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Physical and numerical investigation of the hydrodynamic implications of aquaculture farms

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ABSTRACT

Effects of long-line mussel farms on flow structure have been studied in this paper. Experiments in a tidal basin facility on Froude scaled long-lines were used to better understand how droppers impact flows. The observations demonstrate that flow speeds within the long-line is reduced by 25–30% from ambient, and material transport to downstream droppers is significantly reduced. These results suggest that neglecting the physical barrier imposed by the aquaculture installations will result in a considerable overestimation of nutrient supply to the bivalve and thus an overestimation of carrying capacity. An existing two-dimensional depth integrated model has been refined to better predict hydrodynamics and solute transport within suspended aquaculture farms. The numerical model has been refined to include both the form drag imparted by the individual mussel droppers and the blockage effect that the suspended canopy presents. Additional turbulent kinetic energy production is incorporated into the two equation $k-\varepsilon$ closure model. Data collated in the laboratory was used to calibrate and validate the numerical model. It has been demonstrated that predicted velocities and solute transport correlate well with experimental results. The numerical model was applied to a designated aquaculture site on the West Coast of Ireland, Casheen Bay. The effect of long-lines on hydrodynamics and solute transport was analysed. Flushing studies were used to study particle renewal terms in the embayment. Several flushing characteristics were calculated, including, the average residence time and the exchange per tidal cycle coefficient. The viability of using relatively simple flushing studies formulae to assess the development potential of small scale aquaculture projects is discussed.

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1. Introduction

The cultivation of shellfish via suspension culture in Ireland is carried out at a number of locations along the West Coast. This method of cultivation involves the suspension of bivalves in the water column on ropes suspended from floatation units. These installations represent a suspended canopy that consists of distributed drag elements that collectively form a porous obstacle to flow. The impact of these organisms on the surrounding ecosystem is twofold: suspension feeding depletes ambient water of particulate food, while the presence of the aquaculture structure can impact particle renewal by retarding flow via enhanced drag. A substantial amount of research has been carried out on the growth and feeding patterns of marine bivalves (Gibbs et al., 1991; Grant, 1996), however, most carrying capacity studies focus on budgeting of particulate food depletion and renewal (Raillard and Menesguen, 1994; Pilditch et al., 2001; Simpson et al., 2007). The effect of the frictional resistance of mariculture structures on flows has mostly been ignored. This is particularly true of numerical modelling studies on the subject (McKindsey et al., 2006).

The impact of aquaculture structures on currents has been observed in field measurements. Gibbs et al. (1991) measured local circulation patterns around long-line mussel farms in Pelrous Sound, New Zealand. The flow patterns indicate that water movement through the farm are attenuated to approximately 30% of the upstream flow velocity. Current meter studies investigating the effects of canopy spacing on flow rates demonstrated a reduction in flow to 13% and 25% of ambient within droppers spaced at 60 cm and 90 cm respectively (Boyd and Heasman, 1998). Pilditch et al. (2001) observed a 40% reduction in flow speed within a 80 m × 50 m suspended scallop culture lease in Nova Scotia; Plew et al. (2005) demonstrated similar reductions within larger long-line mussel farms, and showed evidence of wake development downstream.

The hydrodynamic effects of an aquaculture installation are similar in many ways to the impediment to flow posed by submerged aquatic vegetation. A significant amount of research has been conducted in this area. Naot et al. (1996), investigated the hydrodynamic behaviour of partly vegetated open channel flow via a three-dimensional, empirically-based model that included detailed turbulence modelling. The vegetation was modelled as an

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internal resistance that exerts drag force, produces energy of turbulence and interferes with its anisotropy and length scale. Jackson and Winant (1983) analysed the effect that kelp forests had on coastal flows. Field data indicated that velocity through the canopy was between 43% and 54% that of velocities at the control point outside the system. The drag exerted by the forest was found to be up to ten times greater than that of a non-kelp area.

A number of studies have directly linked a reduction in flow speeds with poorer growth rates of suspension feeders (Lenihan et al., 1996). Stroheimer et al. (2005) measured flow speeds, meat content and food availability in a commercial long-line mussel farm in Southern Norway. Friction from the mussels and farm structure reduced current speed inside the farm to less than 30% of ambient. Chlorophyll-a depletion was considerable with more than 50% of depletion occurring within the first 30 m of the lease. The reduction in currents resulted in food depletion and lower meat content within the farm. Boyd and Heasman (1998) observed reduced growth rates within mussel droppers spaced at 60 cm as opposed to 90 cm; the primary limitation on growth was found to be flow speeds rather than ambient advection patterns which underlines the effect that this level of flow impediment may have.

Numerical modelling of the hydrodynamic effects of aquaculture structures include studies on the distribution of wastes from fish cages in the Gulf of Maine (Panchang et al., 1997); a model of the effect of kelp and scallop culture on tidal current speed and flow patterns in Sungo Bay, China (Grant and Bacher, 2001); and a depth-averaged model of the effects of suspension farms on flows (Plew, 2011). Grant and Bacher (2001) developed a two dimensional finite element model of Sungo Bay, China. The effects of suspended mariculture of marine bivalves was parameterized by local increases in bottom friction and the results compared with the default case of no aquaculture. The numerical model predicted a 20% decrease in velocities in the navigation channel through the farm and a 54% reduction in current speeds through the main culture area. Plew (2011), used a numerical model to consider the effects of long-line mussel farms on tidal currents within two embayments in Pelorus Sound, New Zealand. The long-line farms were parameterised in the model by modifying the bed friction coefficient to account for drag from the farm structures. Shi et al. (2011) adopted a three-dimensional, physical-biological coupled model to study the growth rates of cultured kelp farms. The physical impediment introduced by the kelp systems reduced average surface current speed by 40%, thereby decreasing water exchange with the open sea and as a direct consequence kelp production. The authors noted that the primary source of nutrients for the growth of kelp was dissolved inorganic nitrogen (DIN) from the open sea, and the aquatic vegetative obstruction was the main reason for the deficient DIN within the kelp culture area. Aure et al. (2007) developed a rate conditional box model to simulate carrying capacity and flow reduction within a long-line farm as a function of the physical properties of the farm and ambient upstream velocity. The long-lines were represented by a frictional resistance coefficient determined empirically from field data. Current speeds within the farm was found to reduce as long-line length increased and long-line spacing decreased. The width to length ratio of the farm was also found to be of importance with a ratio approaching one being optimal.

In the present research, aquaculture installations are incorporated into an existing two-dimensional, hydrodynamic model to predict the effects of long-line mariculture on tidal circulation and flow patterns and the associated implications for food supply to the organisms. The numerical model was amended to incorporate form drag and a porosity term which describes the degree of fluid penetration throughout the farm. Both a mixing length and a two equation $k-\varepsilon$ turbulence closure model were considered with the $k-\varepsilon$ model further refined to include the production and dissipation of turbulent energy due to the presence of the structures. Scale modelling studies carried out in a tidal basin facility were used to quantify drag imparted by the droppers and analyse material transport within the system. These data are used to determine model coefficients and fine tune the numerical model. The model was applied to a designated aquaculture development site in the West of Ireland, Casheen Bay. The impact of the culture leases on the system hydrodynamics is discussed.

Flushing studies provide a time scale analysis of the effects of the aquaculture infrastructure on water circulation patterns. The viability of using relatively simple flushing studies formulae to assess the development potential and environmental impact of small scale aquaculture projects is discussed, as opposed to other relatively more expensive modelling techniques. In the following sections: the hydrodynamic model is developed, the laboratory experimental methods and results are presented and discussed, the model output and experimental data are compared, and finally, the model is used to assess the canopy effects on both hydrodynamics and material flushing and retention times at a bay-scale level.

2. Methodology

2.1. Introduction

The numerical model used for this study is DIVAST (Depth Integrated Velocity and Solute Transport), a two-dimensional, depth-averaged, finite difference model which consists of two coupled modules: (1) a hydrodynamic module, and (2) a solute transport and water quality module. Depth-averaging simplifies the governing equations of flow at the cost of sacrificing information on the vertical velocity distribution; the use of such models is common practice when modelling shallow, well mixed coastal water-bodies where vertical velocities are not significant. The hydrodynamic module is based on the solution of the depth integrated Navier–Stokes equations and includes the effects of local and advective accelerations, the rotation of the earth, barotropic and free surface pressure gradients, and bed resistance. Solute transport and water quality are computed using the general depth integrated advection-diffusion equations and incorporate local and advective effects, turbulent dispersion and diffusion, wind effects, source and sink inputs and decay, and kinetic transformation processes. A more complete description of DIVAST may be found in Falconer and Liu (1995).

The physical modelling study was conducted in a tidal basin facility at National University of Ireland, Galway. The aim of the physical modelling was to observe the complex hydrodynamic flow regime within and around aquaculture installations. Material transport and flow dynamics in the tidal basin were investigated using detailed dye studies and velocity measurements.

2.2. Numerical modelling

The purpose of the numerical model is to accurately predict the effects of mussel dropper long-lines on flow dynamics and material transport. To achieve this, the governing hydrodynamic equations are amended to simulate the effects of the water passing through a dense canopy of suspended mussel droppers. The effect of the droppers on turbulence production and intensity is also incorporated in the model by including a refined turbulence closure model. Hereafter, this amended model is referred to as the "aquaculture numerical model" (ANM).

2.2.1. Hydrodynamic module

To assess the effects of the aquaculture canopy on flow dynamics, the mathematical algorithm must be representative of the

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