in degrees) from north; 3 simple characteristics that may be measured at the site(s) of interest. The final layout of the cages, shown to scale, can be verified visually before commencement of the modelling process. Cage movement and hydrographic data are entered by calling spreadsheet files through the dialogue boxes. Settling velocities are calculated by comparing the known pellet size of the feed used against known settling velocity distributions (Chen et al, 1999[b]; Cromey et al, 2002). The initial input of carbon waste from the fish farm through uneaten food and faecal waste is calculated using a mass balance. Two methods are used, either from total production biomass and feed conversion rates, or from know feed input. Both methods take into account percentage carbon in the feed, estimates for carbon lost as production (i.e. harvested) and carbon lost through respiration and excretion (after Perez et al, 2002).

Carbon outputs through feed and faecal wastes were treated independently with the concentrations in each calculated through mass balance. The total quantity of carbon in each were divided equally between the number of cages and then sub-divided between each hydrographic measurement (typically measured every 20 minutes over 15-days using an appropriate current meter). This portion is then referred to as a “packet” of waste. Each packet is dispersed in 3-dimensions based on water depth (bathymetry) and time-specific current speed and direction (based on Gowen et al, 1989) and random feed and faecal settling velocity. The settling velocities for feed and faecal particles, for the particular type of feed being used, are calculated using a technique that randomly selects a settling velocity for each packet of waste from within the range “mean ± 1 SD”. The effect of varying seabed bathymetry on waste distribution is included by extracting water depths from digital Admiralty Charts covering the 250,000 m^2 modelled area in a 50 x 50 cell grid (each cell = 10 m^2). Half the average annual tidal range for the area is added to the water depth in each grid cell to adjust to mean annual water depth.

Cage movement is registered by temporarily shifting the position of the cage centre horizontally in X and Y, relative to the cage starting position, by an amount read from the cage movement data file. Initial spatial input of waste is then randomly defined within this temporary cage area. Distribution of particles commences at the net depth, removing the need to correct for differences in water speed inside and outside the cage (Inoue, 1972), the assumption being that the particulate waste is not subject to lateral movement within the cages. During the modelling of settlement through the water column, the waste packet is iteratively dispersed in 1m-depth intervals, based on water flow and particle settling velocity, and stops when packet and water depth are equal. The quantity of feed or faeces being modelled at the time is assigned to this grid cell, before the distribution of the next packet of waste begins. For the next packet of waste the previous cage position is further shifted by reading from the next line in the cage movement spreadsheet and so on until the whole cage movement file is used. Vertical and horizontal resolution of movement in the model is 1m.

Values of waste settled within specific grid cells is then interpolated, filtered and finally corrected using the procedure described by Perez et al (2002), before generation of the final model outputs. The interpolation process assumes that the first carbon packet deposits in grid cell XY_1, followed by the next packet in grid XY_2 and so on, based on the 20 minute intervals between hydrographic measurements. In reality there is a more even distribution between the two points over time, not just at the two end-points. After iterations are complete, interpolation is used within the GIS to smooth the distribution of waste. This results in initial over-estimation of the total deposited wastes, which is finally corrected by the application of a correction factor (CF) (equation 1, after Perez et al, 2002) that ensures the total amount of waste in the raster image is equal to the total generated through the mass balance.

$$CF = \frac{\text{Total predicted carbon waste (kg)}}{\text{Waste carbon in the image (kg)}} \quad (1)$$

MATERIALS AND METHODS

The site used for collection of field data and as a basis for the model data was located on the west Coast of Scotland and consisted of 12-off 70m circumference (~ 22m dia.) circular cages in a 2 x 6 arrangement. Relative to magnetic North the cages were orientated at 80º. Each of the cages had a net depth of ~10m. Distance between the cage centres within a row was 40m and distance between rows was 48m.

Hydrographic Measurements

Two Valeport BFM106 current metres (Valeport, Dartmouth, Devon) were deployed <100m from the cage site for a complete spring/neap tidal cycle (15 days) in August 2001. The sampling period was 60 seconds every 20 minutes. Meters were deployed in approximately 26m depth on a u-shaped mooring, 3m below surface at the lowest predicted tide during deployment and 3m above the seabed. The overall settlement vector for each time point during deployment was calculated by averaging flow and direction recorded by surface and seabed current meters at each time point. These data were used in the model. Data was saved as a comma delimited (.csv) ASCII file (current speed, direction) and imported into the model by being called

Measurement of cage movement

Movement of a single 22m-diameter Polar Circle cage was measured on 4 occasions in 2002 (16th October, 23rd October, 29th October and 5th November) at the fish farm. A Wild TC1010 Total Station theodolite equipped with a Leica electronic distance-measuring device (Leica AG, Heerbrugg, Switzerland) was used to take measurements of 2 reflectors, positioned on opposite sides of cage every 20 minutes for 8 hours inclusive of feeding periods.

The measurements composed of a horizontal and vertical angle and slope distance from a point of origin on the shore. These data were converted into Eastings (Es) and Northings (Ns) values (in metres) using Leica's LISCAD Plus Surveying and Engineering Environment Software version 4.0 (Leica AG, Switzerland and LIStech, Boronia, Victoria, Australia), which gave a resolution of 0.01m. The first reading each day was converted to point (0,0) E and N respectively and each subsequent measurement was relative to this origin. Two reflectors were used to confirm that each side of the cage moved simultaneously and therefore changes in distance were not caused by rotation only. All cages were assumed to move by the same amount. Data were incorporated in the model as a comma delimited (.csv) ASCII file.

Model validation

Waste input calculation

Feed input to a single but representative cage at the field site was measured to an accuracy of ± 0.1 kg day^{-1} using the feedback mechanism from a CAS adaptive feeding system (Akvasmart UK Limited, Inverness). In keeping with other models (e.g. Cromey et al, 2002; Perez et al, 2002), each of the 12 cages at the site was assumed to have the same feed input.

The carbon content of 10 feed pellets (% dry weight (DW)) was measured in triplicate (n = 30 in total) using a Perkin Elmer 2400 SeriesII CHNS/O Autoanalyser with integrated AD-4 Autobalance on samples weighing 4 – 6mg. Water content of the feed was calculated as the difference in weight after drying at 90 ºC for 24 hours, as a percentage of the original weight (n = 10 for each feed size), being 5% in all cases. Feed settling velocity was based on the relationship developed by Chen et al (1999b) for standard EWOS diets at 10 ºC and salinity 33.0. Faecal settling velocity distribution was 0.032 ± 0.011 ms^{-1} (after Cromey et al, 2002)

The level of feed uneaten by fish and lost directly to the environment was set at 3% (after Cromey et al, 2002). It was assumed that 14.3% of the carbon consumed was used for growth (Chen, 2000) and 60% was respired/excreted (Gowen et al, 1991). The remaining carbon was assumed to be incorporated into faeces.

Comparison between observed and predicted sedimented carbon

Predicted carbon outputs from the GIS-based model were compared against observed sedimentation measured in the field using sediment traps. Each trap had 4 replicate tubes, with an individual area of $0.005m^2$, for sediment collection. Hydrographic data and mass balance data were as specified above. Sediment trap samples were collected from the same positions in August 2001, February 2002 and April 2002, every 3 days over 15-days on each occasion. Sediment traps were positioned using a mooring system, as shown in Figure 2, under the cage and at 5m, 15m and 25m from the cage edge, in a direction perpendicular to the main water flow and at a distant (~ 800m) reference station.

Sediment trap samples from each tube were analyzed for total carbon (as % DW) as described for fish feed, multiplied by the total DW of the sample and corrected for depositional area to give deposition in g C m^{-2} $3d^{-1}$. The 5 samples collected at each sampling occasion were added together to give total carbon levels in g C m^{-2} $15d^{-1}$, which was used for comparison against the modelled output. Analysis and observation of samples showed no feed pellets were collected in the sediment traps during deployment and it was therefore assumed collected sediments were from faecal and "background" suspended material only. Carbon levels found within each trap were corrected to account for background deposition, which was collected simultaneously from a reference station on the specified dates and calculated as described above.

Thus model validation was conducted for faecal material only (after Cromey et al, 2002).

Comparison between observed deposition and modelled deposition was assessed in two ways. Firstly, as a factor indicating comparability, calculated as

$$\text{Factor} = \frac{\text{Observed}}{\text{Predicted}} \qquad (2)$$

This was used for comparison at each sampling station at each time point. Secondly, overall accuracy of the model combining all data for each time point was calculated as an absolute value using (Cromey et al, 2002)

$$\text{Overall accuracy} = \frac{\left(\sum\left(\frac{\text{Observed} - \text{predicted}}{\text{Observed}} * 100\right)\right)}{n} \qquad (3)$$

Where n = number of observation for all stations measured.

RESULTS

Measurement of cage movement

Data collected on the 5th November 2002 was rejected due to poor light resulting in less than 8 hours of data being collected. Plus and minus distances between dates were arbitrary as the position of the measuring device varied slightly between each of the trial dates and the starting position of the cages was arbitrarily set at (0,0). Maximal variation occurred on 29th October at 10.1m and 7.7m, easting and northing respectively, being up to half the cage diameter, when tidal range was low (1.67m). Tidal range on all dates was broadly similar (1.61m and 1.87m on 16th and 23rd respectively) but the wind on the 29th October was stronger and may account for the higher movement during this period, although this was not measured. Wind on other days was negligible. Overall the movement of the cages was limited by the layout of the moorings and depended on the state of the tide.

Movement of cages resulted in the effective area of deposition directly under cages being increased by 72%, as shown in Figure 3. The spatial starting position and relative settlement position of waste feed and faecal material within the cage would therefore vary with the rise and fall of the tide. This has not been taken into account in available fish farm waste dispersion models used by environmental regulators at present.

Model operation and outputs

Data input to the model was achieved using the dialogue boxes as a mixture of raw data entry (cage positions, bathymetry, mass balance data) and spreadsheet files (hydrography and cage movement). After data entry the model run time was approximately 10 minutes. Predicted carbon settlement to the seabed was automatically generated within IDRISI as a raster-image, with added legend and bathymetric contours, both of which can be varied to match the specific requirements. Cages could also be added to the output by simply adding a cage layer.

Mass balance calculations showed 3.84 t of particulate carbon entered the marine environment as waste, 3.06 t as faeces and 0.78 t as uneaten feed. Figure 4 (a) shows the predicted distribution of total carbon waste for a model run that does not incorporate cage movement, where peak deposition occurred under the cages at a rate of 1.55 Kg C m^{-2} 15-$days^{-1}$. The inclusion of cage movement within the model resulted in predicted deposition level directly under cages being reduced (Figure 4 (b)) to a peak of 1.07 Kg C m^{-2} 15-$days^{-1}$. The higher predicted deposition in cages 11 and 12 resulted from the shallower depth of water present under these cages. There was no change in the overall extent of the predicted footprint between each of the model runs.

Table 2 shows the average modelled deposition within an area 7m-diameter area around the centre of the cage starting position and 4.5m-diameter around positions equivalent to the location of the sediment traps. This was achieved by applying a mask over the raster-image in IDRISI, which allow data extraction from only the cells of interest, and averaging the data from each cell. Given the 1m cell resolution used, averaging over this number of cells provided a more appropriate measure for comparison than simply choosing a single cell; and also reflected the extent of the movement experienced by cages, identified above.

Cage movement reduced the average modelled feed and faecal settlement at the cage centre by 23% and 11% respectively. Modelled feed dispersion showed little difference with and without cage movement at distances greater than 5m from the cage edge, due to feeds high settling velocity, which results in the majority of these particulates being deposited under or very near to the cage. The combination of current direction and cage movement resulted in overall deposition increasing slightly in a NNE direction, as shown by the shift in the “blue” area in Figure 5 (b). This explains why the feed component of settlement at 5m distance decreased along the transect (Table 2), which was on the opposite side of the cage in a SSE direction. The modelled faecal dispersion increased in concentration at the 5m station and results from the lower settling velocity for faeces, allowing time in the model for the quantity that would have previously been predicted for deposition under the cage to be spread more evenly in all directions despite the cage movement (Figure 6).

Validation

Validation was carried out for the integrated GIS model including incorporation of cage movement. Table 3 provides a comparison between observed and predicted faecal carbon deposition. Variability in predicted carbon deposition at each sampling station with time was a reflection of variability in production levels giving different mass balance calculations.

Observed deposition of nutrient material was shown to be high under the cage and reduce with increased distance from the cage edge up to 25m. The deposition model prediction mirrored this high to low gradient. The 'Factor' (observed/predicted) (Table 3) gives a comparison models' prediction against the observed deposition. For the most part, the model predictions were higher than the actual deposition, as indicated by a Factor greater than 1 at the majority of stations. Model predictions for deposition directly under the cage were considerably higher than observed faecal deposition. Model predictions were closer to observed deposition as distance increased from the cage centre (as indicated by the reduction in the factor towards 1 at the 25m station). Thus the model over-predicts deposition at near-field stations, with an increase in parity between modelled and observed data at the far-field stations.

Although far-field data was seen to be comparable the near-field discrepancies resulted in variable overall accuracy in the model. The overall accuracy based on August 2001 data was ± 50.9%, on February 2002 ± 72.8% and on April 2002 ± 50.6%. Summarizing the data resulted in an overall average predictive accuracy of ± 58.1%.

DISCUSSION

The particulate dispersion model presented here was targeted at predicting the distribution of feed and faecal carbon waste, either annually or over the course of a full production cycle (18 – 24 months), through a wholly integrated GIS-based model. The model outputs generated for this study covered 15-days of production commensurate with both available hydrographic data and sediment trap collections used for validation. Although designed with whole production cycles in mind the model was sufficiently robust to allow variable data and timescales to be simulated.

Irrespective of their complexity, computer based models are simplified representations of the processes, variables and relationships that function in the natural environment. Since their inception for fish cage culture (Gowen et al, 1989), particulate waste dispersion models have undergone various transformations as the influences on where particulate waste is deposited on the seabed have become better understood and the means of modelling these influences has become available (Silvert, 1992; 1994; McDonald *et al*, 1996; Hevia et al, 1996; Chen et al, 1999a,b; Cromey et al, 2002). Variable bathymetry, random settling velocity, random particle starting position and estimates of waste through mass balance generated by the above work are all included in this GIS-based model. Further, this study has shown that the movement of cages has a small but important influence on the deposition of particulate farm waste.

Sensitivity of the model to cage movement

Primary sensitivity analysis for this model has been carried out elsewhere (Brooker, 2002) and shows that of the many key parameters tested four, - the effect of constant verses variable water depth (bathymetry), constant verses variable settling velocity, changes in percentage feed wastage and changes in FCR, - will have the most effect on predicted deposition. The extent of that effect is specifically influenced by site characteristics, feed characteristics and husbandry practice rather than any underlying universal principle that holds true for all sites.

In this study the validity of applying cage movement to dispersion models has clearly been demonstrated and resulted in a redefined distribution of carbon settlement, lower predicted peak values and a reduction in the predicted particulate settlement directly under cages. Thus the inclusion of cage movement in waste dispersion models is an important parameter in determining the extent and magnitude of particulate settlement, especially close to a fish cage. Inclusion of cage movement into dispersion models, however, is only appropriate when the model has a spatial scale that can register the movement, which would exclude models using greater than 5m spatial resolution (Dudley et al, 2000; Cromey et al, 2002). Conversely, although any spatial resolution can potentially be used in the GIS model used, here a resolution of 1m allowed the extent of the measured movement to be fully integrated and for the effect to be measurable through the data and images generated.

Validation of predicted dispersion with observed sedimentation

Model validation is an important function within model development, assessing agreement between the predictions from the model with data collected in the field (GESAMP, 1991), whilst at the same time clarifying the assumptions and functional relationships. The GIS model provided a realistic measure of actual deposition at the site, giving an average overall accuracy of ± 58.1 %, which compares favourably with other proprietary models, such as DEPOMOD (Cromey et al, 2002) which has a published accuracy of ± 23.1 % at a site with similar water dynamics. Overall, predictions and observations were a similar order of magnitude and the degree of accuracy reflected the variability seen at all stations in sediment trap data collections over the 6 weeks of sampling (data was not shown). Model predictions followed a similar pattern to field data, with decreasing deposition at increasing distances from the cage edge and there was no patchiness in the interpolated raster-image.

The inclusion of a feed loss element in the GIS model was vital for calculating the quantity of faecal material produced, via the mass balance calculations. Had zero feed loss been assumed in the mass balance then faecal loss would have been over-estimated and this is important where validation occurred against the faecal portion of the modelled output. DEPOMOD (Cromey et al, 2002), for example, calculates faeces in a different manner, through water content and digestibility, and 100% of the feed is assumed to be eaten resulting in an over-estimation of predicted faecal carbon, which was not taken in to account during validation. Within the DEPOMOD model 100% feed consumption is required, however, because only a single model output is produced, being either total solids or total carbon. The GIS model therefore has a distinct advantage because feed and faeces are treated independently and separate raster-images generated, which allows feed loss to be used in the model even though validation was for the faecal portion only. Feed loss can therefore correctly be included in the model and allows for a further validation in the future as more detailed data on spatial and temporal loses of feed becomes available.

Validation of modelled faecal deposition only is not uncommon (Cromey et al, 2002) and was carried out because a very high proportion of the sediment trap collections, spanning 6 weeks of sampling, contained faecal material only as indicated by the carbon content (data was not shown), with very low feed identified. The use of faeces only for validation affects the robustness of the model to a certain extent, especially near to the cages, but exclusion of feed does not significantly affect predicted deposition at greater distances from the cage because high settling velocity results in the majority of feed depositing directly under the cage. It is only under the cage, therefore, that deposition would be expected to be higher than the model suggests were feed to be included and the sensitivity of the model affected.

Feed loss is a transient process within cage culture and infinitely depends upon physical, biological and feeding characteristics at a farm site. The quality of staff feeding the fish to satiation, the stress on the fish in any one day, the prevailing weather conditions, tidal speed through the spring-neap cycle, water quality, water temperature variation with season and level of parasite infestation will all influence feed loss over varying temporal scales. The model assumes that feed loss occurs uniformly across all hydrographic measurements, but in reality feed loss is limited to feeding periods only. Subsequently there is a difficulty in assuming that the feed element of any deposition model is an accurate depiction of the actual settlement.

The best current estimates, for modelling purposes, assess that 3% direct feed waste is a reasonable assumption based on digestibility data and current husbandry practice at farm sites (Cromey et al, 2002) with historic estimates (Cho, 1991; Enell and Ackerfors, 1994) now outdated. Feed loss, specifically when using current husbandry practice and new technology, is an area that requires further investigation.

If it is assumed that no errors were present in field collected data, subsequent measurement of sediment trap contents and model input data then differences between predicted and observed sedimentation may have been due to processes that are not included in the model, such as losses from leaching and post-depositional movement through saltation (Chen, 1999b) and re-suspension (Cromey et al, 2002). There is also a reliance on 2 dimensional hydrographic data (current speed and direction) that takes no account of shear stresses between water layers, such as before and after slack water, eddies and wind generated movement that adds to turbulent mixing and affects the dispersion.

There are also elements that are not currently included in any commercially available or research models, which requires further work to be carried out. Hydrographic data is measured within 100m of farm sites to represent current speed and direction through the farm. There is, however, an acknowledged reduction in current speed and alterations in direction as a result of the presence of nets (Inoue, 1972; Black, pers. comm.) and fouling of nets over time. Fish may also play a part in distributing waste, by having a tendency to swim in circles that creates a vortex, giving rise to suction of water through the bottom of the net and movement away through the cage at shallow depths (Beveridge, 2004). Such influences may particularly affect the dispersion directly under cages, the area where the GIS dispersion model predictions are least accurate. Henderson et al, (2001) noted that all of these processes would need to be investigated to provide a comprehensive model, with data tested for sensitivity within the model. Importantly, increasing the validation accuracy under certain conditions and at certain sites may limit the general applicability of the model to represent species specific cage culture as a whole, which must remain the ultimate goal of such a model.

General conclusions

Modern GIS is a powerful modelling environment with the capability to develop user defined modules as extensions. This was achieved in this work using DELPHI 3 and the IDRISI Application Programming Interface (API). This capability provides the opportunity to develop new applications, which can then be processed within the GIS framework. The output is a set of raster images from which further graphical or statistical information can be generated depending upon the requirements of the particular application. The system can operate at any spatial resolution and the 1m^2 used in this work is particularly suitable for farm level particulate dispersion modelling and with the potential to use larger scales in an assessment of complex multi-site systems.

The model presented here provides easy data entry and a requirement for smaller data sets, which IDRISI or other GIS software packages are easily capable of interpolating. Predictive capability in the model enables a range of applications to be addressed. It allows this model to be used as part of an Environmental Impact Assessment decision-making process, in determining whether a site is acceptable for farming, under the banner of site selection (Perez et al, 2003). It is also able to be used during production for monitoring and to assess the impact of proposed increases/decreases in production. Although there is an acknowledged need to more fully understand the nature of fish farm waste settlement and dispersion, the model presented generally over-estimates which provides a safety net under precautionary principles in evaluating new site proposals.

Although this dispersion model provides the industry with a free-standing tool that can be tested at the farm scale, it has even greater potential when used as part of a suite of tools designed for environmental management of aquaculture sites, including aspects such as carrying capacity prediction, land-water interactions and multi-site effects. This is an area of on-going research. Importantly, the GIS framework used as the basis for this model allows the integration of varying spatial scales within the same framework. This will be particularly important in the future development of Coastal Zone Management Plans (CZMP) in which waste dispersion is one sub-model (See Ross, 1998; Nath et al, 2000) within a framework that could ultimately provide a fully integrated sustainable decision support system for aquaculture site selection and future development.

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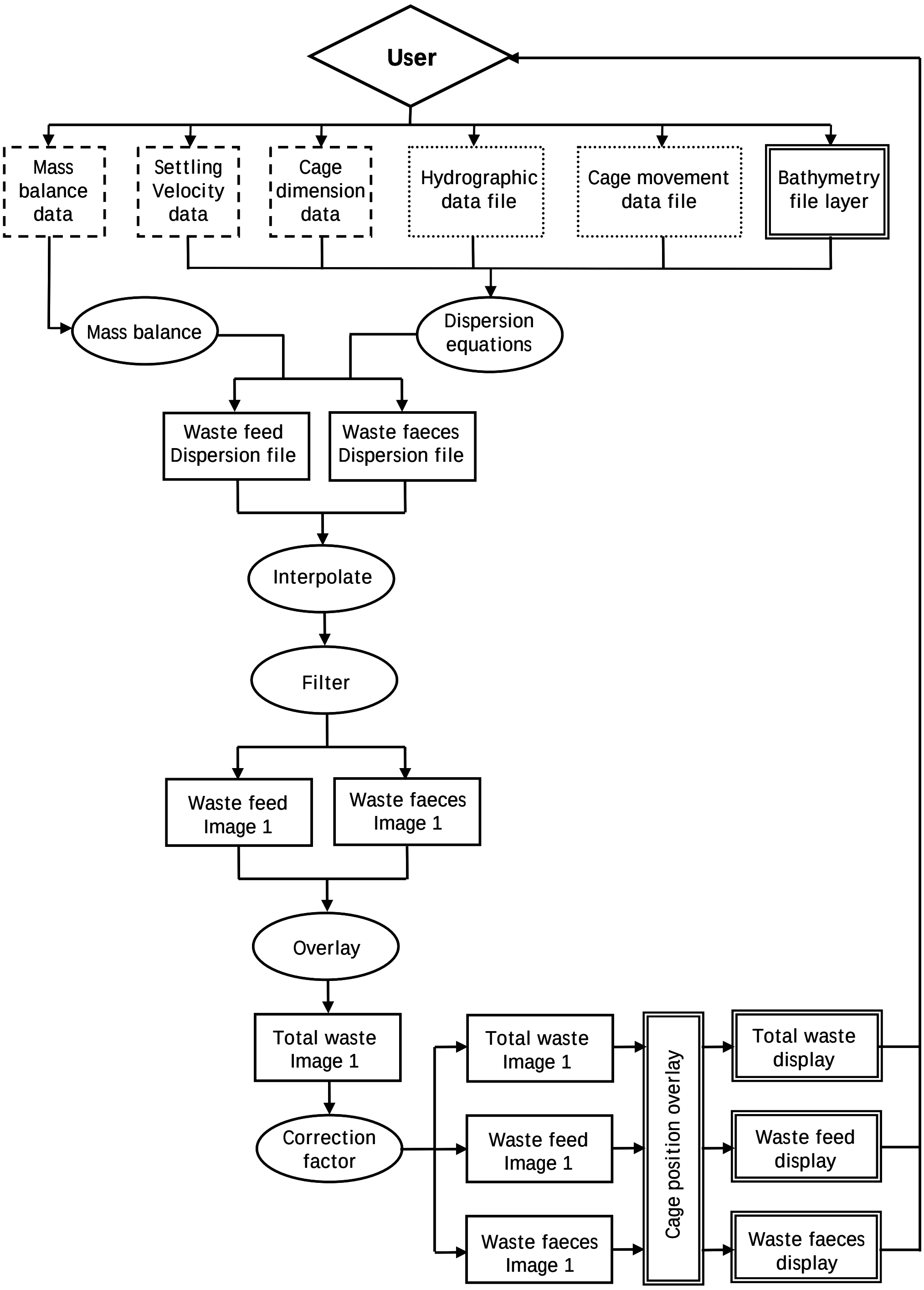

Figure 1: Architecture of the integrated model showing the communication links between the module processes within GIS. Boxes = data, as direct input (-----), as spreadsheet file (⋯⋯), as GIS data file (——) or as a GIS layer (═). ○ = GIS process.

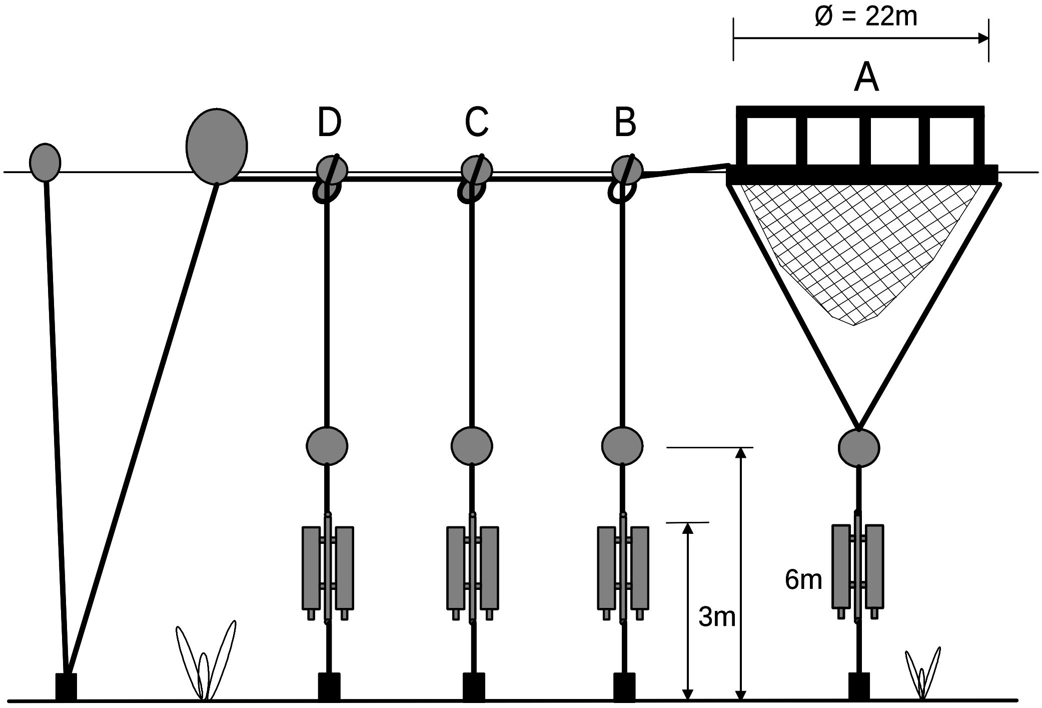

Figure 2: Sediment trap layout on a transect from circular fish farm cage. Traps deployed at distances A = under cage, and B = 5m, C = 15m and D = 25m from cage edge respectively. Not to scale.

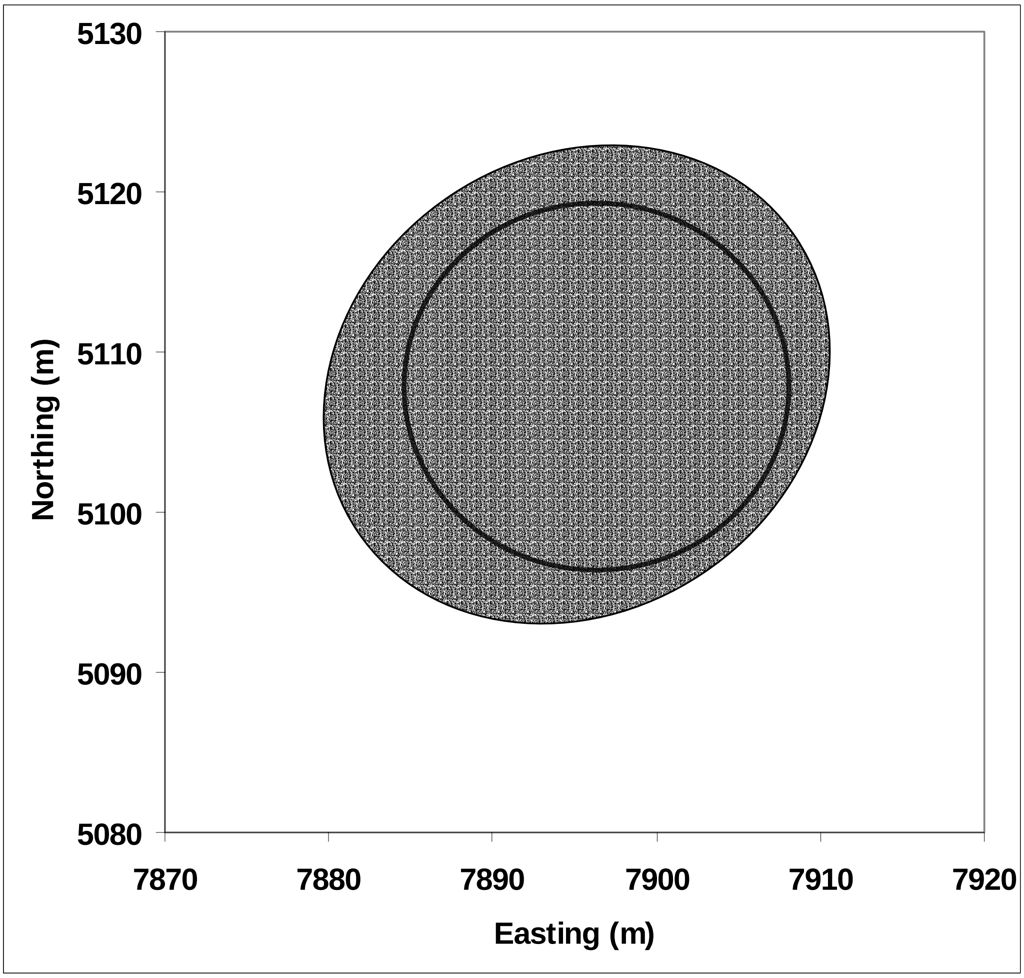

Figure 3: Figure 6.3: Representation of the additional area of seabed covered by a 22m-diameter Polar Circle marine cage as a result of measured movement of the cage on 23rd October 2002. Black circle represents cage starting position.

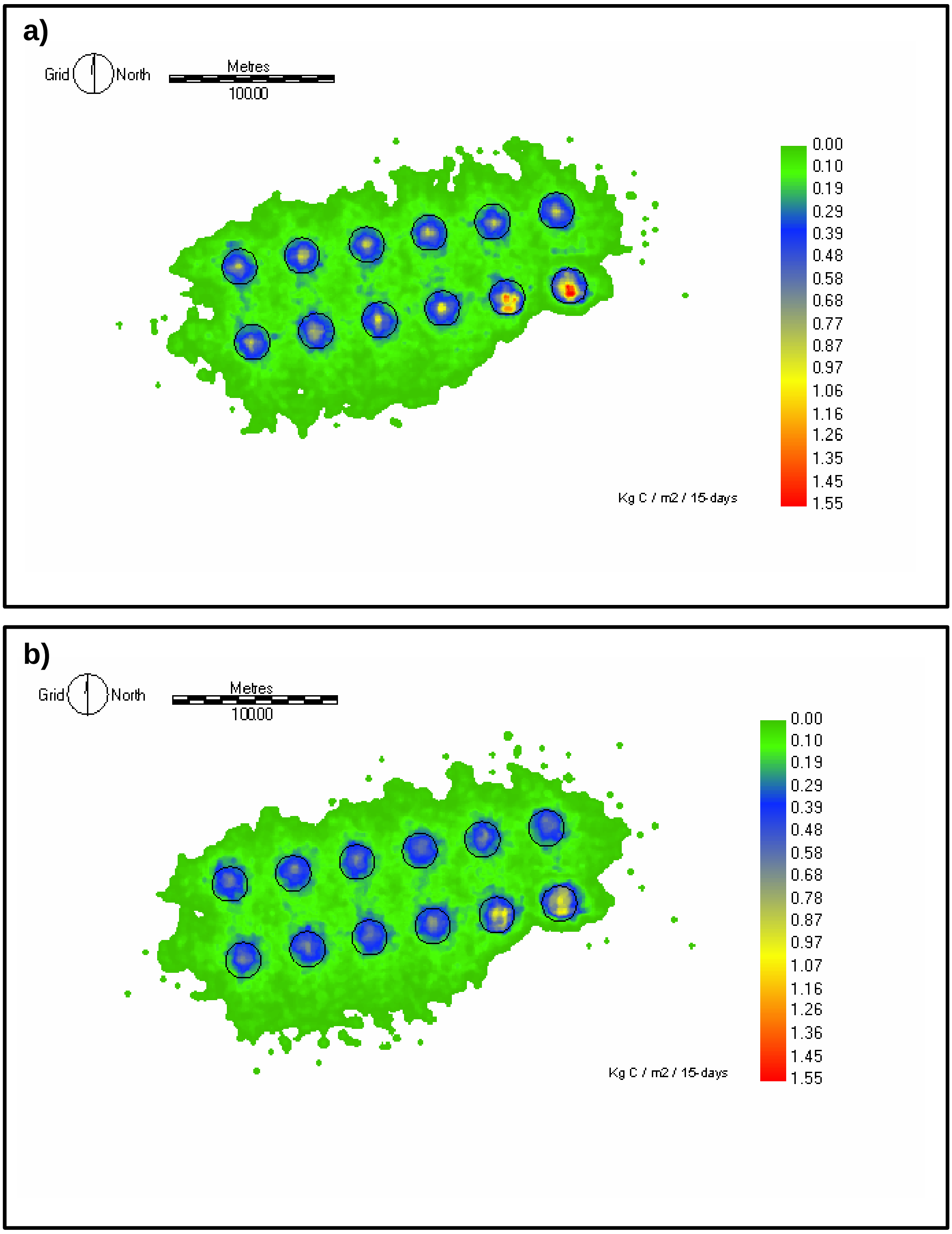

Figure 4: Contour rastor-image for fish farm site showing predicted <u>total carbon</u> settlement to the sediment, using GIS dispersion model. (a) static cages model (b) moving cages model.

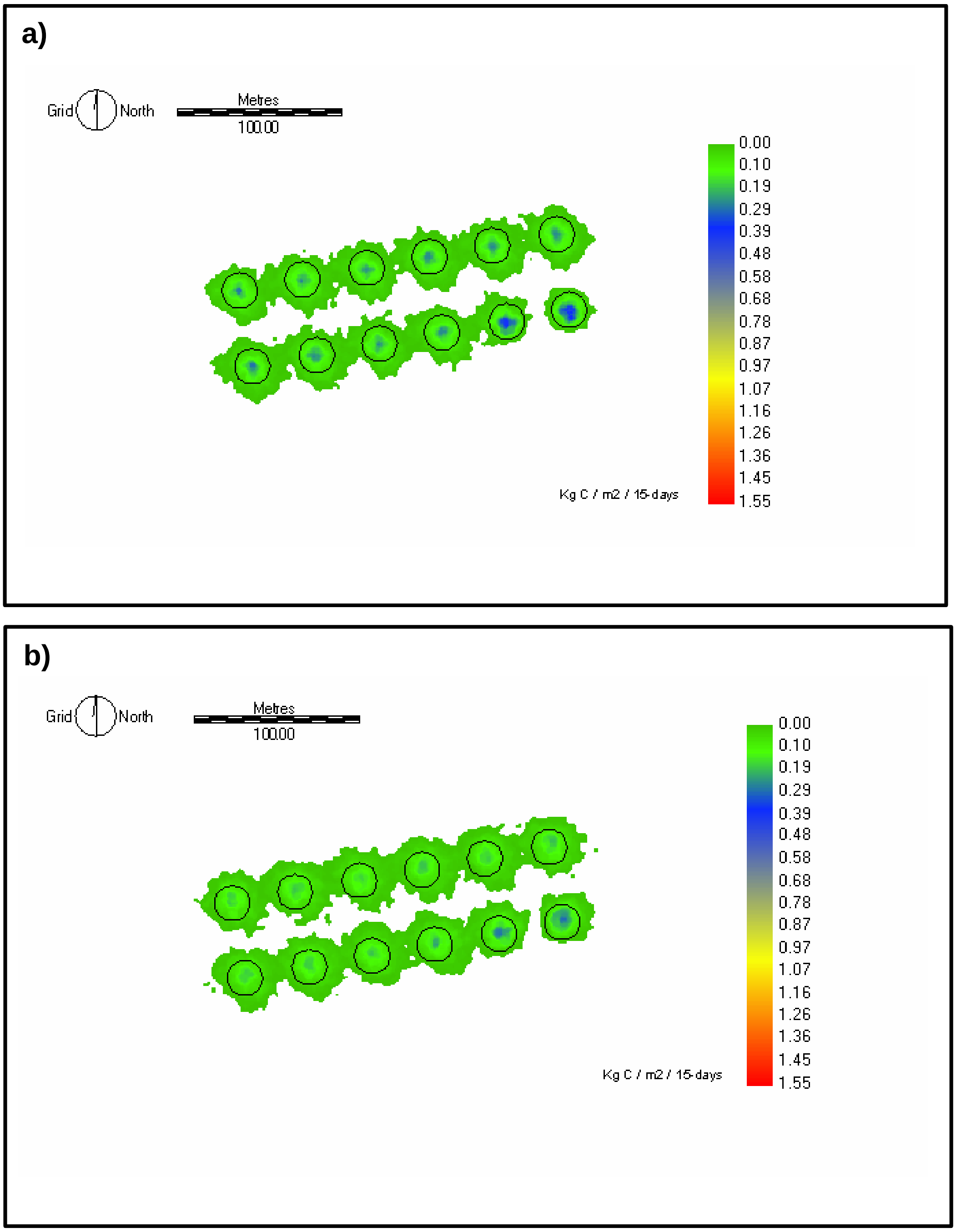

Figure 5: Contour rastor-image for fish farm site showing predicted feed carbon settlement to the sediment, using GIS dispersion model. (a) static cages model (b) moving cages model.

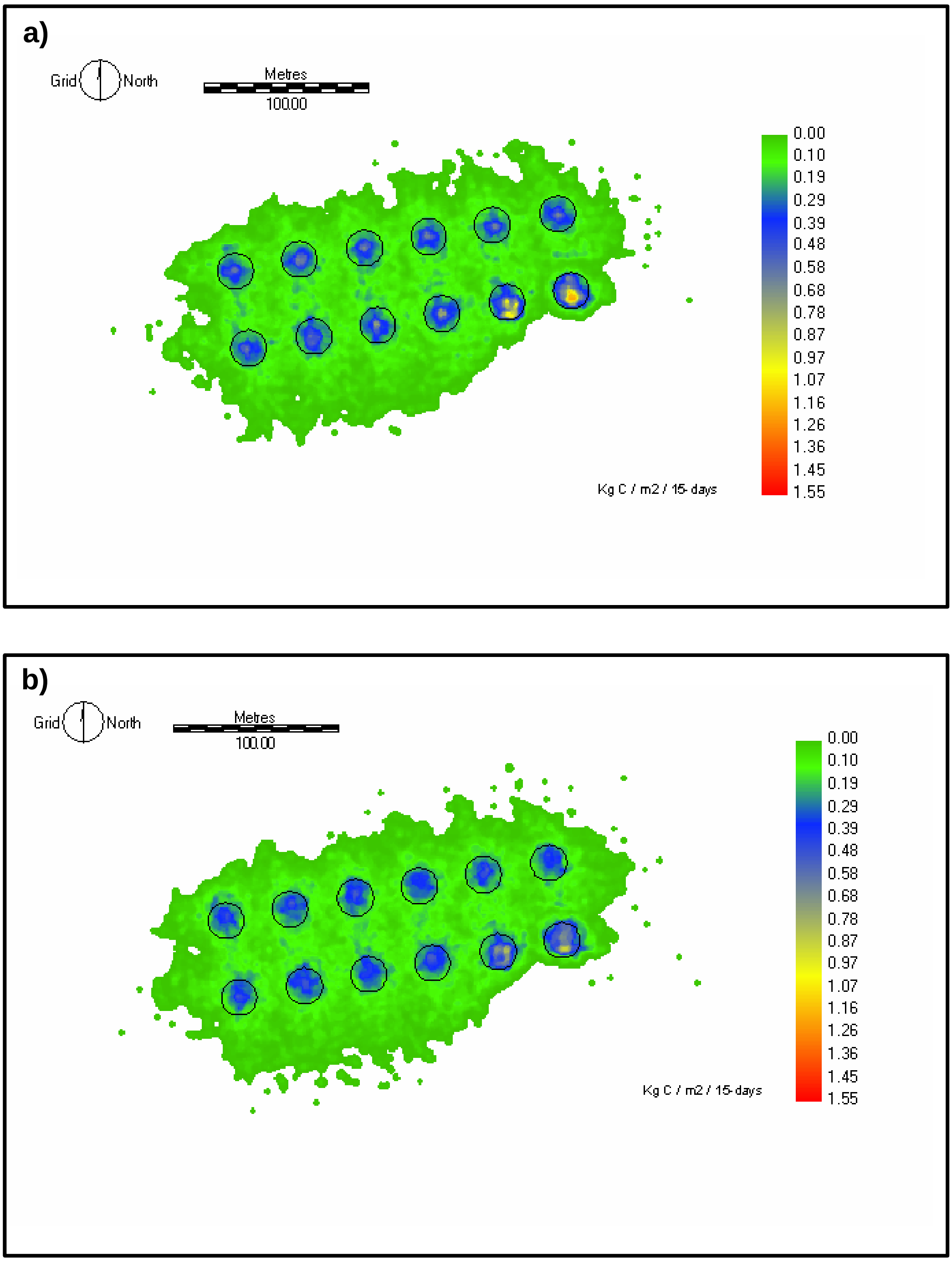

Figure 6: Contour rastor-image for fish farm site showing predicted faecal carbon settlement to the sediment, using GIS dispersion model. (a) static cages model (b) moving cages model.

Table 1: Mass balance data used in waste dispersion model for 15-day trial periods at fish farm site.

Trial date	Production in trial cage (kg)	Feed input (kg)	FCR	Feed size (mm)	Mean feed settling velocity (cm s^{-1})	Feed carbon content (% DW)
August 2001	3964	4360	1.10	3 and 6	8.26	51.0
February 2002	2983	3460	1.16	9	10.81	49.5
April 2002	2814	3152	1.12	9 and 12	12.92	51.0

Production = fish growth between start and end of experimental periods from growth curves and feeding algorithms within a CAS Adaptive Feeding System (Aquasmart UK Limited, Inverness).

Table 2: Average predicted deposition under and at specified distances from the edge of fish cage. Predictions generated using GIS dispersion model assuming static and moving cages, based on production and mass balance for the period August 16th – 31st 2001. Units: g C m^{-2} 15-$days^{-1}$.

Component	Under cage		5m		15m		25m	
	Static	moving	static	moving	static	moving	static	moving
Faeces	480.71	426.60	115.04	129.04	59.71	58.76	24.01	27.45
Feed	216.81	166.89	38.77	21.81	1.94	1.04	0.23	0.19
Total	679.51	593.50	153.81	150.86	61.65	59.80	24.24	27.65

Table 3: Comparison of 15-day measured observations verses predicted faecal particulate carbon deposition. Observed deposition measured using sediment traps. Predictions generated using a GIS dispersion model, incorporating cage movement and based on mass balance for 15-days production in tonnes. FCR = Feed Conversion Ratio. Station distance = distance from cage edge (m). Factor = observed/predicted. Number of cells averaged under cage (n) = 38, at remaining stations n = 16. Units: g C m^{-2} 15-$days^{-1}$.

Collection	Production (t)	FCR	Under cage			5m station			15m station			25m station		
			Obs.	predicted	Factor	Obs.	predicted	Factor	Obs.	predicted	Factor	Obs.	predicted	Factor
August 2001	3.84	1.10	234.3	426.6	1.82	75.8	129.0	1.70	41.0	58.8	1.43	29.8	27.5	0.92
February 2002	3.06	1.16	85.2	310.7	3.65	120.8	133.8	1.11	55.6	51.0	0.92	22.5	24.3	1.08
April 2002	2.82	1.12	159.6	323.3	2.03	109.5	61.6	0.56	61.7	39.1	0.63	49.5	39.8	0.81
Average			159.7	353.5	2.21	102.0	108.1	1.06	52.8	49.6	0.93	33.9	30.5	0.90