# Modelling encounter and collision rates of fish with tidal range projects

Report No: 835

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# Contents

## List of figures

# List of tables

# Glossary

**Advection:** horizontal movement of water masses.

**Bayesian Network**: a type of probabilistic graphical model that can be used to build models from data and/or expert opinion.

**Bidirectional (ebb and flood) generation**: electricity is generated on the ebb and flood tides.

**Bulb turbines**: turbines with their generators enclosed within a bulb shaped structure upstream of the runner blades.

**Cavitation**: cavitation is caused by the rapid formation of vapour pockets or bubbles within the low pressure zones around the runner blades leading edge. The bubbles collapse violently as they travel to areas with higher pressure within a turbine, resulting in the formation of high pressure jets, high levels of turbulence and localised high pressure shock waves.

**Circulation models:** mathematical or computational model that simulate the movement of water and dispersal of ichthyoplankton within a water body.

**Collision Risk Models (CRM)**: models designed to estimate collision, injury or mortality rates during passage through turbines and other water passage structures such as sluices.

**Computational Fluid Dynamics (CFD)**: modelling built on the principles of fluid mechanics where equations governing fluid motions provide insight and predictions of behaviour of physical systems.

**Delphi approach**: an approach to answering a research question through the identification of a consensus view across subject experts.

**Deterministic model:** mathematical model that gives an exact value for an outcome as a function of parameters and without the involvement of randomness.

**Draft tube**: the draft tube acts as a decelerator for the water passing through the runner blades diffusing the remaining kinetic energy and creating a smooth streamflow to the tailrace.

**Ebb generation**: electricity is generated twice a day as the tide recedes.

**Empirical Transport Model (ETM)**: analytical model which estimates entrainment based on the volume of water withdrawn by a power scheme and the distribution of entrainable age groups.

**Encounter Risk Models (ERM)**: models designed to assess processes prior to a fish entering the Entrainment Zone.

**Entrained:** passage of fish through a water intake.

**Entrainment Zone (EZ)**: area upstream of the tidal range power scheme where flow exceeds the MSSS and there is limited escape potential.

**Eulerian Lagrangian and Agent-based Models (ELAM)**: combination of hydrodynamic model and particle tracking with an individual based model to model complex animal movements made independent of advection.

**Flood generation**: electricity is generated twice a day as the tide rises.

**Francis turbine**: an inward-flow reaction turbine combining radial and axial flow sat in a spiral casing.

**Head difference:** difference in water level between where the water enters into the hydro system and where it leaves.

**Hydrodynamic modelling**: study of fluids in motion.

**Ichthyoplankton**: eggs and larvae of fish.

**Individual Based Models (IBM)**: estuarine circulation models which can simulate complex individual animal behavioural responses to external stimuli.

**Kaplan turbine**: a propeller type reaction turbine with adjustable blades which sits inside a tube in horizontal or vertical axis.

**Maximum Sustainable Swimming Speed (MSSS)**: maximum speed that can be maintained by a fish for more than 200 minutes without exhaustion.

**Physoclists**: fish that lack a connection between the swim bladder and the alimentary canal.

**Physostomes:** fish with a swim bladder connected to the alimentary canal.

**Shear and turbulence**: both expressions of changes in water velocity and direction and occur when two masses of water moving at different velocities are adjacent to or intersect each other.

**Stay vane**: vanes that remain in a stationary position and guide water to the runner blades of the turbine.

**Stochastic model**: model that presents data and predicts outcomes that account for certain levels of unpredictability or randomness.

**STRAFLO turbines**: rim generator turbines with the generator rotor attached to the runner blade tips sealed from the waterway.

**Three-dimensional modelling**: modelling of a flow field with variation in all three coordinate directions.

**Tidal range power:** generation of power from using a head difference between two water bodies separated by a wall.

**Tidal stream power:** generation of power from capturing kinetic energy from fast-flowing tidal currents.

**Two-dimensional modelling**: modelling of a flow field in which the velocity varies in two dimensions

**Wicket gate**: wicket gates control and direct the flow and quantity of water entering the intake flume prior to passing through the runner blades.

# Crynodeb gweithredol

Mae cynlluniau pŵer amrediad llanw, sy'n cynhyrchu trydan o'r gwahaniaeth mewn uchder llanw rhwng dau gorff o ddŵr, yn ffynhonnell ynni adnewyddadwy ragweladwy a dibynadwy. Mae Cymru, gyda'i hamrediadau llanw uchel, yn cynnig potensial cryf ar gyfer datblygiadau o'r fath.

Fodd bynnag, gallai'r cynlluniau hyn effeithio ar boblogaethau pysgod mewn sawl ffordd: anaf neu aflonyddwch wrth deithio drwy'r tyrbin, newidiadau i gynefinoedd, newidiadau mewn ansawdd dŵr, ac aflonyddwch sŵn. Mae teithio drwy dyrbinau, yn benodol, yn peri risg sylweddol o farwolaeth pysgod. Felly, mae asesu effeithiau posibl ar bysgod yn hanfodol.

Mae deall anafiadau i bysgod o dyrbinau yn cynnwys tair prif elfen: (1) y tebygolrwydd y bydd pysgod yn mynd i mewn i'r tyrbinau, (2) y risg o anaf neu farwolaeth wrth deithio drwyddynt, a (3) effeithiau hirdymor ar unigolion a phoblogaethau. Oherwydd cymhlethdod y dyluniadau, yr ychydig gynlluniau ynni dŵr llanw sy'n bodoli eisoes, ac oherwydd bod arsylwadau uniongyrchol naill ai'n anodd neu na ellir eu gwneud cyn eu gosod, mae angen modelu rhagfynegol. O ystyried yr ansicrwydd mewn modelu, mae efelychu a dadansoddiad sensitifrwydd yn allweddol i wella hyder yn y canlyniadau.

Dau derm a ddefnyddir yn aml mewn modelu effaith tyrbinau yw "Modelau Risg Cyfarfyddiad" a "Modelau Risg Gwrthdrawiad". Nid yw'r termau wedi'u diffinio'n gyson. Yn yr adolygiad hwn, mae risg cyfarfyddiad yn cyfeirio at brosesau cyn i bysgodyn fynd i mewn i'r pwynt lle na all osgoi mynd trwy'r cynllun pŵer amrediad llanw. Mae risg gwrthdrawiad yn cyfeirio at amcangyfrif cyfraddau gwrthdrawiadau, anafiadau neu farwolaethau wrth fynd trwy'r tyrbinau neu strwythurau eraill fel llifddorau.

Mae dros 100 o rywogaethau pysgod yn nyfroedd Cymru, llawer ohonynt â statws gwarchodedig neu bwysigrwydd masnachol a allai olygu bod angen asesu effeithiau cynlluniau amrediad llanw. Nod yr adolygiad hwn, a gomisiynwyd gan Cyfoeth Naturiol Cymru (CNC), yw nodi a gwerthuso modelau sy'n addas ar gyfer asesu effeithiau pysgod o dan wahanol gyfundrefnau amgylcheddol a thrwyddedu.

Roedd yr adolygiad yn cynnwys:

- Chwilio llenyddiaeth ar gyfer modelau a ddefnyddir ar gyfer technolegau ynni llanw ac ynni dŵr tebyg
- Dechrau sgrinio modelau gan ddefnyddio meini prawf ansoddol
- Disgrifiadau manwl o fodelau a ddewiswyd, gan gynnwys allbynnau, anghenion data, cymhlethdod, statws dilysu, a rheoli ansicrwydd
- Argymhellion ar gyfer modelau neu gyfuniadau o fodelau, eu cryfderau a'u gwendidau cymharol, a'u cymhwysedd;
- Dadansoddiad bylchau ac argymhellion ar gyfer gwaith pellach

Archwiliodd yr adolygiad llenyddiaeth fodelau ar gyfer rhywogaethau eraill fel adar a mamaliaid morol hefyd. Gwerthuswyd modelau gan ddefnyddio matrics sgorio yn seiliedig ar werth a hyder. Adolygwyd pob model a ddewiswyd o ran ei strwythur, ei hanes, sut y'i defnyddiwyd yn y gorffennol, ei anghenion data, a'i gyfyngiadau.

Cafodd dau fodel cyfarfyddiad—Modelau Seiliedig ar Unigolion a Modelau Parth Tynnu Amgen—y sgôr uchaf am eu hyblygrwydd a'u gallu i archwilio ymddygiadau cymhleth pysgod. Fodd bynnag, maent yn peri heriau o ran casglu data, gofynion cyfrifiadurol a dilysu.

Cafodd dau fodel risg gwrthdrawiadau—Deng-Kaplan a STRIKER—sgoriau uchel hefyd am eu perthnasedd, eu gallu i asesu effeithiau cyfansawdd, a'u triniaeth o ansicrwydd. Sgoriodd STRIKER ychydig yn is oherwydd tryloywder cyfyngedig (dyluniad ("blwch du") a dibyniaeth ar ddata tyrbinau perchnogol.

Mae'r argymhellion yn cynnwys mynd i'r afael â'r bylchau hyn, dilysu modelau, ymgorffori effeithiau anuniongyrchol, a datblygu offer asesu ar lefel y boblogaeth. Mae creu modelau safonol i'w cymhwyso'n ehangach ledled Cymru a'r DU yn argymhelliad allweddol wrth symud ymlaen.

# Executive summary

Tidal range power schemes, which generate electricity from the difference in tidal height between two bodies of water, are a predictable and reliable renewable energy source. Wales, with its high tidal ranges, offers strong potential for such developments.

However, these schemes may affect fish populations in several ways: injury or disruption during turbine passage, habitat changes, water quality shifts, and noise disturbance. Turbine passage, in particular, poses a significant risk of fish mortality. As such, assessing potential impacts on fish is critical.

Understanding fish injury from turbines involves three main components: (1) the likelihood of fish entering the turbines, (2) the risk of injury or death during passage, and (3) long-term impacts on individuals and populations. Due to design complexity , the few existing tidal hydropower schemes in existence, and because direct observations are either difficult or cannot be made before installation, predictive modelling is necessary. Given the uncertainty in modelling, simulation and sensitivity analysis are key to improving confidence in results.

Two terms often used in turbine impact modelling are "Encounter Risk Models" and "Collision Risk Models." The terms are not consistently defined. In this review, encounter risk refers to processes prior to a fish entering the point of not being able to prevent passage through the tidal range power scheme. Collision risk refers to estimating; collision, injury or mortality rates during passage through the turbines or other water passage structures such as sluices.

There are over 100 fish species in Welsh waters, many with protected status or commercial importance which may require assessment of impacts from tidal range schemes. This review, commissioned by Natural Resources Wales (NRW), aims to identify and evaluate models suitable for assessing fish impacts under various environmental and permitting regimes.

The review included:

- A literature search of models used for tidal and similar hydro power technologies
- Initial model screening using qualitative criteria
- Detailed descriptions of selected models, including outputs, data needs, complexity, validation status, and uncertainty management
- Recommendations of models or combinations of models, their relative strengths and weaknesses, and applicability;
- Gap analysis and recommendations for further work

The literature review also examined models for other species like birds and marine mammals. Models were evaluated using a scoring matrix based on value and confidence.

Each selected model was reviewed for its structure, history, past applications, data needs, and limitations.

Two encounter models—Individual Based Models and Alternative Draw Zone Models—were rated highest for their flexibility and ability to explore complex fish behaviors. However, they pose challenges in terms of data collection, computational demands, and validation.

Two collision risk models—Deng-Kaplan and STRIKER—were also rated highly for their relevance, ability to assess compound impacts, and treatment of uncertainty. STRIKER scored slightly lower due to limited transparency (“black box” design) and reliance on proprietary turbine data.

Recommendations include addressing these gaps, validating models, incorporating indirect impacts, and developing population-level assessment tools. Creating standardized models for broader application across Wales and the UK is a key recommendation moving forward.

# 1.Introduction

## 1.1 Overview of tidal range power

Tidal range power schemes have the potential to produce vast amounts of electricity and are a reliable and predictable renewable energy source (Waters & Aggidis, 2016b). Tidal range power is created using a head difference (difference between high and low tide) between two bodies of water. To create the required head difference a wall is used to separate the two areas and as the tide flows in or out, the wall blocks the flow of the tide and creates a head difference. In some operating concepts pumping (through running the turbines in reverse) is employed to increase the head difference. When the head difference has reached an optimum level, water is released through turbines or sluices/passes in the wall/embankment and creates energy due to the water turning turbines within the wall. Tidal range power schemes are considered low head schemes as they are operated at a head of less than 30m. The types of turbine suitable for low head schemes within a tidal environment centre around axial flow (the flow through the blades is aligned with the axis of their rotation), reaction type machines (the turbine blades are fully submerged and produce energy from the reaction of water pressure against the runner blades) whether within the vertical or horizontal plane. For maximum heads less than 10m, horizontally aligned axial turbines are generally the optimal machine selection. The basic components of a turbine of this type include an intake flume, stay vanes/column, wicket gates, runner blades and a draft tube. The wicket gates control and direct the flow and quantity of water entering the intake flume prior to passing through the runner blades. There are three types of axial turbine which may be operated in the horizontal axis in a tidal range power scheme; Bulb-Kapeller, Bulb-Kaplan and STRAFLO. Bulb turbines all have their generators enclosed within a bulb shaped structure upstream of the runner blades. STRAFLO units are a type of rim generator turbine with the generator rotor attached to the runner blade tips sealed from the waterway. Bulb type machines are distinguished via their type of regulation. There are four main ways by which a turbine can be regulated; double regulated, single regulated (runner blades), single regulated (wicket gates) and unregulated.

There are three different operating cycles tidal range power schemes can operate optimally: (1) ebb generation, where electricity is generated twice a day as the tide recedes; (2) flood generation, where electricity is generated twice a day as the tide rises; and (3) bidirectional (ebb and flood) generation, which generates electricity on the ebb tide and the flood tide per day but requires more complex turbines optimised to operate in both directions. Each of these methods use a mixture of filling the basin behind the wall with water, holding the water in the basin to create the required head difference as the tide falls, using the turbine to generate electricity and an optional method involving pumping and sluices to increase the head difference (Waters & Aggidis, 2016b). In addition to aiding filling of the basin, sluices can also increase the permeability of the tidal range power scheme and aid fish passage.

The first designs of tidal range power schemes involved the construction of a barrage across the full width of an estuary. The most famous example in Europe is the La Rance power plant in France, built in 1967 and still operating successfully today. In 1984 a tidal range power scheme was built in Annapolis, Canada and was shut down at the beginning of 2019 due to equipment failure. The most recent scheme developed is in South Korea at Sihwa. An artificial lake was constructed as a land reclamation project in 1994. Following closure of the lake water quality deteriorated and the decision was made by the Korean government to construct a tidal power plant at the site to improve seawater circulation and generate electricity. Construction commenced in 2004 and the plant became operational in 2011. Tidal range power schemes can create large quantities of energy, but further deployment has been hampered by concern regarding the potential for significant environmental concerns, including impacts on the tidal cycle and tidal habitats, interference with fish and marine mammal migration, and mortality of aquatic animals during passage through the turbines (Waters & Aggidis, 2016b). However, despite these environmental concerns, the large and predictive energy generating potential of a tidal range projects mean they remain an attractive prospect and the potential for new project developments are continually under consideration (Neill *et al.,* 2018).

Modifications to the across estuary barrage approach have been considered in more recent studies with the intention to reduce environmental harm amongst other more engineering and cost considerations. A tidal lagoon system can be designed to not completely block a river or estuary although some designs may encompass one or more river mouths. They can either be shore-connected devices, with a dam-like wall forming a horseshoe shape, with the land finishing the enclosure, or 'offshore' where the dam structure forms a complete enclosure, and the energy created is transported to shore through underground cables or in cables within the scheme walls. Lagoons do not physically block the migratory paths of fish, as long as no water courses are encompassed within the lagoon, but there is still a risk of fish becoming entrained and killed when the turbines operate.

## 1.2 Impact mechanisms of tidal range power on fish

The operation of a tidal range power scheme has the potential to impact fish in several different ways: (1) disruption to fish passage through injury mechanisms or non-fatal effects; (2) habitat change or loss; (3) changes to water quality; and (4) anthropogenic noise disturbance. Disruption to fish passage through, in particular, passage through the turbines, is likely to be the primary source of direct fish injury and mortality from a tidal range power scheme and consequently make a significant contribution to overall effects of a tidal range power scheme upon fish populations in the vicinity of such a development. Any such tidal range power scheme will therefore, require the assessment of potential impacts upon fish populations. The direct and indirect effects of fish turbine passage will be essential to assess quantitatively or qualitatively.

Tidal range turbines, like in-river hydropower turbines, are generally set in draft tubes (a specialised tube that is a connection between the intake flume and turbine exit) within a barrage or lagoon wall. Tidal range power turbines are however larger and rotate more slowly (usually <100 rotations per minute (rpm)) than in-river hydropower turbines (>300 rpm) which directly influences risk of fish injury or mortality. Once an animal enters the area upstream of the tidal range power scheme where flow speed exceeds the maximum sustainable swimming speed (MSSS), there is limited escape potential and it is highly unlikely the animal could manoeuvre itself to avoid turbine passage (Coutant & Whitney, 2000; Schweizer *et al.,* 2011).

There are effectively three components to understanding or modelling turbine passage and injury risk to fish from a tidal power scheme: (1) the probability of fish that become entrained into the turbine draft tube; (2) the probability that fish are killed or sustain mortal injury when passing through the turbine and the draft tube; and (3) the number of fish which are subject to longer-term lethal and sub-lethal impacts of turbine passage on individuals and populations.

Because of the number and complexity of processes involved, the infancy of many tidal range designs, and because empirical observations are either difficult or cannot be made until the scheme is installed, modelling is required to predict the impacts of tidal range power schemes on fish. There are numerous examples of such models for water abstraction, in-river hydropower, tidal stream, and wind, but studies specific to tidal range power have been few. Therefore, it may be necessary to use, adapt, or learn from models developed for other technologies and taxa.

## Probability of entrainment

The number of fish entrained will be a function of the density of fish upstream of the tidal range power scheme (inclusive of turbine and sluice structures) and the probability that fish are within or enter the Entrainment Zone (EZ) when the turbine is operating. For mobile individuals, this probability is partly dependent on the size of the EZ, determined by flow fields upstream of the turbine and the swimming capability of fish to resist entrainment (Johnson *et al.,* 2004; Čada & Schweizer, 2012; Willis, 2010). Behavioural traits (avoidance or attraction) as well as residence/passage time in the vicinity of the scheme, migratory paths and habitat utilisation will also affect the likelihood of fish being entrained. It is generally assumed that if a tidal range project is constructed in or across an estuary, or rivers discharge inside the lagoon severing the migratory path of a diadromous species, then migrating individuals will attempt to pass through the turbines by voluntarily entering the entrainment zone because of attracting flows (Wilkes *et al.,* 2018). This is because if a tidal range power scheme effectively blocks a migratory route, then the turbine draft tubes, sluices or other passage structures (such as fish passes or locks) will be the only routes for diadromous fish to complete their life cycle in their homing river or will stray to another river. Other species might be deterred from approaching the entrainment zone while the turbine is operating because they sense noise and vibrations depending on their hearing capability and underwater noise and vibration levels of the operating turbines or may also pass through the scheme. The tidal range project may offer attractive shelter or foraging opportunities, and any fish selecting to utilise habitat near the structure may be vulnerable to entrainment when the turbine operates (Hammar *et al.,* 2015; Martins *et al.,* 2014; Viehman & Zydlewski, 2014). Migratory fish species, as well as other fish species, have the potential to be entrained multiple times during their movement through, or residence within, the estuary. For ichthyoplankton, which have limited or no mobility, it is the circulation patterns of the estuary that will determine the probability of entrainment (Heimbuch *et al.,* 2007).

## Probability of mortal injury

The mechanisms by which fish are injured or killed during turbine passage are generally grouped into 4 categories: (1) mechanical; (2) pressure; (3) shear and turbulence; and (4) cavitation. Mechanical injury may include strike from turbine blades or from other structures such as wicket gates, abrasion from contact with surfaces such as the draft tube, and grinding on turbine components. Water pressure changes considerably as it passes through a turbine. The general profile is one of pressure build-up through the intake channel, reaching a peak within the turbine casing and then rapidly decreasing as the water passes through the runner blades, exhibiting its lowest pressure near the blade tip (Becker *et al,* 2003, Davies, 1988). Shear and turbulence are both expressions of changes in water velocity and direction and occur when two masses of water moving at different velocities are adjacent to or intersect each other. Cavitation is the collapse of bubbles or vapour pockets, resulting in the formation of high-pressure jets, high levels of turbulence and localised high pressure shock waves. Each of these mechanisms can lead to direct mortality of a fish. Additionally, if injuries are not immediately lethal, fish may suffer delayed and indirect mortality sometime after passage through the turbine. For any given turbine the probability of a fish being injured, and the extent of any resulting injury, is dependent not only upon the species and life stage in question but also the route by which it passes through the turbine. Additionally, fish may be indirectly killed or suffer from non-lethal effects, as a result of disorientation, increased predation, delay to migration and sub-lethal stressors limiting the capacity for the normal activity of the fish including reproduction (through the effects of stress including increased hormones and diversion of energy away from reproduction).

The probability and frequency of a fish passing through a tidal power scheme turbine (or other passage structure), and the injuries it may sustain, are dependent upon the species, its life stage and morphology, the turbine and wicket gate geometry and operating conditions. The injuries sustained by a specific fish depend upon the route of passage taken through the structure in relation to its vertical position in the water column, its orientation at the point of entry, transit time and whether the fish attempts to swim with or against the flow. Depending upon the extent of tidal excursion within the waterbody at the point of the tidal power scheme and the residence/passage time of fish receptors there is also the potential for an individual fish to make numerous passages through the structure.

In addition to the size, species and behaviour of a fish as it passes through a turbine, the specific design of the scheme, its turbine units and the way in which it is operated have the potential to influence the magnitude of the resulting effects upon the fish receptors. It is generally considered, for example, that the probability of a fish being struck by a turbine blade decreases as the turbine size increases, the number of blades reduces and the rotation speed decreases, resulting in increased open area for safer fish passage. The operation mode of the scheme also affects the probability of a fish being exposed to a generating turbine as opposed to a freewheeling turbine (blade rotating but not generating energy) or sluice, which, although not benign, pose lower risks of injury to fish. Fish survival from most turbine passage impacts is also considered likely to be greatest when turbines are operating at their highest efficiency and flow paths are at their smoothest.

Data on fish mortality and injury from turbine passage from existing hydropower schemes predominantly those in freshwater with limited tidal power examples may aid predictions of the potential effects of a proposed tidal range power scheme upon fish receptors. Mortality estimates gathered from field observations from predominantly freshwater hydropower schemes range depending on scheme design and operation characteristics, fish species and life stages and as such widely vary from the extremes of 0% to 100% mortality. Mortality rates of greater than 50% are, however, considered to be rare, and in a literature review by Pracheil *et al.,* (2016) average mortality for the two most common designs of turbine was found to be 8% and 28% (Kaplan and Francis turbines, respectively). Variation in mortality between species can be high, with eels (*Anguilla* spp.) transiting Francis turbines having low mortality compared with most salmonids, cyprinids, and percids, but higher mortality when transiting Kaplan turbines (Pracheil *et al.,* 2016). Regarding ichthyoplankton, the shear forces and pressure changes in low-head bulb turbines (i.e., the type likely to be used for tidal range power) are unlikely to cause ichthyoplankton mortality (Cada, 2019). The probability of contact with turbine blades is related to size of the fish, meaning a negligible proportion of ichthyoplankton will be struck (Cada, 2019).

Studies on the potential for tidal power generation in UK waters and the possible impacts upon fish date back to the 1980s. As part of studies to inform the potential for a tidal power scheme in the Severn Estuary experimental investigations were undertaken in the 1980s to better understand the potential effects to fish and shrimps from passage through tidal power turbines. These experimental investigations remain the primary dedicated laboratory investigations specifically undertaken for tidal power schemes in the UK. The investigations included experimental trials to determine the effects of pressure, cavitation, shear stress and mechanical strike (Turnpenny *et al*., 1992, Turnpenny, 1998, Turnpenny & Everard, 1999 and McEwen & Scobie, 1992).

In more recent years a requirement for increased fish protection, in particular in the US, sparked the commencement of a series of laboratory based and experimental studies investigating the effects of turbine passage upon fish. These studies have increased the understanding of thresholds of effects from mechanical and fluid dynamic mechanisms as well as indirect effects from which assessment for hydro power installations can be informed. To enable application of the thresholds of effects, a series of investigations have also been undertaken to investigate the fluid dynamics during passage through a draft tube and turbine. In particular, this modelling has considered shear stress and pressure which could be experienced by a fish during passage (e.g. Franke *et al*., 1997, Turnpenny *et al*, 2000, Neitzel *et al*., 2000, 2004 and Guensch *et al*., 2002).

## Number of fish subject to non-lethal effects

Regarding impacts on fish migration and population connectivity, there are some fundamental differences between tidal range power and in-river hydropower, and perhaps more similarities with tidal stream power. Critically, return passage is either difficult or impossible after passing through an in-river hydropower facility (depending on if an effective fish pass has been erected), meaning a net loss to the upstream population (Pelicice & Agostinho, 2008). For tidal range turbines, passage through the turbine draft tube can occur in both directions, potentially resulting in less impact on connectivity and migration, but meaning fish might encounter the turbine on multiple occasions over their lifetime (Willis & Teague, 2011). For bidirectional generation, turbine mortality becomes a risk each time a fish passes through the turbine draft tube. For ebb and flood generation, mortality risk arises on the downstream and upstream journey, respectively. Alternatively, at tidal lagoon sites, fish could become stranded in the lagoon where habitat may not be suitable, be unable to complete migrations and fish may experience salinity stress or be at greater risk from predators.

Based on the discussion above, Figure 1 shows a conceptual schematic describing how fish may encounter and be impacted by a tidal range power scheme. Fish may enter the

EZ either due to attracting flows when the turbine is operating (e.g., for migratory fish), advection by estuarine circulation (ichthyoplankton), to complete passage through or within the estuary or because the EZ offers attractive habitat when the turbine is not operating. Fish outside of the EZ may be deterred from entering the EZ (if they do not have a drive to pass in that direction) when the turbine is operating following distant detection of sensory stimuli emitted by a turbine.  The rates of injury and mortality from turbine passage will depend on the operating design of the scheme and species, life-stage, size, and body shape. When exiting the draft tube fish are likely to be at increased risk of predation and may be exposed to environmental stressors if the habitat is not optimal, for example a tidal lagoon.

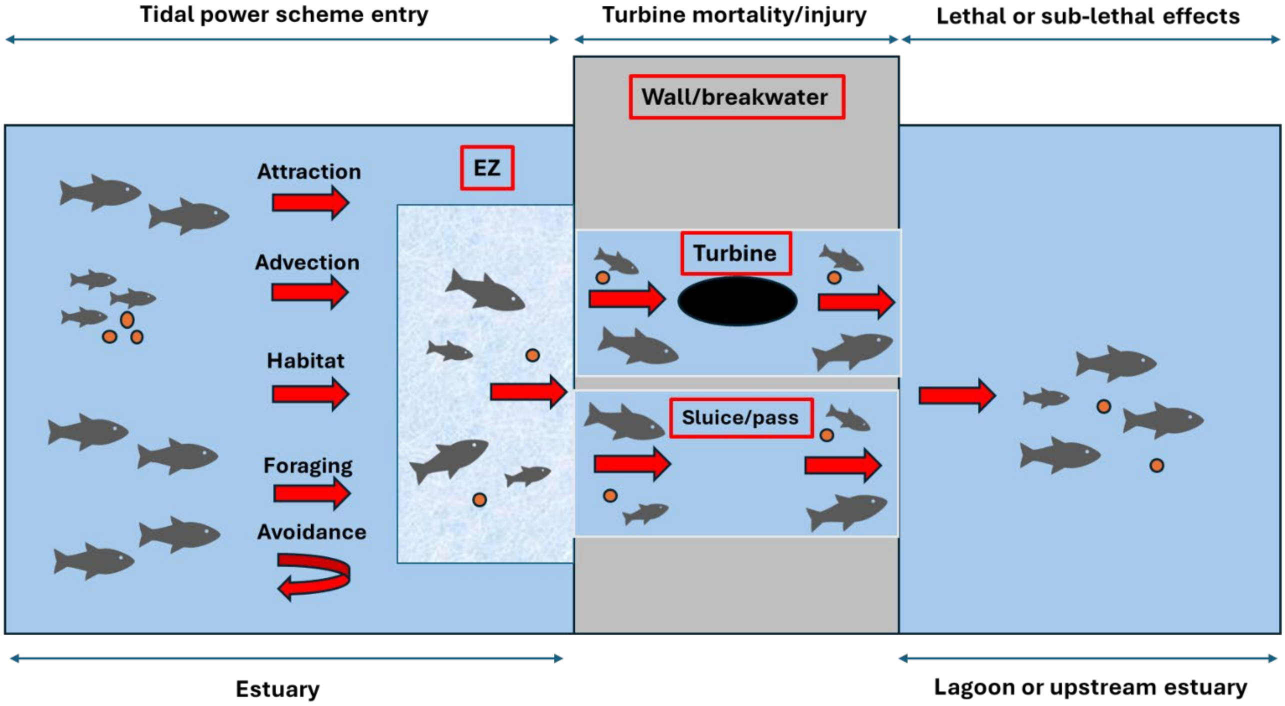


Figure 1: Conceptual schematic diagram of how fish will encounter and be impacted by a tidal range facility.

## 1.3 Modelling approaches and background

Two common terms for models developed to predict the impacts of turbines on wildlife are Encounter Risk Models (ERMs) and Collison Risk Models (CRMs). The terms, however, are not consistently defined (Band *et al.,* 2016), and whilst frequently used for tidal stream and wind turbine scenarios, have rarely been used in studies focused on tidal range or hydropower. In one of the first studies to differentiate encounters from collisions, Wilson *et al.,* (2006) define an encounter as a close interaction which could lead to a collision. The collision rate is the product of the encounter rate and the probability that an animal does not take evasive action (avoid at near distance) or avoid the encounter following distant detection of sensory stimuli emitted by a turbine (Wilson *et al.,* 2006). Accordingly, CRMs often estimate both the encounter and collision risk, for example, in the Band Model regularly used for windfarm assessments of impacts upon bird species (Band *et al.,* 2000). Stage 1 of the Band Model estimates the number of birds expected to fly through the rotor swept area of wind turbines (i.e., the encounter rate), and Stage 2 the probability of a bird being hit by a rotor blade (i.e., the collision rate).

For the purposes of this review, encounter risk refers to processes prior to a fish entering the EZ, including avoidance of tidal range infrastructure, whilst collision risk refers to models that estimate collision, injury, or mortality rates during passage through turbines and other water passage structures such as sluices (as per stages in Figure 1).

### 1.3.1 Encounter risk

Encounter risk modelling for hydropower and abstraction has focused on entrainment which is directly relevant to a tidal range power scheme where water circulation and tidal currents are of key importance. The empirical transport model (ETM) is an analytical model which estimates entrainment based on the volume of water withdrawn by a power scheme and the distribution of entrainable age groups (Boorman and Goodyear, 1981). More recent studies have utilised computational fluid dynamics (CFD) to simulate the flow characteristics upstream of the turbine intake to define the size of the EZ for fish with different swimming capabilities (Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021).

For tidal range power or abstraction from estuaries it is recognised that estuarine circulation is important for estimating the encounter and entrainment probability. Simulations that couple particle tracking with hydrodynamic models of estuarine circulation are suitable for studying the movement of passive particles, and hence are only suited to examining the entrainment risk for ichthyoplankton (Heimbuch *et al.,* 2007; Smith *et al.,* 2020). To estimate encounter rates for mobile individuals, studies have combined estuarine circulation models with individual based models (IBMs) which can simulate complex individual behavioural responses to external stimuli (Willis & Teague, 2011; Rossington & Benson, 2019; Benson et al., 2021; Tidal Lagoon Swansea Bay, 2021).

Models developed for tidal stream and wind turbines are generally quite interchangeable and are more common in the recent literature relative to hydropower and tidal range power. Two of the earliest models are the Tucker (Tucker, 1996) and Band Model (Band *et al.,* 2000) which were developed to estimate the number of birds that could be expected to encounter and collide with the turbines of windfarms and have since been applied to seal encounter risk with tidal stream turbines (Band *et al.,* 2016). A second early model applied to a variety of taxa is the selective length-based survival rate (SLSR) model (Wilson *et al.,* 2006) which involved repurposing equations that were initially intended to predict encounters between predators and prey in aquatic environments. In these modified equations the ‘predator’ was substituted by the turbine rotor blades.

### 1.3.2 Turbine passage and post passage risks

The earliest models to calculate fish mortality due to turbine passage are the Von Raben equations (Von Raben, 1957). These equations are specific to Francis and Kaplan style turbines, two of the most common designs of turbines used in hydropower and tidal range power. A more recent approach is to create a computer model of the turbine to simulate collision rates and to estimate mortality and injury from other causes, such as barotrauma and shear stress (Richardson *et al.,* 2014; Klopries & Schüttrumpf, 2020).

The Band, Tucker, and SLSR models are based on simple analytical equations and their fundamental function is to estimate the number of individuals over a specified period that will occupy the same spatial and temporal extent as the rotating turbine blades. The input parameters are the design of the turbines and array (number and location of turbines, turbine size, rotation speed etc.) and the density and movement behaviours of the population observed prior to installation. Most CRMs developed since have followed similar principles but have added greater complexity in terms of stochastic simulations, animal behaviour and the lethality of a collision (e.g., Band *et al.,* 2007; Hammer *et al.,* 2015; Copping *et al.,* 2017; McGregor *et al.,* 2018; Copping & Grear, 2018; Onoufriou *et al.,* 2021), or have adapted the principles to novel animal scenarios (e.g., Grant, 2014; Band *et al.,* 2016). It is the behavioural movement input requirements of the models which are complex to determine for fish.

### 1.3.3 Uncertainty management

There are inherent limitations and uncertainty with any modelling assessment approach. For modelling environmental impacts for a tidal range power scheme this is enhanced by the fact that there are very few operating schemes and for those that do exist there is little empirical data. Thus, validation of models has seldom been possible. The behaviour of migratory fish in estuarine and bay environments is also not well known in addition to their potential interaction with a tidal power impoundment and its turbine and sluice structures. To understand uncertainty, some ERM and CRMs studies have explored different potential outcomes. This can be through either running several separate models with parameter values manually selected across the range of observed values or by using a resampling approach, such as Monte Carlo Simulation, to calculate confidence intervals from multiple iterations (thousands) with different parameter values drawn from a probability distribution (e.g., McAdam, 2005; Deng *et al.,* 2007; Eichhorn *et al.,* 2012; Tidal Lagoon Swansea Bay, 2021). A second important statistical technique to understand uncertainty is sensitivity analysis. This involves running multiple models with values for each parameter varying by reasonable ranges and is used to identify which parameters have the greatest effect on the model predictions and therefore require further data collection, or alternatively, which parameters contribute little and might be removed to produce a simpler model.

## 1.4 Fish receptors

The first step in any assessment and modelling process will be to identify the fish Valued Ecological Receptor (VER) species that will be subject to assessment. Six independent VER criteria are usually used to reflect different quality attributes of the fish assemblage. The approach is analogous to the criteria used to assess value in ecological impact assessments. Fish VERs are usually identified on the basis of:

- Known utilisation of the scheme area during one or more of the species life stage;
- Particular value to biodiversity (e.g. relative contribution to the overall assemblage);
- Special spawning/recruitment dependencies making them more susceptible to effects;
- Social/community value (e.g., recreational importance);
- Economic value (commercial landings); or
- Legal protection status/presence in protected areas.

Where numerous fish VERs require consideration within an assessment, it is common practice to group species into ecological or functional groupings for some elements of the assessment process. Functional guilds are generally used for this purpose as they are particularly well suited to identify effect pathways (which will be similar for species with similar functional use of the habitat) and are acknowledged as best practice in fish ecological assessments in the marine environment. The UKTAG Functional Guild definitions (UKTAG, 2014) are usually used for consistency with UK WFD methods and to acknowledge the potential for differential use of estuarine quality attributes by migrating juvenile fish as well as different levels of sensitivity to the effects of a scheme. Where more detailed assessments are required and suitable information/data is available, individual species assessments should be considered. This is particularly true of the migratory VERs (i.e. species within the Diadromous Functional Guild) due to their listing as features within various designated sites around the UK, wider conservation status and other aspects such as recreational/social importance, in particular within dynamic estuarine environments. In line with general requirements due to the potential longevity of a tidal range power scheme, the potential for climate change to affect the fish assemblage should also be considered, in particular, the potential for species known to occur further south, potentially moving northward. It is recommended that for the purposes of tidal range power impact modelling and assessment that the fish VERs are split into model and non-model species. The assessment of non-model species is likely to be undertaken at the Functional Guild level, with where possible, species specific information providing further detail. These species are generally not subject to modelling/quantitative assessment, semi-quantitative and qualitative assessments are likely to be undertaken. VERs identified as Model Species should be considered within numerical modelling of the effects of entrapment and collision risk from passing through the turbines.

With regards to fish species in Welsh waters, over 100 fish species have been recorded within the Severn Estuary alone. There are a number of fish species which are features of sites within the National Site Network (NSN) in Wales including Atlantic salmon (*Salmo salar*), twaite shad (*Alosa fallax*), allis shad (*Alosa alosa*), sea lamprey (*Petromyzon marinus*) and river lamprey (*Lampetra fluviatilis*). In addition, the internationally protected catadromous European eel (*Anguilla Anguilla*) is also present around the Welsh coastline. Other protected or important fish species of potential concern for a tidal range power scheme in Wales could include for example; sea trout (*Salmo trutta*), smelt (*Osmerus eperlanus*), cod (*Gadus morhua*), herring (*Clupea harengus*), plaice (*Pleuronectes platessa*), sole (*Solea solea*), whiting (*Merlangius merlangus*), blue whiting (*Micromesistius poutassou*), hake (*Merluccius merluccius*), horse mackerel (*Trachurus trachurus*), ling (*Molva molva*) and saithe (*Pollachius virens*), thornback ray (*Raja clavate*), spiny dogfish (*Squalua acanthias*) and angel shark (*Squatina squatina*).

## 1.5 Project background

This review was commissioned by NRW who are seeking to gain greater understanding of which models have been used, or have the potential to be used, to assess the impact of tidal range power on fish. Assessing impacts is required for environmental assessment required under legislation (e.g., EIA regulations 2017, Habitats Regulations, Water Framework Directive (WFD)) as part of the permitting regimes, such as Development Consent Orders and Marine Licence. NRW would like to identify which models, or combinations of models, would be suitable for these assessments.

To address the above objective this review undertakes the following tasks:

- A literature search of models which have been used to estimate the impacts on animals of tidal range power and comparable power generating technologies;
- High level screening of models based on qualitative scoring criteria to identify potential candidate models;
- A detailed description of candidate models, covering; outputs, data requirements, computational complexity, validation, and how the models deal with uncertainty;
- Recommendations of models or combinations of models to be used, their relative strengths and weaknesses, and applicability to different tidal range scenarios; and finally,
- Gap analysis and recommendations for further work.

# 2. Approach and methodology

## 2.1 Literature search

Literature was collected using the Google Scholar search engine with consideration of peer-reviewed literature, as well as grey literature from tidal power development assessments and research institute investigations. The knowledge of the project team was also utilised to explore further sources such as from specific development assessments including the Severn Tidal Power Strategic Environmental Assessment, references relating to Tidal Lagoon Swansea Bay, and known research institutes outside of the UK such as the Electric Power Research Institute (EPRI), Alden Laboratories, Pacific Northwest National Laboratory (PNNL) and others with a focus on tidal power/hydropower research.

Google scholar was the key search engine used as it is generally more likely to find grey literature as well as peer-reviewed literature (compared to programmes such as EndNote or Mendeley).

The following search strategy was used to search literature targeted at the models for each taxonomic group considered (fish, mammals, birds):

- Taxa name
- AND “collision risk model” OR “encounter risk model” OR “CRM” OR “ERM” OR “turbine passage” OR “IBM” OR “entrainment” OR “entrapment”
- AND “tidal power” OR “tidal lagoon” OR “tidal barrage” OR “tidal stream” OR “tidal range” OR “hydropower turbine” OR “low head turbine” OR “Kaplan turbine” OR “bulb turbine” OR “offshore wind” (birds only)

For example: ("fish") AND collision risk model” OR “encounter risk model” OR “CRM” OR “ERM” OR “turbine passage” OR “IBM” OR “entrainment” OR “entrapment”) AND (“tidal power” OR “tidal lagoon” OR “tidal barrage” OR “tidal stream” OR “tidal range” OR “hydropower turbine” OR “low head turbine” OR “Kaplan turbine” OR “bulb turbine”)

Up to the first 100 search results for each taxa were screened (title, abstract) using the exclusion criteria below:

1. Exclude because study does not provide information on CRM or ERMs; and,

2. Exclude because the study does not provide/has limited information on tidal power or offshore wind mechanisms for interactions.

If a paper was deemed to be relevant and of use but did not appear in the first 100 screened results, it was added on the grounds of expert knowledge.

## 2.2 Model assessment

Models selected after the title and abstract screening were subject to more detailed screening using the value and scoring assessment criteria outlined below. If papers used a similar modelling approach, then these were grouped together for the model assessment; for example, papers using computational fluid dynamics to model the entrainment zone were grouped under ‘Entrainment Zone CFD’ models.

### 2.2.1 Value and Confidence assessment screening method

The benefits and limitations of each model were assessed using a comprehensive and transparent value and confidence assessment methodology developed by APEM. There are several methods available to assess confidence in an existing evidence base to inform decision-making. The value and confidence assessment method developed for this study follows a matrix-based approach, which is similar to other studies within the marine environment such as Perez-Dominguez *et al.* (2016), Tillin & Tyler-Walters (2014), and Scorey & Teague (2019).

The matrix-based approach applies a qualitative scoring method to determine the value of the method for contextualising the impacts upon fish populations, and the confidence that can be placed in the outputs of the method. The assessment process allows for the identification of high-quality and robust methods to inform decision-making from a wide range of expert advice sources, as well as the most appropriate method to use in particular circumstances (for example where greater confidence is needed in an output, or where a multi-year assessment is required).

The value assessment was scored on a scale of 0-3 (Table 2-1) and is based on the following criteria:

1. **Applicability of the model**: Assessment based on whether the model is relevant to tidal range scenario and to fish, and ability for adaptation if required;

2. **Ability to use model openly**: consideration of whether the model is open source and easily adapted with scheme and site-specific parameters or whether it is a ‘black box’ model or with IP constraints which restricts its wider use and ability to review.

**3. Multi species and life stage**: Value of the model for the ability to include multiple species and life-stages within a single model or could be applied to multi species and life stages separately;

**4. Temporal modelling**: Value of the model for capability of multiple passages over time.

The confidence assessment was scored on a scale of 1-3 (Table 2-2) and is based on the following criteria:

**5. Existing evidence and data gaps**: considering the availability of parameter evidence and data for application of the model, the requirement for evidence data gathering or scheme/environment/technology specific physical parameters for application of the model and also the identified evidence and data gaps for the model;

**6. Ability to fill evidence and data gaps**: considering the practicalities of parameter data collection for application of the model, whether it is likely that sufficient parameter data can be collected for individual projects to fill the evidence and data gaps or whether scheme/environment/technology specific parameters are required. The aim of this criterion is to assess whether it is possible to collect data to apply the models for a project. This data can be collected either during project development or during operation, but ideally sufficient data should be collected at the project development and assessment stage to allow it to be considered during the determination process;

**7. Method validation data**: considering the availability of operational monitoring data to validate the models or laboratory/field-based research to validate the model parameters, and the need to conduct post-hoc analysis to understand the retrospective power of predictions made; and,

**8. Residual uncertainty**: How residual uncertainty is accounted for within the model considering the evidence and data gaps, as well as consideration of how to assess the confidence in predictions made. This will consider the means of dealing with this uncertainty, for example through qualitative methods, or quantitative statistical methods, as well as how to report predictions made.

These aspects of value and confidence, and the criteria that the evidence has been assessed against, have been developed considering the Government Chief Scientific Adviser’s Guidelines on the Use of Scientific and Engineering Advice in Policy Making (Government Office for Science, 2010).

For the assessment value criteria (criteria 1 to 4), a score of either Not applicable (0), Low (1), Medium (2) or High (3) has been given to each assessment method. This indicates whether the method can be used to provide information on the relevant type of assessment indicated, and the value of the method for the modelling application and for relevant fish receptors.

For the assessment confidence criteria (criteria 5 to 8), a score of Low (1), Medium (2) or High (3) has been given to each method. A traffic light system has been applied to this scoring for easy visual interpretation; Low/Not applicable (red), Medium (amber) and

High/Applicable (green). The assessment process outlined above allows for the identification of high-quality and robust methods to inform decision-making, from a wide range of expert advice sources, as well as the most appropriate method to use in specific circumstances (for example where greater confidence is needed in an output).

Table 2-1: Assessment value criteria and associated scoring

| Assessment value criteria (maximum score = 12) | Not applicable (score = 0) | Low (score = 1) | Medium (score = 2) | High (score = 3) |
|---|---|---|---|---|
| **1. Applicability of model** | Model is not relevant to a tidal range scenario and fish | Method is of low value to a tidal range scenario and fish and requires substantial adaptation to be used as such. | Method is of medium value to a tidal range scenario and fish and requires moderate adaptation to be used as such. | Method is of high value for value to a tidal range scenario and fish and requires no adaptation to be used as such. |
| **2. Ability to use model openly** | The model is a ‘black box’ or has significant IP restrictions meaning it cannot be easily reviewed, adapted, or used on a range of schemes | The model is open but has IP constraints or requires confidential parameters which cannot be easily determined or adjusted. | The model is open source, and all parameters can be collected without IP or confidential constraints. | Ability to use model openly |
| **3. Multispecies and life stage** | Model cannot be used to determine effects upon multiple species or life stages. | Model is of low value for providing coverage of multiple species and life stages. | Model is of medium value for providing coverage of multiple species and life stages. | Model is of high value for providing coverage of multiple species and life stages. |
| **4. Temporal modelling** | Model does not account for temporal aspects such as multiple passages over time (or number of tides) e.g., linear or one-pass models. | Model is of low value for accounting for multiple passages over time. | Model is of medium value for accounting for multiple passages over time. | Model is of high value for accounting for multiple passages over time. |

Table 2-2: Assessment confidence criteria and associated scoring

| Assessment confidence criteria (maximum score = 12) | Low (score = 1) | Medium (score = 2) | High (score = 3) |
|---|---|---|---|
| **5. Existing evidence and data gaps** | None, or little of, the required evidence to apply the model is<br>• Available;<br>• Of good quality;<br>• Applicable; and<br>• Draws clear conclusions<br>Therefore, an extensive programme of further data collection or research activities would be required to fill the evidence gaps for a robust application of the method. | Some of the required evidence to apply the model is:<br>• Available;<br>• Of good quality;<br>• Applicable; and<br>• Draws clear conclusions<br>Whereas the other evidence does not pass all four tests. Further data collection or research activities would be required to fill the evidence gaps for a robust application of the method | All, or the majority of, the required evidence to apply the model is:<br>• Available;<br>• Of good quality;<br>• Applicable; and<br>• Draws clear conclusions.<br>Therefore, the model can be robustly applied with no further data collection or research activities |

| Assessment confidence criteria (maximum score = 12) | Low (score = 1) | Medium (score = 2) | High (score = 3) |
|---|---|---|---|
| **6. Ability to fill evidence and data gaps** | Data must be collected by use of novel methods, or must be collected at a scale beyond which may be achievable for an individual project. Insufficient data is available to conduct detailed *a priori* statistical power analysis to ensure data collected is robust. | Data can be collected using established methods but may require collection at a scale beyond which may be achievable for an individual project or will need to be scheme/environment/technology specific with potential IP constraints. Limited, dated or non-specific data is available to conduct detailed *a priori* statistical power analysis to ensure data collected is robust. | Data can be collected simply, efficiently and at an individual project scale using established methods with no IP restrictions. Sufficient recent data is available to conduct detailed *a priori* statistical power analysis to ensure data collected is robust. |
| **7. Model validation** | Model predictions cannot be validated by empirical data which is either unavailable or very difficult to collect. Unable to conduct post-hoc statistical power analysis to understand the power of the predictive models. | Model predictions could be validated by empirical data but these data would need to be collected and. Post-hoc statistical power analysis to understand the power of the predictive models can be partially conducted. | Model predictions could be validated using empirical data that is either available or straightforward to collect. Post-hoc statistical power analysis to understand the power of the predictive models can be conducted. |
| **8. Uncertainty management** | Uncertainties within the model outputs which cannot be appropriately documented or managed effectively. | Uncertainties are present within the model but can be appropriately documented qualitatively. | Uncertainties are present within the model but can be documented and managed effectively, qualitatively, or quantitatively. |

For the model value assessment, any model that scored 0 for the Applicability of the model criterion was automatically screened out and not scored for other criteria. The temporal modelling criterion of the value assessment is only relevant to encounter rate probability and therefore for CRMs this criterion was assigned a value of 3, since any CRM could theoretically be coupled with a temporal ERM.

All models that received a score >0 for the Applicability of the model criterion were taken forward for detailed review in Section 4: Review of Fish or Section 5: Review of other taxa models. The review of each model includes the following:

- Model summary
- Examples of model application
- Method Value and Confidence Assessment
- Applicability of model
- Multi-species and life stages
- Temporal modelling
- Ability to use model openly
- Data availability

- Data collection
- Existing evidence and data gaps
- Method validation data
- Residual uncertainty
- Assessment Matrix
- Method Conclusions
- Applicability for Environmental Assessments

For models that scored 0 for the Applicability of the model criterion a brief description of the model and justification for the zero score is provided.

# 3. Model screening results

The literature search in Google Scholar using the search strings specified in the methodology returned 886 results for fish, 113 results for marine mammals and 373 results for birds.

# 4. Review of fish models

This section of the report provides a detailed description for each of the models including an explanation of the method, history/background of its development, where it has been used in the past, its data requirements, any validation that has been undertaken and its limitations/uncertainty. Commentary is provided on the general application of the models, their application to the different species groups and where appropriate for individual species.

## 4.1 Encounter Risk Models

### Entrainment Zone CFD

**Method summary**

Computational fluid dynamics (CFD) (including types of 2D and 3D hydrodynamic modelling) has become the predominant method for undertaking detailed modelling of flow fields surrounding turbine intakes and water passing through turbines (Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021). CFD models the flow of fluids by dividing the study area into a grid of small cells. These cells are assigned properties such as velocity, pressure, and temperature, and mathematical equations governing fluid motion, are solved for each cell. By iteratively solving these equations, CFD calculates the flow patterns and characteristics of the fluid.

The basic parameters required are bathymetric and hydrodynamic data for the waterbody upstream of the turbine and details of the tidal power structure and intake design which are used to create a two-dimensional or three-dimensional spatial model (or mesh) for the study site. The stratification profile is an additional parameter that can be included (Langford *et al.,* 2021). Flow fields and velocities are then calculated according to the abstraction rates of the hydropower scheme whether tidal or in-river, as illustrated in Figure 2.

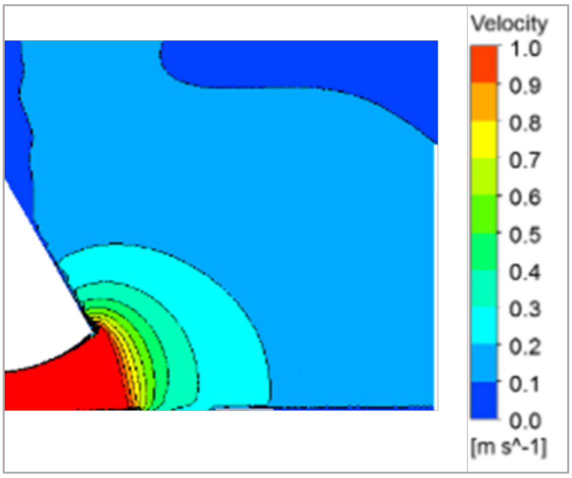


Figure 2: Two-dimensional CFD output for the turbine intake flow field at the Mica Dam, Canada (taken from Langford *et al.,* 2021).

With information on flow and acceleration fields, the next step to define the EZ extent is to link flow velocities to fish swimming speeds and their ability to resist entrainment. The volume or extent of the high-risk zone for fish entrainment generally increases exponentially with decreasing threshold swimming speed (Langford *et al.,* 2021). Thus, the high-risk zone for weaker swimmers located adjacent to the intakes is much greater than that of fish with greater swimming capabilities.

**Examples of model application**

Bao *et al.,* (2022) developed fish entrainment risk curves (ER curves) for two species of interest based on field survey work, a literature review, and professional judgment of swimming capability, and combined these ER curves with CFD modelling to estimate the EZ at a hydropower facility. The ER curves were based on determining entrainment risk in relation to velocity distribution and turbulence kinetic energy, both of which were derived from 2D hydrodynamic models. The hydropower facility is a freshwater reservoir-based scheme in China. The value for ER ranged from 0 to 1, with 0 representing the lowest ER and 1 representing the highest ER. The fish entrainment risk volume (ERV) was defined based on the fish ER by applying equal weight to the hydrodynamic variables of velocity and turbulent energy estimated by CFD. The ERV was used to evaluate two fish ERs under various reservoir operation scenarios. ER zones were further divided into high-risk zone (HRZ), moderate-risk zone and low-risk zone. The study explored different turbine operating schemes and was intended to inform fish friendly dam operation.

A CFD model of the EZ (in this case termed ‘draw zone’) was incorporated into the Alternative Draw Zone (ADZ) model (discussed in more detail below) used for the Tidal Lagoon Swansea Bay environmental impact assessment (Tidal Lagoon Swansea Bay, 2021). The model identified draw zones under different operation scenarios and the volumes of water within which if fish are present they will be drawn into the turbine draft tubes unless they exhibit avoidance behaviours. The draw zone volume represents accelerating flows as they approach the turbine structure with greatest flows experienced within the draft tube. An example of an output from this modelling approach is provided in Figure 3.

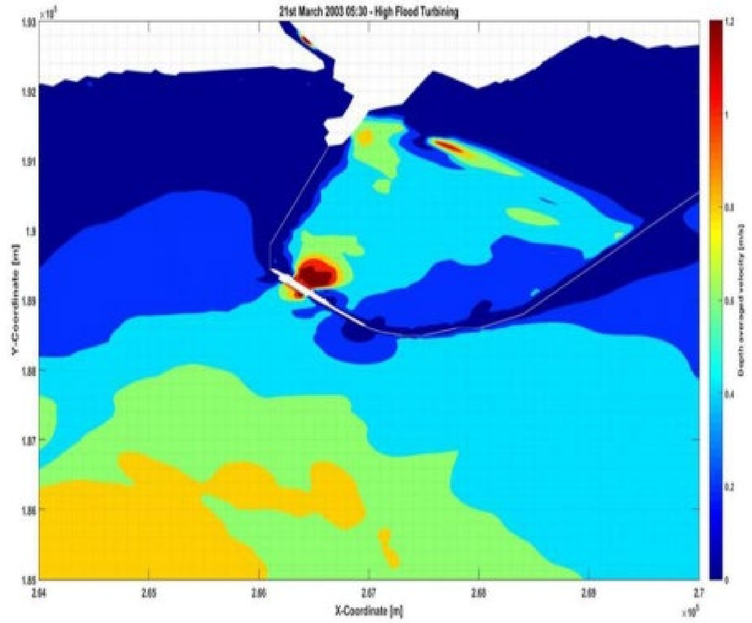


Figure 3: Example model output of the draw zone for a Swansea tidal lagoon operation regime during flood generation at high water (taken from TLSB, 2021)

Parrado & Rueda-Bayona (2024) developed a 3D hydrodynamic model which enabled the simulation of hydrodynamics of the Buenaventura Bay, Colombia to evaluate the hydraulics of a tidal barrage without sluicing with the use of CFD modelling, see Figure 4. The 3D model was built in Delft3D and was validated and calibrated using in situ data including currents, water levels, weather and bathymetry. The model investigated flow velocities through the example scheme to investigate electricity production potential and power generation estimates. Although developed for the purposes of investigating energy generation potential, it is anticipated that the model could be interpreted or adapted to estimate the EZ.

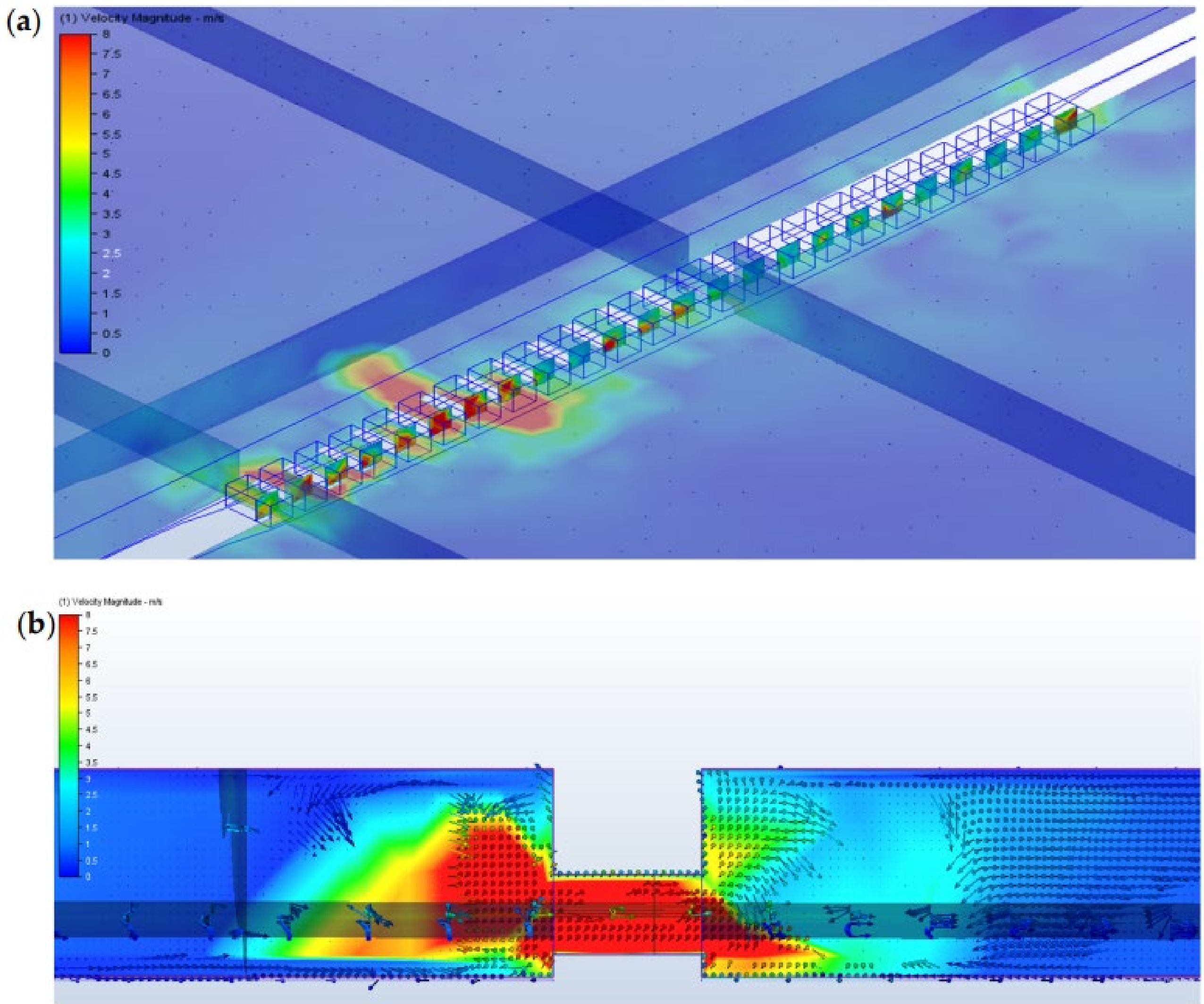


Figure 4 3D CFD velocity results along a barrage line within Buenaventura Bay, Colombia during ebb tide generation a) top view of the surface layer and b) longitudinal-sectional view (taken from Parrado & Rueda-Bayona, 2024)

**Applicability of model**

Gaining an understanding of the flow fields in front of a tidal power scheme for each passage structure including turbines and sluices is essential for development of an EZ and ultimately an ERM. Modelling including using CFD is an effective way of developing this understanding and allows visual representation and interpretation of the information. For a more complete assessment of the encounter risk CFD model outputs need to be coupled with a fish behaviour model or fish distribution data. An example of this coupled approach is the ADZ model (Tidal Lagoon Swansea Bay, 2021) discussed in more detail below. CFD models of this type are directly applicable for use in tidal power ERM modelling but would need to be developed in combination with a fish swimming/behaviour model.

**Multi-species and life stages assessment**

The CFD approach of modelling the EZ is adaptable to any species or life-stage where data on swimming capabilities is available or could feasibly be assessed and can be used to assess passive life stages such as larvae and eggs. Lack of a suitable evidence base on fish swimming and behaviour may limit the use of the model for some less studied species.

**Temporal modelling**

A CFD model of the EZ can vary according to temporal conditions (e.g., tidal cycle or withdrawal rate), different operation modes and can be coupled with a temporal model of fish behaviour to assess the risk of multiple passages.

**Ability to use model openly**

There are several software platforms for CFD modelling, with a popular platform being the commercially available ANSY CFX solver, HECRAS and Delft3D. CFD software are generally inexpensive and often a company involved with power generation will already have a license and will use CFD as a tool for assessing scheme operational performance. Building and running a CFD model however, does require specialist expertise.

**Data availability**

Data on swimming speed and fish behaviour may be available from the literature for many of the more studies fish species but is likely to be absent for others in particular within a suitable estuarine/coastal environment. If species/environment specific data are not available, then data for a similar species could be substituted as a proxy. Information on the tidal power design and operation characteristics will be required which will need to be provided by the scheme developer or turbine manufacturer depending on the specific data requirements. Data or models of the estuarine environment will be required on which to base the CFD model including bathymetry and water current information. This data is most likely to take the form of a hydrodynamic model. Hydrodynamic models of estuarine circulation can be expensive and time consuming to make and calibrate, particularly around complex coastlines and estuaries as well as requiring detailed information on aspects such as bathymetry and local physical processes. Hydrodynamic models may however, already be available and accessible if they have been a requirement of a previous Environmental Impact Assessment or have been developed for other purposes or may need to be developed specifically for the scheme under consideration due to location or level of modelling detail required (Willis & Teague, 2011).

**Data collection**

In the event that suitable data on fish swimming speeds and behaviour are not available, including for potential proxy species/environments then it may be necessary to undertake laboratory or field based investigations or use expert judgement to populate model parameters. It will be necessary to determine in collaboration with the statutory authorities what is the most appropriate data sets to use to parametrise these aspects of the models, what is considered to be acceptable and the management of the uncertainty within the input parameters. Laboratory investigations were undertaken for the 1980s Severn tidal power scheme investigations and for studies such as the EA's R&D programme on fish swimming speeds; Phase 1 and 2 (Clough & Turnpenny, 2001 and Clough *et* al., 2004). Such laboratory investigations are usually undertaken in swim tunnels and flumes with fish swimming performance and behaviour recorded for varying flow speeds.

Environmental data will also be required to form the basis of the EZ model. The collection of bathymetric data is routinely undertaken within estuarine and coastal environments predominantly for the purposes of navigation. Site specific data may however, be required to be collected to enable the fish mesh model development required for an EZ model. Estuarine hydrodynamic models are usually developed using a combination of field observations and mathematical modelling techniques. Field measurements are carried out to gather data on various parameters such as water velocity, salinity, temperature, and tidal variations within the estuary. These measurements are usually collected using instruments like current meters, water samplers, and sensors deployed at strategic locations throughout the estuary and although may be available in some instances, are likely to require some site specific data collection. The data collected provides a foundation for understanding the physical processes and circulation patterns within the estuary.

**Method validation data**

Validation of EZ CFD models has been undertaken for studies using scale models of the turbines (Huang *et al.,* 2015) and in the field using acoustic doppler current profiling (Langford *et al.,* 2021). Empirical data on how fish will interact with the scheme and their behaviour in the EZ and ultimately entrainment through the schemes water passage structures however, is more challenging to collect. Such data collection can also only be collected post scheme development or at operational schemes to validate the results of a site/development specific model. Given the limited development of tidal range power schemes worldwide such model validation data is therefore, currently absent. Techniques such as the use of tagging and telemetry and underwater acoustic imaging (such as with the use of a DIDSON camera), has however, successfully been applied to measure the entrainment rates of fish at run of river and reservoir/loch hydropower facilities (Martins *et al.,* 2013).

**Uncertainty management**

Most studies using CFD and fish swimming speeds to model the EZ have not explored or reported uncertainty in model outputs or validated the fish behavioural data used within them (e.g., Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021). Parameters such as fish swimming speeds and behaviour characteristics as well as varying scheme operating scenarios could however, be resampled within a model to explore outputs across the range of uncertainty, as undertaken for the ADZ model (Tidal Lagoon Swansea Bay, 2021).

**Assessment Matrix**

CFD modelling of the EZ received a score of 10 for the value assessment and 8 for the confidence assessment, giving a combined score of 18. The scores for each criterion are shown below in Table 4-1.

Table 4-1 CFD model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 2 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 2 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 2 |
| **Value Score** | 10 | **Confidence Score** | 8 |

**Method Conclusions**

EZ modelling using CFD is an appropriate technique for estimating encounters with tidal range power infrastructure but would need to be coupled with fish behaviour model or fish distribution data. The model builds would also be reliant upon existing hydrodynamic models being available for the development area or the collection of detailed hydrographic and physical process data. A key strength of this modelling approach is the flexibility of the method to be adapted to different life-stages and species, although the availability of suitable biological data for an estuarine/coastal environment is likely to be limited especially for less studied species.

**Method Applicability for Environmental Assessments**

Entrainment zone modelling alone would not provide an adequate assessment of environmental risk but was one component of the model (ADZ model) used for the Tidal Lagoon Swansea Bay EIA (Tidal Lagoon Swansea Bay, 2021 demonstrating how it can be successfully used in a suite of modelling approaches for tidal power assessments in the UK. The additional modelling approaches that would need to be considered in such a suite are discussed further under the ADZ model and STRIKER sections below.

## Empirical Transport Model (ETM)

**Method Summary**

The Empirical Transport Model (ETM) developed by Boreman & Goodyear (1981) is one of the earliest examples of an attempt to estimate the numbers of fish entrained at power plant sites. A limitation of the ETM is that it assumes individuals behave like passive particles and is thus only suited to Ichthyoplankton (Heimbuch *et al.,* 2007). It may however, be possible to modify the model or it’s assumptions to consider mobile particles.

The model in its most complex form requires knowledge of the morphometry of the water body, the scheme flow rates, and the duration, distribution, and abundance of entrainable age-groups. The probability of surviving entrainment is included in the model, but the main objective is to estimate the number and age structure of fish that are entrained.

The basic equation for the proportion of a fish population that are entrained and die (*E*) is based on the rate of power scheme water abstraction during a specified time interval, the fraction of entrained fish that die during passage the ratio of these two factors and the volume of the waterbody.

Complexity can be added to the base model equation by including terms that describe the distribution of different life-stages among regions of the waterbody, and therefore the proportion of each life-stage entrained. Generally, age or life-stage vital rates (e.g., egg survival, larval survival) do not make an equal contribution to population growth, meaning it could be important to estimate demographic variation in entrainment risk.

As noted by Boreman and Goodyear (1981), this more complex equation can be reduced to include only the region of the waterbody where fish are vulnerable to entrainment.

The most advanced equation presented by Boreman and Goodyear (1981) attempts to model multiple cohorts of ichthyoplankton. The idea here is that power station abstraction may vary over time and therefore a cohort's risk of entrainment may vary depending on the time of birth. Because spawning may occur over an extended period, more than one larval/juvenile development stage may be present in the water body at any given time. If conditions in the water body that influence entrainment (such as power plant abstraction rates, tidal height etc.) change over time, the susceptibility of an egg or larvae to entrainment and subsequent mortality will be dependent upon when, during the spawning period, that individual was spawned. For example, if power plant abstractions are reduced in the latter part of the spawning period, then larvae from eggs (or in their own right) deposited later in the spawning period will experience less entrainment mortality.

An important feature of the ETM is that the distribution of fish is defined by information derived from field samples (e.g., ichthyoplankton trawls) rather than by simulation. Boreman and Goodyear (1981) present this as a positive modelling feature and will certainly reduce uncertainty through using site specific data, especially if collected over a suitable temporal scale to include temporal change. Equally however, the feature could be problematic for prior risk assessment and planning since patterns in ichthyoplankton and fish distribution may change after power scheme construction. This seems particularly likely for tidal range power schemes that might substantially alter estuarine circulation and physical habitat.

An assumption in the application of the ETM highlighted by Boreman and Goodyear (1981) focuses on near-field depletion in that organisms redistribute instantaneously among geographical regions of the water body between age-groups, but do not move among regions within each age-group. Near- field depletion of organisms is therefore, assumed in the model due to entrainment within one region and no geographical offsetting by movement of other organisms of the same age into the depleted geographical region within a temporal region of a given time frame. If the organism distribution data are collected during power plant operation, the databases reflect the geographical and temporal distribution of organisms and as such near-field depletion and the degree to which it is offset by organism movement during the time interval is considered realistic.

This confidence in geographical and temporal organism model parameterisation will not be possible if the plant has yet to be constructed.

The output of the ETM is the conditional rate, which is the fractional reduction in year-class strength due to entrainment if other sources of mortality are density-independent.

**Examples of model application**

After describing their model, Boreman and Goodyear (1981) provide an example case study for entrainment into the cooling intakes of a proposed nuclear-fuelled electric generating station. The biological input data was the distribution of the egg and larval stages of striped bass (*Marone saxatilis*) collected in a single year by Chesapeake Biological laboratory. Analysis within the paper focused on a 4-week period when striped bass spawn and they used the multiple cohort version of the ETM to represent temporal changes in spawning intensity, and therefore the densities of eggs and larvae. Physical input data were the water volumes of seven equally spaced geographic regions and the proposed daily average water abstraction of the plant. Mortality rate of entrained individuals was assumed to be 1.0 (100% mortality). The modelling results showed that entrainment mortality over 4 weeks due to entrainment represented 0.142% for eggs, 0.234% for yolk-sac larvae, and 0.022% of the estimated fin-fold larvae population.

**Applicability of model**

Entrainment risk is an important process to understand the impact of tidal range power generation on fish. The ETM provides an analytically simple method to calculate entrainment rates but involves several simplifications regarding hydrodynamics and the behaviour of fish, in particular an assumption of passive transport. The method could be applied to a tidal range power scheme scenario but is limited in its current form to only entrainment of ichthyoplankton. Evidence that passage through low-head propeller turbines causes injury or mortality in ichthyoplankton is limited (Cada, 1990), and therefore modelling ichthyoplankton is unlikely to be the primary factor of importance for assessing impacts on fish populations.

**Multi-species and life stages assessment**

The ETM assumes individuals behave as passive particles and is thus best suited to ichthyoplankton. It must also be noted that some ichthyoplankton have a limited capacity for self-directed movement and therefore do not always behave as passive particles.

**Temporal modelling**

The ETM is a temporal model but assumes removal of fish from the population on first passage through the system and as such was not designed to assess multiple passages through turbine structures. Two models could possibly be run in parallel to estimate entrainment from either side of the barrage, but modifications would be required to describe how ichthyoplankton distribute after each entrainment event.

**Ability to use model openly**

The ETM is a set of relatively simple equations that are well explained and defined in an open access article (Boreman & Goodyear,1981), can be operated in a simple spreadsheet platform and could be easily implemented by a modeller or statistician with no previous experience of the ETM.

**Data availability**

It is unlikely that contemporary ichthyoplankton data will be available at sufficient temporal and spatial resolution without a site/scheme specific monitoring programme. Given the simplifications inherent in the hydrodynamic elements of the model, it may be possible that required data can be adequately estimated from standard marine charts.

**Data collection**

Ichthyoplankton surveys (e.g., plankton trawls) would be required to assess composition, distribution, and density over the time duration being modelled and over a temporal period to take into consideration seasonal changes.

**Method validation data**

Case studies have not validated the model predictions with empirical data (Boreman and Goodyear, 1981;1988). It would be possible to collect entrainment data from a power station cooling water system have such field-based data collection would be more complex for a tidal power scheme. Empirical data to validate predictions of losses at a population/stock level are unlikely to be possible with sufficient statistical confidence given the likely percentage reductions requiring validation and the difficulty in accurately estimating fish population levels in estuarine and marine environments.

**Uncertainty management**

The ETM calculation is deterministic, and therefore the model does not report uncertainty. A key area of uncertainty is whether the data used to establish the spatial and temporal distributions of organisms are accurate. Problems associated with sampling gear biases, species and life-stage identifications, sampling design, and data interpretation reduce overall accuracy of the ETM estimate. It would be straightforward with moderate statistical and programming skills to resample the model parameters to provide an estimate of output range and uncertainty, especially as the model is a spreadsheet-based tool. Determining the ranges to be implemented for the parameters however, is likely to be subjective and require an element of expert judgement application. Sensitivity analysis of the ETM was undertaken by Boreman and Goodyear (1978) however, the source literature was not presented in the paper.

**Assessment Matrix**

The ETM received a score of 7 for the value assessment and 7 for the confidence assessment, giving a combined score of 14. The scores for each criterion are shown below in Table 4-2.

Table 4-2 ETM model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 1 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 3 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 1 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 2 | **Uncertainty management** | 2 |
| **Value Score** | 7 | **Confidence Score** | 7 |

### Method conclusions

The ETM is a method of estimating ichthyoplankton entrainment that has mainly been applied to assess the impact of cooling water abstraction by power schemes. It is computationally simple and not data demanding, but relevance to a tidal range power scheme scenario is limited during to its restrictive use for passive life stages only.

### Method applicability for Environmental Assessments

Given the limitations of use of this model type to passive life stages and the simple equation-based model build, this model is not considered likely to be widely adopted or accepted as a robust tool for tidal range power scheme assessments in the UK, when compared against more modern computationally advanced options.

## Particle Tracking

### Method summary

The ETM model assessed above assumes that the probability of entrainment of ichthyoplankton varies only in response to changes in the volume of water withdrawn at a power scheme and ignores the significant role of estuarine circulation in driving the distribution of ichthyoplankton (Heimbuch *et al.,* 2007). To overcome this limitation the ETM can be coupled with estuarine circulation models and particle tracking simulations.

Particle tracking simulations of plankton involve the use of computer models to simulate the movement and behaviour of planktonic organisms in aquatic environments. These simulations aim to replicate real-world conditions and provide valuable insights into the dynamics of plankton populations. Individual plankton particles are represented as virtual entities that interact with their environment and respond to various factors such as water currents, temperature, nutrient availability, and biological interactions. The simulations utilise mathematical equations, numerical algorithms, and physical principles to calculate the particle trajectories and simulate their behaviour over time.

**Examples of model application**

An illustrative example of a particle trace simulation is work by Heimbuch *et al.,* (2007) who calculated the entrainment mortality rate of fish at cooling water intakes of a power scheme. Particles totalling 819,912 and representing eggs and larvae were released into a three-dimensional estuarine circulation model consisting of 5,309 grid cells. Equal numbers of particles were released into each grid cell at the bottom or midway point of the water column on a biweekly basis over an 11-week period in real time. The two-dimensional distribution of particles was informed by empirical sampling of ichthyoplankton. Each particle was tracked for 14 days after its release. If a particle changed its position by the start of the next 2-week period, the probability of entrainment was calculated based on its new position by applying the ETM. As with the ETM, particles were assumed to be neutrally buoyant and passive, but the authors acknowledge that some ichthyoplankton may not be neutrally buoyant and some are capable of self-directed movement.

**Applicability of model**

Entrainment risk is an important process to understand the impact of tidal range power generation on fish. Particle tracking overcomes some of the limitations of the ETM by providing a more realistic description of how plankton disperse or move in an estuarine environment. The model could be applied to a tidal range power scheme scenario however, it is limited to entrainment of ichthyoplankton only. Evidence that passage through low-head propeller turbines causes injury or mortality in ichthyoplankton is limited (Cada, 1990), and therefore modelling ichthyoplankton is unlikely to be the primary factor of importance for assessing impacts on fish populations.

**Multi-species and life stages assessment**

Particle tracking assumes individuals behave as passive particles and is thus only suited to ichthyoplankton. It must also be noted that some ichthyoplankton have a limited capacity for self-directed movement and therefore do not behave as passive particles.

**Temporal modelling**

Case studies using particle tracking have not considered multiple passages, but particle tracking is a flexible simulation approach which should be adaptable to this purpose.

**Ability to use model openly**

Existing programmes for particle tracking coupled with estuarine circulation models are often site or task specific, for example the dsm2 programme for the San Francisco Estuary area (Smith *et al.,* 2020). Considerable effort and modelling expertise may therefore, be required to repurpose or create programmes for a novel location and scheme.

Various software packages are available for simulating particle tracking of plankton. Two of the most used platforms are the commercially available MATLAB and the MATLAB Particle Tracking Toolbox and the opensource OpenFOAM computational fluid dynamics (CFD) software package.  OpenFOAM provides a flexible framework for simulating fluid flow and particle tracking in complex environments, including the ocean.

**Data availability**

Estuarine circulation models can be expensive and time consuming to develop and calibrate, particularly around complex coastlines and estuaries. The models may however, be already available and accurate if they have been a requirement of a previous Environmental Impact Assessment (Willis & Teague, 2011). A freely available and flexible software platform for hydrodynamic modelling is TELEMAC-2D, developed by EDF-LNHE (Willis & Teague, 2011; Rosington & Benson, 2019). It is unlikely however, that contemporary ichthyoplankton data will be available at sufficient temporal and spatial resolution for modelling.

**Data collection**

Estuarine hydrodynamic models are developed using a combination of field observations and mathematical modelling techniques. Field measurements are carried out to gather data on various parameters such as water velocity, salinity, temperature, and tidal variations within the estuary. These measurements are usually collected using instruments like current meters, water samplers, and sensors deployed at strategic locations throughout the estuary. The data collected provides a foundation for understanding the physical processes and circulation patterns within the estuary. Mathematical models are developed to simulate the behaviour of estuarine circulation based on the collected field data and experimental results. These models utilise mathematical equations, such as the Navier-Stokes equations, to represent the physical processes governing fluid flow, including tidal forcing, river inflows, wind effects, and mixing due to turbulence. The mathematical models are then validated by comparison of the outputs with field data.

Ichthyoplankton surveys (e.g., plankton trawls) would be required to assess species composition, distribution, and density.

**Method validation data**

Validation of particle tracking can be achieved by comparing the simulation outputs with empirical temporal data of ichthyoplankton distribution. Smith *et al.,* (2020) used a Bayesian hierarchical model fitted from various empirical data spanning 20 years to validate and measure uncertainties in their estimates of entrainment mortality for larval delta smelt (*Hypomesus transpacificus*). The approach was data intensive and statistically complex and would require substantial expertise to replicate. Hydrodynamic models can be validated by field collection of current speed data (Rosington & Benson, 2019).

**Uncertainty management**

A key area of uncertainty is whether the data used to establish the spatial and temporal distributions of organisms are accurate. Problems associated with sampling gear biases, species and life-stage identifications, sampling design, and data interpretation reduce overall accuracy of the particle tracking. A second area of uncertainty is in the simulation of estuarine circulation, which can be difficult to model around complex coastlines. Case studies of particle tracing to assess entrainment risk have not explored these uncertainties.

### Assessment Matrix

Particle tracking models received a score of 7 for the value assessment and 7 for the confidence assessment, giving a combined score of 14. The scores for each criterion are shown below in Table 4-3.

Table 4-3 Particle tracking model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 1 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 1 | **Model validation** | 2 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 1 |
| **Value Score** | 7 | **Confidence Score** | 7 |

### Method conclusions

Particle tracking is a method of estimating ichthyoplankton entrainment that has mainly been applied to assess the impacts of cooling water abstraction by power scheme. It is computationally demanding and requires detailed data on estuarine circulation and the distribution of ichthyoplankton. Relevance to the tidal range scenario is limited because entrainment mortality or injury by low head propeller turbines is expected to be negligible for ichthyoplankton.

### Method applicability for Environmental Assessments

Given the limitations of use of this model type to passive life stages and the complex and detailed data collection requirements for the model build, this model is not considered likely to be widely adopted or accepted as a robust tool for tidal range power scheme assessments in the UK.

## ELAMs

### Method summary

Eulerian Lagrangian and Agent-based Models (ELAMs) combine the hydrodynamic model and particle tracking approach (Eulerian Lagrangian) with an individual based model (IBM, also known as an Agent Based Model) that models complex animal movements made independent of advection.

Individual-based models have become common place in ecological research as access to high computing power has increased and are the most appropriate method for simulating complex behaviours. IBMs consider a population from the viewpoint of individuals, or agents, with population level behaviours emerging from the behavioural responses of the individuals to various stimuli, which can be both internal (i.e., biological) and external (i.e., environmental). Individuals within a system are defined by traits (e.g., size, age, or sensitivity to a stressor) and behaviours it can perform (e.g., migration).

The main steps in developing an IBM for investigating the impacts of marine infrastructure on wildlife are summarised as follows:

1. Define the study area and species: The first step is to define the geographical area of interest and the species or populations being studied.

2. Collect data: Data on the behaviour, movements, and ecological characteristics of the target species are collected through various means such as field observations, satellite tracking, or acoustic monitoring. Data on hydrodynamics might also be required if not already available.

3. Develop the model: Based on the collected data and knowledge of the species' behaviour, an IBM is developed to simulate individual animals within the population. The model incorporates the ecological characteristics of the species, such as their movement patterns, foraging behaviour, and responses to environmental variables.

4. Incorporate renewable energy infrastructure: The IBM is modified to include representations of marine renewable energy devices, such as tidal turbines or wave energy converters. The model takes into account the spatial distribution of these devices and their potential effects on the surrounding environment.

5. Simulate encounters and interactions: Using the IBM, researchers can simulate individual animal movements and behaviours in the presence of marine renewables. The model can estimate the likelihood of encounters between wildlife and renewable energy infrastructure and assess potential impacts, such as collision risk, changes in habitat use, or displacement from preferred areas.

**Examples of model application**

The ELAM approach was used by Willis & Teague (2011) to investigate the number of times salmon smolts would pass through the turbines or sluices of five shortlisted options for low head tidal range power in the Severn Estuary. The ELAM model was also used within initial investigations of impacts upon fish from the Swansea Bay Tidal Lagoon development as detailed within the Environmental Statement.

The hydrodynamic conditions (Eulerian model) for each of the proposed schemes were simulated using 2D, depth-averaged flow model TELEMAC-2D. The authors initialised two sets of particles at each of the tributary mouths within the model area. The first set was modelled as passive drifters and the second as swimming fish. The basis of the IBM was a correlated random walk. At each step in a correlated random walk an animal continues in the direction of the previous step with the addition of a consistent level of error at each step. Thus, a correlated random walk can vary between a continuous straight line in a particular direction (very little or zero error at each step) and a fully random walk where the introduced error is so high at each iteration that the direction of each step is totally uncorrelated to the previous direction (Brownian motion). Behavioural reactions to things which happen during the model were expressed in terms of position, speed, directedness or direction. Possible behaviours of salmonid smolts were: 1) move (correlated random walk); 2) navigate (aim towards next way point), 3) hit land (turn at right angles left or right chosen randomly), 4) day/night (slow down and get advected less to model the effect of vertical movement toward the bed), 5) advect, and 6) turbine and sluice (get dragged through). The model output was the number of times each individual smolt passed through the barrage over a predefined time. Turbine mortality was not included in the model which was considered under a separate cumulative injury/mortality CRM model; hence it is considered as an ERM which fed into the overall combined risk model.

Rosington & Benson (2019) used an ELAM (named HydroBoids) to examine the collision rate for migrating European eels (*Anguilla anguilla*) with a tidal stream array. Their approach was very similar to Willis & Teague (2011) except the ELAM was coupled with the CRM developed by Band et al., (2012) for wind farm risk assessments. Rosington & Benson (2019) used the model to simulate a real-world case study of a tidal stream installation at Strangford Lough.

**Applicability of model**

ELAMs are highly applicable to the tidal range scenario. Importantly, they can simulate the complexity of fish interactions with tidal range infrastructure, including advection, migration, avoidance and attraction, and multiple passages. The ELAM by Willis & Teague (2011) is one of only a few examples of a model directly applied to the tidal range scenario. The ELAM model was initially used within the assessment of impacts upon the Swansea Bay Tidal Lagoon development however, alternative methods were adopted for the final ES. The flexibility of ELAMs is demonstrated by the HydroBoids platform which has been applied to assess the impacts of pile driving noise on fish behaviour (Benson et al., 2016) and the impacts of a tidal stream array on migrating eels (Rosington & Benson, 2019).

**Multi-species and life stages assessment**

An ELAM could theoretically be parametrised for any species and life stage for which data are available. Past case studies illustrate this flexibility, having covered silver eels, juvenile eels, salmon smolts, and adult cod (*Gadus morhua*). More than one species can be modelled simultaneously through assuming the same behavioural parameters between the different species for grouped species or seeding the models with numerous sets of particles representing different species and their differing behavioural parameters. It is also possible to define interactions between species (Benson *et al.,* 2016). Thus, an ELAM could be used to explore indirect impacts of tidal power, such as increased predation risk through defining predator-prey particle characteristics for different species interactions.

**Temporal modelling**

The study by Willis & Teague (2011) is almost unique in modelling multiple passages through the turbines of a tidal range facility and demonstrates this is a particular strength of the ELAM/IBM approach. In addition to considering the tidal exchange built into the hydrodynamic model, it was also possible to consider known fish migration behaviours within the estuary such as straying behaviour. Such additional complex and site specific behaviours can be considered either post model processing as was the case by Willis &

Teague for the Severn Tidal Power Scheme or as part of the model through particle release and behaviour parameterisation.

**Ability to use model openly**

HydroBoids and the ELAM by Willis & Teague (2011) are both programmed in the licensed platform MATLAB and use open-source data from TELMAC for the hydrodynamic model. The use of a flexible coding language means models can be adapted for different scenarios (Benson *et al*., 2016). The availability of the HydroBoids code to be used by other researchers however, is not clear, although considered unlikely given it has been developed by a consultancy firm and it is likely that running and modifying the model would require considerable programming skills and experience with MATLAB and IBMs. Likewise for the ELAM by Willis & Teague (2011).

**Data availability**

An IBM relies on knowledge of animal behaviour that can be quantified and described by relatively simple algorithms if a suitable evidence base exists on which to parameterise it. In the case studies of ELAMs discussed and ADZ IBM discussed below, the information was sourced from the literature, previously collected data and expert judgement. This availability of data may however, not always be available for less intensively studied species or for every location.

Population data (i.e., population size and demography) need not necessarily be based on empirical measurements. In the case study at Strangford Lough by Rosington & Benson (2019) the number of silver eels seeded into the model was arbitrary since the objective was only to estimate the proportion of fish that would collide with the turbines and the mortality rate. If the objective is to predict population dynamics, then empirical estimates of starting population size and demographic structure would be required but could be built as a separate population/stock model to which proportional losses are applied. Availability of the data required to parameterise such population/stock models will depend on the species conservation or commercial importance and will vary between locations.

Estuarine circulation models can be expensive and time consuming to develop and calibrate, particularly around complex coastlines and estuaries. The models may however, be already available and accurate if they have been a requirement of a previous Environmental Impact Assessment (Willis & Teague, 2011). A freely available and flexible software platform for hydrodynamic modelling is TELEMAC-2D, developed by EDF-LNHE and integrated into the HydroBoids model and ELAM by Willis & Teague (2011).

**Data collection**

IBMs potentially require a breadth of different data, depending on the modelling objective. If all these data needed to be collected by surveys or experiments, then building an ELAM would be a resource intensive and costly task. Fish surveys would likely include tracking studies over a large spatial scale to understand movement behaviours and surveys of population size and demographic structure. Methods for developing hydrodynamic models have already been described in sections on Particle Tracking and Entrainment Zone CFD.

**Method validation data**

In theory the parameters used to develop an ELAM could be validated after a scheme is installed using fish tracking methods to detect fish interactions with infrastructure. For example, if fish were electronically tagged and receivers installed within the turbine draft tubes then predictions by Willis & Teague (2011) of smolt turbine passage frequency could be validated. Such a validation experiment would however, require substantial resources to undertake. Validation of population/stock level impacts however, would be very difficult to achieve at the required statistical accuracy to detect the likely predicted levels of change.

A case study of a validation experiment is the ELAM for pile driving noise described by Benson *et al*. (2016). Trials were performed over 6 days, during which pile driving was carried out twice daily for two hours, with a one hour pause between the two periods. The trial was undertaken in a dock and netting erected to prevent fish from entering or exiting. In each trial the movements of between 14 to 24 (~18 on average) acoustically tagged cod were measured. The batches of cod were reused for 3 piling periods, to give a total of 71 cod tested. Recorded movements of cod were compared with simulation results for HydroBoids and the results showed the measured distances of the fish from the piles were largely contained within the standard error of the modelled distances which suggests that the model captured the variability in the data.

**Uncertainty management**

The realism and visual presentation of IBMs is very appealing, however, this realism requires that numerous complex parameters must be estimated, introducing considerable uncertainty. A fundamental problem is how to implement and validate a numerical method for decision making in animals (Rossington and Benson, 2019). For example, how do fish react when they encounter the barrage, do they display searching or delayed passage behaviour within the vicinity of the EZ or move away? Data on such behavioural predictions is both difficult to obtain and the number of decisions that require parameterising can be many. There is a need for more research into how fish respond to their environment and more focused observations of how fish deal with currents and structures, such as barrages, in dynamically active water would be particularly helpful to inform better models (Willis & Teague, 2011).

Because IBMs are often stochastic, i.e., no single iteration of the model should produce an identical result, running multiple iterations generates a probability distribution to quantify uncertainty, but can require considerable computing power. When many parameters are included with large probability distributions however, then the confidence intervals of the model predictions can be very wide, and therefore limit the use or confidence of the model outputs. The requirements for assessing impacts on a precautionary basis for protected sites and species may necessitate the use of a highly precautionary and likely unrealistic scenario and confidence interval. Keeping the number of decisions and range around parameters to a minimum is therefore important, although too few will make the simulation unrealistic. Sensitivity analysis can guide selection of model parameters and priorities for further data collection.

Willis & Teague (2011) did not undertake stochastic modelling, highlighting the considerable computational resources that is required. They also provide a valid argument that such an exercise is only worthwhile when an absolute answer is being sought, i.e., how many times do salmon smolts pass through the turbines, rather than a comparison of passage frequency for different scenarios, as was the objective in their study. For the purposes of an environmental assessment for a single scheme design however, stochastic modelling would be a requirement given the likely need to manage the inherent uncertainty in such modelling approaches with restricted parameter evidence bases. For HydroBoids, stochastic iterations can be run with error terms for parameters defined by the user (Benson *et al*., 2016).

### Assessment Matrix

The ELAM approach received a score of 11 for the value assessment and 7 for the confidence assessment, giving a combined score of 18. The scores for each criteria are shown below in Table 4-4.

Table 4-4 ELAM model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 3 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 2 |
| **Value Score** | 11 | **Confidence Score** | 7 |

### Method conclusions

An ELAM approach coupled with a CRM and potentially population/stock assessments as well as higher trophic impact modelling would be an extremely powerful combined modelling approach to investigate the impact of a proposed tidal range power scheme. The combined modelling approach would be capable of modelling each of the processes outlined in Figure 1 and the associated uncertainties. The challenges of implementing this approach would be the technical skill and computational resources required. At a local scale and for certain species their maybe shortcomings in the available data that would require substantial and costly investigation to rectify.

The next steps for ELAMs would be to understand the availability of the code developed by Willis & Teague (2011) and for Hydroboids as well as other modellers operating IBM's. If the code can be acquired, then the scripts should be compared to assess which is most advanced in terms of modelling the tidal range scenario and capabilities such as stochastic modelling. The selected code could then be developed to improve useability and coupled with an appropriate CRM for tidal range power (e.g., The STRIKER model) as well as follow on assessment tools and models to assess population/stock and potential higher trophic level impacts.

**Method applicability for Environmental Assessments**

The stochastic nature of the Hydroboids model and potential for this development within the IBM approach, allows presentation of probability prediction outputs with the ability to assess confidence percentiles. This probability output function of the model provides increased confidence in the use of the model for assessment purposes in particular, where 'scientific doubt' requires consideration under the Habitats Regulations and enables the management of uncertainty.

## Alternative Draw Zone model

**Method summary**

The Alternative Draw Zone Model (ADZ model) was developed for the Tidal Lagoon Swansea Bay environmental impact assessment. The model combines a spreadsheet based ADZ approach for the encounter risk assessment and STRIKER for the collision risk assessment (Tidal Lagoon Swansea Bay, 2021). It is included here as an ERM because STRIKER is covered separately in the CRM section below.

The ADZ model was originally developed in Microsoft Excel 2013 but later also considered in the software package; R. These are therefore, currently the optimum software for running the models but could be adapted to run in other stochastic modelling packages. The calculations are split across multiple sheets within the model, with a model provided for each species or population under consideration. The parameters of the model are as follows:

- A nominal starting population: this value has no bearing on the outcome of the model as predicted mortalities are always taken as proportional to this Starting Population. This could however, be progressed further in future iterations/developments to consider population or stock levels.

- The injury and mortality rate distributions generated for each species and life-stage of interest from the STRIKER turbine passage model (described in detail within the CRM section below).

- Population range: This is the geographic area that fish of each modelled species and life-stage inhabit for the duration of presence and swimming speeds chosen. Consequently, the value varies depending upon the species and life-stage being modelled.

- Duration of presence: This is the period, measured in single tidal cycles, that individuals spend within the model. This is based on data available in published evidence of timing and duration of migration and/or spawning and data from fish tagging and tracking studies.

- Swimming speed: Swimming speeds for each model iteration are selected from a distribution of fish lengths that are consistent with the distribution used for the STRIKER model, and a distribution of body length per second 'cruising' swimming speeds that are available for many species from published literature (such as the EA's Fish swimming R&D reports as discussed earlier).

- Draw zone area (i.e., entrainment zone): The area of the draw zone is linked to the chosen swimming speed of the individual and by a separate hydrodynamic modelling exercise to estimate flow fields surrounding the turbine draft tubes.

- Avoidance rate: The proportion of individuals, upon encountering the draw zone, that show a response and avoid being drawn into and through the turbines.

Draw-zone areas were generated in the model every three minutes, and these were assigned to the operating phases of the proposed tidal range facility. Because the ADZ was developed specifically for a tidal lagoon scenario, it has the capability to calculate the population level impacts of retention in the lagoon and predation in the lagoon through predictions of percentage losses which could then be contextualised outside of the model in terms of population/stock size.

The outputs of the ADZ model are the annual mortality rates due to turbine passage for each species and life-stage/age and population impacts in terms of egg losses (or % impact on egg deposition). The calculation considers outward migration of individuals from rivers as juveniles, periods of residence whilst maturing, single or multiple spawning events and the potential for residency in between spawning. Version 1 of the model was deterministic whereas the final version (v2) was stochastic.

**Examples of model application**

The ADZ model (v2) was used for the Tidal Lagoon Swansea Bay EIA process (Tidal Lagoon Swansea Bay, 2021). The proposed tidal range power scheme was in the tidally energetic Bristol Channel and would have up to sixteen turbines and up to ten sluices with an installed capacity of 320 Megawatts (MW), generating 500-600GWh net annual output. The Lagoon would enclose part of Swansea Bay from the eastern side of the River Tawe (western landfall) to the eastern edge of the new Swansea University Bay Campus (eastern landfall). The new sea walls would total ~ 9.5 km in length and extend approximately 1.5 km offshore.

Ten species of commercial or conservation importance were modelled as part of the study, these being: Atlantic cod, European eel, Herring, river lamprey, Atlantic salmon, sandeel (*Ammodytes* sp.), sea lamprey, sea trout, shad, and whiting (*MerlangiusMerlangius merlangus*). The study covered juvenile and adult life stages and extended over a large spatial area (Bristol Channel). Atlantic salmon were modelled separately for populations spawning in different rivers.

The assessment undertaken for the purpose of marine licensing used standard methods, whereby the magnitude of mortality predicted by the model and the species commercial and conservation value were scored on an ordinal categorical scale of severity. In accordance with requests from the regulators, the impact magnitude was assessed using the 95th and 99th percentile values for mortality. The results of the assessment predicted a major impact on river lamprey, shad, sea lamprey, and Atlantic salmon and moderate impact on European eel, Atlantic cod, sea trout, and whiting.

### Applicability of model

The ADZ model is highly applicable to the tidal range scenario. Importantly, the ADZ model can simulate the complexity of fish interactions with a tidal range infrastructure, including migration, avoidance and attraction, and multiple passages. It is the only model reviewed here that has been applied directly to assess the environmental impacts of a tidal range power scheme. The model attempts to assess encounter probabilities, turbine mortality, and the fate of fish that successfully pass through the turbine (i.e., the three major processes of the conceptual schematic in Figure 1). The model doesn't require any adaptation for use in a tidal range scenario as the model development has already factored in these requirements although would need to be reparameterised and adapted for a specific development. One limitation is that hydrodynamics inclusion are limited to the setting of the EZ/draw zone area only, which are essential for understanding encounter rates for ichthyoplankton and might also be important for free swimming fish.

### Multi-species and life stages assessment

The ADZ model is preloaded with species specific data to model ten common and high value fish species in south Wales. Because the model is built in Excel it may be difficult to add additional species compared to models based on a flexible programming language such as MATLAB, R, or Python. Juveniles and adults are modelled for each of the 10 species.

### Temporal modelling

The ADZ model is almost unique in its capability to model multiple passages through the turbines of a tidal range facility.

### Ability to use model openly

A user guide to the ADZ model was provided within the Tidal Lagoon Swansea Bay Alternative Fish Impact Assessment – Addendum 1 (2017). The parameter information is also published and it is considered possible to replicate the approach for future schemes under assessment.

### Data availability/collection

Data availability and data collection constraints are as described for STRIKER and IBMs (see ELAM section).

### Method validation data

It is understood that the only outputs from the ADZ model are the annual mortality rate from turbine passage and the change in egg deposition rates. Such population level effects will be more difficult to validate with empirical data than behavioural outputs, such as the frequency of turbine passage, although it may be possible to extract this with some model adaptation. Quantifying the survival rates of fish is notoriously difficult, as is disentangling the various drivers of temporal variation, which in addition to the tidal power scheme, could include changes to environmental conditions or anthropogenic disturbances, such as fishing mortality.

**Uncertainty management**

Several assumptions were applied in relation to some of the model input parameters in assessment for Tidal Lagoon Swansea Bay. In making such assumptions a conservative approach was taken where necessary, thus creating a level of precaution within the assessment, and giving greater confidence that any impacts that may be realised will be below those modelled. To understand the importance of these assumptions the ADZ programme (v2) includes Excel sheets for stochastic modelling (Monte Carlo simulation) and sensitivity analysis. The most critical assumptions were as follows:

- The baseline population of fish present in the region remained either constant on each day per month of fish presence or were removed depending on the species and their migratory nature. Thus, any fish lost due to turbine entrainment were assumed to be ‘replenished’ after each tidal cycle or were removed if represented a migratory species.

- Where fish were predicted to be injured passing through the turbines from turbine strike they were, for the purposes of the calculations, regarded as mortalities. This acknowledges that whilst a proportion of ‘struck’ fish may survive as fish are simply deflected, such fish may be at greater risk of fish predation whilst disorientated.

- For all species, the demographic structure of the coastal population was not precisely known and was estimated from limited empirical data or from expert opinion.

- When a fish entered the Draw Zone, it was assumed that, despite having a maximum sustainable swimming speed and even faster burst speed, it may be unable to escape, and be drawn into the turbine housing, although an element of avoidance rate was considered.

- It was assumed that fish present in the draw-zone when the turbines or sluices operate do not exhibit an escape response although an element of near and far field avoidance was considered.

- Cut-off dates were applied to specific life-stages of some species. The principle was that fish retained after the cut-off date, whilst not necessarily killed, will not be able to complete their migration and either contribute to the spawning or complete their seaward migration and are more likely to be predated upon. For example, to be precautionary, it was assumed, in the absence of evidence to the contrary, that all salmon smolts impounded within the lagoon after 16th June cannot undertake their natural migration and are therefore lost.

In addition to the above assumptions regarding what is included within the assessments, there were several factors which were not included:

- The tidal movement of fish and their subsequent likely horizontal or vertical position relative to the turbine housing were not considered. For example, fish moving in-shore, or into estuaries on the flush of the flood tide may pass the turbines prior to the start of generation and sluicing.

- Given the location of the turbines in the lower half of the water column, fish swimming close to the surface may be able to avoid being drawn into the turbines

- It was assumed that some avoidance behaviour is exhibited by fish in the vicinity of the turbines when operating. The avoidance rate used in the models was based on limited empirical evidence from other marine energy installations.

- The models included a predation parameter which was fixed at an arbitrary 5% for all species and most life-stages. Unlike other parameters this did not have an upper and lower values applied.

### Assessment Matrix

ADZ model received a score of 1111 for the value assessment and 7 for the confidence assessment, giving a combined score of 18. The scores for each criterion are shown below in Table 4-5.

Table 4-5 ADZ model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 3 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 2 |
| **Value Score** | 11 | **Confidence Score** | 7 |

### Method conclusions

The advantages of the ADZ compared to Hydroboids is that the model is already coupled to an appropriate CRM and set-up specifically for the tidal range power scheme scenario and most fish species relevant to Wales. The coupled CRM however, is not open source and may need to be redeveloped for use across different developments. Having been developed in Excel it is probably less flexible however, to be adapted to new scenarios or to integrate additional processes, although future versions could potentially be built in R to potentially overcome this and should be investigated further.

### Method applicability for Environmental Assessments

The ADZ model is unique in having been integrated into an assessment for Tidal Range power scheme in Wales. The stochastic nature of the model allows presentation of probability prediction outputs with the ability to assess confidence percentiles. This probability output function of the model provides increased confidence in the use of the model for assessment purposes, in particular where 'scientific doubt' requires consideration under the Habitats Regulations and enables the management of uncertainty. The model would however, have to be updated and reparametrised to make it applicable for use with different tidal range power developments.

## 4.2 Collision Risk Models

There are three main types of potential techniques for the assessment of injury and mortality rates resulting from passage through turbines and to a lesser extent sluices. Of these, two are quantitative via either one-dimensional calculation based upon known turbine characteristics (hereafter blade strike models) (although some forms of computation modelling may be required in the model back data) and the second three-dimensional modelling simulating the conditions experienced during turbine passage usually in the form of CFD modelling of flow fields. The third method is a qualitative expert judgement technique with the use of known thresholds or previous examples of injury and mortality rates. Historically collision risk models have focused on mechanical injury predominantly from blade strike. Later models have also considered other potential injury mechanisms, in particular pressure and shear and subsequently 'compound' injury/mortality. The different techniques require varying amounts of information and accurate detail regarding the scheme and fish populations to be assessed.

### Blade strike models

**Method summary**

The assessment of fish strike from turbines dates back to the 1930s and although adapted and advanced over the years, has largely followed similar principles since this time. The rate of fish strike by a turbine blade is dependent upon the ratio of the length of the fish and the distance between successive blades, termed 'water length'. The technique for determining the rate of strike is to model the water length for each turbine specification, and on the basis of the length of each of the fish species and life stages, calculate the strike rate probability. Hinterleitner (1937), cited in Pavlov et al., (2002) was the first to develop an equation investigating the passage of fish through a turbine. His equation was based upon the length of a fish which could safely pass through a turbine without being struck by the runner blades.

The first model to determine the probability of blade strike of a fish of a given size was developed by Von Raben in 1957 and has since been expanded upon by a number of subsequent authors, however, fundamentally remains very similar. The basis of the Von Raben strike probability equation and those derived by subsequent authors, is that the probability of a fish being struck by a blade is relative to the length of time taken for a fish to pass the path of the rotating blades and the time interval between the rotation of successive blades.

Initial assessments assumed a 100% mortality of all individuals struck and took no consideration of relative mutilation ratios of different species and life stages, nor the phenomena of small fish being transported around the leading edge of the blade avoiding strike. Ploskey and Carlson (2004) undertook a review of deterministic blade-strike models presented within four papers (Von Raben, 1957; Bell, 1991; Turnpenny, 2000 and Pavlov *et al*., 2002) and standardised the variables presented within them for direct comparison (Table 4-6). All four techniques were deemed to be essentially very similar with the notable addition within the Turnpenny *et al*. (2000) method of a mutilation ratio.

Table 4-6 Standardised variable names for blade-strike equations within the four reviewed papers (adapted from Ploskey & Carlson, 2004 with ft changed to m).

| Standardised variable name | Definition | Von Raben (1957) | Bell (1991) | Turnpenny *et al.*(2000) | Pavlov *et al.* (2002) |
|---|---|---|---|---|---|
| *P* | Probability of a blade strike | *P* | *P* | *P* | *P* |
| *l* | Fish length, m | *l* | *L* | *L* | *L* |
| *n* | Number of runner blades | *n* | *n* | No. blades | *N* |
| *N* | Runner rotation rate, revolutions per minute | $R^1$ | *N* | RPM of runner | $n^1$ |
| $A_{TIP}$ | Area swept by the runner: $\pi$*($R_{TIP}^2$ – $R_{HUB}^2$)$^2$, m$^2$ | *a* | $=\pi*(r_0^1-r_1^2)$ | Runner swept area | $=\pi*(R^2-r^2)$ |
| $\theta$ | Angle between axial water velocity vector and the absolute water velocity vector | $\alpha$ | $\theta$ | *a* | $\alpha$ |
| Q | Discharge, m$^3$/s | *f* | Q | Discharge | Q |
| $V_{axial}$ | Axial velocity (m/s); = Q/$A_{TH}$ | $a/f=1/V_{axial}$ | $V_{axial}$ | Discharge / runner swept area | $V^{-1}$ |

RPM = revolutions per minute
rtip = radius of a circle formed by the runner blade tip, and $r_{hub}$ = radius of a circle formed by the runner hub

The majority of variables required can be easily obtained, estimated or determined, however, the determination of angle $\theta$ is more complex requiring a series of calculations starting at the level of the wicket gate and ending at the level of the runner blades as follows (Ploskey & Carlson, 2004). It should be noted that determination of this angle also requires detailed information on the expected operation pattern as well as a defined turbine type and manufacturer. Developers may be unwilling to share this detail and as such it may not be available at the accuracy required at the environmental assessment stage.

Von Raben (1957)

The results of experimental studies undertaken to investigate the accuracy of Von Raben's equation have been varied including close approximations to often lower observed injury rates than predicted. This has been attributed to the differing design specifics of a turbine, the angle of the fish upon passing through the blade space, the inertia of the fish and the fish's flexibility.

To take account of such variances Von Raben introduced an error coefficient of 0.43 designed to be altered depending upon turbine type and hydraulic conditions for example. This error coefficient was however, based upon eel and was defined as a measure of the proportion of the number of eel hitting the runner. It was intended that this be used in conjunction with a critical blade impact velocity to determine the potential of sustaining an injury. The critical impact velocity was defined as 14 ms$^{-1}$ above which it was deemed an injury would be sustained.

Turnpenny et al. (1992)

The probability of blade strike for a moving turbine was defined by Turnpenny et al. (1992) in relation to water passing through an arc between the leading edge of the runner blades and the projection of the length of a fish onto the arc.

Franke et al (1997)

Von Raben's equation although taking into account the meridional length of the fish does not take into account the tangential component of its length. Franke *et* al. (1997) took the tangential projection of the length of the fish into consideration through modification of the equation.

This equation was subsequently further adapted by Franke et al. (1997) incorporating Euler's equation to determine flow angle based upon key turbine parameters such as head and discharge. Euler's equation states that 'the reaction torque on the runner is equal to the change in angular momentum of the flow through the runner'. Additionally a correlation factor, λ was included within the equation to take account of several factors not initially included such as; the fact that the fish may not lay in the exact plane of revolution, a length related fraction of strike in relation to contact with different parts of the fish body and the phenomenon that the localised flows at the leading edge of the blade runner may transport fish around the blade avoiding strike.

A lambda value of 0.2 was initially suggested by Franke et al. (1997) based upon the ratio of measured and predicted fish mortality rates however insight from Wanapum Dam which directed fish into areas of leading edge strike indicated that this strike mortality correlation factor attributed all fish mortality to strike, indeed higher than the total injury rates observed. In response to this, equations were re-run with an arbitrarily chosen lambda value of 0.1 resulting in strike mortality rates within the range of experimental uncertainty.

Turnpenny (1998)

Turnpenny (1998) investigated the importance of fish strike and other hydraulic effects as part of a study investigating passage of fish and shrimps through tidal power turbines in relation to a Severn Tidal Power scheme. The investigations were based on a 9m diameter reference turbine. The characteristics of an operating 9m turbine were investigated using Computational Fluid Dynamics (CFD). Biological dose experiments were then carried out to determine the tolerance of a range of fish species to the determined CFD turbine characteristics. The resultant developed model enabled the prediction of the relative importance and impact of the range of turbine passage related effects based on specific turbine parameters and operating conditions. The model was based on Von Raben's blade strike equation.

Headrick (1998)

Headrick (1998 cited in Amaral, 2001) developed a simple predictive model to assist in the determination of the survival of fish passing through an axial turbine. The model was based upon a stepwise regression analysis of a database of turbine survival from a number of field based assessments of axial turbine survival.

Deng *et al*., (2007)

The novel contribution made by Deng et al., (2007) was to produce a stochastic version of deterministic equations for Kaplan turbines by Von Raben (1957) and mutilation ratios by Turnpenny *et al*. (2000) and to undertake validation of the model outputs. A further improvement was to consider variation in fish orientation because a fish is more likely to be struck if it is oriented perpendicular rather than parallel to a runner blade.

**Examples of model application**

Ferguson *et al*. (2008) combined classical life cycle modelling (age structured Leslie matrix) with deterministic blade strike models to produce a tool for evaluating effects on fish populations from passage through hydropower turbines at dams. With similar objectives, Wilkes *et al*. (2018) integrated deterministic blade strike models into a Bayesian Network framework (described in detail later). Analytical blade strike models were also integrated into the Tidal Lagoon Swansea Bay EIA (Tidal Lagoon Swansea Bay, 2021), as described in sections on the ADZ and STRIKER models.

An adaptation of the stochastic Deng model assessing compound mortality was also implemented for the DECC Severn tidal Power study (O'Keeffe *et* al., 2010) combined with the IBM model described above and Leslie matrix population models to understand population level impacts upon migratory fish species in particular.

**Applicability of model**

Blade strike models for Kaplan and Francis turbines are highly relevant since these turbines are the most likely to be used for tidal range power. The stochastic approach by Deng *et al*. (2007) and O'Keeffe *et al*. (2010), integrating the Von Raben (1957) equations with mutilation ratios by Turnpenny *et al*. (2000), are the most comprehensive but were developed only for Kaplan turbines.

**Multi-species and life stages assessment**

As described for the STRIKER model below.

**Temporal modelling**

As described for the STRIKER model below.

**Ability to use model openly**

The models are relatively simple equations that are described in several open-source peer reviewed papers and modelled in spreadsheet or freely open packages such as R.

**Data availability**

Depending on the equations being used; deterministic or stochastic, single input parameters maybe required or a range of variables to enable probability predictions to be developed. Data requirements are mechanical parameters of the turbine (e.g., turbine hub diameter, turbine runner diameter, number of blades) and fish species data (e.g., length distribution, length distribution and fish orientation). All versions of the model require detailed information on the scheme and fish biological traits as input parameters. Some of this data will not be scheme specific and as such will be readily available, others will require scheme specific investigations.

Fish species data is largely available for most species and life stages and can be based off published literature data or site-specific data. Mutilation ratio relates back to a single equation based on fish body form. Fish orientation will largely be unknown especially for a new scheme and there is little data available from operating schemes. This function is therefore, generally input as a random variable. Fish swimming speeds won’t be known for all species and life stages and will be dependent upon published data and proxies for some species. This variable, however, is often set as 0, on the assumption that fish will move passively with the water flow through the turbine rather than swimming with or against the flow.

**Data collection**

As described for the STRIKER model below.

**Method validation data**

Validation of the deterministic and stochastic blade strike models for Kaplan turbines was undertaken by Deng *et al*., (2007). Blade-strike probabilities predicted by both the deterministic and stochastic models were comparable with those observed in both prototype-scale live fish survival studies and a physical turbine model using neutrally buoyant beads. Predictions from the stochastic model were closer to experimental data than predictions from the deterministic model because the stochastic model considered the aspects of fish approaching to the leading edges of turbine runner blades.

**Uncertainty management**

As described for the STRIKER model below.

**Assessment Matrix**

Blade strike models received a score of 11 for the value assessment and 9 for the confidence assessment, giving a combined score of 20. The scores for each criterion are shown below in Table 4-7.

Table 4-7 Blade strike models assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 3 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 2 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 3 |
| **Value Score** | 11 | **Confidence Score** | 9 |

**Method conclusions**

The blade strike models are directly applicable for fish turbine passage for tidal range power schemes having been developed for hydropower schemes and with direct applications to tidal range power schemes in the UK. The models can be effectively used to assess turbine impacts of a tidal range power scheme upon the full range of fish species and life stages where suitable fish biology data exists. The model takes into consideration the three main fish injury stressors; blade strike, shear stress and pressure as well as determining compound injury rates. There is also the potential for consideration of some of the other forms of strike on other structures such as the wicket gates and stay vanes on some of the more advanced modelling approaches. It does not however, consider indirect or delayed impacts. The model considers a single turbine pass only but can be combined with ERM to provide compound passage impacts, although with no cumulative probability risk consideration. The latest versions of the model include stochastic MCS function, enabling probability output predictions to be made, improving confidence in any associated impact assessments from the modelling.

The data required for model development and operation is largely available in published literature and requires limited collection of site-specific information. The main limiting factor is the requirement for detailed manufacture specific turbine fixed and operating parameters which could be protected by IP and may not be accurately available at the assessment stage in the detail required. No tidal range power validation data is currently available for the models due to no tidal power schemes having been consented and developed to date. Detailed monitoring programmes would be required to collect empirical data which could be complex and costly given the hostile environment in which the monitoring would be required and the volume of water passing through large turbine structures.

The models are largely formula/spreadsheet based and although built with stochastic functions could be easily replicated by other users with site and scheme specific model parameterisation.

**Method applicability for Environmental Assessments**

The models assess direct injury and mortality factors only and do not consider the wider potential indirect or delayed impacts from turbine passage, although the models can be built to assume that all fish struck die, effectively factoring in an element of delayed impacts. The stochastic nature of the most recent versions of the models allows presentation of probability prediction outputs with the ability to assess confidence percentiles. This probability output function of the models provides increased confidence in the use of the model for assessment purposes where 'scientific doubt' requires consideration under the Habitats Regulations and enables the management of uncertainty.

## STRIKER

### Method summary

The STRIKER™ model (Turnpenny *et al.,* 2000) (a proprietary version of the blade strike model) is an approach to calculating turbine passage mortality that blends CFD and dose response building on analytical strike rate models for Francis and Kaplan turbines by Von Raben (1957) with the addition of mutilation ratios. The STRIKER™ model was developed as a follow-on model from that presented in Turnpenny (1998) with the intention of being targeted at low head run of river hydroelectric power schemes following acknowledgement that the original model was likely less accurate for smaller turbine schemes. The original STRIKER™ model as presented in the 2000 report was designed to predict mortality for low-head small Francis and Kaplan turbines. The model predicts probabilities of death caused by barotrauma (pressure flux) shear/turbulence, and blade strike and the resultant compound mortality rate which is the product of the three mortality causes. Pressure conditions are taken from a reference CFD analysis for the turbine types but it is possible to alter predicted pressure conditions and blade strike probabilities by altering the following inputted parameters:

- Guide vanes: present/absent
- Runner inlet height (Francis)
- Turbine flow: at percentage load
- Runner diameter
- Runner speed
- Number of runner blades
- Angles of incidence (Kaplan)
- Draft tube height

Since original model development and application at largely run of river hydroelectric schemes, the model has undergone a number of iterations with the most recent reported version of the model being STRIKER™ V.

### Examples of model application

The original 1998 model was developed for use in the early assessments of tidal range power schemes in the UK, in particular in the Severn Estuary. The first named STRIKER model version was subsequently adapted for low-head run of river hydropower schemes for Francis and Kaplan turbines. This version of the model and later adaptations under version II and III of the model were used in the assessment of run of river hydropower schemes throughout the UK.

Versions IV and V of the model were used to assess the potential impacts upon fish from turbine passage at the proposed Swansea Tidal Power scheme. The model was adapted and enhanced for this specific scheme assessment, in particular through the development of the stochastic version V of the model.

**Applicability of model**

Following original development of STRIKER for low head riverine hydroelectric schemes, versions IV and then V of the model were specifically developed for tidal range power schemes. The model is directly relevant to tidal range power scheme collision risk assessments in the UK as it was developed for this specific application as well as the range of fish species and life stages found within this environment. The model doesn't require any adaptation for use in a tidal range scenario for fish as the model development has already factored in these requirements.

**Multi-species and life stages assessment**

The original 2000 model was built specifically for application with salmonid smolts, subsequent adaptations of the model however, have enabled it to be used for any species or life stage where suitable biological data exists.

A key biological data requirement is fish length distributions for the different species and life stages. These distributions can be varied for any species and can also be site specific if suitable data exists. Aspects of fish behaviour can also be altered for specific fish species if appropriate, such as their swimming orientation when entering the turbine (i.e. facing upstream or downstream or random), swimming speed and sinuosity.

Other aspects of the model such as mutilation ratio, pressure flux and shear stress can be altered for key species/life stage individual traits such as fish length, weight and swimbladder type. The fundamental supporting data for these factors and equations however, relate back to experiments reported on by Turnpenny *et al*., 1992, 1998 and 2000. These experiments were undertaken on a limited number of species/life stages and may not therefore, be directly appropriate to all species to be included in tidal power scheme assessments in UK waters.

**Temporal modelling**

The STRIKER model itself is a single run model, in that injury predictions made by the model are on the basis of a fish only passing through the turbine once. The model is designed to be combined with outputs from an ERM to determine cumulative passage effects. The model however, assumes the same potential for injury on each passage and does not consider any potential for injury probability to increase on subsequent passages from previous injuries sustained which may effect fish behaviour or swimming performance.

**Ability to use model openly**

The original 2000 STRIKER$^{TM}$ model version was a simple excel spreadsheet that could be used and interrogated by the developer; Fawley Aquatic Research Laboratories LTD (FARL). Subsequent versions of the model lead to the model becoming trade marked and a graphic user interface (GUI) being incorporated into the model. The GUI enables specific parameters to be inserted for model use. However, the back-room equations and model operation are not discoverable. Although the model input parameters and background equations are published in reports and papers they cannot be directly interrogated within the model and nor can the model outputs.

The latest versions of the model STRIKER$^{TM}$ IV and V are owned by Turnpenny and Horsfield Associates and can only be operated by these parties.

**Data availability**

All versions of the model require detailed information on the scheme and fish biological traits as input parameters. Some of this data will not be scheme specific and as such will be readily available, others will require scheme specific investigations. Depending on the version of the model being used; deterministic or stochastic, single input parameters maybe required or a range of variables to enable probability predictions to be developed.

The following information is required for the model;

- Fixed turbine parameters – rotation rate (rpm), turbine hub diameter, turbine runner diameter, number of blades, guide vane presence
- Operating turbine parameters – flow rate (at ebb or flood, or through the tide), nett operating head, blade angle of incidence and guide vane angle (if present)
- Turbine CFD data – CFD modelling data predicting the probability of occurrence of fish stress mechanisms from pressure and shear stress

The fixed turbine and operating turbine parameters require the selection of a specific turbine type and manufacturer and liaison with the manufacturer to determine parameters including turbine CFD modelling outputs. Some of these parameters may be protected under intellectual property of the manufacturers and as such may not be able to be presented publicly in reports or may not be provided accurately until detailed scheme design. This could limit the detail or accuracy of the models used within assessments which are often undertaken at a point prior to detailed design and specific manufacturer selection.

- Fish stress response data – fish biological response data from stress mechanisms; pressure and shear stress.
- Fish species data – swimbladder type, length distribution, mutilation ratio (fish fineness ratios)
- Fish behaviour – fish orientation, swimming speed and sinuosity

Fish stress response data remains reliant on experiments reported on by Turnpenny, 1992. These experiments were restricted to 8 species representing the following fish groups;

salmonids, clupeids, flatfish, European eel, percids and gadids. Pressure stress assessments are restricted to two equations based on two swimbladder categories; physostomes and physoclists.

Fish species data is largely available for most species and life stages and can be based off published literature data or site-specific data. Mutilation ratio relates back to a single equation based on fish body form. Fish fineness ratios (length divided by maximum body diameter) are required for the equation. Fineness ratios can be calculated with data specific to the fish population in the region of the proposed scheme or can rely on published data in Turnpenny 1998 and 2000.

Fish orientation will largely be unknown especially for a new scheme and there is little data available from operating schemes. This function is therefore, generally input as a random variable. Fish swimming speeds won't be known for all species and life stages and will be dependent upon published data and proxies for some species. This variable however, is often set as 0, on the assumption that fish will move passively with the water flow through the turbine rather than swimming with or against the flow. Sinuosity is generally set as 1 for most fish with the exception of eels and lamprey which is reported for the Swansea Tidal Power assessment as 0.9 due to the body form of these species and their greater ability to curve and flex.

**Data collection**

With the exception of turbine specific fixed and operating parameters, which will require consultation with specific manufacturers, there is limited data that requires site specific collection for operation of this model. Site specific fish data could be collected to inform length frequencies and fineness ratios but is not essential and could be based on published literature.

The biggest limiting factor of general application of the model to any scheme is the requirement for turbine specific parameters. This information may not be accurately readily available at the time of assessment which could reduce confidence in the model outputs. It is recommended that as accurate as possible input parameters for these variables are used for the modelling and assessment of impacts which will require early turbine manufacturer liaison.

**Method validation data**

The outputs of STRIKER I were validated by Turnpenny *et al.,* (2000) with empirical data collected from real world operating run of river hydropower turbines (one Kaplan and one Francis). These turbines were at the smaller end of the size spectrum ($\leq 2m^3 s^{-1}$) as this made fish capture from the tail race less difficult than with a larger flow. The approach was to position nets across the draft tube exit or in the tail race to capture migrating fish or fish remains. Wild fish were supplemented by introducing (for ethical reasons) freshly killed fish into the turbine inlet and recapturing them in the net. The results showed that the compound mortality predictions of STRIKER v I were very similar to observed rates (Kaplan turbine: 29% mortality predicted 35.5% observed; Francis turbine: 21.8% mortality predicted 17.9% observed) and that the relative importance of different mortality causes were also correctly predicted.

It has not been possible to validate the predictions made by STRIKER™ IV or V models on tidal range power schemes. Assessments undertaken with these model types are restricted to the Swansea Tidal Power scheme which has not been consented to date and as such there is no empirical data.

The requirement for collecting empirical scheme data should be built into any future consented tidal power scheme that utilises this or any other assessment model type to enable validation of the model parameters and outputs. The design of such a monitoring scheme should be considered during the design of the scheme to ensure that data can be collected efficiently and safely. Collection of fish passing through the turbines on a large tidal range power scheme will be complex and likely require an expensive monitoring programme. Any monitoring programme would need to considered the power analysis of data collected to ensure that it can adequately be used to validate the outputs of the model.

**Uncertainty management**

STRIKER™ IV is a deterministic model which considers single fixed input parameters only and subsequently outputs single predictions per model run. As part of the Swansea Tidal Power scheme assessment it was determined that single fixed model predictions, given the level of uncertainty in the input parameters, did not provide the confidence required for the assessment. STRIKER™ V was therefore developed as a stochastic model which considered variable inputs for a number of parameters based on probability using a Monte Carlo Simulation (MCS) function in the model build. The stochastic version of the model also enables predictions to be made at one minute time steps of operation rather than taking a single point of operation as per the deterministic version of the model.

Version V of the model takes into consideration probability variability of the following input parameters;

- Turbine flow rate, turbine rotational speed and wicket gate angle
- Fish length
- Fish turbine radial passage position
- Fish mutilation ratio (M)
- Fish orientation at front plane of runner blade

A stochastic model allows a range of possible injury rates to be presented with a prediction of the frequency of each rate occurring. The ability to present a range of potential injury rates provides confidence in an assessment especially those subject to assessment under the Habitats Directive which requires a conclusion with no ‘scientific doubt’. A suitable percentile of injury prediction frequency can be selected such as 90%ile or above to provide confidence that it is unlikely that the resultant impact will be higher than that assumed within the assessment.

Not all aspects of the management of residual uncertainty are clear within the model as the assessment of the variable parameters is dependent upon the presentation of the parameters within accompanying model reports. The ability to be able explore and further adapt the back-room of the model may allow further improvement in the management of residual uncertainty.

Due to no tidal range power schemes being operational in UK waters to date it has not been possible to validate the outputs of the model against empirical scheme specific study data. In the absence of such empirical data validation an element of residual uncertainty remains, as it does within any model. The incorporation of stochastic function to the model however, and the ability to select percentiles of injury prediction frequency, allays some of the concerns around confidence in model predictions for environmental assessments.

### Assessment Matrix

The STRIKER™ version V model received a score of 9 for the value assessment and 9 for the confidence assessment, giving a combined score of 18. The scores for each criteria are shown below in Table 4-8.

Table 4-8 STRIKER™ version V model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 3 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 1 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 2 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 3 |
| **Value Score** | 10 | **Confidence Score** | 9 |

### Method conclusions

The STRIKER™ V model version is directly applicable for fish turbine passage for tidal range power schemes having been developed specifically for this purpose and with its origin in early tidal power studies. The model can be effectively used to assess turbine impacts upon the full range of fish species and life stages where suitable fish biology data exists. The model takes into consideration the three main fish injury stressors; mechanical injury (including turbine blade strike and wicket gate injury), shear stress and pressure as well as determining compound injury rates. It does not however, consider indirect or delayed impacts. The model considers a single turbine pass only but can be combined with ERM to provide compound passage impacts, although with no cumulative probability risk consideration. The latest version of the model includes stochastic MCS function, enabling probability output predictions to be made, improving confidence in any associated impact assessments from the modelling.

The data required for model development and operation is largely available in published literature and requires limited collection of site-specific information. The main limiting factor is the requirement for detailed manufacture specific turbine fixed and operating parameters which could be protected by IP and may not be accurately available at the assessment stage in the detail required. No validation data is currently available for the models due to no tidal power schemes having been consented and developed to date. Detailed monitoring programmes would be required to collect empirical data which could be complex and costly given the hostile environment in which the monitoring would be required and the volume of water passing through large turbine structures.

The model is trademarked and sole owned by a company with full IP limiting its use on a range of schemes without this company's involvement. The model is also effectively a 'black box' with no view of the back-room of the model, its build, detailed input parameters and outputs. An accompanying report is therefore, required from which the input parameters can be reviewed. No direct model interrogation is however, possible.

**Method applicability for Environmental Assessments**

The model assesses direct injury and mortality factors only and does not consider the wider potential indirect or delayed impacts from turbine passage. The stochastic nature of the most recent version of the model; STRIKER™ V allows presentation of probability prediction outputs with the ability to assess confidence percentiles. This probability output function of the model provides increased confidence in the use of the model for assessment purposes where 'scientific doubt' requires consideration under the Habitats Regulations and enables the management of uncertainty.

## BioPA

**Method summary**

The Biological Performance Assessment (BioPA) toolkit uses computational fluid dynamics (CFD) to estimate the probabilities that fish will encounter specific conditions during passage through a turbine (Richmond et al., 2014;PNNL, 2023). This is done with a proportional sampling scheme that uses stream traces in a CFD simulation to model potential pathways through the turbine.

The key steps in the simulation process are as follows:

- CFD model**:** A CFD model of the flow fields within the turbine system is created form technical drawings of the design. The model must resolve flow features at areas of interest (blades, wicket gates, stay vanes, tip gaps, etc.) at a scale smaller than the length of a fish.
- Stream trace sampling: The model inlet is seeded with a large number of points, each representing a possible location of a fish entering the turbine. Because of the heterogeneous nature of the flow, all parts of the turbine environment are not equally likely to be visited by fish. Some areas will receive more traffic than others, so these places should be sampled in higher proportion. The seeds are distributed in accordance with available field observations, or a distribution may be assumed based on expected behaviours of the species of interest. For example, if fish are

known to be concentrated in the upper part of the water column, seeds are proportionately denser in these areas.

- Exposure probability**:** After stream traces have been generated, the pressure and sheer conditions and collisions with the turbine along each path are determined to calculate the frequency of injury or mortality from each of these three causes.

- Performance score**:** The BioPA score is computed by combining the dose–response information obtained from laboratory studies with the exposure probability determined through stream trace sampling. The score is the sum of the products of the probability of mortal injury (the dose–response) and the probability of exposure (the exposure estimate) over all stressor-variable values. The scores can then be used to compare competing turbine designs, refine a new design, or evaluate the performance of an existing hydropower turbine.

**Examples of model application**

In the paper by Richmond et al. (2014) the BioPA method was applied to the John Day Dam (JDA) Kaplan turbine to assess juvenile Chinook salmon exposure to rapid pressure change. The John Day Dam is located on the Colombia river about 150km east of Portland, Oregon. During the spring the juvenile Chinook salmon migrate downstream and must pass through the JDA. Previously it was estimated that survival rates for Chinook salmon on their downstream migration through JDA turbines were at 84% (Weiland et al., 2011). The BioPA results for the John Day Dam turbine showed several features:

- Higher discharges tend to increase mortal injury rates from exposure to low pressures.

- A sigmoidal seed distribution, with a higher density of seeds closer to the roof of the intake, has slightly lower pressure mortal injury values than uniformly distributed seeds. Fish distribution at turbine entry could be a more significant factor at projects where intake screens are not used.

- Depth of fish acclimation is a significant factor in the prediction of passage mortal injury due to rapid pressure change.

**Applicability of model**

The BioPA toolkit can be applied to a wide range of turbine types operating under different site conditions, and case studies have been based on turbine designs likely to be used for tidal range power. The method can assess the three major causes of injury and mortality caused by ducted turbines (collisions, barotrauma, and sheer stress)

**Multi-species and life stages assessment**

According to Pacific Northwest National Laboratories (PNNL) who are the developers of BioPA, the toolkit can be used to evaluate the biological performance of turbines on over 20 species of fish. It is indicated however, that these species are all from North America. In theory, any species could be modelled provided adequate dose-response data are available, however, it is understood that new species can only be added to the toolkit by PNLL (PNNL, 2023).

**Temporal modelling**

BioPA is a single run method, in that mortality predictions made by the model are on the basis of a fish only passing through the turbine once, however, the model could easily be combined with outputs from an ERM to determine cumulative passage effects. The model, however, assumes the same potential for injury on each passage and does not consider any potential for injury probability to increase on subsequent passages from previous injuries sustained which may affect fish behaviour or swimming performance.

**Ability to use model openly**

The toolkit is owned and developed by the Pacific Northwest National Laboratory (PNNL) and licensing of the model for use by turbine manufacturers and scheme developers is possible at an unknown cost. BioPa is built around commercial software packages together with custom post-processing scripts. It was designed to give turbine designers a convenient tool that could be incorporated into their normal workflow with minimal disruption to cost, and computational resources. The BioPA uses inexpensive, off-the-shelf software components, often already employed by hydro turbine manufacturers, using Microsoft Windows environments and consists of three components:

1. CFD solver: simulations software that generates the model results.

2. Stressor calculator: a Tecplot360 application that samples CFD using stream trace and computes statistics.

3. Scoring application: a Microsoft Excel application that computes BioPA scores based on stream trace statistics.

**Data availability**

The fixed turbine and operating turbine parameters will require liaison with the manufacturer to determine parameters for CFD modelling. Some of these parameters may be protected under intellectual property of the manufacturers and as such may not be able to be presented publicly in reports or may not be provided accurately until detailed scheme design. This could limit the detail or accuracy of the models used within assessments which are often undertaken at a point prior to detailed design and specific manufacturer selection.

The CFD solver component of BioPa does not require a specific package, so long as it meets the requirements listed below:

1. The model should be constructed at prototype scale.

2. The model must generate a steady-state solution. A transient solution may produce a more-accurate representation of the flow, the BioPA is not currently configured to accommodate this additional level of complexity.

3. To model the moving components to the turbine with a steady-state solution, a multiple reference frame (MRF) scheme is necessary. With the runner in a fixed position, the surrounding fluid is modelled in a rotational reference frame to simulate the appropriate movement.

4. The model must resolve flow features at areas of interest (blades, wicket gates, stay vanes, tip gaps, etc) at a scale smaller than the length of fish.
5. The model output file must be in a format that can be imported into Tecplot360 and contain, at a minimum the following variables for each node in the mesh:
    - Position coordinates
    - Velocity components in the stationary reference frame
    - Velocity in the rotational reference frame
    - Static pressure

Biological data come preloaded within the BioPA toolkit for 20 species, but as previously highlighted, these species are limited to North America. Fish stress response data for species native to the UK remains reliant on experiments reported on by Turnpenny, (1992). These experiments were restricted to 8 species representing the following fish groups: salmonids, clupeids, flatfish, European eel, percids and gadids. Pressure stress assessments are restricted to two equations based on two swim bladder categories (physostomes and physoclists). Basic biological data (e.g., fish lengths) are largely available for most species and life stages and can be based off published literature data or site-specific data.

Fish orientation will largely be unknown especially for a new scheme and there is little data available from operating schemes. Orientation is therefore, generally input as a random variable. Fish swimming speeds won't be known for all species and life stages and will be dependent upon published data and proxies for some species. This knowledge gap has led many researchers to assume that fish follow flow streamlines when encountering the high velocities of the turbine environment. This is also assumed in the BioPA.

**Data collection**

Except for turbine specific fixed and operating parameters, which will require consultation with specific manufacturers, there is limited data that requires site specific collection for operation of this model. Site specific fish data could be collected to inform length frequencies but is not essential and could be based on published literature.

The biggest limiting factor of general application of the model to any scheme is the requirement for turbine specific parameters. This information may not be accurately readily available at the time of assessment which could reduce confidence in the model outputs. It is recommended that as accurate as possible input parameters for these variables are used for the modelling and assessment of impacts which will require early turbine manufacturer liaison.

**Method validation data**

The BioPA depends on data generated through numerical modelling of the turbine environment. Whilst CFD modelling has successful application in a variety of fluid-flow problems, the lack of comprehensive prototype-scale validation data must be noted. As direct measurement of multiple flow variables in an operating turbine environment is extremely complicated (Cada, 2001; Moursund and Carlson, 2004), model validation is limited to confirmation of overall performance measures and data from reduced-scale laboratory physical models. Furthermore, even within laboratory physical models, comprehensive velocity and pressure measurements are seldom performed. Despite this, the use of CFD modelling of hydro turbines is routinely used in the industry for developing and evaluating turbine designs (Keck and Sick, 2008). To our knowledge, BioPA predictions of injury and mortality have not been validated.

**Uncertainty management**

Richmond et al., (2014) highlight some of the limitations and uncertainties of the BioPA simulation process. First, BioPA depends heavily on the availability of biological test data relating to fish response to stress. For reasons of cost and time, laboratory experiments tend to evaluate very specific situations, which in some cases only approximate the actual conditions within the turbine. Extrapolation of this data to more general situations is a challenge. Moreover, injury studies that yield dose–responses generally do not account for the synergistic effects of multiple doses of a particular stressor or the combined effect of multiple stressors because each injury mechanism is evaluated in isolation. Second, the behaviour of fish before and during turbine passage is a subject of considerable uncertainty among biologists. Of significance to turbine passage is the observation that fish tend to exhibit different body orientations as they pass through the intake which may influence the risk of injury. Third, the depth to which fish are acclimated is a significant factor in pressure related injuries but is not accounted for in the simulation, Finally, while CFD modelling has a long history of successful application in a variety of fluid-flow problems, including hydro-turbine applications, there has been a lack of comprehensive validation because direct measurement of many flow variables in an operating turbine is exceedingly difficult.

**Assessment Matrix**

BioPA received a score of 7 for the value assessment and 6 for the confidence assessment, giving a combined score of 13. The scores for each criteria are shown below in Table 4-9.

Table 4-9 BioPA model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 3 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 1 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 1 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 3 | **Uncertainty management** | 1 |
| **Value Score** | 8 | **Confidence Score** | 6 |

**Method conclusions**

The BioPA toolkit is suitable for modelling fish turbine passage for tidal range power schemes and takes into consideration the main fish stressors: blade strike, shear stress, and barotrauma. The model can theoretically be used to assess turbine impacts upon the full range of fish species and life stages where suitable fish biology data exists. However, there are major limitations that restrict its suitability, namely a lack of flexibility for the user to include new species within the toolkit, IP constraints, and an absence of empirical validation of fish injury and mortality. Adding additional species would expand the toolkits relevance to territories outside of North America.

**Method applicability for Environmental Assessments**

The BioPA model assesses direct injury and mortality factors only and do not consider the wider potential indirect or delayed impacts from turbine passage. The model in its current form is deterministic and as such does not manage or assess the inherent uncertainty in the model parameters and its outputs. The deterministic nature of the model restricts the use of the model for the purposes of HRA assessment in particular which requires consideration of a precautionary approach to the assessment.

## Bart Model

**Method summary**

Van Esch (2012) details CFD analysis of flow passing through a mixed-flow pump (with a helical impeller) to assess the effects of pressure variation and shear stress and combines this information with a blade strike model to predict the potential for mechanical injury of fish passing through centrifugal pumps. The model development focuses upon pumping stations in The Netherlands.

The CFD analysis of flow through a typical mixed-flow pump is undertaken using commercial code FLUENT® based on the Reynolds-averaged Navier-Stokes (RANS) equations with the standard k-$\varepsilon$ model to calculate the Reynolds stress. Pressure-velocity coupling uses the SIMPLE algorithm. Both pressure drop and shear stress is modelled within the CFD analysis under different flow rates.

The Von Raben turbine blade strike equations were adapted to estimate probability of fish survival in a centrifugal pump to enable compound mortality to be determined. It is highlighted by the author that blade strike is considered to represent the greatest risk of fish injury.

**Examples of model application**

The combination of the CFD analysis and blade-strike equation outputs were compared against measured rates of injury and mortality from several field studies at pumping stations in The Netherlands. The results of the modelling were considered to be largely comparable to injury/mortality rates observed through field sampling.

**Applicability of model**

The Bart model follows the same general approach as the other blade-strike models discussed above with the Von Raben equations forming the basis of the model. The addition of CFD analysis to enable the inclusion of pressure and shear force related injuries is similar to the approach taken within the STRIKER model to identify potential damaging zones and rates within the turbine casing.

The modelling approach was developed specifically in this case for application at pumping stations with centrifugal pumps in The Netherlands. The general approach which follows well documented blade strike equations, does not advance on other existing equation-based approaches and the adaptations made for use with centrifugal pumps reduces the model use for a tidal range power scheme.

**Multi-species and life stages assessment**

This model, as with other blade-strike equation approaches, is in theory suitable for implementation with any set of target species or life-stage provided an adequate evidence base can be sourced to enable model parametrisation.

**Temporal modelling**

The Bart model is a single run model, in that injury predictions made by the model are on the basis of a fish only passing through the turbine once. The model does not have any provision for multiple passes given it has been developed for application at pumping stations which will have a single passage only. There may be potential to couple the model with a encounter model to enable multiple passage contextualisation, however, this would need to be investigated further.

**Ability to use model openly**

The blade strike element of the model is equation based and as such can be operated within open platforms such as excel spreadsheets or R. The CFD modelling element for pressure and shear stress impact predictions would require the use of specialist software packages such as FLUENT®.

**Data availability**

The model will require detailed information on the scheme in particular the turbine design and fish morphological parameters. Some of this, in particular regarding fish morphology may not require scheme specific information and could be taken from literature based sources.

**Data collection**

With the exception of turbine specific fixed and operating parameters, which will require consultation with specific manufacturers, there is limited data that requires site specific collection for operation of this model. Site specific fish data could be collected to inform length frequencies and fineness ratios but is not essential and could be based on published literature.

The biggest limiting factor of general application of the model to any scheme is the requirement for turbine specific parameters. This information may not be accurately readily available at the time of assessment which could reduce confidence in the model outputs. It is recommended that as accurate as possible input parameters for these variables are used for the modelling and assessment of impacts which will require early turbine manufacturer liaison.

**Method validation data**

Van Esch (2012) compares modelled and field collected data from pumping stations around The Netherlands and found a good correlation between the modelled and empirical fish injury probabilities.

Van Esch and Spierts (2014) also undertook specific studies to validate the predictions of the model. A total of 1,253 live fish including predominantly cyprinids as well as European eel were allowed to pass through a centrifugal turbine typical of those operated at pumping stations in a test rig. The limited number of fish available for each test condition resulted in a wide confidence interval (CI) band however, data for cyprinids generally correlated with fair agreement to the model predictions.

**Uncertainty management**

The model as described in Van Esch is a probabilistic model however, given it is based on blade-strike equations which have elsewhere been adapted into a stochastic model, it is considered likely that such an adaptation would also be possible for this model.

The management of uncertainty in the CFD analysis for pressure and shear stress would require re-running the analysis under varying input parameters which could be time consuming.

**Assessment Matrix**

The Bart model received a score of 8 for the value assessment and 8 for the confidence assessment, giving a combined score of 16. The scores for each criteria are shown below in (Table 4-10).

Table 4-10 Bart model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 2 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 2 |
| **Temporal modelling assessment value** | 2 | **Uncertainty management** | 2 |
| **Value Score** | 9 | **Confidence Score** | 8 |

### Method conclusions

The Bart model is not directly applicable for fish turbine passage for tidal range power schemes having been developed specifically for centrifugal pump passage at pumping stations in The Netherlands. The model can be effectively used to assess turbine impacts upon the full range of fish species and life stages where suitable fish biology data exists. The model takes into consideration the three main fish injury stressors; blade strike, shear stress and pressure and as such can determine compound injury rates. It does not however, consider indirect or delayed impacts. The model considers a single turbine pass only but could be combined with ERM to provide compound passage impacts, although with no cumulative probability risk consideration. The model in its current form is probabilistic and as such does not support uncertainty management, although is it likely to be adaptable to achieve this.

The data required for model development and operation is largely available in published literature and requires limited collection of site specific information. The main limiting factor is the requirement for detailed manufacture specific turbine fixed and operating parameters for the CFD analysis which could be protected by IP and may not be accurately available at the assessment stage in the detail required. Validation data is available for the models however, for centrifugal pumps at pumping stations and as such is not therefore, of direct relevance to a tidal range power scheme. Detailed monitoring programmes would be required to collect empirical data at a tidal power scheme to validate its use in this scenario, which could be complex and costly given the hostile environment in which the monitoring would be required and the volume of water passing through large turbine structures.

The blade-strike model is operated using equations in spreadsheets and as such can be easily adapted and operated through reproduction of the equations for a specific scheme development. The CFD analysis to determine the pressure and shear stress related risks however, would require analysis within specialist software.

**Method applicability for Environmental Assessments**

The model assesses direct injury and mortality factors only and does not consider the wider potential indirect or delayed impacts from turbine passage. The model is currently probabilistic but could be adapted to have stochastic function.

## Fish-Net

**Method summary**

Wilkes *et al.,* (2018) integrated traditional blade strike risk models for Kaplan and Francis turbines and expert elicitation for shear stress and barotrauma mortality into a Bayesian network model (named Fish-Net) for assessing fishway passage. Fish-Net was targeted at run of river hydroelectric power schemes to predict the barotrauma and shear-related mortality rates during downstream passage for Francis and Kaplan turbines.

The Bayesian network (BN) approach similar to the Delphi approach uses expert elicitation which can provide a reliable basis for management decisions (Knol et al, 2010). The expert elicitation protocol allows for a mathematical accumulation of expert opinion to be incorporated within a BN.

A combination of data sources to model mortality rates were used. The response variables were separated into the three main sources of mortality during downstream passage, namely barotrauma, shear, and blade strike. Causal variables were derived from literature on pressure and shear related mortality, and blade strike models for Kaplan (Deng et al, 2007) and Francis (Ferguson et al, 2008) turbines were used to determine causal variables for blade-strikes. The description and source of the causal nodes for blade strike mortality are noted below.

- Turbine design – parameters of blade strike models (BSMs) for Francis and Kaplan turbines from seven real turbines in Chile.
- Fish body length – total length of fish as input to BSM sourced from three representative lengths for non-recreational fish.
- Relative discharge – ratio between the turbine design discharge and the actual turbine discharge sourced from a realistic range.

The description and source of the causal variable used to predict shear mortality rate was:

- Maximum strain rate – maximum shear stress fish are exposed to during passage through turbines or spillways (cm $s^{-1}$ $cm^{-1)}$ sourced from a realistic range.

The description and source of the causal nodes used to predict barotrauma mortality rates are noted below:

- Acclimation depth – depth at which fish are acclimated (neutrally buoyant) before passage through turbines or spillways (m) sourced from known acclimation depths up to 10m.

- Ratio of pressure change – ratio between the acclimated pressure and the nadir pressure during fish passage through turbines or spillways sourced from the range of nadir pressures commonly found.

- Swim bladder morphology – type of swim bladder (or no swim bladder) of species considered sourced from three categories of swim bladder morphologies (Brown et al., 2014).

**Examples of model application**

The Bayesian Network modelling framework was applied by Wilkes et al, (2018) to a hydropower case-study in the temperate Southern Hemisphere, where the resulting probabilistic models were used to predict the rates of mortality during downstream passage of all fish through Kaplan and Francis turbines and spillways. The BN focused on a 72-hour mortality rate, including indirect mortality due to increased susceptibility to disease and predation. Expert elicitation was used to populate conditional probability tables from the BN. The results indicated that the swim bladder morphology was the most influential factor affecting mortality through barotrauma, followed by the ratio of pressure change. Acclimation depth was understood to have very little effect on the 72-hr mortality. Additionally, experts were more uncertain about the mortality rate for physoclistous species than other swim bladder morphologies. Blade-strike was also an important source of mortality with higher mortality rates in Kaplan turbines than in Francis turbines for larger bodied fish, with the exception of higher discharges up to 140% of the turbine design discharge. Overall, the model predicted that almost the complete range of possible mortality rates (0%-100%) was plausible, dependent on turbine design and the characteristics of target species.

**Applicability of model**

The Fish-Net method was developed for predicting mortality through hydropower turbine passage and could be applied to a wider range of turbine types operating under different site conditions. Wilkes et al. (2018) focused on Kaplan and Francis turbines which are the types of turbines most likely to be employed for tidal range power generation. Fish-Net is not however, described by the developers as a ‘tool’ and the usability of Fish-Net and flexibility for adaption to specific scenarios is not clear. It is likely that some program development by a person familiar with Bayesian statistics would be required.

**Multi-species and life stages assessment**

The elicitation approach for modelling mortality rates is in theory suitable for implementation with any set of target species or life-stage provided adequate expertise can be sourced.

**Temporal modelling**

The Bayesian Network method is a single run model, in that mortality predictions made by the model are on the basis of a fish only passing through the turbine once, but could easily be combined with outputs from an ERM to determine cumulative passage. The model, however, assumes the same potential for injury on each passage and does not consider any potential for injury probability to increase on subsequent passages from previous injuries sustained which may affect fish behaviour or swimming performance.

**Ability to use model openly**

The Fish-Net model is implemented with Netica v5.24 (Norsys Software Corporation, 2016). The algorithm for estimating mortality would have to be requested from the developer (http://martinwilkes.co.uk), along with all electronic files corresponding to the Bayesian networks for use in Netica and may not be released.

**Data availability**

Data availability in terms of the elicitation process would require availability of experts in the field of barotrauma- and shear-related mortality for involvement in the interview process. Wilkes at el. (2018) focused on obscure fish species of little commercial importance yet were able to a collect together a group of experts consisting of six senior scientists and one PhD student, which together represented more than 100 years of relevant accumulated experience.

**Data collection**

In term of data collection for the elicitation protocols it is understood that biases related to knowledge availability, anchoring and group dynamics can all impact on efforts to employ expert knowledge to a good standard (Burgman, 2005; Martin et al., 2012). Thus, the use of carefully managed elicitation protocols is important to provide a reliable basis for management (Knol et al., 2010). The protocol used during the Fish-Net method is described by Little et al. (2018) and involved the mathematical accumulation of expert opinion in a manner that allowed direct incorporation into the BN. The collation of expert opinion entailed several consultations with experts to define the prototype BN, and then separate expert elicitation workshops. The first focused on barotrauma- and shear-related mortality and was attended by three experts with the most experience in downstream passage. The second was related to upstream passage.

For the Fish-Net study, experts were asked four questions for each unique combination of causal node states connected to each response node. The basic forms of the questions in the “four-point” elicitation protocol are as follows:

(i) What is the minimum you would realistically expect?

(ii) What is the maximum you would realistically expect?

(iii) What is your most likely (best) estimate? and

(iv) how confident are you that this range includes the true number?

Experts wrote their responses by hand in a pre-prepared document in which each question was printed on a separate page. They were asked not to refer back to previous answers. After every second question, the facilitators quizzed the experts with numerical trivia to distract them from previous answers, mitigating for anchoring bias. In each workshop, experts answered all questions twice. In the first round, experts were not permitted to confer or discuss their answers in any way but could refer to published results. First-round answers were then inputted into a spreadsheet, converted to probability distributions and shown to all experts, revealing any convergence or divergence in opinion. After suitable opportunity to discuss any differences in opinion, experts were asked to provide new answers or maintain their initial answers. Final probabilities used in constructing the conditional probability tables were taken as the mean of all first- and second-round answers. For a description of the logic underpinning these aspects of the elicitation process, see Little et al. (2018).

**Method validation data**

Fish-Net was used in a hydropower case-study in the temperate Southern Hemisphere, where the resulting probabilistic models were used to predict the rates of mortality during downstream passage of fish through Kaplan and Francis turbines. The results were not validated by empirical data.

**Uncertainty management**

Because BNs provide probabilistic results, the approach explicitly acknowledges the uncertainty in fish turbine mortality. The expert elicitation protocol within the BN approach is designed within a robust cognitive psychological and mathematical framework (Little et al., 2018), however residual bias in probabilities derived from expert knowledge cannot be ruled out. The probabilities derived from the expert opinion may also be affected by the statistical treatment of the data gathered at the workshops. A minimum cross entropy (MCE) calculator optimises beta distributions by spreading residual uncertainty throughout the range 0-1 (Salomon, 2013). The MCE method transforms the results of four-point elicitation protocols into statistically representable distributions. For the continuous causal variables, general linear models were fitted to the mean and variance of the expert elicited distributions to interpolate between the discreate values forming the questions posed to the experts. While linear responses were consistent with the knowledge of the experts and the available empirical data on several sport species, the possibility of asymmetrical or complex relationships that are not captured in Fish-Net could not be ruled out. This possibility could be reduced by asking experts more questions across the range of values of interest. Time and “expert fatigue” are likely to limit the number of questions that can reasonably be included in expert elicitation workshops. Further biases potentially remaining despite the careful expert elicitation protocol used are discussed in detail by Little et al. (2018).

Wilkes et al (2018) performed a sensitivity analysis on each response node of the BN. The results showed the 72-hour mortality due to blade strike is most heavily influenced by the turbine design followed by the fish body length. Overall, the relative turbine discharge was less influential, although it was clearly a more important variable for Kaplan turbines than Francis turbines.

**Assessment Matrix**

The Fish-Net model received a score of 8 for the value assessment and 7 for the confidence assessment, giving a combined score of 15. The scores for each criterion are shown below in Table 4-11.

Table 4-11 Fish-Net model assessment scoring

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 2 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 2 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 2 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 2 | **Uncertainty management** | 2 |
| **Value Score** | 8 | **Confidence Score** | 7 |

**Method conclusions**

The BN modelling approach is applicable for fish turbine passage for tidal power schemes. The model can be used to assess turbine impacts upon the full range of fish species and life stages where suitable fish biology data is present. The model takes into consideration the three main fish injury stressors; blade strike, shear stress, and pressure, including indirect mortality due to increased susceptibility to disease and predation within a 72hr period. The model considers a single turbine passage and assumes the same potential for injury on each passage and does not consider any potential for injury probability to increase on subsequent passages from previous injuries sustained which may affect fish behaviour or swimming performance.

The data required for the model development and operation is largely available in published literature and requires limited collection of site-specific information. A main limiting factor is the requirement for detailed manufacture specific turbine fixed and operating parameters which could be protected by IP and may not be accurately available at the assessment stage in the detail required. In terms of data collection for the elicitation protocols, it is understood that biases related to knowledge availability, anchoring and group dynamics can all impact on efforts to employ expert knowledge to a good standard (Burgman, 2005; Martin et al., 2012). Thus, the use of carefully managed elicitation protocols is important to provide a reliable basis for management (Knol et al., 2010).

Because BNs provide probabilistic results, the approach explicitly acknowledges the uncertainty in fish turbine mortality, but model predictions have yet to be validated by empirical data.

The model is heavily based on the knowledge and expertise of the expert panel which in the area of tidal power modelling is likely to be limited in relation to the number of suitable individuals and confidence in their validated evidence base. Given the complexity of the causal nodes and the lack of validated models for tidal power schemes, implantation of this model type is considered to be limited at this time, but could be investigated further once development of tidal power schemes and the modelling of impacts have further developed/advanced.

**Method applicability for Environmental Assessments**

The model in its current form is not directly applicable to a tidal range power scheme in the UK, as it is specifically focused on defined scheme specific turbine characteristics and temperate southern hemisphere fish species. Given the elicitation protocols used to develop the model predictions, application to a tidal power scheme in the UK and for relevant fish species and life stages would require the elicitation protocols to be undertaken from the beginning with identification of suitable experts. It is considered that upon comparison to other available techniques this approach is less robust, adaptable and able to assess and manage uncertainty and withstand scrutiny.

# 5. Review of other taxa models

## 5.1 Encounter Risk Models

Models for other taxa have been developed for wind or tidal stream turbines and generally couple models that estimate the encounter and collision probability. It was concluded that encounter elements of these models were not relevant to tidal range scenario and thus scored zero in the assessment of this criterion as discussed further in Section 6 below. An explanation for the zero score is provided in Section 6: Non-Applicable Models.

## 5.2 Collison Risk Models

This section refers specifically to the turbine collision risk elements of models for birds and mammals, rather than the encounter risk elements. As with analytical blade strike models developed for ducted turbines (e.g., Von Raben, 1957, Deng *et al*., 2007), most of the models are very similar, relying on simple equations to estimate the probability that an animal of a given size and speed occupies the same spatial and temporal extent as the rotating turbine blades. This section starts with a review summarising the development and key principles of blade strike models for birds and mammals at tidal stream and wind turbine facilities and then proceeds to assess the suitability of the models (as a group) according to the value and confidence criteria. Some individual models were assigned marginally different scores which are shown in Appendix A: Model Value and Confidence Assessment.

**Methods summary**

<u>Tucker model</u>

The Tucker Model (Tucker,1996) is a deterministic equation incorporating observed empirical data to analyse the probability of a bird collision with a single turbine rotor, calculated as a ratio of the time taken for a turbine blade to complete a single revolution compared to the time taken for a bird to move through the rotor swept area. It predicts the probability of a collision occurring when the bird glides through the area swept by the blades, which are either one or three-dimensional, assuming the bird does not evade the rotor blade. The parameters are the size and speed of the bird and the mechanical design of the turbine (length, width, twist, and rotation speed). Tucker (1996) was the first publication detailing a complete analysis of bird-rotor collisions; however, it does not account for evasion of the rotor blades or distinguish between different severities of collisions and assumes the bird is two dimensional, rectangular and moves on fixed wings.

<u>Hamer Model (Holmstrom et al. 2011)</u>

The Hamer model is based on the Tucker Model but extended to include oblique angles of approach flight to the wind turbine, as the authors state to be an important improvement since birds often follow flight paths that are not dependent on the wind direction, but rather on established migratory routes or geologic features such as valleys or coastlines (Holmstrom et al. 2011). The algorithm created by the authors calculates probability of a bird-rotor collision given a specific flight path through the rotor plane. Limitations are the same as those listed in the description of the Tucker Model above.

Band Model

The discussion here covers the Basic Band Model (Band et al., 2000) and subsequent versions of the model (Band et al., 2012; Marsden, 2015; Band et al., 2016; McGregor et al., 2018). The Band Model has been widely utilised for wind farm environmental assessments in the UK (Marsden & Cooke, 2016).

The Basic Band Model is a deterministic calculation implemented in Excel to predict the collision mortality risk of birds colliding with turbines. The probability that an encounter results in a collision is calculated from the size of the bird (both length and wingspan), the breadth and pitch of the turbine blades, the rotation speed of the turbine, and the flight speed of the bird. To facilitate calculation, many simplifications are made. The bird is assumed to be of simple cruciform shape, with the wings at the halfway point between nose and tail, and its flight speed is independent of wind speed and direction. The turbine blade is assumed to have a width and a pitch angle (relative to the plane of the turbine), but to have no thickness and all collisions are assumed fatal.

Several adjustments to the Basic Band model have been made since Band et al., (2000). The extended Band Model (Band et al., 2012) allows different options for the flight height of the bird when entering the rotor swept area and includes an additional term describing the flying style (flapping or gliding). In terms of the collision risk, the justification for this addition is that the probability of a collision is greater at the turbine hub compared to the rotor blade tips which is also considered within equivalent fish hydropower strike models. In 2016, Band et al. (2016) updated the model to be more suitable for marine mammals and tidal stream turbines by relaxing the assumption that every collision is fatal and accounting for swimming style, rather than flight style. Work by Bolker *et al* 2014 developed the Band model by considering how the layout of wind turbines within an array (the geometry) would influence collision risk. Finally, a stochastic version of the Band Model using Monte Carlo Simulation was developed by Marsden (2015) using the open-source programming language R and later revised by McGregor et al., (2018) to improve usability (including speed), transparency and robustness, and create a user-friendly Graphical User Interface (GUI). The band Collision risk model has been coupled to encounter risk IBMs for birds (Eichorn *et al* 2012) and fish (Rossington & Benson, 2019).

SLSR model

Work by Wilson (2006) was focused on estimating marine mammals and fish collisions with tidal stream turbines and involved repurposing equations that were initially intended to predict encounters between predators and prey in aquatic environments. In these modified equations the predator is substituted by turbine rotor blades.

The model of Wilson (2006), known as the SLSR model, requires empirical data on the animal at the depth horizon of the turbine ($D$), the cross-sectional area of the rotor blades perpendicular to their axis of rotation modified for the size of the animal ($A$), the swimming speed of the animal ($u_a$) and the rotary speed of the turbine blades ($u_b$). From these parameters the probability of an animal occupying the same space as a turbine blade at a point in time ($Z$) is calculated as

Podolsky Model

This model is presented in a patent document (Podolsky, 2008) and describes the bird, the turbine and the wind farm. The model follows a similar method to Band et al., (2007) and Tucker (1996) calculating the distance travelled across the rotor disc and thus the time required which is then compared to rotor speed and the time required for a single revolution of the blades. The bird is represented as a cross with length and wingspan and uses the largest linear dimension of the bird so that the most conservative results are produced. The model considers oblique angles of approach, not only those parallel to the wind and includes a proportion of birds which avoid collision. The probability of collision is calculated for a bird colliding with a single rotor and subsequently the model calculates the probability of collision for a given row of wind turbines and for multiple rows.

Biosis CRM

The collision risk model developed by Biosis Propriety Limited has been widely used to assess wind energy developments in Australia since 2002 (Smales et al., 2013). The collision risk calculation follows similar principles to the deterministic Band, Tucker, and Podolsky Models but uniquely includes collision with static components of the wind turbine such as the tower. It also does not assume that birds always approach the turbine perpendicular to the blades or from a specific angle but rather flights can approach turbines from any direction meaning all dimensions of the turbine contribute to the area with which a flying bird might collide.

Copping *et al*. (2017)

Focusing on harbour seals, the model by Copping *et al*. (2017) has five main components or steps leading to a collision: 1) probability a seal will swim near a turbine; 2) the probability a seal swims at the depth where the turbine is located; 3) the probability a seal enters the rotor swept area 4); the probability a seal then encounters a spinning blade; and 5) if the outcome is to sustain injury sufficient to cause major injury or death. The input parameters for the model are generated from: A) utilising telemetry data from harbour seals; B) turbine blade size and velocity; and C) tissue and collision experiments to assess potential injury or death. The 5$^{th}$ component (and parameter C) of this model focusing on extent of injury or death could be removed if aiming to replicate the model while only focusing on expected number of encounters without aiming to assess severity of collisions.

Copping & Grear (2018)

The Copping & Grear model uses a Monte-Carlo simulation to sample the probabilities of each event leading up to a collision. The underlying model is simple, utilising three equations to predict collisions. The primary equation calculates the probability of an animal entering the swept area of a turbine blade ($P_{rotor}$).The second equation deals with where on the blade of the turbine the collision is likely occur, split into root, middle and tip of the blade.

The third equation includes the rotating speed of the turbine compared to the speed of the mammal passing through to predict if blade is likely to strike the animal as it moves through the area swept by the blade ($P_{enc}$).

Schmitt *et al,* 2017

The Schmitt *et al*., model was developed to calculate harbour seal collision rate with sub-sea tidal kite. The model uses a numerical algorithm to analyse the animal's position in a 4D space relative to the turbines location to predict collisions. This model utilises open source freeCAD toolbox for the numerical analysis (source code available). Collision probability is predicted from the parameters of rotational velocity, number of blades; swimming velocity, angle of animal relative to flow direction, and length of animal.

Horne *et al.,* (2022)

The Horne *et* al (2022) model uses Blender, an open-source 3D modelling and game-design software, interfaced using Python script to setup and run collision simulations between an animal and tidal stream turbine, simulated many times to give a collision probability estimate. Collision speed and the location of the collision on the animal's body are considered within the simulation to give a mortality estimate from probable collisions using mortality thresholds that can be hypothetical or based on empirical literature data. The input parameters are the biological characteristics of the animal (speed, shape, and size) and three-dimensional design of the turbine. In the study by Horne *et al.,* (2022) the animals swimming speed and the turbine rotation speed were resampled to explore different outcomes.

**Applicability of models**

The CRMs used for birds and marine mammals at wind or tidal stream facilities share the principles of CRMs developed for fish and ducted turbines (e.g., Von Raben, 1957, Deng et al., 2007). They require similar data (the mechanics of the turbine and animal speed and size) and use relatively simple equations to estimate the probability that an animal occupies the same spatial and temporal extent as the rotating turbine blades.

Fundamentally, there are no reasons these models originally developed for birds or marine mammals cannot be applied without adaptation to fish. Indeed, the Band and SLSR models have been used to estimate collision risk at tidal stream facilities for European eels and herring, respectively (Rossington & Benson, 2019; Wilson et al., 2007). Very few of the models include parameters that are specific to the biology of birds and mammals, and where they do, the terms can easily be removed or adapted for fish (e.g., the flying style parameter in the Band Model to fish swimming behaviour). The difference between the nature and operation of wind and tidal stream turbines however, is noted and any models from these scheme types would need to be fully investigated to determine their applicability for adaptation to an enclosed tidal range turbine arrangement.

Applicability to the tidal range power scheme scenario is more limited and models would require adaptation. First, some mechanical features of ducted turbines are not represented in models for tidal stream or wind turbines, for example, guide vanes and wicket gates. Second, models do not include mortality or injury from barotrauma or shear stress since these factors are not considered a concern for tidal stream or wind turbines (Hammer et al 2015). Third, models for wind or tidal stream turbines make the reasonable assumption that the animal enters the rotor swept area head on, whereas the most advanced models for ducted turbines (e.g., Deng et al 2007) include fish orientation because high water velocities and turbulence mean fish have very limited directional control on their approach. Finally, models for wind or tidal stream turbines include animal swimming or flying speed, although this could easily be substituted for water velocity which will determine the 'swimming' speed in ducted turbines.

One recent development in CRMs for birds and marine mammals that is somewhat novel and potentially useful for the tidal range scenario, is the use by Horne et al (2022) of the Blender 3D modelling and game-design software to run collision simulations between an animal and tidal stream turbine. The advantage of this approach is that the software is open source and adaptable to novel turbine designs, but unlike similar simulation-based models for ducted turbines (e.g., BioPA and STRIKER) pressure and shear are not modelled.

**Multi-species and life stages assessment**

In theory, the models can be used for any species or life stage where suitable biological data exists (fish length distributions for the different species and life stages).

**Temporal modelling**

The models are single run models, in that injury predictions are based on an animal only passing through the turbine once but could easily be combined with outputs from an ERM to determine cumulative passage effects. An example of this coupled approach is the tidal stream ELAM for European eels by Rossington & Benson (2019) which was coupled to the Band Model.

**Ability to use model openly**

The equations for these models are freely available and software are either opensource or licenses are commonly owned (e.g., MS Excel).

**Data availability**

Depending on the equations being used; deterministic or stochastic, single input parameters maybe required or a range of variables to enable probability predictions to be developed. Data requirements are mechanical parameters of the turbine (e.g., turbine hub diameter, turbine runner diameter, number of blades) and fish species data (e.g., length distribution and fish orientation). Fish species data is largely available for most species and life stages and can be based off literature data or site-specific data, with potential requirement to consider proxy species information for the less studies species.

**Data collection**

With the exception of turbine parameters, which will require consultation with specific manufacturers, there is limited data that requires site specific collection. Site specific fish data could be collected to inform length frequencies but is not essential and could be based on published literature.

The biggest limiting factor of general application of the model is the requirement for turbine specific parameters. This information may not be accurately readily available at the time of assessment which could reduce confidence in the model outputs. It is recommended that as accurate as possible input parameters for these variables are used for the modelling and assessment of impacts which will require early liaison with turbine manufacturers.

**Method validation data**

The standard method for validating CRMs for birds is to collect corpse data in the vicinity of the wind farm (Marsden and Cooke, 2016). This approach is not suited to the marine environment and validation for fish has not been undertaken.

**Uncertainty management**

Early equations were deterministic but stochastic versions have been recently developed (e.g., stochastic Band Model, McGregor *et al.*, 2018)

**Assessment Matrix**

CRMs developed for birds and marine mammals at wind or tidal stream facilities received a score of 9 for the value assessment and 8 for the confidence assessment, giving a combined score of 17. The scores for each criterion are shown below in Table 5-1. The applicability of model assessment value however, is worthy of being drawn out as considered to be Low with a value of 1. This score reflects the relative simplicity of these model types in comparison to some of the ducted turbine models discussed above. The low value of this score needs to be considered as a key value scoring criteria and expresses the limited value of further exploring the development of these model types for fish passage through tidal range power schemes.

Table 5-1 bird and marine mammal model assessment scores

| Value criteria | Score (0 – 3) | Confidence criteria | Score (1 – 3) |
|---|---|---|---|
| **Applicability of model assessment value** | 1 | **Existing evidence and data gaps** | 2 |
| **Ability to use model openly** | 3 | **Ability to fill evidence and data gaps** | 2 |
| **Multispecies and life stage assessment value** | 3 | **Model validation** | 1 |
| **Temporal modelling assessment value** | 2 | **Uncertainty management** | 3 |
| **Value Score** | 9 | **Confidence Score** | 8 |

***Method conclusions***

CRMs used for birds and marine mammals at wind or tidal stream facilities share the principles and general data requirements of CRMs developed for fish and ducted turbines (e.g., Von Raben, 1957, Deng et al., 2007). Some modification to the models would be required for a tidal range scenario. However, since established models for ducted turbines are equally computationally simple and have been and validated for fish, there are no reasons to recommend that adaptation should be undertaken. Advances in computational platforms for model development such as the use of Blender 3D may be considered for any future model development to determine whether they may offer any significant advantages over the current variable platforms used for the range of fish modelling.

***Method applicability for Environmental Assessments***

The bird and marine mammal models considered would largely be applicable for use in environmental assessments and indeed are widely recognised as best practice use in environmental assessment for wind farm and tidal stream developments for birds and marine mammals. They are therefore, models widely recognised and understood by the range of statutory authorities in the UK.

# 6. Non-applicable models

The models that scored zero for the applicability criterion of the value assessment were those that estimated encounter rates with tidal stream or wind turbines (listed in Appendix A: Model Value and Confidence Assessment). The fundamental reasoning for scoring zero and being excluded from the detailed review is that a wind or tidal stream turbine exists within an animal's natural habitat and can be passed through, over, below, or around, and at any time. Accordingly, most wind or tidal stream ERMs, such as the well-known Tucker, Band and SLSR models, are based on simple analytical equations and the assumption that natural movement behaviours (e.g., migration, foraging) observed prior to the scheme will continue after installation.

Based on observed flight or swimming paths, the models calculate the probability that individual specimens will complete their natural movements after the scheme is installed by either (1) passing through the rotor swept area (an encounter) or (2) by passing around the turbine(s). This contrasts with a tidal barrage which, when the turbines or sluices are not operating, is an impenetrable physical structure; a fish moving in this location cannot behave as it did before. The choice for the fish is either (1) remain close to the barrage, (2) swim away, (3) pass through sluices, or (4) pass through the barrage by encountering the turbines. Unlike wind or tidal stream turbines, passage through the barrage can only occur for short periods of time (i.e. when turbines or sluices are operating).

An ERM for wind and tidal stream turbines would only predict whether a fish attempting to cross the barrage will encounter locations of the turbine ducts, but because subsequent behaviours if the turbine is not operating are not modelled and the turbines can only be passed during specific time windows, the probability of entering the turbine duct is not estimated. Furthermore, the turbine entry probability for different species and life-stages is influenced by the hydrodynamics of the entrainment zone which has not been included in models for wind and tidal stream turbines. These differences mean ERMs for wind and tidal stream turbines are in poor conceptual alignment with the tidal range scenario in comparison to existing models more suited for fish specific assessments for hydropower schemes whether tidal or in-river. The behavioural responses of fish to a tidal barrage and the temporal complexities of turbine passage is why ERMs developed specifically for a tidal range scenario have used IBMs (Willis & Teague; Tidal Lagoon Swansea Bay, 2019), whereas IBMs have been utilised in only two out of many models for wind or tidal stream turbines (Eichhorn *et al.,* 2012; Rossington & Benson, 2019).

# 7. Summary and recommendations

## 7.1 Model selection

### ERMs

The scoring assessment identified IBMs and CFD models as the best approach for estimating encounter probabilities, with the ELAM and ADZ model both scoring 11 out of a maximum 12 for the value assessment and 7 for confidence. ELAM and ADZ models have been developed specifically for the tidal range scenario, can model multiple species and life stages simultaneously, can account for multiple passages, and have stochastic capabilities.

Their greatest advantage however, is their flexibility to explore the complex and poorly understood behaviours of fish when they approach tidal range infrastructure. The encounter probability maybe the single biggest factor which sets a tidal scheme apart from hydropower and turbine arrays and likely represents both the greatest determinant of predicting resultant mortality and highest factor of uncertainty within the assessment process. The encounter factor will be unique to the individual site and cannot be inferred from any other existing schemes. It will be dependent upon the site location and conditions, the fish populations that may pass through the area and the design and operation of the scheme itself. Modelling through the combination of a hydrodynamic model of the site- and species-specific IBMs is considered to be the most advanced means of predicting fish encounter prior to construction. As with any modelling approach however, it is based on theoretical information often backed up with limited or uncertain data and as such is fraught with uncertainty and open to challenge and criticism of the input data.

Accordingly, the ELAM and ADZ models both scored lower at 7 out of 12 for the confidence assessment for both model types, since numerous site-specific ecological data are required which might not be available and are difficult to collect. Validation of the models has also not been undertaken and it is recognised that this would likely be extremely difficult to validate, especially population level impacts. Positives for the ADZ model over the ELAM are that stochastic functions are inbuilt whereas it appears that modification of the code will be required to create stochastic outputs for ELAMs developed by Willis & Teague (2011) and Rossington & Benson (2019). A further disadvantage of both the ELAM and ADZ models is their computational complexity, often requiring considerable programming skill to implement if coding modifications are required, and considerable computing power. The ADZ model is written for Excel or R which might be an advantage for those unfamiliar with computer coding although still requiring advanced excel/R coding and programming skills. It is however, difficult to assess useability and adaptability without having used the programmes. The ELAM model has greater visual and graphic capability than the ADZ model but is more difficult to interrogate by stakeholders and replicate.

The modelling approaches of Willis & Teague (2011), Rossington & Benson (2019) and the ADZ model share many similarities, but one key difference is that ADZ model does not appear to have any mechanism for incorporating river flows and estuarine circulation into the encounter modelling which may be an important factor, in particular for migrating species and for ichthyoplankton. However, an advantage of ADZ model is that it has already been coupled with a relevant CRM (STRIKER) and has an inbuilt, although limited, capacity to model indirect effects of turbine passage into a lagoon. The ELAM model was also coupled with an adaptation of the Deng CRM model for the DECC Severn Tidal Power Scheme assessment as well as population/life cycle modelling to determine population level impacts. These two modelling approaches therefore, offer a complete workflow for assessing the impacts of tidal range power schemes on fish.

The other encounter modelling approaches (entrainment zone CFD, ETM, and particle tracking) are highly relevant to a tidal range scenario but their usefulness is limited relative to ELAM and ADZ models because they are either only suitable for ichthyoplankton or only relevant to one aspect of the encounter risk. However, they could be integrated into other model types , as is the case for the ADZ model which includes a CFD model of the entrainment zone.

## CRMs

The CRM with the highest combined value and confidence score was the Deng Kaplan turbine model (score = 20) followed by STRIKER model (score = 19). These are then followed by stream trace simulations and the Bayesian network approach of Wilkes *et al.,* (2017), which both scored 13 and 15 respectively. The Deng model scored higher than the STRIKER model as it is an Excel-based model with no GUI with hidden back coding and data (as is the case with the STRIKER model) and therefore, open access and easily adaptable for any scheme parameters. STRIKER scored highly given its relevance to tidal power schemes, having been developed specifically for this scenario. Both models have been developed for the most common turbine designs, and combine stream trace simulations with the analytical models of Von Raben (1957). The advantage of combining these approaches is that both collision mortality and barotrauma and shear stress mortality can be estimated to produce compound impact estimates. In terms of confidence, there is reasonable empirical evidence validating the outputs of both models and they can both be run stochastically to assess uncertainty. One significant limitation of STRIKER is that it is a ‘black box’ model with a GUI and hidden parameters and functions, preventing its interrogation by stakeholders. The model is also licenced to a single organisation limiting its use across the range of potential tidal power schemes in the UK in coming years.

All but one of the CRMs for birds and mammals received a combined value and confidence score of 12, with the exception being the stochastic Band Model which received a score of 13 due to its improved capacity to assess uncertainty. Unlike the Deng and STRIKER models for fish, the CRMs for wind and tidal steam turbines rarely calculate the mortality rate of collisions, and even if mortality was estimated it is unlikely the results would be relevant to a tidal range turbine, given the differences in rotation speed. Moreover, CRMs for tidal stream and wind are generally focused only on collisions because pressure and shear injuries are not considered a major concern (Hammer *et al.,* 2015). A positive of CRMs for wind and tidal stream turbines is their analytical simplicity, but the analytical equations used by the Deng and STRIKER models are equally simple and have the advantage of having been tested using ducted turbine designs relevant to the tidal range scenario. The wind and tidal stream turbine models also focus on blade strike from the turbine only and do not factor other potentially injury generating structures within the turbine casing such as wicket gates and stay vanes. Finally, whilst not of critical importance, some parameters included in wind and tidal stream turbines, such as the angle of flight or swimming approach, are not relevant to a turbine in a duct and would need to be removed.

## 7.2 Gap analysis

The conclusion of this review is that the optimal approach for modelling the impact of tidal range power schemes on fish in the UK would be a stochastic approach coupling an IBM/ADZ and hydrodynamic model for the encounter risk and with a Deng or STRIKER based model for collision and mortality calculation. The constraints to implementing this approach are as follows:

- There is limited information on behavioural aspects of the encounter probability, which likely represents both the greatest determinant of predicting resultant mortality and highest factor of uncertainty within the assessment process.
- The existing IBMs/ADZ models discussed here may not be adaptable to a range of scenarios and it may require considerable computing skills to improve flexibility.
- Local population and movement/residence data for species and life-stages required to parameterise the model (e.g., population range, density, migration patterns) may not be available.
- Local hydrodynamic data may not be available or of sufficient quality however, it is likely to be required as part of the wider development of the scheme to determine energy generation potential and assess other potential environmental impacts such as habitat loss/change and water quality/sedimentation changes.
- The indirect impacts of tidal range power infrastructure (e.g., predation risk) are currently poorly understood and not assessed quantitatively by all existing models (input parameters for predation were included in the ADZ model).

No validation data is currently available for the models due to no tidal power schemes having been consented and developed to date. Detailed monitoring programmes would be required to collect empirical data which could be complex and costly given the hostile environment in which the monitoring would be required and the volume of water passing through large turbine structures. Collection of fish passing through the turbines on a large tidal range power scheme will be complex and likely require an expensive monitoring programme. The use of robotic sensor fish is a possible proxy to collect computerised data rather than collecting and analysing empirical fish data. Limitations of this approach in terms of representation of a range of different fish species with differing morphology however, would need to be considered. Any monitoring programme would need to consider the power analysis of data collected to ensure that it can adequately be used to validate the outputs of the model.

## 7.3 Recommendations

It is recommended as a next step, that the following activities are considered:

- A review of the available literature detailing behavioural interactions between fish and underwater infrastructure, prioritising studies most relevant to a tidal range scenario to provide set agreed parameters for use in model development (e.g., Martins *et al.,* 2014; Viehman & Zydlewski, 2014). Development of standardised and agreed parameters as far as possible through an expert panel approach (and updating them as empirical data becomes available) would ensure consistency across schemes, reduce modelling and stakeholder discussion time for individual developments.

- Modelling through the combination of a hydrodynamic model of the site- and species-specific ELAM or ADZ models is considered to be the most advanced means of predicting fish encounter prior to construction and suitable models for deployment at tidal range power scheme in the UK should be developed. Developing defined model types with clear implementation/user guidelines and parameter specifications would standardise the approach across individual developments.

- A review of potential indirect impacts of tidal range infrastructure and how best to consider these impacts into the CRM aspect of the modelling approach. To fully consider compound impact of fish passage through a tidal range power scheme a form of quantification of all impact mechanisms including indirect impacts is required. Further investigation and development of the best way to include these mechanisms is recommended as a priority.

- Detailed evaluation of the functionality of IBM programmes discussed here and improve useability, flexibility, and functionality, as required (e.g., as per McGregor *et al* 2018 for the stochastic Band Model) with consideration of more advanced open access software programmes if appropriate.

- Assess the NRW data archives and other sources to identify the spatial extents of fish and hydrodynamic data suitable for modelling to enable the commencement of standardised parameter development and full identification of data gaps.

- Development of the Deng CRM model base to provide an open access, stochastic model that can be interrogated by stakeholders and parametrised with pre-agreed peer reviewed metrics that don’t require site or scheme specific variables. Will enable the development of a model that can be adapted for use across a range of schemes.

- Development of defined population/stock assessment models to provide a full assessment tool from encounter to population loss predictions to allow full assessment of potential impacts of a tidal range power scheme at a population/stock level and against aspects such as conservation objectives.

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# Appendix A: Model value and confidence assessment

**Table 1:** Value assessment of models (Legend: M – marine mammals, F – fish and B – birds)

| Model | Taxa | Turbine type | Applicability of model | Multispecies and life stage | Temporal modelling | Ability to use model openly | Score |
|---|---|---|---|---|---|---|---|
| **Band CRM ++ (Band *et al.,* 2016)**: Most recent version of the Band model, with several new parameters added to estimate lethality and injurious outcomes for seals. Originally used with birds and wind turbines and modified for use with marine organisms and turbine arrays. | M<br>B | Tidal Stream<br>Wind | 1 | 2 | N/A | 3 | 6 |
| **Copping *et al.,* (2017) CRM:** uses a Monte-Carlo simulation to sample the probabilities of each event leading up to a collision. The underlying model is uses three equations to predict collisions; (1) the probability of animal entering the rotor swept area; (2) where on the blade the collision will occur: and (3) the speed of the collision. | M | Tidal stream | 0 | N/A | N/A | N/A | 0 |
| **Schmitt *et al.,* (2017) CRM:** Developed to calculate harbour seal collision rate with sub-sea tidal kite. The model uses a numerical algorithm to analyse the animal's position in a 4D space relative to the turbines location to predict collisions. | M | Tidal Stream | 0 | N/A | N/A | N/A | 0 |
| **Onoufriou *et al.,* (2021*)* CRM:** This model uses the Band ++ CRM, improving upon the model by incorporating aspects of avoidance behaviour in seals based on evidence that during turbine operation. This model requires species- and site-specific telemetry data. | M | Tidal Stream | 0 | N/A | N/A | N/A | 0 |
| **Horne *et al.,* (2022) CRM**: uses Blender, an open-source 3D modelling and game-design software, interfaced using Python script to setup and run collision simulations between individuals and marine turbines, restimulated many times to give a collision probability estimate. Incorporates both the animals speed and the point of collision on the body to estimate mortality and injury. | M | Tidal stream | 2 | 2 | NA | 2 | 6 |
| **Copping *and Grear* (2018) CRM**: Focusing on Harbour seals, this model has five main components or steps leading to its find outcome: (1) probability a seal will swim near a turbine; (2) probability a seal swims at the depth where the turbine is located; (3) probability a seal enters the rotor swept area; (4) probability a seal then encounters a spinning blade; and (5) if the collision is sufficient to cause major injury or death. | M | Tidal stream | 1 | N/A | N/A | N/A | 0 |
| **SLSR ERM (Wilson et al., 2008):** The model repurposes equations that were initially intended to predict encounters between predators and prey in aquatic environments. In these modified equations the turbine rotor blades are the 'predator'. | F<br>M<br>B | Tidal stream | 0 | N/A | N/A | N/A | 0 |

| Model | Taxa | Turbine type | Applicability of model | Multispecies and life stage | Temporal modelling | Ability to use model openly | Score |
|---|---|---|---|---|---|---|---|
| **Tucker CRM (Tucker, 1996):** Equation incorporating observed empirical data, this model analyses the probability of a bird-rotor collision of a single transit (upwind, downwind, or across wind) and a single turbine rotor, calculated as a ratio of the time taken for a turbine blade to complete a single revolution compared to the time taken for a bird to move through this rotor swept area. | B | Wind | 1 | 2 | N/A | 3 | 6 |
| **Basic Band CRM (Scottish Natural Heritage, 2000; Band et al, 2007):** Calculates the probability of a fatal collision between a bird and a rotor by assessing two stages. Stage one calculates the number of birds flying through the rotor and stage two examines the probability of a collision from a single transit of a rotor. | B | Wind | 1 | 2 | N/A | 3 | 6 |
| **Extended Band CRM (Band *et al.,* 2012):** Built on the basic model, the Extended Band Model is more refined, 'more realistic'; designed to include flight height distributions in the calculation. | B | Wind | 1 | 2 | N/A | 3 | 6 |
| **Stochastic Band CRM (Marsden 2015; McGregor *et al.,* 2018):** A stochastic Monte Carlo modification of the Band Model considering the effect of wind speed and direction, and variations in flight height on the probability of an individual collision at a single turbine. | B | Wind | 1 | 2 | N/A | 3 | 6 |
| **Podolsky (2008) CRM:** The model describes the bird, the turbine, and the windfarm, calculating the probability of a collision by the distance travelled across the rotor disc and thus the time required, which is then compared to rotor speed and the time required for a single revolution of the blades | B | Wind | 1 | 2 | N/A | 3 | 6 |
| **Desholm Stochastic CRM (Desholm, 2006)**: This model was developed to estimate the number of bird fatalities at the Nysted offshore windfarm in Denmark. The collision probability was assumed to be fixed and was calculated from Tucker (1996). | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Holmstrom *et al.,* (2011) CRM:** Based on the Tucker Model (1996), but extended to include oblique angles of approach flight to the wind turbine, as the authors state to be an important improvement "since birds often follow flight paths that are not dependent on the wind direction, but rather on established migratory routes or geologic features such as valleys or coastlines | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Eichhorn *et al.,* (2012) CRM:** Combining the Stage 2 calculations from the Band Model, the Eichhorn Simulation Model is an agent-based spatial collision risk model generating a random, virtual landscape. | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Biosis CRM (Smales *et al.,* 2013): C**alculates a predicted number of collisions between turbines and a population of birds. By using a topological, non-affine mapping technique to calculate the average number of turbines likely to be encountered, the model can estimate collision risk as the sum of the average number of turbines encountered per flight within a scattered wind turbine array, rather than for all turbines in an array | B | Wind | 1 | 2 | N/A | 3 | 6 |

| Model | Taxa | Turbine type | Applicability of model | Multispecies and life stage | Temporal modelling | Ability to use model openly | Score |
|---|---|---|---|---|---|---|---|
| **US Fish and Wildlife Service (2013) CRM:** This model was developed for predicting eagle fatalities by using a Bayesian estimation framework instead of including details on the mechanisms of collision and was designed to be updated with observed collision incidents. | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Bolker *et al.,* (2014) CRM:** This model looked at turbine locations, flight direction, and survival probability for each bird passing through the wind farm, so to determine the average number of turbines encountered if birds move through the wind farm. Designed to be 'particularly straightforward mathematically', the authors note that all you need is a calculator or a spreadsheet | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Grant (2014) exposure time ERM:** Developed for evaluating the collision risk between diving birds and tidal turbines, assessed at the population level, rather than the individual, to assess the amount of acceptable addition mortality caused to the population by collisions, while still meeting a specified population growth rate. First, a population model must be developed from which the 'acceptable' additional mortality thresholds can be estimated. Then collision probability is estimated by looking at the amount of time the birds spend at the depth of the turbine and the proportion of that depth occupied by the turbines. | B | Tidal stream | 0 | N/A | N/A | N/A | 0 |
| **Kleyheeg-Hartman *et al.,* (2018) CRM:** This model is an empirical collision risk model which determines collision probability for birds flying through an entire wind farm area, using existing collision data. Avoidance is included in the model, which is assessed through looking at known data for flux through a reference wind farm, with actual collision rates from the reference wind farm | B | Wind | 0 | N/A | N/A | N/A | 0 |
| **Hammer *et al.,* (2015) ERM:** A simple probabilistic model for estimating the population level ecological risks of turbine arrays. | F | Tidal stream | 0 | N/A | N/A | N/A | 0 |
| **Shen *et al.,* (2016) ERM:** probabilistic model for fish encounters with tidal stream array that includes: 1) probability of fish being at device-depth when the device is absent; 2) probability of fish behaviour changing to avoid the device in the far-field; and 3) probability of fish being at device-depth in the near-field when the device is s present | F | Tidal stream | 0 | N/A | N/A | N/A | 0 |
| **CFD entrainment ERM:** A general approach using computer simulation to estimate the entrainment zone at power plant intakes (e.g., Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021). | F | Hydropower | 3 | 3 | 1 | 2 | 9 |
| **Empirical Transport ERM (Boreman *et al.,* 1981):** One of the earliest examples of an attempt to estimate the numbers of fish entrained into turbines at power plant sites. A central assumption is that entrained individuals behave like passive particles, and thus the model is suited only to ichthyoplankton | F | Cooling intakes | 3 | 1 | 3 | 3 | 10 |
| **Particle tracking simulation ERM:** Simulation approach for examining patterns in the distribution of passive particles (representing ichthyoplankton) over time that are transported by flow fields, such as tidal currents. Used to estimate numbers of fish entering the entertainment zone (e.g., Heimbuch *et al.,* (2007). | F | Hydropower<br>Cooling intake | 3 | 1 | 3 | 2 | 9 |

| Model | Taxa | Turbine type | Applicability of model | Multispecies and life stage | Temporal modelling | Ability to use model openly | Score |
|---|---|---|---|---|---|---|---|
| **Alternative Draw Zone ERM (Tidal Lagoon Swansea Bay, 2019):** Individual Based model developed to assess fish impacts of the Swansea Bay Tidal lagoon. Turbine mortality calculated by STRIKER. | F | Tidal Range | 3 | 2 | 3 | 3 | 11 |
| **ELAM ERM (Willis & Teague, 2011; Rossington & Benson, 2019):** Individual based model coupled with a hydrodynamic model to examine encounter probabilities. | F | Tidal Range<br>Tidal Stream | 3 | 3 | 3 | 3 | 12 |
| **Stream trace simulation CRM (Richmond *et al.,* 2014; Klopries & Schüttrumpf 2020):** a general approach using computation fluid dynamics to simulate the trajectory of fish passing through a turbine and the probability of collision or barotrauma | F | Hydropower | 3 | 3 | N/A | 3 | 9 |
| **Kaplan turbine CRM (Deng *et al.,* 2007):** A numerical approach, rather than simulation, to calculate the probability of blade strike when fish pass through a Kaplan turbine. The theory behind the model is that to avoid strike by a runner blade the fish must pass through the plane of the leading edges of the blades in a turbine runner after the sweep of one blade and before the sweep of the next. | F | Hydropower | 2 | 3 | N/A | 3 | 8 |
| **Bayesian Network CRM (Wilkes *et al.,* 2017):** The analytical strike rate models for Kaplan and Francis turbines do not estimate mortality from barotrauma or sheer stress. To overcome this limitation, Wilkes *et al.,* (2018) integrated these two analytical strike risk models into a Bayesian network approach which used information priors gathered through expert elicitation for sheer stress and barotrauma mortality. | F | Hydropower | 3 | 3 | N/A | 2 | 8 |
| **STRIKER CRM (Turnpenny *et al.,* 2000):** The Striker model is an approach to calculating turbine passage mortality that blends the CFD approach of the and analytical strike rate models for Francis and Kaplan turbines. It was used to assess the impact on fish of the Swansea Bay Lagoon. | F | Tidal Range | 3 | 3 | N/A | 3 | 9 |
| **KHPS (Tomichek, 2015):** A 2-Dimensional probabilistic approach to determine the overall risk of strike to sturgeon by using a product of independent sub-probabilities. The model considers a 2D lateral cross section of the channel at the location of the turbine and comprises seven major parameters relating to power plant design, water velocity, fish distribution, and fish behaviour. | F | Tidal Stream | 0 | N/A | N/A | N/A | 0 |

## **Table 2:** Confidence assessment of models

| Model description | Taxa | Turbine type | Existing evidence and data gaps | Ability to fill evidence and data gaps | Model validation data | Uncertainty Management | Score |
|---|---|---|---|---|---|---|---|
| **Band CRM ++ (Band *et al.,* 2016)**: Most recent version of the Band model, with several new parameters added to estimate lethality and injurious outcomes for seals. Originally used with birds and wind turbines and modified for use with marine organisms and turbine arrays. | M<br>B | Tidal Stream<br>Wind | 2 | 2 | 1 | 1 | 6 |
| **Horne *et al.,* (2022) CRM**: uses Blender, an open-source 3D modelling and game-design software, interfaced using Python script to setup and run collision simulations between individuals and marine turbines, restimulated many times to give a collision probability estimate. Incorporates both the animals speed and the point of collision on the body to estimate mortality and injury. | M | Tidal stream | 2 | 2 | 1 | 2 | 7 |
| **Tucker CRM (Tucker, 1996):** Equation incorporating observed empirical data, this model analyses the probability of a bird-rotor collision of a single transit (upwind, downwind, or across wind) and a single turbine rotor, calculated as a ratio of the time taken for a turbine blade to complete a single revolution compared to the time taken for a bird to move through this rotor swept area. | B | Wind | 2 | 2 | 1 | 1 | 6 |
| **Basic Band CRM (Scottish Natural Heritage, 2000; Band et al, 2007):** Calculates the probability of a fatal collision between a bird and a rotor by assessing two stages. Stage one calculates the number of birds flying through the rotor and stage two examines the probability of a collision from a single transit of a rotor. | B | Wind | 2 | 2 | 1 | 1 | 6 |
| **Extended Band CRM (Band *et al.,* 2012):** Built on the basic model, the Extended Band Model is more refined, 'more realistic'; designed to include flight height distributions in the calculation. | B | Wind | 2 | 2 | 1 | 1 | 6 |
| **Stochastic Band CRM (Marsden 2015; McGregor *et al.,* 2018):** A stochastic Monte Carlo modification of the Band Model considering the effect of wind speed and direction, and variations in flight height on the probability of an individual collision at a single turbine. | B | Wind | 2 | 2 | 1 | 2 | 7 |
| **Podolsky (2008) CRM:** The model describes the bird, the turbine, and the windfarm, calculating the probability of a collision by the distance travelled across the rotor disc and thus the time required, which is then compared to rotor speed and the time required for a single revolution of the blades | B | Wind | 2 | 2 | 1 | 1 | 6 |

| Model description | Taxa | Turbine type | Existing evidence and data gaps | Ability to fill evidence and data gaps | Model validation data | Uncertainty Management | Score |
|---|---|---|---|---|---|---|---|
| **Biosis CRM (Smales *et al.,* 2013):** Calculates a predicted number of collisions between turbines and a population of birds. By using a topological, non-affine mapping technique to calculate the average number of turbines likely to be encountered, the model can estimate collision risk as the sum of the average number of turbines encountered per flight within a scattered wind turbine array, rather than for all turbines in an array | B | Wind | 2 | 2 | 1 | 1 | 6 |
| **CFD entrainment ERM:** A general approach using computer simulation to estimate the entrainment zone at power plant intakes (e.g., Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021). | F | Hydropower | 2 | 2 | 2 | 1 | 7 |
| **Empirical Transport ERM (Boreman *et al.,* 1981):** One of the earliest examples of an attempt to estimate the numbers of fish entrained into turbines at power plant sites. A central assumption is that entrained individuals behave like passive particles, and thus the model is suited only to ichthyoplankton. | F | Hydropower Abstraction | 2 | 2 | 1 | 1 | 6 |
| **Particle tracking simulation ERM:** Simulation approach for examining patterns in the distribution of passive particles (representing ichthyoplankton) over time that are transported by flow fields, such as tidal currents. Used to estimate numbers of fish entering the entertainment zone (e.g., Heimbuch *et al.,* (2007). | F | Abstraction | 2 | 2 | 2 | 1 | 7 |
| **Alternative Draw Zone ERM (Tidal Lagoon Swansea Bay, 2019):** Individual Based model developed to assess fish impacts of the Swansea Bay Tidal lagoon. Turbine mortality calculated by STRIKER. | F | Tidal Range | 1 | 1 | 1 | 3 | 6 |
| **ELAM ERM (Willis & Teague, 2011; Rossington & Benson, 2019):** Individual based model coupled with an hydrodynamic model to examine encounter probabilities. | F | Hydropower | 1 | 1 | 1 | 2 | 5 |
| **Stream trace simulation CRM:** a general approach using computation fluid dynamics to simulate the trajectory of fish passing through a turbine and the probability of collision or barotrauma (e.g. Richmond *et al.,* 2014). | F | Hydropower | 2 | 2 | 1 | 1 | 6 |
| **Kaplan turbine CRM (Deng *et al.,* 2007):** A numerical approach, rather than simulation, to calculate the probability of blade strike when fish pass through a Kaplan turbine. The theory behind the model is that to avoid strike by a runner blade the fish must pass through the plane of the leading edges of the blades in a turbine runner after the sweep of one blade and before the sweep of the next. | F | Hydropower | 2 | 2 | 2 | 2 | 8 |

| Model description | Taxa | Turbine type | Existing evidence and data gaps | Ability to fill evidence and data gaps | Model validation data | Uncertainty Management | Score |
|---|---|---|---|---|---|---|---|
| **Bayesian Network CRM (Wilkes *et al.,* 2017):** The analytical strike rate models for Kaplan and Francis turbines do not estimate mortality from barotrauma or sheer stress. To overcome this limitation, Wilkes *et al.,* (2018) integrated these two analytical strike risk models into a Bayesian network approach which used information priors gathered through expert elicitation for sheer stress and barotrauma mortality. | F | Tidal Range | 2 | 2 | 1 | 2 | 7 |
| **STRIKER CRM (Turnpenny *et al.,* 2000):** The Striker model is an approach to calculating turbine passage mortality that blends the CFD approach of the and analytical strike rate models for Francis and Kaplan turbines. It was used to assess the impact on fish of the Swansea Bay Lagoon. | F | Flexible | 2 | 2 | 2 | 2 | 8 |

M = Marine mammal, B = bird, F = fish

**Table 3:** Combined value and confidence scores for ERMs

| Model description | Taxa | Turbine type | Value score | Confidence score | Total score |
|---|---|---|---|---|---|
| **CFD entrainment ERM:** A general approach using computer simulation to estimate the entrainment zone at power plant intakes (e.g., Bao *et al.,* 2022; Huang *et al.,* 2015; Langford *et al.,* 2016, 2021). | F | Hydropower | 10 | 8 | 18 |
| **Empirical Transport ERM (Boreman *et al.,* 1981):** One of the earliest examples of an attempt to estimate the numbers of fish entrained into turbines at power plant sites. A central assumption is that entrained individuals behave like passive particles, and thus the model is suited only to ichthyoplankton. | F | Hydropower<br>Abstraction | 7 | 7 | 14 |
| **Particle tracing simulation ERM:** Simulation approach for examining patterns in the distribution of passive particles (representing ichthyoplankton) over time that are transported by flow fields, such as tidal currents. Used to estimate numbers of fish entering the entertainment zone (e.g., Heimbuch *et al.,* (2007). | F | Abstraction | 7 | 7 | 14 |
| **ELAM ERM (Willis & Teague, 2011; Rossington & Benson, 2019):** Individual based model coupled with an hydrodynamic model to examine encounter probabilities. | F | Hydropower | 11 | 7 | 18 |
| **Alternative Draw Zone ERM (Tidal Lagoon Swansea Bay, 2019):** Individual Based model developed to assess fish impacts of the Swansea Bay Tidal lagoon. Turbine mortality calculated by STRIKER. | F | Tidal Range | 11 | 7 | 18 |

**Table 4:** Combined value and confidence scores for fish based CRMs.

| Model description | Taxa | Turbine type | Value score | Confidence score | Total score |
|---|---|---|---|---|---|
| **Stream trace simulation CRM:** a general approach using computation fluid dynamics to simulate the trajectory of fish passing through a turbine and the probability of collision or barotrauma (e.g. Richmond *et al.,* 2014). | F | Hydropower | 7 | 6 | 13 |
| **Kaplan turbine CRM (Deng *et al.,* 2007):** A numerical approach, rather than simulation, to calculate the probability of blade strike when fish pass through a Kaplan turbine. The theory behind the model is that to avoid strike by a runner blade the fish must pass through the plane of the leading edges of the blades in a turbine runner after the sweep of one blade and before the sweep of the next. | F | Hydropower | 11 | 9 | 20 |
| **Bayesian Network CRM (Wilkes *et al.,* 2017):** The analytical strike rate models for Kaplan and Francis turbines do not estimate mortality from barotrauma or sheer stress. To overcome this limitation, Wilkes *et al.,* (2018) integrated these two analytical strike risk models into a Bayesian network approach which used information priors gathered through expert elicitation for sheer stress and barotrauma mortality. | F | Tidal Range | 8 | 7 | 15 |
| **STRIKER CRM (Turnpenny *et al.,* 2000):** The Striker model is an approach to calculating turbine passage mortality that blends the CFD approach of the and analytical strike rate models for Francis and Kaplan turbines. It was used to assess the impact on fish of the Swansea Bay Lagoon. | F | Tidal range | 9 | 9 | 18 |
| **Bart model (2012 & 2014):** Combination of equation based blade-strike modelling and CFD analysis for pressure and shear stress. No consideration of delayed or indirect mortality. Model built for centrifugal pumps at pumping stations in The Netherlands. Empirical data collection has been undertaken to validate the model. | F | Centrifugal | 8 | 8 | 16 |

**Table 5:** Combined value and confidence scores for bird and marine mammal CRMs.

| Model description | Taxa | Turbine type | Value score | Confidence score | Total score |
|---|---|---|---|---|---|
| **Band CRM ++ (Band *et al.,* 2016)**: Most recent version of the Band model, with several new parameters added to estimate lethality and injurious outcomes for seals. Originally used with birds and wind turbines and modified for use with marine organisms and turbine arrays. | M<br>B | Tidal Stream<br>Wind | 6 | 6 | 12 |
| **Horne *et al.,* (2022) CRM**: uses Blender, an open-source 3D modelling and game-design software, interfaced using Python script to setup and run collision simulations between individuals and marine turbines, restimulated many times to give a collision probability estimate. Incorporates both the animals speed and the point of collision on the body to estimate mortality and injury. | M | Tidal stream | 6 | 7 | 12 |
| **Tucker CRM (Tucker, 1996):** Equation incorporating observed empirical data, this model analyses the probability of a bird-rotor collision of a single transit (upwind, downwind, or across wind) and a single turbine rotor, calculated as a ratio of the time taken for a turbine blade to complete a single revolution compared to the time taken for a bird to move through this rotor swept area. | B | Wind | 6 | 6 | 12 |
| **Basic Band CRM (Scottish Natural Heritage, 2000; Band et al, 2007):** Calculates the probability of a fatal collision between a bird and a rotor by assessing two stages. Stage one calculates the number of birds flying through the rotor and stage two examines the probability of a collision from a single transit of a rotor. | B | Wind | 6 | 6 | 12 |
| **Extended Band CRM (Band *et al.,* 2012):** Built on the basic model, the Extended Band Model is more refined, 'more realistic'; designed to include flight height distributions in the calculation. | B | Wind | 6 | 6 | 12 |
| **Stochastic Band CRM (Marsden 2015; McGregor *et al.,* 2018):** A stochastic Monte Carlo modification of the Band Model considering the effect of wind speed and direction, and variations in flight height on the probability of an individual collision at a single turbine. | B | Wind | 6 | 7 | 13 |
| **Podolsky (2008) CRM:** The model describes the bird, the turbine, and the windfarm, calculating the probability of a collision by the distance travelled across the rotor disc and thus the time required, which is then compared to rotor speed and the time required for a single revolution of the blades | B | Wind | 6 | 6 | 12 |
| **Biosis CRM (Smales *et al.,* 2013):** Calculates a predicted number of collisions between turbines and a population of birds. By using a topological, non-affine mapping technique to calculate the average number of turbines likely to be encountered, the model can estimate collision risk as the sum of the average number of turbines encountered per flight within a scattered wind turbine array, rather than for all turbines in an array | B | Wind | 6 | 6 | 12 |

M = Marine mammal, B = bird, F = fish