

# CAPOT: A flexible rapid assessment model to estimate local deposition of fish cage farm wastes

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## ARTICLE INFO

### Keywords:

Cage aquaculture  
Carrying capacity  
Environmental impact  
Fish farming  
Particulate waste  
Waste dispersion

## ABSTRACT

The Cage Aquaculture Particulate Output and Transport (CAPOT) model is an easy to use and flexible farm-scale model that can rapidly estimate particulate waste deposition from fish cage production. This paper describes and tests the model and demonstrates its use for Atlantic salmon (*Salmo salar*) and Atlantic cod (*Gadus morhua*). The spreadsheet-based model gives outputs for waste distribution in a variety of spatial modelling software formats, used for further analysis. The model was tested at a commercial Atlantic cod farm and commercial Atlantic salmon farm under full production conditions. Sediment trap data showed predictions, using actual recorded feed and biomass data, to be 96% ( $\pm 36\%$ ) similar for Atlantic cod beyond 5 m from the cage edge, giving a satisfactory estimate of local benthic impact in the vicinity of the farm. For Atlantic salmon, using estimated production biomass and FCR (Feed Conversion Ratio) to calculate feed input, the model overestimated wastes directly beneath the cages ( $120\% \pm 148\%$ ) and underestimated beyond 5 m from the cage edge, being 48% ( $\pm 42\%$ ) similar to sediment trap data. CAPOT is a suitable initial, rapid assessment model to give an overview of potential impact of particulate waste from new or expanded fish cage farms, with little operator expertise by a wide range of stakeholders.

## 1. Introduction

Cage-based fish aquaculture is important for food production and economic gain, and the societal benefits this brings. To maximise such benefits in a sustainable way it is essential to assess potential environmental impacts, such as the effects of fish cage wastes (e.g., uneaten feed, urinary products and faecal material) (Henderson et al., 2001; Beveridge, 2004). Cage aquaculture is an ecologically open system, but the wider environment provides dilution and assimilative “ecosystem services” to remove and mitigate waste impacts (Alleway et al., 2019). However, waste loading from fish cages can result in changes to the water column and benthic environment (Kalantzi and Karakassis, 2006; Sarà et al., 2018). Suitable environmental conditions near to the fish cages are paramount for aquaculture production and to minimise environmental impacts, so it is important to know and understand the amount of waste entering the local environment, and its fate. Such assessments use predictive models to ensure the level of fish production is within the carrying capacity of the system to support it (Ross et al., 2013).

A range of modelling approaches and platforms have been used to

estimate waste dispersion from fish cage systems (Henderson et al., 2001), simulating soluble (Jansen et al., 2018) or particulate wastes (Cromeey et al., 2002; Corner et al., 2006). Waste dispersion models allow aquaculture producers and environmental regulators to assess how much waste is likely to accumulate in the environment and where. In some countries, use of predictive models is a regulatory requirement as part of the planning and aquaculture licensing process (Luthman et al., 2019). Recently, most attention has focused on use of approaches that involve complex three-dimensional hydrodynamic models (Banister et al., 2016; Broch et al., 2017; Jansen et al., 2018; Carvajalino-Fernández et al., 2020). However, these models often require specialised modelling software, a significant amount of data, considerable computing power, and time and expertise to use and interpret the model outputs. Though complex models can simulate environmental effects more accurately and account for a larger number of environmental factors, they are poorly suited to initial rapid scoping of potential locations where distribution of fish cage wastes is a major factor defining the level of aquaculture production based on localised impacts on seabed sediments within a designated area.

During preliminary investigations of potential sites, a quick

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<https://doi.org/10.1016/j.marenvres.2022.105788>

Received 16 May 2022; Received in revised form 21 October 2022; Accepted 22 October 2022

Available online 27 October 2022

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assessment on the fate of wastes allows decision makers, including aquaculture producers, to evaluate the trade-offs necessary when considering site suitability. It also allows them to determine if further resources for more in-depth modelling analysis is justified. A rapid assessment of local waste loading for the planned fish production at a preliminary stage, using commonly available and familiar software, is useful.

The Cage Aquaculture Particulate Output and Transport (CAPOT) model estimates the particulate waste outputs from fish cage production as total suspended solids or particulate organic carbon and predicts their distribution over a specified time period. The model was initially developed as an academic tool (Telfer, 1995) for scoping for research sites, but has now been refined into a more user-friendly and flexible tool under the EU H2020 TAPAS project (Telfer et al., 2018). It has been designed to be used as an inexpensive, rapid assessment model for environmental fate of particulate fish cage wastes for use by non-experts. The model is wholly encapsulated within standard spreadsheet formats, with '.xslm' and '.odsm' versions available. Visualisation of the output is achieved using proprietary contour plotting software, such as Surfer™ (Golden Software, CA, USA) and open-source Geographic Information System (GIS) software, but can be carried out in a more limited form within the spreadsheet itself. Visual Basic for Applications (VBA) macro scripts within the spreadsheets perform calculations and data formatting to produce outputs in Surfer™ and ESRI (GIS) grid formats.

Here we use, as an example, the model version for the Excel™ spreadsheet (Microsoft Corp, WA, USA) with Surfer™ for visualisation. Using this, we describe the CAPOT model, its operation, its validation and its use in two coastal water case studies for rapid scoping of environmental conditions near fish cages.

## 2. Materials and methods

The CAPOT model uses VBA macros within the spreadsheet software to process the data entered, perform calculations and format outputs for the visualisation software. A version of the model where these processes are performed manually within the spreadsheet (without coded macros) is also available. This latter version allows greater flexibility, alteration of default parameters and changes to grid resolution to give multiple combined outputs in a single spreadsheet, but its use requires expertise in spreadsheet functions and commands for operation. Particulate waste input can be modelled, in both versions, over the whole of a fish production period or any portion (in days), using either actual/planned feed input and biomass increase per fish pen, or an estimated Feed Conversion Ratio (FCR) for the site over a specified production period.

The underlying theory and the operation of the model is given here. The spreadsheet model itself and a step by step instruction manual are made available in Supplementary Information 1.

### 2.1. Model operation

Model operation requires basic data; hydrographic data, water depth, size and arrangement of cages, depth of nets, fish production per cage or FCR for the site. Ideally, hydrographic data should be collected from two or three depths in the water column, representing surface currents, mid-water currents and near seabed currents. Speed (m/s) and direction (deg N) can be taken at any time interval (though normally every 10–20 min) for a minimum of 15 days, to account for a single spring/neap tidal cycle. However, any available period of current data can be accommodated. Water flow recording devices should be placed within 100 m of the fish farm position to be representative of currents near the farm. In using single point water flow data, water movement is assumed to be homogenous over the modelled area.

On entry of the water flow data, the model averages current speeds (m/s) and directions (deg N) over the depth range for each time-point. This gives a reasonable approximation for the path of initial waste

settlement through the water column for that time point, assuming that the current meters have been placed at equidistant depths throughout the water column.

There are two phases to modelling particulate waste dispersion; the first calculates the amount of waste and in what form it is released to the environment; the second is a two-dimensional estimation of the dispersion of that waste settling to the seabed. The particulate wastes deposited can be modelled as organic carbon or total suspended solids.

The amount and form of wastes are calculated using a mass-balance technique (Pérez et al., 2002; Beveridge, 2004) using either actual feed-used and biomass change over the modelled/production period, or total fish production and FCR to estimate feed used. The mass-balance model requires values for nutrient uptake by the fish. These can be user defined from empirical experimentation or the literature for the specific feed used and/or species cultured. Each can be changed within the model parameters, but the default values used for Atlantic salmon are according to Chen et al. (1999a, 1999b) and Wang et al. (2012), and those for Atlantic cod are according to Cromey et al. (2009) and Oliver (2008), defined in Table 1.

Mass balance calculations for organic carbon inputs are according to Pérez et al. (2002):

$$C_{in} = (FCR \times P_T) \times C_{food} \text{ or } C_{in} = (\text{Actual food input}^1) \times C_{food} \quad (1)$$

$$C_{waste} = C_{in} \times U \quad (2)$$

$$C_{con} = C_{in} - C_{waste} \quad (3)$$

$$C_{harv} = P_T \times C_{fish} \quad (4)$$

$$C_{resp} = C_{con} \times R \quad (5)$$

$$C_{faeces} = C_{con} - C_{harv} - C_{resp} \quad (6)$$

Where:  $C_{in}$  is the carbon input through feed (kg);  $P_T$  is required fish production over modelled time T (kg);  $C_{food}$  is the carbon content of feed (%) – see Table 1; U is uneaten feed (%) – see Table 1;  $C_{con}$  is the amount of carbon (kg) consumed by the fish during production time T;  $C_{harv}$  is the amount of carbon in fish produced (kg);  $C_{fish}$  is the carbon content of fish flesh (%) – see Table 1; R is amount of carbon respired relative to that consumed (5) – see Table 1;

Once the carbon waste from feed ( $C_{waste}$ ) and faecal materials ( $C_{faeces}$ ) are calculated over time, its horizontal dispersion prior to initial settlement to the seabed is modelled using the equation developed by Gowen et al. (1988); see equation (7)

**Table 1**

Nutrient input parameters and assumptions for Atlantic salmon and Atlantic cod.

Parameter	Atlantic salmon	Atlantic cod
Carbon content of feed	47%–50% <sup>a</sup>	42%–48% <sup>b</sup>
Uneaten feed relative to total fed	3%–10% <sup>c, d</sup>	3%–5% <sup>b</sup>
Carbon content of fish flesh (biomass)	14.6–30% <sup>d, e</sup>	28% <sup>f</sup>
Amount of carbon respired relative to the amount consumed	48% <sup>e</sup>	52% <sup>f</sup>
Particulate carbon (faeces)	19% <sup>g</sup>	8.5% <sup>f</sup>

<sup>a</sup> Chen et al. (1999a).

<sup>b</sup> Cromey et al. (2009).

<sup>c</sup> Cromey et al. (2002).

<sup>d</sup> Wang et al. (2012).

<sup>e</sup> Pérez et al. (2002)

<sup>f</sup> Oliver (2008).

<sup>g</sup> Chen et al. (2003).

<sup>1</sup> Actual food input (kg) is often profiled in advance by the feed provider based on growth and production required.

$$D = \frac{dV}{v} \quad (7)$$

where:

- D = horizontal distance dispersed (m)
- d = water depth (m)
- V = current velocity (m/s)
- v = settling velocity of wastes (m/s).

This equation assumes that 1) there is no redistribution of settled wastes through re-suspension or saltation (though resuspension can be estimated as a *post hoc* option), and 2) the depth under the cage is assumed to be flat over the modelled distances (up to 500 m from the cages). The calculations are based on the depth beneath the cages, which can be defined in the model depending on the cage size. A 'flat' bathymetry is assumed in the current version of the model, though this may lead to an overestimate of some values away from the cages if seabed is steeply sloped. Dispersion of feed and faecal particles are calculated separately using empirically derived settlement velocities for formulated fish feeds and resulting faecal matter. For Atlantic salmon this was an average of 0.116 m/s for feed and 0.042 m/s for faecal material (Chen et al., 1999a, 1999b, 2003). For Atlantic cod this was an average of 0.107 m/s for feed and 0.037 m/s for faeces (Cromey et al., 2009). The model allows these values to be entered so if information is available for new or non-standard feeds the model can be updated. This also allows settling velocities to be changed for growth stage specific feed, if only a short period of the production cycle is modelled.

The dispersion is estimated for individual fish pens in 10m intervals for a distance of 500m within sectors along eight compass axes (North, Northeast, East, Southeast, South, Southwest, West, and Northwest), each defined as an arc 45° wide centred on the directions given. An even input of particulate waste over the entire area of the individual cage is allowed for within the model. These are combined as additive overlays within the final model, as in Fig. 1. All cages in the block can be modelled individually, accounting for different production rates in each cage. Positioning of the pens in the model in relation to each other is

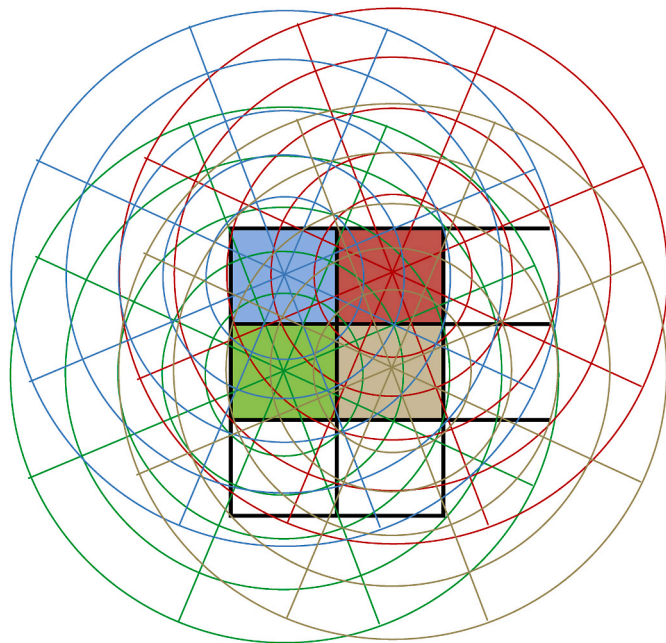


Fig. 1. Diagram showing the overlay of sectors. Here 4 × 10 m grids are shown as colours, which constitute a single 20 m wide square fish cage within a cage block. The sectors correspond to eight compass points and are divided into concentric 10 m bands.

highly flexible and done individually, allowing unconventional layouts with different size fish pens to be considered.

The amount of waste falling into each sector defined by the arc subtended at the dispersal point each with 10 m length, is calculated. The amount of particulate material entering each sector is corrected assuming that spreading in the water column and settlement to adjacent sectors weighted by the relative probability. This is accomplished by calculating the relative probability (Z) for 10m length sectors in each direction to the maximum dispersion distance for waste up to 200m from the cage, which are then combined to give the overall weighting for each 10 m sector. This is based on the distance from the cage for particle dispersion in a given direction, the mean distance over which the particles are distributed in that direction, and the standard sample deviation of distances over which the particles are dispersed in that same direction, over the modelling period (Equation (8)). This is calculated separately for feed and faecal inputs:

$$Z = \frac{1}{\sigma\sqrt{2\pi}} e^{1/2((Y-u)/\sigma)^2} \quad (8)$$

where:

- Z = relative probability
- σ = sample deviation of distances of particle settlement (feed or faeces) in a given direction over the modelling period (m)
- Y = distance of individual sector from the fish farm (m)
- u = sample mean distance for a given direction over the modelling period (m)

The overall waste input for each sector is converted to input over the equivalent 10m grid cells within the sectors. The spreadsheet pages showing results for the distribution of waste from each cage are combined using a simple additive calculation on a single spreadsheet page. At this stage a checksum and re-scaling is performed to confirm that the total dispersed wastes do not exceed the calculated total output amount from the mass balance.

The final data output from the model is given as waste material accumulation rate in 10 × 10m grid cells over a 1000m by 1000m area in two file formats for export to visualisation software and for further analysis:

- ASCII format for import to Surfer™ (Golden Software Inc, CA, USA) software.
- ESRI ASCII format for import to GIS software, such as ArcGIS (ESRI, CA, USA) or freeware QGIS (QGIS project).

In addition, a contour chart output from the model can be plotted within the Excel software. See Supplementary Information 2. This gives a basic visualisation to aid interpretation but does not allow further analysis of the results using external software. Visualisation here uses Surfer™, that allows further analysis of the plot, including the planar area of impact, the total amount of material deposited in this planar area over a fixed time period, and profiles of waste distribution levels in specific directions. To estimate the area of the possible zone of effect on benthos, an example carbon deposition contour representing 1 gC/m<sup>2</sup>/day is highlighted, representing the minimum deposition threshold at which there is likely to be a detectable environmental impact (Cromey et al., 1998; Hargrave, 1994). However, this threshold value is dependent on location/climate and can be plotted for any other substantiated value for a given location or from further research.

## 2.2. Case study sites

The model can be used as a rapid assessment of waste distribution for any species grown in cages where basic data described above is available, although further validation would be useful. In this study, to

illustrate the two types of production data available, the model was used and tested at an Atlantic cod farm in Shetland using fish biomass and feed input data for each individual cage, and at an Atlantic salmon farm on the West Coast of Scotland using overall estimated FCR over a production cycle. At each location water flow and direction measurements were taken within 100m from the cage site at three water depths (4m from the surface, mid water and 4m from the seabed) over a 15-day period using three Valeport Midas ECM current meters (Valeport Ltd, Totnes, UK) on a single tension mooring. Current speeds (m/s) and directions (deg N) were recorded every 10 min during deployments.

Modelling was carried out over a 6-month period, September 2005 to February 2006 at the cod farm, during which time actual feed input and biomass increases for each individual cage were used within the model parameters. Conversely, modelling was completed for a whole production cycle of 600 days for the salmon farm based on total production and overall farm FCR over the modelled period. The values for the mass balance calculations and feed/faecal settling velocities were set to the model defaults for both sites.

The model was tested using sediment traps deployed over three-day periods at both locations. The sediment traps used were according to the design and method employed by Chen (2000). Each sediment trap consisted of four replicate tubes (60 cm height and 8 cm diameter, ensuring an aspect ratio of >5:1 according to Hakanson et al., 1989) (See Supplementary Information 2, Figure S2.1). The sediment trap assemblies were deployed on a tension mooring, with the opening suspended 3m above the sediment surface (See Supplementary information 2, Figure S2.2). At the cod farm the sediment traps were deployed beneath the most northerly cage in the block and at 5, 15 and 25 m to the NE and at 10 and 30 m to the NW from the cage edge. At the salmon farm the sediment traps were deployed at 5, 17, 27 and 37 m from the centre of the central cage in the block.

### 3. Results

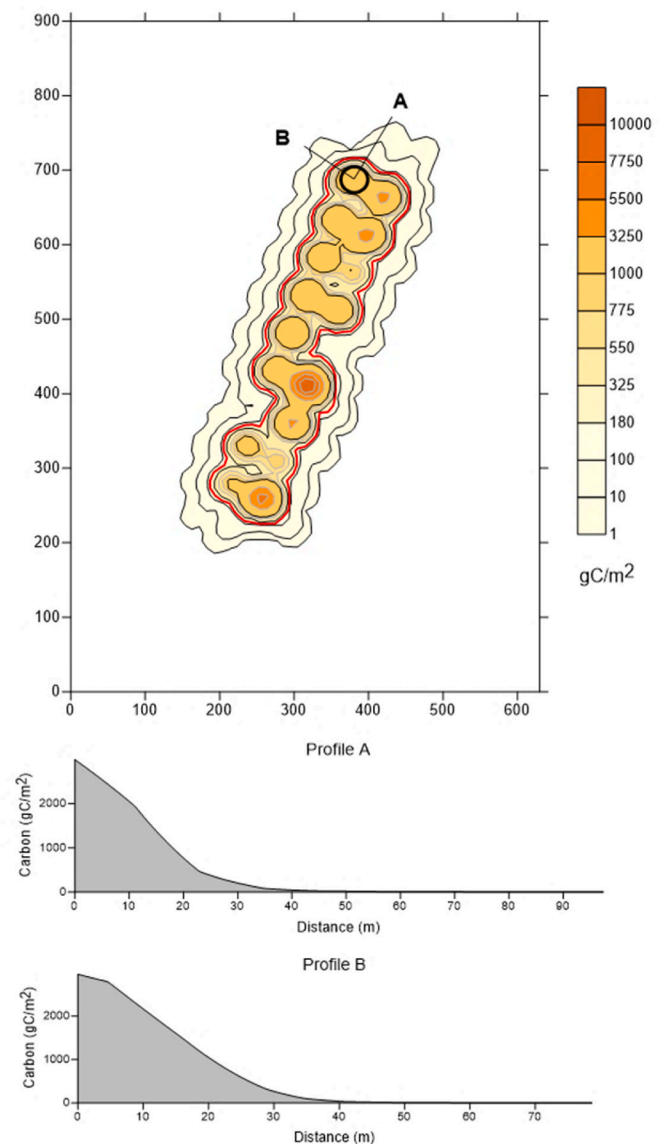
#### 3.1. Modelling of cod in Shetland

The production of cod was modelled over a six-month period using actual feed and fish production for each individual cage for a farm site in Shetland with an overall biomass limit of 1500 tonnes. Current data was taken over a 15-day period within 100 m of the farm site. The outputs of the model as plotted using Surfer™ are given in Fig. 2. This shows the output in sediment carbon per m<sup>2</sup> distributed in the proximity of the cages. The red contour line shows the boundary for the 1 g C/m<sup>2</sup>/d limit. This contour (zone of impact) covers an area of 4.2 ha with a total modelled carbon input within this area of 48.3 tonnes over the 6-month period.

As can be seen from the contour lines, the distribution of the waste is variable beneath the cages due to each cage being individually modelled. The mid-block gap is due to the position of the feeding barge. For illustration purposes these results are plotted using Excel, see Supplemental information, Figure S2.3.

The model was tested using sediment trap deployments for 3 days in September and 3 days during November. The model outputs for these deployment periods are given in Fig. 3a and b respectively. The modelled and sediment traps results are compared in Fig. 4a and b. Here we see that for deposition beneath the cages in November the model over-estimates. Unfortunately, the sediment trap data for September was compromised, due to a broken mooring, so was not included in this study. From 5 m and beyond from the cage edge the modelled estimates are a reasonable approximation of the observed results from sediment traps.

This comparison is shown in more detail in Fig. 5a and b. In particular, for 5 m and beyond, there is close alignment. There is an over-estimate for modelled input as shown by the difference between the dotted line (equal) and the line of best fit. Comparison of percentage difference in observed and predicted values of sediment settled shows



**Fig. 2.** Initial particulate waste dispersion to the seabed over 6 months production in a cod farm (Sept 2005 to Feb 2006). Red contour = 1 gC/m<sup>2</sup>/d threshold used for assessment of environment impact (Hargrave, 1994). Axis units are in metres. Black circle indicates a 30 m diameter net-pen collar, with gradients of carbon deposition given along Profiles A and B.

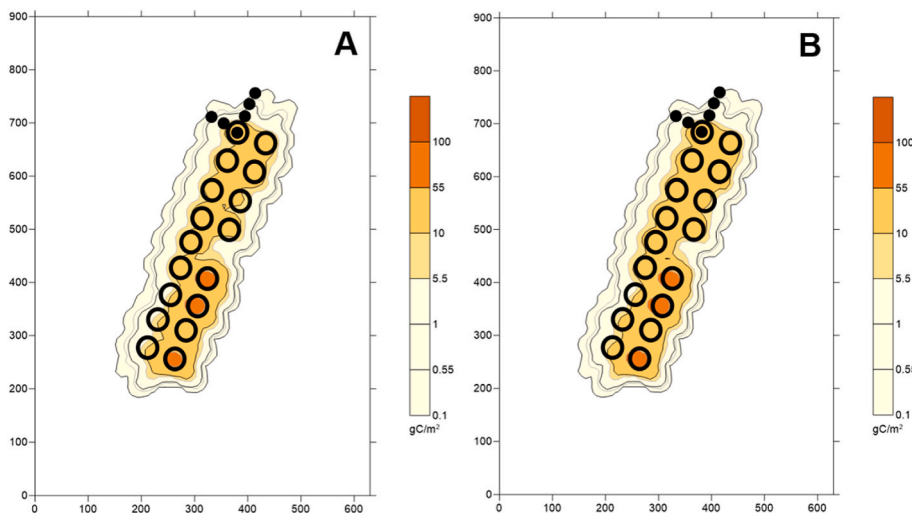
that for all data the model gives an average 114% ( $\pm 62\%$ ) of the observed data. For data collected 5 m and beyond the cage edge, the model gives an average of 96% ( $\pm 36\%$ ) of the observed data, with an R<sup>2</sup> value between observed and predicted results of 0.937 (Fig. 5).

#### 3.2. Modelling of salmon on the West Coast of Scotland

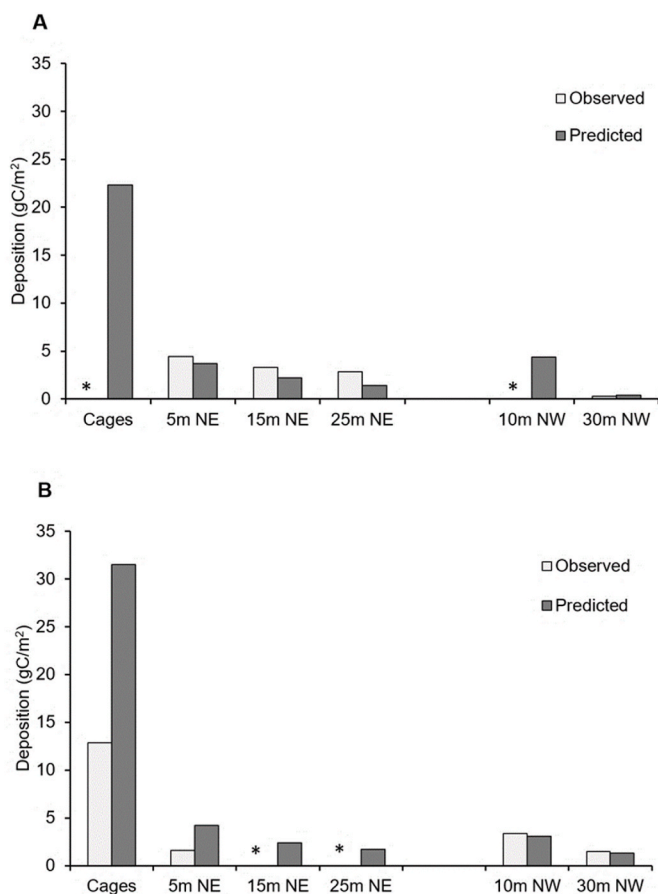
The production of salmon was modelled over a full production period (600 days) at the farm site on the West Coast of Scotland. The total production and FCR was used to drive the mass balance calculations. The biomass limit at the site was 100 tonnes. The outputs of the model plotted using Surfer™ are given in Fig. 6. This shows the output in sediment carbon per m<sup>2</sup> distributed in proximity of the cages. The red contour line shows the boundary for 1 g C/m<sup>2</sup>/d. This contour (zone of detectable impact) covers an area of 0.74 ha with a total modelled carbon input within this area of 3.5 tonnes over the production period.

The model was tested using sediment trap deployments for 3 days during production. The model outputs for this period are given in Fig. 7.





**Fig. 3.** Initial settlement of cod particulate dispersion ( $\text{gC/m}^2$ ) over a three-day period during A) September 2005, and B) November 2005. Axis units are in metres. The black dots shown the positions of the sediment traps. Black circles indicate the net-pen collar positions.



**Fig. 4.** Comparison of modelled (predicted) and sediment trap collected (observed) particulate waste from a cod farm over a three-day period; A) September 2005, B) November 2005. \* technical issue with sediment collection and no data available for comparison.

The modelled and sediment traps results are compared in Fig. 8. Here we see that for deposition beneath the cage (5 m from the centre) the model over-estimates. From 5 m from the cage edge (17 m from the centre) and beyond the modelled estimates are a reasonable approximation of the observed results from sediment traps.

This comparison is shown in more detail in Fig. 9a and b. In particular, for 5 m from the cage edge (17 m from the centre) and beyond, there is closer alignment with the dotted line (equal). Comparison of percentage accuracy shows that for all data the model gives an average similarity of 120% ( $\pm 148\%$ ) to the observed data, though there is a significant overestimate by the model under the cages (see Fig. 8), for data 5 m and beyond the cage edge the model gives an average similarity of 48% ( $\pm 42\%$ ) to the observed data, with an  $R^2$  value between observed and predicted of 0.920 (Fig. 9).

#### 4. Discussion

This study presents a spreadsheet model that can be used to estimate waste dispersion from fish cages. The CAPOT model is designed to give an approximation as a pre-scoping tool and is not intended as a replacement for more complex modelling approaches (e.g., Ferreira et al., 2012; Bannister et al., 2016; Broch et al., 2017; Jansen et al., 2018; Carvajalino-Fernández et al., 2020). It is not a ‘regulatory’ model, but instead provides a simple and quick approach for non-experts to assess the potential suitability of sites for fish production from some basic information related to hydrography, water depth and easy to determine waste estimates based on feed use or production and FCR. It is valid as a precursor that determines if it is worth investing in more comprehensive *in-situ* monitoring and modelling, as part of a formal planning and licencing process. Though resuspension can be taken into account as a post hoc option, this is based on bottom current speeds, and does not take potential turbulent mixing by wind generated waves into account.

The CAPOT model appears to overestimate deposition directly under the cage in comparison with the material collected in sediment traps, though predictions are more accurate around 5 m and beyond from the edge of the cages for both species and locations modelled. This limitation, in relation to better predictions away from a farm, compared to under the farm where the highest deposition is known to occur, does not specifically invalidate use of this simple model at the scoping stage in any initial assessment or licence application process. Comparison of the modelled results with measurements directly beneath the cages reflects the difficulty in applying sediment traps in shallow water environments to assess variable point source wastes but is consistent with the distribution of the different types of waste from the fish cages and is the approach used to validate other more established models. Due to the higher settlement velocity of feed (Chen et al., 1999a; Chen et al., 1999b) most waste feed will settle beneath or nearer to the cage, whereas faecal material with its lower density and slower settling

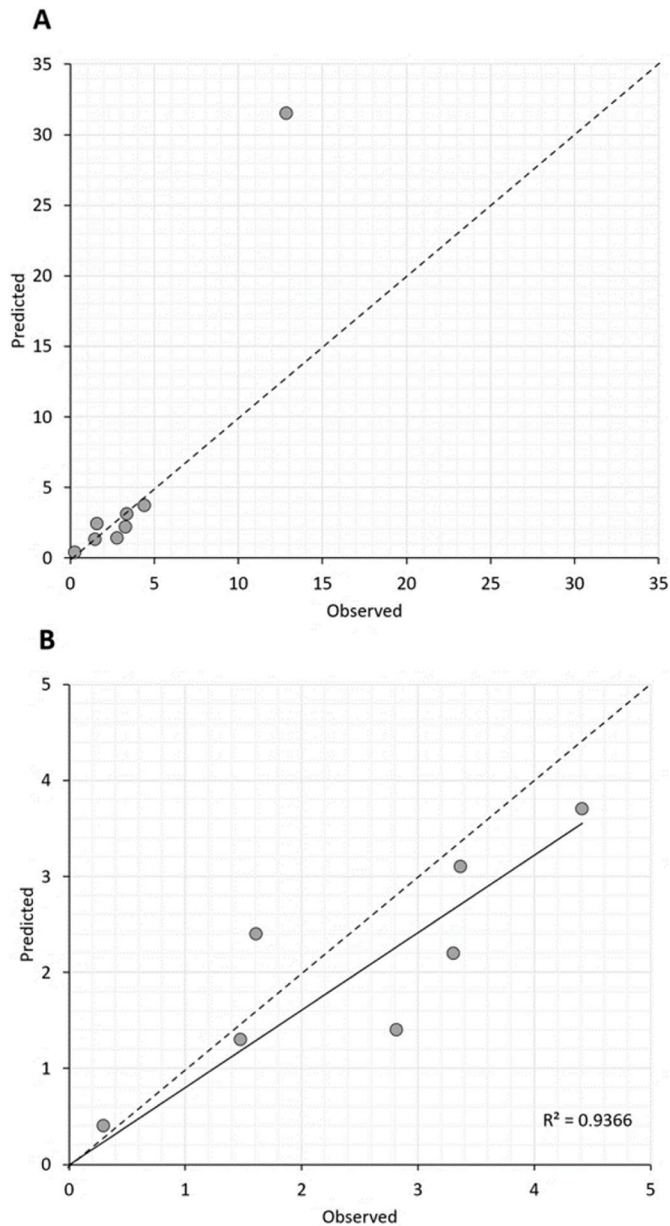


Fig. 5. Comparison of predicted vs observed for A) all data and B) data 5 m and more from the cage edge, of a cod farm. Units are  $\text{gC}/\text{m}^2$  over a three-day period in September and November 2005. The solid line is the line of best fit through the data.

velocity will tend to be more dispersed. Thus, the fractions of the different wastes making up the settled nutrient material collected will vary with distance from the farm. Uneaten feed waste settles in the form of pellets, which are not distributed evenly, so settlement traps beneath and very near to cages may only intermittently receive a feed pellet due to their narrow diameter and required aspect ratio to avoid out-washing. Conversely faecal materials are higher in volume and more evenly dispersed and so more likely to be collected. Consequently, because the CAPOT model calculates feed and faecal distribution evenly over the 10 m resolution grids, the likelihood is that it will model for a higher level of feed than actually settles in the sediment traps. As the faecal material has a greater fraction of the settled nutrient waste further away from the cages, and they have a greater tendency to be collected by the sediment

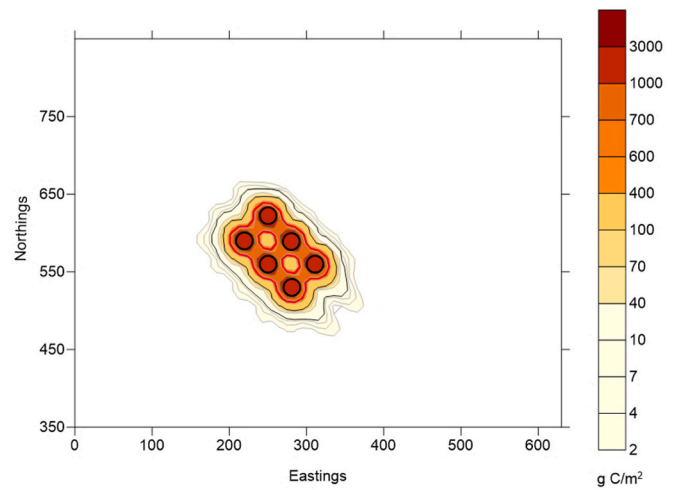


Fig. 6. Initial particulate waste dispersion to the seabed over 600 days production in a salmon farm. Red contour shows limit representing  $1\text{gC}/\text{m}^2/\text{d}$  threshold used for assessment of environment impact (Hargrave, 1994). Axis units are in metres. Black circles indicate the net-pen collar positions.

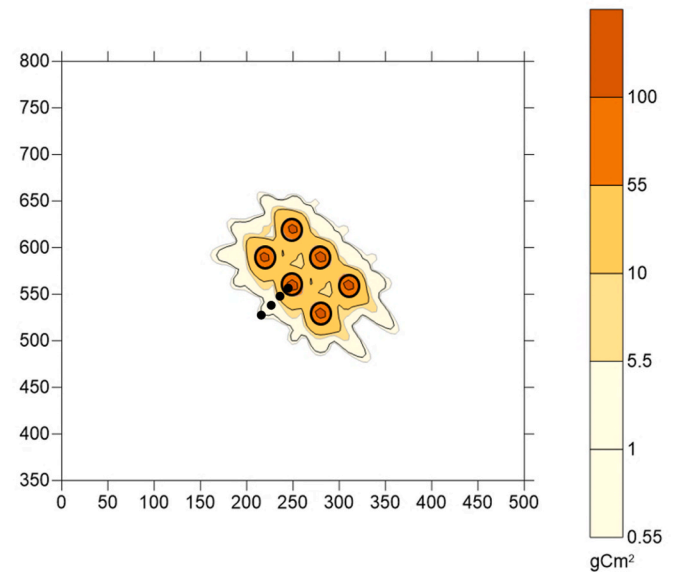
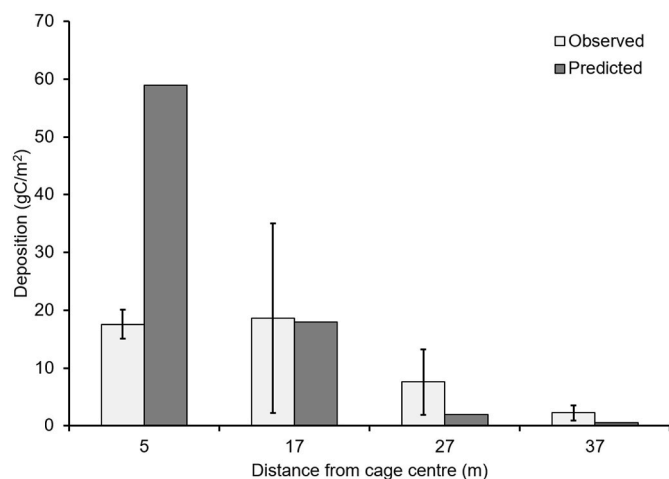


Fig. 7. Initial settlement of salmon particulate dispersion ( $\text{gC}/\text{m}^2$ ) over a three-day period. Axis units are in metres. The black dots show the positions of the sediment traps. Black circles indicate the net-pen collar.

traps these have a more representative comparison between actual and modelled data. Importantly, with the greater accuracy of the model further away from the farm, we can reasonably estimate the zone of immediate detectable impact defined as a contour with settlement of  $1\text{gC}/\text{m}^2/\text{d}$  (Cromey et al., 2009; Hargrave, 1994), as an area or distance from the cage edge that is a satisfactory estimate of possible impacts that can be measured as benthic change, for scoping purposes.

Models are often developed for a particular purpose and are not easily applied to other species or areas which do not have the same level of data (Chary et al., 2019). Environmental models are often complex, need large amounts of data and take considerable time and expertise to operate (Nobre et al., 2010). It is essential, therefore, that a scoping model as described is quick and easy to use by non-experts, as well as



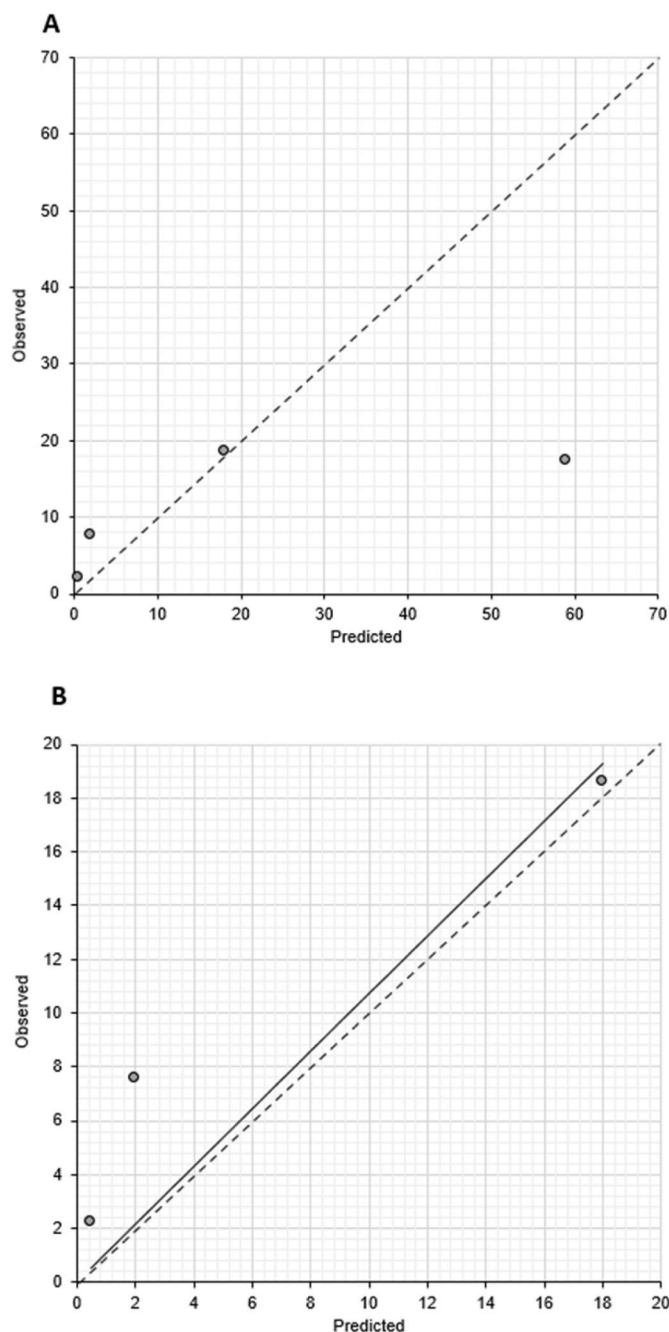
**Fig. 8.** Comparison of modelled (predicted) and sediment trap collected (observed) for salmon farm waste distribution over a three-day period. Error bars give standards deviations of the mean.

being flexible, even if not giving the level of accuracy expected for more complex models. The cage positioning tool within CAPOT allows cages of any size to be represented and arranged as appropriate. Specific sensitivity analysis has not been undertaken because validation has been undertaken using specific known data from two farms, with validation using measured data. However, farmers can run the model using different combinations of cage sizes and layouts to assess impact of changes within the same location, and across locations depending on their scoping requirements and potential business/economic models for fish production. In addition, once the model is run (using the inbuilt VBA macro routines) the parameters on the 'Data Input' worksheet can be altered and the 'Output' worksheets update immediately without the need to re-run the model, which gives the option to easily test production/feed input or FCR scenarios as part of the scoping analysis conducted by the farmer or other stakeholders. If individual cage production and feed data is available, then the output can give a good estimate of waste distribution on the seabed (around 95% similarity to measured). If this data is not available a less accurate estimate can still be obtained using approximate production and expected FCR (around 78% similarity to measured).

CAPOT can also be used and adapted for other purposes. Being a spreadsheet, the model is flexible as users can add bespoke worksheets to manipulate the outcome as necessary, i.e., treatment dose (Telfer et al., 2006), oxygen demand (Telfer and Robinson, 2003) and multiple species within different sized and complex or irregularly organised cage systems (Ferreira et al., 2008). The model outputs can also be imported directly into GIS software where they can be visualised and inspected on their own, or used as layers and integrated within site suitability, aquatic resource use or coastal management models (e.g., Hunter et al., 2006; Ross et al., 2009).

## 5. Conclusions

Waste dispersion models are important for predicting potential effects of fish aquaculture on the environment. CAPOT is an addition to the growing suite of modelling approaches and tools that are available to support aquaculture planning and management. The model serves as a flexible scoping tool that can be used during preliminary investigation of a site to ascertain whether or not more complex models and in-depth analysis is justified but should not be used as a replacement for these more in-depth approaches. Respecting the challenge of validation of models using sediment traps, it remains a recognised approach and the accuracy of the model is within acceptable levels of error given the scoping application defined and compares favourably with established



**Fig. 9.** Predicted vs observed for A) all data and B) data 5 m and more from the cage edge for a salmon farm. Units are gC/m<sup>2</sup> over a three-day period.

models used previously for environmental regulation (Cromey et al., 2002). It also gives a satisfactory estimate of the zone of local impact (as defined by Hargrave, 1994) on the benthic sediments on which to base further investigation.

CAPOT is shown to be a suitable scoping model to give an acceptable overview of potential impact through particulate waste dispersion, quickly, efficiently, with limited data requirements and little operator expertise. The simplicity of model and data entry will allow rapid adaptation to other species for cage culture and shows CAPOT to a suitable tool for initial and rapid assessment of new and existing cage farm sites, for use by a range of stakeholders. To this end, there is considerable potential to use the CAPOT model, in an adapted form, in less data rich environments within African or Asian cage culture systems.



## Author contributions

**Trevor Telfer, John Bostock:** Conceptualisation, **Trevor Telfer, Robert Oliver, Richard Corner, Lynne Falconer:** Data curation, **Trevor Telfer, Robert Oliver, Richard Corner, Lynne Falconer:** Formal analysis, **Trevor Telfer, Lynne Falconer:** Funding acquisition, **Trevor Telfer, John Bostock, Robert Oliver, Richard Corner, Lynne Falconer:** Investigation, **Trevor Telfer, Robert Oliver, Richard Corner:** Methodology, **Trevor Telfer, John Bostock:** Software, **Trevor Telfer:** Supervision, **Trevor Telfer, Lynne Falconer:** Roles/Writing - original draft, **Trevor Telfer, John Bostock, Robert Oliver, Richard Corner, Lynne Falconer:** Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

This work has been partially supported by the Tools for Assessment and Planning of Aquaculture Sustainability (TAPAS) project which has received funding from the EU H2020 research and innovation programme under Grant Agreement No 678396. RLAO received funding from Seafish Ltd and Highlands and Islands Enterprise. RAC received funding from a NERC CASE studentship. The authors owe a debt of gratitude to Dr Marc Rands, Dr Yrong Song Chen, Dr Malcolm Beveridge and Professor James Muir for suggestions and various inputs over the years.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marenvres.2022.105788>.

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