Coupling of hydrodynamic and particle models for simulating larval sea lice dispersal workshop report

Executive Summary

A MASTS supported workshop was held at the Marine Scotland Science (MSS) Marine Laboratory, Aberdeen, on best practice in modelling sea lice dispersal using coupled hydrodynamic – particle-tracking models. The workshop was attended by delegates from MSS, the Scottish Association for Marine Science, the Norwegian Institute of Marine Research and Inland Fisheries Ireland. During the workshop, models developed and run by the different institutions were discussed before reviewing the key components required for both the hydrodynamic and biological modelling with regard to simulating larval sea lice dispersal. There was agreement on the modelling approaches used and on the areas where improvement was required. Areas that could be improved are sea lice loss of infectivity, egg production, and vertical swimming behaviour, especially in the presence of strong haloclines. Generally, the approach has developed by different parties along similar lines, and the meeting participants, concluded that a standardised modelling approach could be produced. A problem remains with presenting results, and graphical methods to do this are being developed.

1. Introduction

Sea lice are considered to be the most serious pathogen limiting the potential for the expansion of Atlantic salmon aquaculture and with potential to impact on wild salmonid populations. They are therefore a priority area for research in aquaculture. Owing to their planktonic larval phase, the dispersal of sea lice through marine currents is a key issue for understanding interactions for spatial management and control of sea lice. Coupled hydrodynamic – particle-tracking models with an application to sea lice have been developed for several years in salmon farming countries and sharing of practice allows optimisation and standardisation of these models. A recent development has been the expansion of modelling to larger areas of interaction such as the Scottish Shelf Model used by Marine Scotland Science (MSS), the Scottish West Coast Model used by Scottish Association for Marine Science (SAMS), and modelling of the whole Norwegian coast to identify large scale lice management regions as well as detailed lice distribution, even weekly results in an operational procedure ("now cast"), by the Institute of Marine Research (IMR). In addition, the North Atlantic Salmon Conservation Organization (NASCO) has provided funding through the Inland Fisheries Ireland to develop a model of sea lice dispersal in Killary Harbour as an exemplar European standardisation of sea lice modelling. It therefore is a highly appropriate time to overview modelling practice for coupled hydrodynamic – particle-tracking models for larval sea lice dispersal.

A MASTS funded workshop was held at the MSS Marine Laboratory in Aberdeen on 21st – 22nd February on the use of coupled hydrodynamic – particle-tracking modelling for sea lice dispersal with the aim of identifying agreed best practice and to identify areas where more work was required. This workshop involved comparison of modelling practice by MSS, the SAMS, the IMR and the IFI. The workshop was supported by MASTS who funded attendance for one delegate from each of SAMS, IMR and IFI; IMR sent an additional four delegates.

The full list of attendees were:
MSS – Sandy Murray, Berit Rabe, Alejandro Gallego, Catherine Collins, Campbell Pert and Nabeil Salama
IMR – Lars Asplin, Bjørn Ådlandsvik, Anne D. Sandvik, Ingrid A. Johnsen, and Jofrid Skardhamar,
SAMS – Thomas Adams
IIF – Samuel Shephard

The meeting was divided into two half days with the Tuesday afternoon largely devoted to hydrodynamic and oceanographic issues while the Wednesday morning largely covered biological issues for the particle-tracking modelling.

At the opening of the meeting, presentations were given on on-going work by MSS, SAMS and IMR. These covered Loch Linnhe and the Scottish Shelf Model (MSS), Loch Fyne and the Scottish west coast model (SAMS), and an operational lice assessment for Norwegian coastal waters (IMR).

Over the following two days the delegates discussed the requirements for modelling sea lice dispersal, including those elements that are already handled well, and those that could be improved in order to identify the components required by a satisfactory sea lice dispersal model.

2. Issues and questions concerning hydrodynamic modelling

Good forcing data and boundary conditions for hydrodynamic models are essential. Data are also needed to validate the model. The different components are analysed below.

2.1. Boundary conditions and forcing

Boundary conditions in terms of currents, tides, salinity, and temperatures beyond the model domain are very important for driving models. The closer the boundary to the area of interest the more effect conditions at that boundary have on driving model behaviour within the area, therefore the less reliable the boundary data, the further out the boundary should be. A range of nested models are available that can drive conditions at the boundary, so necessity for obtaining robust data on boundary conditions can be circumvented but a longer spin-up period may be needed. Different, wider shelf models are available to provide this boundary data.

Variability of the water mass stratification resulting in internal pressure gradients can be very important for the establishment of long lasting currents (associated with the propagation of long internal waves). Climatology runs are unsatisfactory for models of internal waves that occur at a timescale of a few days, but this is not an issue for Scottish and Irish coastal waters.

If using similar forcing data but with different models, similar results will still be obtained. Therefore good forcing data are very important.

Wind forcing of surface currents is also important, particularly for issues of smaller scale importance of <50 km or so. Wind is highly variable, depending on local topography, this variability is particularly important in fjordic systems surrounded by mountains. Wind is typically available at 10 km resolutions from Met Offices, so local finer scale wind modelling may be required to obtain local winds. Coupling of wind and wave models could improve interaction of currents with wind forcing (IMR and SAMS uses a wind model for local detail). Wind can play a role in transporting sea lice but is also important for mixing of upper water layers.

Freshwater input and the establishment of brackish surface layers could be improved by better resolution of input data or hydrological models based on precipitation, runoff (SSM incorporates river runoff model, SAMS have inputs at river mouths) and/or snow melt. Precipitation may also vary locally with topography (SAMS incorporate rainfall and evaporation in every grid square). In Scotland, gauged river data is much more available for the east than the west coast. Brackish layers are important in spring, the warm season (especially spring with snow melt), and projected climate scenarios indicate more precipitation and warmer conditions (i.e. less snow accumulation). Obtaining data is expensive, and given scenario runs need specific data appropriate for the time simulated. The nature of rivers and inputs varies between countries and this may have a major impact on sea lice, for example Scottish west coast rivers are generally small, whereas some Irish rivers are very large; snow melt is far more important in Norway than in Scotland or Ireland. Also strong rainfall affects river runoff, and this is important in Norway.

2.2. Model setup

Horizontal grid structure needs to be fine enough to address dynamical length scales as the internal radius of deformation (typically ~5 km at our latitudes) and local topography, but specific grid is a matter of choice. Variable grid structure (for example in FVCOM) resolves fine coasts but costs of computer time for execution are based on smallest grid squares. Nesting of models allows computation to be reduced by using coarser models for areas of less interest. Fixed grid structure is used for example in POLCOMS.

Vertical structure is an issue of more concern that may require more work, and appropriate structure is dependent on local conditions (i.e. the stratification needs to be resolved). The upper 1-2 m of the water column is an area of high vertical variability from e.g. the logarithmic decrease of wind stress momentum or the brackish layer pychnocline, and to model these variations a relatively fine vertical grid spacing is needed (< 0.5 m). Several representations of the vertical coordinate exist, and most used are sigma levels, zeta levels or density. Sigma levels has the advantage that they move up and down with the variable surface, making it possible to maintain a high vertical resolution in the upper 1-2 m and at the same time allow for high tidal amplitudes of the sea surface. Disadvantages of the sigma coordinate are potential erroneous pressure gradients and excessive mixing in connection with steep topography. The areas in which to maintain a fine grid resolution should be the upper 10-20 m and also the bottom boundary layer. Sigma coordinate (the vertical coordinate follows the bathymetry) and Zeta models (vertical coordinate is depth) used for vertical structure. Layers of differing resolution (thickness) with thin surface layer (to resolve area where sea lice occur) and thicker deeper layers, although thin layers near bottom to allow simulation of interaction with sea bed.

If tide is the dominant dispersal force, then vertical velocity does not change much.

Internal waves (top 50 m) are important in fjords and can transport particles over 50 kilometres in a given direction, while tides move them back and forth. Such internal waves can happen several times a month, lasting for several days, followed by intervening calm periods. These are important and difficult to predict since their forcing will be variability of the coastal water masses far upstream. Internal waves are important in Norway and less important in Scotland and Ireland, where stronger tides lead to mixing and less stratified water masses, which reduce horizontal differences into the fjords/lochs and prevent internal waves forming.

Salinity is important for the density structure of models and has a large effect on sea lice survival. Salinity is driven by freshwater inputs and mixing with seawater. Future sea lice modelling might use the hydrodynamic model output of salinity fields to explicitly simulate effect on sea lice survival or avoidance behaviour (vertical migration/positioning), but this is not done as yet, partly because biological models tend to use a single fixed mortality rate. It is only worth outputting salinity if this is both accurately simulated, output at an appropriate resolution, and its biological effects are modelled in more detail, including effects on lice behaviour. When investigating sea lice behaviour, it is important to evaluate the difference in salinity compared to the absolute value.

Temperature outputs similarly have major impacts on lice growth, vertical swimming behaviour and are important for hydrodynamic model validation. The tendency for models to use a single parameter value for maturation time for any single scenario appropriate for the typical temperature experienced by lice of that scenario means that explicit temperature outputs are not needed, and again this might change with future modelling.

Hydrodynamic model outputs are typically no coarser than hourly outputs, because of the need to resolve tidal currents. Models may use long-term residual averages plus tides, but still need to resolve the tides. Finer time scale can be used but there is a computational cost. Compression of data is used to reduce storage requirements, but compression itself takes time and also increases the time required to read the data when it is used. As well as current velocities, model outputs include turbulent diffusion, both horizontal and vertical (random walk). The response from sea lice to turbulence is not clear.

2.3. Validation of hydrodynamic models

Validation of models will be important to illustrate how well the results reproduce the observations, thus giving credibility to the results as well as an indication of their accuracy. It should be mentioned that neither model results nor (usually) a sparse number of observations will describe the natural system fully. However, the combination of model results and a few observations will increase the validity of both. Also, it should be mentioned that numerical models will not typically use observations as forcing or calibration, and if this is done anyway (e.g. in a data assimilation scheme) the observations used for input to the model should not be used for a later validation.

There are different opinions as to what data are best to validate hydrodynamic models. Current data are thought to be important. However, validating currents can be quite difficult and it is easier to collect and look at temperature and salinity data and on water elevation.

Hydrodynamic models need to be validated before they can get coupled to the particle-tracking model. There are different opinions as to what data are best to validate hydrodynamic models but in general as much data as possible is best. Current data are thought to be important. However, validating currents can be quite difficult and it is easier to collect and look at temperature and salinity data.

Data for modal validation are expensive, for example current meters cost about £25,000 and at least 2-3 current meters need to be deployed year-round to better understand a system's behaviour.

Drifter buoys are useful for understanding currents in inshore areas over short-term periods of 5-10 hours. There are some problems with these types of drifters, such as a tendency to exhaust batteries quickly or become beached. Drift can be very variable even for buoys released at very similar locations, and to obtain robust data then large numbers of releases are needed. Drifters give an illustration of real system variability and this is an issue given limits of 2-D resolution of models.

Old-fashioned tide gauges give a lot of information very cheaply and have been available for long time periods. Although representing a single location, the tidal height integrates effects of currents over a substantial area. Modern water level recorder data can also be useful.

There is also a need for more gauged river flows for freshwater inputs and more spatially detailed recording of precipitation, particularly in Norway with its very complex topography leading to very localised rainfall patterns.

Data on turbulence is important for assessing particle dispersal both horizontally and vertically, although swimming lice may counteract the latter.

In future, drones may be useful for measuring surface currents. This is also the case for temperature where Infrared sensors are useful. Satellites and aircraft also useful for IR data and ocean colour data, particularly in good weather. Surface radar can give detailed information on surface currents, but is expensive to install. Tomography gives data on deeper currents at the large scale but requires stable temperature to calculate the speed of sound.

Big data means that if large amounts of data are available, then precision is less important as errors cancel out. For example, 100s of fish farms recording temperature at 10 minute intervals at three fixed depths in Norway is a source of much data. Similarly, in Scotland, SEPA requires current velocities, and other environmental data are collected as part of the licencing process. Also, in coastal waters relatively large changes in temperature and salinity can occur, these differences can be detected by less precise instruments and these will be cheaper than highly precise instruments. Identifying and investigating sources of low quality but high quantity data could be beneficial.

Because hydrodynamic models are used so widely, and are based on well understood physical laws, there can be a reasonable confidence in the behaviour of un-validated hydrodynamic models for general properties of a system. However, validation is required for confirming behaviour in specific cases or for specific periods.

2.4. Validation of sea lice particle tracking model.

Sentinel cages integrate data over time as opposed to short term plankton tows, in obtaining correlations between empirical field data and model predictions. Collecting both may be useful as potentially possible to investigate relationships between numbers in plankton and numbers settling on fish.

Wild sea trout have been used in Norway to validate models. The same trends are observed as with sentinel cages. There will be uncertainty as to where the trout actually have been and collected lice. Typically these tend not to swim very far from their home river (< 5 km) and also to feed in the littoral, but more precise data are needed.

Migrating smolts are trawled in the mouth regions of Norwegian fjords and the abundance of lice is assessed. This will be used to quantify the infestation rates calculated with virtual population model analyses.

3. Biology of sea lice particles

Sea lice in the models are represented as particles that are moved by the simulated currents output from the hydrodynamic model. These particles have properties and exhibit behaviours that also influence how far they are transported as infectious larvae, and hence where risks exist.

3.1. Sea lice production, maturation and survival

Sea lice mature through non-infectious nauplii to infectious copepodids. This process is temperature sensitive, with a time linearly related to degree days, but deviating at low temperature. Much published data is available on this, but these data are based on lab experiments and there is a possible question as to whether there are any differences to this in the field. Generally, model scenarios are run with a single value for maturation time based on average temperature at the time of year. It is better to use instantaneous model temperature and calculate the degree day (age) for each lice particle. There may be inaccuracy in detailed temperature fields generated from hydrodynamic models (for example SSM, possibly due to fixed river temperatures), so local temperature at a specific location of the model is not used to drive this. Therefore, despite the question of application of lab data in the field, there is strong agreement on this effect and no more detailed modelling is required, unless detailed local temperature fields are simulated. SAMS is investigating temperature data for freshwater input so modelled temperature fields can be improved.

Sea lice survival and infectivity is a bit more complicated in its interaction with the environment, being dependent on both temperature and salinity. Lab effects are likely to be more serious at introducing error in estimation of field rates in that mortality might be accelerated by stress to the larval lice. Within these caveats, there are good published data on survival.

Some consideration should be given on the ability of sea lice larvae to adapt and survive in relation to salinity, dependent on the salinity in which eggs developed and hatched.

Survival is further complicated by changes to infectivity of lice that remain alive but have reduced ability to infect hosts with age. Infectivity may be particularly reduced at low temperatures <5˚c and at low salinity. Current velocities and turbulence may also affect infectivity, which also relates to host swimming speed. Experimental flow tanks consisting of a circular ‘doughnut’ shaped tank set up for lice at Aberdeen University and MSS Aultbea 2001 - 2005 – host interaction experiments may have exaggerated infectivity by giving multiple opportunities for infection to occur.

Despite all these potential complexities, a fixed mortality rate of 1% h^{-1} or 17% d^{-1} has been adopted widely and is considered appropriate, unless salinity is reduced (for example in the Norwegian model sea lice have the ability to escape freshwater

by sinking to more dense deeper layers). This parameter covers both actual mortality and reduced infectiousness.
Grazing by animals such as zooplankton and mussels can affect larval lice survival. However, there is no reason to believe that such grazers are concentrating on larval lice, since their numbers are low relative to other similar larvae, but this could lead to random changes in survival if zooplankton blooms occur, and if the presence of grazers is not equally distributed in space and time. One possible effect noted is that lumpfish eat gelatinous zooplankton, and also graze on larval lice, leading to a possible negative effect on lice control.

Egg production and survival is increasingly required to drive sea lice population models. There are data available, but there is a need for a standard model. Most eggs (94.8%) do survive, so production and hatching should be similar, except under stress such as low salinity. Age of females is important, with the first clutch being smallest. Also, lice on wild fish can produce far more eggs, ~1000, while those on farms produce about 300-350. There is also a seasonal effect with high egg production, low survival in winter and the opposite in summer.

Self-infection of farms considered relative to infection from neighbours produces a network of connectivity. Source and sink sites can be identified. With population models, this can be used to assess strategic treatment regime's and the impact of opening or closing specific sites on the larger scale population of sea lice. Simulation will require developments in lice population models and their linkage to networks generated from the hydrodynamic – particle-tracking connection matrices. The use of multiple independent models can increase confidence and give the results more security, and similarities in conclusions between climatological Scottish Shelf Model and specific scenario driven West Coast model results are a case in point.

Data for such infestation population models are available in Norway from individual farms available frequently. This could be improved, as counting is based on only 20 fish, and on adult female lice, and some subjectivity is possible. In Scotland only monthly average counts are available as averages for large reporting areas. The role of wild fish as a source of lice is not well assessed, and may be particularly important in areas with relatively few farms or after area fallowing. Possible future recording of lice counts using cameras and connecting with an Internet of Things approach, the technology exists because of laser lice control technology.

3.2. Sea lice behaviour

Unlike viruses or bacteria, larval sea lice are capable of swimming, allowing them to maintain depth to select appropriate currents and depths and locations at which hosts may be encountered. Swimming may be relevant both strategically to obtain the correct depth, and tactically, allowing larval lice to swim to hosts in a burst.

One issue with sea lice particles is their behaviour at the coastal boundary where current velocity may appear to drive particles across the boundary. In this case they may stick or bounce or move along the boundary while ceasing motion that would take them across the boundary. Some models take particles no further when they "stick" to the boundary; some allow them to be moved horizontally, but not vertically.

The end result of both approaches is an aggregation of sea lice along the shore. The collection of particles along borders can depend on the vertical structure of the model. If only the upper layers are used, particles will collect at the border, but less so if other vertical distributions used. Transport issues at the coastal boundary depend on time step, and vector velocity, and there are no obvious changes required.

Sea lice have the ability to maintain their position vertically. The simplest approach to modelling this is to maintain the lice particles in the surface layer and only move them in 2D. Passive particles mix with vertical water movements and so moved in 3D, but sea lice are not passive. More complex models may include explicit simulation of vertical movement, which may be either a constant attempt to maintain a particular depth (which may be determined by avoiding low salinity or to select an optimum temperature) or diurnal migration modelling. A speed of 0.5 mm/s is used in Norwegian models. This vertical swimming velocity allows larval lice to overcome most downwelling currents, but not all. Nauplii tend to be weaker swimmers while copepodid more actively seek locations near the surface.

Lice may avoid low-salinity surface waters, in which they have high mortality rates. Larvae concentrate below haloclines. Strong haloclines are more a feature of Norwegian than Scottish or Irish waters, but there is a need for greater understanding of the response of sea lice to salinity (changes or absolute levels) so that this can be appropriately modelled. Since currents vary with depths, it is important to get the vertical position of sea lice larvae right. Internal waves create vertical mixing so it is necessary to know the vertical distribution of sea lice larvae to investigate the effects of internal waves.

Techniques such as skirts or snorkels that protect farmed salmon from exposure to surface layers of the water are effective at preventing infection precisely because lice maintain themselves in these surface layers. There may be a possibility of selecting for lazy lice that do not swim as has occurred for treatment resistance and early maturation.

Short-term swimming in bursts of about 5 cm are important for host location. Lice appear able to do this repeatedly without tiring. If lice and hosts accumulate in fronts and at downwelling locations along coasts, then close proximity can potentially greatly increase infection pressure relative to apparent pressure given the volume of the sea.

It should be remembered that nauplii and copepodids behave differently.

It was strongly suggested that studies to provide data on sea lice behaviour for dispersal modelling should be influenced by modellers. Possible experimental studies could include mesocosms in the natural environment for example to investigate vertical position of sea lice, freshwater avoidance, etc.

4. Graphical outputs from models

The coupled hydrodynamic – particle-tracking models create very large amounts of quite complex data. This requires graphical outputs that allow the data to be visualised in a meaningful way.

One of the simplest ways is contour maps of sea lice particle concentrations; these have been used since this type of modelling was first used. The scale may be linear or logarithmic and maps show variability of concentrations

However, particles may move around and high concentrations, accumulate and disperse or move with fronts. This means that zones with high concentration may be missed with contour maps. Video presentations of moving concentrations can help, but present difficulties for interpretation.

Connectivity between farms and their relative significance as source and sinks can be described using network diagrams. There is work that can be taken from other areas such as indices of connectivity between marine protected areas based on graph theory (Andrello *et al*. 2013 PLOS one journal.pone.0068564).

In Norway, the development of traffic light systems provides a simple means of visualising impacts of sea lice than can easily be understood. However, these apparently simple maps actually require very large quantities of data or different types and the methods of integrating these into a risk score is the problem to ensure the output means what it appears to mean. Expert groups work inter-institutionally in 13 regional areas that cover the entire Norwegian coast. Dispersion models are recognised as a key source of information for assessing risk.

The stakeholder's requirements should drive the need for appropriate graphs and outputs.

5. Conclusions

The workshop has reviewed key features of coupled hydrodynamic-particle models and found a general agreement on approaches. Certain areas were identified as needing better data or models including decay of infectivity (as opposed to mortality), egg production and vertical swimming behaviour, particularly in the presence of haloclines.

The capacity exists to create a standardised manual on the state of the art for best practice modelling sea lice dispersal. This output would include international recommendations and act as a seal of approval. We would suggest that this be undertaken by an expert working group, possibly under to umbrella of the recently reformed ICES aquaculture group, bringing in expertise and experience from North America and ideally Chile.

Collaboration involving MSS, IMR and IFI through NASCO funding is about to begin on a project focusing on Killary Harbour as a case study and this creates potential for working on best practice.