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Modelling of surface and 3D pellet distribution in Atlantic salmon (*Salmo salar* L.) cages

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ABSTRACT

Feed represents the greatest single cost factor in the production of Atlantic salmon (*Salmo salar* L.). Focusing on the problem of maximising the available feed for the fish while minimising the feed waste, a mathematical model of the feeding process has been developed. The model covers the feed spreader delivering the feed, water currents, pellet sinking speed and turbulent diffusion, fish appetite as a function of temperature, gut fullness and population structure, and is intended as a tool both for optimising general feeding strategies, and to support the daily handling of the feeding process. The process of horizontal and vertical diffusion of feed pellets in the model has been parametrised and validated through two low level validation experiments. Furthermore, global distribution patterns simulated by the model were verified by comparisons with experimental data from the literature.

1. Introduction

Feed represents the most important cost factor in the production of Atlantic salmon, representing about 50% of the total production cost from hatched eggs to marketable fish meat (Directorate of Fisheries, Norway, 2011), and is also the primary driver of fish growth. One of the key challenges in the salmon industry is therefore to maximise the feed intake of the fish, while at the same time minimising the amount of wasted feed. Farmers may approach this problem in several different ways, but the most common method today is to visually monitor the fish and the feed using underwater cameras. Feeding can then be reduced or stopped when either behavioural cues indicate a reduction in appetite, or uneaten pellets are seen to sink towards the bottom of the cage. The efficiency of this method depends strongly on how well the system operator is able to interpret such signs and act accordingly. Consequently, the skills of individual operators may have a significant direct impact on fish growth and feed utilisation at fish farms.

The success of a feeding operation depends on a number of physical and biological factors. The feed delivery system plays an important role, as it determines how well the feed is dispersed over the cage surface, and how far from the cage edges the feed is delivered. Different feeder types produce different surface dispersal patterns, and Oehme et al. (2012) documented how the patterns produced by a single feeder type depend on the physical configurations of the feeder. In addition, environmental effects such as wind and waves, may affect the actual surface pellet dispersal after it leaves the nozzle of the feeder. Below the surface, sinking rate and transport of feed due to water current are the primary factors, along with the feeding behaviour of the fish.

In situations with high water temperatures and low current speeds, dissolved oxygen may become a limiting factor for the fish (Oppedal et al., 2011), with low levels causing reduced appetite (Remen et al., 2012). When aware of possible hypoxic conditions, feed distribution can be adjusted accordingly. Furthermore, the cages themselves restrict water flow and cause reduced current speeds within and downstream of each cage (Fredheim, 2005), and biofouling may reduce the permeability of the cage netting, leading to stronger effects on the current speeds (Gansel et al., 2010). Such perturbations of current patterns in and around cages may directly impact the spatial underwater distribution of pellets, and influence water exchange to and from a cage. This may again have

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consequences for the oxygen supply within a cage, especially when several cages are placed together (Loland, 1993; Johansson et al., 2007; Gansel et al., 2011).

In the face of such a wide range of influencing factors, we believe that the best way to approach this problem is via a mathematical model. An earlier effort has been made to address this by modelling the transport of pellets in a two dimensional grid (Alver et al., 2004). The 2D model performs well, but is not well suited for representing the circular cages that have now become the industry standard in large scale production of salmon. Detailed representations of feed dispersal patterns over the cage surface are also difficult to represent in 2D.

In this work, the model developed by Alver et al. (2004) was generalised to three dimensions, and a new feed input module designed to realistically represent the feed distribution over the cage surface. Some of the basic properties of the model have been validated through experimental work (see Skøien et al., submitted for publication), and the ability of the model in predicting dispersal patterns on a cage scale were verified using experimental data from literature.

2. Materials and methods

The model equations are presented in the following sections. All model parameters, state variables and inputs are listed in Table 2.

2.1. Pellet transport in 3D

The continuous model formulation given in Eqs. (1)–(4) in Alver et al. (2004) is generalised to 3D by adding the relevant terms for the third dimension. After expanding the diffusion term, assuming omnidirectional diffusion, the full equation in 3D can be written as follows:

$$\frac{\partial c}{\partial t}+v_x\frac{\partial c}{\partial x}+v_y\frac{\partial c}{\partial y}+(v_z+u_v)\frac{\partial c}{\partial z}+\kappa\left(\frac{\partial^2}{\partial^2 x}c+\frac{\partial^2}{\partial^2 y}c+\frac{\partial^2}{\partial^2 z}c\right)=u-f_I \tag{1}$$

where $c(x, y, z, t)$ is the local feed concentration, x, y and z are the spatial coordinates along the two horizontal axes and the vertical axis, respectively, $v_x(x, y, z, t)$, $v_y(x, y, z, t)$ and $v_z(x, y, z, t)$ are the three components of the local water current, u_v is the sinking speed of the feed pellets, κ is the diffusivity, $u(x, y, z, t)$ is the feed addition and $f_I(x, y, z, t)$ is the local ingestion rate of the fish.

The model is then discretized along the three spatial dimensions using the same method as in Alver et al. (2004). The variable $c_{i,j,k}$, where $i \in \{1, \ldots, i_{max}\}$, $j \in \{1, \ldots, j_{max}\}$ and $k \in \{1, \ldots, k_{max}\}$ represent the indexes along the two horizontal dimensions and the vertical dimension, respectively, represents the amount of feed in cell (i, j, k).

The equation for c is as follows:

$$\dot{c}_{i,j,k}=f_{A(i,j,k)}+f_{D(i,j,k)}+u_{i,j,k}-f_{I(i,j,k)} \tag{2}$$

where f_A denotes the change due to advection, f_D the change due to diffusion, u the feed supply rate into cell (i, j, k) and f_I the rate of feed ingestion in the cell. The advection term is derived in the same way as for the two dimensional model, except that we must now allow for both positive and negative currents along all dimensions:

$$f_{A(i,j,k)}=|v_{x(i,j,k)}|\frac{c_{i^*,j,k}}{\Delta x}+|v_{y(i,j,k)}|\frac{c_{i,j^*,k}}{\Delta y}+|(v_{z(i,j,k)}+u_v)|\frac{c_{i,j,k^*}}{\Delta z}-\left(|v_{x(i,j,k)}|\frac{1}{\Delta x}+|v_{y(i,j,k)}|\frac{1}{\Delta y}+|(v_{z(i,j,k)}+u_v)|\frac{1}{\Delta z}\right)c_{i,j,k} \tag{3}$$

where the indexes marked by * represent a step in the opposite of the transport direction along each dimension:

$$i^*=i-\operatorname{sgn}v_{x(i,j,k)}$$
$$j^*=j-\operatorname{sgn}v_{y(i,j,k)}$$
$$k^*=k-\operatorname{sgn}(v_{z(i,j,k)}+u_v)$$

For cells along the surface, bottom and horizontal edges of the grid, some of the terms above will be outside the grid. The feed content in such outside cells is set to the ambient value, which for feed pellets equals 0.

To adapt the diffusion we simply need to add a term for the third dimension:

$$f_{D(i,j,k)}=\kappa\left(\frac{c_{i+1,j,k}-2c_{i,j,k}+c_{i-1,j,k}}{\Delta x^2}+\frac{c_{i,j+1,k}-2c_{i,j,k}+c_{i,j-1,k}}{\Delta y^2}+\frac{c_{i,j,k+1}-2c_{i,j,k}+c_{i,j,k-1}}{\Delta z^2}\right) \tag{4}$$

Again, some of these terms will be outside of the grid for cells along the edges. All such cells are assumed to hold the ambient value (0 for feed pellets), except for cells above the surface ($k = 0$), which are assumed to have the same value as the cell at $k = 1$. The latter rule sets a diffusion rate of zero through the surface.

2.2. Cage shape

The discretised model is most easily implemented in a computer as a cubic array of cells. To represent the actual shape of the cage, a second cubic array of binary values is defined, where 1 denotes a cell inside the cage, and 0 denotes a cell outside. The transport equation is integrated on the entire cubic array, but only cells inside the cage are taken into account when calculating ingestion rates and feed waste.

To represent a standard salmon cage we use a circular cylinder with radius R and height D_c above a conical section with its base matching the cylinder and its tip pointing downwards and reaching a total depth of D_{tot}. The height of the conical section is thus $D_{tot} - D_c$. Cells that have their centre within this cylindro-conical shape are considered part of the cage.

2.3. Modelling the feed input

The surface distribution of the feed pellets delivered to the cage can have a significant effect on feed wastage. A higher dispersion of feed over the surface leads to lower local concentrations of feed, and in the model this will to some degree be reflected in a more even distribution of the feed between the size classes of fish. Depending on the current speed and direction, the surface distribution of feed can also affect the likelihood of feed pellets to drift out before they can be eaten.

The actual spread pattern of pellets given by a pneumatic feeding system with a rotor spreader was investigated by Oehme et al. (2012). A number of boxes were arranged diagonally across a square cage with the spreader placed in the cage centre, and the relative number of pellets landing in each box was calculated for a number of different spreader settings and various pellet sizes. In this set-up, each box covers a certain sector of the annular area representing an interval of distances from the spreader. The boxes closest to the feeder thus cover a larger angular sector compared to the boxes that are placed further away. After correcting for these differences, a probability distribution can be drawn for the distance travelled by each individual pellet. Oehme et al. (2012) found that the distribution of distance travelled by single pellets resembled a skewed normal distribution rather than being uniform for the entire range