Fisheries and Oceans Canada | Pêches et Océans Canada
Ecosystems and Oceans Science | Sciences des écosystèmes et des océans

Pacific Region

Canadian Science Advisory Secretariat
Science Response 2021/042

HYDRODYNAMIC CONNECTIVITY BETWEEN MARINE FINFISH AQUACULTURE FACILITIES IN BRITISH COLUMBIA: IN SUPPORT OF AN AREA BASED MANAGEMENT APPROACH

Context

Fisheries and Oceans Canada's (DFO) Aquaculture Management Division (AMD) is the regulatory body for managing aquaculture in British Columbia (BC). The aquaculture management regime in BC is robust and complex, with oversight from provincial and other federal regulatory agencies. Licenses and their associated conditions are the primary tool used to manage the fishery, and are issued under the authority of the Pacific Aquaculture Regulations and the Fisheries Act. AMD licenses marine finfish, marine shellfish, and land-based hatchery and production facilities, including approximately 114 marine finfish farms, which is the focus of this review. AMD has made a commitment to move towards Area-based Management (ABM) in BC, which has also been a recommendation made by a number of external groups. This new approach will shift AMD away from assessing and managing each individual finfish farm in isolation, and support ongoing collaborative work with external partners (e.g., environmental non-government organizations, First Nations, industry and other stakeholders).

Individual farms can be connected to each other by the flow of water; and they are similarly connected to wild fish and fish habitat that are proximal to the farms. Hydrodynamic connectivity between marine finfish aquaculture facilities can present transmission risks between farms, and between farmed salmon and wild salmon, specifically related to sea lice (Adams et al., 2012; Cantrell et al., 2018, 2020) and pathogens (Bravo et al., 2020; Foreman et al., 2015b). Regional BC data, along with that from other fish farming nations, indicates that an area based management approach involving coordinated farm treatments, stocking plans, fallowing, etc. can be more effective than individual farm management when managing disease and pest outbreaks. This approach may also decrease transmission and risk to wild fish.

AMD is requesting that DFO Science Branch provide science advice on hydrodynamic connectivity between existing marine finfish aquaculture sites, in order to delineate "compartments" that could be a basis of area-based management of finfish farms in BC.

The assessment and advice arising from this Canadian Science Advisory Secretariat (CSAS) Science Response (SR) process will be used to inform area management decisions, and conditions of license for 2022. Consultations are anticipated in 2021 prior to licensing. In addition, this information will be one element brought forward to broader multi-stakeholder discussions on area-based management.

This Science Response results from the Regional Science Response Process of February 15, 2021 on the Hydrodynamic Connectivity between Marine Finfish Aquaculture Facilities in British Columbia: in support of an Area Based Management Approach.

Background

Building up from previous work: hydrodynamic and particle tracking models

Hydrodynamic ocean models have been previously used by DFO to assess the connectivity between aquaculture sites in BC. in relation to pathogens and sea lice transport and transmission (e.g. Stucchi et al. 2011, Foreman et al. 2015a, Foreman et al. 2015b, Mimeault et al. 2017). The present study focuses on purely hydrodynamic connectivity, i.e. how neutral, passive particles disperse from farms and reach other sites given only the flow fields in their surrounding environment. This approach estimates the farthest possible reach of the particles (since they do not actively sink nor decay with environmental conditions – they just move with three-dimensional flow fields), and hence, the greatest potential farm connectivity. The modelled particles do not represent or have the characteristics of any specific pathogen or organism. Following Foreman et al. (2015a) methods, we used three hydrodynamic coastal ocean models developed by DFO to generate three-dimensional flow fields and used these as input to a passive particle tracking model. Two of the hydrodynamic models are described in Foreman et al. (2015a), the Broughton Archipelago and Discovery Islands models (Figure 1). The third model is a newer development for the west coast of Vancouver Island and will be described briefly in the next section; the differences with the older two models will be described. All three models are applications of the unstructured grid, primitive equation Finite Volume Community Ocean Model (FVCOM) developed by Chen et al. (2003, 2006, 2013).

The PTrack particle tracking model was originally developed by Chen et al (2006, 2013) and embedded in FVCOM. Because the particles do not affect the hydrodynamics, it is computationally more efficient to track them using the output flow fields from FVCOM rather than embedding the particle tracking within the FVCOM model run. The current application of PTrack differs somewhat from Foreman et al. (2015a) (see summary in Table 1). In the latter, 50 neutral particles were released each hour at points randomly distributed within a three-dimensional rectangular prism (100 m x 100 m x 10 m) within the area of a farm tenure; in this study, 30 neutral particles were released at the surface every two hours, randomly distributed within a 100 m x 100 m square (an area, rather than a volume, was used given that the particles do not sink). These changes provided a balance between computational expense and sufficient resolution of the tidal forcing. The duration of the tracking was extended from 11 to 14 days to address more long-lived particle scenarios. To allow for repeatability in our tracking experiments, representation of subgrid-scale particle movement using a random walk-type process (as done in Foreman et al., 2015a) was not included here. Ptrack simulates the particle trajectory until any of three termination conditions occur: advection outside the model domain, exceeding the 14-day tracking limit, or encountering land. In Foreman et al. (2015a), the land termination included a condition which allowed particles advected onto land to continue their trajectory if a subsequent flow field advected them back into water.

While the internal calculations in FVCOM are made on the order of seconds, the three-dimensional output fields are stored at longer intervals (e.g., hourly). Foreman et al. (2015a) reviewed the effect of reducing the FVCOM output interval for use in the particle tracking model. The benefits of added temporal resolution were considered variable depending on region and period, while the additional computational load was consistently significant. Consequently, this study used hourly flow files as in Foreman et al. (2015a), which is enough temporal resolution to resolve the major tidal constituents.

Furthermore, PTrack requires the definition of two time intervals: one to determine how often to calculate the position of the particle and a second interval to output the particle position. Given that our coastal FVCOM models use irregular grids with resolution as high as 60 m in narrow channels, strong currents can quickly move particles through several grid elements. Therefore, to resolve the particle movements, our PTrack simulations calculated the particle position every two minutes and saved it to an output file every 20 minutes.

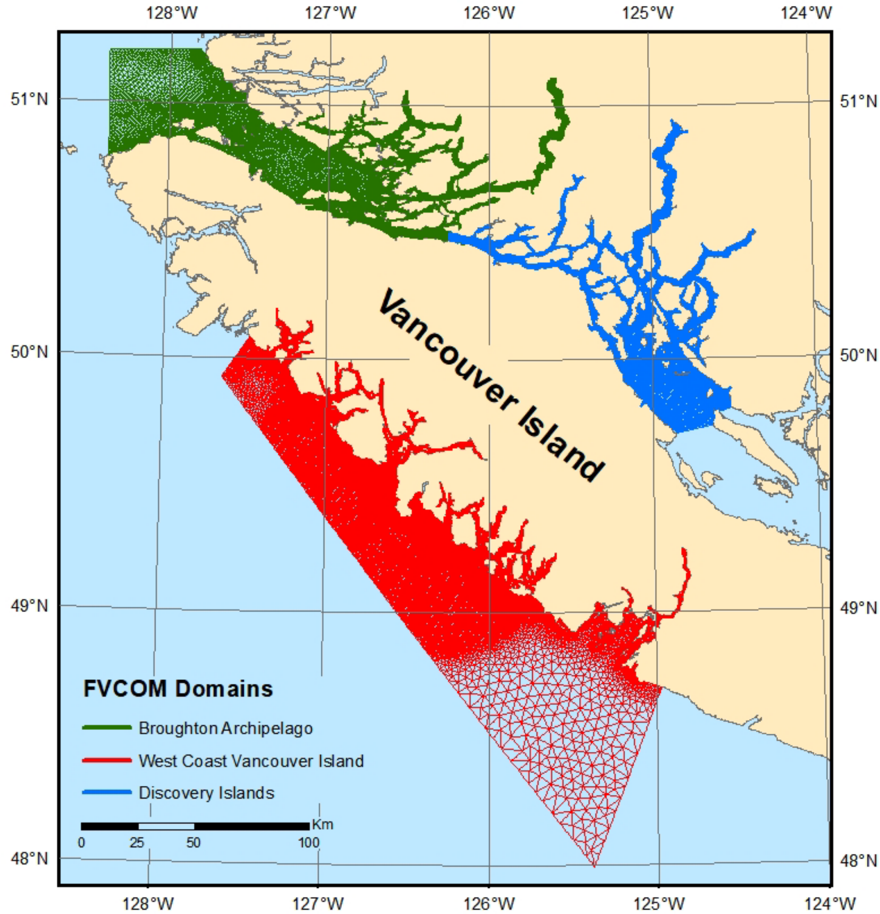

Figure 1. Three FVCOM domains. Broughton Archipelago (BA, cyan), Discovery Islands (DI, blue) and west coast of Vancouver Island (WCVI, red), BC, Canada.

Table 1. Differences between the setup of the particle tracking model between Foreman et al. (2015a) and the current report.

Model details	*Foreman et al. (2015a)*	*Current setup*
Particles released	50 particles, Released every 1 hour, From 100 m x 100 m x 10 m box, Tracked for 11 days	30 particles, Released every 2 hours, From 100 m x 100 m box, Tracked for 14 days
Random walk	Yes	No
Particles reaching land	Do not ground. Stay at their last water location and flow away with currents	Ground. Stop tracking

Analysis and Response

Description of hydrodynamic models

As mentioned in the Background section, we used the FVCOM simulations for the Discovery Islands (DI) and the Broughton Archipelago (BA) as described in Foreman et al. (2015a). The simulation of DI covered the period from April 1 to October 31, 2010 (214 days), while BA went from March 1 to July 31, 2009 (153 days). The BA model is an updated version (with a refined grid) of the model described by Foreman et al. (2009); the DI model was first described by Foreman et al. (2012). Model domains are shown in Figure 1 and further details on them can be found in Foreman et al. (2015a) and in Table 2.

The third model represents the west coast of Vancouver Island (WCVI) and extends from Barkley Sound in the south to Kyuquot Sound in the north (Figure 1). The horizontal resolution goes from less than 60 m in the coastal inlets up to 9.2 km at the edge of the continental shelf. In particular, the highest resolution is found in Clayoquot and Nootka Sounds, where most of the finfish farms are located. This model development took advantage of the newer version of FVCOM (version 4.1; DFO's GitLab repository and Chen et al. 2013). In addition, it included several of the recommendations for future work stated in Foreman et al. (2015a). For instance, it uses a regional atmospheric model to provide forcing information at the surface (i.e., winds and surface heat fluxes), the High Resolution (2.5 km) Deterministic Prediction System (HRDPS) developed by Environment and Climate Change Canada (ECCC) (Milbrandt et al. 2016). Moreover, it uses a regional ocean model to obtain its initial and open boundary conditions, the Coastal Ice Ocean Prediction System for the West coast (CIOPS-W) developed by the Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) (Paquin et al. 2019, Blanken et al. 2019). Model simulations available so far cover the period from March 1 to June 30, 2016 (122 days). Further details can be found in Table 2 and in an upcoming publication by Foreman et al[1].

Table 2. Details of FVCOM model setup for the three domains (BA: Broughton Archipelago, DI: Discovery Islands, WCVI: west coast of Vancouver Island)

Model details	*BA*	*DI*	*WCVI*
Grid:			
Nodes	97,192	35,859	76,611
Elements	166,602	65,930	137,644
Vertical layers	20	20	20
Min - Max depth	5 - 500 m	5 - 678 m	5 - 366 m
Atmospheric forcing (winds and surface heat fluxes)	Based on observations	Based on observations	From High Resolution Deterministic Prediction System (HRDPS)

[1] Foreman M., Chandler P., Wan D., Krassovski M., Thupaki P., Bianucci L., Cooper G., and Spears D. 2022. A Circulation Model for Inlets along the Central West Coast of Vancouver Island. In preparation.

Model details	*BA*	*DI*	*WCVI*
Initial conditions	Based on observations	Based on observations	From Coastal Ice Ocean Prediction System for the West coast (CIOPS-W)
Open boundary conditions	Based on observations	Based on observations	From CIOPS-W
River forcing	Based on observations	Based on observations	Based on observations, regression analyses and watershed areas
FVCOM version	2.7	2.7	4.1

Particle tracking and hydrodynamic connectivity analysis: procedure

DFO AMD provided the location of 90 finfish farms within the FVCOM domains (31, 21, and 38 farms in BA, DI and WCVI, respectively). All of these farms are licensed, except for one (Ga-guump is a proposed farm in the BA region). For the purpose of this document all farms within each FVCOM domain are considered to be operating synchronously. Using the central latitudes and longitudes of the 90 farms, representative boxes of 100 m by 100 m centered at those locations were identified as ‘farms’ for particle release and capture purposes. In five cases (Doctor Bay in DI, Ghi Ya and Hardy Bay in BA, and Jane Bay and San Mateo in WCVI), the boxes were moved slightly away from land (Figure 2). At these locations, the models did not have high-enough resolution to represent properly the coastline of these small bays (note that these areas were not the focus of study during model development). In particular, the bay that contains the Jane Bay farm was not even included in the model domain (Figure 2a). With the exception of Doctor Bay, Hardy Bay, Jane Bay, and San Mateo (see Figure 2), all final squared boxes were confirmed to lay within the area of license tenure for each farm. While we may refer to the boxes as “farms” in this document, they are a simplified representation of farms rather than a realistic characterization, given that real farms can vary in shape, area, and orientation.

Inside each squared box, 30 randomly-distributed, neutral particles were released every two hours starting at the 9th day of the simulation (the first eight days were not used to avoid the effects of the model’s initial conditions on the flow field). Each particle moved with the three-dimensional currents for 14 days or until reaching a boundary (either land or the open ocean boundary of the model), whatever happened first. Note that the simulations tracked passive neutral particles and the trajectory was not influenced by any particle behaviour, e.g., swimming or sinking by their own weight. Buoyant particles that remain at the surface were also investigated, but neutral particles were found to present a more conservative result (the particles had greater reach) and were therefore used (see Appendix). The hydrodynamic connectivity of farms within a modelled region was determined by how many of the particles from the total released by a “release farm” reached or crossed any other squared boxes (referred to as “capture farms”). We performed this connectivity assessment for 14 time periods: 1 day (i.e., within 24 hours) after release of each particle, 2 days (48 hours) after release of each particle, etc., up to 14 days after release of each particle.

When this information is organized in a table format (i.e., rows and columns showing capture and release farms, respectively), we obtain 14 connectivity matrices (one per time period of analysis). In addition, the number of particles reaching each capture farm was also presented as the percentage of the total number of particles released, i.e. the number of particles reaching the capture farm divided by the total number of particles released from the release farm (note that each of the 14 periods counted with the same total number of particles released, irrespective of whether we analyzed the first 24 hours or the total 14 days). Therefore, for each modelled region, we create the following information:

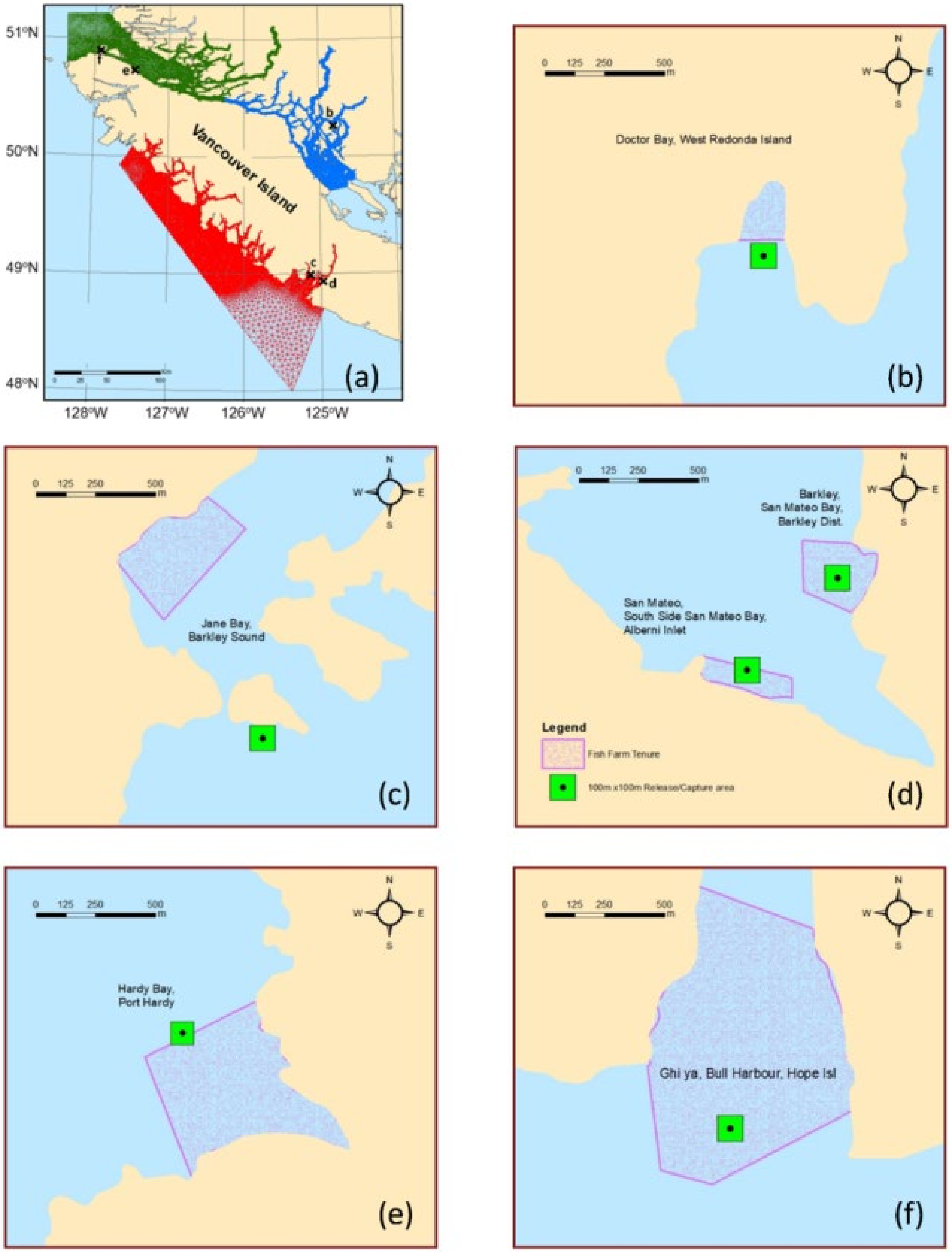

Figure 2. (a) Map that shows (with black crosses) the overall location of the five 100 m by 100 m boxes that were moved from their central location towards the ocean to avoid issues due to coarse coastline resolution. The crosses are labeled according to the panel that shows the detailed final location (in green) of the 100 m x 100 m boxes: (b) Doctor Bay in DI, (c, d) Jane Bay and San Mateo in WCVI, (e, f) Hardy Bay and Ghi Ya in BA. Shaded pink regions show license tenure areas.

- A spreadsheet with 28 sub-sheets: 14 sheets with connectivity matrices showing particle counts and 14 sheets with connectivity matrices showing percentages (one sheet per time period of analysis, i.e. 1, 2, 3, …, 14 days since release).
- Fourteen matrix plots (one per time period of analysis) showing particle counts and colour-coded by percentage.

The matrix plots show the estimated connectivity between the capture and release farm sites. The high degree of connectivity along the diagonal indicates that the farm releasing particles also receives all of those particles. Symmetry about the diagonal indicates a mutual exchange of particles between farms, while asymmetry can largely be explained by the average background (surface estuarine) flow fields. All of the generated information is discussed per modelled region in the next subsections. We also created maps showing the particle tracks for the last 24 hours for each time period of analysis (i.e., tracks from release time to 24 hours, tracks from 24 to 48 hours, etc.); an example is provided in the Appendix (Figure A1). Given the large number of figures and files only a subset is shown in this document.

West coast of Vancouver Island

The WCVI model simulated ocean conditions from March 1 to June 30, 2016 (122 days). The release of 30 particles every two hours from March 9th 2016 at 0:00 until two weeks before the end of the simulation (June 17th at 0:00) resulted in the tracking of a total of 36,000 particles released from each of the 38 farms (location of farms shown in Figure 3).

Most farms showed some degree of connection to nearby farms right within the first 24 hours after particles were released (Figure 4), which can be seen by having some coloured and/or numbered cells in the row of each capture farm (beyond the red cell that represents the particles released by that same farm). The exceptions were Surprise Island in Kyuquot Sound (farm #1872) and Jane Bay in Barkley Sound (farm #270). The latter started receiving some particles from farms within Barkley Sound (San Mateo and Barkley, farms #224 and 169, respectively) after the first 24 hours (Figure 5); however, these particles always represented less than 0.1% of the 36,000 particles released.

As time progressed up to day 14 (Figure 6), hydrodynamic connectivity further established within most areas. More coloured cells appeared (i.e., connectivity among more distant farms established) and colours turned from gray to purple to blue (i.e., connectivity among nearby farms intensified). These changes were most notable in Clayoquot Sound (farms Eagle Bay to Dixon Bay in Figures 3, 4 and 5), but also noticeable in Esperanza Inlet (farms Charlie's Place to Whiteley Island) and Nootka Sound (farms Hecate to Steamer Point). The exceptions were Barkley Sound (farms San Mateo to Jan Bay) and Surprise Island in Esperanza, where the connectivity established the first 24 hours did not change much during the whole 14 days of analysis.

In this study, the most connected farms were San Mateo and Barkley (in Barkley Sound) and Hecate and Lutes Creek (#1862 and 1078, respectively, in Esperanza Inlet). The latter two maintained the same level of connectivity (within 70 and 75% for both of them) during the 14 days of analysis (i.e., from 24 hours after release until 14 days after release). In contrast, in Barkley Sound, San Mateo received most particles from Barkley (up to 65-70%), while the opposite connection was weaker (up to 15%).

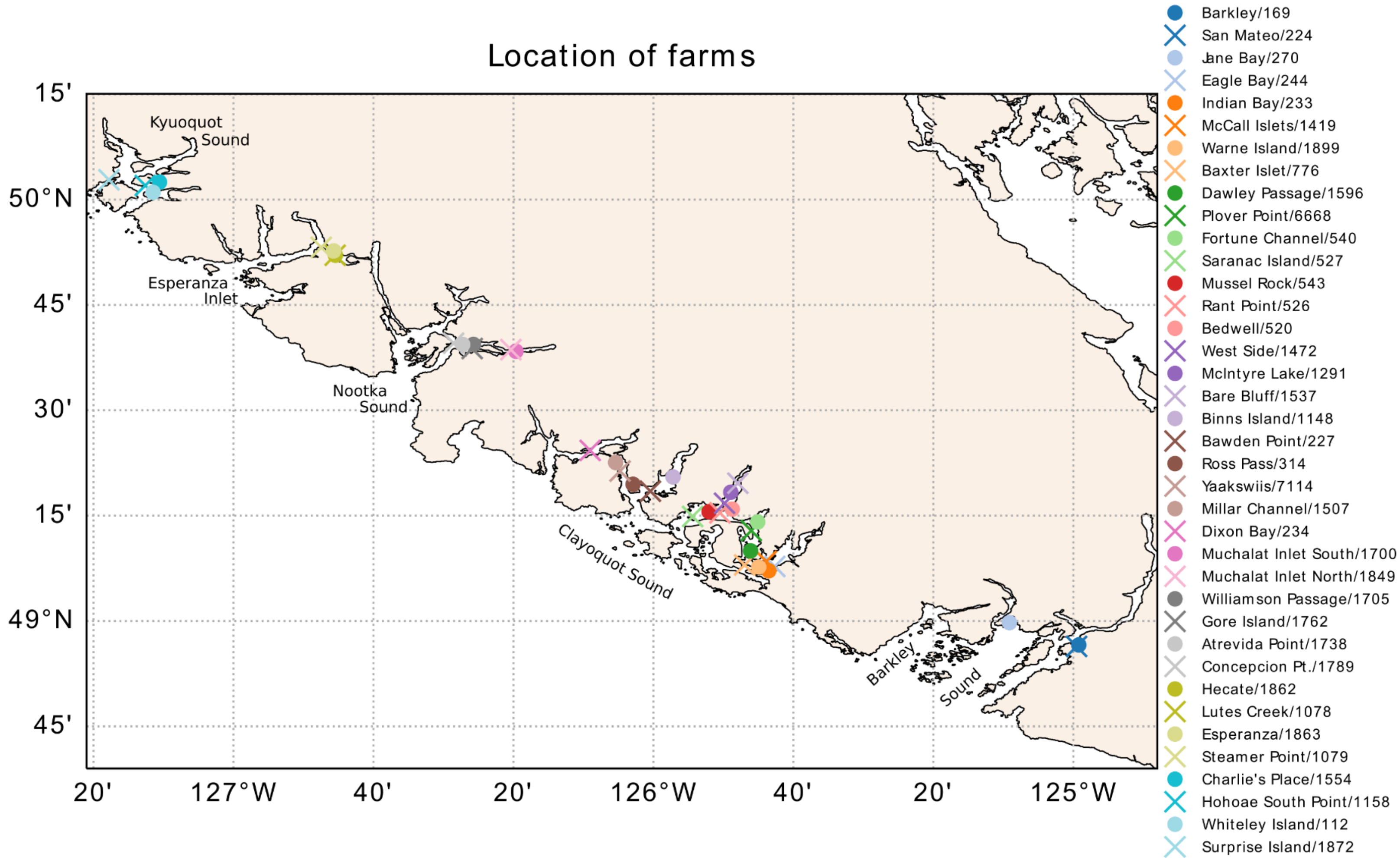

Figure 3. Location of 38 finfish farms used for the analysis of hydrodynamic connectivity with the west coast of Vancouver Island (WCVI) model. Legend shows the farm names and their facility reference numbers.

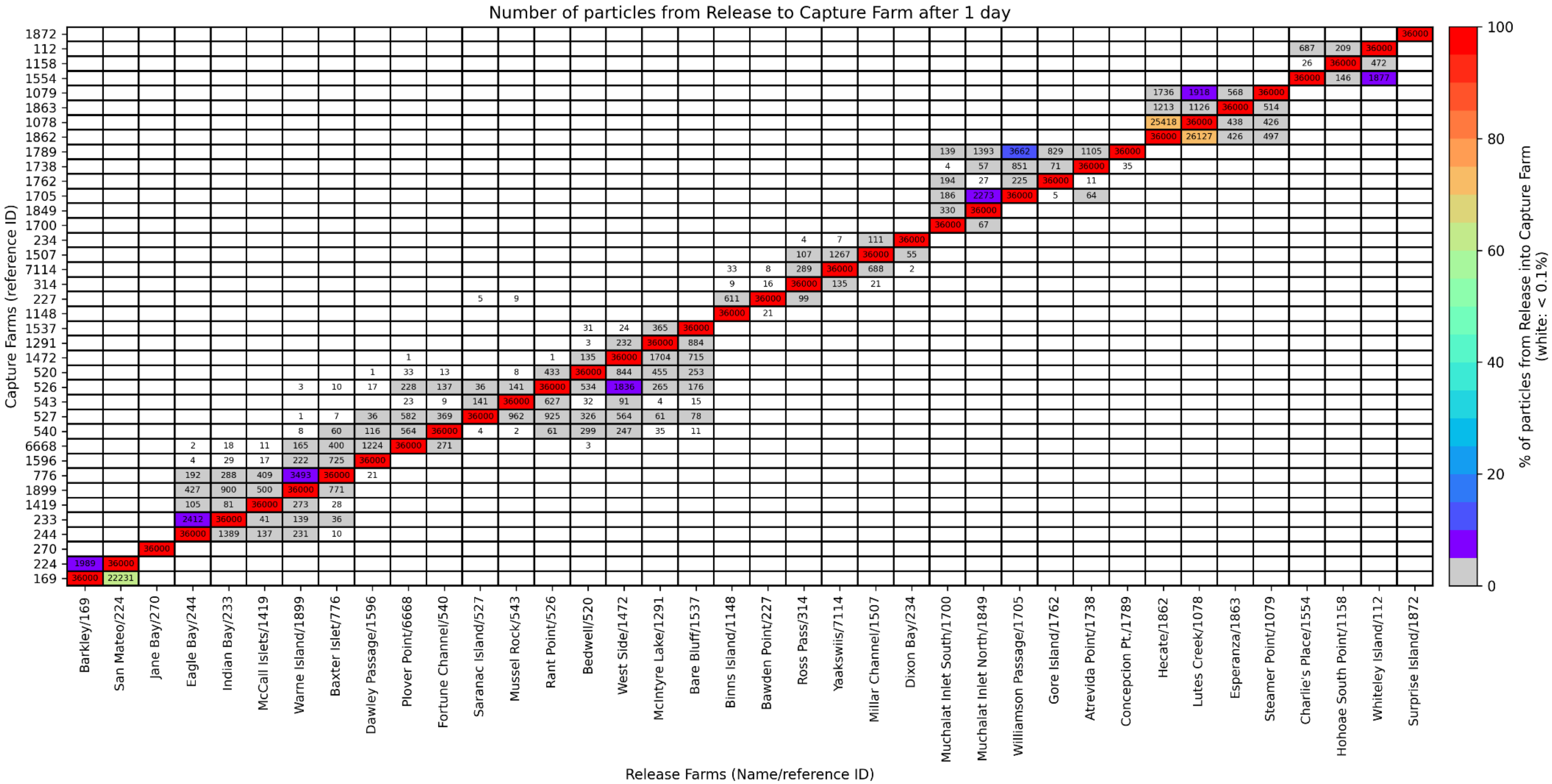

Figure 4. Hydrodynamic connectivity matrix for the 38 farms in the west coast of Vancouver Island (WCVI) domain, 24 hours after the release of particles. Farms releasing and receiving particles are listed in the x and y axis, respectively. Each cell shows the number of particles that reached a given "capture farm" (zeros not shown). Colour scale represents the percentage of released particles reaching the capture farm (colours change every 5%, except for values under 0.1 %, which are shown in white). Farm locations are shown in Figure 3.

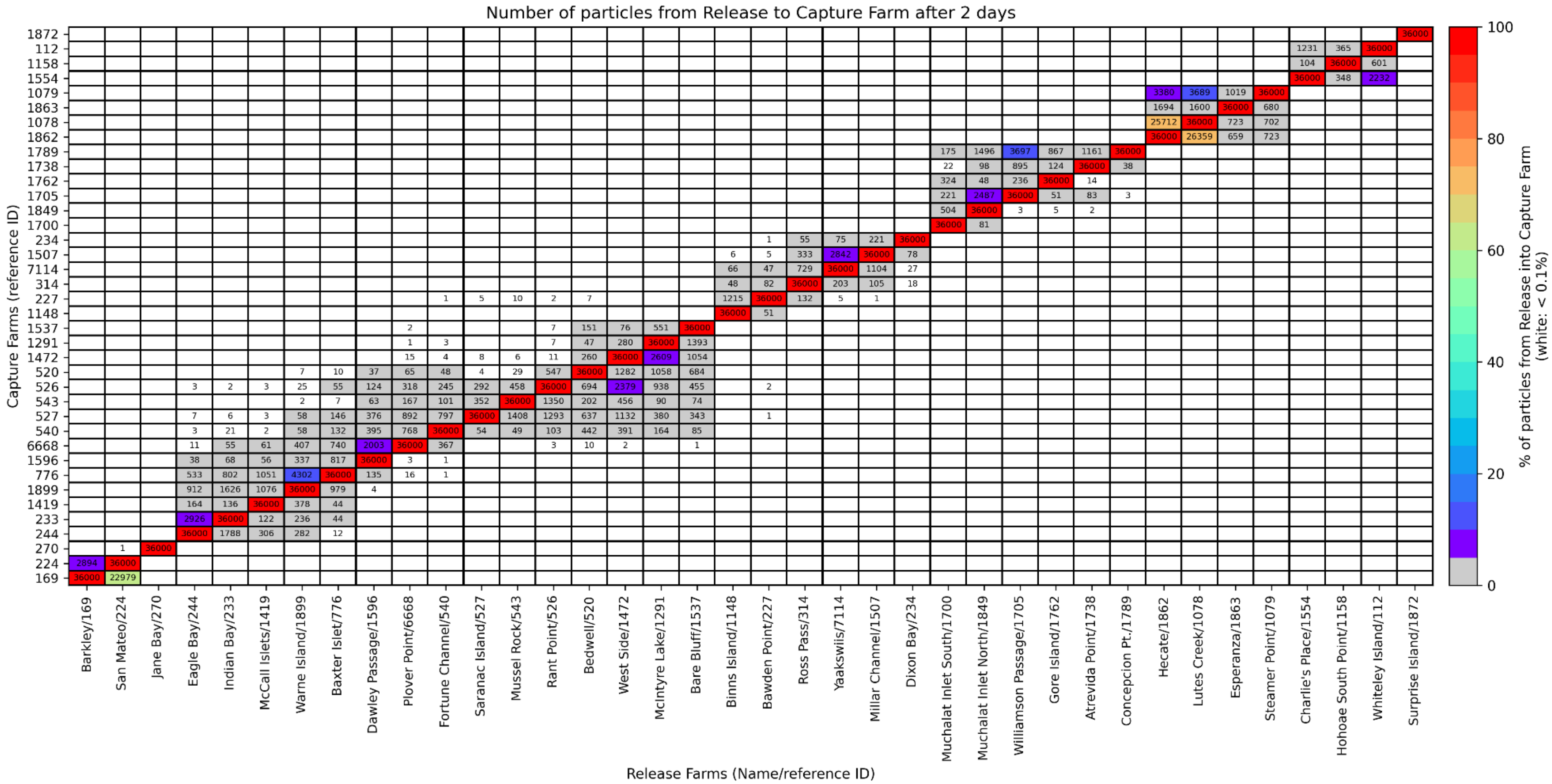

Figure 5. Hydrodynamic connectivity matrix for the 38 farms in the west coast of Vancouver Island (WCVI) domain, 48 hours after the release of particles. Plot details are as in Figure 4. Farm locations are shown in Figure 3.

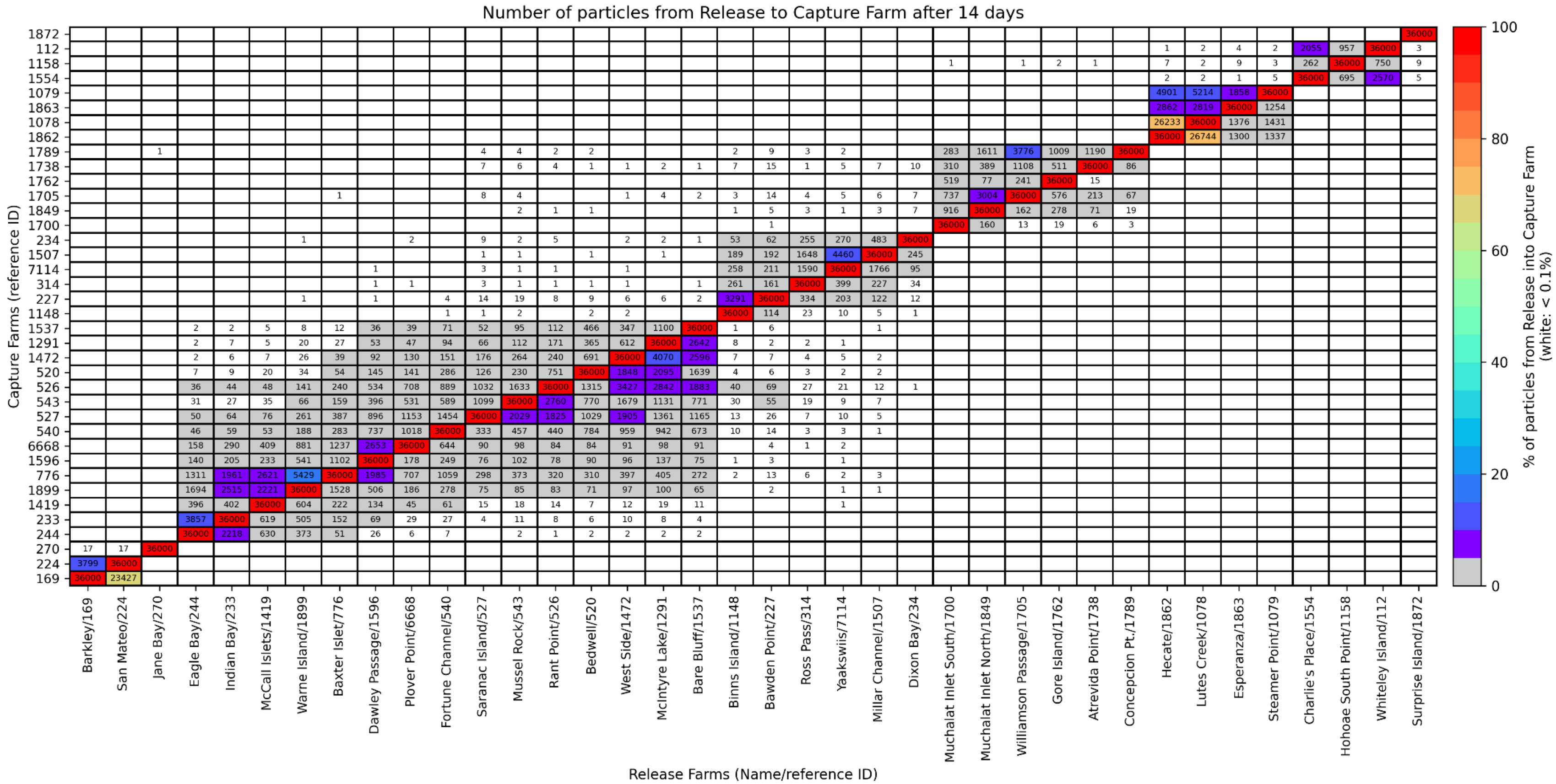

Figure 6. Hydrodynamic connectivity matrix for the 38 farms in the west coast of Vancouver Island (WCVI) domain, 14 days after the release of particles. Plot details are as in Figure 4. Farm locations are shown in Figure 3.

Discovery Islands

The DI simulations were the longest, covering the period April 1 – October 31, 2010 (214 days). By releasing 30 particles every two hours starting on April 9th at 0:00, the model tracked a total of 69,120 particles released from each of the 21 farms.

The strongest hydrodynamic connectivity was observed mostly among farms in the same channels and close to each other (Figures 7, 8, and 9). For example:

- Okisollo Channel: farms Barnes Bay (#871), Sonora Island (#211), Venture Point (#306), and Brent Island (#401) connected among each other up to 15%;
- Hoskyn Channel: Read Island (farm #447) connected up to 20% with Dunsterville Bay (#138) - but the reverse connection was always <5%; and
- Chancellor Channel: Chancellor Channel (#790) connected up to 20% with Lees Bay (#100) - but the reverse connection was always <5%.

Most farms received between 0.1 and 5% of the 69,120 particles released from at least one farm (grey cells in Figures 8 and 9). One farm, Doctor Bay (farm #456), was completely isolated from the other farms (i.e., it did not receive nor provide particles during the 14 days of analysis, Figure 7 and 9). This isolation was due to its location, far from other farms in a secluded channel (Figure 7). Raza Island (#304) and East of Maude Island (#216), neither of which has a neighbouring farm, were also quite isolated from the rest and only received 5 and 22 particles from other farms within 14 days, respectively (≤0.03% of the total number of particles released).

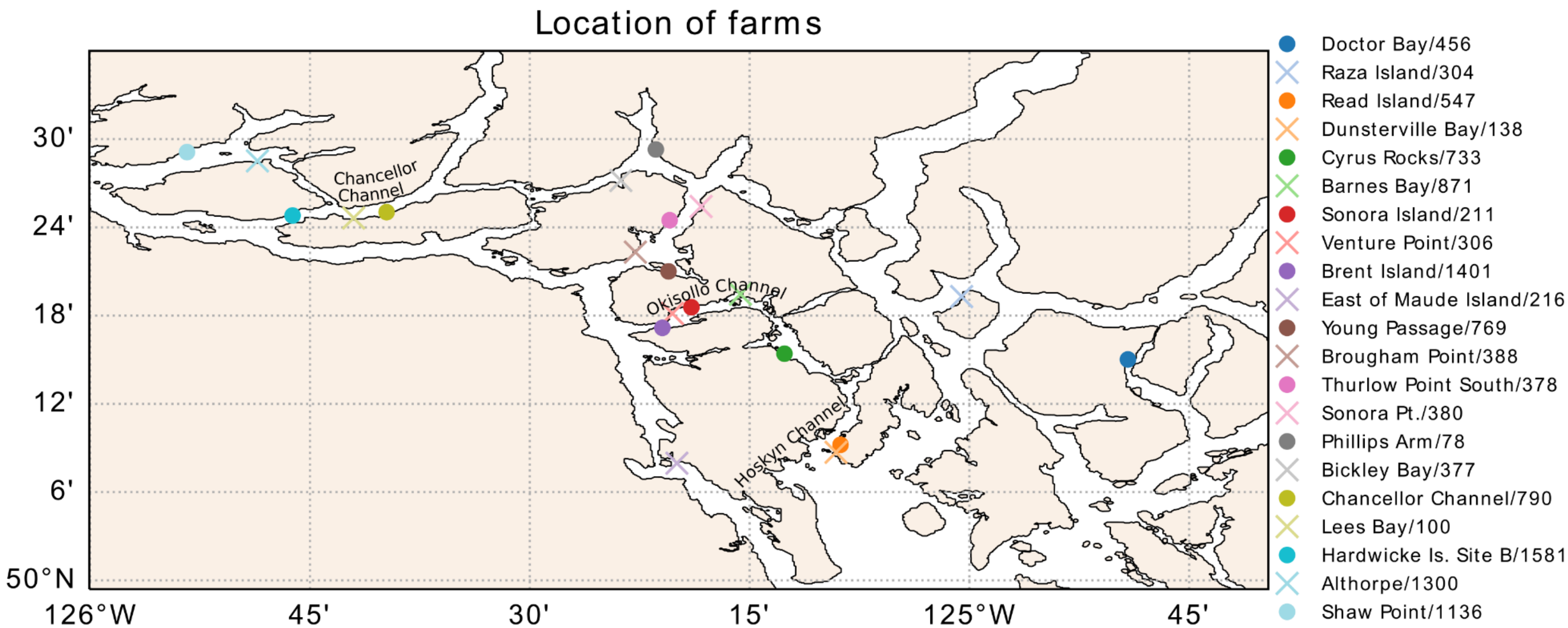

Figure 7. Location of 21 finfish farms used for the analysis of hydrodynamic connectivity with the Discovery Islands (DI) model. Legend shows the farm names and their facility reference numbers.

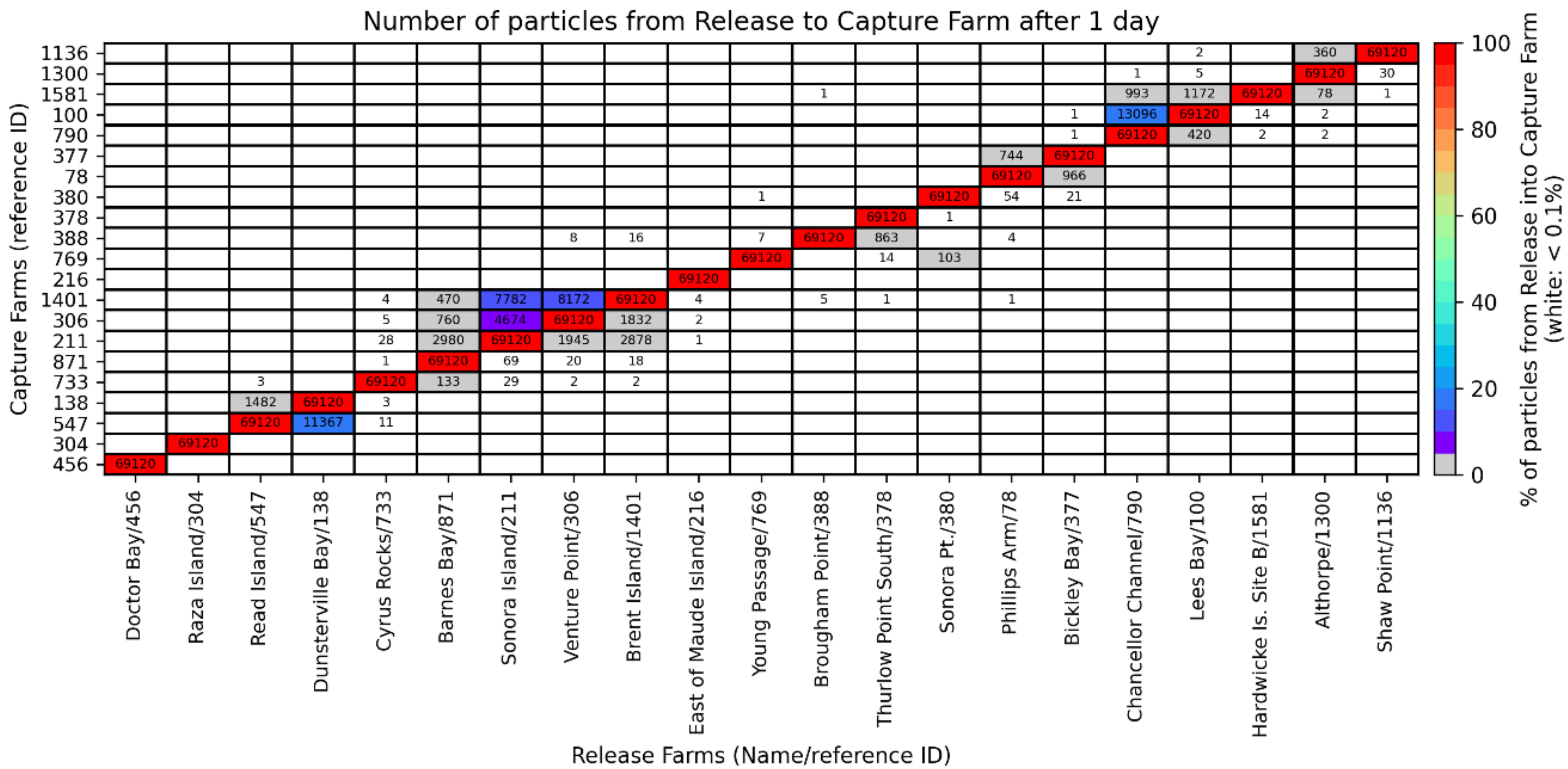

Figure 8. Hydrodynamic connectivity matrix for the 21 farms in the Discovery Islands (DI) domain, 24 hours after the release of particles. Farms releasing and receiving particles are listed in the x and y axis, respectively. Each cell shows the number of particles that reached a given "capture farm" (zeros not shown). Colour scale represents the percentage of released particles reaching the capture farm (colours change every 5%, except for values under 0.1%, which are shown in white). Farm locations are shown in Figure 7.

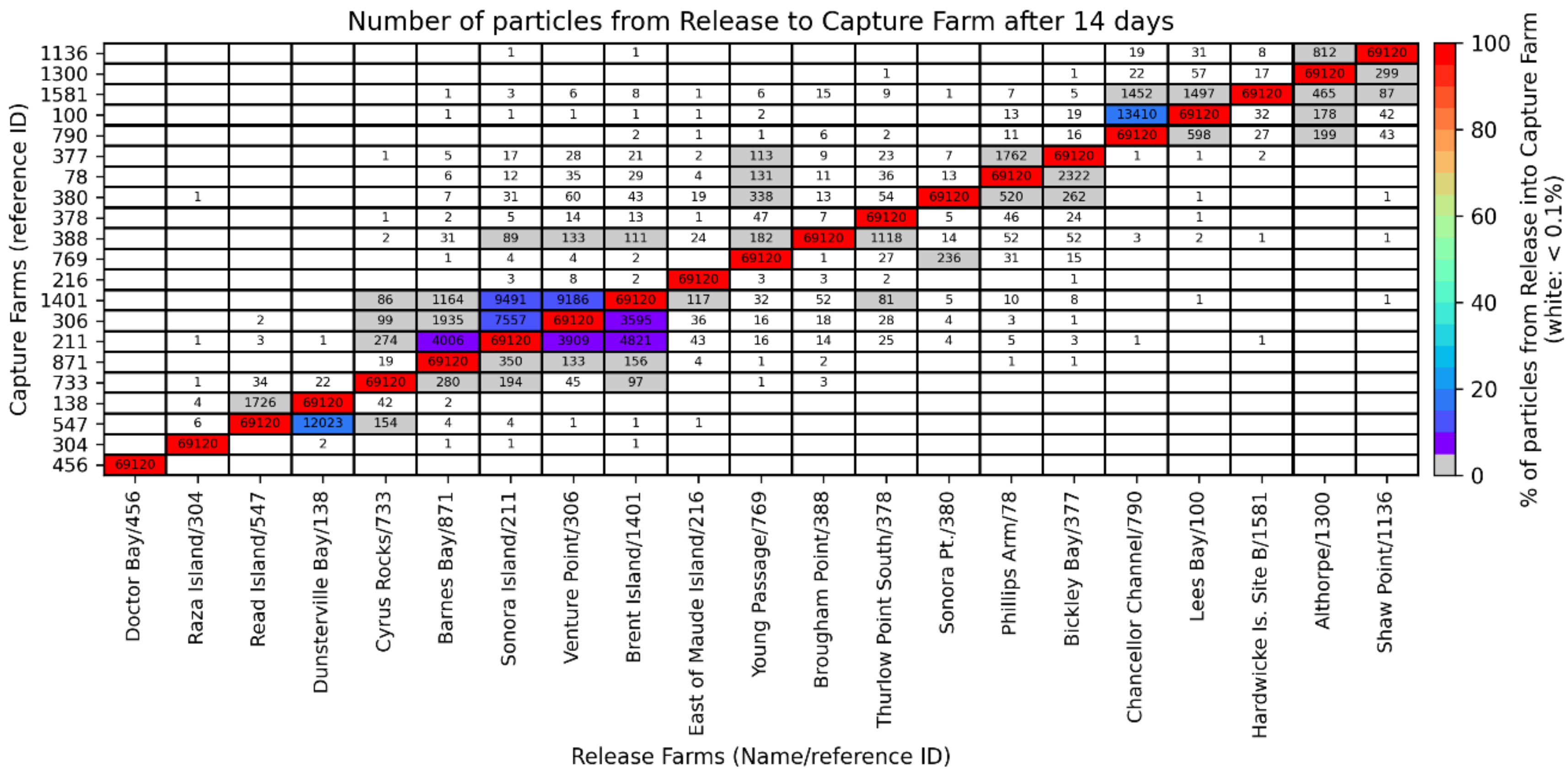

Figure 9. Hydrodynamic connectivity matrix for the 21 farms in the Discovery Islands (DI) domain, 14 days after the release of particles. Plot details are as in Figure 8. Farm locations are shown in Figure 7.

Broughton Archipelago

Simulations in BA covered the period March 1 to July 31, 2009 (153 days). The total number of particles tracked was 47,160 per farm (30 particles every two hours starting on March 9th 2009 at 0:00).

Hydrodynamic connectivity among farms in this region (Figure 10) was relatively low during the first 24hrs (Figure 11), when only two capture farms received more than 5% of particles from a release farm (Ghi Ya #7053 captured <15% of the particles from Wanx talis #7054 and Whelis Bay #1335 received <10% from Simmonds Bay #1336). Actually, most farms showed connectivity <5% during the 14 days of analysis (white or grey cells in Figure 12), with some exceptions:

- Goletas Channel: Ghi Ya (farm #7053) connected up to 15% with Wanx talis (#7054) - but the reverse connection was always <5%;
- Wells Passage: farms Wanx talis (#7054) and Simmonds Bay (#1336) connected among each other up to 10%;
- Greenway Sound: Cecil Island (#819) connected up to 10% with Maude Island (#869) - but the reverse connection was always <5%;
- Clio Channel: Tsa-ya (#7273) connected up to 10% with Noo-La (#1825) - but the reverse connection was always <5%; and
- Northern margin of Queen Charlotte Strait: Robertson Island (#1382) connected up to 10% with Marsh Bay (#1351) and Shelter Bay (#1350) - but the reverse connection was always <5%.

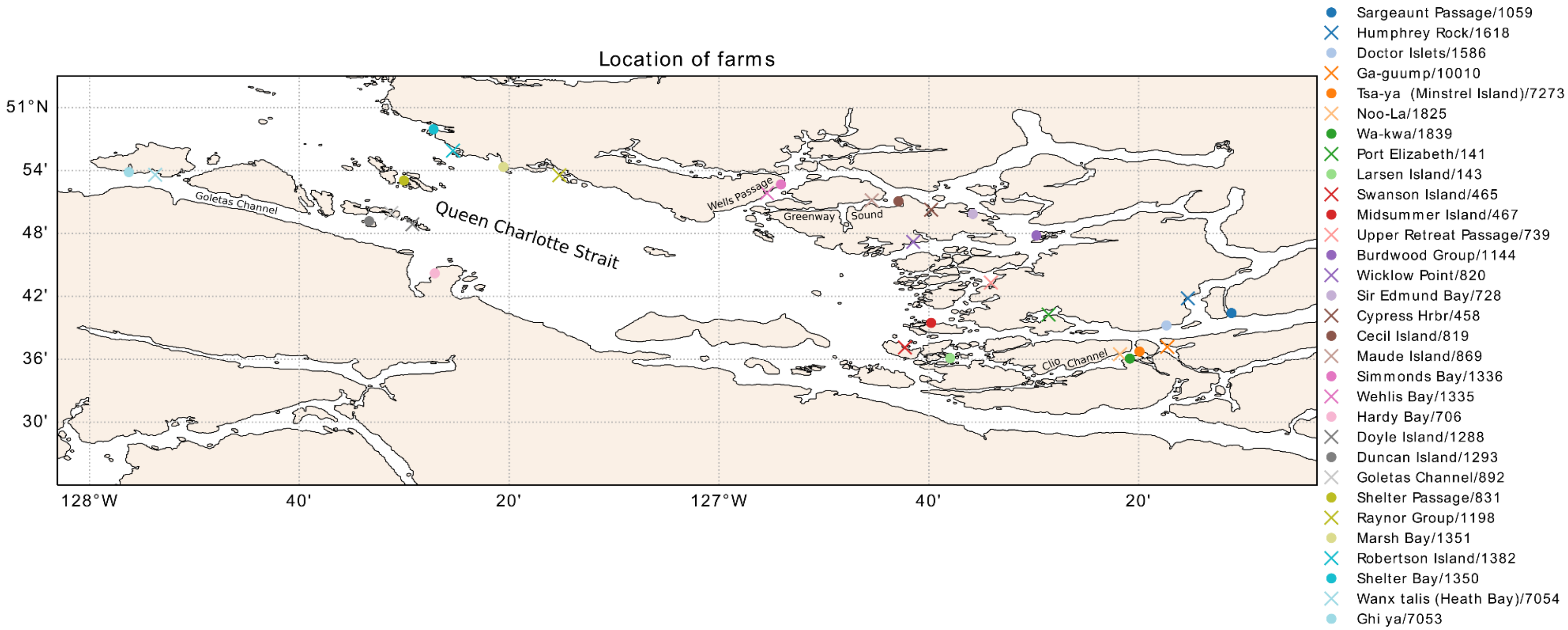

Figure 10. Location of 31 finfish farms used for the analysis of hydrodynamic connectivity with the Broughton Archipelago (BA) model. Legend shows the farm names and their facility reference numbers.

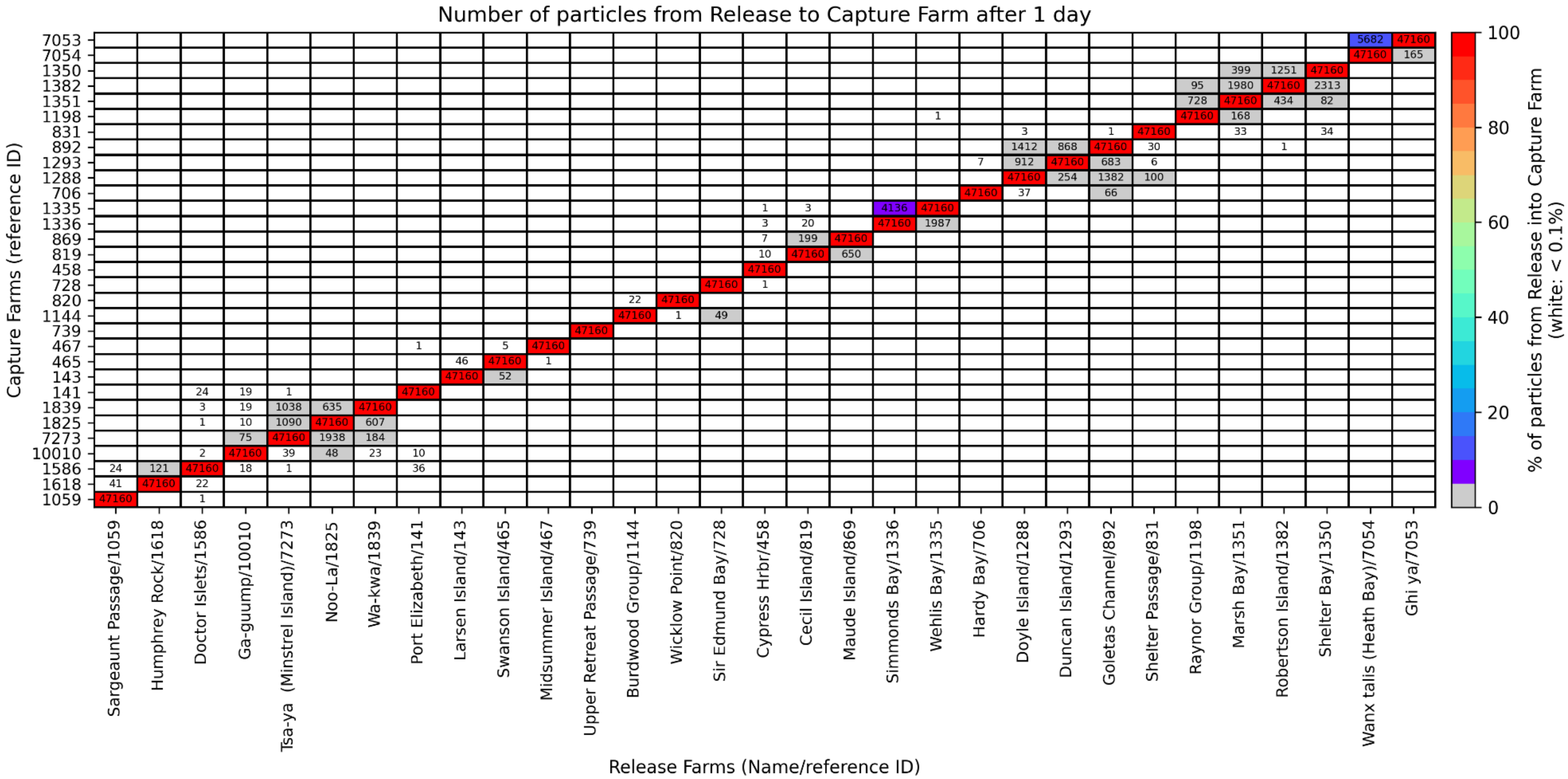

Figure 11. Hydrodynamic connectivity matrix for the 31 farms in the Broughton Archipelago (BA) domain, 1 day after the release of particles. Farms releasing and receiving particles are listed in the x and y axis, respectively. Each cell shows the number of particles that reached a given "capture farm" (zeros not shown). Colour scale represents the percentage of released particles reaching the capture farm (colours change every 5%, except for values under 0.1%, which are shown in white). Farm locations are shown in Figure 10.

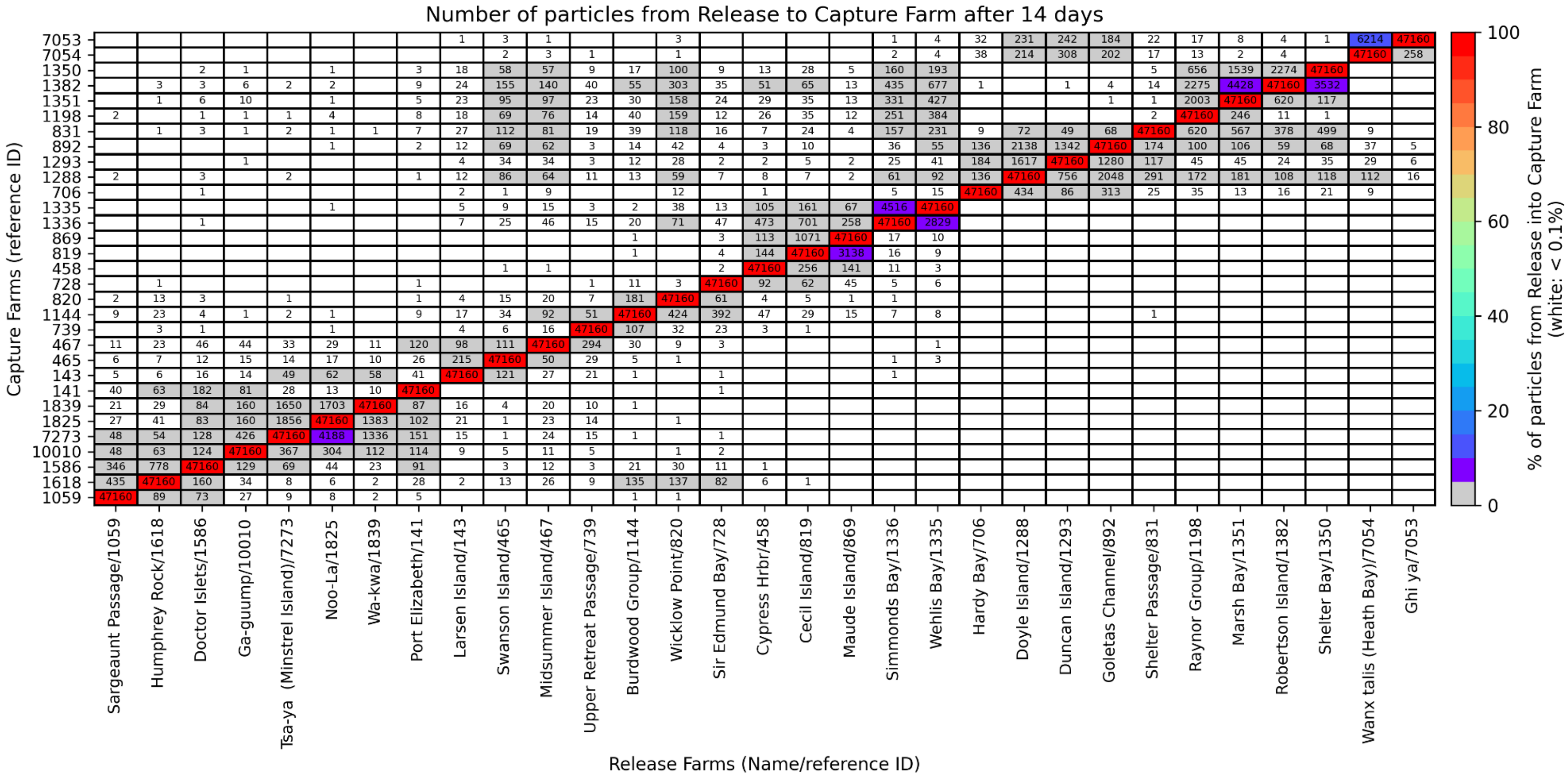

Figure 12. Hydrodynamic connectivity matrix for the 31 farms in the Broughton Archipelago (BA) domain, 14 days after the release of particles. Plot details are as in Figure 11. Farm locations are shown in Figure 10.

Conclusions

In this report, we described three hydrodynamic models for the British Columbia coast that exist within DFO and followed the approach of Foreman et al. (2015a) to produce hydrodynamic connectivity matrices on a day to day basis for 14 days for each individual/existing farm in British Columbia. These connectivity matrices were identified as the unique objective in the Terms of Reference (TOR) for this document. Our analysis of the connectivity matrices was intentionally brief, since a detailed analysis is beyond the scope of the TOR. Nevertheless, all the produced data (connectivity matrices in both plot and spreadsheet format, as well as the particle trajectories like the one presented in the Appendix) are available for further examination by AMD. In this section, we take the opportunity to highlight some caveats and limitations of the current study, as well as some identified recommendations for future work.

Caveats and limitations

As with any numerical modelling work, correct interpretation is paramount. Some of the key issues to keep in mind when analyzing and utilizing the hydrodynamic connectivity results are listed below:

- In this study, particles were considered passive (only moved by the currents) and neutral (no sinking by their own weight), and they do not intend to represent any specific type of farm release (e.g., sea lice, viruses, pesticides). Different species and pollutants behave differently, may sink and be subjected to currents at different depths, and may need to be tracked for different periods of time. To answer connectivity questions regarding a specific organism or contaminant, the modelling approach can be modified to represent specific dispersion characteristics (e.g., ability of the particle to swim or avoid certain ocean conditions, sink, decay at some known rate with ultra-violet radiation, etc.). For example, such modelling has been undertaken for Mimeault et al. (2017). The current selection of passive, neutral particles tracked for up to 14 days represents the greatest potential farm connectivity over this time period. The modelled particles do not represent or have the characteristics of any specific pathogen or organism.
- Ocean circulation fields from FVCOM can only represent the time period stated for each model (DI: April 1 to October 31 2010; BA: March 1 to June 30 2009; WCVI: 1 March to 30 Jun 2016). These periods correspond to several months of a given year, thus cannot represent the complete seasonal cycle and/or interannual variability. Furthermore, while tidal currents are generally quite regular and predictable, the wind driven and estuarine components of the current, and thus the dispersion patterns arising from them, can vary over a wide range of time scales. Therefore, particle tracking and connectivity results may look different if different time periods are modelled. Though running our models for a wider range of conditions and using those results to estimate variability and uncertainty would be one way of addressing this issue, such an approach would require significant resources (personnel and computers) and a risk analysis could show it not to be worthwhile.
- While ocean models aim to represent the real ocean, their results are simulated occurrences (may not reflect reality). Circulation model inaccuracies arise from a variety of reasons such as insufficient grid resolution, inaccurate forcing fields and boundary conditions, inaccurate (e.g., smoothed) bathymetry, inaccurate numerical approximations to the governing (primitive) equations, inaccurate mixing and diffusion parameterizations, and physics not captured by the governing equations. Some of the deficiencies in the models are known, while other are harder to identify/isolate. Consequently, inaccuracies in the particle tracking results will arise from those in the circulation model fields. Previous publications have

evaluated the accuracy of several versions of the BA (Foreman et al. 2009) and DI (Foreman et al. 2012, 2015b) models with respect to available observations.

- We now have access to atmospheric and regional models that can provide surface and boundary forcing for our simulations, as recommended by Foreman et al. (2015a) (the newer WCVI application uses these forcings). The immense advantage of using these larger scale models is that we can easily obtain the necessary inputs to simulate different periods. However, the atmospheric models available (at 2.5 and 1 km resolution) still lack sufficient resolution to represent appropriately winds over the complex coastlines of British Columbia. Therefore, there is still room for improvement in terms of the surface forcing available for our coastal hydrodynamic models.

Recommendations

Some further testing and experiments would be advisable to improve the methods presented in this document:

- As mentioned in the second bullet point of the previous subsection, longer FVCOM simulations could be attempted, provided that human and computational resources are available. For instance, either a representative or an extreme-conditions year could be selected to perform a full year FVCOM simulation. Note however that, while our computational resources have increased considerably since Foreman et al. (2015a), the computation and storage expense of the resulting outputs could still be considerably high. Monthly FVCOM output files are currently 20, 68, and 74 Gb for DI, BA, and WCVI, respectively.
- While making long-term simulations might be prohibitively expensive (both in terms of computer and human resources), performing and comparing simulations for different periods and/or under different conditions might provide useful information. For instance, by performing FVCOM simulations that change only one forcing (e.g., river discharge or winds), the role of that particular forcing in the dispersion of particles could be better understood.
- Here, we have released 30 passive, neutral particles simultaneously every two hours; Foreman et al. (2015a) released a similar amount (50). Preliminary tests have shown that 30 may be an acceptable number, at least in the WCVI domain. For instance, 30 particles were released at slightly different (also random) locations in the WCVI's 100 m by 100 m boxes, resulting in quite similar connectivity matrices. In this test, we found that while the actual number of particles reaching another farm could vary, the percentage they represented from the total number of releases usually remained the same or only changed within ±5%, with some few exceptions showing larger percentage differences. Another test releasing 100 particles from one of the farms in Nootka Sound showed basically the same connectivity as when releasing 30 particles. Nevertheless, results could differ if the latter test was performed in a region with stronger tidal currents (e.g. Clayoquot Sound). Therefore, further testing would be beneficial to gain full confidence in the number of particles needed in each region to capture all the variability in the modelled circulation fields. Ideally, these tests would be performed each time a new region or new time period is analyzed. The objective of the tests would be to find the smallest number of particles such that results do not change significantly if a) more particles are released and b) releases occur in slightly different locations.
- We have found some inconsistencies on the timing of the output that could be related to the use of single precision (e.g., the time stamp of the output is not exactly every 20 minutes, but can vary, for instance, between 19.6875 and 20.039062 minutes). Preliminary tests assessed that the inconsistencies do not arise from outputting the time variable in single

precision. The PTrack code should be checked for calculations in single versus double precision and, if indeed some calculations are currently performed at single precision, the code should be modified and simulations performed at double precision to verify that the choice of precision does not affect results. However, we do not expect the results to change significantly (or at all) once the small inconsistencies in the time vector are resolved.

Contributors

Contributor	Affiliation
Laura Bianucci	DFO Science, Pacific Region
Wendy Callendar	DFO Science, Pacific Region
Peter Chandler	DFO Science, Pacific Region
Michael Foreman	DFO Science, Pacific Region
Jon Chamberlain	DFO Science, Pacific Region

Approved by

Andrew Thomson
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada

September 30, 2021

Sources of Information

Adams, T., Black, K., MacIntyre, C., MacIntyre, I., and Dean, R. 2012. Connectivity modelling and network analysis of sea lice infection in Loch Fyne, west coast of Scotland. Aquacult. Environ. Interact. 3, 51–63.

Blanken, H., Paquin, J.-P., Lu, Y., Smith, G., and Taylor, S. 2019. Coastal ice-ocean prediction system (CIOPS-W): a snapshot of Northeast Pacific conditions in 2018. In: State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018 (Editors: Boldt, J.L., Leonard, J., and Chandler, P.C.). Can. Tech. Rep. Fish. Aquat. Sci. 3314: vii + 248 p.

Bravo, F., Sidhu, J.P.S., Bernal, P., Bustamante, R.H., Condie, S., Gorton, B., Herzfeld, M., Jimenez, D., Mardones, F.O., Rizwi, F., and Steven, A.D.L. 2020. Hydrodynamic connectivity, water temperature, and salinity are major drivers of piscirickettsiosis prevalence and transmission among salmonid farms in Chile. Aquacult. Environ. Interact. 12, 263–279.

Cantrell, D.L., Groner, M.L., Ben-Horin, T., Grant, J., and Revie, C.W. 2020. Modeling Pathogen Dispersal in Marine Fish and Shellfish. Trends Parasitol.

Cantrell, D.L., Rees, E.E., Vanderstichel, R., Grant, J., Filgueira, R., and Revie, C.W. 2018. The use of kernel density estimation with a bio-physical model provides a method to quantify connectivity among salmon farms: spatial planning and management with epidemiological relevance. Frontiers in veterinary science. 5, 269.

Chen, C., Liu, H., and Beardsley, R.C. 2003. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. J. Atmos. Ocean. Tech. 20: 159-186.

Chen, C., Beardsley, R.C., and Cowles, G. 2006. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. Oceanography, Special Issue on Advances in Computational Oceanography. 19: 78-89.

Chen, C., Beardsley, R.C., Cowles, G., Qi, J., Lai, Z., Gao, G., Stuebe, D., Liu, H., Xu, Q., Xue, P., Ge, J., Hu, S., Ji, R., Tian, R., Huang, H., Wu, L., Lin, H., Sun, Y., and Zhao, L. 2013. An unstructured grid, finite-volume community ocean model. FVCOM user manual. SMAST/UMASSD-13-0701

Foreman, M.G.G., Czajko, P., Stucchi, D.J., and Guo, M. 2009. A finite volume model simulation for the Broughton Archipelago, Canada. Ocean Modelling, 30(1), pp.29-47.

Foreman, M.G.G., Stucchi, D.J., Garver, K.A., Tuele, D., Isaac, J., Grime, T., Guo, M., and Morrison, J. 2012. A circulation model for the Discovery Islands, British Columbia. Atmosphere-Ocean 50(3): 301-16.

Foreman, M.G.G., Chandler, P.C., Stucchi, D.J., Garver, K.A., Guo, M., Morrison, J., and Tuele, D. 2015a. The ability of hydrodynamic models to inform decisions on the siting and management of aquaculture facilities in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/005. vii + 49 p.

Foreman, M.G.G., Guo, M., Garver, K.A., Stucchi, D., Chandler, P.C., Wan, D., Morrison, J., and Tuele, D. 2015b. Modelling Infectious Hematopoietic Necrosis Virus Dispersion from Marine Salmon Farms in the Discovery Islands, British Columbia, Canada. PLoS One, 10, e0130951.

Milbrandt, J.A., Bélair, S., Faucher, M., Vallée, M., Carrera, M.L., and Glazer, A. 2016. The Pan-Canadian High Resolution (2.5 km) Deterministic Prediction System. Weather and Forecasting, 31(6), 1791-1816.

Mimeault, C., Wade, J., Foreman, M.G.G., Chandler, P.C., Aubry, P., Garver, K.A., Grant, S.C.H., Holt, C., Jones, S.R.M., Johnson, S.C., Trudel, M., Burgetz, I.J., and Parsons, G.J. 2017. Assessment of the risks to Fraser River Sockeye Salmon due to Infectious Hematopoietic Necrosis Virus (IHNV) transfer from Atlantic Salmon farms in the Discovery Islands of British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/075. vii + 75 p.

Paquin, J.-P., Smith, G., Lu, Y., Taylor, S., Blanken, H., Davidson, F., Le Clainche, Y., Bernier, N., Dupont, F., Lei, J., Marcotte, G., Roy, F., Sutherland, G., Holden, J., Babalola, S., Hu, X., and Zhai, L. 2019. CIOPS-W: An operational forecasting model for oceans off Canada's West Coast to support the Ocean Protection Plan. OceanPredict'10 – GODAE OceanView Symposium, 6 - 10 May 2019, Halifax, NS, Canada.

Stucchi, D., Guo, M., Foreman, M.G.G., Czajko, P., Galbraith, M., Mackas, D.L., and Gillibrand, P.A. 2011. Modelling sea lice production and concentrations in the Broughton Archipelago, British Columbia. In Salmon Lice: An integrated approach to understanding parasite abundance and distribution. Edited by S. Jones and R.J.Beamish. Wiley-Blackwell, Oxford. pp 117-150.

Appendix

Maps of particle tracks

Besides the connectivity matrices for the three regions, we created maps showing the particle trajectories for the last 24 hours for each time period of analysis (i.e., tracks from release time to 24 hours, tracks from 24 to 48 hours, etc. until the very last 14th day). Therefore, 14 maps were created for each releasing farm, generating a total of 90 x 14 = 1260 maps. Most interestingly, they show that at day 14, some particles might be quite far from their release point, while some others are still lingering close to the it (example from the WCVI area shown in Figure A1).

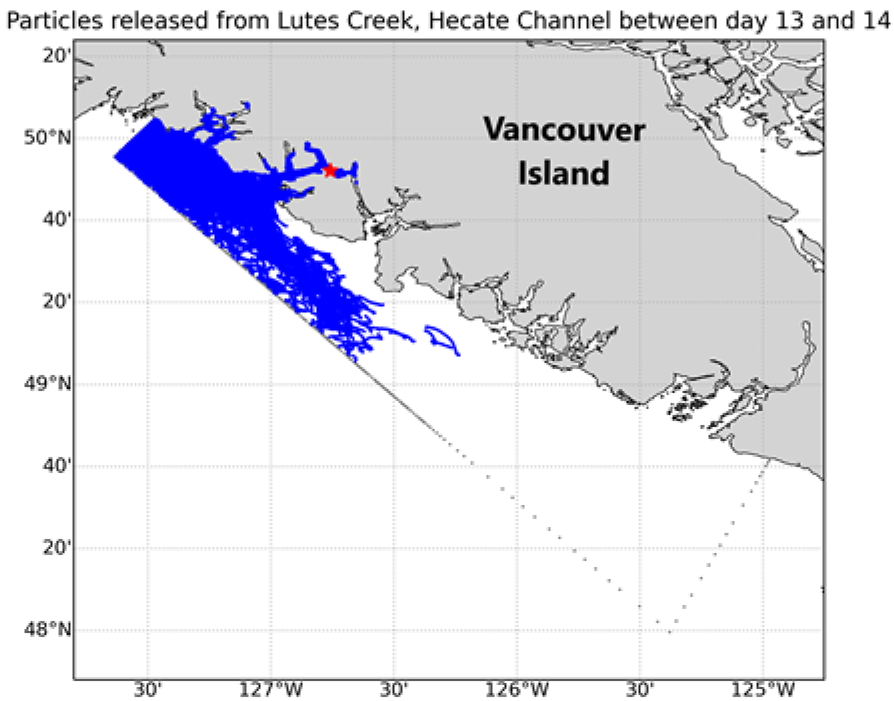

Figure A1. Particles (blue dots) released from Lutes Creek (farm #1078) between day 13 and 14 (last day of the 14-day analysis period). Location of the farm is shown in the red start. Grey dotted line represents the boundary of the WCVI model domain.

Buoyant vs Neutral Particle Tracks

We investigated both buoyant and neutral particles; the former remain at surface and are moved only by surface currents, while the latter can change their depth as they follow three-dimensional flow fields. Neutral particles consistently travelled further, therefore offering a more conservative solution to the question of farm connectivity. Particle tracks from three example farms are shown in the figure below; neutral and buoyant particles were released at the same time but the buoyant particles remained close to their release farm or grounded early (buoyant particle tracks shown in black; neutral particle tracks are colour-coded by their depth). The average distance travelled by buoyant particles released from Concepcion Pt, Bare Bluff and San Mateo was 14 km, 9 km, and 24 km, respectively. For neutral particles released at the same three farms, the average distance travelled was 34 km, 38 km, and 28 km.

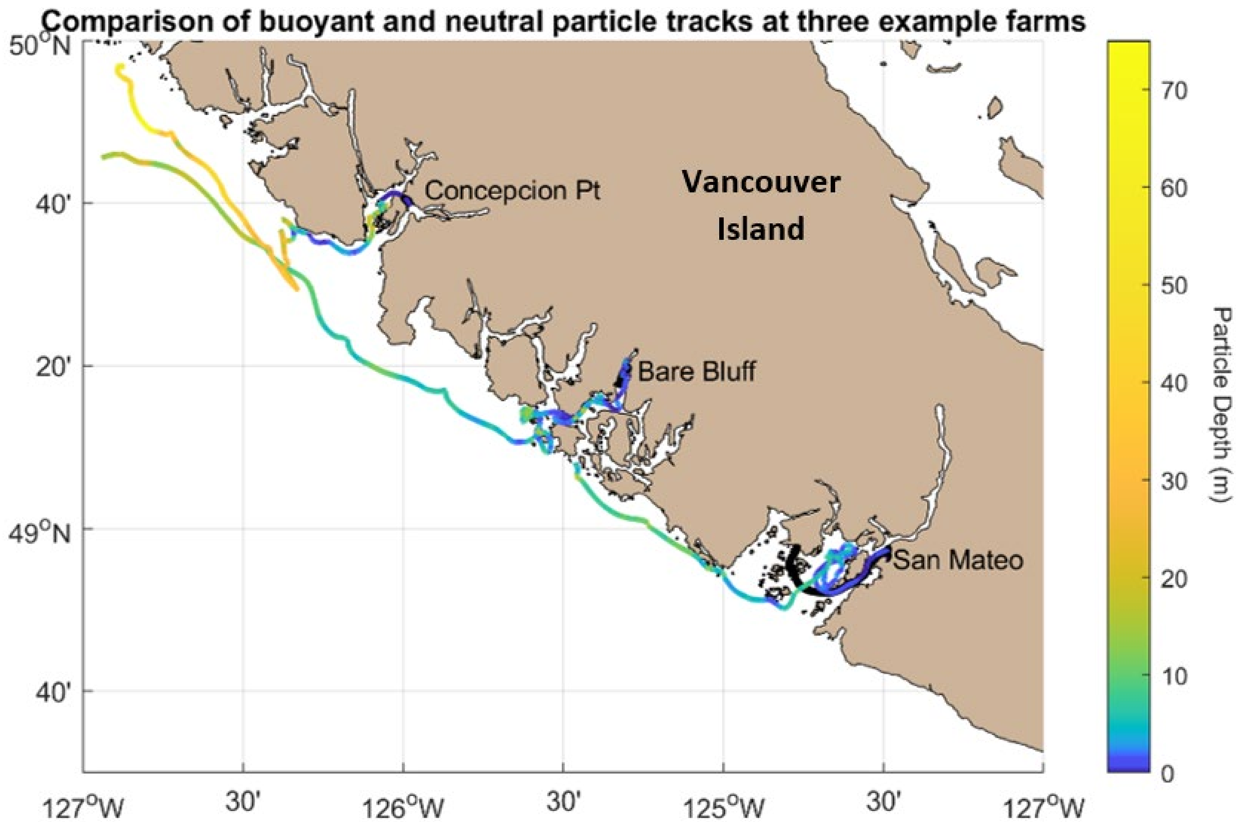

Figure A2. Comparison of buoyant and neutral particles released from 3 example farms. Black tracks indicate buoyant particles that remain at the surface; multi-coloured tracks indicate neutral particles, where the colour shows the depth of the particle.

This Report is Available from the:

Centre for Science Advice (CSA)
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

Telephone: (250) 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-3769
ISBN 978-0-660-40760-9 Cat. No. Fs70-7/2021-042E-PDF

Correct Citation for this Publication:

DFO. 2022. Hydrodynamic Connectivity between Marine Finfish Aquaculture Facilities in British Columbia: in support of an Area Based Management Approach. DFO Can. Sci. Advis. Sec. Sci. Resp. 2021/042.

Aussi disponible en français :

MPO. 2022. Connectivité hydrodynamique entre les installations de pisciculture marine en Colombie-Britannique : À l’appui d’une approche de gestion par zone. Secr. can. des avis sci. du MPO. Rép. des Sci. 2021/042.