ICES CM 2008 H: Ecological carrying capacity in shellfish culture
Operational models of carrying capacity applied to a Norwegian fjord

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Abstract
Estimation of production carrying capacity for shellfish culture has become a major focus in research, with operational models applied at culture sites worldwide. Fundamental to these efforts are an understanding of the relationship between nutrients, primary production, and shellfish bioenergetics. The potential for manipulation of nutrients via artificial upwelling has been undertaken in a Norwegian fjord in the CANO Project. Research in this area includes several types of models at varying spatial scales. One of the more useful configurations has been a box model allowing variation in the location of the upweller as well as the sites of mussel culture. In a companion conference paper in by Filgueira and Grant, optimization routines are used to maximize mussel production in the upper fjord based on projected nutrient-phytoplankton enhancement by the upweller. The present paper considers the initial stages of a fully spatial companion model where the results can be mapped in detail.

Introduction
Cultured shellfish have potentially important trophic interactions with their food supply, namely exerting top-down pressure as grazers and controlling phytoplankton biomass (Grant et al. 2008). When culture is first introduced to a coastal ecosystem, there is only a minimal grazing influence and bottom up regulation is possibly more significant. This is especially true in highly stratified waters where nutrients are often limiting in summer. Norwegian fjords have great culture potential for shellfish since they are deep and pristine, with large open areas available for farming. The idea of using artificial upwelling to enrich the summer euphotic zone for phytoplankton production has been put into practice in Lysefjord, in southern Norway (Aure et al. 2007).

Because the upwelling is highly localized and the dispersed nutrients have an unknown trajectory, a spatial model is necessary to track the fate of nutrients, subsequent primary production, and placement of bivalve farms. Tides, winds, and river input drive these processes such that a fully coupled physical-biological model is required for prediction of particle fields in relation to aquaculture.

In the following study, we present the physical model used to drive circulation in upper Lysefjord, its use in predicting dispersal of a conservative tracer, and the initial coupling to an ecological model containing primary producers and grazing mussels. This study is complementary to those using a box model (Filgueira and Grant, this conference) in which spatial regions are collapsed, but optimization routines may be more readily applied.

Study site
Lysefjord (head at 59.054487°N, 6.647792°E) is about 40 km long and at its mouth joins the Hogsfjord where it reaches more open bays over the course of another 35km. From there it is 25 km to the open North Sea. Lysefjord has a small river at its head and a larger flow of freshwater from hydroelectric input a few km from the head. Massive cliffs define its sides, with

substantial long-fjord winds, and depths in the centre ~150 m. Tidal range is <1m. At a point about 1km from the head, a pump was used to inject brackish surface to 30m depth (Aure 2007). Although this could not break the thermocline, enhanced diffusion of deep nutrients to surface waters via buoyancy increased surface nutrients by an order of magnitude.

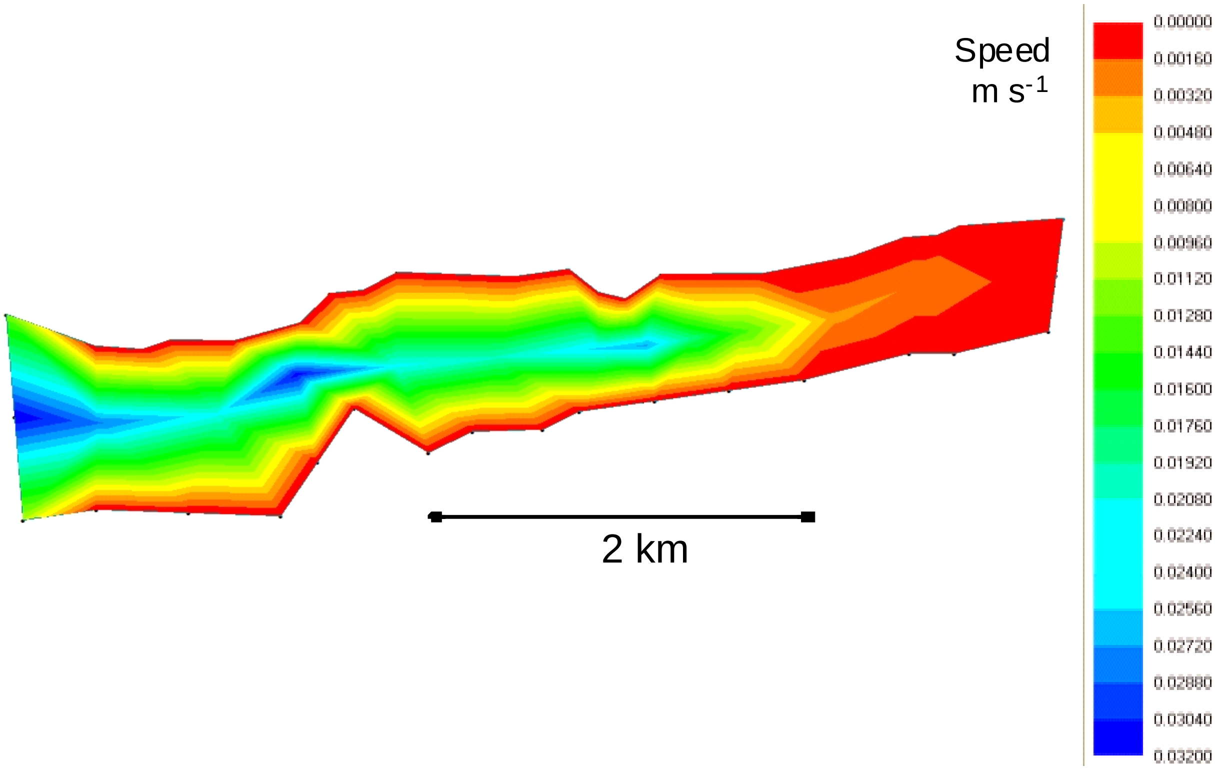

Fig. 1. Spatial distribution of current speeds within the upper portion of Lysefjord, southern Norway.

A 2D finite element circulation model based in Aquadyn (http://www.synexusglobal.com) was used to determine velocities and thereby exchange volumes for the grid triangles. Beyond tidal forcing, the model contains circulation from riverine input near the upweller and lesser freshwater input from the small river at the head. In addition, a constant supply of conservative tracer was introduced into the model at the point of the upweller to simulate nutrient dispersion. Despite the 3D structure of the fjord, we have modelled only the upper 5 m of the water column, given that this is the primary zone of upwelling influence on phytoplankton. In addition, horizontal exchange in summer is much greater than vertical exchange (Gillibrand 2001) and the latter can be ignored for these modelling purposes. The physical model was coupled to an ecosystem model developed in Simile (www.simulistics.com), which included phytoplankton, nutrients, detritus, and mussels.

Initial results

Results are presented as maps of either velocity or concentration, interpolated from the finite element grid. In this version of the Aquadyn model, we have intentionally made the grid coarse because when small grid cells experience high velocities the consequently high exchange rates tend to crash the Simile model.

A map of velocities within the upper part of Lysefjord indicates that there is a strong lateral trend in flow, with a ‘pipe’ type cross-fjord profile as expected in such a narrow location (Fig. 1). In addition, there is a strong length-wise gradient in speed with a rather stagnant region in the uppermost fjord. This hydrodynamic regime has implications for the artificial upwelling as described below.

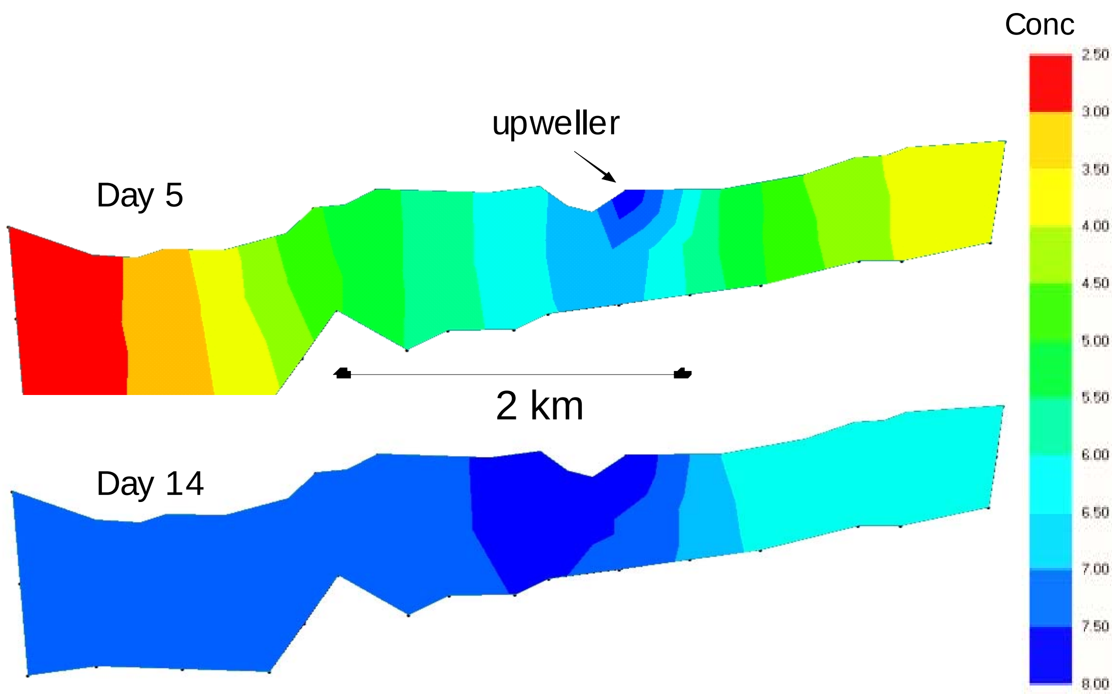

Fig. 2. Spatial distribution of conservative tracer introduced by artificial upwelling in the upper portion of Lysefjord, southern Norway. Two time periods after the initiation of upwelling are indicated. Concentration is in arbitrary units.

A map of a conservative tracer (referred to as nutrients) shows the time and space dependence of initiating upwelling (Fig. 2). Assuming no input of nutrients from the North Sea, after 5 days the distribution of nutrients is somewhat symmetrical around the upweller. The distribution is more compressed on the landward side due to the terminus of the fjord. The original upwelled concentration of 8 units persists close to the upweller, but it diminished by two-thirds within 1-2 km away. By 14 days, the upwelled nutrients have dispersed to the seaward end of the model domain in an essentially uniform distribution. The poorly flushed head of the fjord still displays slightly reduced concentrations. These results indicate the time scale of nutrient spread throughout the uppermost fjord occurs within a period of 2 weeks. Groundtruthing of these simulations may be inferred from the field studies of Aure et al. (2007), which indicate that the region of upwelling influence is ~10 km^2.

The Aquadyn model containing only physical exchange and a tracer hints at the dynamics of artificial upwelling, but the resulting phytoplankton field contain more complex interactions that must be explored with the ecosystem model. This research is presently underway. The results of a box model for Lysefjord are further developed, wherein the gradient of phytoplankton distribution (Aure et al. (2007) is used to validate the model in the absence of mussels and then serve as a benchmark for carrying capacity as mussel biomass is added to the system.

References

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