Numerical modelling of fish in response to underwater noise

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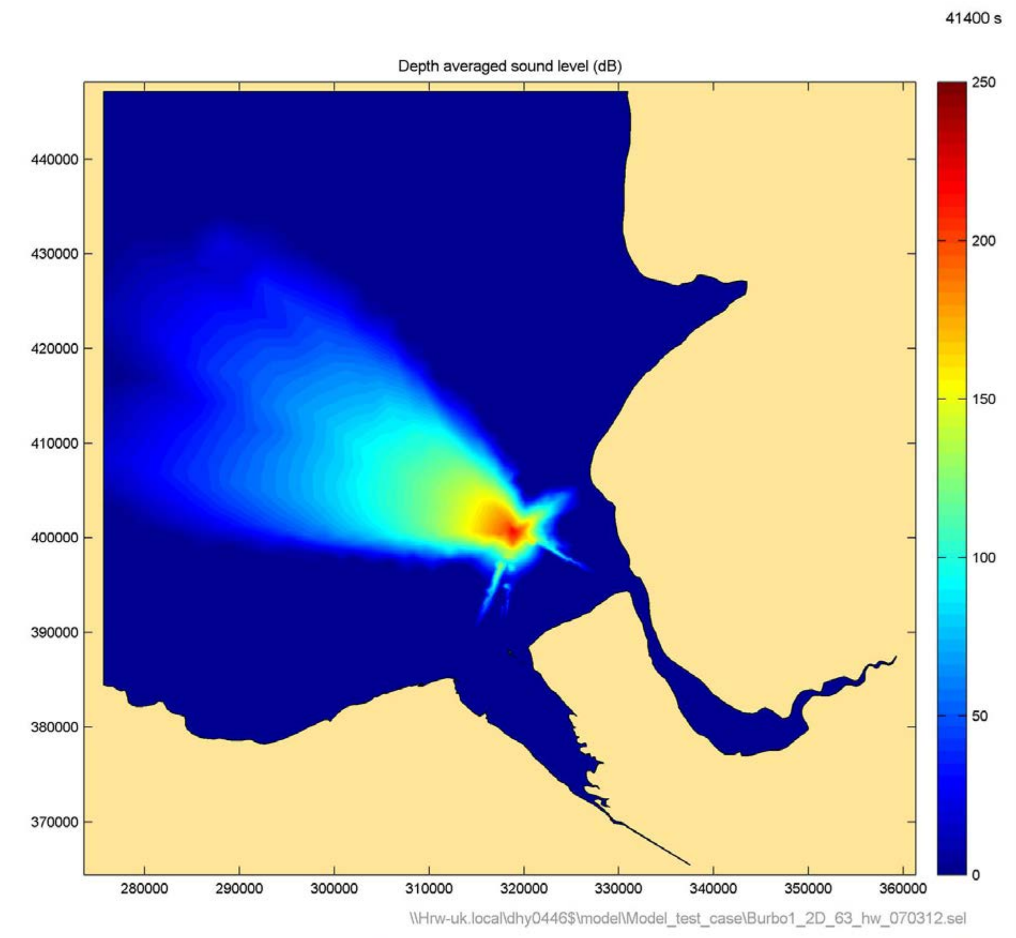
Introduction

Water is an excellent medium for sound transmission, which leads to concern about anthropogenic noise impacts on sensitive species. Models now exist that can predict a soundscape, taking into account hydrodynamic features, such as stratification, and seabed properties. A key challenge is to predict ecological responses, particularly to inform environmental impact assessments, prior to new marine developments. Individual and Agent Based Models (I/ABMs) provide an opportunity to assist in this ecological response prediction.

Such models use behavioural data from species of interest to provide behavioural rules for particles which represent individuals of that species. This simulates a response to the environment within the model. Our IBM has been developed to predict the response of fish to underwater noise and is part of a suite of models employed within the underwater noise assessment tool, HAMMER (Hydro-Acoustic Model for Mitigation and Ecological Response).



Soundscape resulting from foundation piling at Burbo Bank offshore windfarm

Simulation test species, Cod

Model description

Within our IBM, each particle is moved by advection in the first instance. Fish particles then follow a series of behavioural rules to determine their movement. These are summarised in Table 1 and the main features are described in more detail below.

Correlated Random Walk (CRW)

The CRW is a pattern of movement where the direction of the next step is dependent on the previous step plus an error term. To define a new position at every step in a correlated random walk we only need:

> the present position;

> the present direction;

> the error in retaining the present direction based on environmental influences and determination to continue in the present direction;

> the 'speed' or distance travelled at each step (velocity vector magnitude) (Willis 2011).

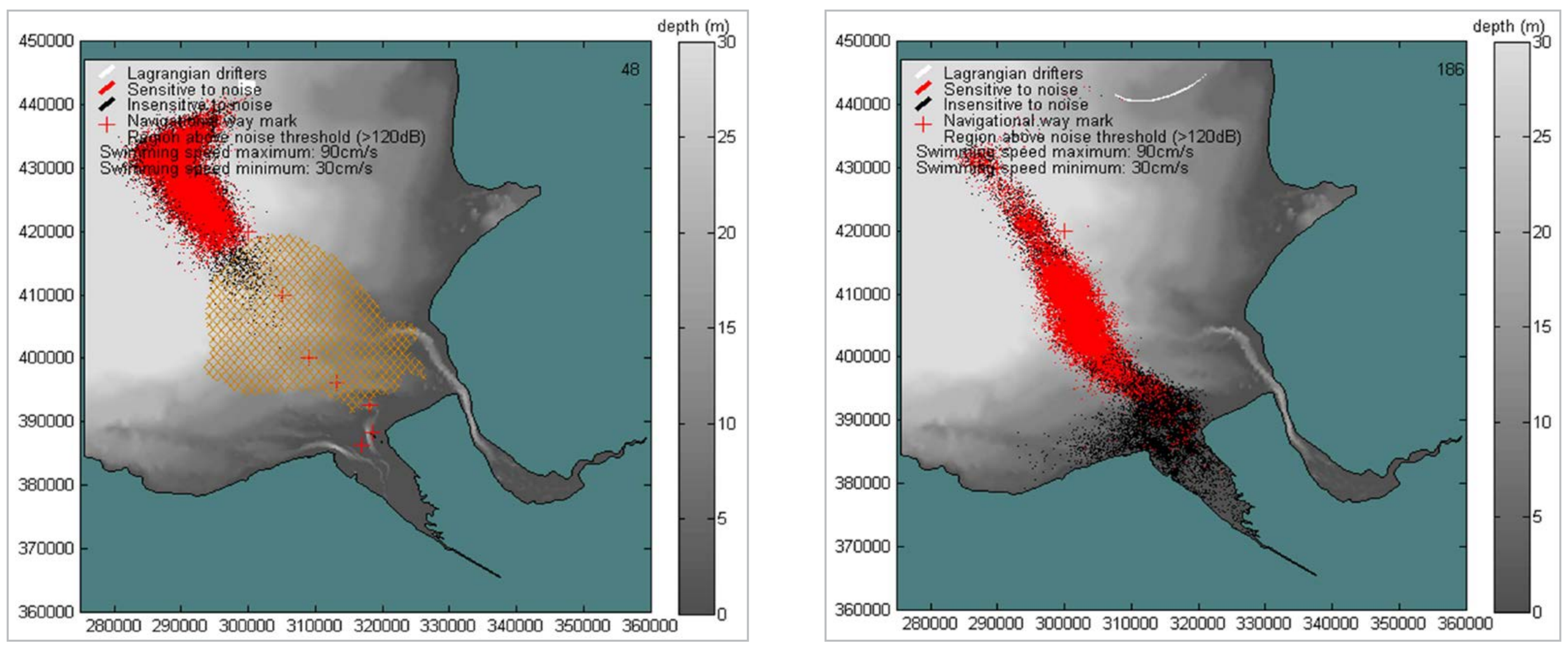
Navigation

During a simulation of fish migration, "way points" along the migration route are provided as the logical sequence of points towards a destination. A proportion of the 'fish' particles are selected to navigate at each time step.

Response to noise

Modelled fish which are "sensitive" to noise have behavioural responses to noises above a certain threshold. Behavioural response always includes changing swimming direction to move away from the noise and may involve a change in swimming speed. The sensitivity of the modelled fish to noise varies between fish based on a normal distribution.

Fish movement after 48 (left) and 186 (right) hours of model simulation. Noise insensitive fish (black) move through the noise field (hatched area), noise sensitive fish (red) move around the field. Noise sensitive fish (red) have taken longer to reach the end point (Dee Estuary).



Model application

During simulation, we designate particles as sensitive to noise, insensitive to noise and Lagrangian drifters. The last particle type has no behavioural characteristics and shows what would happen to particles moved only by advection with no swimming behaviours. The sensitive/insensitive split is made to show how unaffected populations and affected populations are predicted to behave, to discriminate potential effect.

Model setup

The IBM requires inputs from other models to provide:

> Hydrodynamics – currents and flow velocities used to calculate the advection of the particle

> Noise field – The predicted noise field is modelled using the noise component of HR Wallingford's HAMMER tool and is used to predict where the behavioural response of the fish to noise will occur.

Behavioural data

Data is required to parameterise fish behaviour within the model.

> Response to noise

There are numerous publications available on what a fish species can hear (Popper et al. 2014) which can be used in the model. Behavioural response is less well known but surrogate species data can be used if specific data is not available.

> Swimming behaviour

Swim speed within the model accounts for fleeing/evading swimming and normal swimming. These two functions are parameterised using body length, the stride length of a particular species (Videler & Wardle 1991) and species specific variables for sustained and prolonged swim speeds. Stride length is the distance covered during one tail beat cycle and can be expressed as a fraction of the body length of a fish within a species at moderate to high swim speeds (Videler & Wardle 1991).

> Variation between individuals

Fish exhibit behavioural traits of boldness and shyness e.g. the willingness to explore a novel environment or object (Sneddon 2003). The characteristics of boldness and shyness can be influenced by environmental and physical factors e.g. presence of a predator or hunger (Thomson et al. 2012) and by the perceived riskiness of a situation e.g. an extremely bold fish may exhibit less bold traits when exposed to risk in the environment (Frost et al. 2013). As boldness can influence how a fish may react to a perceived risk, in this case a noisy environment, the behavioural parameter boldness has been added to the ecological model.

Rules that can be applied to simulated fish

Behaviour	Parameters	Notes
Advection by current	Position	Reposition as if carried entirely by current (no inertia etc.)
Hit land or stuck on intertidal	Direction	Turn 90° left or right, chosen randomly. Sensed by a lack of any movement.
Navigate	Way points Average interval	Define 'correct' direction at randomly chosen step (chosen from a distribution with a pre-defined average interval – i.e. once every 3 hours on average). Way points are introduced at start of model run
Noise avoidance	Direction Speed	Change direction (away from noise) and speed (from 0 ms^{-1} to double the fish's current speed)
Move	Directional error Speed	Correlated random walk, error and speed are fixed, except when speed is changed due to noise response.
Hold position/ nest guarding	Position Direction	Fish will change direction to swim towards their assigned nest. This behaviour applies if they are within 2 to 100 m of the nest (beyond 100 m they are assumed to have "abandoned" the nest).
Schooling	Direction Speed	Fish modify their swimming speed and direction based on the behaviour of surrounding fish to maintain: > separation > alignment and > cohesion.

Conclusions

Modification and addition of behavioural parameters has been successful and is based on the best available scientific literature and research. The IBM has also been reviewed by behavioural scientists who carry out research on the response of fish to noise.

Further work is required for the model to be more realistic and to provide behavioural response predictions for a wider range of fish species. Further data on physiological response is required to support predictive modelling and other assessments. Other ways of modelling the movement of fish along a migration route may be a significant improvement to the model as not all species of interest do migrate from breeding to feeding grounds, or vice versa. A suggestion has been to model the movement of the fish food source e.g. plankton blooms, and have the 'fish' follow the food in the hydrodynamic model. The movement response of fish needs to be investigated further to determine what direction they move in if they respond to the noise e.g. move to the bed to escape or turn 180° and swim in the opposite direction, and also how long this behaviour persists after hearing a noise.

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