Appendix 9.3

Fish Turbine Encounter Modelling

Swansea Tidal Lagoon

ELAM[1] Fish Turbine Encounter Modelling

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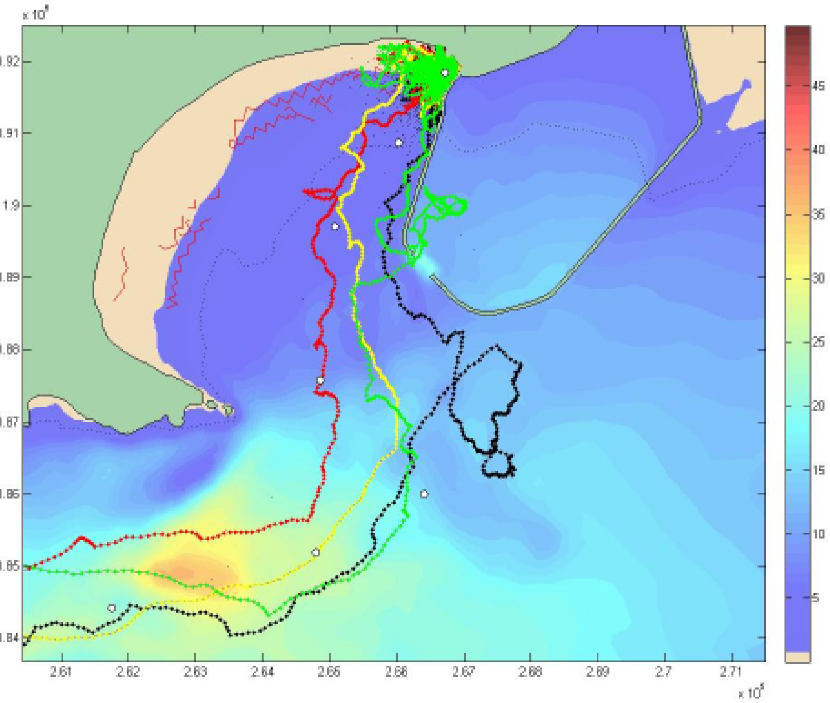

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[1] Eularian Lagrangian Agent Method

Swansea Tidal Lagoon: ELAM Fish Turbine Encounter Modelling

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Swansea Tidal Lagoon: ELAM Fish Turbine Encounter Modelling

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1.0 Introduction

1.0.0.1 Individual Based Models (IBM) predict the impact of changes to the environment of a population of animals where extrapolation using existing population data may be unreliable or not possible. IBM's focus on the individual animal, where we can be relatively certain about motivations, sensitivity to stimulus, cognitive capability and therefore behaviour. The models require parameters and rules. Parameters are fixed values or capabilities of a single animal such as swimming speed, and rules are a definition of behaviour, such as 'swim North', or avoid shallow water. The intention with these models is to use the minimum plausible model which reflects the real system that is being modelled. All superfluous elaboration of parameters and rules is to be strongly avoided, which makes interpretation more tractable. Plausibility is a subjective concept when the full capability of animals is unknown and it emphasises that these models are tools to inform and shape expert opinion. Essentially these models accurately show the implications of expert opinion about a very limited set of parameters and rules, they are not an attempt to model the full richness of an animal or its habitat.

1.0.0.2 The underlying basis for these individual based models is natural selection, and the concept that each animal is motivated to maximise individual lifetime reproductive success. If these models are used to model a small section of an animal life history such as part of a migration for salmon for instance, the overall evolutionary goal can be proxied by survival or quickness of migration. It has been shown explicitly that time taken for migration is the strongest determinant of survival for juvenile salmon for instance. Therefore if there is any requirement to choose a most likely motivation for a model fish at any point this must be done in the context of evolution by natural selection and the likelihood that it will act to maximise its lifetime reproductive success. This may seem obvious, but for the social insects for instance it is far from simple, and similar models have been used with great success for ants for instance.

1.0.0.3 There is a rich scientific history of using individual based models coincident with the advent of computers. In marine science in particular they have been used to focus on the complex problem of recruitment to fisheries from larvae which are often at the mercy of ocean currents for long periods (Willis, 2011). IBMs have been used to model birds in flocks, and fish schools, as well as bacteria, moulds, ants, bees and practically every family of animal including humans. Human response to traffic situations and evacuation response from rooms and buildings have long been studied using individual based models.

1.1 Basic definition and movement of fish objects

1.1.0.1 In programming language all objects in a program have attributes and methods. Attributes are information stored by the object that indicate its state as the program progresses, and methods define all the things that can happen to an object (which change its state). No other information is needed to define an object. The fish model is based on a (Lagrangian) drifting particle in a (Eulerian) hydrodynamic model which has added movement based on powered swimming. So the fish object is pushed around by the water currents just like a neutrally buoyant particle of sediment with the addition of a vector for powered swimming (Fig. 1).

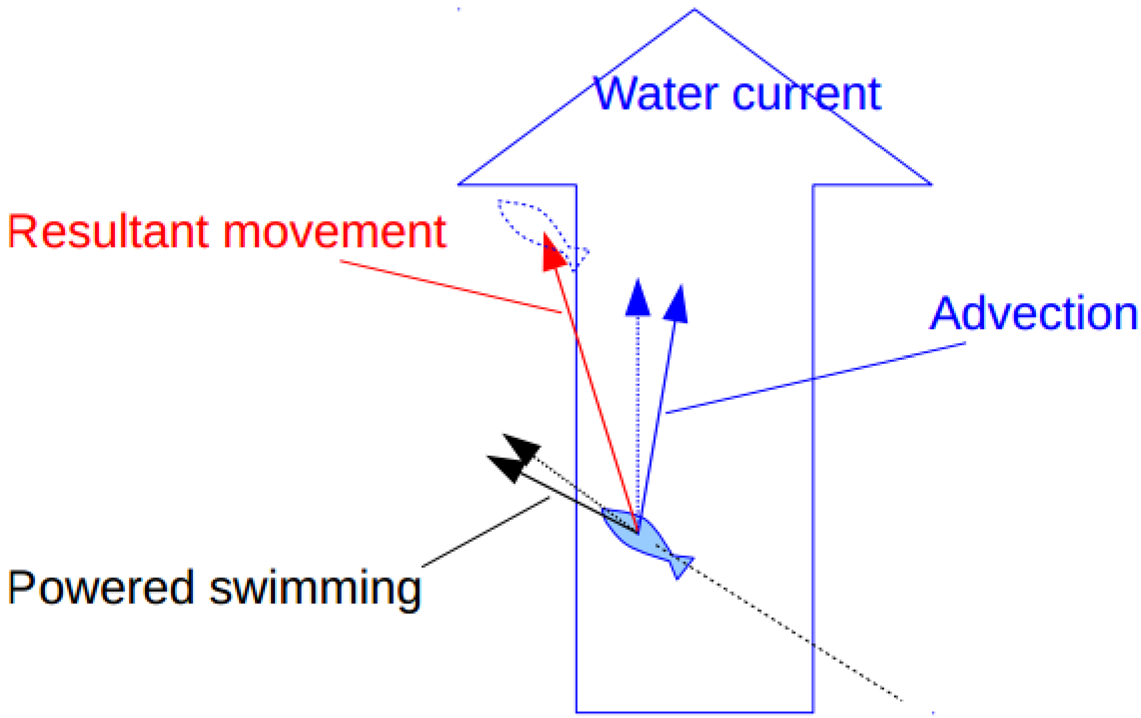

Figure 1. Vector addition to calculate position of fish after one time step. The velocity of the water current (blue) is added to the fish swimming velocity (black). Both have random normally distributed error added (shown by alteration to the 'pure' directions shown by dotted arrows). The error in current is added to indicate turbulence below the spatial resolution of the water model (coefficient of dispersion) and the error in swimming to indicate steadfastness (aka. determination or ability to stay on existing direction).

1.1.0.2 In order to move, at each time step, the fish object needs to know the water current at its location, which includes the magnitude of the current and the direction – these are measured as u and v values (m/s) interpolated in space and time from the hydrodynamic model. The fish object also needs to know its swimming speed and swimming direction and how much error needs to be added – its steadfastness.

1.1.0.3 In summary these are all the pieces of information stored with a fish that relate to its movement:

i. swimming speed, (m/s)
ii. swimming direction, (radians)
iii. steadfastness. (error term – standard deviation in radians)

1.1.0.4 No other information exists in the model that results in the movement of a fish in the normal circumstances of it swimming in water (i.e. when it jumps into an illegal position some other movements are sometimes incorporated to put it back into a legal position). In addition to the above, the fish object stores its position in coordinates (x,y), and that, in combination with the above, is all the basic information that is stored with the fish object. That is, a fish is defined by these parameters, in programming language these are all its attributes.

2.0 Uncertainty and parameterisation

2.0.0.1 The aim of the individual based model is to make a prediction about the probability of an event or a condition. Thus there is a target within the model. The targets of marine based models are very often about locations, for instance, how long it take eels, spawned in the Sargasso Sea, to reach the rivers of Southern Europe. The target provides the mechanism to report a result with formal scientific uncertainty; that is, as a probability with confidence intervals. The target therefore should be selected carefully to balance the functionality of the model and the information on which it is based. In the case of Swansea Tidal Lagoon the target was mortality which related to the likely passage of fish through turbines and sluices. A great benefit of IBM's is that they suggest new possibilities for actual situations, for instance that fish would be aggregated in some area by the tides which was hitherto unknown. These suggestions lead to excellent targets for new designed experiments or targeted observations with the real animals in the real environment. It is one of the great strengths of IBMs that they provide these potential insights, but it is important to recognise that, when used in this way, they are theoretical models in ecology, and their place in the scientific method is before new experiments as part of hypothesis creation. This is distinct from predictive ecosystem models which are designed to use best available scientific evidence to inform a management decision. In this case these models are being used to support the latter function when used in combination with expert opinion.

2.0.0.2 In order to use an IBM to make a prediction about a population statistic, and report the result, it is necessary to have enough individuals in the model to represent the population. There is no absolute best value for this number but it depends on the target statistic, and generally more is better than less. In the early days of this type of modelling, before the wide availability of fast desktop machines, and software, the number was usually 500, nowadays we regularly use 10,000 and often 100,000 individuals in a model, and it is not rare to see several millions. In the models used for Swansea Tidal Lagoon assessment models were used that contained 10,000 individual model fish, which is perhaps more than the abundance of some of the modelled populations (Tawe salmon for instance). From a statistical perspective this is not important as it is assumed that the real population (or at least those which have been 'sampled' or measured and are therefore known about) are part of an imaginary very large population which also is represented by the model fish.

2.0.0.3 In a real population there is always some variance among the individuals for any attribute that could be modelled – this is a consequence and a condition of evolution by natural selection. Take a population of salmon smolt, and consider an attribute such as swimming speed. Swimming speed is positively correlated to length for most fish and the population will have a variation of individual sizes and thus swimming speed. The whole population might swim faster in higher temperatures (up to a thermal limit) so the mean speed may vary, or some fish may have eaten better in their younger life and be faster than average, or some may have hatched earlier, and swam from further up the river and so be faster and larger when reaching the sea. So each river may have a population which varies differently. One would assume a longer river would have more variation in swimming speeds of its smolt, as they would have hatched over a wider range of distances to the sea, or a river with a steeper gradient may have higher variation than one with a shallower gradient because of the higher variation in temperature exposure for different smolt hatched at different temperatures, and so forth. So each river will have a population which varies in their swim speed attribute in a way that is typical for that river, but which will also vary year on year, depending on wider environmental cycles. The same will be true of any other modelled attribute. In statistical terms each of these attributes are often called a dimension (Fig. 2). The knowledge base for salmon and trout is extensive and can be used to model the full range of a dimension like swimming speed.

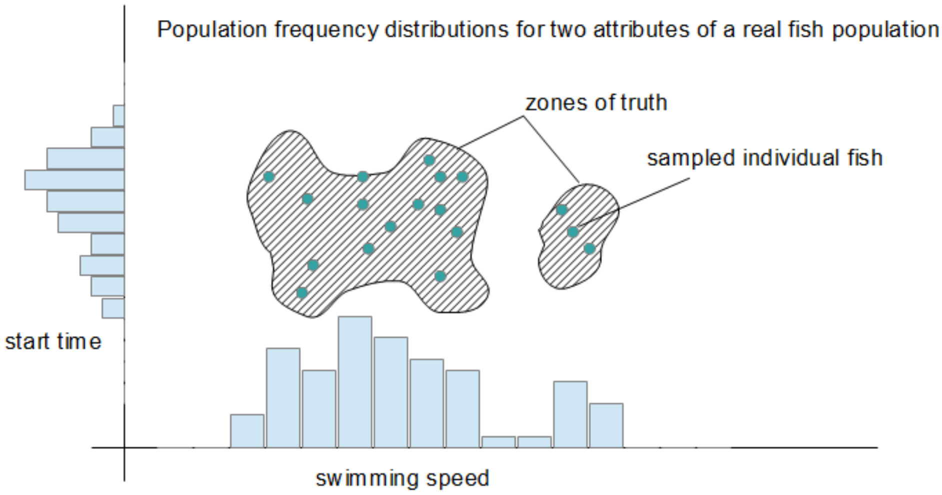

Figure 2. Two attributes of a real fish population for a migratory phase of their life. Start time could be when they leave the river mouth for instance, and swim speed will be different for each fish. If the fish form schools, many individuals will have synchronised times, and often similar swim speeds. In these cases the models represent the smallest school unit (the atomic unit).

2.0.0.4 One key advantage of IBM models is that they attempt to directly sample across this population variation, where models based purely on mathematical equations can become impossibly complicated. So each modelled attribute is modelled by a probability density function and the attributes of each individual fish in the model is drawn from these distributions (fig. 2). In fact, mathematical constructions such as this are now routinely solved using sampling from probability distributions and sequential 'pathways' such as Markov chains so the distinction between an IBM and a mathematical description is often purely one of presentation and interpretation.

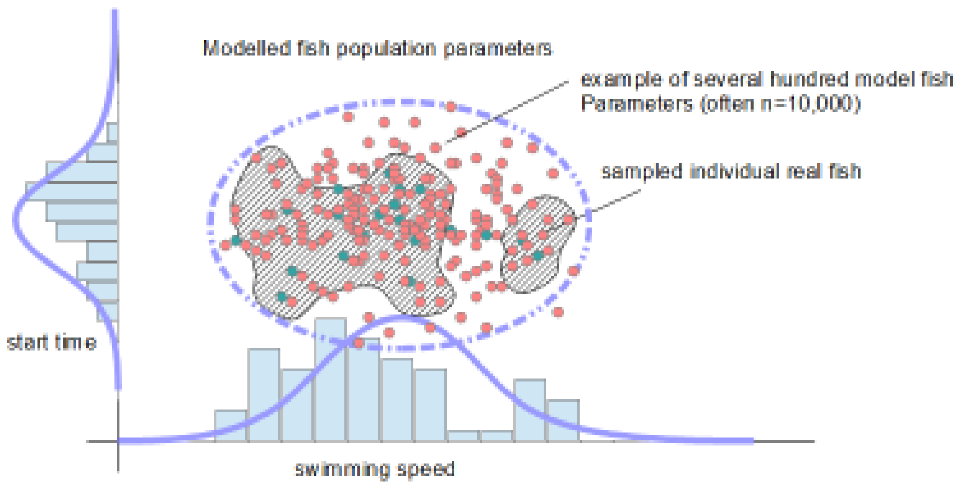

Figure 3. Model fish (red dots) have attributes in the model which are drawn from the probability estimates derived from the samples of the real population. Usually (because the normal distribution is infinite) the range of the model fish will be larger than the real samples (because there are usually a smaller number of them), there are usually 1000's of model fish and 10's or hundreds of real samples. If attributes are correlated, then the model samples cover a wider range still (which is not a disadvantage necessarily), if the pairs of attributes are very well correlated it is questionable if both need to be used in the model independently, and the correlation should be explicitly modelled.

3.0 Calibration

3.0.0.1 Calibration of Individual Based Models (IBMs) is complex because these models are explicitly aimed at causes, rather than at correlations, and the assumption that correlations are caused by something which can be modelled (correlations may not have a cause, and they may have ones which are very complicated, including thresholds, reversals, and so forth and it for this reason that they make very poor predictors outside the range of known data, although this is often ignored as they are routinely used to extrapolate). IBMs are also modelling living systems which are unimaginably complex and unknown to a substantial degree.

3.0.0.2 In models of physics the fundamental laws are assumed to provide the cause, and calibration can be accurate against a model that is so well believed as to be called a law. However, in IBMs calibration means ensuring that the model captures the full range of the known parameters of the population and that simultaneously it is not falsified by any known facts. The intention is to err on the side of uncertainty and to model a situation which is highly likely to contain the true situation. Practically this means defining the envelope of the modelled parameters to enclose the true situation (Fig. 3) and subsequently to check if the model is particularly sensitive to these boundaries. Because if the model is very sensitive to the boundaries it is a signal that the choice of boundary is too much of a determinant of the result, and therefore that the result is unreliable because it is dependent on what is a subjective choice. A stronger model would show insensitivity to the choice of boundaries, and so in this case it is usual to extend the boundaries outward to a point that the model is insensitive to minor alterations, in this way the model now envelopes the area of former uncertainty around the tighter boundaries. Which means the model can be used to explicitly forecast what is likely to happen around the point of sensitivity – which is useful and interesting. So for example, take a model of a swimming trout which is 0.42 m long. It cannot sustain a swimming speed (v) of 100 km/h ($v < 28$ m/s), and we are equally sure that it swims ($v > 0$). While it may seem ludicrous to assume the former, it is equally ludicrous to assume the latter, and yet many models have been built around estimating the interaction between even large mammals (which may indeed reach speeds in the range of 20 m/s) and built structures under that assumption. The process of calibration is thus one of choosing a range of parameters that encompass all known real data, and testing the sensitivity of those choices. The other equally important part of calibration is the iterative process of ensuring the models reflect expert opinion, and this is a process of looking at the patterns formed in the model and deciding if they correspond with what is known of the actual species in the actual environment.

3.1 Model focus and null models

3.1.0.1 In consideration of the target of the model and in order to reduce the computational effort to manageable levels it is necessary to look to sections of the model space that can be ignored or simplified. In terms of the Swansea Lagoon the impact analysis is focused on the worst cases. So for instance, in all cases, impact was greatest when fish were released during spring tides. Releases were tested for neap tides and in between, but when it had been established that in no cases were these releases more impactful, they were ignored. This type of bounding of the problem is very important, because the point of calibration is to bring the envelopes around the parameters to the most relevant extents only. For instance to add elements into the model where there is no possibility of impact would serve to dilute the information in the model and reduce the probability of the result.

4.0 Calibration examples

4.0.0.1 Here follows the example of calibration of several species for adult and juvenile stages. Calibration is a two stage process, 1) the literature is studied for examples of fish swimming in as natural setting as possible, and 2) expert opinion is solicited to focus the model on the critical life history events that are likely to be most impacted by the structure. Once the baseline model is calibrated in this way it is checked to ensure that it is not falsified by any known field data, and that it represents a plausible pattern of behaviour.

4.1 Calibration example salmon smolt

4.1.0.1 **Behaviour description:** smolt leave natal rivers and swim continuously toward the ocean when in the thalweg, or in a direction midway between the thalweg of the main estuary and the ocean when entering the main estuary. Smolt have been shown to orientate (stay on a bearing) using the main magnetic field of the Earth and are assumed to navigate (choose a bearing) using olfaction and sensitivity to currents (rheotaxis). Smolt change depth in the upper several metres of water, but do not get close to the bed or banks intentionally, so are advected by the depth averaged currents throughout their estuarine travel. They do not use selective tidal stream transport.

Key reference for species (Moore et al. 1998).

4.1.0.2 Key reference because, similar species, nearby (200 km), similar transition between river and estuarine, specific ground speed range quoted, specific length distribution of 30 fish quoted, diagram of example track published.

Basic model parameters

4.1.0.3 Number of fish objects: 10,000 for each run
Lagrangian model time step: 60 seconds
Eulerian model time step: 15 minutes (results files of hydrodynamic model)
Model run time: 48 hours for smolt models – folded water model has no limit
Model spatial resolution: double precision (16 decimal places of a metre)

4.1.1 Smolt. Model parameterisation and calibration

Key parameter: swim speed

4.1.1.1 Figure from Moore et al. 1998 shows the track of an individual smolt. The mean ground speed is quoted in the paper, the lengths of fish in study are given, we combine these with data from a well resolved hydrodynamic model of Southampton Water to give mean ebb tidal current, and subtract from ground speed to get swim speed.

i. from Moore 1998 - mean length of 30 fish = 164.5×10^{-3} m
ii. from model of Solent - mean water flow at fish = 0.15 m s^{-1}
iii. from Moore 1998 - mean ground speed of fish on ebb = 0.35 m s^{-1}

4.1.1.2 Therefore mean swim speed is calculated as follows:

$$0.35 - 0.15 = 0.2\, m\, s^{-1}$$

$$\frac{0.2\, \not{m}\, s^{-1}}{0.1645\, \not{m}} = 1.22\, s^{-1}$$

$$= 1.22\, body\ lengths\ (bl)\ s^{-1}$$

Modelled swim speed

4.1.1.3 Swim speed. 1.22 bl s^{-1}
Fish length: 0.15 m

4.1.1.4 Moore 1998 was used to estimate the swim speed of smolt in body lengths per second. Moore et al. 1998 was used to estimate the variance in size of a group of smolt. This leads to a speed frequency distribution in the model between 0.1218 m s^{-1} and 0.2382 m s^{-1}. Others suggest the swimming speed is higher, around 2 body lengths per second (Hansen and Quinn, 1998), but these estimates have been made without newer tag based tracks.

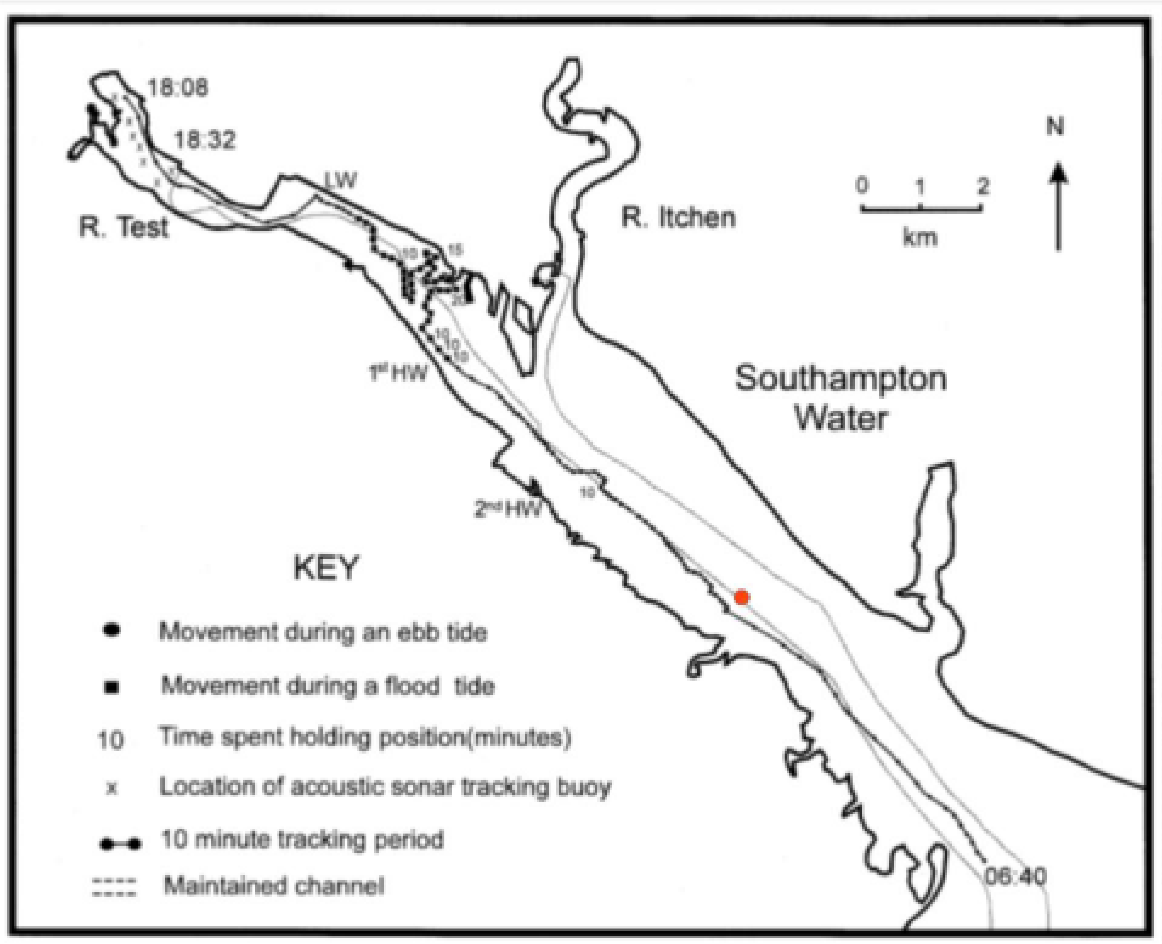

Figure 4 reproduced from Moore et al 1998, shows the acoustic tag track of a salmon smolt leaving the river Test. Hydrodynamic model used to provide tidal velocity at red dot.

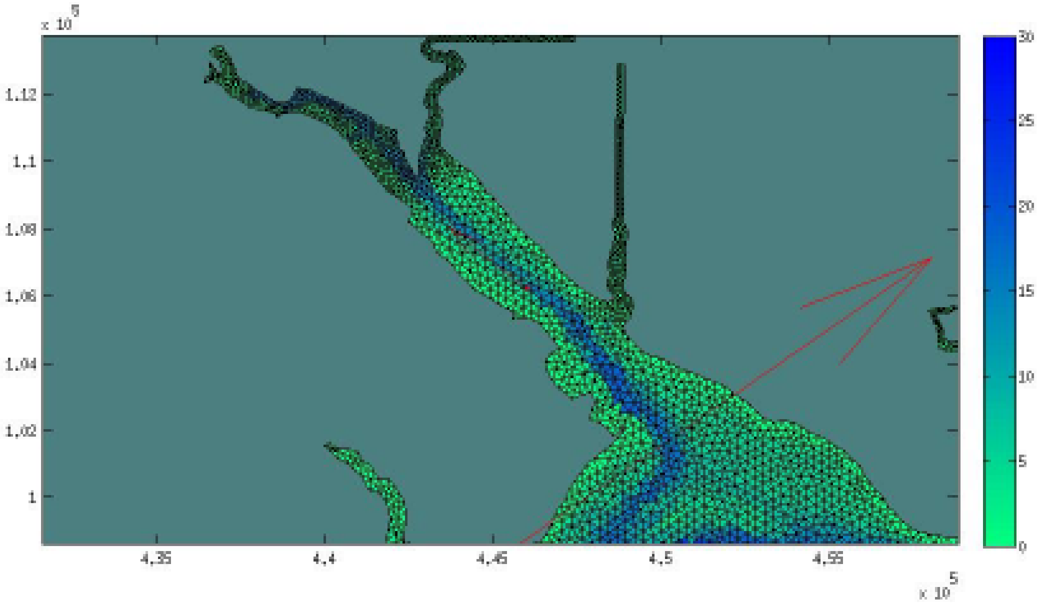

Figure 5. Hydrodynamic model detail for tidal flow data.

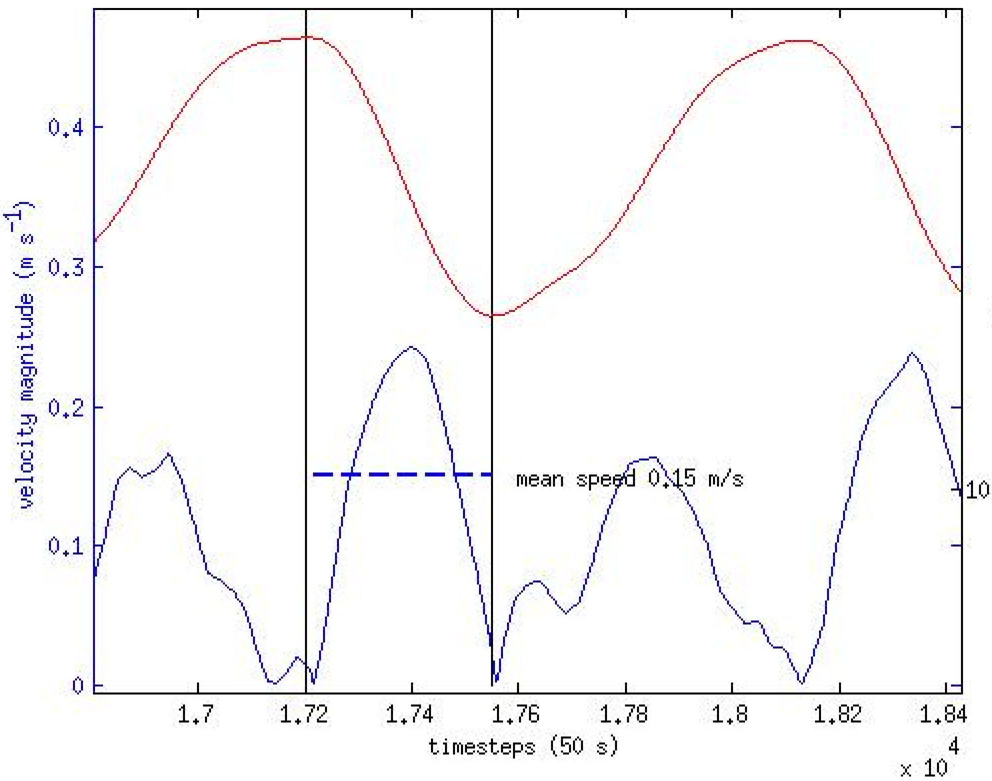

Figure 6. Modelled flow of tide in Southampton Water near to smolt track recorded in Figure 1. Mean speed of ebb tide calculated for neap tide as shown.

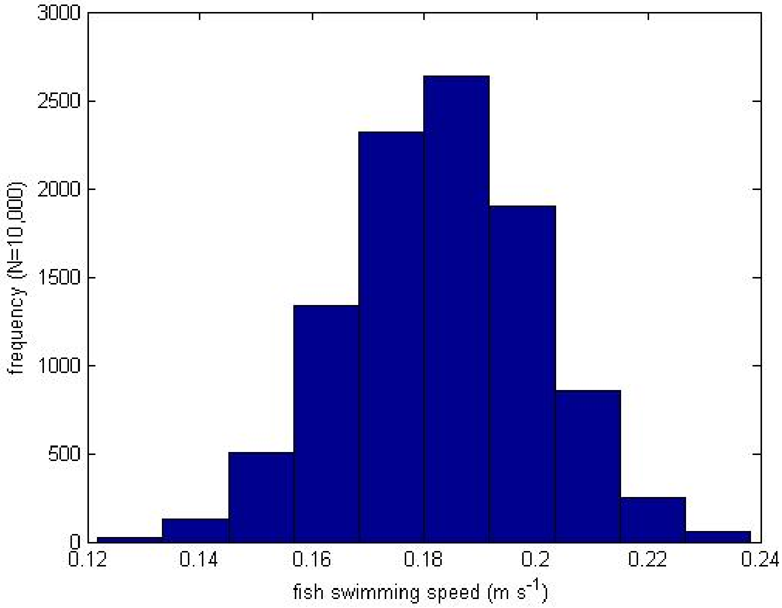

Figure 7. Smolt individual swim speed variation in the model for 10,000 model smolt.

4.1.2 Navigation parameters

4.1.2.1 **Navigational accuracy:** 3 km. This is the limit of influence of the navigational track points – when the fish is closer than this to a navigational waypoint it can no longer 'see' it and is orientated to the next on the path. This value is arbitrary and the model is insensitive to this parameter.

4.1.2.2 **Frequency of navigational information**: 4 minutes (the time between accurate bearing information – the model is insensitive to this parameter but it relates to land avoidance and general sinuosity of track – see Willis, 2011)

4.1.2.3 **Directedness:** 0.1 (x pi) – detail regarding the correlated random walk. Model is insensitive to this parameter, and it relates to land avoidance and sinuosity.

4.1.3 Initialisation times, variance and tidal state

4.1.3.1 A key variable is the time of release. The particles were randomly assigned a start time step in an 8 hour window around high tide, using a uniform random distribution. Various start times were tested across the full range of the spring/neap tidal cycle.

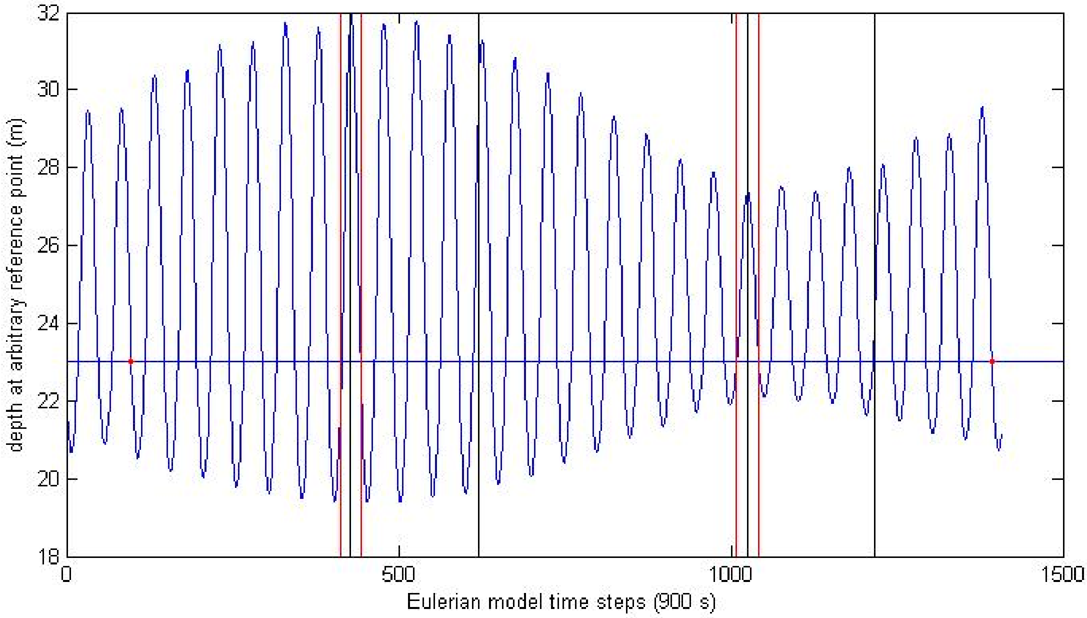

Figure 8. Blue line shows the depth at an arbitrary reference point and highlights the full tidal cycle between spring and neap tides. The red dots show the points at which this model is folded round to run continuously should that be required. The black vertical lines indicate the top of a spring and a neap tide and the red lines indicate an 8 hour window around those times. The smolt were released in a uniformly randomly distributed sequence through these windows. The run times of 48 hours are indicated by the black vertical lines after the red/black groups.

4.1.4 Calibration of swimming speed and navigational parameters

4.1.4.1 The swim speed and other parameters have been directly calculated from Moore et al. 1998 and visual inspection of video and diagrammatic information is used to confirm that the recorded tracks of smolt in the model are similar to those in the literature. Features of the tag tracks are faithfully reproduced in the individual based model, such as general sinuosity and variance in ground step length. There is increased sinuosity, and reduced ground step length in ebb tide, and some navigational variation around intersections with coastline and islands. There are no implausible activities such as beaching and getting caught in complex spaces – all fish leave the immediate area of the lagoon and those which pass into the lagoon all pass out within one or two tidal cycles.

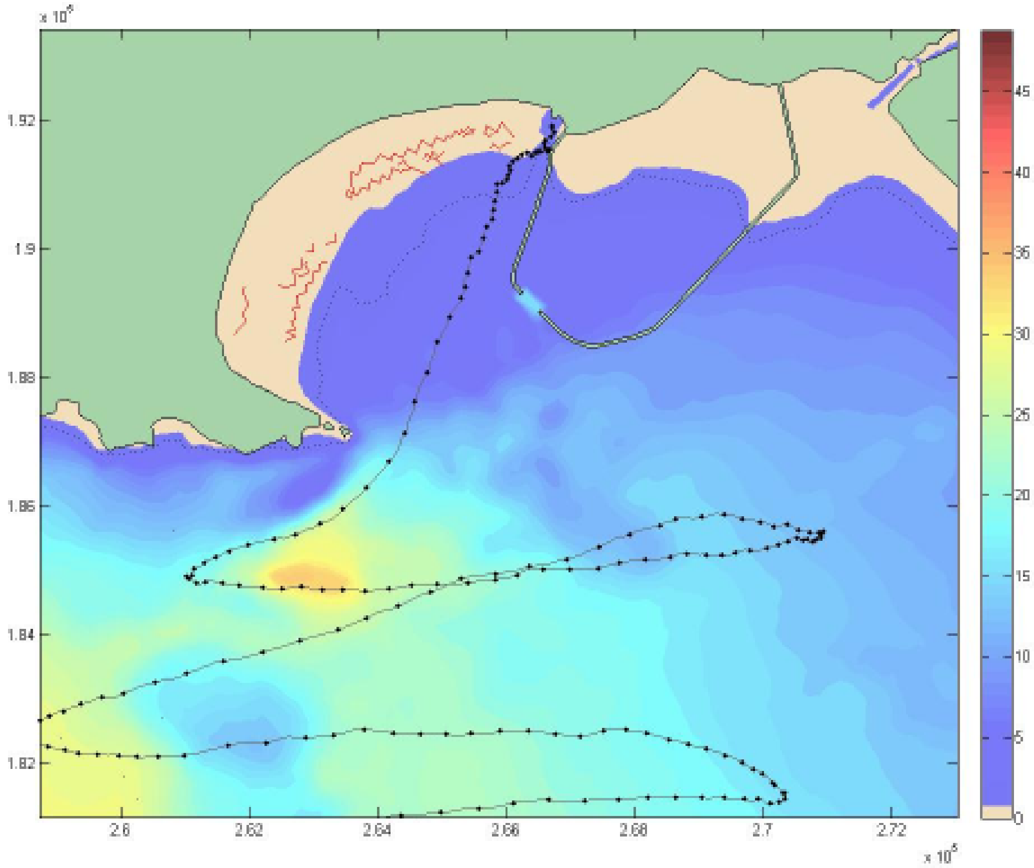

Figure 9. Arbitrarily chosen track of a single salmon smolt, from a model run of 10,000, moving out from the Aber Tawe. Tick marks on the axes are 2 km apart and the general shape of the track matches those recorded in the literature very well. Tracks have been marked with dots at 10 minute intervals to match Fig 1 from Moore et al. 1998. Similar patterns of increased sinuosity and lack of movement at flood tide and gradual stretching out of a straightened track over the ebb tide are evident. Bathymetry is shown at medium to low tide and the depths are shown on the colour bar in metres.

4.1.5 Example interim results

4.1.5.1 The key results are interactions with the turbines and sluices.
There are 2 banks of turbines with sluices in between them. The west bank and the east bank.
The model records every interaction with these.

Table 1. Results for smolt for N=10,000

	West Crosses	Sluice Crosses	East Crosses	No. fish encountering turbines	1 turbine cross	2 turbine crosses	3 turbine crosses	4 turbine crosses
Spring	66	22	77	81	17	64	0	0
Neap	107	34	95	107	17	87	1	2
Neap	29	75	8	29	23	5	0	1

4.1.5.2 These results show that the level of impact is independent of start point in tidal cycle, and the numbers are approximately 100 per 10,000 or 1%. Mortality can be easily calculated from the number of crosses. Bearing in mind that a fish can cross a turbine on the way in and come out via the sluices and so forth.

4.1.6 Model sensitivity and confidence

4.1.6.1 The model is insensitive to a range of plausible input parameters. There has been no situation discovered which is any more impactful overall than the results quoted here, for instance in the navigational parameters or pathway all impacts are logical and easily anticipated. The swimming speed impacts the results in a correlated way, as would be expected, as it approaches zero, the impact begins to resemble random drifters.

4.2 Calibration example salmon adult

4.2.0.1 **Behaviour description:** Salmon return to their natal rivers after several years at sea. Over 98% of their body weight has been added during their time in the ocean. Some adult salmon return to rivers which are not their own (~10%) and this is an important part of their evolved life history as this behaviour ensures that populations do not get isolated to a single river, and provides population resilience in the case where a river has become impassable – for instance through an earthquake etc.. Thus it is not likely that those that stray are 'lost', rather that they have some intent to stray for some unknown reason. Straying also allows us to track changes in sub-populations directly through genetic analysis.

4.2.0.2 Salmon are thought to be able to home to their natal river through three primary mechanisms; 1) magnetic properties of the Earth, 2) olfaction (analogous to a sense of smell in humans) and 3) sensitivity and alignment with currents (rheotaxis). The general consensus of scientific opinion is that some magnetic properties of the entrance of the natal river are imprinted during smoltification (in addition to the original imprinting before or at emergence from egg). The adult salmon is then able to swim toward this remembered way point. This method of navigation is necessarily very inaccurate (by human standards of GPS for instance) because the main magnetic field of the Earth is variable (both in predictable cycles and randomly) in comparison to the strengths of gradients and absolute values (the signals) in the field. The balance of these factors means that it is likely that this method of homing is accurate to within around 50-100 km at best. The general opinion is that when it gets to within this range the adult salmon begins to rely on olfactory senses. There have been many experiments on salmon which have demonstrated clearly that they can discern olfactory trails between their natal rivers and other rivers close by, and other rivers which are tributaries of their own. It has been shown that they can use olfactory trails to navigate very complex coastlines and rivers with many entrances and tributaries. Nevertheless, their journeys (revealed by tags) are not sure and direct. Adult salmon paths are similar to a bouncing ball – they tend not to follow complex coastlines close to shore, but rather move inshore in short exploratory moves and then move back into deep water if they sense that they have not reached their river mouth. Adults generally swim continually and 'home in' on their chosen river after several days of these trial movements.

4.2.0.3 The target for this model are twofold; 1) to analyse the impact of the proposed scheme on the olfactory trails of the natal rivers, and 2) model the movements of adult salmon using the modelled trail and predict their interaction with the scheme. The first target will identify likely impact explicitly and with a high degree of confidence, because the model is well calibrated and based on the laws of physics. Olfactory trails for salmon are suspected to be made of organic compounds which they can detect at extremely low concentration. These compounds will have a decay lifetime in the ocean and will move in the water as neutrally buoyant packets of water, thus they are very well modelled in the hydrodynamic models, but the trails are very dynamic and move with the tides. The second target is more complex and depends to a large extent on the behaviour of salmon. An adult salmon can swim fast and continuously, so is able to swim directly against any natural oceanic currents and has unknown cognitive and sensory capability. Thus the results of these models must be moderated by our knowledge of the behaviour of salmon because, if they detect the scheme, they are capable of avoiding any impact. Nevertheless, the movements of modelled adult salmon can be compared with the tracks in the scientific literature and are well modelled as correlated random walks with intermittent navigation.

Key references for species (Aprahamian et al. 1998, Davidsen et al. 2013, Pascual and Quinn, 1991).

4.2.0.4 Key reference because, similar species, nearby (100 km), similar transition between river and estuarine. First IBM of a closely related species.

Basic model parameters

4.2.0.5 Number of fish/drifting olfaction objects: 10,000 for each run
Lagrangian model time step: 60 seconds
Eulerian model time step: 15 minutes (results files of hydrodynamic model)
Model run time: 20 days for drifters' olfaction trail – folded water model has no limit
Model spatial resolution: double precision (16 decimal places of a metre)
Salmon length mean 73.1 cm, with a standard deviation of 10 cm (Fishbase).
Initialisation over 16 hour period centred at same times as smolts (Fig. 5)

4.2.1 Salmon Adult Olfaction. Model parameterisation and calibration

4.2.1.1 The object of this phase of the modelling is to identify a reasonable trail for the adult salmon to travel from the wider estuary to the river mouth. The model is run by releasing neutrally buoyant particles over a time period and recording their positions. The prediction is that their averaged positions will give an indication of the centre of the olfactory trail. Ten thousand model particles were released over a 7 day model period. After particles reached 7 days old they decayed and left the model, so there was always 10,000 particles moving in the model after the initial 7 day run-in period. The particle positions were recorded every 10 minutes for 20 days. The particle's distance from the origin (the mouth of Aber Tawe) were calculated every 10 minutes of the model run time. The mean position of all particles within 1 to 2 km (and 2-3, 3-4 and so on) from the origin within each 10 minute period were calculated. Here we refer to these mean positions as ephemeral way points, and they represent the centres of mass of the scent trail in segments defined at 1 km intervals up to 20 km away from the river mouth. The mean positions of these ephemeral waypoints (the mean of means) over the whole model run are the predicted way points of the olfactory trail. A snapshot of the model shows how the ephemeral way points can be moved far from their averaged positions by the very fast moving currents in this area (Fig. 12).

4.2.2 Results – olfaction trail

Strength of trail

4.2.2.1 The numbers of particles in the 1 km segments moving away from the origin decreased in an approximately exponential decay, with an anomaly defined by the shape of Swansea Bay at around 5 km from the river mouth. This is the expected form of decay of particle numbers which is very familiar in studies of pelagic larval duration in shell fish larvae for instance (it is known as Crisp's law (Crisp, 1958)). The decrease in numbers of particles with distance of the baseline situation was not significantly different from that of the scheme (Fig. 11).

Distribution of trail

4.2.2.2 A comparison between all the ephemeral waypoints of the baseline and with-scheme scenarios shows that the distribution of the trails is very different (Fig. 12). The scheme olfactory trail switches back and forth between the left hand and the right hand side of Swansea Bay. The trail is more diffuse in the Bay. In the baseline situation the trail is well defined and the ephemeral waypoints are densely positioned along the northern coastline of the Bristol Channel.

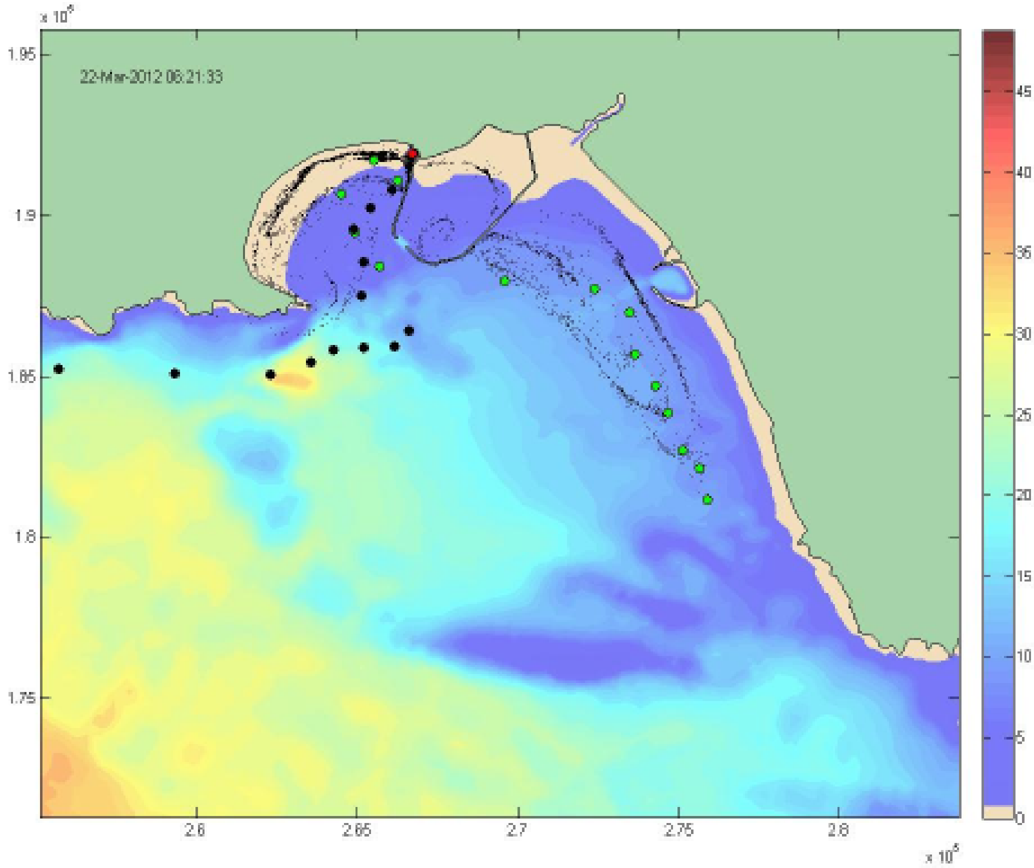

Figure 10. Example of olfactory trail model. The green circles are the ephemeral mean positions of the particles in zones defined by the distance from the origin in kilometre increments of the passively drifting particles (10,000 small black dots). The heavy black dots are the means of the ephemeral waypoints throughout the model to this point (~15 days). The red dot is the origin. Bathymetry (depth in metres) is shown in the colour bar. The ephemeral trail has swung over to the right of Swansea Bay although it is generally on the left. An adult salmon, which can swim comfortably against any natural tidal current and thus may be moving in any area of the Bay at any tidal state, may therefore pick up this trail at any ephemeral position.

False trails

4.2.2.3 Adult salmon may be encouraged to swim through the turbines or over the sluices into the proposed tidal lagoon if sufficient olfactory stimulants are drawn into the lagoon and then ejected in a way that may confuse the salmon into following a false trail into the lagoon. During the olfactory run the maximum number of particles that were in the lagoon at any time was around 500, the average number was 58. (Fig. 13). The maximum number of particles ejected in any single event was about 200. These particles were ejected into the water ebbing from the enclosed area to the left of the lagoon which is similar in volume to the lagoon and which contained on average around 5000 particles. Thus it is likely that the ejected water from the lagoon contains an olfactory signal close to a maximum of 4% of the main river signal.

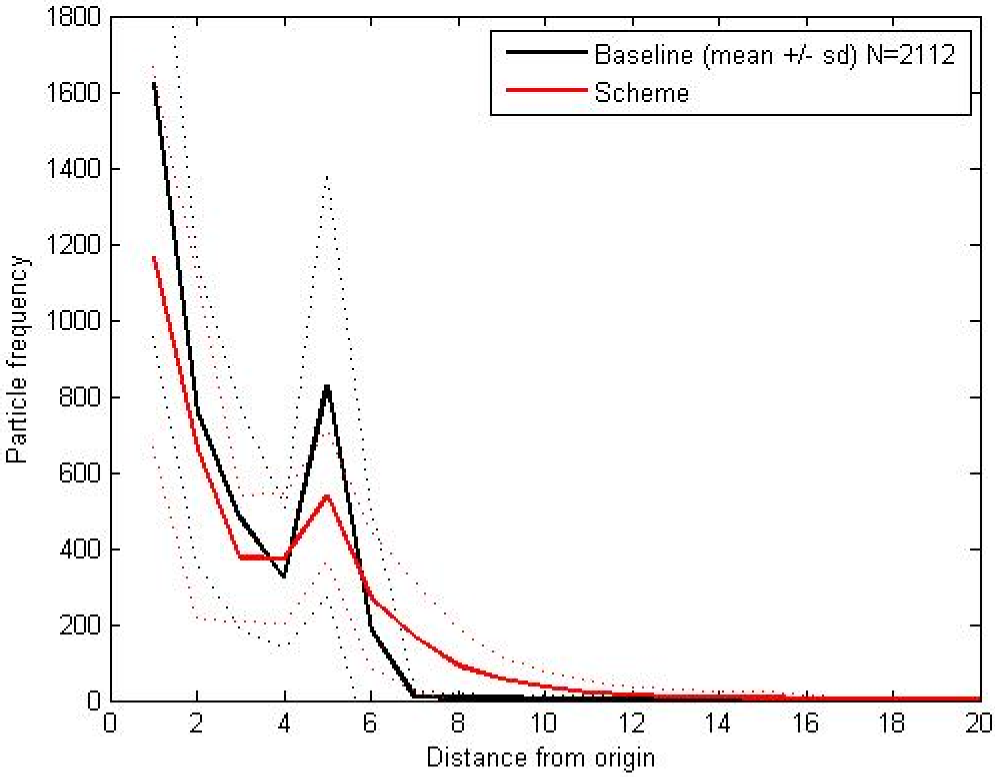

Figure 11. Mean numbers of particles against distance away from origin for the baseline and scheme scenarios. The dotted lines are one standard deviation from the mean. The two sets of data are not statistically significantly different from one another at any distance from the origin. The sharp peak at 5 on the x-axis (between 5 and 6 km from the origin) is caused by the shape of Swansea Bay and in particular the way currents are reversed around Mumbles Head and some particles are swept back at around this distance.

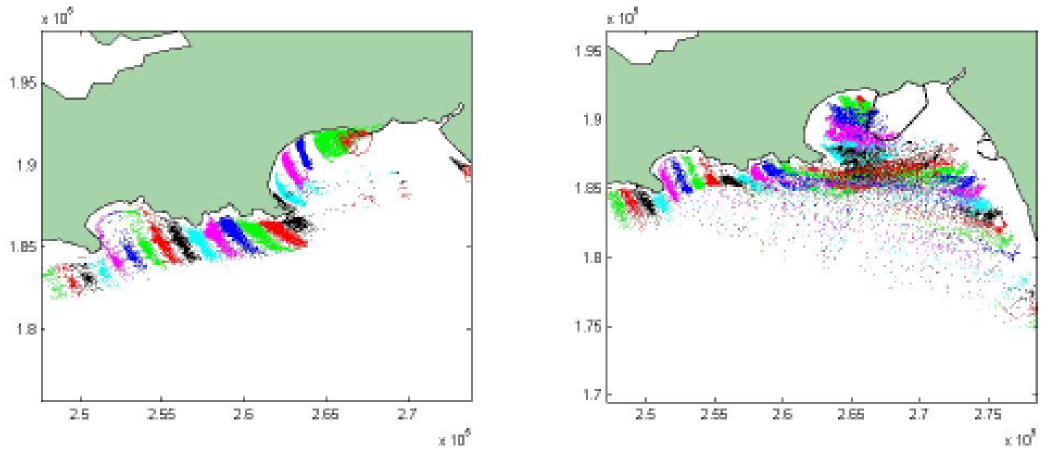

Figure 12. Plots of all the ephemeral way points for the baseline (left panel) and with-scheme scenario (right panel). The colours are arbitrarily applied to distinguish waypoints within the 1 km zones at distances between 1 and 20 km from the origin (Tawe river mouth). The figures show that the baseline trail (left panel) is well defined and runs along the northern coastline of the Bristol Channel. The with-scheme trail is more diffuse and has a second 'arm' on the right of the Bay leading up the Bristol Channel. This may be advantageous for adult salmon homing, in that the river mouth scent is broadcast more widely, and signalled from both directions. Alternatively it may cause confusion. It is also noticeable how few times the ephemeral way points are inside the lagoon.

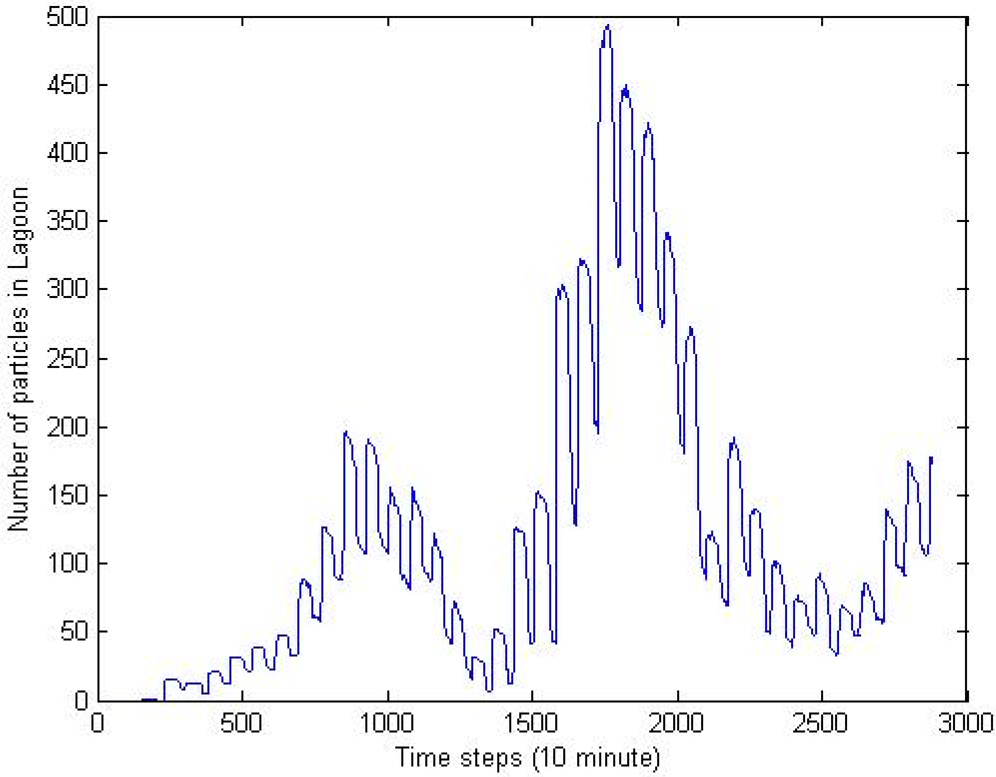

Figure 13. Number of particles within the lagoon for each 10 minute period of the olfactory trail model. The key statistic is the number exiting at any one event as these particles form the olfactory signal to the salmon swimming up river – the maximum is about 200. These particles are ejected into the zone containing the origin at the same time as the tide is ebbing from this area (which contains around 5000 particles). Thus the erroneous signal is at maximum around 4% and on average around 1%.

4.2.3 Results – swimming adults

Table 2. Results for adult for N=10,000

	West Crosses	Sluice Crosses	East Crosses	No. fish encountering turbines	1 turbine cross	2 turbine crosses	3 turbine crosses	4 turbine crosses
Spring[1]	881	530	165	621	273	291	39	17
	873	489	175	625	275	298	34	15
Spring[2]	639	328	73	427	193	198	24	9
Spring[3]	1301	766	176	752	291	313	76	48
Spring[4]	254	194	37	149	62	52	21	10
Spring[5]	343	196	24	174	54	79	20	14
Neap[6]	203	144	29	110	39	48	9	8
Neap[7]	8	9	1	5	1	4	0	0

1. Western approach Navstep 5, determination 0.2, speed 1.5 bl
2. Western approach Navstep 4, determination 0.1, speed 1.5 bl
3. Eastern approach, nav 4, det 0.2, 1.5 bl, route 05E
4. Eastern approach, 4, 0.2, 1.5, route 05E
5. Eastern approach, 4, 0.2, 1.5, route 06E
6. Eastern approach
7. Western approach

Note that a fish can cross a turbine on the way in and come out via the sluices and so forth.

4.2.4 Summary results

4.2.4.1 Turbine impact in all states and from both approaches: 357.87 of 10,000 = 3.6%
Standard deviation of results: 283.8 = 2.8%
Impact percentage: 3.6% ± 2.8%

4.2.5 Descriptive results

4.2.5.1 The tracks for the swimming adults closely resemble tracks of adult salmon and other marine animals, with more directed and straighter sections interspersed with more circuitous and slower sections (Fig 11).

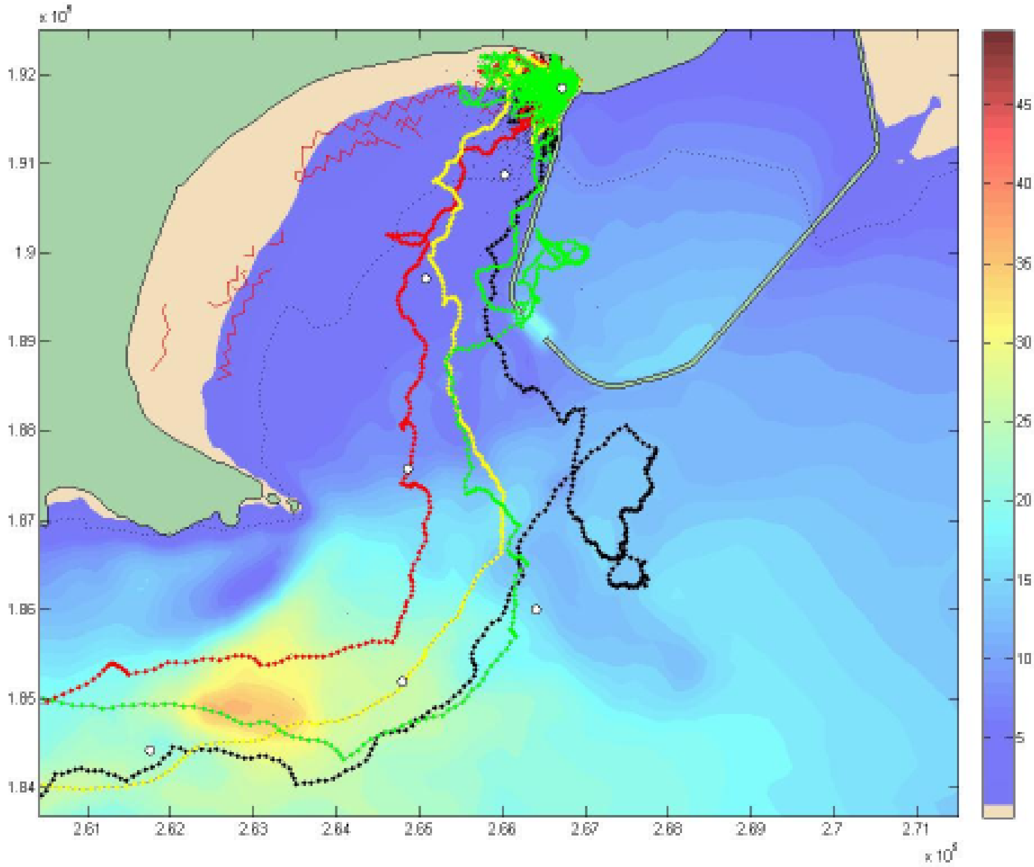

Figure 14. Four typical tracks of modelled adult salmon approaching the mouth of Aber Tawe during 2 days around spring tides with the proposed scheme in place. The navigational way marks from the olfactory trail model are shown as white filled circles, and the positions at each 1 minute time step are shown as coloured dots. The depths at the initialisation time are shown as filled contours with the colours indicated on the colour bar in metres. The axis tick marks are in 1 km intervals on the OSGB grid in metres. Red lines are ancient fish traps and the light dotted line is chart datum. The fish are swimming at a mean speed of 1.5 body lengths per second, and are a mean of 60 cm long. The overall ground speed is similar to that reported for tagged wild Atlantic salmon approaching their natal river entrance (Davidsen et al., 2013). The tracks are very similar to wild tagged salmon and other animal tracks.

4.2.6 Results – size and vulnerability

4.2.6.1 The modelled fish that were smaller and thus swam slower (in the model) were impacted to a greater extent than those that were larger, but the difference was not significant for the range of fish in the model (Figure 12).

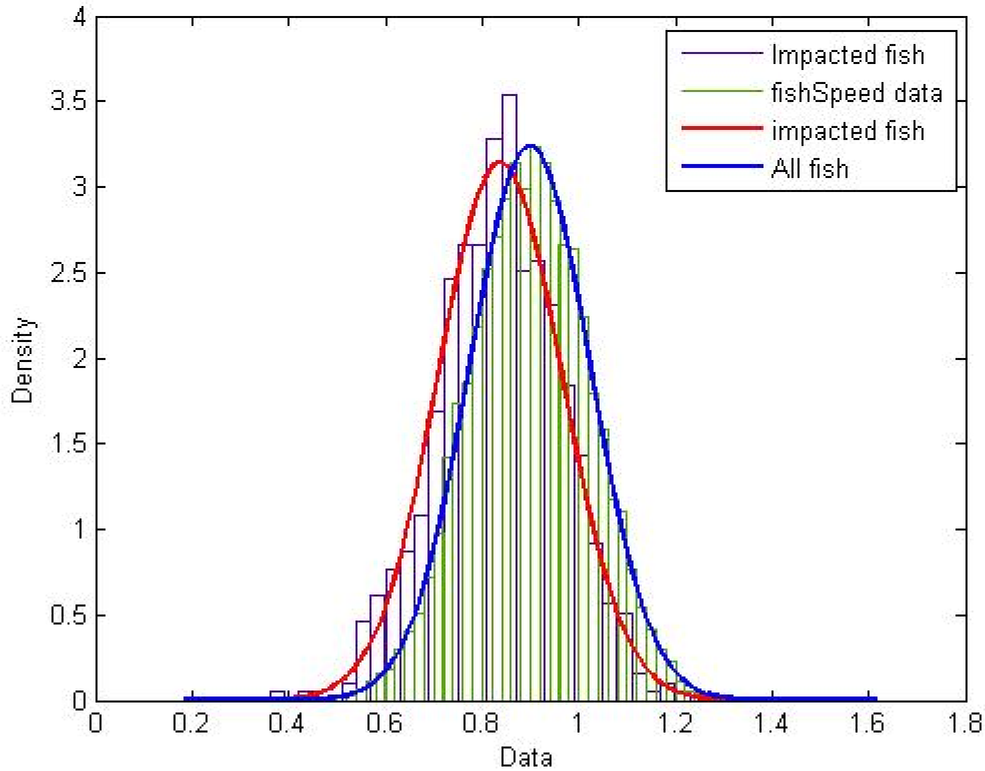

Figure 15. Normal distributions fitted to the data for all fish swimming speeds (blue line) and fitted to only those fish which encountered the lagoon (went over either the turbines or sluices). Fish encountering the lagoon have a slightly slower speed on average than the group of all fish, but the two distributions are not statistically significantly different. This shows that all fish are likely to be effected regardless of swimming speed but possibly smaller slower fish will be impacted slightly more often. N=10,000 for all fish, N=627 for impacted fish (Spring tide, western approach, Nav step 5)

4.2.7 Salmon adults: Calibration and parameterisation

4.2.7.1 Reducing swim speed and reducing navigational information both have the impact of slowing the ground speed and increasing the time to reach the river mouth. In general these reductions increase the modelled interaction with the proposed works. There is also a limit to both parameters, which are correlated to some extent, at which model fish do not make headway against the tide and/or are unable to locate the river mouth. The experimental data for tagged wild salmon demonstrate that all salmon tagged move directly and quickly into their target river mouths (at a reported ground speed which we use to calibrate our model) (Davidsen et al., 2013) (Figure 14). Also there are many data on swimming speeds of adult salmon from lab tests. The parameters we use are judged to be close to the conservative limit based on tagged wild salmon and the fact that salmon adults are able to swim into the rivers Tawe and Neath. Salmon are thought to be able to sense their natal rivers through olfactory clues for about up to 50 km distant (Hansen & Quinn, 1998) and bearing in mind the exponential drop in signal strength; it is reasonable to assume that when they are within 20 km of the target their orientation is accurate (this strong directedness is confirmed in tagging studies) (Davidsen et al., 2013). Finally the models are calibrated through direct analysis of video based and figure based track data through expert opinion and comparison with behaviour and tracks from previous studies of these and other species.

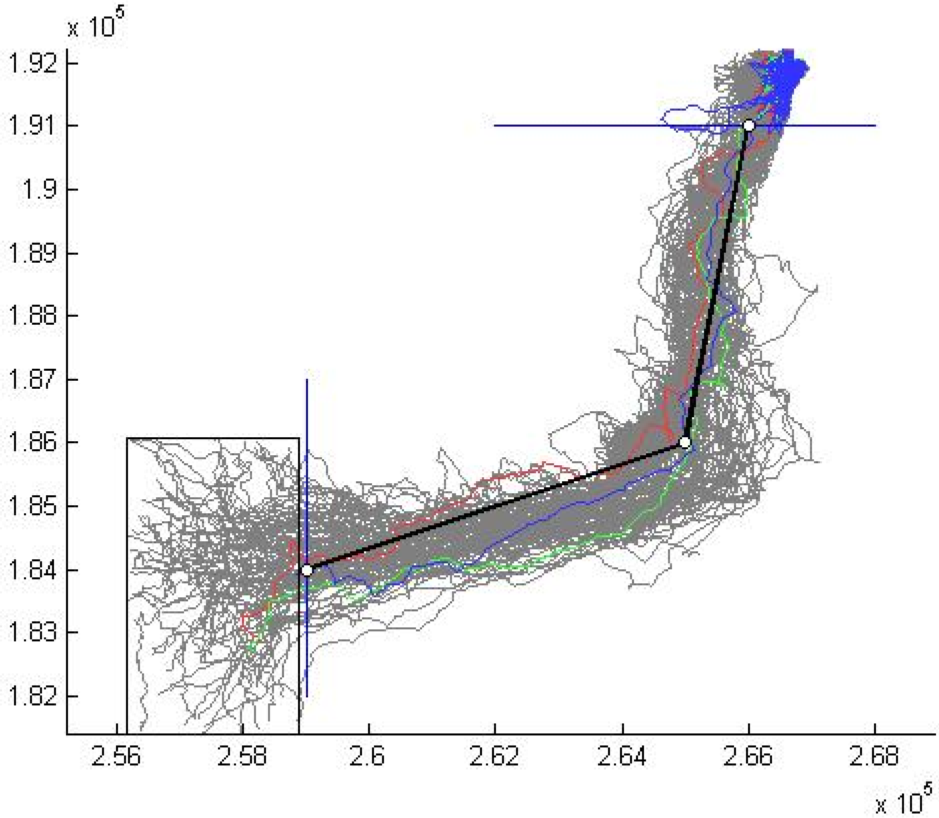

Figure 16. Tortuosity analysis to replicate tag based ground speed calculations. The ground speed of a fish is dependent on its swimming speed, its navigational characteristics, and the complexity of the tidal currents and route. Here 100 tracks of modelled adult salmon are shown in grey with three highlighted in red blue and green. The initialisation area is the black box on the left, and the start and end line of the ground track are shown in blue, the direct ground line is shown by the heavy black line and the white filled circles. The ground speed recorded for the model fish can be compared with those recorded by tracking actual fish with different parameters for navigation (tortuosity, and accuracy) and swimming speed.

4.2.7.2 The migratory speed of the salmon is the ground speed between two distant points on its navigational journey. Davidsen et al. (2013) recorded these migratory speeds during the final phase of adult Atlantic salmon homing in terms of body lengths per second. We used 1000 example tracks in the area outlined in Figure 12, during spring and neap tides and calculated the migratory speed in terms of body lengths for various combinations of navigational parameters and swim speed to body length ratios. This allowed us to 'tune' the model fish to the same migratory speed as the recorded fish (Figures 16 and 17). Taking a fish mean length (from Fishbase (2013) for this species and confirmed by Aprahamian et al. (1998)) of 0.731 m, the calibrated model parameters were 1.2294 body lengths per second swim speed, and a navigational frequency of 4 minutes, and the angular standard error of 0.2 pi/step radians.

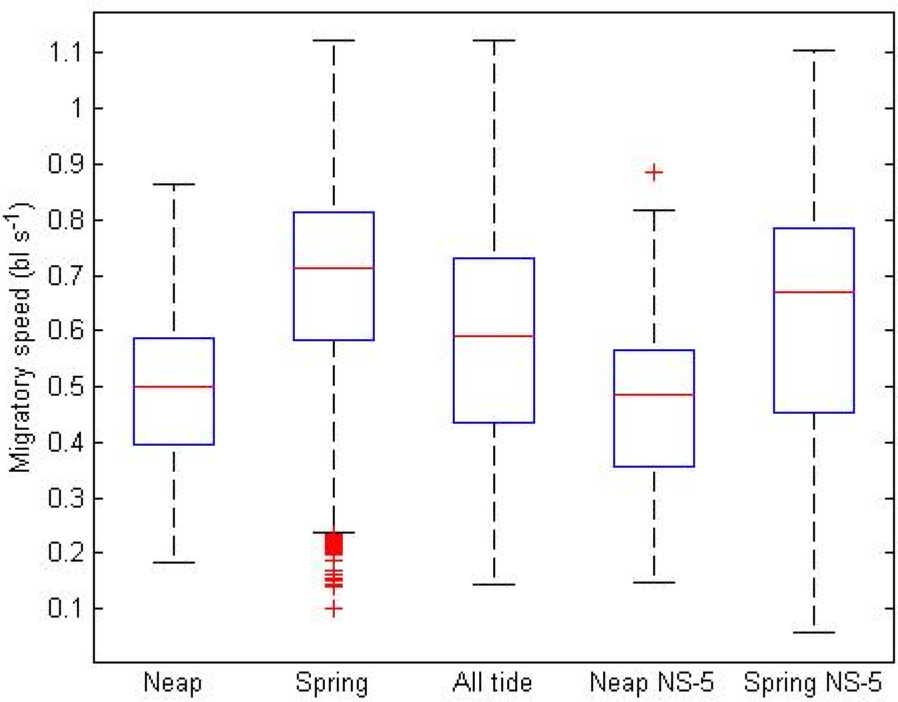

Figure 17. Box plots of migratory speeds for 1000 modelled fish in spring, neap and both tidal states in the area shown in figure 12. These show mean (red line) and interquartile range (box) and range (whiskers). NS-5 refers to a navigational step on average every 5 time steps (5 minutes), the default was 4. This plot shows that although the 'in water' swim speed of the fish was set at 1.22 body lengths a second, or a mean of about 0.9 m s^{-1}, the migratory speed has a mean of between 0.5 and 0.6 body lengths per second due to the tortuosity of the track caused by turbulence, tides and navigational inaccuracies which are modelled explicitly in the model. The red crosses are outliers (and are a result of some temporary captures in the lagoon). The Navigational frequency slows down the migratory speed, this demonstrates the fine tuning that is possible to calibrate the model against field data. The parameter of 4 for navigational frequency was most well calibrated to the field data.

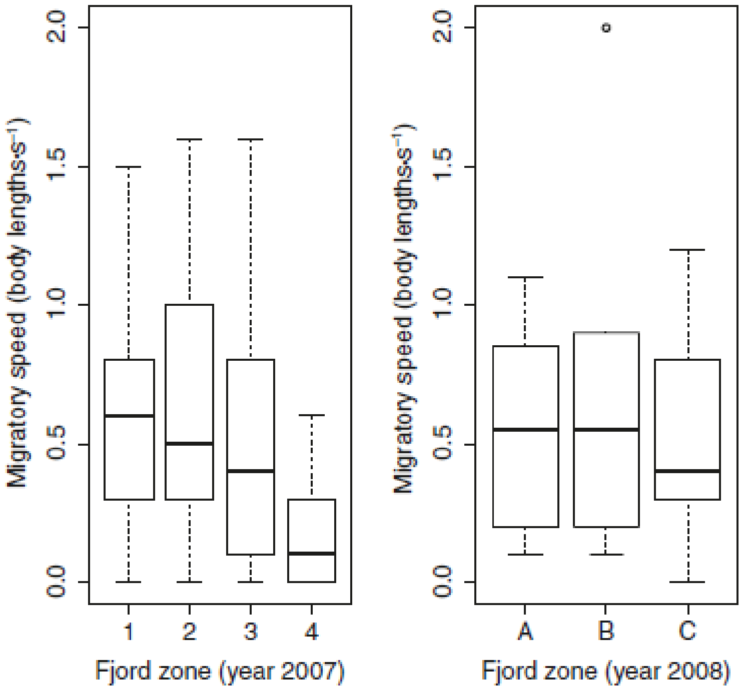

Figure 18. Migratory speeds of homing Atlantic salmon (Salmo salar) in the Alta Fjord in 2007 and 2008, copied from Davidsen et al 2013. Overall the calibration of the model was reasonably good against this field data for the same species, albeit in a different (less active) tidal regime and over slightly different distances, water clarity, bed substrate, temperature, and coastal profile.

4.3 Example calibration sea trout adult

4.3.0.1 Key reference: Bendall, B., Moore, A. and Quayle, V. (2005), The post-spawning movements of migratory brown trout Salmo trutta L. Journal of Fish Biology, 67: 809–822. doi: 10.1111/j.0022-1112.2005.00786.x

4.3.0.2 Overview of key reference: tracks 45 kelts (female trout that have spawned) leaving and returning to Fowey Estuary on the Southern UK coastline (~200 km distant). Results show direct travel from fresh to salt and reverse. Out migration starts on the full and continues during the ebb, usually all out within 16 hours, Incoming migration on the ebb, moving directly into river with no holding. No spring/neap association, no diurnal pattern until in fresh water.

4.3.0.3 Key stats from reference:
Fish length: males 40.8 ± 28 (SE), females: 42.3 ± 11.2
(Resampled general distribution: 0.42 ± 0.18)

4.3.1 Interim results – trout (*Salmo trutta*) adults

4.3.1.1 Model calibration is an iterative process of running the model in various configurations and cross checking the patterns via expert opinion. In the cases where a number of variants were tried that were indistinguishable from that perspective, the most impactful parameterisations were chosen. Here follows the kind of interim results table that was produced for adult trout with various changes to parameterisation, outlined in the table footnotes.

Table 3. Results for adult trout for N=10,000

	West Crosses	Sluice Crosses	East Crosses	No. fish turbine encountering turbines	1 turbine cross	2 turbine crosses	3 turbine crosses	4 turbine crosses
Spring[1]	881	530	165	621	273	291	39	17
	873	489	175	625	275	298	34	15
Spring[2]	639	328	73	427	193	198	24	9
Spring[3]	1301	766	176	752	291	313	76	48
Spring[4]	254	194	37	149	62	52	21	10
Spring[5]	343	196	24	174	54	79	20	14
Neap[6]	203	144	29	110	39	48	9	8
Neap[7]	8	9	1	5	1	4	0	0

1. Western approach Navstep 5, determination 0.2, speed 1.233 bl
2. Western approach Navstep 4, determination 0.1, speed 1.5 bl
3. Eastern approach, nav 4, det 0.2, 1.5 bl, route 05E
4. Eastern approach, 4, 0.2, 1.5, route 05E
5. Eastern approach, 4, 0.2, 1.5, route 06E
6. Eastern approach

5.0 Summary of run scenarios and video output

5.0.0.1 The following species and reference numbers were used for the initial set of scenarios

1. TEM-A01 Salmon adult
2. TEM-J01 Salmon smolt
3. TEM-A02 Sea trout adult
4. TEM-J02 Sea trout smolt
5. TEM-A03 Shad
6. TEM-A04 Herring adult

7. TEM-A05 Eel adult
8. TEM-J05 Eel elver
9. TEM-A06 River Lamprey adult
10. TEM-J06 River Lamprey transformer
11. TEM-A07 Sea Lamprey Adult
12. TEM-J07 Sea Lamprey transformer
13. TEM-A08 Bass adult
14. TEM-J08 Bass juvenile
15. TEM-J09 Plaice juvenile

5.0.0.2 Following expert opinion and further consultation the following additional runs were made:

TEM-A10 Adult salmon Neath orientated
TEM-A11 Sandeel
TEM-J10 Smolt salmon Neath orientated
TEM-A12 Adult trout Neath orientated
TEM-J12 Smolt trout Neath orientated

5.0.0.3 In addition all the above scenarios were run in the baseline water model, passive drifters were run in both scenarios, and double scenarios of adult salmon and trout that were orientated around the Aber Neath and Aber Tawe in the same model were also produced (the latter pair being for presentational purposes).

5.1 Output notes: TEM-A01 Salmon adult

5.1.0.1 Standard round fish functions, and:

i. Life history segment: Inward migration to natal rivers from sea
ii. Initialisation zone: Uniform random distribution across olfactory trail ‘gateway’ zone for Swansea Bay.
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow

5.1.0.2 Source of calibration and validation: see above example calibration for details of salmon

5.1.0.3 Key references: Davidsen et al. (2013), Aprahamian et al. (1998), FishBase (2013), Moore et al. (1998).

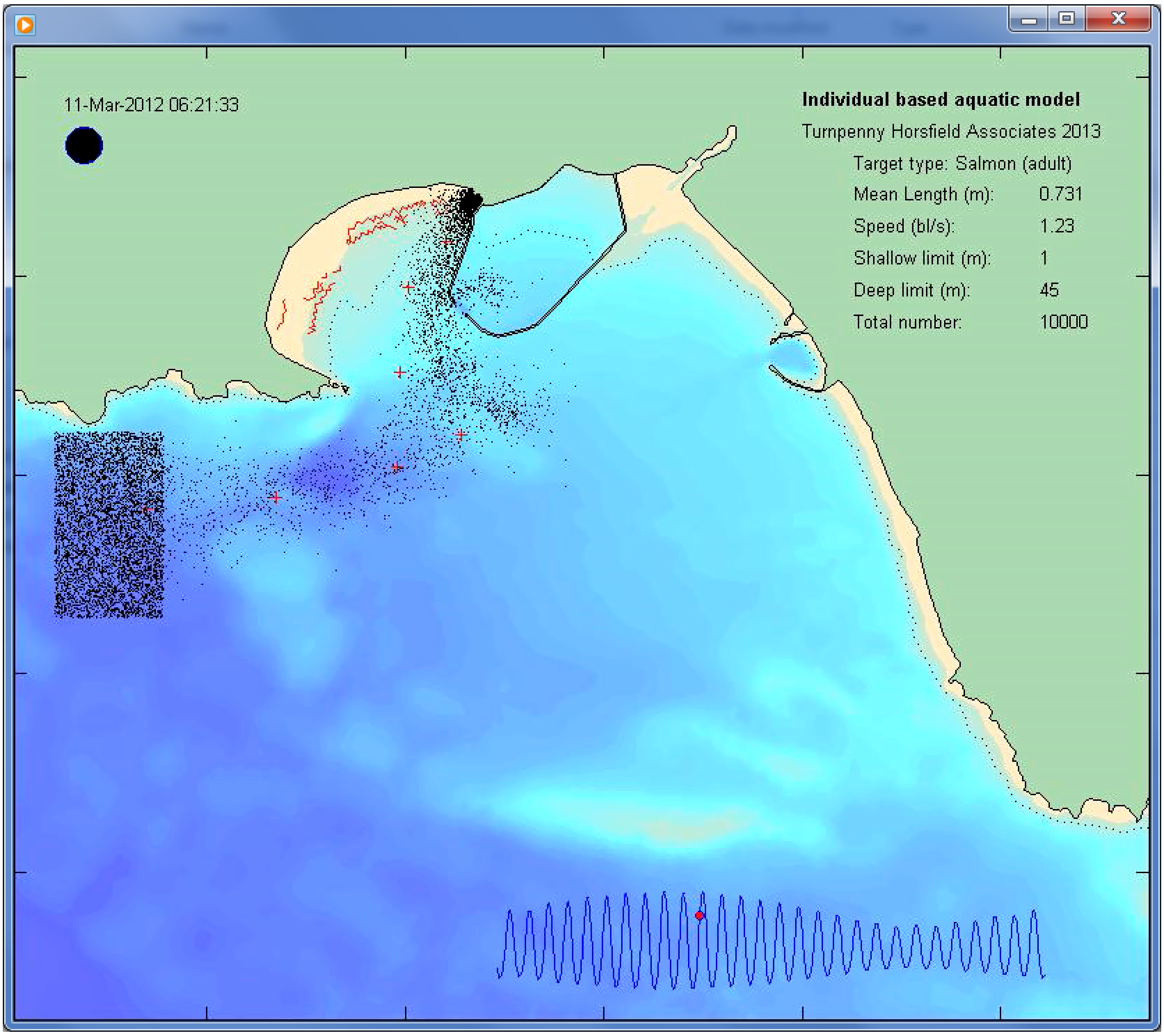

Figure 19 Video output capture of salmon adult. The text in the upper right gives the basic model parameters, and identifies the species. Upper left is a timer which is coincident with the hydrodynamic model start time (this timer is not necessarily important for fish migration and relates purely to the tidal cycle). The filled black circle indicates that the sun is below the horizon at this time – it will change to yellow during the day. The black dots are individual modelled fish (there are 10,000), and the red crosses are the navigational waypoints which approximate the olfactory scent trail which had been modelled using the same hydrodynamic model. The blue line at the base of the figure is an indicator of depth at an arbitrarily chosen reference point, and the red dot indicates the present level. In this case this tidal display shows that the model is just approaching high tide, around the highest spring levels. The colours in the background show the water depths when this model run was initiated (running from zero to around 40 m depth), and the dotted line around the coast is roughly chart datum (lowest wet contour). The red lines on the beach are ancient fish traps. The axis tick marks are 5 km apart.

5.2 Output notes TEM-J01 Salmon smolt

5.2.0.1 Standard round fish functions, and:

I. Life history segment: Outward migration from natal rivers to sea
II. Initialisation zone: Point initialisation in river mouth
III. Initialisation times: Uniform random distribution 4 hours each side of spring high tide
IV. Navigational mode: Trail follow

5.2.0.2 Source of calibration and validation: see above example calibration for details of salmon

5.2.0.3 Key references: Davidsen et al. (2013), Aprahamian et al. (1998), FishBase (2013), Moore et al. (1998).

5.3 Output notes TEM-A02 Sea trout adult

5.3.0.1 Standard round fish functions, and:

i. Life history segment: Inward migration to natal rivers from sea
ii. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay.
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow

5.3.0.2 Source of calibration and validation: see above example calibration for details of trout

5.3.0.3 Key references: Davies et al, (2004), Claridge et al (1986).

5.4 Output notes TEM-J02 Sea trout smolt

5.4.0.1 Standard round fish functions, and:

I. Life history segment: Outward migration from natal rivers to sea
II. Initialisation zone: Point initialisation in river mouth
III. Initialisation times: Uniform random distribution 4 hours each side of spring high tide
IV. Navigational mode: Trail follow

5.4.0.2 Source of calibration and validation: see above example calibration for details of salmon/trout smolt

5.4.0.3 Key references: Davies et al, (2004), Claridge et al (1986).

5.5 Output notes TEM-A03 Shad

5.5.0.1 Standard round fish functions, and:

i. Life history segment: Inward migration to natal rivers from sea (going past Swansea Bay up the Bristol Channel)
ii. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay, extended to 5 km in vertical extent to facilitate population level statistic across Bristol Channel.
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow

5.5.0.2 Source of calibration and validation: expert opinion

5.5.0.3 Key references: Maitland & Herdson, (2009)

5.6 Output notes TEM-A04 Herring adult

5.6.0.1 Standard round fish functions, and:

I. Life history segment: Inward migration to historic spawning location – includes an exploratory 'run' by minority of population followed by full run in, several tides spawning and then a full 'run out'.
II. Initialisation zone: Uniform random distribution across general 'gateway' zone for

Swansea Bay.

III. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
IV. Navigational mode: Target zone

5.6.0.2 Source of calibration and validation: expert opinion

5.6.0.3 Key references: 6. Aneer et al, (1983) and Nøttestad et al, (1996)

5.7 Output notes TEM-A05 Eel adult

5.7.0.1 Standard thixophilic fish functions, and:

i. Life history segment: Outward migration from natal rivers to sea
ii. Initialisation zone: Point initialisation in river mouth
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow

5.7.0.2 Source of calibration and validation: expert opinion

5.7.0.3 Key references: Vøllestad, (1992), Wheeler, (1978), Claridge et al (1986)

5.8 Output notes TEM-J05 Eel elver

5.8.0.1 Standard thixophilic fish functions, and:

I. Life history segment: Inward migration to any rivers from sea
II. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay.
III. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
IV. Navigational mode: Trail follow, Selective Tidal Stream Transport (STST), Night time travel

5.8.0.2 Source of calibration and validation: see above example calibration for details of salmon

5.8.0.3 Key references: Maitland & Herdson, (2009; Davies et al, (2004); Wheeler, (1978); Lythgoe & Lythgoe, (1975), Bos, (1999); Jager, (1999).

5.9 Output notes TEM-A06 River Lamprey adult

5.9.0.1 Standard thixophilic fish functions, and:

i. Life history segment: Inward migration to natal rivers from sea
ii. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay.
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow, Selective Tidal Stream Transport (STST), Night time travel

5.9.0.2 Source of calibration and validation: expert opinion

5.9.0.3 Key references: Maitland & Herdson, (2009; Davies et al, (2004); Wheeler, (1978); Lythgoe & Lythgoe, (1975).

5.10 Output notes TEM-J06 River Lamprey transformer

5.10.0.1 Standard thixophilic fish functions, and:

I. Life history segment: Outward migration from natal rivers to sea
II. Initialisation zone: Point initialisation in river mouth
III. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
IV. Navigational mode: Trail follow, Selective Tidal Stream Transport (STST), Night time travel

5.10.0.2 Source of calibration and validation: expert opinion

5.10.0.3 Key references: Maitland & Herdson, (2009; Davies et al, (2004); Wheeler, (1978); Lythgoe & Lythgoe, (1975).

5.11 Output notes TEM-A07 Sea Lamprey Adult

5.11.0.1 Standard thixophilic fish functions, and:

i. Life history segment: Inward migration to natal rivers from sea
ii. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay.
iii. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
iv. Navigational mode: Trail follow

5.11.0.2 Source of calibration and validation: expert opinion

5.11.0.3 Key references: Maitland & Herdson, (2009; Davies et al, (2004); Wheeler, (1978); Lythgoe & Lythgoe, (1975).

5.12 Output notes TEM-J07 Sea Lamprey transformer

5.12.0.1 Standard round fish functions, and:

I. Life history segment: Outward migration from natal rivers to sea
II. Initialisation zone: Point initialisation in river mouth.
III. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
IV. Navigational mode: Trail follow, Selective Tidal Stream Transport (STST), Night time travel

5.12.0.2 Source of calibration and validation: expert opinion

5.12.0.3 Key references: Maitland & Herdson, (2009; Davies et al, (2004); Wheeler, (1978); Lythgoe & Lythgoe, (1975).

5.13 Output notes TEM-A08 Bass adult

5.13.0.1 Standard round fish functions, and:

i. Life history segment: Inhabitation of coastal intertidal areas
ii. Initialisation zone: In target depth zone
iii. Initialisation times: Uniform random distribution 1 hours each side of spring high tide

iv. Navigational mode: Return to original position (continual homing)

5.13.0.2 Source of calibration and validation: expert opinion

5.13.0.3 Key references: Rijnsdorp et al., (1985), Sabriye et al., (1988), Pickett et al., (2004), Colclough et al. (2002, 2000).

5.14 Output notes TEM-J08 Bass juvenile

5.14.0.1 Standard round fish functions, and:

I. Life history segment: Inward migration to natal rivers from sea
II. Initialisation zone: Uniform random distribution across olfactory trail 'gateway' zone for Swansea Bay.
III. Initialisation times: Uniform random distribution 8 hours each side of spring high tide
IV. Navigational mode: Trail follow

5.14.0.2 Source of calibration and validation: see above example calibration for details of salmon

5.14.0.3 Key references: Rijnsdorp et al, (1985), Sabriye et al, (1988)

5.15 Output notes TEM-J09 Plaice juvenile

5.15.0.1 Standard flat fish functions, and:

i. Life history segment: Area inhabitation based on substrate type
ii. Initialisation zone: Uniform random distribution across target depth
iii. Initialisation times: Uniform random distribution 1 hours each side of spring high tide
iv. Navigational mode: Area inhabitation showing preference to certain substrates (and resting on those which are preferred more than those which are not, and related to depth preferences also.

5.15.0.2 Source of calibration and validation: see above example calibration for details of salmon

5.15.0.3 Key references: Claridge et al (1986)

6.0 Summary parameters and results

Table 4. Summary parameters.

Species	Scenario identifier	Mean swim speed m/s	SE swim speed	Min swim speed	Max swim speed	Mode
Salmon adult	TEM-A01	0.9	0.12	0.41	1.36	Trail follow
Salmon smolt	TEM-J01	0.18	0.02	0.12	0.24	Trail follow
Sea trout adult	TEM-A02	0.52	0.02	0.43	0.59	Trail follow
Sea trout smolt	TEM-J02	0.28	0.02	0.21	0.35	Trail follow
Shad	TEM-A03	0.52	0.07	0.28	0.78	Trail follow
Herring adult	TEM-A04	0.45	0.02	0.4	0.51	Homing zone
Eel adult	TEM-A05	0.75	0.2	0	1.51	Trail follow
Eel elver	TEM-J05	0.07	0.01	0.04	0.11	Trail follow
River Lamprey adult	TEM-A06	0.35	0.03	0.26	0.45	Trail follow
River Lamprey transformer	TEM-J06	0.16	0.02	0.1	0.22	Trail follow
Sea Lamprey Adult	TEM-A07	0.6	0.05	0.41	0.81	Trail follow
Sea Lamprey transformer	TEM-J07	0.22	0.02	0.11	0.32	Trail follow
Bass adult	TEM-A08	0.3	0.05	0.12	0.48	Area usage
Bass juvenile	TEM-J08	0.1	0.05	0.1	0.29	Area usage
Plaice juvenile	TEM-J09	0.08	0.01	0.04	0.11	Area usage
Neath adult salmon	TEM-A10	0.9	0.12	0.41	1.36	Trail follow
Sandeel	TEM-A11	0.4	0.1	0.03	0.76	Area usage

Table 5. Overview results.

Species	Scenario identifier	No. encountering turbines	Turbine Passes	Difference in/out	Mean mortality %	SE Mortality %
Salmon adult	TEM-A01	603	997	0	0.87	0.09
Salmon smolt	TEM-J01	125	373	0	0.12	0.03
Sea trout adult	TEM-A02	2044	3906	0	2.52	0.14
Sea trout smolt	TEM-J02	149	503	0	0.16	0.04
Shad	TEM-A03	56	241	0	0.77	0.08
Herring adult	TEM-A04	6368	9065	0	26.69	0.34
Eel adult	TEM-A05	223	365	0	0.19	0.04
Eel elver	TEM-J05	393	1287	-3	0.07	0.03
River Lamprey adult	TEM-A06	999	2677	-1214	1.35	0.11
River Lamprey transformer	TEM-J06	120	399	0	0.02	0.02
Sea Lamprey Adult	TEM-A07	1399	4390	-2	1.86	0.13
Sea Lamprey transformer	TEM-J07	101	343	0	0.15	0.04
Bass adult	TEM-A08	1186	4377	1851	0.27	0.01
Bass juvenile	TEM-J08	1702	1982	280	0.27	0.01
Plaice juvenile	TEM-J09	38	181	14	0.69	0.01
Neath adult salmon	TEM-A10	1	3	0	0.002	0.005
Sandeel	TEM-A11	41	161	0	0.01	0.01

7.0 Functions and coding

7.1.0.1 All code is written in a scripting language, similar to Matlab™

7.1.0.2 In Pseudocode the operation of the program is as follows:

1. Define fish object
2. Input general run parameters, such as total time
3. Send fish object and general parameter set to Main Run program
4. Return results structures and off-line analyse results
5. Write results to file

7.1.0.3 Pseudocode detail or full functions follow:

Set up fish function:

```
function fish = setupSalmon()
% function to set up the initialisation structure.

fish.name = 'Salmon (adult)';
fish.length = 0.731; % mean length in m
fish.lengthSD = 0.1; % sd deviation of length m
fish.speed = 1.23; % body lengths per s
fish.restProp = 'na'; % proportion of time on average resting on bed
fish.determ = 0.2; % number related to steadfastness * pi for error at each step

% behavioural modes
fish.type = 2; % 1 is a flat fish or eel which can touch bed, 2 is a round open-
water fish, 3 is a drifter or larva
fish.depth = 1; % does it respond to depth
fish.subs = 0; % does it respond to substrate
fish.sstress = 0; % does it respond to shear stress
% fish.bounce = 60; % seconds in bounce mode

% preferences
fish.tooShallow = 1; % low depth preference
fish.tooDeep = 45; % max depth preference
% subNames = {'Sandy mud', 'Sandy gravel', 'Muddy sandy gravel',...
%    'Muddy sand', 'Medium sand', 'Gravelly sand', 'Gravel', 'Fine sand', 'Bed-
rock'};
fish.subsPref = 'na'; % preferred substrates
fish.navTrail='adultTrail03';
fish.navStep=5; %7 how many steps between navigation information provision

% initialisation
fish.box = 1.0e+005 *[  2.5616 ,   1.8607;... % top left to bot right placement
box.
                        2.5890 ,   1.8141];

fish.startPeriod = 16; % hours
```

Main Run program (550 lines of script)

```
1. Open water model output file and set up structure
2. Input lat long, timesteps, durations
3. Set up timeline (each step has a time, a real time, etc)
4. Run timeline through sunlight function to find daylight at each step
5. Set up, open and paint base figure
6. Define total number of fish objects
```

7. Instantiate fish objects from base object
8. Load or input navigational or other functional data
9. Make further definitions for fish objects
10. Load turbine positions, lagoon area, and other objects
11. Set up text fields on output videos and figures
12. Initialise video file
13. Start main loop – running through timeline
    a. Interpolate water model to time step
    b. Record tidal state
    c. Calculate depth at fish object positions
    d. Navigate
    e. Behave with respect to tide, substrate, or depth
    f. Advect
    g. Add turbulence below the spatial resolution of the model
    h. Swim
    i. Track fish across water model grid in legal movements
    j. Check depth
    k. Beach – get off beach using a sub-model correlated random walk
    l. Track legal movement over turbines or sluices
    m. Build results tables
    n. At output interval repaint graphics and video
14. End main loop
15. Close open files and variables

8.0 References

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