Aquaculture 430 (2014) 195–206

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Numerical studies on the hydrodynamic effects of a salmon farm in an idealized environment

Pablo Cornejo [a,*], Héctor Hito Sepúlveda [b], Marcelo H. Gutiérrez [c], Gonzalo Olivares [d]

[a] Mechanical Engineering Department, Faculty of Engineering, University of Concepción, Concepción, Chile
[b] Geophysics Department, Faculty of Physical and Mathematical Sciences, University of Concepción, Concepción, Chile
[c] Programa COPAS Sur-Austral, University of Concepción, Concepción, Chile
[d] i-mar Center, University of Los Lagos, Puerto Montt, Chile

ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form 10 April 2014
Accepted 11 April 2014
Available online 21 April 2014

Keywords:
Salmon farm
Fishing net cage
Porous jump
Hydrodynamics

ABSTRACT

A Large Eddy Simulation (LES) model was used to describe the hydrodynamic effects of a salmon farm on an incident current with constant and semidiurnal variability. In particular, we describe the formation of a zone of low velocity (wake) downstream of the farm and the advection of a passive tracer released inside the farm. The mesh of salmon farm net cages was described using a porous jump approximation, validated with experimental data available in the literature. A set of simulations were run to analyze the effects of the mesh drag coefficient and the current intensity on wake formation and current dynamics. The results show that the extension of the wake depends directly on current intensity, where larger extensions are associated with more intense currents; whereas the drop in velocity within the wake appears to be solely a function of the mesh drag coefficient, where meshes with higher drag coefficients generate higher velocity drops. We also find high turbulent diffusion in the contour area of the wake, attributable to a high strain rate in that region. Moreover, given semidiurnal current variability, we find the formation of a positive wake (high velocity area) at the beginning of flow direction change during each semidiurnal period. Additionally, we analyze the advection of a passive tracer initially released inside the salmon farm, which indicates that, in fish farms with meshes of high drag coefficient, the tracer is almost entirely advected away from the vicinity of the farm after the third simulation day; while for low drag meshes, the tracer is retained around the salmon farm. We discuss the potential application of this model for analyzing the transport of organic and inorganic components, such as organic matter, nutrients, parasites and antibiotics, and the impacts on biologically relevant pools of non-conservative elements, such as oxygen.

1. Introduction

The sustained growth of global aquaculture in recent years has led to its expansion into new geographical regions (Asche et al., 2008; Bostock et al., 2010) where optimal water quality ensures the growth of "healthy" fish and where hydrodynamic characteristics ensure adequate site ventilation and minimize environmental impacts. Moreover, there are certain minimum requirement conditions that are necessary to guarantee the technical sustainability of this activity in some environments (Bostock et al., 2010). One such region identified as optimal for the development of aquaculture in Chile is the channels and fjords of Chilean Patagonia, with suitable water quality and oxygenation conditions (Tironi et al., 2010). Although in last years there has been a growing development in oceanographic knowledge of this remote area (Pantoja et al., 2011), little is known about the potential impacts of implementing fish farming systems on the hydrodynamics and ecosystem functioning of the fjords and channels.

In situ measurements (Johansson et al., 2007) showed that salmon farms have an effect on the hydrodynamics of local currents, oxygen content inside fish cages, and the swimming behavior of fish. Thus, farm-induced changes on hydrodynamic conditions must be considered in the design, orientation and distribution of farms, as they directly influence the diffusion and transport of materials released during the production process (e.g. excess food, feces, antibiotics, disease), which impact environmental quality and are sub-optimal for fish health. The effect of cages on local circulation can be determined experimentally through the continuous monitoring of oceanographic variables (Fredriksson et al., 2007), however this is highly costly and requires long-term sampling effort. Therefore, studies have been focused on evaluating some specific aspects such as the dynamic interaction between waves and fish cage geometry (Lader and Fredheim, 2006) and the effect of particular structures used in aquaculture on some parameters such as turbulence, velocity field and stratification (Plew et al., 2006; Stevens and Petersen, 2011), as well as on the retention

---

* Corresponding author at: Mechanical Engineering Department, University of Concepción, Edmundo Larenas s/n, Concepción, Chile. Tel.: +56 41 2203547.
E-mail address: pabcornejo@udec.cl (P. Cornejo).

http://dx.doi.org/10.1016/j.aquaculture.2014.04.015
0044-8486/© 2014 Elsevier B.V. All rights reserved.

time of products used in the treatment of infections (Corner et al., 2011). An alternative approach is numerical simulation, which can be used to describe physical phenomena and can be calibrated and validated by in situ measurements. Regional oceanographic numerical models, such as FVCOM (Chen et al., 2003) and ROMS (Shchepetkin and McWilliams, 2005), are commonly based on the resolution of primitive equations, i.e. the Navier–Stokes equations averaged over time (Reynolds Averaged Navier–Stokes, RANS) simplified under the Boussinesq and hydrostatic approximations. Although there are efforts to develop non-hydrostatic versions of these models (e.g. Shchepetkin et al. (2007) for ROMS and Lai et al. (2011) for FVCOM) and alternative non-hydrostatic models, ICOM (Piggott et al., 2008) and MITcgm (Adcroft et al., 2004), the use of regional oceanographic models in the description of fluid dynamics involving microscale (3D turbulence) processes is restricted. Nevertheless, some efforts using regional oceanographic models in the scale of farm structures on marine environments have been developed (Hasegawa et al., 2011; Shapiro, 2011; Work et al., 2012; Yang et al., 2013). The results indicate changes in current velocity and transport in the order of tens of kilometers (Neill et al., 2009; Shapiro, 2011, 2012), i.e. larger than a salmon farm, suggesting that the effect of such structures on the aquatic environment is non-negligible and should be characterized. However, studies involving fish farm systems include a wide range of scales e.g. the net mesh scale (Patursson et al., 2010; Tsukrov et al., 2011), the fish cage scale (Fredriksson et al., 2003; Huang et al., 2006, 2007; Lader et al., 2008) and the fish farm scale (Fredriksson et al., 2007; Xu et al., 2012) to be considered in the models.

Computational fluid dynamics (CFD) represents an alternative tool for describing and assessing the hydrodynamic effects in the scales of fish farming systems. CFD has long been applied to resolve problems in a wide range of areas, such as aerospace, automotive, mining, energy, medicine, food and refineries. In the field of fish aquaculture, the most common approach for studying the interaction between farm site structures and the environment has focused on the effects of currents on these structures, such as changes in tension on anchoring lines under different current and wave scenarios (Lee et al., 2008), the behavior of a fish cage against a mooring line break (Xu et al., 2012), and the reduction of effective volume inside the fish cage due to deformation induced by ambient flow or extreme events (Huang et al., 2006, 2007, 2008). Other studies have focused on structural aspects of aquaculture facilities, for example the differences in mechanical stress between the top and bottom parts of fish cages using floating devices (Lader and Fredheim, 2006), the estimation of load capacity of some structural parts (Moe et al., 2010), the response of fish cages to regular (Fu and Moan, 2012) and irregular wave fields (Xu et al., 2011, 2012), and the forces acting upon anchors under different wave conditions. However, few studies have focused on describing changes in hydrodynamic field under the presence of a fish farm obstacle. Such effects can be summarized as: loss of free stream momentum due to the salmon farm structures (Johansson et al., 2007; Zhao et al., 2012), decrease of free stream turbulent diffusion (Stevens and Petersen, 2011), indirect effects associated with the transport of materials from farming systems, and alteration of the hydrographic characteristics of the water column (Plew et al., 2006). From a hydrodynamic standpoint, aquaculture cages represent a momentum sink to the incident current (Patursson et al., 2010). Although the details of microscale hydrodynamic processes can be captured by simulating each of the filaments that compose the meshes, the different spatial scales involved in this approach require high computational and time costs which render it impractical. As an alternative to this method, the momentum sink of the fluid flow can be quantified using a porous jump condition based on Darcy's law and extended to capturing inertial effects (Patursson et al., 2010; Zhao et al., 2007). In this context, the objectives of this study are: i) to validate the porous jump approach by quantifying the hydrodynamic drag of the mesh panel over an incident current; ii) to study the hydrodynamic effects of a salmon farm in a three dimensional idealized environment (no coastline, no bathymetry, no wind, no fish inside) characterized by both a constant and a semidiurnal current, employing a LES model implemented within a computational fluid dynamics code; iii) to compare the impact of changes in parameters such as mesh drag coefficient and current intensity (constant and variable) on the advection of a passive tracer released into the salmon farm. Finally, we discuss the implications of our findings on fish health parameters in fish farming systems and on the carrying capacity of areas where fish farming is carried out.

2. Theory

2.1. Mathematical model: hydrodynamics

Regional oceanographic models are commonly based on the resolution of the Reynolds Averaged Navier Stokes (RANS) equation simplified under Boussinesq and hydrostatic approximations. However, these approaches limit the use of regional oceanographic models at the scale of the fish farming system. Considering these modeling constraints, CFD tools appear to be a powerful alternative to address microscale problems, given the structure of the equations and numerical schemes available in existing CFD codes. In particular, this study proposes the use of a LES model (*Large Eddy Simulation*) to describe the hydrodynamic effects of a salmon farm on an incident current. The advantage of modeling approaches based on LES over the conventional RANS lies in its capacity to more realistically capture the flow field, since the process of filtering the Navier–Stokes equation is over space, rather than time as in the RANS method. In LES models, large turbulent structures (larger than the computational grid) are calculated directly, while smaller structures (sub-grid structures) are modeled. In practice, LES models solve the time dependent Navier–Stokes equations filtered over space, leading to a convolution product between the governing equations and a filter function. The filtered variable $\overline{\phi(x)}$ is defined as

$$\overline{\phi(x)} = \int_D \phi(x')G(x,x')dx \qquad (1)$$

where D is the control volume and G the filter function. In particular, CFD codes make use of the fact that the finite volume discretization implicitly carried out the filtering operation, thus the filter refers to computational grid,

$$G(\mathbf{x},\mathbf{x}') = \begin{cases} 1/V, & \mathbf{x}'\in v \\ 0, & \mathbf{x}'\text{Otherwise} \end{cases} \qquad (2)$$

where V is the cell volume in the finite volume discretization. By replacing the filter 2 in Eq. (1) we obtain the new variable filtered by the computational grid,

$$\overline{\phi(x)} = \frac{1}{V}\int_v \phi(x')dx', x'\in v. \qquad (3)$$

The complete derivation of all filtered Navier–Stokes equations is complex and beyond the scope of this study. However the main governing equations are summarized below.

Continuity equation

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho\overline{u}_i) = 0. \qquad (4)$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho\overline{u}_i) = \frac{\partial}{\partial x_j}\left(\sigma_{ij}\right) - \frac{\partial\overline{p}}{\partial x_i} - \frac{\partial\tau_{ij}}{\partial x_j} \qquad (5)$$

where σ_{ij} is the stress tensor associated with the molecular viscosity