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Ecosystems and Oceans Science

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ASSESSMENT OF THE ABILITY OF HYDRODYNAMIC AND PARTICLE TRACKING MODELS TO INFORM DECISIONS ON SITING AND MANAGEMENT OF MARINE FINFISH AQUACULTURE FACILITIES IN BRITISH COLUMBIA

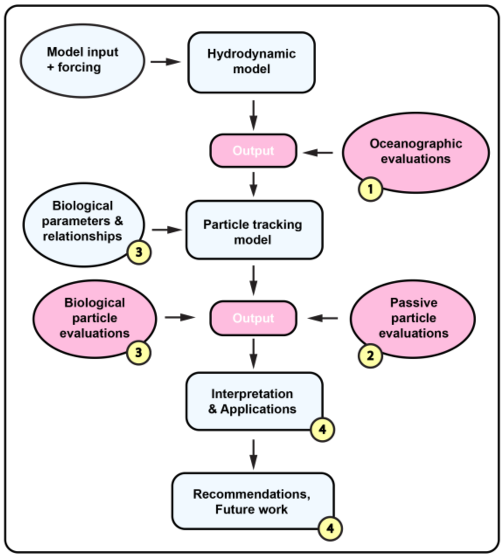

Figure 1 Schematic representation of the components required in the development, evaluation, and application of hydrodynamic and particle tracking models to the dispersion of particles from aquaculture facilities (adapted from Salama and Rabe 2013). The numbers within the yellow circles refer to objectives listed in the terms of reference for this assessment.

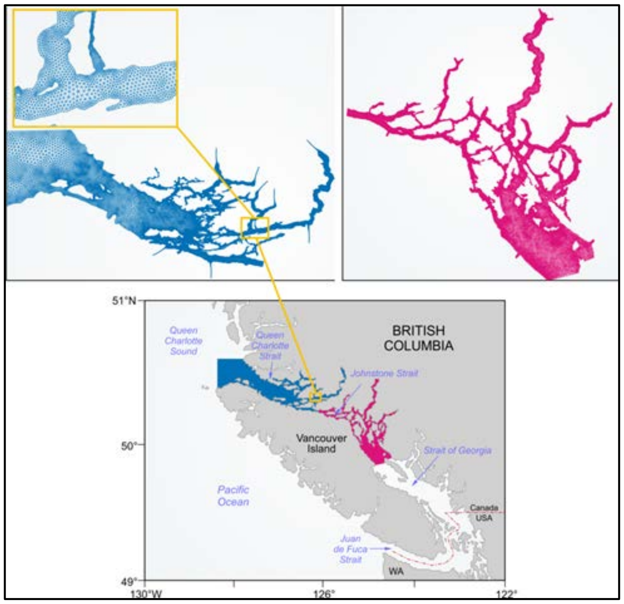

Figure 2. The areas represented by the hydrodynamic and particle tracking models: the variable resolution irregular triangular grid in the Broughton Archipelago (blue) with a close-up around the Knight Inlet and Tribune Channel confluence (yellow box), and the grid in the Discovery Islands region (red)

Context:

Fisheries and Oceans Canada (DFO) is responsible for the regulation and management of the aquaculture industry in British Columbia (BC). These responsibilities include the licensing of aquaculture sites and the specification of conditions of license. DFO recognizes that there are interactions between aquaculture operations and the natural environment. The risks associated with these interactions are considered and addressed through a suite of regulatory tools.

The siting criteria for marine finfish aquaculture currently applied by DFO were adapted from those previously applied by the Province of British Columbia. These criteria are science-based and have evolved as new information has become available. The application of siting criteria for aquaculture activities is designed to create buffers (proximity or separation distance) in relation to either general, or

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specific, ecosystem attributes (environmental or socio-economic). The current siting criteria are a set of generic considerations that are applied on a coast-wide basis.

As part of the Department's commitment to evaluating interactions between aquaculture operations and the natural environment to inform regulatory and management decisions, research has been undertaken to improve understanding of the likely fate of both passive and biological particles subject to area-specific conditions in the Broughton Archipelago and Discovery Islands regions. Understanding the factors and uncertainties that influence particle dispersal can potentially provide area-specific guidance on the evaluation of current siting criteria and the potential development of aquaculture management zones.

This Science Advisory Report is from the January 20-22, 2014 meeting 'Assessment of the ability of hydrodynamic and particle tracking models to inform decisions on siting and management of marine finfish aquaculture facilities in British Columbia'. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- The modeling methodology used to simulate hydrodynamics (FVCOM) and particle movements provides a scientifically sound approach to representing two oceanographically complex areas of the British Columbia coast (Broughton Archipelago and Discovery Islands).
- The hydrodynamic model (FVCOM) developed for the Broughton Archipelago and Discovery Islands regions effectively reproduced the major ocean circulation features and temperature and salinity values that were measured during the time periods evaluated.
- The passive particle tracking model is able to provide information on the dispersion distance, rate and particle concentrations. Satisfactory agreement was shown with distribution patterns of surface drifters released in the Broughton study region in March 2008.
- A validation of the passive particle tracking model in the Discovery Islands study region has not been conducted due to the absence of drifter experiments. However, based on drifter studies in other regions, and the ability of FVCOM to simulate the hydrodynamics of this region, a similar level of agreement between observed drifter movement and simulated particle dispersion to that seen in the Broughton study region is expected.
- This particle tracking model is capable of simulating the fate of particles with biological characteristics such as the diel movement of sea lice and susceptibility of a pathogen to UV radiation. Uncertainties around the biological parameterizations and characteristics require caution in interpretation of results. Specifically, evaluation of the environmental consequences of simulated biological particle behaviour was beyond the scope of this review.
- It was recognized that further validation of simulations of the biological particle tracking model may be needed. This work should be preceded by (a) an assessment of model sensitivity to biological assumptions and parameter uncertainty, and (b) a cost-benefit analysis relative to the intended application.
- A number of tools derived from the outputs of the coupled hydrodynamic and particle tracking models were reviewed. These tools include matrix diagrams of connectivity between aquaculture sites, particle concentration maps that can be produced at specific time intervals, particle flux diagrams showing primary dispersion trajectories and animations of particle dispersion that help to visualize likely movement patterns.

- The utility of the model tools to inform decisions related to aquaculture management was recognized. Depending on the question of interest, simulations may be required for a range of time periods, representative weather conditions, freshwater discharge conditions, and for regions yet to be modeled.
- The hydrodynamic and particle track models have potential non-aquaculture applications. These may include modelling particles from pollutant spills or larval dispersion. They may also have application to tidal power investigations.

INTRODUCTION

Rationale for Assessment

Fisheries and Oceans Canada (DFO) is responsible for regulating and managing the aquaculture industry in British Columbia, including the licensing of aquaculture sites and the specification of conditions of license. To inform regulatory and management decisions, research has been undertaken to better understand the interactions between aquaculture operations and the natural environment by modelling the fate of both passive and biologically active particles. Two models have been developed for this purpose: (1) an ocean circulation model that hindcasts three-dimensional currents, salinities, temperatures and two-dimensional surface elevations, and (2) a particle tracking model that uses the outputs of the ocean circulation model to simulate the dispersal behaviour of particles released at specific times and locations. The assessment will examine the ability of the combined models to estimate potential connectivity of finfish aquaculture sites in the Broughton Archipelago and Discovery Islands with respect to particle transport and to identify priorities related to further refinement of the models. These regions include complex coastal-ocean systems and are important regions for salmon net-pen aquaculture in BC. Understanding the factors and uncertainties that influence particle dispersal can potentially provide area-specific guidance on the evaluation of current siting criteria and the potential development of aquaculture management zones.

Background

DFO is the primary regulator of the aquaculture industry in British Columbia. The Department recognizes that there are interactions between aquaculture operations and the natural environment and the risks associated with these interactions are considered and addressed through a suite of regulatory tools including siting criteria for existing and proposed aquaculture facilities. The current siting criteria are a set of generic considerations that are applied on a coast-wide basis. As part of the Department’s commitment to evaluating interactions between aquaculture operations and the natural environment, research has been undertaken to improve our understanding of the likely behaviour and fate of both passive and biologically active particles subject to area-specific conditions. Linked hydrodynamic and particle tracking models have been developed for the purpose of simulating particle dispersion. Understanding the factors and uncertainties that influence particle dispersal can potentially provide area-specific guidance on the evaluation of current siting criteria and the potential delineation of aquaculture management zones.

The Broughton Archipelago and Discovery Islands regions are a network of narrow channels and deep fjords with a hydrodynamic regime that is among the most complex in the world for aquaculture use. Hydrodynamic models with sufficient spatial resolution to capture both the complexity of the systems and the currents around aquaculture sites have been developed for these regions of the British Columbia coast (Figure 1, 2). These ocean circulation models produce and save three-dimensional currents, salinities, temperatures, mixing fields and two-dimensional surface elevations for specific time periods. These modelled results are used as a driver for a second model, the particle tracking model, which estimates the dispersion of “particles” that are released at specific times and locations within the regions. The particles in the tracking model can be passive, or they can be assigned specified behavior (e.g., swimming or sinking capabilities), or biological or chemical attributes (e.g. mortality dependencies, degradation).

This assessment examines the ability of the two models to represent hydrodynamic conditions and simulate the likely dispersion of particles in the Broughton Archipelago and Discovery Island study regions. It explores the usability of the models as a tool in developing siting criteria for management zones, the limitations or assumptions that have to be considered when using the models and additional data and analysis that may be required to validate the application of these models for specified purposes.

ASSESSMENT

Hydrodynamic Model

There are a limited number of hydrodynamic models available for modelling complex hydrodynamic regimes including deep fjords and narrow channels. The Finite Volume Community Ocean Model (FVCOM, formerly Finite Volume Coastal Model) is the standard model used by DFO for these complex regions. FVCOM characterizes velocity and density variations arising from tidal, atmospheric forcing and the mixing of fresh and salt water. The model uses a horizontal variable-resolution triangular grid capable of defining the fine scale details of the coastline and narrow passages and terrain-following depth layers to accommodate the significant variations in bottom depth common on the British Columbia coast. The variable-resolution triangular grid allows for increased flexibility in representing regions with complicated coastlines and bathymetric features, such as those found in BC. FVCOM applies tidal boundary conditions from associated larger domain models or from measurements of water elevation and flow, and fresh water and meteorological (wind stress and heat flux) forcing from either measurements or other modelled output.

There are underlying assumptions within the equations used in FVCOM that may limit their ability to describe all types of oceanic circulation problems. Water is assumed to be incompressible and as a consequence, sound waves and the thermal expansion of ocean water due to climate warming cannot be modelled. Dynamics involving highly convective flows or internal waves such as those observed around the sill in Knight Inlet cannot be represented because of the assumption within the model that the pressure at any point in the ocean is only due to the weight of the water above it. In addition, assumptions and parameterizations in both the vertical and horizontal mixing terms in the primitive equations are topics of ongoing research and may not capture the actual mixing processes accurately.

FVCOM-based circulation models have been developed for the Broughton Archipelago and Discovery Island regions, with minimum resolution at 50 m (Figure 2). Digitized coastline and bathymetry information for the development of the triangular grids for these regions was available from the Canadian Hydrographic Service (CHS). Increased detail could be attained with smaller triangles and an increase in the total number of triangles needed to cover the desired region. However, these factors increase computation time and consequently the choice of grid resolution is often determined by a balance of computer resources and the requirement to resolve important features with sufficient accuracy. The ability of FVCOM to have variable grid resolution in areas of specific interest is an important attribute.

FVCOM forcing and initial fields

FVCOM requires three-dimensional temperature and salinity fields as initial conditions. This input is generally from a combination of historical and recent CTD observations with varying levels of spatial and temporal coverage.

Tidal forcing is required for FVCOM. Typically the largest 5-8 constituents are used as they account for approximately 60-85% of the tidal range in the diurnal and semi-diurnal frequency bands. This information is available from a combination of analyses of historical tide gauge records, and/or results from tidal models covering a larger domain. A minimum depth of 5 m is imposed throughout the model as the steep-sided topography typical of fjord regions makes the need to model the intertidal zone (wetting and drying) unnecessary.

Freshwater discharge data are obtained for some rivers from a hydrometric network maintained by Environment and Climate Change Canada (ECCC): estimates must be made for ungauged rivers. In the Broughton Archipelago, discharge data were available for six rivers and this information was extrapolated to the Glendale, Ahta and Kakweikan Rivers by comparing watershed areas, as described in Foreman et al. (2006). In the Discovery Islands, freshwater discharge data were available for four rivers and estimations were made for eight other watersheds; the salinity of discharge was generally set to zero. River temperatures were typically estimated from nearby surface CTD observations.

Specification of atmospheric forcing is challenging due to the scarcity of weather stations and the absence of atmospheric models with sufficient resolution to adequately capture variations dictated by the mountainous terrain in the study regions. Wind is an important factor in the regional circulation within inlets; therefore, a network of stations was installed throughout the Broughton Archipelago in May 2007 and the Discovery Islands in April 2010. These stations, in combinations with EC stations at Port Hardy and Campbell River airports, and a few stations at fishing resorts, have generally produced usable observations since those times. Two methods were developed for interpolating/extrapolating the wind observations to all the model grid elements. A strategy was also developed to fill data gaps due to equipment malfunction or siting location limiting winds from specific directions. Although there has been some success at filling these gaps using correlations with the observations from nearby or permanent stations (e.g., those from the Port Hardy and Campbell River airports) the development of a high resolution atmospheric model with either full or simplified (e.g., Hayco 2010) dynamics would be the preferred long term solution.

Results and evaluation of model simulations

The Broughton and Discovery hydrodynamic models have been previously reviewed and are published in the primary literature (Foreman et al. 2009 and Foreman et al. 2012). The resolution of the original Broughton grid was 43,000 nodes with spatial resolution down to 200m. The Discovery grid had approximately 36,000 nodes and a resolution of approximately 100 m at its finest. Since these publications, a finer resolution grid has been developed for the Broughton region with about 98,000 nodes and a spatial resolution as small as 50 m near aquaculture sites. In the previous analysis by Foreman et al. (2009, 2012), hindcasts were conducted for relatively short periods due to limitations in adequate forcing fields and in situ current observations for those time periods. The original hindcasts neglected heat flux forcing and used the best available forcing fields (winds, tides, discharge) to run the Broughton and Discovery ocean circulation models for March-April 2008 and April 2010, respectively, and then compare the model results with available observations at specific sites within the model domains. Since these publications, additional hindcasts that included heat flux forcing, have been run for these regions.

Broughton hindcast runs	i)	May 1 - 22, 2008
	ii)	May 10 - 31, 2010
	iii)	March 1 to July 31, 2009
Discovery hindcast runs	iv)	April 29 to October 31, 2010

An evaluation of the new model results against current meter or measured temperature and salinity and temperature data have not been completed. Therefore evaluations presented in this assessment are examples from the previously published results in Foreman et al (2009, 2012), using the coarse grid and without surface heat flux forcing.

Broughton March 2008. In general, there was a good correlation between the modelled and measured values for the Broughton in March 2008. Wind was the major driver of currents and the additional weather stations improved the definition of the wind field. Some weather stations had partial sheltering from the steep-sided coastal terrain and required some interpolating. Therefore, some regions in the model domain had more accurate wind forcing than others.

The model captured, but slightly underestimated, a strong eastward wind event on March 16. However, there were inconsistencies with interpolated wind values (during a period when wind data were not available) and the measured wind events immediately prior to and after these periods caused concern. There were possible negative implications on the modelled currents due to the quality of the wind forcing parameters. The observed and model currents showed reasonable agreement when wind forcing was included, however, the modelled currents were more accurate in deep waters (> 50m) than those near the surface (< 20m). The correlation coefficients for deep water were consistently higher than 0.72. In comparison the correlation coefficients for near surface waters ranged from 0.47 and 0.84. Since winds influence currents more near the surface whereas those at depth are influenced more from the tides, the uncertainties with the wind forcing likely reduced the accuracy of the modelled currents in waters less than 20 m depth.

Low variability in temperature and salinity in March 2008 made an assessment of model performance difficult. However, considering this limitation, comparison of surface water temperature suggests reasonable accuracy (root mean square difference < 1°C). Greater variation occurred between modelled and measured salinity. This variation is possibly a result of salinity being more sensitive to local scale influences. Poor freshwater discharge estimates or inaccurate winds estimates of river plume transport could result in this variability.

Discovery Islands April 2010. The modelled baroclinicity in the Discovery Islands in April 2010 did not adequately capture the observed values through the water column. There were three areas used for the comparison, Discovery Passage, Nodales Channel and Cape Mudge. Although there is reasonable agreement between the modelled and observed tidal current amplitudes near the surface, this was less-so deeper in the water column. The modelled surface speeds were reasonably accurate at Discovery Passage but exceeded observed values at Nodales Channel and were underestimated at Cape Mudge. There were also inconsistencies in flow at depths greater than 100m in Discovery Passage and off Cape Mudge.

Foreman et al. (2012) indicated the primary deficiency with the Discovery circulation model simulations was the poorer representation of model currents deeper in the water column than at the surface. As many particles originating from fish farms start at and generally remain close to the surface where the model current accuracy is greater, the dispersion model employs model results at depths where there is greater accuracy. However, the inaccuracies at depth warrant further investigation. A newer higher resolution grid, particularly in regions with large depth gradients, will reduce inaccuracies. The hindcast models and comparisons with measured data will be repeated with this new higher resolution grid.

Particle Tracking Model (Passive)

This model uses 3D velocity, temperature, salinity fields computed and saved at regular intervals by FVCOM and applies them to disperse and age or kill “particles” that are released at specific times and locations. Subgrid-scale turbulence not represented in FVCOM can be included in the dispersion by adding a random-walk component. Care needs to be taken so that the random component is realistic.

Land boundaries require special attention when particles approach coastlines. In these models, the particle is held at the land boundary until the velocity field moves the particle away. In essence, the particle in the model can become temporarily grounded but will float away when the velocity field allows that to happen.

Particle trajectories are based on times and regions which have hydrodynamic output. Since the Runge-Kutta solver used in the trajectory model typically takes smaller time steps to compute the trajectories of particles than the (typically) hourly output from the FVCOM model, the frequency of the FVCOM output may influence the trajectories. Sensitivity runs of the model based on conditions in March 2009 in the Queen Charlotte Strait indicated that 15 minute intervals were preferable to the one hour intervals presently used for FVCOM model output. However, as this result can be expected to be location and time dependent, 15 minute sampling may not always be adequate. Experiments examining variations in model results, based on FVCOM time interval storage will be required for different regions and times.

Passive particle tracking simulations were carried out in the Discovery Islands region for April 2010. The model results suggest that even though the majority of the particles move to the western boundary of Johnstone Strait, some particles could move to the southeast and into the Strait of Georgia. However, these model results have not been evaluated against measured data.

The particle tracking model treats open ocean boundaries in a similar manner to land boundaries and holds the particles in that location until they are moved away from the boundary by a different vector; thus there is an accumulation of particles at this boundary that is not realistic as they would continue to move north into Queen Charlotte Strait and the Broughton Archipelago model region. At present the two model domains are not linked, however to test possible subsequent movement of the particles, new particles were seeded into the Broughton model along the boundary with the Johnstone Strait model. Wind information was not available for the Broughton model in 2010 and was instead tested with data available from March 2009. Although different years and time period were used, the test demonstrated that particles, under the conditions examined, could be transferred from the Discovery Islands to farms in the Broughton Archipelago(Figure 3A). This demonstrates that the linking of models from different regions could inform on particle movement over a larger geographic regions but additional work would be required to validate these modelled results and to estimate the transit times over these regions.

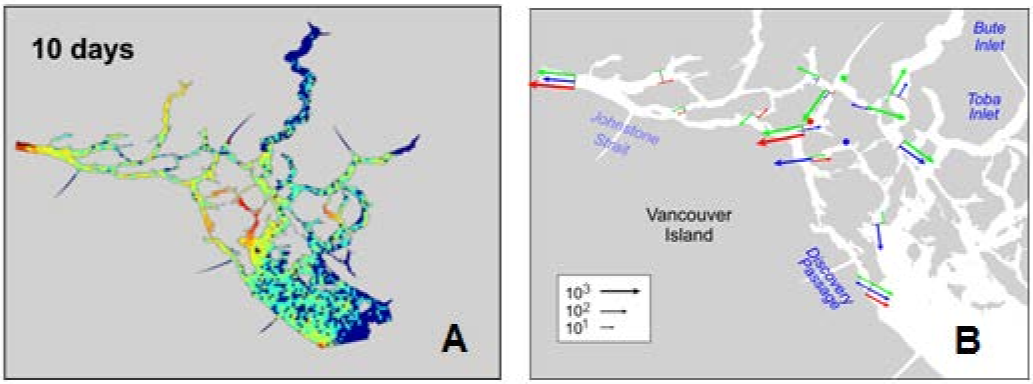
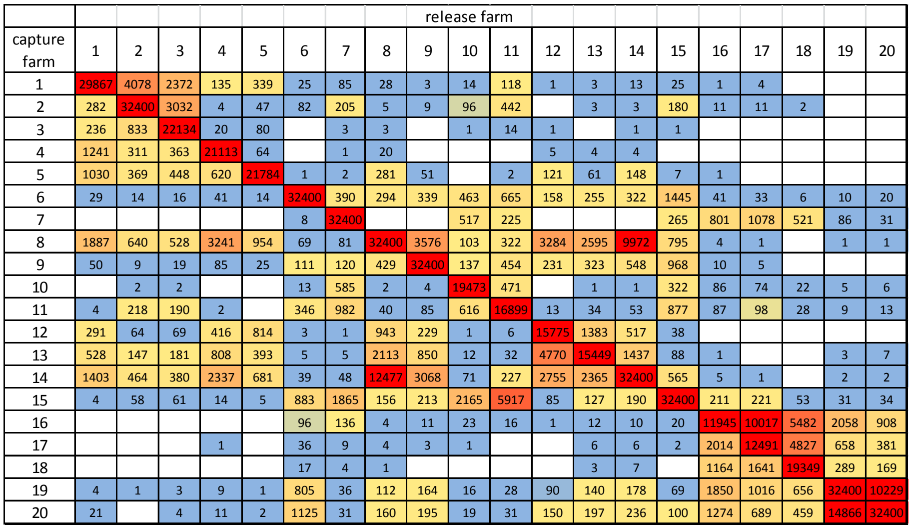


Figure 3. (A) Simulated dispersion of passive particles 10 days after they were released at 32 sites in the Discovery Islands region in April 2010. Red (turquoise) colours denote higher (lower) concentrations. (B) Particle fluxes of virtual particles released at three locations (dots) and tracked crossing 13 transects in key passages within the Discovery Islands. The vectors represent the direction and density of the simulated particle trajectories.

The model simulation of particle release in the Discovery Islands in April 2010 was also used to examine variability in the direction and rate of particle movement from three release locations (Freddie Arm, Brougham and Barnes farm locations, Figure 3B). The results suggest that there is high variability in the direction and speed of the particles and that alternate routes could be taken by different particles released at the same sites.

Passive particle simulations were conducted in the Broughton Archipelago based on conditions in March 2009 to investigate the hydrodynamic connectivity between farm locations. Preliminary results are presented in a connectivity table to characterize simulated transfers between farms (Figure 4). The highest connectivity was always with the farm of origin (diagonal red line). This table can be interpreted as a heat map where ‘hotter’ colors symbolize a greater connectivity. Symmetry about the diagonal (e.g. farms 14 and 8) indicates a mutual exchange of particles. Asymmetry can largely be explained by the average surface estuarine flow fields and the receiving farm being seaward of the release farm.



	release farm																			
capture farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	29867	4078	2372	135	339	25	85	28	3	14	118	1	3	13	25	1	4			
2	282	32400	3032	4	47	82	205	5	9	96	442		3	3	180	11	11	2		
3	236	833	22134	20	80		3	3		1	14	1		1	1					
4	1241	311	363	21113	64		1	20				5	4	4						
5	1030	369	448	620	21784	1	2	281	51		2	121	61	148	7	1				
6	29	14	16	41	14	32400	390	294	339	463	665	158	255	322	1445	41	33	6	10	20
7						8	32400			517	225				265	801	1078	521	86	31
8	1887	640	528	3241	954	69	81	32400	3576	103	322	3284	2595	9972	795	4	1		1	1
9	50	9	19	85	25	111	120	429	32400	137	454	231	323	548	968	10	5			
10		2	2			13	585	2	4	19473	471		1	1	322	86	74	22	5	6
11	4	218	190	2		346	982	40	85	616	16899	13	34	53	877	87	98	28	9	13
12	291	64	69	416	814	3	1	943	229	1	6	15775	1383	517	38					
13	528	147	181	808	393	5	5	2113	850	12	32	4770	15449	1437	88	1			3	7
14	1403	464	380	2337	681	39	48	12477	3068	71	227	2755	2365	32400	565	5	1		2	2
15	4	58	61	14	5	883	1865	156	213	2165	5917	85	127	190	32400	211	221	53	31	34
16						96	136	4	11	23	16	1	12	10	20	11945	10017	5482	2058	908
17				1		36	9	4	3	1			6	6	2	2014	12491	4827	658	381
18						17	4	1					3	7		1164	1641	19349	289	169
19	4	1	3	9	1	805	36	112	164	16	28	90	140	178	69	1850	1016	656	32400	10229
20	21		4	11	2	1125	31	160	195	19	31	150	197	236	100	1274	689	459	14866	32400

Figure 4. Example of modelled simulations to explore hydrodynamic connectivity between farm sites. These are based on modelled simulations for the Broughton Archipelago in March 2009. The simulated dispersion results have not been validated with observed events.

Evaluation of Passive Particle Tracking Model

GPS (Global Positioning System) drifter studies and FVCOM simulations were carried out in the Broughton Archipelago in March 2008 allowing the evaluation of the particle tracking model during this time period. The simulated movements of 6000 particles compared to the tracks of six drifters revealed that FVCOM model output at a one hour time step will initially (up to six hours) create inconsistency between the modelled and observed positions. Comparisons at later times show good agreement between the drifter positions and the cloud of particles. Both the simulated particles and the drifters followed paths away from the mid-channel and towards the shorelines, however the model allowed particles to continue moving after shoreline contact had occurred whereas the drifters stopped moving once they encountered the shoreline. Adjusting model parameters governing shoreline behaviour may improve the agreement between particles and drifters.

No drifter studies have been conducted in the Discovery Islands at this time. Evaluations of FVCOM and particle tracking model conducted in both the Atlantic and Pacific confirm that the discrepancies between modelled and observed dispersions are within normal range associated with uncertainties in the models' characterization of horizontal and vertical water movement. However, additional drifter studies will be required to validate the model output in complex regions such as the Discovery Islands.

Particle Tracking Model (biologically-active)

The biological particle tracking model is similar to the passive model except that the particles are influenced by their ambient surroundings. They can be assigned behaviour (e.g., swimming or sinking capabilities) and be given biological or chemical attributes that, for example, simulate life stage progression and mortality dependencies or degradation into different substances. Sea lice and IHNv are two examples of biological particles that have been modelled with particle tracking. They were presented as examples to represent the types of additional information that are required when modelling biological particles and the increased uncertainty that the biological particles can have on the model outputs. Based on these examples, it was evident that the particle model would need to address parameters specific to a biological particle in order to provide a meaningful characterization of the fate of the particles. The assessment of the

FVCOM and particle models indicated that these have the capacity to incorporate parameters associated with biological parameters. However, the uncertainty of the biological parameters increases the overall uncertainty of model outputs.

Application to aquaculture siting criteria and management zones

Presentation of the results of particle tracking experiments to assist in decision making for aquaculture siting could include particle snapshots of dispersion clouds for specific time periods following the release of particles (e.g., Figure 3A), vector diagrams and particle flux diagrams to examine the dominant direction and rate of dispersion (e.g., Figure 3B) and connectivity tables to summarize the likelihood of transmission between aquaculture sites or other specific locations (Table 1). In addition, animations of particle dispersion can be constructed to examine changes over specific time periods. Statistics on the average position and variability within a dispersion cloud (e.g., Figure 11 and Figures 46-52 in Page et al. 2013) can be computed from model outputs. However, in the complicated network of channels along the BC coast, interpreting these results can be difficult.

In order to avoid the heavy cost of developing and maintaining operational models that could at any time, forecast the dispersion of particles and thus allow a manager to estimate potential transmission vectors, it would be possible to pre-compute a set of maps showing particle dispersion for a variety of seasonal (e.g., river discharge) and weather conditions. These outputs would lend themselves to subsequent integration with other geo-referenced data (e.g., migration routes of wild fish stocks, marine protected areas, shellfish harvesting areas).

Sources of Uncertainty

1. Limited availability of forcing data means that model simulations have only been carried out for specific periods of time. Physical oceanographic conditions in coastal BC can vary widely over time. The wind driven and estuarine components of currents, temperature and salinity can have considerable variability. In this application, the FVCOM model has been run for relatively short time periods and in specific years and may not have captured all this variability.
2. Not all particles are the same and will behave differently. They may be found at different depths and are therefore subject to different currents, and may need to be tracked for different periods of time depending on their expected persistence. Therefore a single particle model output for a specific time will not reflect the distribution of all types of particles.
3. In the present model, particles that reach the model boundary do not pass the boundary but will remain at the edge creating artificial accumulations.
4. Initial temperature and salinity fields based on a combination of both historic and recent CTD observations may not have adequate spatial and temporal coverage.
5. Inaccuracy in hydrodynamic model outputs may result from:
    a. Grid resolution – higher resolution will be better but requires more computing resources;
    b. Inaccuracy in forcing fields;
    c. Smoothed representations of bathymetry due to available resolution;
    d. Numerical approximation of advection;
    e. Inaccurate mixing and diffusion parameterizations;
    f. Physics not captured by governing equations;

6. Inaccuracies in particle tracking model outputs may result from:
    a. Propagation of inaccuracies in the FVCOM model to the particle tracking model;
    b. Random component added to the model to accommodate physics not represented in the model;
    c. The frequency that FVCOM model results are stored for input to the particle tracking model, i.e., are the time steps appropriate to the particle of interest?
7. Freshwater discharge data are only available for some river systems in the study regions. For other rivers, input was inferred which may increase the uncertainty of the freshwater discharge; a major hydrodynamic driver in fjord environments.
8. In the absence of direct measurements, river water temperatures were usually estimated from nearby surface water temperature observations; this input will influence the flow patterns and mixing layer, and is a key output field.
9. In the absence of adequate atmospheric models, there are limited weather data for forcing the hydrodynamic models. Wind forcing is important, as is heat flux, and direct observations need to be interpolated/extrapolated to all model grid elements. The greatest potential for model improvement could be accrued through higher quality wind forcing inputs that provided better representation of local conditions.
10. Depending on the particular type of particle being modeled, their behaviour after shoreline contact may need to be modified. The analysis considered here allowed particles to float away from shorelines; specific applications may require that particles become grounded when contacting shorelines;
11. Depending on the question of interest, specific information will be needed on the characteristics and behavior of the biological particle being tracked. The biological uncertainties may be much greater than the uncertainties in the hydrodynamic model.
12. Drifter studies have not been conducted in the Discovery Islands to validate the passive particle tracking model in this region. However, based on drifter studies in other regions, a similar level of agreement between observed drifter movement and simulated particle dispersion to that seen in the Broughton study region is expected for the Discovery Islands model.

CONCLUSIONS AND ADVICE

The FVCOM hydrodynamic and particle tracking models are appropriate for simulating particle dispersion from point sources in the complex Discovery Island and Broughton Archipelago regions of British Columbia. Applications can be extended to consider connectivity between aquaculture sites and ecosystem features (e.g., river estuaries, shellfish harvesting areas, or other ecologically sensitive locales). Example applications reviewed depended on hind-casting the fate of particles based on historical inputs. However the models can be applied to forecasting future particle dispersal provided forecasts exist for all forcing fields, which is currently not the case.

In particular, the models could be applied to simulate the likely dispersal of particles under a variety of management and production scenarios. Similarly, opportunities exist for informing decisions related to introducing new aquaculture facilities into the study regions or changes to the number of facilities in a given area.

The models can simulate the dispersion of particles including those with biological characteristics. Uncertainties around the biological parameterizations and characteristics require caution in interpretation of results.

Improvement to FVCOM hydrodynamics model performance could be realized through the provision of more accurate atmospheric forcing inputs, implementation of finer grid resolution, and improvement of the open boundary conditions. With respect to the particle tracking model performance, some particle types may require alternative assumptions regarding their behavior at boundaries (e.g. shorelines), and at varying depths (e.g., diel migration).

Constraints to operationalizing the models suggest that effort should be directed into the creation of stored outputs that represent a range of time periods, representative weather conditions and freshwater discharge conditions. These outputs would lend themselves to subsequent integration with other geo-referenced data (e.g., migration routes of wild fish stocks, marine protected areas, shellfish harvesting areas).

The hydrodynamic and particle track models have potential non-aquaculture applications. These may include modelling particles from pollutant spills or larval dispersion. They may also have application to tidal power investigations.

SOURCES OF INFORMATION

This Science Advisory Report is from the January 20-22, 2014 meeting ‘Assessment of the ability of hydrodynamic and particle tracking models to inform decisions on siting and management of marine finfish aquaculture facilities in British Columbia’. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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MPO. 2018. Évaluation des capacités du modèle hydrodynamique et du modèle de suivi de particules afin d'éclairer les décisions sur le choix des sites et la gestion des installations de pisciculture marine en Colombie-Britannique. Secr. can. de consult. sci. du MPO, Avis sci. 2018/023.