VALIDATING PARTICLE TRACKING MODELS OF SEA LICE DISPERSION IN SCOTTISH SEA LOCHS
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ABSTRACT
Lepeophtheirus salmonis is a naturally occurring parasite on wild salmonids. Infestations of this sea louse pose a major economic burden to the Atlantic salmon aquaculture industry and may be linked to the decline of wild salmonid populations. Coupled models of surface circulation and louse biology have been used to understand the dispersion of planktonic larval lice from a point source, such as a fish farm. We have developed a sea lice dispersion model for Loch Torridon, a fjordic-type sea loch on the west coast of Scotland, using output from two different hydrodynamic models. Surface circulation within Loch Torridon shows significant deviation across-loch from expected estuarine transport due to the complex shoreline geometry and relatively low freshwater input. Validation of transport has been carried out with a combination of current meters and drifter studies, in order to ensure transport patterns within the loch are represented. Simulated dispersal patterns of viable sea lice demonstrate a high dependence on wind and freshwater forcing, such that validation must be carried out under a range of environmental conditions. Further, complex coastlines of Scottish fjords mean that wall parameterizations can have significant influence on individual particle tracks. As this cannot be validated using drifter studies, a numerical exploration of the impact of varying wall parameterizations is undertaken.

1 Introduction
Scotland’s aquaculture industry operates in the often-fjordic environments of the West Coast, Western Isles, and Shetland island group and shares the natural environment with wild fish populations. A threat to both of these groups lies in the naturally occurring sea lice Lepeophtheirus salmonis (and to a lesser extent Caligus elongatus) which parasitize fish. Both wild fish and farmed fish are at risk from sea lice epizootics and information about the spread of infectious sea lice is needed to allow for careful and sustainable management of Scotland’s aquaculture industry.

To understand the dispersion and transport of sea lice through a Scottish sea loch, a monitoring program has been studying lice distribution within the Loch Torridon system for over six years. In conjunction with this work, coupled bio-physical particle-tracking models are being developed to assess the potential dispersion of sea lice from infected areas. This work discusses two of the challenges of that ongoing research; the validation of simulated wind driven circulation and the interaction of particles with boundaries in particle tracking routines. Each section is followed by a brief discussion while recommendations for good practice are listed in the conclusions.
1.1 Sea Lice in Loch Torridon
The Loch Torridon sea loch system is located on the west coast of Scotland (Figure 1). Similar to many lochs, Torridon is a fjordic estuary, with silled regions blocking the flow of deep water to the coastal ocean. Specifically, Loch Torridon can be described as a three-basin system, with the inner basins (Upper Loch Torridon and Loch Shieldaig) separated from the outer basin (Loch Torridon) by a series of sills. Freshwater input into Loch Torridon is via five small rivers located around the basin. Two of these are of greater interest (the Rivers Shieldaig and Balgy) due to wild sea trout populations.

The planktonic stages of the sea louse life cycle begin at hatching, where the nauplius I emerges and develops through nauplius II into an infective copepodid. This process takes several days, depending on temperature, about 4 d at 10 °C. These phases are planktonic, with the nauplii, and to a lesser extent the copepodid, having very limited swimming abilities. It is commonly believed that planktonic lice are retained within the surface layers (0 – 5 m) of the water by the small amount of vertical swimming ability the lice posses. To map the dispersion and infectious potential of the lice, we therefore use two-dimensional particle tracking models to estimate the dispersion of lice from their point of origin over the typical time (on the order of two weeks) that a louse will remain in the planktonic phases.

1.2 Physical Circulation
To drive the particle-tracking model, three-dimensional circulation models are needed to predict local surface currents. Initially, work was begun using output from the model described in detail in Gillibrand and Amundrud (2007), based on the GF8 model of Saucier et al. (2003). Failure of this model to reproduce observations has
led to the adaptation of further models (POLCOMS, Bergen Ocean Model) to Loch Torridon. However this is work is still in progress and is not discussed here. In brief, GF8 is a three-dimensional Cartesian coordinate numerical model on an Arakawa C-grid. Horizontal grid sizes of 100 m are used with vertical grid spacings fixed in the horizontal. In these simulations, the top five vertical layers are set to 4m thick and the uppermost layer is used as input to the particle tracking scenarios for sea lice. The model is forced by tidal elevations at the seaward boundary, freshwater input at the six rivers, rainfall, and the density of offshore coastal waters. The grid representing the loch was rotated 49° counter clockwise to increase numerical efficiency.

Gillibrand and Amundrud (2007) note that the model used in this study could not reproduce the surface circulation, particularly the strong up-loch flows observed under NW wind forcing in Loch Shieldaig. This type of circulation is significant for sea lice dispersal, as it potentially can carry nauplii and copepodids towards river mouths and concentrate them at shorelines. This paper investigates this failure to reproduce observed transport and discusses recommendations for validation of hydrodynamic output used for particle tracking models.

1.3 Particle Tracking Model

The particle tracking model is a simple 4\textsuperscript{th} order Runge-Kutta solver for the Lagrangian equation of motion (equation 1, terms 1 to 3) where \( p(x_n,y_n) \) is the position of the particle as a function of \( x \) and \( y \) at time \( n \), \( u(x_n,y_n) \) is the velocity, and \( \Delta t \) is the time step. Observed surface velocity at the particle location are calculated by interpolating surface velocities linearly in time and by the inverse square of distance in horizontal space. Diffusion is incorporated into the particle-tracking model as a random walk component (term 4 in equation 1). Here, \( R \) is a random number uniformly distributed within the domain \([-1,1]\) and \( D_h \) is the horizontal diffusion coefficient.

\[
p(x_{n+1},y_{n+1}) = p(x_n,y_n) + u(x,y)\Delta t + \sqrt{6RD_h\Delta t}
\]  

Equation 1 uses a constant value for the diffusivity, \( D_h \). While horizontal eddy diffusivity is often related to the horizontal velocity shear (Murray and Gillibrand, 2006), it can cause aggregation of particles in areas of low diffusivity (Visser, 1997; Ross and Sharples, 2004). Expected values for \( D_h \) based on experiments are suggested to be 0.1 - 1.0 m\(^2\) s\(^{-1}\) (Turrell and Gillibrand, 1995).

The basin walls are defined within the particle tracking routine as linear, ‘sticky’, boundaries where particles approaching land are subject to sticky conditions: if their trajectory would carry them onto land, they are instead held at their previous position, \( p(x_{n+1},y_{n+1}) = p(x_n,y_n) \).

Further, a bio-physical particle tracking model of sea lice requires information about the biological life cycles of lice. Preliminary work in developing this model is described in Murray and Gillibrand (2006) and is in progress. However, fundamental to particle tracking models are accurate representations of the physical circulation and behaviour of the particles. This paper focuses on the validation of circulation models and the development of appropriate wall constraints for particle tracking. As such, no biological behaviours are included in the particle tracking simulations discussed here.
2 Particle Tracking Model Validation

2.1 Model Validation

Numerical model validation is traditionally done via comparisons with current meters, acoustic doppler current profilers, water level recorders, and CTD profiles. In their 2007 paper, Gillibrand and Amundrud demonstrate that the circulation model in Loch Torridon reproduced both the tidal characteristics and density evolution of the loch over a three-month period. However, we suggest that such validation is not sufficient for particle tracking as direct comparisons with the observed motion of GPS-tracked drifters revealed significant discrepancies between modelled and observed transport. In the following section we expand on the results of the wind-driven circulation briefly mentioned by Gillibrand and Amundrud (2007).

To obtain validation data, GPS tracked drifters were deployed multiple times in Loch Shieldaig during August 2005, November 2005, and July 2006 with each trial lasting several hours. Data from August 2005 are chosen for comparison as they represents a natural experiment when winds from the north-west (NW) transported drifters against the tide towards the mouth of the River Shieldaig; therefore providing a mechanism whereby sea lice could be concentrated on the shoreline near a sensitive sea trout river. Two trials where the drifters travelled towards the River Shieldaig are shown here (Table 1). Drifters were constructed in-house and consist of a large holed sock connected by a buoyant marker to a dhan buoy that had a GPS unit mounted on the shaft. The GPS units recorded positions at one-minute intervals and after the trials, the units were retrieved and the data downloaded.

<table>
<thead>
<tr>
<th>Trial</th>
<th># of Drifters</th>
<th>Time of deployment</th>
<th>Tides</th>
<th>Average Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0800-1230 BST</td>
<td>HW 1119</td>
<td>3.3 m s⁻¹ NNW</td>
</tr>
<tr>
<td>2</td>
<td>2,2</td>
<td>1245-1945 BST</td>
<td>LW 1729</td>
<td>2.7 m s⁻¹ NNW</td>
</tr>
</tbody>
</table>

Table 1: List of drogue deployments on the 11th of August, 2005. Tidal range was 3.3m. Under number of drifters, the notation ‘2,2’ indicates that there were two locations where two drogues were released. Wind was recorded at the Shieldaig field station. Due to the highly variable nature of wind, all values are approximate.

Drifter data were then transformed and rotated from GPS coordinates to positions in the numerical model coordinate system. While these transformations, along with the error inherent in the GPS measurements (estimated to be < 15m) undoubtedly introduced a degree of uncertainty in the drogue data, this error is on the order of 10 m and is insignificant when compared with the discrepancy between modelled and observed flow.

For model validation, we attempted to reproduce conditions at the time of observations although direct environmental data was not available for August 2005. Due to the low rainfall during the fieldwork in August, no fresh water input was assumed. Coastal density distributions were also unavailable due to instrument failure and were therefore assumed to be constant throughout the simulation at the July 2001 observed levels.

A known weakness of the circulation model has been the reliance on wind forcing obtained from a meteorological station a considerable distance away inland (over 50km to the WNW at Loch Glascarnoch; Gillibrand and Amundrud, 2007). Ongoing
research, including the deployment of a meteorological buoy into the centre of Loch Shieldaig, is attempting to improve the wind forcing. Meanwhile, an estimate of the wind forcing was obtained from a consumer-grade weather station mounted at the mouth of the River Shieldaig (Figure 1; Table 1). Due to the sheltered location of the field station it is unlikely that the wind measurements made there are representative of conditions throughout the loch. However, this wind data provides the best estimate of local winds for the August simulations. The NW orientation of Loch Shieldaig means that the field station is most exposed to winds from that direction and, as at the time of the drogue survey in August, winds were observed to be NNW, the wind data is assumed to be a reasonable estimate for this period.

To provide a best estimate of the wind, the model was forced with a north-westerly wind that oscillated daily between zero and 10 m s\(^{-1}\) with a maximum wind at 4pm. Original simulations with constant winds (Gillibrand and Amundrud, 2007) were found to have smaller wind driven currents due to ponding than oscillating winds. Further, oscillating winds are expected to better represent real wind patterns. The oscillating wind is much higher than observed winds during trial 2 (as peak wind of 10 m s\(^{-1}\) exceeds observed winds of 2.7 m s\(^{-1}\)) but provides more realistic forcing during trial 1, where the wind halfway through the simulation (at 1000 BST) is approximately 5 m s\(^{-1}\), closer to the observed value of 3.3 m s\(^{-1}\) at the mouth of the Shieldaig River. These overestimates of wind forcing are not intended to reproduce real wind forcing but are chosen to demonstrate the model’s inability to reproduce the observed magnitude of the wind driven circulation.

Figure 2 and Figure 3 show the results of the simulated tracks compared with observed drogue motion during the August field season for trials 1 and 2. Consistent in both plots is the failure of the model to account for the high velocities achieved by the drogues. In Figure 2, modelled tracks are shown with and without freshwater input (here freshwater is represented by average values from 2001; Gillibrand and Amundrud, 2007). The modelled direction agrees with observations for the no freshwater case, which is intuitively pleasing as very little freshwater input was observed immediately preceding and during the field program.

In Figure 3, the model shows a better match to the one set of drifters (bottom) at both a 10 m s\(^{-1}\) wind and the more realistic 5 m s\(^{-1}\) maximum wind (both set to oscillate over 24 hours with maximum values at 4 pm). However, even with the overestimated wind forcing (black curve), the model is unable to reproduce the observed high velocities. Further analysis of the modelled currents over three months of simulation reveals that the currents never approach the observed velocities.

### 2.2 Model Validation: Discussion

The motion of the drifters towards the river mouth suggests that the wind-driven circulation dominates the tidal and estuarine circulation in the surface layer. Figure 3 shows that both the model tracks and the drifters are travelling towards the head of the loch during an ebb tide (low water at 1729, British Standard Time). While the model does pick up the general pattern of transport, its inability to reproduce the magnitude of the transport suggests that the GF8 model does not appropriately represent the wind-driven circulation in the surface layer. As the model uses established algorithms to represent the drag on the surface from the wind, it is doubtful that the faults lie in the basic parameterisation (Gillibrand and Amundrud, 2007). Instead the assumptions made in the model, namely the definition of the vertical grid and the applied wind forcing, may be causing the misrepresentation of the surface circulation.
Figure 2: Movement of the drogues (blue) on 11th August 2005 (trial 1) as compared with the modelled particle track (black) from the results of the circulation model. The lower black track refers to a simulation run without freshwater (FW) input and shows much better agreement with the direction of observed motion (if not the magnitude). All distances on axis are in km.

A potential limitation of the model is the fixed Cartesian grid levels in the vertical. The vertical resolution is fixed such that changes in tidal elevation are handled by adding a surface elevation factor, $\eta$, to the thickness of the surface layer. For Torridon, where the tidal range is in excess of 4 m, the upper surface layer will vary between 2-6 m and the surface layer velocity will be an integrated value corresponding to up to 6 m of water. Therefore high surface currents extending only in the upper few meters of the water column may not be resolved and could explain part of the discrepancy between the drogues and the observed currents.

However, the configuration of the layer depths in the model will not be the sole contributor to the model’s failing. Consider trial 2 (Figure 3) where the tide was ebbing through most of the trial; here the surface layer would be $< 4m$ and should represent the velocities experienced by the drifters. It therefore is unlikely to be the layer depths alone that are restricting the response of the surface layer to the wind.

Another problematic assumption in the GF8 model is the application of a homogeneous wind forcing over the entire loch. Due to the complex local topography, some regions of the loch may be more sheltered than others. Models of wind and topography (Barlettani and Jones, 1997) have shown accurate results for simpler topographic regions, but preliminary work with these models have demonstrated that they cannot be applied directly to the mountainous area around Loch Torridon as the topography is too steep. Observations of the winds are equally difficult, and often limited spatially to point measurements (as with the meteorological station at the mouth of the River Shieldaig). Work is ongoing to investigate developing better models of the wind forcing.
3 Particle Tracking Wall Constraints

Initial model runs of the sea lice model (Murray and Gillibrand, 2006) revealed a tendency for particles to aggregate at coastlines, highlighting the interaction of particles with the coast as an area of interest. Consider the interaction of an object in the water with an irregular coastline, such as the coastline of a sea loch. The object’s behaviour will depend on its vertical behaviour within the water column (is it passive, neutrally buoyant, or does it have some vertical swimming ability?) as well as the shape of the coastline itself. Small inlets and bays may trap objects, while promontories deflect them. Traditional forms of particle tracking models ignore this variation and include a homogeneous response for particle collisions with walls. In the following section we look at simple case studies showing the sensitivity of particle trajectories to wall type and time steps, and note that this is an area in need of future research efforts.

Figure 3: Movement of the drogues (blue tracks) on 11th August 2005 (trial 2) for two release points (top and bottom) as compared with the modelled particle tracks (black, red) from the results of the circulation model with varying maximum winds (10 m s$^{-1}$ and 5 m s$^{-1}$ respectively). All distances on axis are in km.
3.1 Wall interactions: time steps
The highly dynamic environment of a Scottish sea loch has interesting implications for the choice of time step within a particle-tracking model. Recent experiments with sticky boundary conditions at the walls, as used by other researchers (C. Chen (U. Mass, pers, comm. 2005) has revealed that results are highly sensitive to the parameterizations of the walls and the time steps of the simulation, in the absence of diffusion.

Figure 4 shows the particle tracks from a two-day simulation without dispersion where the only variation is the particle time step, which ranged from 20 to 400 seconds. The particles tracked together until they reached the coastline, indicated on the figure by an open circle. There, small differences in position (on the order of meters) that had accumulated due to small differences in the interpolated velocities resulted in very different trajectories. (Due to the highly variable horizontal circulation, small differences in the time that point velocities, \( u(x,y) \) in equation 1, are calculated can result in small, but significant, differences in position.) Two particles located slightly east of their counterparts (red line, \( \Delta t=20,40 \) seconds) were able to move along the coast and into the upper loch while the majority (\( \Delta t=60, 120, 200, 240, \) and \( 300s \)) remained trapped in the area where they hit the wall. However three other particles (green \( \Delta t=80s \); purple \( \Delta t=100s \); grey \( \Delta t=400s \)) ended up with vastly different trajectories.

![Figure 4: Particle tracks from the surface layer lasting 2 days. Particles were released at the site marked by the cross and subject to the same forcing, but their positions were calculated using different sub time steps. Time steps for particle tracking were 20, 40, 60, 80, 100, 120, 200, 240, 300, and 400 seconds.](image)

We note that the case shown in Figure 4 is the most dramatic scenario encountered within numerous tests and for many trials at different starting points and times, the particles track almost identically.

3.2 Wall interactions: wall definition
Figure 4 shows the interaction of a particle with a linear, and therefore unrealistic, coastline. More accurate modelling would allow some representation of the complex interactions between a particle and a rough coast typical of Scottish sea lochs (This analysis ignores the impact of tidal wetting and drying and focuses on the many areas of sea lochs that have steep sides). As an example, we replace the linear...
walls of our model with a simplistic structure to simulate a more complex coastline by imposing a relative distance criteria for 'land'. For a particle with one adjacent land cell and three adjacent water cells, the particle is considered to be on land if its position is within a radius of ½ a cell from the land node. This criterion is reversed for a particle with three adjacent land cells, while a simple horizontal boundary is used for the case of two land and two water cells. One feature of this coastal condition is that for a coastline represented within the grid as a diagonal boundary, the coastline takes a curvy form (Figure 5). While this curvy form is not representative of reality, it provides a case for comparison with the linear boundary conditions.

Figure 5: Schematic showing the difference between curvy and linear wall definitions. Land cells are coloured green.

Figure 6: Particle tracks from the surface layer lasting 2 days for a simulation using curvy walls. Particles were released at the site marked by the cross and subject to the same forcing, but their positions were calculated using different sub time steps. Model time step was 20 minutes and time steps for particle tracking were 20, 40, 60, 80, 100, 120, 200, 240, 300, and 400 seconds.
Tests of the two wall constraints (curvy vs. linear) show that repeating the experiment in Figure 4 for the curvy wall condition demonstrates similar results (Figure 6). The main differences lie in the retention of the particle with $\Delta t=80\text{s}$ (green) within Loch Shieldaig, the retention of the particle with $\Delta t=100\text{s}$ at the area of coastal interaction, and the escape of the particle with $\Delta t=120\text{s}$ (cyan) into the outer loch. However, at first glance the general pattern of particles looks similar.

Figure 7: Maps indicating the locations of particles throughout the 2 day simulations. Data is expressed on a logarithmic scale as the number of particle hours per grid cell divided by the total number of particle hours.
3.3 Wall interactions: Discussion

We can assess the importance of the above results by considering that particle-tracking models are run over large numbers and include diffusion in particle motion (equation 1). It is expected that this diffusion will mask the pattern of particle-wall interaction. Running the particle tracking model for two days with 200 particles and $D_h=0.1 \text{ m}^2\text{s}^{-1}$, maps of particle position using 1s and 10s time steps can be visually compared (Figure 7). Maps are constructed by assigning a particle count to each grid cell containing a particle at each time step. This concept is useful for looking at the distribution of infectious particles such as sea lice, but is also useful here to represent particle dispersion. As the two simulations are run with different time steps (1s and 10s), the maps are normalized by the total number of particle counts and displayed on a logarithmic scale for clarity. It is immediately obvious that the variation in behaviour on single particle scales does not correspond to large differences in behavioural patterns for the particles. Therefore it is expected that the above discrepancy in trajectories upon wall interaction will not greatly affect the dispersion pattern of a large number of particles. However, specific implementations of particle tracking models where diffusion is low, or not present, must consider the impact of wall interactions and experimental design should be robust enough to avoid allowing this feature to influence results.

4 Summary and Conclusions

The above sections have highlighted two separate features of the particle-tracking model implemented in Loch Torridon. First, the circulation model is unable to reproduce the high surface velocities observed by drifters in some areas of the loch. For particle-tracking models of surface particles used for management purposes, this may result in an underestimate of transport and inappropriate management decisions. We feel it is essential that particle-tracking models are validated using drifter studies to ensure that the wind-driven circulation is represented appropriately.

Secondly, the different trajectories shown in Figure 4 and Figure 6 illustrate the sensitivity of a particle’s trajectory to the exact position (and time) of approach to a coastline. This is due to the highly variable nature (spatial and temporal) of the circulation within Loch Torridon. Small differences in position and time can result in very different particle velocities and final trajectories, which may be relevant for some particle-tracking applications. However, the influence of diffusion and the large number of particles tracked in most simulations is expected to dominate over the wall interactions in most instances.

To conclude, we suggest several recommendations for particle tracking models where wind driven circulation is expected to play a significant role in transport and/or for enclosed coastal areas with highly variable circulation (often tidally-driven).

1. Validation of circulation models should be done with GPS drifters in the area of concern under various environmental forcing conditions to ensure that the wind-driven circulation is appropriately represented.

2. Extra consideration should be given to wind-driven circulation when designing circulation models, including the parameterisation of the surface layers and wind forcing.

3. The interactions of particles with coastlines should be visually inspected to see if results are sensitive to both wall parameterisation and chosen coastlines.
References


