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Collision Risk of Fish with Wave and Tidal Devices

Date:	July 2010
Project Ref:	R/3836/01
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marine environmental research

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Summary

The Marine Renewable Energy Strategic Framework for Wales (MRESF) is seeking to provide for the sustainable development of marine renewable energy in Welsh waters. As one of the recommendations from the Stage 1 study, a requirement for further evaluation of fish collision risk with wave and tidal stream energy devices was identified.

This report seeks to provide an objective assessment of the potential for fish to collide with wave or tidal devices, including a review of existing impact prediction and monitoring data where available. The study has been progressed as a desk-based review of existing information together with targeted consultation with device developers and relevant research organisations. A conceptual model of fish collision risk was developed at the start of the study and has been used to focus the review and consultation exercises.

The conceptual model has been developed based around a standard environmental risk assessment model and focuses on four key factors contributing to collision risk:

- Exposure - based on whether a fish has ecological traits which will influence exposure to wet renewable (wave and tidal) devices which could cause a behavioural avoidance response;
- Long range avoidance - based on operational underwater noise characteristics of devices and fish hearing and responses to underwater noise;
- Close range evasion - based on relevant device characteristics and fish visual acuity, fish swimming speeds and traits; and
- Collision damage – based on likely consequences of collision between a fish and a device.

The study has collated available information on the characteristics of wave and tidal devices that influence the magnitude of risks to fish (Section 3) and also considers environmental characteristics of potential deployment locations in Wales and how this might influence the composition and abundance of fish exposed to collision risk (Section 4).

Detailed evaluations of the three key factors contributing to collision risk are provided in Sections 5 to 7 taking account of specific information relating to wave and tidal devices where available and making use of more generic information from other comparable activities. Significant information gaps highlighted by this review are described in Section 8. An assessment of overall collision risk for different types of fish and different wave and tidal devices is presented in Section 9 together with a discussion of the limitations of existing scientific knowledge and priorities for additional research. Potential mitigation and monitoring options are described in Section 10.

The key conclusions from the study (Section 11) are:

- There is a general lack of information on relevant environmental characteristics of devices that might inform the evaluation of collision risk. Where information is available, it relates to single prototype devices and there is little if any information available on the environmental characteristics of multiple devices.

- There is limited information on the environmental characteristics of wave and tidal stream device deployment locations and the associated fish assemblages. In particular, the fish assemblages of tidal stream environments are poorly documented, reflecting the difficulties of quantitative sampling in such areas.

- The opportunity for fish to engage in long range avoidance is likely to be a function of the source levels of underwater noise associated with wave and tidal devices (particularly during operation), background noise levels (the extent to which device noise levels might be masked by ambient background noise) and the particular hearing sensitivities of different species of fish. The analysis suggests that hearing sensitive fish (such as herring) may be able to detect and avoid individual operational tidal stream devices at distances between approximately 120 to 300m (depending on the depth of the water) even when background noise levels are comparatively high. For wave energy devices, source noise levels are estimated to be lower and thus the distances at which avoidance behaviour might occur would be reduced to around 35 to 200m (depending on the depth of the water). For hearing insensitive fish, the projected source noise levels for wave and tidal devices are likely to be below levels at which these species might exhibit an avoidance reaction. Significant uncertainties exist concerning the source noise levels of most devices, the ability of fish to differentiate broad spectrum device noise from broad spectrum background noise as well as the precise levels at which fish (both at individual or shoal level) might choose to exhibit an avoidance response. There are no direct observation studies documenting the response of fish to underwater noise associated with wave or energy devices to test the predictions that have been developed, although the predictions are reasonable based on experiences with other human activities generating underwater noise. Overall confidence in these predictions is therefore low.

- The extent to which fish might exhibit close range evasion of wave and tidal stream devices is a function of the ‘visibility’ of the devices, details of device structure and operation, the visual acuity and maximum swimming speeds (‘C-start’ or ‘burst’ speed) of different species of fish and near-field behavioural responses. In relatively shallow water with low turbidity, devices are likely to be visible in the day time at distances of around 5 to 10m. At night time visibility of devices would be significantly lower. Assuming that a normal fish response to the appearance of an unfamiliar object would be avoidance, the scope for fish to actively avoid a device will relate to its maximum swimming speed relative to ambient flow speeds. Relatively few UK fish species would be capable of actively swimming upstream against the high flows associated with tidal stream environments or wave surge environments. However, fish would be able to actively swim against the generally lower flows associated with offshore wave deployment environments. There are no published direct observation studies on the near-field interaction of fish with wave or tidal stream devices and it remains unclear how fish might respond on encountering such devices, for example whether they might swim towards the tip of a blade or towards the centre. The risk assessment has sought to categorise near-field evasion response primarily based on burst swimming speed of different fish species. Given the uncertainties in near-field response the confidence in all the evaluations is low.

- The extent of damage to fish associated with collision with a wave or tidal stream device is largely a function of the characteristics of that device. The position of the device in the water column is also important in governing the exposure of fish to collision risk. There are no published direct observation studies relating to fish collision with wave or tidal devices and the assessment has been based on comparisons with analogues. For tidal stream turbines, some of the research studies for hydropower turbines are useful in identifying both the factors causing damage to fish and various thresholds at which particular types of damage occur. In general the speed of rotation of most tidal turbine blades is such that towards the terminal end of blades (where velocities may be of the order of 10 to 12m/s) there is a significant risk of physiological damage should a collision occur. However, towards the proximal end of the blades, the relatively lower velocities pose a lesser risk of physiological damage. For wave devices, the risks of damage associated with a collision are generally much lower. The lack of direct observation studies means that there are significant uncertainties relating to the magnitude of collision damage for tidal stream devices and confidence in the assessments is low. In contrast, wave devices generally all pose a low risk of collision damage and confidence in this assessment is high.

- Based on the main factors influencing collision risk and impact, an overall assessment of collision risk for different types of fish species, devices and locations can be made. It is recognised that there is currently a lack of quantified information about some of the factors influencing risk. However, the generic model is considered to be helpful in identifying the factors influencing risk and clarifying the priorities for further research. In particular, the following priorities for research have been identified:
    - Direct observation (e.g. using hydro-acoustic techniques) of near-field behaviour of fish in the vicinity of operation tidal turbines; these studies might also be used to inform effective mitigation measures/strategies;
    - Laboratory studies of near-field behaviour of fish in the vicinity of rotating blades and of any collision damage; these studies might also be used to inform effective mitigation measures/strategies; and
    - Field measurements of underwater source noise associated with a wider range of wave and tidal stream devices.

- A limited range of possible mitigation options have been identified, particularly for tidal turbines where collision risks are higher. However, given the current lack of information on impacts, the extent to which such measures might be required is unclear. Possible measures include:
    - Acoustic deterrents;
    - Improvements to the visibility of rotating blades (use of lighting, colour); and
    - The monitoring of fish in the marine environment is expensive and any monitoring programmes need to be clearly targeted towards clarifying impacts. General monitoring of fish assemblages in the vicinity of devices is unlikely to provide conclusive data on impacts because the scale of impacts associated with devices is not likely to be large at a population level and variation in the distribution and abundance of fish will mask minor impacts. While general monitoring of fish assemblages is unlikely to significantly improve the scientific knowledge base of wave and tidal stream device impacts, some monitoring may nevertheless be required to address possible concerns of local fishermen or wider public interest. Direct observation of fish movements and behaviour in the vicinity of devices is likely to be more useful in refining evaluations of risk and impacts, but such studies would be better progressed as part of the wider research on device impacts and it is unlikely to be appropriate to require individual developers to fund such studies.

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Abbreviations

ABPmer	ABP Marine Environmental Research Ltd
ADCP	Acoustic Doppler Current Profiler
AFD	Acoustic fish deterrent
BAP	Biodiversity Action Plan
BERR	UK Department for Business Enterprise and Regulatory Reform
CCS	Carbon capture and storage
CFD	Computational Fluid Dynamics
DECC	UK Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DTA	Devine Tarbell and Associates Inc
DTI	UK Department of Trade and Industry
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre
ES	Environmental Statement
ETSU	Energy Technology Support Unit
FAD	Fish aggregating device
FERC	Federal Energy Regulatory Commission
FMPP	Fish Monitoring and Protection Plan
ICES	International Council for the Exploration of the Sea
IECS	Institute of Estuarine and Coastal Studies
JNCC	Joint Nature Conservation Committee
KHPS	Kinetic Hydropower System
LIMPET	Land Installed Marine Powered Energy Transformer
MCT	Marine Current Turbines
MLLW	Mean Lower Low Water
MNCR	Marine Nature Conservation Review
MRESF	Marine Renewable Energy Strategic Framework for Wales
MSPC	Mean Spring Peak Currents
OSPAR	The Convention for the Protection of the marine Environment of the North-East Atlantic
RITE	Roosevelt Island Tidal Energy Project
RMS	Root Mean Square

RTT	Rotech Tidal Turbine
SEA	Strategic Environmental Assessment
SI unit	The International System of Units
SPL	Sound Pressure Level
SRT	Startle response time
SSG	Sea Wave Slot Cone Generator
TEC	Tidal stream energy converters
TEL	Tidal Energy Limited
TISEC	Tidal Instream Energy Conversion
WEAM	Wave Energy Acoustic Monitoring
WEC	Wave energy converters

Units

atm	Atmospheres
dB	Decibels
Hz	Hertz
kHz	Kilohertz
kPa	kilopascal
m	Metre
mc	Metre candles
m/s	Metres per second
MW	Milliwatts
Min	Minutes
nm	nautical miles
Pa	Pascal
μPa	micropascal
psi	pounds per square inch
rpm	rotations per minute
s	second

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1. Introduction

1.1 Purpose

Stage 1 of the Marine Renewable Energy Strategic Framework for Wales (MRESF) was completed in September 2008 (RPS, 2008). The Framework is aimed at combining renewable energy extraction from the Welsh marine environment (wind, wave and tidal stream) and carbon capture and storage (CCS), with the intention being to minimise impacts on environmental resources and socio-economic activities while maximising the potential for sustainable energy production to be gained from Welsh waters. The report provided an overview of the data gaps highlighted during the Stage 1 study, together with an indication of the priority for addressing these gaps in Welsh waters. The potential for fish to collide with wet renewable (wave and tidal devices) was one area where data gaps were highlighted and where further research was considered necessary.

The aim of this report is therefore to provide an objective assessment of the potential for fish to collide with wave or tidal devices, including a review of existing impact prediction and monitoring data where available.

1.2 Approach

1.2.1 Scope

The scope of the study is limited to marine renewable devices that can be classed here as either wave energy converters (WEC) or tidal stream energy converters (TEC). Although other marine renewable energy devices such as tidal range technologies (i.e. lagoon or barrages) and wind energy devices are outside the scope of the work, relevant research and literature in these fields has been reviewed to help inform the assessment.

The study is focused on Welsh territorial waters, i.e. from baseline (usually mean high water spring) seawards to the 12nm limit, but is more generally applicable. A number of studies have investigated the wave and tidal energy resources across the UK continental shelf including the UK Atlas of Offshore Renewable Energy Resources (ABPmer, 2004), the Phase II UK Tidal Stream Energy Resource Assessment (Black & Veatch, 2005) and the Welsh Marine Energy Site Selection (PMSS Ltd., 2006). The studies highlighted that the main tidal energy resources in Wales are based in Pembrokeshire, the Bristol Channel, Anglesey and the Lleyn peninsula (Bardsey Island) with almost the entire exploitable wave energy off the Pembrokeshire coast (ABPmer, 2004; 2008; PMSS Ltd., 2006; PMSS Ltd., 2007; RPS, 2008). A number of different locations in Welsh territorial waters are proposed or in use as test sites for wave or tidal stream devices (Table 1).

A collision in the context of this report is considered to be an interaction between a fish and a wet renewable energy device that may result in a physical injury (however slight) to the organism. A collision could therefore either involve actual physical contact between a fish and device or an interaction with its pressure field (Wilson *et al*., 2007).

The risk of collision of fish with tidal stream or wave devices depends on the particular characteristics of the devices, the operation of such devices and the nature of the receiving environment (distribution, behaviour and abundance of fish receptors) (ABPmer, 2009).

Table 1. Identified interest in potential and actual marine renewable energy projects in Welsh waters

Energy Group Type	Company	Location	Development Status
TEC	Lunar Energy	Ramsey Sound, St. Davids, Pembrokeshire	Scoping study submitted end October 2007
	Skerries Tidal Stream Array	Between the Skerries and Camel Head on the Isle of Anglesey	Scoping Study submitted July 2006
	South Stack Tidal Stream Array	2-3km from the west Anglesey Coast	Scoping Study submitted July 2006
	Swan Turbines	River Tawe, Swansea	Tested scale model of Swan Turbine
	Swan Turbines	Milford Haven	Investigating potential deployment in Milford Haven
	Tidal Hydraulic Generators Ltd	Tidal River Cleddau, possibly between Severn Crossings and/or Ramsey Sound, Pembrokeshire	Previous trials undertaken, recent linkage with Peter Brotherhood Ltd to install a full scale system (location unknown). Trials in Milford Haven complete
	Unknown	Bristol Channel	Understood that data are being acquired by the Welsh Energy Research Centre for a potential tidal stream turbine site in the Bristol Channel.
	Tidal Energy Limited (TEL)	Ramsey Sound	Scoping study submitted November 2008
WEC	Wave Dragon precommercial demonstrator	1.7km west of St Ann's Head at Long Point, Pembrokeshire	Environmental Impact Assessment (EIA) submitted April 2007

(Based on information from: RPS, 2008)

1.2.2 Methodology

The study has been progressed through the completion of four main tasks:

- **Creation of a collision risk model:** In order to assess potential collision risk a simple model of collision risk factors has been created which has guided the literature review and consultation and by which a broad evaluation of potential risk can be assessed.

- **Literature review and consultation:** A review of existing relevant literature and consultation with various wet renewable device companies.

- **Evaluation:** Based on the information obtained from Sections 2-7, the nature and significance of collision/impingement risks to fish arising from wave and tidal stream devices has been evaluated including consideration of the pathways by which such risks arise using a standard impact assessment methodology (see Figure 1). Where possible, the evaluation has sought to develop generalised conclusions about the sources of risk and the pathways by which receptors are exposed to environmental changes. Matrices are used to present a broad assessment of the level of avoidance response and physiological damage associated with different device groups. The information from these are then used to produce an overall risk score for each device group with the aim of identifying those devices that might require further design considerations, monitoring or mitigation measures. This assessment is designed as a 'broad-brush' approach, and does not infer that more specific receptors will not be affected by site-specific developments. This would need to be investigated in detail in an EIA.

- **Future monitoring and mitigation:** The identification of potential future monitoring and mitigation measures that might be applied to reduce environmental changes or modify receptor exposure to those changes has also been identified.

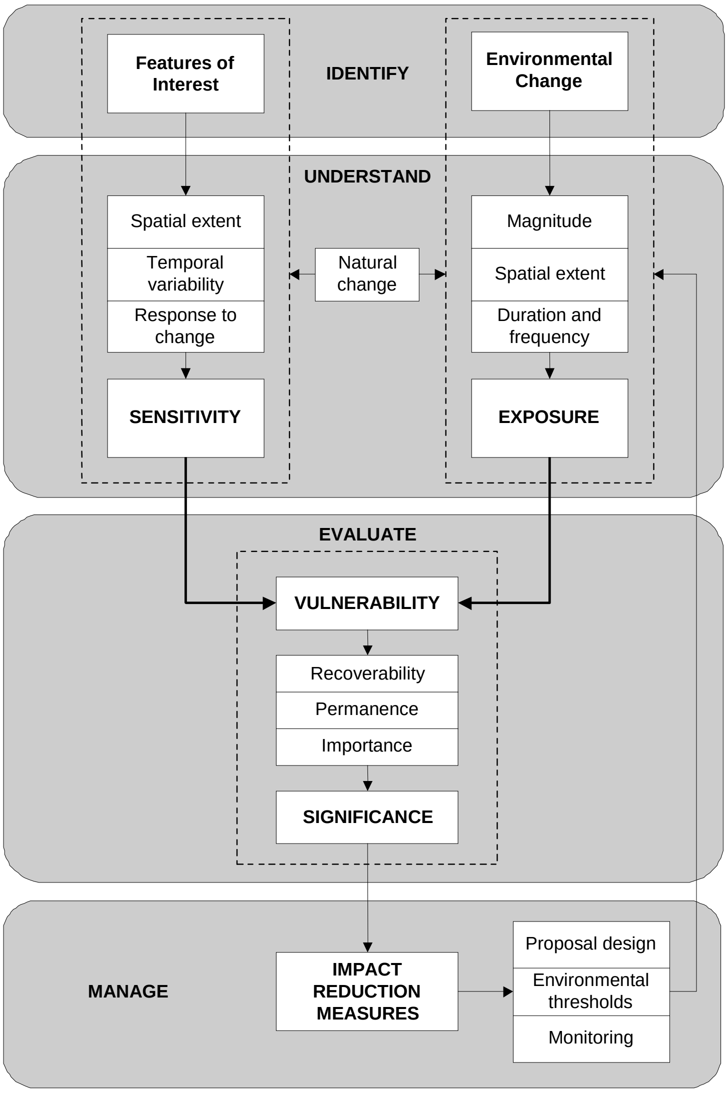

Figure 1. Processes Involved in Environmental Impact Assessment

2. Collision Risk Model

Ecological factors, such as the habitat preferences of a fish, migration routes and the position of a fish in the water column, will all influence the likelihood of a fish being exposed to features of a wet renewable device. For example, demersal species such as blennies and gobies that primarily inhabit the sublittoral fringe are unlikely to be seen in the vicinity of tidal stream devices but could be encountered near oscillating wave columns attached to the shoreline.

Behavioural responses of fish to perceived threats can be broadly categorised in two ways: avoidance and evasion. With respect to marine renewable devices, fish may therefore demonstrate two types of response: long range avoidance (i.e. avoiding the area within the vicinity of the device) or close range evasion (i.e. during a close encounter with a turbine blade). The specific response will depend on the distance at which the device is perceived. Long range avoidance in the context of this report is considered to be avoidance at distances further away than where a visual response can be undertaken i.e. through noise and vibration cues. Close range evasion is considered to be a response initiated at distances where the primary stimulus for the response is triggered by a visual reaction to the physical characteristics of the device. Some devices will have features which have the potential to cause severe damage or mortality to a fish whereas other devices could be considered as having characteristics which are unlikely to cause harm to a fish.

Collision risk can therefore be seen as a function of the extent of exposure, avoidance response (both long range avoidance and close range evasion) and the potential physiological damage caused by a wet renewable device. The extent of any risk will also be dependant on device characteristics and will be modified by various environmental features (Figure 2).

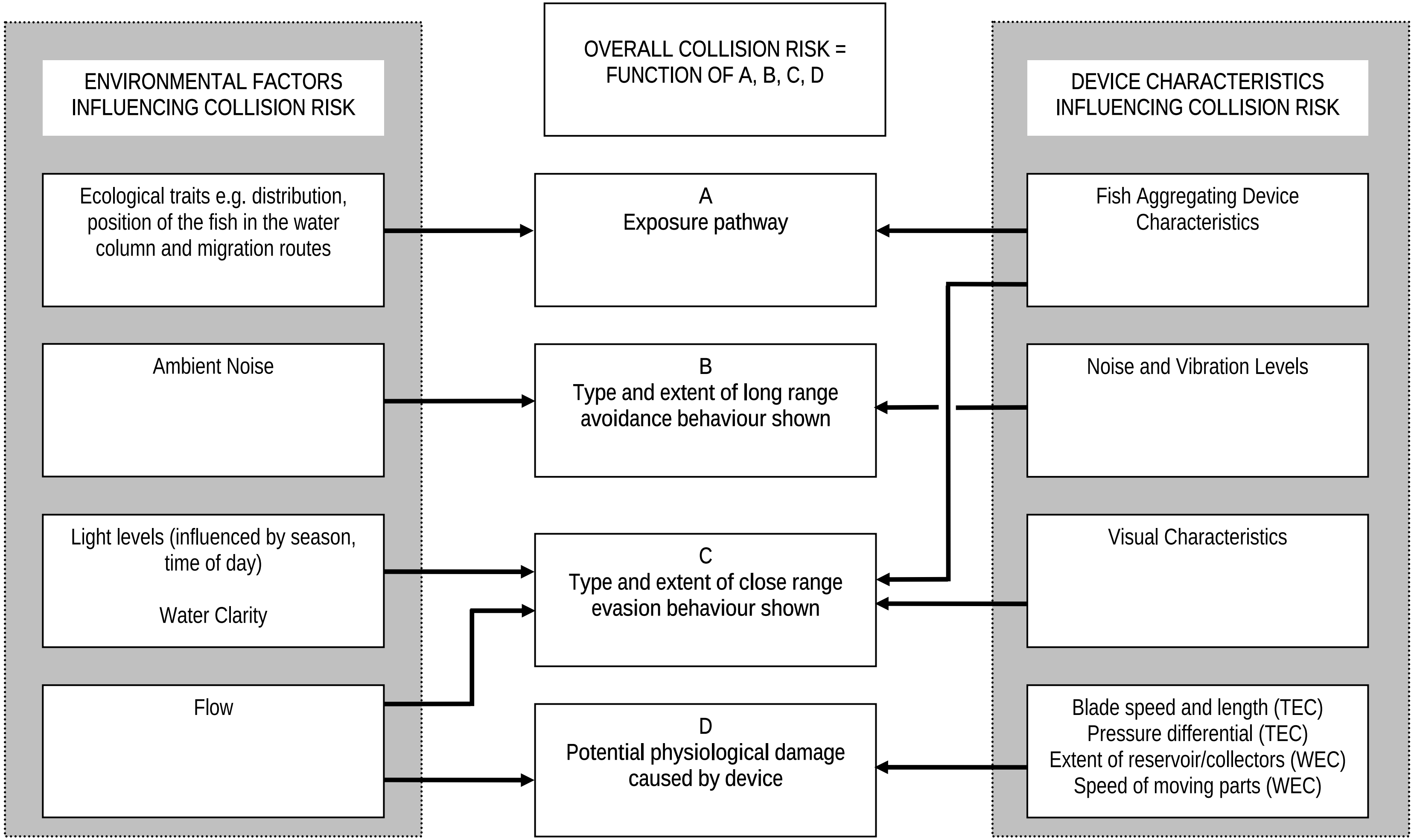

Figure 2. Collision Risk Model

3. Device Characteristics Influencing Collision Risk

3.1 Device Groups

Based on a review of wet renewable energy devices currently being installed or tested the following broad classification scheme has been adopted (Table 2).

Table 2. Classification of relevant wet renewable energy devices

Energy Group Type	Device Type	Description
TEC	Horizontal axis turbine	Device rotating horizontally in the tidal flow.
	Vertical axis turbine	Device rotating vertically in the tidal flow.
	Venturi	The Venturi effect is used to accelerate water through the device, creating a pressure drop to drive a turbine.
	Hydrofoil	Use of hydroplanes, hydrofoils or sails moving in the vertical in response to tidal flow.
WEC	Attenuator	An attenuator is a floating device, which works perpendicular to the wave direction and effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a lower area parallel to the waves in comparison to a terminator, so the device experiences lower forces.
	Point absorber	A point absorber is a floating structure, which absorbs energy in all directions through its movements at/near the water surface. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors.
	Oscillating Wave Surge Converter	This device extracts the energy caused by wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves.
	Oscillating Water Column	An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity.
	Overtopping devices	This type of device relies on physical capture of water from waves, which is held in a reservoir above sea level, before being returned to the sea through conventional low-head turbines, which generate power. An overtopping device may use collectors to concentrate the wave energy.
	Submerged pressure differential	These devices are typically located near shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure can then pump fluid through a system to generate electricity.

(Based on information from the: European Marine Energy Fund EMEC www.emec.org.uk)

A number of characteristics of both wave and tidal stream devices have the potential to cause environmental changes, which could pose a collision risk to fish. For tidal stream devices relevant characteristics include the length of the foil/rotor, the average speed of this through the water, any pressure fields associated with the device and the position of the turbine in the water column. Relevant characteristics for wave energy devices include the size of the device, the position of the device in the water column, the speed of any moving parts such as joints or oscillating components and any components such as reservoirs/water collectors in which fish may become trapped or squeezed through (grinding). For both tidal and wave devices the type of device mooring could influence the number of fish found around a structure by acting as a fish aggregating device (FAD). This is discussed in more detail in Section 6.5. The noise generated by wet renewable devices will also be a factor as this could influence the type and extent of fish avoidance behaviour shown towards a device (and therefore the level of collision risk associated with that device).

3.2 Tidal Stream Devices

Information on the characteristics of a variety of tidal stream device types are summarised in Table 3. It is noted that this table is not an exhaustive list of current devices, but a selection of devices for which information on some of the characteristics were available. The information was collated from currently available environmental statements and reports from developers, websites and through consultation with developers. The significance of the device characteristics listed in Table 3 is discussed in relation to potential impacts on fish in Sections 5-7.

Table 3. Characteristics of different tidal stream devices which could pose a collision risk for fish

Device Type	Device Examples	Length of the Foils/Rotor	Average Speed of Foils/Rotors Through the Water	Pressure Differential Values	Position/Depth in the Water Column	Base Type	Noise Level Emitted by the Device
Horizontal axis turbine	Marine Current Turbines (MCT) - SeaFlow and SeaGen.	SeaFlow: 11m rotor with 2 blades.	SeaFlow: 23 rotations per minute (rpm).	SeaFlow: no information available.	SeaFlow installed in a mean depth of water of 25m.	SeaFlow: monopile	SeaFlow: measured underwater noise levels: effective source level of 166 dB re. 1µPa at 1m.
		SeaGen consists of twin axial flow rotors, 16m in diameter, each rotor has 2 blades.	SeaGen: 15 rpm, blade tip velocity 10 - 12m/s.	SeaGen: no information available.	SeaGen: currently envisaged operating in water depths of 20 to 40m.	SeaGen: Piled. The twin power units of each system are mounted on wing-like extensions either side of a tubular steel monopole 3m in diameter drilled into the seabed	SeaGen: No operational noise information is currently available (MCT pers. comm.)
Horizontal axis turbine	Verdant Power – RITE Project Kinetic Hydropower System (KHPS).	5m rotor tip diameter. 3 blades mounted on cylindrical hub of 0.75m diameter and 0.5m axial length. Solidity ratio 16% (blade frontal area / total rotor area).	Approx 35 rpm (at full load) with tip speed of approx 7.6 m/s. Operational at water velocity of 1 m/s. Rpm limit (no load) approx 70-90 (tidal velocity dependant).	Verdant Power turbine, pressure differential calculated 2 kPa.	Nominal depth 10m.	Demonstration array monopiles. Next generation to be gravity-based triframe mounts (3 turbines on one mount).	Source level of 145 dB re 1µPa at 1m.
Horizontal axis turbine	Tidal Energy Ltd – Delta Stream.	Blades 5-6m long, fixed pitch. Nacelle 4m long x 1m diameter. Seabed to blade tip 18.5m. Blade clearance to seabed 3.5m.	Dependant on tidal current.	No information available.	Can be installed in a range of water depths, including deep sea where currents are strongest. No real upper limit to the depth of water Delta Stream can be deployed in. Rotor will extract energy from water flow approx. 5 – 20m above the seabed.	Gravity base. 30m wide triangular seabed fixed frame supporting 3 turbines. Vertical support 1m diameter. During operation 2 concrete blocks 3x3x3m will be required to sit on the seabed either side of the device. These 'sinkers' will anchor the lifting bridle, cable and mooring chain, taut on the seafloor.	No information currently available (TEL. pers. comm.)

Device Type	Device Examples	Length of the Foils/Rotor	Average Speed of Foils/Rotors Through the Water	Pressure Differential Values	Position/Depth in the Water Column	Base Type	Noise Level Emitted by the Device
Venturi (ducted) Horizontal axis turbine	Lunar Energy – Rotech Tidal Turbine (RTT) a bidirectional horizontal axis turbine housed in a symmetrical venture duct which speeds flow through turbine.	1MW RTT unit: duct diameter 15m, duct length 19.2m; turbine diameter 11.5 m.	Tip speed 12-20 m/s.	No information available.	On seabed, 40 – 60m depth.	Three leg gravity foundation.	No noise level information available. State on website "In the same way that fish and mammals are deterred by the noise of a ship's propeller it was felt that they would also be aware of the low level noise from the RTT turbine".
Venturi (ducted) Horizontal axis turbine	Hydro Green Energy – Hydrokinetic turbine.	Rotor diameter 12 feet (approx. 3.7m).	Rotor tip speed of 3.67 m/s at 21 rpm.	No information available.	Surface suspension system.	Surface suspension system.	No information available.
Venturi (ducted) Horizontal axis turbine	Clean Current Power Systems – Clean Current Tidal Turbine a bi-directional ducted horizontal axis turbine.	In commercial scale model, hole in centre of rotor will be > 4m in diameter. Length of blades not stated.	Rotation speed of turbine will vary between 20 and 70 rpm depending on current speed and unit size.	No information available.	Installed in approx. 20m of water, July – Sept 2006 (Race Rocks Tidal Energy Project, Canada).	Pile mounted.	Low frequency noise < 100 Hertz (Hz) will be produced at rpm between 20 and 70. Detailed acoustic signature of unit to be performed after deployment.
Vertical axis turbine	GCK Technology Inc. - Gorlov Turbine.	1m diameter x 2.5m height with frontal area of $2.5m^2$. 3 blades with 140mm chords.	Rotates at twice the velocity of the water current flow.	No information available.	Can be installed in water as shallow as 4 ft (approx. 1.2m) in depth.	Suspended off barge or attached to sea floor.	No information available.
Vertical axis turbine	Ponte di Archimede Company, ENERMAR project - Kobold turbine Operating in the Messina Strait, Italy since 2001 delivering electricity to a local grid.	Cross flow rotor, 6m in diameter equipped with 3 blades with a span of 5m.	5 rpm.	No information available.	The system is moored where the water depth is 18-25m and the expected current velocity is approx. 2 m/s.	The system consists of a buoyant support platform with kobold turbine attached, moored by four anchoring blocks.	No information available.
Hydrofoil	Pulse Generation Ltd. – Pulse Generators.	Pulse generators cause hydrofoils to oscillate up and down like a dolphin's tail. Two foils 12 m in length. Vertical sweep of foils approx. 5m.	Period of oscillation will vary with tidal flow but the min period (i.e. highest speed) will be 5s, equivalent to foil speed of approx. 4 m/s. Average speed through the water is 2 m/s.	It is anticipated that a small mobile pressure field and eddies will be generated around device during operation.	Designed primarily for shallow water sites. At high water the device will protrude 5 m above the water and 12 m at low water.	Twin steel piles (1m diameter) driven into seabed.	An Environmental Statement (IECS, 2007) stated the operational noise is expected to be very low (no actual noise levels given).

(Sources: DTI (2005); Richards *et al.* (2007); Douglas *et al.* (2008); Fraenkel (2006); DTA (2006); Verdant Power (2008a); Verdant Power (2008b). Tidal Energy Ltd. (2008); Bedard *et al.* (2005); Lewis (2007); IECS (2007); http://www.eusustel.be/public/documents_publ/WP/WP3/WP3%20report%20-%20Marine%20Currents%20and%20Wave.pdf; http://www.lunarenergy.co.uk/productOverview.htm; http://www.hgenergy.com/technology.html; http://cleancurrent.ca/technology/.

3.2.1 Hydrodynamic Interactions of Tidal Stream Devices and the Water Column

The majority of academic literature researching the hydrodynamic performance of tidal stream devices focuses on horizontal axis turbines. Tidal stream horizontal axis turbines operate on a similar principle to wind turbines (Wang *et al*., 2006) and much can be transferred about the physical and operational performance of these devices from the design and operation of wind turbines and ship propellers (Batten *et al*., 2008). However there are fundamental differences in the design and operation of marine current turbines, because of the higher density of water compared with air and the much slower speed of rotation (Fraenkel, 2004). One major difference that arises from using water as the working fluid rather than air is the phenomenon of cavitation, which is the formation of vapour pockets caused by extremely low pressure at the blade tips, which subsequently collapse violently producing local shock waves. Cavitation will develop at any point on the rotor blade where the pressure level is reduced to the level of saturated vapour pressure of the ambient water (Wang *et al*., 2006). Undesirable effects of cavitation with respect to turbine operation include erosion of the blade and associated noise and shaft vibration; the radiated noise level of a tidal stream device will be increased considerably by the presence of cavitation. However, cavitation also poses a potential environmental impact as it has been identified as one of the mechanisms by which fish injury and mortality occurs in fish passing through hydroelectric turbines (see Section 7.1). It has been calculated that the phenomenon of cavitation will limit marine turbine rotor tip velocities that can reasonably be used near the surface to about 10 or 12m/s (Fraenkel, 2004, Wang *et al*., 2006).

Any structure in the water column has the potential to change the flow patterns in its surrounding area including reduction of current flow, the generation of turbulence (when fluid particles move in a highly irregular manner, even if the fluid as a whole is travelling in a single direction), the formation of vortices (spinning, often turbulent, flows of liquid) in front of the structure and the generation of wake effects (a region of relatively slow, turbulent flow) behind the structure (Robert Gordon University, 2002). Hydrodynamic changes arising from arrays of tidal devices in particular may be significant as they tend to result in a re-distribution of tidal flow locally and reductions in energy both upstream and downstream of the device (ABPmer, 2009). The velocities needed for potentially cost-effective power generation involve relatively rapid tidal currents typically with peak velocities at Spring Tide in the region of 2 to 3m/s (4 to 6 knots) or more (Fraenkel, 2004). Marine current devices will have to operate in turbulent flows, and their presence will increase downstream turbulence through vortex shedding and wake effects (Mueller and Wallace, 2008). Hence, another potential source of environmental impact on fish from tidal stream turbines is the perturbed velocity field and associated wash effect induced by the vortices in the slipstream of the turbine (Wang *et al*., 2006) and this is discussed further in Section 7.2. Available information regarding the hydrodynamic interactions (rotor speed, blade tip velocity, pressure differentials across the blades) of marine tidal devices with the water column is included in Table 3.

3.2.1.1 Verdant Power - Roosevelt Island Tidal Energy Project

Verdant Power's Roosevelt Island Tidal Energy (RITE) Project in New York has deployed six Kinetic Hydropower System (KHPS) turbines in the east channel of the East River. The KHPS turbine is an open (i.e. non-ducted) horizontal axis 3 bladed turbine of 5m diameter. Rotation at full load is relatively slow at approx. 35 rpm with tip speeds of approx. 7.6 m/s (Verdant Power, 2008a). Further device characteristics for these turbines are shown in Table 3.

Verdant power conducted both Computational Fluid Dynamics modelling and *in situ* hydrodynamic evaluations of the KHPS turbine to better understand the near-field effect of rotating blades on flow patterns in relation to increased turbulence or creation of small flow disturbances (eddies) and how aquatic life predator-prey relationships may be affected (Verdant Power, 2008b).

The hydrodynamics in and around a stationary and rotating turbine; rotor, nacelle, pylon and mounting structure (i.e. at the 'micro-scale', within 0.1 to 2D of rotor, where D = rotor diameter) were characterised using Computational Fluid Dynamics (CFD) modelling software (ANYSYS CFX). The mean axial velocity, pressure distribution and turbulent kinetic energy (turbulence 'strength') around a stationary turbine in water flow of 2.5m/s were evaluated. Under these conditions, regions of relatively high and low pressure were created across the pile, pylon, nacelle and cones, resulting in wake and a reduction in water velocity of up to 50% (i.e. <1.25m/s) downstream of those regions of the turbine. The low pressures predicted were above the ambient vapour pressure and so cavitation did not occur. Local flow acceleration was seen specifically at the blade tips and around the pile/pylon. Turbulent mixing was increased near the stationary blades and the base of the pylon.

Modelling demonstrated that a 'helical' tip vortex was shed continuously from the trailing edge tip of each blade when the turbine was rotating. However, accurately modelling the 'behaviour' (e.g. decay rate) of the tip vortex and wake beyond the 'near-field' (i.e. beyond a single turbine unit) was not possible at the micro-scale level.

Meso-scale hydrodynamic analysis (within 2D to 200D of rotor) was used to evaluate the interactions of the 3D wake generated as a result of the turbine (rotating or stationary) in the water body, and the vortex generation associated with the blade rotation, between two or more turbines in the array. Water velocity data at the turbine array site in the East Channel was collected using an Acoustic Doppler Current Profiler (ADCP). Measurements taken along the rotor centre line 13 ft (approx. 4.0m) below Mean Lower Low Water (MLLW) showed that flow velocity was reduced and the flow direction was changed downstream of an operating KHPS turbine. Velocity magnitudes approached zero immediately behind the rotating rotors; evidence of the significant wake behind a generating turbine, whilst velocity direction was up to 90º out of phase with the natural channel velocity, creating 3-D rotating vortex structures which propagated downstream and had the potential to interact with the subsequent turbine.

3.2.1.2 Marine current turbines – SeaFlow and SeaGen

The SeaFlow turbine was the first MCT turbine deployed at sea. SeaFlow is a two-bladed, 11m diameter horizontal axis 300kW tidal turbine system that was installed at Lynmouth, north Devon in May 2003. The environmental impact of the turbine was monitored in a number of ways, including an acoustic study to assess the likely effect of turbine noise on marine life (see Operational Noise section below) and flow measurements looked at the extent of the turbulent wake (DTI, 2005). Whilst using ADCP to record the velocity of the current heading into the rotor and analyse rotor performance, it was stated that upstream of the rotor "the flow started to slow down and spread out some distance upstream of the plane of the rotor", giving a descriptive indication of the effect of the turbine on water flows in the vicinity of the rotor. The same report also stated that cavitation was not detected in either acoustic tests, assessments of rotor performance or through damage to blades.

SeaGen is the MCT turbine which has been deployed at Strangford Lough. SeaGen is a horizontal axis turbine with two rotors, each 16m in diameter and with two blades. During the EIA process for this turbine, hydraulic modelling predicted that tidal velocity differences in the water column were insignificant except immediately around the monopile on which the turbine is mounted, and was only measurable up to 500m from the turbine (MCT, 2005).

3.2.1.3 Pulse Generation Ltd – Pulse Device

The Pulse Stream generator extracts energy from tidal flows through two horizontal hydrofoils which oscillate up and down across the flow when flow speed reaches approx. 1 m/s. The hydrofoils are approx. 12m long and sweep a vertical height of 5m at a frequency of 12 oscillations per minute. The period of oscillation varies with tidal flow speed; the highest speed will be approx. 4 m/s whilst the average speed is 2 m/s.

Experimental tank tests, using a scale model of the device were conducted to assess the effects that the device would have on tidal currents (IECS, 2007). The wake of the device was measured and is likely to be represented by flow acceleration and reduction, and increased turbulence extending and dissipated over a distance of 1–2 times the device width either side of the installation, and approx. 7 – 10 times the device width in the downstream and upstream directions. Flows in the immediate wake of the device (for both ebb and flood flows) might therefore be reduced by up to 25%. A maximum conservative estimate is that the overall extent of the wake (calculated to assess the maximum extent of wake effects on seabed sediments, sediment load and tidal currents) is expected to be approx. 1.8 km^2. The Environmental Statement (ES) (IECS, 2007) that was undertaken to install a tidal power generator in the Humber Estuary, states that it is anticipated that the movement of the hydroplanes during operation will generate a small mobile pressure field and eddies around the device.

3.2.2 Operational Noise Generated by Tidal Stream Devices

Operational noise from tidal stream energy converters may arise from a number of the device components including rotating machinery, flexing joints, structural noise, moving water, moorings, electrical noise (for example from electronic switching units and/or the cable bringing the power ashore) and instrumentation noise (e.g. from echosounders, doppler current meters or acoustic modems).

Sounds have a variety of characteristics, which are relevant to whether and how they will be perceived. The frequency of a sound is the number of vibrations, or pressure fluctuations, per second and the unit is the Hertz (Hz). Sound pressure is the local pressure difference between the medium (in this study, water) and the sound wave. The SI unit for pressure is the Pascal (Pa).

It is usual to express sound levels in terms of decibels (dB). The decibel relates the measurement of noise and it expresses the ratio between the reference unit and the recorded magnitude.

As pressure amplitudes of sound show great variation, they are expressed in terms of a logarithmic scale. The reference unit for marine/underwater noise is typically 1 microPascal (1µPa) (Nedwell *et al*., 2003b).

The sound pressure level (SPL) of a sound of pressure (P) is given in decibels (dB) by:

$$dB = 20x \log (P/Ref)$$

As the pressure level produced by the sound source will generally decrease with distance from the source, when measuring sound it is usual to specify the distance from the source. The source level of a specific sound source is frequently quoted as the sound level that would be measured at a distance of 1 metre from the source. It is standard to give source levels for underwater sound sources in units of dB re 1µPa at 1 metre, (or dB re 1µPa-1m). If source levels cannot be measured directly they are calculated using measurements at a known distance from the source and estimating the losses between the actual and theoretical (1 metre from source) measurement distances using attenuation models.

A summary of the main noise sources and frequencies emitted for different types of tidal stream energy converters is given in Richards *et al*. (2007) and a summary is shown in Table 4.

Table 4. Summary of the main noise sources associated with different types of tidal stream device types

	Noise Source						Frequency Band (Hz)				
Tidal Device	R	F	S	A	W	M(1)	0-100	100-500	500-5k	5k-20k	>20k
Horizontal turbines	✓		✓		✓	✓	■	▓	▒	░	░
Vertical turbines	✓		✓		✓		■	▓	▒	░	░
Venturi units			✓	✓	✓		▒	▓	▓	▒	░
Oscillating hydrovanes	✓	✓	✓				■	▓	▒	░	░
Generic Noise											
Electrical							▓		■	▒	
Instrumentation										▒	■

The grey scale indicates the relative noise in each part of the spectrum, with black indicating the highest level and white indicating no or negligible noise.
R = Rotating Machinery noise; F = Flexing joint noise; S = Structural noise; A = Moving air noise; W = Moving water noise;
M = Mooring noise (1) mooring noise applicable only to moored turbines, not piled turbines.

(Source: Richards *et al*., 2007)

Information on the acoustic signatures of operational tidal stream devices is limited and research into the operational acoustic emissions and vibration during demonstrator projects has been highlighted as a priority by the Marine Renewable Energy Research Advisory Group (BERR, 2006). Tidal turbines appear to emit broadband sound covering frequency range from 10 Hz up to 50 kHz with significant narrow band peaks in the spectrum. Depending on size, it is likely that tidal current turbines will produce broadband source levels of between 165 and 175 dB re. 1µPa at 1m (OSPAR, in press). Further details explaining the noise terminology used can be seen in Section 4.4. Underwater operational noise information was available for only two tidal stream energy converter devices and these are described below.

3.2.2.1 Marine current turbines – SeaFlow

Underwater operational noise measurements were made of the MCT SeaFlow turbine (see Table 3 for device characteristics) located at Lynmouth, north Devon and were compared to baseline ambient noise levels, measured when the turbines were not operating (Richards *et al*., 2007). The results showed that operational sound pressure levels measured at similar distances from the turbine were highly variable and that at times the ambient noise level, which included shipping, shore and surf noise, was higher than the noise levels generated by the turbine. The results implied that an effective source level from the operational turbine was 166 dB re. 1 µPa at 1m. The study also showed that the spectrum level of noise from the turbine was significantly higher than that of ambient noise over most of the spectrum (101 – 105 Hz) when measured at a range of 250m.

3.2.2.2 Verdant Power - Roosevelt Island Tidal Energy Project

Verdant Power conducted an underwater acoustic evaluation both pre and post deployment of their 6 turbine demonstrator array in the east channel of the East River in New York, to assess the biological significance of the noise generated by the turbines. The ambient underwater noise levels, measured prior to deployment of the turbines, was found to be high and this was attributed to the shallow water environment (<15m), the high level of river navigational traffic and the presence of a variety of urban facilities (e.g. subway tunnel under riverbed, nearby power station).

Underwater noise measurements were made within the demonstration project area and at distances of up to 1850 m away using a hydrophone measuring a frequency range of 0.5Hz to 250 kHz. The results indicated an operational sound pressure level of 145 dB re. 1µPa at 1m, a noise level found to be comparable to that recorded when the subway was active (range approx. 132 – 148 dB re. 1µPa at 1m).

3.3 Wave Devices

Information on a variety of wave device ‘types’ are summarised in Table 5. It is noted that this table is not an exhaustive list of current devices, but a selection of devices for which information on some of the characteristics were available. The information was collated from currently available environmental statements and reports from developers, websites and through consultation with developers. The significance of the device characteristics listed in Table 5 is discussed in relation to these potential impacts on fish in Sections 5-7.

Table 5. Characteristics of different wave devices which could pose a collision risk for fish

Device Type	Device Examples	Size of Device	Position/Depth of the Device in the Water Column	Speed of Any Moving Parts Such as Joints or Oscillating Components	Existence and Extent of Any Reservoirs/Water Collectors	Base Type	Noise Level Emitted by the Device
Attenuator	Pelamis Wave Power – Pelamis P-750 Wave Energy Converter. A semi-submerged articulated structure composed of cylindrical sections linked by hinged joints.	150m long, 3.5m diameter.	2.5m draft. Device semi-submerged at sea surface. Designed to be moored in water 50-70m depth, typically 5-10km from the shore.	Not stated.	No reservoirs / water collectors.	Compliant slack moored (1) The mooring system is secured to the seabed via mooring weights and/or embedment anchors, depending on the type of seabed.	Estimated levels due to Pelamis hydraulic motors: 175 Hz: noise level 129 - 140 dB re. 1μPa at 1m. 350 Hz: noise level 127 - 141 dB re. 1 μPa at 1m.
Attenuator	Green Ocean Energy Ltd - Ocean Treader. Harnesses the different responses of horizontally and vertically floating bodies to passing waves.	50m long, 20m beam. Anticipated deployed in farms of 10-20 machines. Ideally employed in water depths of 50-100m, less than 5km from shoreline.	Sea surface, 20m draft.	Not stated.	Not stated. Structures comprise of steel load bearing members with buoyant bodies.	Anchored.	Not stated.
Attenuator	Checkmate Seaenergy – Anaconda. A very large water filled distensible rubber tube floating beneath the ocean surface at right angles to the waves with a power take off the stern.	Possibly 200m long x 5m diameter (currently at scale model testing stage).	Floating just beneath ocean surface.	Not stated.	Closed circuit system, so entrapment of marine animals not possible.	Anchored.	Not stated.
Point absorber	Finavera Renewables – AquaBuOY a vertical-axis two body converter: i) the buoy/acceleration tube assembly and ii) the piston together with the water inside the acceleration tube. Each AquaBuOY contains two single acting hose pumps, 200-400 litre water accumulator, one Pelton turbine.	Tailored to installation location. Makah Bay: 19.5ft (approx. 5.9m) diameter float with 98ft (approx. 11.6m) long x 15ft (approx. 4.6m) diameter acceleration tube.	Sea surface. Float approx. 6 ft (approx. 1.8m) above water surface. 98ft (approx. 29.9m) long acceleration tube extends below water level.	The Pelton turbine operates within the closed-loop system.	Closed system preventing entrapment of fish.	Tethered by tension cable to four floats, which are connected to subsurface mooring buoys located just above seafloor. Subsurface mooring buoys connected to seabed.	Noise from project operation (hose pump, pressurised water, turbine) expected to produce noise levels below the ambient noise.

Device Type	Device Examples	Size of Device	Position/Depth of the Device in the Water Column	Speed of Any Moving Parts Such as Joints or Oscillating Components	Existence and Extent of Any Reservoirs/Water Collectors	Base Type	Noise Level Emitted by the Device
Point absorber	Ocean Power Technologies – PowerBuoy. Ocean-going buoy, most of which is submerged below the water's surface. Inside a moving piston-like structure drives a generator.	For 1 kW PowerBuoy: overall height 9m; height above waterline 1.7m; draft 7.4m, average float diameter 1.5m.	Sea surface. Height above waterline 1.7m, draft 7.4m.	Not applicable.	Not stated. Summary of EIA conducted at Hawaii project site concluded there was “minimal potential for entrapment of marine mammals or sea turtles”.	Adaptable to a variety of anchor and mooring designs.	Summary of EIA conducted at Hawaii project site states “acoustic output similar to that of ship traffic during continuous operation”. No quantitative values given.
Point absorber	Wavebob – Wavebob. An axi-symmetric buoy structure.	Outer torus has diameter of 20m and overall height of 8m.	Sea surface.	Not applicable.	Not stated.	Slack mooring.	Not stated.
Oscillating Wave Surge Converter	Aquamarine Power-Oyster. An oscillator (mechanical flap fitted) with pistons.	18m x 12m x 2m.	On seabed designed to be deployed in near-shore depths around 10-12m.	Not stated.	Not stated.	Not stated.	Not stated. However there is no underwater generator, power electronics or gearbox.
Oscillating Wave Surge Converter	AW Energy – WaveRoller. Consists of plates anchored to the seabed. The plates are moved back and forth by waves and the energy produced collected by a piston pump.	Not stated. Each module consists of 3-5 moving plates.	On seabed. Typical depth for installation 10-25m.	Not stated.	Not stated.	Note stated.	No levels given although website states. “The plant does not generate any noise to surface or shore”.
Oscillating water column	Wavegen - Land Installed Marine Powered Energy Transformer (LIMPET). A wave capture chamber set into the rock face on the shore. Waves cause compression and decompression in the air chamber and the resulting airflow drives a Wells turbine that generates power.	A 500kW prototype device was deployed on the island of Islay and became operational in 2000. The collector was 21m wide, approximately 15m in height up the shore and 7m deep, enclosing three water collectors each 6x6m. The outer wall angles downward over the point of water entry such that the opening is reduced to 4.5m in height.	Shoreline.	Not applicable – no turbine components in the water column.	The collector chamber is considered no different to a naturally occurring blow hole or cave and risk of entrapment of fish likely to be minimal.	Cemented.	No levels given. Noise is created as a result of air compression in the structure and this is carried above ground.

Device Type	Device Examples	Size of Device	Position/Depth of the Device in the Water Column	Speed of Any Moving Parts Such as Joints or Oscillating Components	Existence and Extent of Any Reservoirs/Water Collectors	Base Type	Noise Level Emitted by the Device
Oscillating water column	Wave Energy Centre – European Pico Pilot Plant. Concrete structure forming an air chamber with a frontal submerged opening facing the waves.	Inside dimension of chamber 12m x 12m at mean water level.	Built on rocky seabed, at approx. 8m water depth.	Not applicable - air turbine is above water level in chamber.	Not stated – likely same as for LIMPET (see above).	Bottom mounted shoreline structure.	No levels given.
Oscillating water column	Embley Energy – SPERBOY.	Will vary depending on sea conditions at deployment site, max 30m diameter, 50m overall height, 35m draft.	Preferential deployment in water > 50m depth.	No moving parts below the waterline.	Not stated.	3-4 diametric tethers to subsurface floats moored to suitable seabed fixings.	Not stated.
Overtopping device	Wave Dragon – Wave Dragon.	Two lateral wave-reflecting arms, which are 120 m long and 300 m apart at widest point and concentrate the power of incoming waves Central housing: Width 132m, length 87m, draught 11-14m, max height above sea surface 6m; Reflecting wings: length 145m, width 7m, distance between tips of wings 300m, draught 10m, length (tip of wing to rear of central housing) 170m, max height above sea level 3-6m.	Surface to depth of 10-15m.	Up to 20 slow rotating 3 fixed bladed low head Kaplan turbines (1.2m diameter, 100 to 270 rpm). Max velocity of water through turbine 2 m/s and flow volume predicted to be 75 m^3/s.	A central housing with a large water reservoir receives water from oncoming waves via a ramp. A screen with a grill size of 50 mm is fitted around the turbines to protect marine species and prevent marine debris from damaging the turbines.	Anchored-Concrete gravity blocks and a series of catenary mooring lines (steel cable) linked to a buoy to which the device is fixed.	Estimated from laboratory experiments - sound pressure level = 143 dB re. 1μPa at 1m RMS. Noise levels arising from wave interactions with the body of the device were suggested to be in the range of 164 dB re. 1 μPa at 1m.
Overtopping device	Waveplane A/C – Waveplane.	The wave plane is a V-shaped construction anchored with the tip facing the incoming waves. Below the waterline the device is fitted with an artificial beach, which is designed to improve the capture of wave energy.	Not stated.	The device splits the oncoming waves with a series of intakes, known as lamellas, which guide the captured water into a 'flywheel tube'. The fast moving vortex that is formed then forces the water across a couple turbines, which are located at the end of the two "V-shaped legs", before discharging back into the ocean.	Not stated.	Slack moored.	Not stated.

Device Type	Device Examples	Size of Device	Position/Depth of the Device in the Water Column	Speed of Any Moving Parts Such as Joints or Oscillating Components	Existence and Extent of Any Reservoirs/Water Collectors	Base Type	Noise Level Emitted by the Device
Overtopping device	WAVEenergy - Sea Wave Slot-Cone Generator (SSG)	10m x 22m x 9m	Technology described as being integrated into breakwaters, or floating or fixed offshore installations	Turbine and control gates are only moving parts exposed to seawater	Three reservoirs, varying in height above sea level	Presumably dependant on type of installation - Breakwater, floating or fixed offshore installation	Not stated
Submerged pressure differential	AWS Ocean Energy Archimedes Waveswing. Waves move an air-filled upper casing against a lower fixed cylinder.	48m x 28m x 38m	At least 6m below surface. Requires deployment in water 40-100m in depth	The Archimedes Wave Swing reciprocates with a peak velocity of 1–2 m/s	Not stated	Slack moored suing chains/guy wires	No levels given. Website states “no noisy high speed rotational equipment”

(Sources: http://www.pelamiswave.com/media/pelamisbrochure.pdf; Ocean Power Delivery Ltd. (2003); Richards *et al*. (2007); http://www.greenoceanenergy.com/index.php/about; http://www.checkmateuk.com/seaenergy/; Federal Energy Regulatory Commission (FERC) (2006); Patricio *et al*. (in prep); http://www.oceanpowertechnologies.com/envir.htm; http://www.oceanpowertechnologies.com/hawaii.htm; http://www.wavebob.com/; http://www.aquamarinepower.com/; http://www.aw-energy.com/concept.html; Wavegen (2002); ABPmer (2009); http://www.pico-owc.net/files/33/cms_b6cda17abb967ed28ec9610137aa45f7.doc; http://www.sperboy.com/; PMSS Ltd. (2007); http://www.waveplane.com/; http://waveenergy.no/; http://www.awsocean.com/archimedes_waveswing.aspx?Site=1; http://aspdev.optimle.com/eere/information.aspx?ID=4073f9a7-9500-43c9-9235-7dabd9ff3c09 ans type=tech; Mueller and Wallace (2008))

3.3.1 Wave Device Interactions with the Wave Resource

Wave energy is transmitted through disturbance effects acting at and near the sea surface. Wave energy devices are designed to intercept this predominant surface flux and are therefore likely to be preferentially deployed at the sea surface, although sub-surface devices also exist (Table 5). The behaviour of waves meeting an obstacle can become highly complex and depending on the shape, dimension, buoyancy and response of the device, there may be amounts of wave energy reflected and scattered off the device. Larger structures may also lead to diffraction effects, although in most cases, wave energy converter devices would appear too small to lead to diffraction effects (ABPmer, 2006). Most modelling studies to assess the probable effects of energy loss assume that a WEC structure absorbs 100% of incident wave energy, with no reflection or diffraction, although a more realistic value for wave absorption is likely to be in the order of 30% (ABPmer, 2006). Hydrodynamic impacts of over-topping devices such as Wave Dragon, determined through modelling, appear to be restricted to the immediate vicinity of the device (PMSS Ltd., 2007; see below). Other devices such as floating wave energy conversion buoys (e.g. Aquabuoy on the surface and Archimedes Wave Swing at subsurface level) are likely to result in lower impact on the wave energy climate (Federal Energy Regulatory Commission, 2006 cited in ABPmer, 2009).

3.3.1.1 Wavegen – Land Installed Marine Powered Energy Transformer (LIMPET)

Because the device is situated on the shore at the point where wave energy is finally expended, there will be few hydrodynamic impacts arising from any reduction in wave energy due to the presence of the structure. However, the device may change small-scale hydrodynamic patterns in the vicinity of the device by altering the reflection of waves, both laterally and in front of the device. Such changes are unlikely to be different to the impacts of natural rocky reefs (ABPmer, 2009).

3.3.1.2 Wave Dragon

As Wave Dragon is designed to extract energy from waves, it is expected that there will be a reduction in wave energy on the lee side of the device during operation (PMSS Ltd., 2007). Desk-based modelling predictions have indicated that the devices could result in significant reductions in the wave climate in the lee of the devices and that such changes might be measurable up to 20 km shoreward (Scottish Executive, 2007, commenting on unreferenced modelling studies undertaken for WaveHub). However, these predictions were based on very conservative modelling assumptions that were not relevant to field conditions. Numerical modelling studies carried out for the demonstrator project (PMSS Ltd., 2007) indicated that Wave Dragon reduces wave energy for short period wind sea conditions in the leeside area by over 50%. The impact is reduced to less than 20% within 1.3 km of the device. Swell wave energy is not captured so effectively by the device with large swell waves losing only about 10% energy in the immediate lee of the device, reducing to about 2% reduction close to the shore.

3.3.2 Operational Noise Generated by Wave Devices

The collision/grinding/entrapment risk to fish posed by wave devices will be influenced by the ability of fish to detect the presence of the device (through operational noise and vibration) and the behavioural response to this stimulus. The total noise generated by wave energy converters will be a product of the noise produced by the components of the device and environmental conditions related to oceanographic conditions and sea state (Patricio *et al*., in prep). Mechanical components which can potentially contribute to the operational noise of the device include turbines, generators, hydraulic components (e.g. cylinders, pumps). Other sources of noise may arise from moving parts, moving air (for example in oscillating water column devices which use water movement to move air through turbines), cavitation, vibration of mooring cables and from waves hitting the device. A summary of the main noise source and frequencies emitted for different types of tidal stream energy converters is given in Richards *et al*. (2007) and a summary is shown in Table 6.

Table 6. Summary of the main noise sources associated with different types of wave device types

	Noise Source						Frequency Band (Hz)				
Wave Device	R	F	S	A	W	M(1)	0-100	100-500	500-5k	5k-20k	>20k
Oscillating water column			✓	✓	✓		▒	▓	▓	░	░
Overtopping	✓		✓		✓	✓	▒	■	▓	▒	░
Point absorber/ attenuator	✓	✓	✓		✓	✓	■	▓	▒	░	░
Generic Noise											
Electrical							▓		■	▒	
Instrumentation										▒	■

The grey scale indicates the relative noise in each part of the spectrum, with black indicating the highest level and white indicating no or negligible noise.
R = Rotating Machinery noise; F = Flexing joint noise; S = Structural noise; A = Moving air noise; W = Moving water noise;
M = Mooring noise (1) mooring noise applicable only to moored turbines, not piled turbines.

(Source: Richards *et al*., 2007)

In a recent review of available EIAs on underwater noise from wave energy devices, Patricio *et al*. (in prep) found that only two devices referred to expected or estimated operational noise levels, whilst other devices drew conclusions from literature reviews and comparison to other technologies such as offshore wind farms. The authors highlighted that acoustic data on the sound produced during operation of full scale wave devices in real sea conditions are not currently available. Furthermore they noted that whilst it may not be expected that an individual device would produce a high level of noise, the sound propagating from an array of devices needs to be considered as the device number and layout will influence the acoustic properties of the wave farm. The paper highlighted the Wave Energy Acoustic Monitoring (WEAM) project[1] which aims to develop a monitoring plan of underwater noise emitted by wave energy converters.

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[1] http://www.wavec.org/index.php/31/weam

The underwater operational noise estimates for two wave energy converter devices are described below.

3.3.2.1 Wave Dragon

Sources of underwater noise from the Wave Dragon device include waves interacting with the body of the device (wave slap), the hydroturbines, hydraulic pump and the mooring system. Although no operational underwater noise measurements from the pre-commercial device are currently available, the dominant sources of noise were identified as the electrical and mechanical emissions of the Kaplan turbines and the wake noise from the flume outlet in a testing facility. The operational noise level for the device was estimated from measurements made from one Kaplan turbine in the testing facility which was scaled up to estimate the noise level of the operational pre-commercial device (PMSS Ltd., 2007).

The noise of the turbine increased with increasing height of water head (assessed over range of 1.5 to 3.4m head height) and the results showed that operation of the generator produced broadband noise over a range from approx 10 Hz to 40 kHz. Narrow band noise spikes, typical of electrical device switching noise, occurred at 100 Hz and 1 kHz and wave turbulence at the outlet of the generator flume dominated the noise in the frequency range 1 – 20 kHz. The RMS sound pressure level for one Kaplan turbine operating at a 3.4 m head at a rotational speed of 876 rpm ranged from 129 – 132.6 dB re. 1 µPa at 1m, with the noise level increasing to 148.5 dB re. 1µPa at 1m if the turbine was operated with cavitation present (noise produced by cavitation is typically characterised by a broadband high frequency hiss).

The source level noise for the Wave Dragon demonstrator was estimated from the measurements of the one Kaplan turbine operating at a head of 3.4m, but assuming that there would be approximately 10 turbines operating at any given time and that the turbines would be cavitation free. This produced an estimated operational noise level of 143 dB re. 1 µPa at 1m. The perceived level of sound from the device was estimated to be below ambient sea noise levels (measured at the site) within a 100m distance from the device. This estimated noise level does not incorporate any noise which may arise from waves interacting with the body of the device, the hydraulic pump or the mooring system.

Noise levels arising from wave interactions with the body of the device were suggested to be in the range of 164 dB re. 1 µPa at 1m (and calculated to be below background noise levels at ranges of > 50m from the device) based on measurements of underwater wave slap noise on boat hulls (PMSS Ltd., 2007).

3.3.2.2 Pelamis

Operational underwater noise measurements are not currently available, however, Richards *et al*., (2007) provided tentative estimates of the expected radiated noise levels during normal operation, based on engineering information and a pre-installation noise review. The components of the device expected to make the largest contributions to underwater radiated noise were identified as the hydraulic motor generator packs, the hydraulic rams and associated pipe work and noise from waves breaking on the device. A “tentative” estimate of the radiated underwater noise was made using 'far-field' noise measurements from a steel hulled ship, the steering gear system of which contain hydraulic pumps with a similar design to the motors used in Pelamis. The estimated underwater tonal noise levels were 129 to 140 dB re. 1µPa at 1m at a frequency of 175 Hz and 127 to 141 dB re. 1µPa at 1m at a frequency of 350 Hz.

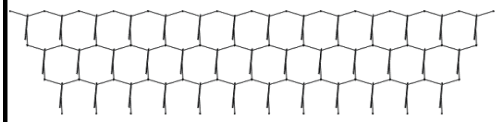
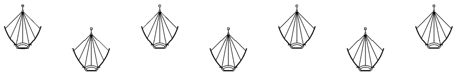
3.4 Arrays

The size and arrangement of the array of wet renewable devices will also influence the potential collision risk for fish.

For tidal stream devices the arrangement of an array is likely to remain as a single row of devices perpendicular to the axis of peak flows (ABPmer, 2006). Any second down-stream devices would similarly be located, with spacing based on multiples of rotor diameters (i.e. 5 to 9 diameters) for the same reason. Large tidal stream arrays would rely on a sufficient width of suitable tidal resource, which in most cases will be highly localised and finite in dimension, unlike wind. As an illustration, a large offshore wind project may extend over distances of several tens of kilometres, whereas in comparison a tidal stream array may have a width of less than one kilometre.

Available considerations for arrays of wave devices show that the layout of an array is entirely device specific. The number of devices for any scheme is likely to be aiming for a total installed capacity in the tens of megawatts. Consequently, this will lead to a fewer number of the higher rated devices, and a larger number of smaller rated devices. The ideal arrangement of an array is likely to be in long rows perpendicular to the axis of the prevailing wave direction, with subsequent rows offset by stagger (Table 7).

Table 7. Example WEC arrays

Example Arrays ↓ (Direction of Approaching Waves)	Example Installed Capacity (MW)	Typical Separation (m)
Pelamis 	29.25 (39 * 0.75MW units)	> twice device length
 Wave Dragon	49 (7 * 7MW units)	> 1 unit width

(Based on information from: ABPmer, 2006)

3.5 Summary

Characteristics of tidal stream devices which have the potential to influence collision risk with fish include the number of blades, the speed of moving parts, the hydrodynamic effects of moving parts on the water column and the levels of noise and vibration emitted during operation which may alert fish to the presence of the device. However, information on the operational hydrodynamic and noise characteristics of tidal stream devices is scarce, either due to lack of data or due to commercial sensitivity. The available information on operational hydrodynamic characteristics of tidal stream devices was particularly sparse, although the limited information available indicated that hydrodynamic effects included reduced water velocities in the immediate wake of the operating device, increased turbulence and the potential for the interaction of such hydrodynamic effects between devices situated within an array. Currently, operational noise assessments have only been made for two tidal stream devices (Marine Current Turbine's SeaFlow and Verdant Power's RITE project KHPS turbines) and the Marine Renewable Energy Research Advisory Group have highlighted that collection of data on the operational acoustic emissions and vibration during demonstrator projects is a priority (BERR, 2006).

Given that most wave energy converter devices are designed to be deployed at the sea surface, direct collision risk appears to be less of a concern in comparison to tidal stream devices. However, some wave devices comprise structures that may entrap fish and overtopping wave devices incorporate turbines within the water column, which will pose a collision risk should fish enter the structures. No data on the sound produced during operation of full scale wave devices in real sea conditions are currently available.

4. Environmental Features of Wet Renewable Locations

4.1 Hydrodynamic Conditions

As discussed in Section 1.2 the main tidal energy resources in Wales are based in Pembrokeshire, the Bristol Channel, Anglesey and the Lleyn peninsula. The minimum current speed at which a device can produce useful amounts of electricity is the key constraint which limits the potential location for siting tidal devices. Research undertaken by ABPmer (2007) found that several developers claim to be able to extract commercially viable energy at tidal flows of 1.5m/s. Maximum flow rates are not commonly stated by developers, however, excessive flow rates will pose engineering challenges for ensuring a stable mounting in relation to the hydrodynamic forces imparted onto the structure and its moorings. Another high flow speed consideration is that the rotor should be designed for a maximum tip speed of 10m/s or less to keep the tips free from cavitation (ABPmer, 2007). Flow rates in tidal streams around Pembrokeshire islands such as in Ramsey Sound experience MSPC (Mean Spring Peak Currents) speeds of 2.5-3.5m/s. In the Bristol Channel speeds up to 3m/s are recorded and Anglesey and Bardsey Island (Lleyn peninsula) have MSPC speeds ranging from 2-3.5m/s (ABPmer, 2007).

As discussed in Section 1.2, almost the entire exploitable wave energy lies off the Pembrokeshire coast (ABPmer, 2004; PMSS Ltd., 2006; PMSS Ltd., 2007; RPS 2008). The area is exposed to high energy waves from the Atlantic, mainly from the south west sector and strong tidal currents. At the proposed Wave Dragon site the 50%, 10% and 1% significant wave height exceedance values (all directions) are 1.0m, 2.9m and 4.8m respectively (PMSS Ltd., 2007).

The strong flows associated with many tidal and wave locations create a range of hydrodynamic conditions in the water column such as eddies, surface turbulence, upwelling and overfalls (Pierpoint, 2008; Elliot *et al*. 1995). Bowers *et al*. (1998) investigated the suspended sediments distribution in the surface waters of the Irish Sea and its relation to tidal stirring. Concentrations were found to be greater in winter than those in summer (by a factor of 2.7 for the Irish Sea as a whole), but the spatial pattern was similar. Highest sediment concentrations were found to occur in the shallow eastern Irish Sea and also in the regions of strongest tidal currents.

4.2 Geology and Habitats

4.2.1 Tidal Rapids

The term 'tidal rapids' is often used to describe the habitat and environmental conditions in which the majority of tidal stream devices are currently or planned to be located in.

The JNCC's Marine Nature Conservation Review (MNCR) defined rapids as 'strong tidal streams resulting from a constriction in the coastline at the entrance to, or within the length of, an enclosed body of water such as a sea loch. Depth is usually shallower than five metres.' In deeper situations, defined in the Biodiversity Action Plan (BAP) Habitat Action Plan for tidal rapids as being more than five metres, tidal streams may generate favourable conditions for diverse marine habitats (e.g. between islands, or between islands and the mainland, particularly where tidal flow is funnelled by the shape of the coastline). Wherever they occur, strong tidal streams result in characteristic marine communities rich in diversity, nourished by a constantly renewed food source brought in on each tide.

Existing prototype tidal stream generators are typically poorly adapted to shallow flows, usually being designed for water at least 25m deep. This means that often they must be positioned some distance from the shore. Research has indicated that predicted operating depths for tidal devices range from 4 to 100m (ABPmer, 2007).

The habitat and geology associated with the seabed in tidal rapids in Wales, where tidal energy can be exploited, typically comprise tide-swept and unstable scoured seabed features such as faunal turf biotopes covered in hydroids, bryozoans and sponges. In shallow water, bedrock and boulders often support kelp and other algae (Brazier *et al*. 1999; Foster-Smith *et al*. 1999). A summary of these locations can be seen in Table 8.

Table 8. Broad habitats and biotopes recorded in tidal rapids in Wales

Tidal Rapid Location	Geology and Habitat	Biotopes Recorded
Pembrokeshire islands such as Ramsey Sound.	The area has a mixture of tide swept bedrock and cobble habitat consisting of faunal turfs and tufts.	SS.SCS.CCS.PomB-*Pomatoceros triqueter* with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebbles. CR.HCR.FaT.CTub.CuSp-*Tubularia indivisa* and cushion sponges on tide-swept turbid circalittoral bedrock. CR.HCR.XFa.ByErSp-Bryozoan turf and erect sponges on tide-swept circalittoral rock.
Bardsey Island, Lleyn peninsula.	The tidal rapids in Bardsey Island mainly consist of plain and rounded cobbles and boulders. The dominant biotope consisting of tide-swept and unstable scoured environments, supporting *Balanus crenatus*, crustose bryozoans, *Flustra foliacea* and scour-tolerant hydroids such as *Sertularia argentea.*	SS.SMx.CMx.FluHyd *Flustra foliacea* and *Hydrallmania falcata* on tide-swept circalittoral mixed sediment.
West and north coast of Anglesey.	Along the Skerries and Carmel Head for example all the rocky surfaces on tide-swept sites are covered in a uniformly dense faunal turf comprising abundant *Tubularia indivisa, Dendrodoa grossularia, Halichondria panacea*. In other areas circalittoral tide-swept silty rock with ascidians dominate.	CR.HCR.FaT.CTub.CuSp *Tubularia indivisa* and cushion sponges on tide-swept turbid circalittoral bedrock.
Severn Estuary and Bristol channel.	In general, the subtidal sediment fauna of the Severn Estuary and inner Bristol Channel is species-poor because of the scouring by mobile sediments and the mobility of substrata as a result of a large tidal range and strong tidal streams. The large tidal amplitude and high tidal streams result in areas of sublittoral hard substrata but elsewhere most areas consist of muddy and sandy sediments. Areas are generally too scoured to allow the colonisation of many epibenthic species.	A range of tide-swept biotopes such as *Sertularia cupressina and Hydrallmania falcata* tide-swept sublittoral cobbles or pebbles in coarse sand (IGS.ScupHyd).

(Based on information from Brazier *et al.* (1999); Foster-Smith *et al.* (1999); Moore *et al.* (1998))

4.2.2 Wave (Exposed Coast) Environments

The seabed in the Pembrokeshire area consists of a wide range of substratum including bedrock, cobble and boulders as well as mobile sediments such as gravel and sand (Barne *et al*., 1995; Foster-Smith *et al*., 1999). A geophysical survey undertaken as part of the Wave Dragon EIA found little sediment cover over the majority of the Wave Dragon study area, with scoured bedrock outcrops covering approximately 90% of the study area. The main biotope recorded was SS.SCS.CCS.PomB (*Pomatoceros triqueter* with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebbles). This is a species poor biotope typical of mobile, wave-swept, stony sediments, which with only a limited set of fauna (primarily barnacles, calcareous tubeworms and encrusting bryozoa) are able to tolerate the frequent scouring action to which the sediment is subjected, particularly in winter. Some small deposits of coarse sediments are present within the surveyed area but these are limited to the numerous small gullies and fissures within the rock surface (PMSS Ltd., 2007).

4.3 Fish Assemblages

Information on the distribution and abundance of fish species in the vicinity of potential wave and tidal stream deployment sites in Welsh territorial waters is helpful in identifying the possible extent of exposure of key species to environmental changes associated with device deployment and operation.

A wide range of fish species are recorded in Welsh territorial waters. The distribution and ecology of fish species around the UK coast (including Wales) has been comprehensively reviewed as part of the UK Department of Energy and Climate Change's (DECC) offshore energy Strategic Environmental Assessment programme (DECC, 2009). Other data sources on fish ecology in Welsh waters were reviewed in the Marine Renewable Energy Strategic Framework for Wales (RPS, 2008). The location of spawning and nursery areas for commercially important fish species in Welsh waters can be seen in Table 9. The conservation status of protected species, which have been recorded around Wales, can be seen in Appendix A.

Table 9. Spawning and nursery areas for commercially important fish species in Welsh waters

Area Type	Species	Location
Spawning areas	Herring	South Pembrokeshire
	Cod	North Wales
	Whiting	North Wales and in Cardigan Bay
	Plaice	North Wales, south Pembrokeshire and in Cardigan Bay
	Lemon sole	Western Irish Sea and off south Wales
	Sole	North Wales and north and south Pembrokeshire
	Sprat	Throughout Welsh waters
Nursery areas	Herring	North east Wales
	Whiting	North and south Wales
	Plaice	Throughout Welsh coastal waters
	Sole	Throughout Welsh coastal waters
	Lemon sole	South Wales

(Based on information from: RPS, 2008)

Fish species found in Welsh territorial seas can be broadly split into four groups:

- **Pelagic bony fish (Osteichthyes) species:** Pelagic species are free-swimming fish that inhabit the mid-water column. They tend to have little association with the seabed and as a result are often distributed over widespread and indistinct grounds, often forming large shoals. Pelagic fish, such as clupeids and mackerel are important prey resources for seabirds and marine mammals (DECC, 2009; ICES, 1996). Pelagic species commonly recorded around the Welsh coast are summarised in Table 10.

Table 10. Common pelagic species recorded around the Welsh coast

Species	Common Name
Clupea harengus	Herring
Sprattus (clupea) sprattus	Sprat
Trachurus trachurus	Horse-mackerel (scad)
Scomber scombrus	(European) mackerel
Hyperoplus lanceolatus	Great sandeel
Belone belone	Garfish
Dicentrarchus labrax	Bass

- **Demersal bony fish species:** Demersal species include bottom-dwelling or mid-water fish that have a close association with the seabed. A list of commonly occurring demersal fish groups recorded in Welsh territorial waters can be seen in Table 11.

Table 11. Common demersal species recorded around the Welsh coast

Species Group	Commonly Recorded Species
Flatfish (Pleuronectiformes)	Species recorded in Wales include: ▪ plaice *Pleuronectes platessa*, ▪ dab *Limanda limand*a, ▪ sole *Solea solea*, ▪ turbot *Psetta maxima,* ▪ brill *Scophthalmus rhombus,* ▪ flounder *Platichthys flesus*, and ▪ top knot *Zeugopterus punctatus*
Gadoids	The most abundant and widely distributed gadoids within the region include: ▪ cod *Gadus morhua*, ▪ whiting *Merlangius merlangus*, and ▪ pollack *Pollachius pollachius*. Other species include: ▪ ling *Molva molva*, and ▪ saithe *Pollachius virens*.
Wrasse *(Labridae)*	Wrasse are common inshore in rocky locations with abundant species including: ▪ cuckoo wrasse *Labrus mixtus*, ▪ corkwing wrasse *Crenilabrus melops*, and ▪ ballan wrasse *Labrus bergylta*.
Other species	Other species recorded include: ▪ conger eel C*onger conger*, ▪ gurnards *Dactylopteridae*, ▪ clingfish *Gobiescocidae*, and ▪ gobies *Pomatoschistus* spp, and ▪ sandeel *Ammodtytidae* spp.

- **Diadromous fish species:** Diadromous fish migrate between salt and fresh water and in Welsh waters include the salmon (*Salmo salar)*, sea trout (*Salmo trutta)*, European eel (*Anguilla anguilla)*, river lamprey (*Lampetra fluviatilis)*, sea lamprey (*Petromyzon marinus)*, twaite shad (*Alosa fallax)* and allis shad (*Alosa alosa)*.

- **Elasmobranchs:** Elasmobranchs are fish which posses a cartilaginous skeleton and include sharks and rays. Species occurring in Welsh waters can be seen in Table 12.

Table 12. Elasmobranch species recorded around the Welsh coast

Location in the Water Column	Species	Common Name
Demersal	Lesser spotted dogfish	*Scyliorhinus canicula*
	Bull huss	*Scyliorhinus stellaris*
	Tope	*Galeorhinus galeus*
	Spurdog	*Squalus acanthias*
	Smooth hound	*Mustelus mustelus*
	Starry smooth hound	*Mustelus asterias*
	Nurse hound	*Scyliorhinus stellaris*
	Spotted ray	*Raja montagui*
	Thornback ray	*Raja clavata*
	Painted ray	*Raja microocellata*
	Blonde ray	*Raja brachyura*
	Common skate	*Dipturus batis*
	Angel shark	*Squatina squatina*
	White or bottlenosed skate	*Rostroraia alba*
	Cuckoo ray	*Raja naevus*
	Electric ray	*Torpedo nobiliana*
Pelagic	Basking shark	*Cetorhinus maximus*
	Blue shark	*Prionace glauca*
	Porbeagle	*Lamna nasus*
	Thresher	*Alopius vulpinas*

Some fish species can be considered ‘resident’ in an area all year around although many species undergo migrations on a seasonal basis. Fish can also show considerable movements on a shorter temporal scale, which also influences the fish assemblage of an area (Table 13).

Table 13. Movements and migrations influencing the fish assemblage of an area

Factor	Background Information
Seasonal movements and migrations	Many marine species undergo migrations along the coast or from deeper offshore areas into coastal waters seasonally. Basking sharks, for example, migrate from deeper water off the continental shelf to feed on zooplankton in coastal regions in spring and summer (Sims *et al*., 2003; Southall *et al*., 2005). Many other species such as bass, herring and mackerel also move inshore to spawn and feed in spring and summer (DECC, 2009). Diadromous fish species migrate between marine and freshwater at different times of the year (see section on diadromous fish above).
Daily movements and migrations (Diel)	Some marine species undergo vertical migrations each day. Herring in some areas, for example, move to the surface at dusk to feed (Blaxter and Parrish, 1965).
Tidal induced vertical movements	An important mechanism used by fish during migration is selective tidal stream transport. A fish exhibiting selective tidal stream transport ascends the water column to drift or swim during the favourable tide and descends to the bottom where currents are weaker to hold position during the opposing tide. Selective tidal stream transport is energetically advantageous in areas of strong currents.

4.3.1 Tidal Rapid Assemblages

In general, limited survey effort on fish assemblages in tidal rapids has been undertaken due to the turbulent conditions, turbidity and rough bottom topography, making quantitative fish sampling and also commercial fishing difficult.

Moore (2004) undertook surveys of seabed habitats and communities in four areas exposed to strong tidal currents around southwest and northwest Wales. Lesser spotted dogfish (*Scyliorhinus canicula*), pollack (*Pollachius pollachius*), bib (*Trisopterus luscus*) and various wrasse species were the most abundantly recorded species in areas of strong tidal flow (Appendix B).

The conger eel (*Conger conger*) was recorded abundantly in holes under boulders in deeper water around the tidal rapids of the Skerries and Carmel Head, west Anglesey (where speeds of up to 6.2 knots (approx. 3 m/s) occur on spring floods) (Brazier *et al*.,1999). Significant recreational tope (*Galeorhinus galeus*) fishing grounds have also been reported in tide races and overfalls (Defra, 2006).

Fish species found closer inshore in the vicinity of tidal rapids e.g. around a headland or island (where flows rates are less than a nearby deeper channel) are likely to reflect a typical inshore fish assemblage for that area. The inshore fish assemblage around areas such as Bardsey Island and north Anglesey, for example, consist of common inshore rocky fish such as blennies and wrasse (Jones and Ann, 2008; Morris, 2006; Moore, 2004).

Tidal streams can be important migratory routes for pelagic fish. Castonguay and Gilbert (1995) found that Atlantic mackerel (*Scomber scombrus*) avoid tidal streams in a direction opposed to migration. Herring travelling near the coast have also been recorded taking advantage of tidal currents by swimming with tidal streams when the tide flowed in the migratory direction (flood tide) and by swimming against them when the tide flowed counter to it (ebb tide) (Lacoste *et al*., 2001). Migrating demersal fish such as cod (*Gadus morhua*) have also been recorded making use of tidal streams as part of their migration (Righton *et al*., 2007). Species travelling in tidal streams are therefore likely to be funnelled through tidal rapids.

Fish travelling through tidal streams can be an important foraging resource for marine mammals. Pierpoint (2008) investigated the foraging behaviour of Harbour porpoise (*Phocoena phocoena*) in Ramsey Sound, Wales. The preferred foraging location for the species is high-energy habitat in south Ramsey Sound where a tide race, overfalls and upwelling zones form during the ebb phase. Porpoises are observed feeding repeatedly in the tidal stream above and adjacent to a steep sided trench on the seabed. Tidal currents and the steep walls of the trench are believed to concentrate prey, which is funnelled towards the waiting porpoises. Predatory fish species such as bass are also recorded in tidal rapids and around tidal overfalls (Righton *et al*., 2007). This behaviour is also likely to ambush passing fish travelling in the strong currents.

Fronts found around areas of strong tidal streams and rapids can be important for planktivorous species such as the basking shark (*Cetorhinus maximus*). Shelf sea and headland fronts occur generally in shallow coastal waters where a combination of strong tidal streams, bathymetry and coastal topography combine to cause powerful local mixing and therefore a reduction in stratification (Speedie and Johnson, 2008). This can be exacerbated where the surrounding offshore water is well stratified, leading to sharply defined and thus highly productive frontal systems. Upwelling and turbulence at these fronts can increase primary production, which can aggregate zooplankton and associated predators near fronts (Gubbay, 2006; Pingree *et al*., 1974; Sims *et al*., 2003; MacKenzie and Legget, 1991). These fronts therefore tend to aggregate basking sharks in the vicinity of tidal streams in locations such as Cornwall and the west coast of Scotland (Sims *et al*., 2005; Speedie and Johnson, 2008). Basking sharks are generally recorded in much lower numbers in Welsh waters with very few records of sharks from strong tidal rapid locations.

4.3.2 Wave (Exposed Coast) Assemblages

The fish assemblage found in the vicinity of a wave device is likely to be site-specific dependent on geographic location, seabed type and water depth. The fish assemblage around the Wave Dragon project for example was predicted to have an assemblage consisting of rocky reef species such as gurnard, goby, wrasse and pollack as well as rough ground flatfish species such as the top knot (*Zeugopterus punctatus*). Pelagic species such as mackerel and herring were also expected to be seen in the area seasonally (PMSS Ltd., 2007).

4.4 Ambient Noise Levels

Ambient (or background) noise is a mixture of both natural (e.g. wind noise) and anthropogenic noise (e.g. sonar). Shipping noise is the dominant contribution to ambient noise in shallow water areas close to shipping lanes and in deeper waters. At longer ranges the sounds of individual ships merge into a background continuum. At higher frequencies the dominant noise source is likely to be locally-generated wind noise (Harland *et al*., 2005). Typical sources and frequency ranges for noise recorded in the Irish Sea can be seen in Table 14.

Existing underwater noise levels can serve as a baseline from which to measure potential disturbance impacts associated with tidal turbine and wave devices. Both natural noise sources, and human generated noise, contribute to the baseline noise conditions of a project site (State of Washington, 2006).

A series of ambient underwater noise measurements were undertaken at the proposed Wave Dragon site (prior to instalment of device) on the Pembrokeshire coast during March 2007 (PMSS Ltd., 2007). The maximum variation in the measured noise occurred in the very low frequency range from 5 Hz to 80 Hz, and at high frequencies from 2 kHz to 20 kHz. Low frequency variation is considered to be due to hydrostatic variation in pressure resulting from shipping noise and wave action, whereas the high frequency variation is likely to be surf noise of a moderate sea state.

Table 14. Ambient noise sources in the Irish Sea

Source	Background Information	Indicative Frequency Range
Wind-sea noise	The dominant mechanism for the generation of wind-sea noise at the ocean surface is breaking waves, although this mechanism is still not fully understood.	A number of early observations of ambient noise suggested that between 500 Hz and 25 kHz the ambient noise levels were dependent on wind speed.
Precipitation noise	The noise is generated by a number of effects. These are impact noise as the rain/hail impacts the surface of the water, oscillation of the bubble entrained by the raindrop and large raindrops can cause a more complex multiple bubble and multiple impact noise. At low wind speeds bubble oscillation is the dominant noise source in UK waters while impact noise dominates at higher wind speeds.	Precipitation in the form of rain or hail can cause significant elevation of ambient noise levels in the 1 to 100 kHz region.
Shore and surf noise	Surf noise can make a significant contribution to the ambient noise field in the near shore region out to at least 9 km offshore (Wilson *et al.*,1985). Breaking waves in the surf zone generate sound through a number of different mechanisms (such as pounding, turbulence and sediment disturbance).	The sound sources are all located in the breaking region and radiate from a few tens of Hz to 500 kHz or more.
Sediment transport noise	Sediment transport occurs in areas of strong current or where wave height is large enough to disturb the seabed. The sediment collides with itself and obstacles on the seabed and this generates high frequency noise. The effect can last for periods of less than a minute up to periods greater than an hour, depending on the tidal conditions. Measuring sediment transport noise is very difficult.	The noise is mostly above 10 kHz with peak frequencies at a few tens of kHz.
Commercial shipping	In the Irish sea commercial shipping mostly originates from traffic to and from the major ports of Liverpool, Dublin and Belfast. The other major contributor to shipping movements is the ferry traffic between Britain and Ireland. Other shipping routes link the smaller ports to the main shipping lanes.	Shipping noise is most evident in the 50-300 Hz frequency range.
Leisure craft	Over a number of years there has been a steady increase in the numbers and types of leisure craft in use around the UK. There has also been a steady increase in the engine power available to such craft. This has resulted in a considerable increase in underwater noise levels produced by this class of sound source and in holiday areas this can be the dominant sound source through the summer months.	This noise typically dominates the signature in the region 5-25 kHz.
Industrial noise	Offshore industrial noise includes the noise generated by the operation of offshore wind farms, oil and gas rigs and offshore construction noise.	Various.
Military noise	The military can generate underwater noise by the use of ships, aircraft, explosives and/or active sonar transmissions (see below).	Various.
Sonar	Sonar is widely used by leisure, fishing and commercial vessels and there is also some limited military usage within the Irish Sea. Typical sonars currently in use are: Echosounders, Fish-finding sonars, Fishing net control sonars, Acoustic modems, Air guns for seismic surveys and reservoir monitoring and Military sonar.	Echosounder 26kHz-300kHz; Air gun; centre frequency between 50-100Hz. Military sonar 1-300kHz
Fishing activity	Commercial fishing can make a contribution to ambient noise in a number of ways. Apart from the contribution by the vessel noise and the use of sonar to find fish and monitor nets, the most significant contribution is trawl noise, particularly from bottom trawls. The sound of chains and rollers being dragged across the seabed can often be heard several miles from the activity.	Less than 1 kHz.
Biological Noise	The most vocal of marine species are the cetaceans, which produce sounds through echolocation and vocalisation.	Species to be found in the Irish Sea can produce sounds over the range 2-200 kHz e.g. harbour porpoise echolocation-130kHz.

(based on information from Harland *et al*., 2005)

The data over the frequency range from 200 Hz to 1 kHz was extremely consistent. Over the frequency range from 1 Hz to 175 kHz, the overall ambient sound levels varied from a minimum of 104 to a maximum of 131 dB re. 1 µPa Root Mean Square (RMS).

At other shallow water inshore sites around the UK similar measurements have been recorded with RMS Sound Pressure Levels that varied from 90 to 155 dB re 1 µPa (Nedwell *et al*., 2003b). It should be noted, however, that the noise expressed in this form is dominated by the low frequency components of the noise spectrum.

4.5 Environmental Factors Contributing to Collision Risk

The risk of collision for fish with wet renewable devices will be modified considerably by a range of environmental factors. The expected level of modification from different environmental factors is summarised in Table 15.

Table 15. Environmental factors contributing to collision risk

Environmental Factor	Background Information	Expected Contribution to Collision Risk	Confidence
Fish distribution and abundance	The occurrence and overall abundance of a fish species in the vicinity of a device will greatly influence the level of collision risk	High	High
Position in water column	The position a fish is normally associated with in the water column e.g. pelagic, demersal will influence the chance of encounter with a device. A large proportion of intake fish mortalities are attributed to water column (pelagic) oriented, schooling fishes that are not associated with demersal habitats for example (Helvey, 1985)	Medium	Medium
Water turbidity	The amount of suspended solids in an area will influence water clarity and fish vision by influencing the distance at which fish are able to see a device. Water clarity is likely to vary greatly seasonally with storms and plankton levels)	Medium	Medium
Flow rates	Strong tidal flows and currents (e.g. on a spring tide) are likely to reduce the time a fish has to avoid a device and influence the speed at which they can swim away from it.	Medium	Medium
Time of day (light)	The very low levels of light associated with night will reduce the ability of a fish to see a device and undertake any short range evasion. Fish entrapment in intakes for example is generally higher at night than during the day (Helvey,1985).	Medium	Medium
Season (fish movement)	Fish, which are resident in an area year round, are more likely to recognise and learn to avoid a device than seasonal visitors.	Medium	Medium
Season (light)	Light levels will vary seasonally with reduced light in winter months.	Low	Medium
Ambient noise	Ambient noise will influence the extent that a fish can hear a device and the subsequent extent and type of any long range avoidance shown.	Medium	Medium

4.6 Summary

Wave and tidal devices are deployed in dynamic environments which show considerable variation both temporally and spatially in physical and ecological features. Some of these features have the potential to influence the level of collision risk through modifying the level of exposure as well as the avoidance and evasion response of a fish.

5. Potential Long Range Avoidance Behaviour

Long range avoidance in the context of this report is considered to be avoidance at distances further away than where a visual response can be undertaken i.e. through noise and vibration cues. Limited research on the behavioural reactions of fish towards wave and tidal stream device noise has been undertaken. However, there is a wide range of information available on fish behavioural responses to comparable stimuli and more general scientific studies on fish physiology and behaviour.

5.1 Underwater Noise and Vibrations

Sound or noise is produced by a vibrating source and consists of pressure variations that propagate in a longitudinal soundwave. The level of sound at a particular point is a function of ambient background noise, the proximity to anthropogenic noise sources, the level of sound generated by the source (source level) and the attenuation of sound as it propagates away from the source (transmission loss). This loss is a function of several factors, including ground geology, temperature gradients, water depth, currents, ambient noise, acoustic wavelength, and the reflective properties of the bottom and surface conditions. As a result, there is a relatively high degree of uncertainty associated with the prediction of underwater sound propagation.

The source pressure levels for the activities associated with tidal turbine and wave devices are generally lower than other anthropogenic noise sources in the marine environment, including shipping, dredging, piling and seismic surveys. For example, pile driving has sound pressure levels which range from 131 dB re: 1 µPa to significantly greater than 192 dB re: 1 µPa with an average of approximately 190 dB re: 1 µPa. The maximum estimated source level of a single tidal turbine device from existing available information is 175dB re. 1µPa-1m (Section 3.2.2). The limited available information on noise generated by wave devices indicates that these are less noisy (generally in the region of 140dB re. 1µPa-1m; Table 5), with maximum noise produced as a result of waves interactions with the body of the device at source levels in the range of 164dB re. 1µPa-1m (Section 3.3.2).

5.2 Propagation of Noise

In order to provide an objective and quantitative assessment of the degree of any environmental risk to fish behaviour it is necessary to estimate the sound level as a function of the range and distance from the source. For this, it is necessary to know the level of sound generated by the source and the rate at which the sound decays as it propagates away from the source (Nedwell and Edwards, 2004).

Transmission loss of noise generated by tidal turbine and wave devices can be characterised by two simple models. Spherical spreading is considered representative of the propagation of noise from a point source, whereby the noise source radiates sound equally in all directions and the sound level is reduced by approximately 6dB for each doubling of distance from the source (State of Washington Department of Transport, 2006). In shallow waters (<15m), the transmission loss of 0.15dB per metre measured by Nedwell *et al*., (2003c) in Southampton Water is considered an appropriate method of predicting the propagation of noise.

5.3 Fish Hearing

Hearing thresholds are the minimum sound pressure levels at which an organism can hear sound. The hearing sensitivity and frequency range of fish varies considerably with different species, with the ability to hear being dependent on the physiology of the species. Typically fish sense sound via particle motion in the inner ear, which is detected from sound induced motion in the fish's body. Most teleost (bony) fish possess a gas filled swimbladder, which is sensitive to the pressure component of a sound wave and converts the pressure waves to vibrations. Detection of sound pressure is restricted to those fish which have gas-filled swim bladders, however fish without swim bladders can detect particle motion. The anatomy of the swimbladder and its proximity to the inner ear determine the hearing sensitivity of fish. Close coupling between swimbladder and inner ear allows vibrations received by the swim bladder to be transferred to the inner ear, increasing sensitivity.

The lateral line canal consists of a series of pores located along the head and flank of a fish which each contain a long neuromast responsive to near field disturbances in water (Sand 1981). Lower frequencies (10-30 Hz) can be perceived through the lateral line mechanoreceptors, which can be responsive to frequencies as high as 300 Hz (Popper and Fay 1993; Coombs and Montgomery, 1999). Sand (1981) confirmed that the trunk lateral line is an acutely sensitive vibration (particle motion) detector. This is essential for fish to be able to detect currents, maintain position in a school, capture prey and avoid obstacles and predators.

Fish can be divided into three broad groups with low, medium or high hearing sensitivities (Nedwell *et al*., 2004c). Those fish with specialist structures have been classified as 'high' sensitivity; non-specialists with a swimbladder are 'medium' sensitivity and non-specialists with no swimbladders are termed 'low' sensitivity. Hearing specialists, include herring. Fish species with medium auditory sensitivity include salmon and European eel. Fish that do not have a swimbladder, such as elasmobranchs, flatfish and lampreys, have low auditory sensitivities. Table 16 describes the hearing sensitivities of various fish species within each of the fish functional groups described in Section 4.3.

Results of hearing examinations can be graphed to produce an audiogram of spectral sensitivity to sound, to graphically illustrate ability to hear sounds over a range of frequencies and intensities. Most audiograms use the reference level of dB (re. 1 µPa). Published curves show that fish fall into two distinctive groups. Those that hear a narrow frequency range (up to around 500 Hz) such as salmon, dab (*Limanda limanda*) and cod, and those that hear a wide frequency range (up to 4000 Hz).

Most commercial fish have a hearing capability extending from a few hertz (Sand and Karlsen 1986) to possibly tens of kilohertz (Astrup and Mohl 1993; Dunning *et al*. 1992). Acute infrasound hearing has been confirmed for cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) (Sand and Karlsen 1986, Karlsen and Sand 1991) and elasmobranchs also respond to low frequency sound just beyond the infrasound limit (40-800 Hz; Myrberg, 2001).

Table 16. Hearing sensitivities of different fish functional groups

Functional Group	Hearing Sensitivity	Example Fish Species	Hearing Structures and Thresholds
Pelagic (bony)	High	Atlantic herring (*Clupea harengus*)	Swim bladder terminates within the inner ear, conferring good hearing ability (Enger, 1967). Herring have a hearing threshold of about 75 dB re 1µPa at 150 Hz with a bandwidth to about 1.5kHz (Enger, 1967; Blaxter *et al*., 1981).
	Medium	Bass (*Dicentrarchus labrax*)	Bass have a hearing threshold of about 98 dB re 1µPa at 100 Hz (Nedwell *et al*., 2004c).
Pelagic (elasmobranch)	Low	Basking shark (*Cetorhinus maximus)*	No swimbladder and relatively insensitive to noise.
Demersal (bony)	Medium	Pollack (*Pollachius pollachius*)	The hearing threshold of pollack is around 81 dB re 1µPa at 60-160 Hz frequency range.
	Low	Wrasse (*Thalassoma bifasciatum*)	The hearing threshold of wrasse is around 100 dB re 1µPa at 300 Hz frequency range.
Demersal (elasmobranch)	Low	Little skate (*Raja erinacea*)	These fish have a low sensitivity to sound - no swim bladder. The hearing threshold of little skate is around 122 dB re 1µPa at 200 Hz (Casper *et al*., 2003).
Diadromous	High	Twaite shad (*Alosa fallax)* and allis shad (*Alosa alosa)*	Although no known auditory information is available for shad species known to occur in Welsh waters, clupeids are considered hearing specialists. They have an efficient linking between the otolith and swim bladder, which takes the form of a gas duct.
	Medium	Atlantic salmon (*Salmo salar*)	Poor hearing ability - swim bladder disconnected from skull/hearing system. Salmon have a minimum hearing threshold of around 95 dB re 1µPa at 160 Hz with a 10 dB bandwidth of about 200Hz (Hawkins and Johnstone, 1978).
	Low	Lamprey	Lampreys are demersal and, although no known auditory information is available, are expected to have low hearing abilities.

(Source: Nedwell *et al*., 2004c)

The sensitivity of particular fish to noise and vibration will therefore depend on (Vella *et al*., 2001):

- Presence of a swimbladder. Fish with swimbladders will be more sensitive than those without. Teleost fish are generally more sensitive than elasmobranch (shark and ray) species without;
- The size of the swimbladder, larger fish whose swimbladders resonate at lower frequencies will be more sensitive than smaller fish whose swimbladder size is less. So that small fish such as gobies will be less sensitive than larger fish;
- Hearing structures and audible threshold; and
- The resonance frequency of the otolith system; there is some evidence that the larger the otolith the lower the frequency that it will resonate at.

5.4 Behavioural Response of Fish Towards Devices

Richardson *et al*. (1995) defined four zones of noise influences, depending on the distance between source and receiver. These are as follows:

- Zone of hearing loss, discomfort or injury- the zone within which hearing or other severe damage results;
- Zone of masking - the region within which noise is strong enough to interfere with detection of other sounds, such as communication or echolocation clicks;
- Zone of responsiveness - the region in which the animal reacts; and
- Zone of audibility - the area within which the animal is able to detect the sound.

Nedwell and Edwards (2004) have developed a generic dB scale, which enables better estimates of the effects of sound on marine species to be made. In their dB_{ht} (Species) scale a frequency dependent filter is used to weight the sound. The suffix ‘ht’ relates to the fact that the sound is weighted by the hearing threshold of the species. A set of criteria based on the use of the dB_{ht} (species) was proposed by Nedwell *et al*. (2007) that allows the likelihood of behavioural effects and damage to hearing to be assessed for a wide range of species (Table 17). Of significance for this assessment, is the conclusion that at $90dB_{ht}$ (species) and above there will be a strong avoidance reaction by all individuals of that species, and that below 50 dB_{ht} (species) there will be a mild reaction by a minority of individuals.

Table 17. Criteria suggested for the effects of underwater noise on marine mammals and fish

Level in dB_{ht} (species)	Effect
Less than 0	None
0 to 50	Mild reaction by minority of individuals
50 to 90	Stronger reaction by majority of individuals but habituation at lower levels may limit effect
90 and above	Strong avoidance reaction by all individuals
Above 110	Tolerance limit of sound; unbearably loud
Above 130	Possibility of traumatic hearing damage from single event

(Source: Nedwell *et al.,* 2007)

Device characteristics for wet renewable devices are summarised in Section 3. The noise generated by a device will be an accumulation of the different sources that produce sounds such as blades moving through equipment, rotors, hydraulic components, cavitation, wave and water impacts on device etc. Most of the noise produced will be underwater and will be transmitted directly to the water column and to the substratum/sediment via sound propagation and the mooring device. The submerged devices that use pressure differentials do not have rotational equipment and are predicted to be quiet.

The maximum distance that a tidal energy device would result in a behavioural reaction in fish has been predicted using the transmission loss models described in Section 5.2. The maximum estimated source levels of these devices are described in Section 3. The results for a tidal turbine device and wave device are presented in Tables 18 and 19 respectively.

Table 18. Maximum distances (m) of behavioural responses to a single tidal turbine device

Fish Hearing Sensitivity	Deep Water[1]		Shallow Water[2]	
	$50dB_{ht}$	$90dB_{ht}$	$50dB_{ht}$	$90dB_{ht}$
High	316	3	333	67
Medium	32	0	200	0
Low	2	0	33	0

[1] Using spherical spreading model.
[2] Using Nedwell *et al*. (2003c) field-based model.

Table 19. Maximum distances (m) of behavioural responses to a single wave device

Fish Hearing Sensitivity	Deep Water[1]		Shallow Water[2]	
	$50dB_{ht}$	$90dB_{ht}$	$50dB_{ht}$	$90dB_{ht}$
High	89	1	260	0
Medium	9	0	127	0
Low	1	0	0	0

[1] Using spherical spreading model.
[2] Using Nedwell *et al*. (2003c) field-based model.

Hearing specialists, such as herring, would exhibit mild avoidance to a single tidal turbine device, as characterised by the $50dB_{ht}$ criterion level, around 300m from the point source of noise. Medium hearing sensitive fish, such as salmon, would show signs of minor avoidance around 30m and 200m away in deep and shallow water respectively. Low sensitive fish, which include elasmobranchs, flatfish and lampreys, would only have a minor avoidance reaction to the device within a few metres in deep water and around 30m in shallow water.

The maximum source levels of wave devices are lower than that of tidal turbines and as such the distances that would invoke a minor avoidance response in fish is less. Hearing specialists would show a minor response up to around 90m and 260m from a single wave device in deep and shallow water respectively. Medium sensitive fish would only show minor behavioural changes within around 10m in deep water and 130m in shallow water of the noise source. The effects on low sensitive fish are far lower, with mild reactions only occurring a few metres away in shallow water and within around 30m from the source in deep water.

A strong avoidance reaction, as characterised by the $90dB_{ht}$ criterion level, to these renewable energy devices would only be evident in hearing specialists. A single tidal turbine would result in a strong behavioural response within 3m in deep water and 67m in shallow water. Wave devices generate less operation noise and would only result in a strong reaction in hearing specialists up to 1m away from the noise source in deep water.

This assessment does not take into account ambient noise levels, which are likely to be relatively high in tidal stream and open coastal environments (see Section 4.4). Ambient noise will influence the extent that a fish can hear a device and the subsequent extent and type of any long range avoidance shown. Both wet renewable devices and background noise have broadband frequency ranges, with peaks occurring in different parts of the spectrum. It is, therefore, difficult to predict the response of fish to these broadband noises and whether they will be able to discern the difference between additional anthropogenic and existing background noise. However, taking account of the measured ambient noise measurements that were made on the Pembrokeshire coast prior to the instalment of the Wave Dragon device (Section 4.4), it is possible to predict the maximum distance that source levels of a wet renewable device would reduce to these background levels (i.e. the distance at which a device might exceed background noise) in both deep and shallow water using the transmission loss models described in Section 5.2.

A tidal turbine device would exceed background noise levels at less than 126m in deep water and 280m in shallow water. A wave device would exceed ambient levels at around 35m from the device deep water and 207m in shallow water. In other words, at greater distances, fish are unlikely to be able to discern between the noise generated by the device and existing ambient underwater noise from waves, surf, shipping etc. At shorter distances from the device, the long range avoidance reactions that were predicted above in Tables 18 and 19 would come into play.

It is also important to note that the cumulative noise of these wet renewable devices will increase where a number of arrays are deployed.

While any avoidance reaction may be considered to be a positive impact, as it will reduce the risk of fish collision, there may also be associated negative impacts. Deterrence resulting from noise may exclude fish populations from areas of suitable habitat leading to a reduction in the resources that are available to the population. This includes opportunities for feeding, reproduction and for refuge. Piscivorous fish can be directly impacted by sound that scares prey fish away. Noise deterrence could also cause fish to avoid certain routes of travel and migration.

Negative impacts caused by additional noise may include the masking of sound information from the environment and from other fish, hindering communication. However the environments in which the devices are deployed (tidal rapids, high wave energy environments) are likely to have high levels of background noise and it may be that the added sounds are not significant, compared to these. The level of this noise will depend on local natural conditions, the type of device and the number of devices deployed so that impacts should be assessed on a case-by-case basis.

5.5 Summary

Currently there is a lack of understanding on the noise levels produced by devices and the effects that these will have on fish.

The noise levels created by the operation of wave and tidal energy devices are not considered to be at a level that would cause physical damage to fish. Data on operational noise levels are unavailable for most devices but it is likely that they will only be discernable from existing background noise beyond around a few tens of metres to hundreds of metres distance, depending on the type of device and whether it is positioned in shallow or deep water. At distances where the noise generated by the device is higher than ambient levels, fish may exhibit 'long range' behavioural avoidance, depending on the hearing ability and sensitivity of the fish. This could possibly lead to a reduction in fish populations in certain areas. At even shorter distances, it is possible that the additional noise may act as a deterrent to fish approaching the devices, so reducing collision risk with turbines and other mechanical parts of devices.

Fish hearing and responses will vary between species so that impacts should be assessed for the common species found where the devices are to be deployed. Such assessments should take into account common fish that may be resident in the area and also rare species and those that may have important migrations pathways within the area. The latter include species such as salmon, shad, lamprey and eel that migrate to and from rivers. As these fish use different environments at different stages of their life, populations are particularly susceptible to declines from cumulative impacts.

6. Close Range Evasion

Close range evasion of a wet renewable device will be dependant on the visual acuity of a fish, fish avoidance behaviour and if the device has the potential to act as a Fish Aggregating Device (FAD). Information specifically for WEC and TEC is limited but more detailed information exists for comparable stimuli as well as more general scientific studies on fish physiology and behaviour.

6.1 Fish Vision and Responses to Objects

Marine animals in high latitude coastal areas have to contend with variable and often poor visual conditions, resulting from fluctuations in ambient light levels and in the light transmission properties of the water. For some predatory fish, vision is particularly important in the location, identification and selection of prey (Brawn, 1969), and variations in the visual conditions, both diurnal and seasonal, may control the time available for feeding by affecting prey vulnerability and visibility. The visibility of an object depends upon the ability of the viewing animal to detect a contrast between the object and the background. This contrast may be of brightness, colour, texture or pattern, or combinations of these characteristics.

The behavioural requirements of a species influences the level of visual acuity and sensitivity recorded in a species. Most species have adequate visual acuity to detect predator attacks as long as light permits with spectral sensitivity being heavily dependant on the depth that they occupy. Most fish occupying the relatively shallow waters have spectral sensitivities extending from 400 to 650 nanometres and teleost fish have cones in their retinae providing colour vision (Bone *et al*., 1995). Fish have well developed eyes and the variety of colour patterns and specific movements that they display invites comparisons between the most visually orientated species among birds and mammals (Guthrie and Muntz, 1993).

Anthony (1981) investigated visual contrast thresholds in cod. Measurements were made of water clarity and downward directed radiance at 25 m depth in Loch Torridon, to investigate the photic environment of Torridon cod. Bringing together these figures and cod contrast thresholds in an underwater visibility equation enabled predictions to be made of the potential range of visibility to cod of objects of prescribed contrast.

Fish could see objects of high contrast in good visibility as far away as 20m, being reduced to about 8m for objects of low contrast. In very poor visibility sighting distance was reduced to less than 5m. These values were predicted for well lit conditions as would occur throughout an average day at 25 m depth. The predictions did not take into account relative movement of the object or object size. Whilst these figures refer to daylight conditions, the cod, and many other fish, are often active over the dusk and dawn where sighting distances were found to be reduced further (Table 20).

Table 20. Environmental factors influencing fish vision

Environmental Factor	Evidence of Fish Response
Light levels (influenced by the time of day, season and depth). At night for example, structures may be visually undetectable and provide little or no opportunity for a behavioural response.	In the controlled environment of tank experiments, using herring, cod, haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*), herring were shown to avoid stationary nets placed across the tank in daylight but started to swim into them at a threshold light intensity of about 0.006 mc (metre candles) (Blaxter and Parrish, 1965). More recent experiments quantified the light level thresholds for the visual reactions of mackerel to monofilament netting were –1 log lux and – 4 log lux (1 – 0.001 lux) for multifilament (Cui and Wardle, 1991). At light levels below these thresholds, fish were unaware of the netting barriers and swam straight through them. In laboratory simulations of the capture of fish in a codend, juvenile walleye pollock (*Theragra chalcogramma*) were able to maintain position, swimming clear of netting panels in nets at light levels simulating daylight at depth in clear oceanic water (0.5µmol photons/m^2/s). If light intensity was dropped to less than 0.002µmol photons/m^2/s, fish became entrained in the mesh (Olla *et al*., 1997).
Suspended sediment concentrations (turbidity).	Johnson *et al*. (1976) reported marked increases in the entrapment of intake-associated species during storms, which may be related to reduced water visibilities prevalent during inclement weather. In poor visibility conditions, fish have been observed only just avoiding collision with an obstacle, whereas in good visibility conditions, fish react further away from trawl otter boards and swim over/under/around trawls (Wardle, 1986).

6.2 Fish Speed and Avoidance Response

Large variations in swimming ability exist among fish. The swimming performance of fish is characterised by the relationship between swimming speed and time until fatigue, and was classified by Webb (1975) and Beamish (1978) into three categories: sustained, prolonged, and burst swimming. Sustained swimming is a speed maintained by fish for more than 200 min without fatigue. Prolonged swimming speed can be maintained between 20 s and 200 min, and ends in fatigue. Burst speed is the highest swimming speed maintained for less than 20 s and is performed anaerobically. Swimming performance depends on numerous biological and physical factors including body shape, muscle function and in ectotherms the swimming speed is temperature dependant. Absolute swimming speed also increases with fish size. Prolonged and burst swimming speeds for saithe (*Pollachius virens*), mackerel and herring can be seen in Table 21.

Table 21. Maximum prolonged swimming speeds and burst speeds

Species Name	Common Name	Length (m)	Prolonged Speeds B.L.S^{-1}	Prolonged Speeds m/s	Burst Speed B.L.S^{-1}	Burst Speed m/s
Pollachius virens	Saithe	0.5	3.4	1.7	6.5	3.25
Pollachius virens	Saithe	0.25	4.9	1.225	8.7	2.175
Scomber scombrus	Mackerel	0.31	4.5	1.4065	18	5.5
Clupea harengus	Herring	0.25	5.5	1.375	No info. available	No info. .available

B.L.S^{-1} = body lengths per second

(Based on information from: Videler and Wardle, 1991)

Quantitative information on burst speeds for many species is limited. Therefore in order to inform the evasion section of the evaluation phase a qualitative classification of burst speeds has been devised (Table 22). The classification is based on what available information on burst speeds is available as well as life history traits which influence fish speed and relative sizes of the fish.

Fish may avoid collisions with marine renewable devices through "startle" (or "C-start") responses. The C-start response can be initiated by transient sound, visual or touch stimuli. For example, herring escape behaviour is a reflex response stimulated by transient sound stimuli, detected in the labyrinth (inner ear) (Blaxter *et al*., 1981). ‘Visually looming’ objects will also trigger evasion behaviour in most if not all species, with a greater response rate to edges moving horizontally rather than vertically (Wilson *et al*., 2007). The behavioural response to an approaching net is to turn and swim in the direction of the moving net, using the minimum swimming speed to avoid the object (resulting in them ‘holding position’ at the mouth of the net) whilst reserving energy for an escape response. However, on exhaustion, the fish turn and allow the net mouth to overtake them (Wardle, 1986; Walsh and Godo, 2003; Breen *et al*., 2004; Jamieson, 2006 cited in Wilson *et al*., 2007).

Table 22. Burst speeds of fish for different functional groups

Functional Group	Burst Speed Classification*	Examples
Pelagic (bony)	Fast	Predatory fish such as mackerel and bass
	Medium	Planktivores such as herring and sprat
Pelagic (elasmobranch)	Fast	Predatory sharks such as blue sharks, mako and porbeagles
	Medium	Basking sharks
Demersal (elasmobranch)	Medium	Skates and rays
	Slow	Bottom dwelling sharks such as dogfish and smooth hound
Demersal (bony)	Medium	Gadoids such as cod, pollack and saithe. Flatfish.
	Slow	Conger eels, gurnard, pipefish, clingfish, blennies, gobies
Diadromous fish	Medium	Salmon, shad
	Slow	Lamprey

* Table is based on adult fish, burst speeds will be less for juveniles as absolute swimming speed increases with fish size.

Fish are therefore likely to demonstrate evasion responses to moving turbine rotor blades, although the quality of the stimulus will be related to the axis of the turbine (e.g. horizontal axis turbines only providing a “good looming image” for part of circular trajectory). However, Wilson *et al*. (2007) notes that the escape responses of schooling fish species may not be as effective in avoiding collision with turbine blades as solitary fish, as although initiation of the response may move fish nearest the blade away, other fish in the school may be carried into the blade.

6.3 Observational Data of Fish Behaviour in Response to Turbine Devices

Some preliminary findings documenting the behaviour of fish towards marine renewable devices comes from Verdant Power’s Roosevelt Island Tidal Energy (RITE) Project, which has six Kinetic Hydropower System (KHPS) turbines in New York City’s East River, along the eastern shore of Roosevelt Island. A recent draft kinetic hydropower pilot licence application (Verdant, 2008b,c) presents the preliminary results of the Fish Monitoring and Protection Plan (FMPP) implemented to gather information on fish populations and behaviour within the turbine deployment area.

Specifically, the project utilised Biosonic split-beam acoustic transducers in fixed positions to provide information on fish spatial distribution and abundance around the array of six turbines, as well as to evaluate fish behaviour (direction and velocity of swimming) near the turbines. These acoustic surveys are currently being supplemented with an experimental DIDSON system, which uses high definition sonar to observe near-field fish interactions with the turbines, although this aspect of the study is ongoing and no results are available yet (Trey Taylor, Verdant Power, pers. comm.).

From analysis of the Biosonic acoustic data collected between January 2007 to May 2007 and June 2007 to March 2008, the initial findings regarding the fish populations and behaviour in the vicinity of the six turbines indicated that:

- There was seasonal variation in fish abundance in the deployment area, with increased abundance between October and December;

- Daily densities of fish were quite low (mean fish per day per frame = 330; range 16 – 1,400) and populations were dominated by smaller fish less than 2.5 ft (approx. 0.76 m);
- Most fish were observed inshore and not in zones occupied by the turbines;
- The greatest movement of fish was observed in the direction of the tide or during slack tide when water velocities were < 0.8 m/s and when the turbines were non-operational;
- Fish abundance in the turbine ‘impact zones’ was a small percentage of the total population, regardless of season; and
- Fish movement during turbine operation is noted to occur predominately in ‘non-impact’ zones, possibly indicating turbine avoidance behaviour, although a similar distribution was observed during periods when turbines were *in situ* but not operational.

The report concludes that the fish zonal location data confirms that fish tended to swim in the inshore (slower velocity, non-turbine) zones of the array area, minimising opportunity for harm. The report also notes that there has been no observed evidence of increased fish mortality or injury, nor any irregular bird activity observed (presumably suggesting no increased predation of disorientated / injured fish) during any of the three turbine deployment periods. Analysis of the results of the new FMPP study protocols developed for deployment period 3 is still ongoing and the data will be provided as a supplement to the draft licence application.

Additional observational data on fish behaviour is available from a study, which monitored fish passage through an Archimedes Screw Turbine (hydropower turbine) on the river Dart (FISHTEK, 2007). Although the study was designed to assess the damage incurred by trout and wild smolts passing through the hydropower device, data was also obtained on fish behaviour. For example, smolt passage through the turbine intake, the screw turbine itself and the outflow channel, was monitored using underwater cameras. Analysis of the footage at the intake showed that larger fish were able to swim actively against the flow for several minutes before passing into the device, whilst the largest fish (over 40cm) resisted entering the device for long periods and had to be “encouraged” into the turbine. The authors concluded that large fish swimming downstream had the ability to turn around and swim away from the fast flowing water intake (head of water 4.5m, mean flow at the study site 8.4m^3/s, water velocity through the turbine approx. 1 m/s), enabling then to avoid passage through the turbine.

6.4 Potential Evasion of Tidal and Wave Devices

Fish would be expected to swim with the flow through strong tidal rapids (using the flow to their advantage) using sustained swimming. Water clarity in tidal rapids is generally low, but it would be expected based on the literature that a fish would be able to initiate an evasion response on visual stimuli from about 5-10m from a device in average visibility. Burst swimming would then be used by a fish to try to avoid the device. The direction that a fish might swim when a startle (‘C-start’) response is initiated is difficult to predict. It is possible that fast swimming fish could turn around and try to swim against the flow to avoid the device. Fish could also try and swim at an angle to try and get around the device. These ‘near field’ responses would need to be the focus of field observations and tank trials using smaller scale models.

Maximum swimming speeds vary significantly between species and with individual size of fish. Adults of pelagic species such as mackerel exhibit burst speeds of up to 5m/s, but the majority of demersal species would have burst speeds of around half of this value (Section 6.2). Small fish (including juveniles of larger species) generally have lower burst speeds (which are a function of overall body length).

Relatively few UK fish species would be capable of actively swimming upstream against the high flows associated with tidal stream environments or wave surge environments. However, fish would be able to actively swim against the generally lower flows associated with offshore wave deployment environments. Depending on the size of device it may be possible for fish to manoeuvre round the side of a device although given the short distance over which visual cues might operate this may not be feasible for fish encountering tidal stream devices in high flow environments. For example a fish moving passively with a tidal flow of 2.5m/s towards a tidal stream device visible at a distance of 5m would have approximately 2 seconds to swim around the device. For a fish approaching near the centre of a 15m diameter blade this would require it to travel a distance of more than 7.5m in that time period. This is beyond the ability of most fish. There are no published direct observation studies on the near-field interaction of fish with wave or tidal stream devices and it remains unclear how fish might respond on encountering such devices, for example whether they might swim towards the tip of a blade or towards the centre. It is noted that fish swimming towards the outer edge of tidal turbine blades will potentially expose themselves to greater risk of collision injury compared to fish swimming towards the proximal part of a blade (which is travelling relatively slowly).

As discussed in Sections 4.5 and 6.1 low light levels and poor visibility are likely to increase the potential for collision as fish vision and any subsequent evasion response are likely to be reduced substantially.

Short range evasion of wave devices is in the most part unnecessary given the relative difficulty of getting trapped in reservoirs or collectors and slow movement of parts.

6.5 FAD Characteristics of the Device

Fish aggregations have been observed around numerous objects, including; vessels (Røstad *et al*., 2006); structures associated with marinas and pontoons in urban areas (Clynick, 2008); net cages used for aquaculture (Oakes and Pondella, 2009); sunken vessels (Arena *et al*., 2007); the piles of off-shore wind farms (Wilhelmsson *et al*., 2006; Linley *et al*., 2007) and underwater depuration systems (Cattaneo-Vietti *et al*., 2003).

The literature on this subject is dominated by studies of FADs and artificial reefs. FADs are floating or moored devices placed in the water to attract fish (see reviews; Castro *et al*., 2002; Dempster and Kingsford, 2004). These exploit the tendency of fish to aggregate under and around floating objects and are mostly used in tropical and semi-tropical waters by fishers to concentrate pelagic fish for capture (Ibrahim *et al*., 1996; Deudero *et al*., 1999). The scientific literature reflects this bias with research mostly conducted in the tropics and on large species, with high commercial value, such as tuna (Dempster and Kingsford, 2004).

As fish are attracted to solid man-made structures placed on the seabed (Seaman and Sprague, 1991) artificial reefs are often deployed to enhance fisheries (Sayer *et al*., 2005). Structures constructed for other purposes such as oil platforms and breakwaters (Helvey, 2002; Ponti *et al*., 2002; Soldal *et al*., 2002) can also serve as new habitats for fish. Structures can change local abiotic conditions allowing species assemblages to form that are different from natural communities present. The monopiles of wind turbines, for example, become encrusted with epibiota such as mussels and barnacles (Linley *et al*., 2007). These modify the habitat and provide food and shelter for fish and invertebrate species (Wilhemsson and Malm, 2008), leading to increased fish abundance and enhancement of the local seabed habitat (Wilhelmsson *et al*., 2006).

Despite the caveat that studies typically have considered structures in marine environments with lower flow rates, it is possible that fish will be attracted to, and aggregate at, structures associated with energy generating devices (Probert and Mitchell, 1983). The composition of fish assemblages attracted to such devices may be variable as fish assemblages associated with oil platform structures have been shown to alter daily and seasonally and even to vary according to the size of the platform studied (Soldal *et al*., 2002).

To determine the degree to which wave energy devices would act as FADs it is useful to identify the factors that attract fish to aggregate around devices. Freon and Dagorn (2000) identified a number of hypotheses to explain the association with floating objects, these include;

- Shelter from predators;
- Concentration of food supply;
- Spatial reference in otherwise featureless environments;
- Resting;
- Indicators of other characteristics, such as productive areas; and
- Meeting points.

The presence and identity of encrusting epibiota have, for example, been demonstrated to influence the abundance and diversity of fish attracted to marina structures (Clynick *et al*., 2008). In other cases, while fish have been shown to be feeding on some epibiota, they are not the primary attractant (Ibrahim *et al*., 1996).

Displacement experiments indicate that fish return to FADs from greater distances, and in spite of currents, than the use of olfactory and vision cues would allow (Dempster and Kingsford, 2004). The authors suggest that fish might be using sound or vibrations from associated fish and the FAD (Dempster and Kingsford, 2004). This suggests that turbine noise and vibrations can act as an attractant. However it is likely that fish have thresholds above which noise is a deterrent (as used in power stations cooling intakes) and that fish may avoid the noisiest areas (See Section 5).

Whenever water flows past a structure, velocity gradients are created which form vortices (Liao, 2007). Fish show a variety of responses to turbulence (defined as chaotic, vortical flows of multiple strengths and sizes superimposed onto a mean flow velocity (Warhaft, 2002). Depending on hydrodynamic conditions, fish can be attracted to or repelled by the turbulence

(Liao, 2009). Extremely high levels of shear stress can damage fish (Odeh *et al*., 2002) and turbulence can increase the energy costs of swimming (Enders *et al*., 2003). Alternatively, altered flows that remain steady, or maintain an aspect of predictability, can be exploited by swimming fish to reduce locomotion cost. Fish can seek refuge from main currents by 'flow refuging' behind structures (Webb, 1998). Most of the work to date on micro-habitat selection in regard to current-swept regions has been based on studies of freshwater species and the available literature on currents, flow refuges, and marine species is very limited (Liao, 2007). In tidally swept locations bentho-pelagic fish such as cod, have been found to use sand ripples as flow refuges to hold station, reducing energetic costs (Gerstner, 1998). Flow refuge patterns are species-specific with smaller and slower-swimming fish, refuging more frequently (Johansen *et al*., 2008). Different size classes within a population also use flow refuges differently (Gerstner, 1998).

6.5.1 The Potential Use of Wave and Tidal Devices as FADs

Wave and tidal energy generating devices consist of structures placed on the seabed and at mid-water/surface, which could potentially act both as artificial reefs and as FADs (Wilhelmsson *et al*., 2006). A number of different mooring devices are currently used in wet renewable projects (Table 23).

Table 23. Mooring types used in wave and tidal stream devices

Category	Sub-Division	Further Detail
Mooring Device	Cemented	Shoreline wave devices
	Weighted (Gravity base)	Some tidal devices, e.g. the Rotech Tidal Turbine above
	Anchored	Both wave and tidal, e.g. Archimedes, Wave Dragon
	Piled	Mostly tidal, e.g. SeaGen above

Given the lack of studies relevant to wave and tidal energy generating devices the degree to which species would aggregate is uncertain. From the available evidence it is predicted that the potential of a device to act as a FAD will be determined by a number of factors. The primary influences are i) the position and size of major elements of the device and ii) the environment in which the device is deployed. Size and position will influence how many fish can gather and, if attraction is based on food supply, the surface area that can be colonised by encrusting organisms that can be eaten (Clynick *et al*., 2007). In areas with high flow rates such as tidal rapids, pelagic fish will be unlikely to aggregate for long periods. Although they may use areas of lower turbulence, e.g. around device columns, as shelter, these are not large enough to allow many fish to gather. Flow rates will also determine the composition of encrusting assemblages on device and hence the potential food supply to fish. The numbers of small pelagic fish gathering may then influence the attractiveness of the device area to larger, predatory fish.

Devices with the highest FAD potential are therefore those with large elements e.g. large mooring points or floating structures. The latter such as wave attenuator devices and overtopping devices may be expected to attract pelagic fish by analogy to floating pontoons and pilings (Clynick *et al*., 2008) and vessels (Røstad *et al*., 2006). Devices with large moorings may provide additional shelter and food (habitat) for small demersal fish such as territorial blennies and gobies (Love *et al*., 2000). Increases in demersal fish have been observed around the piles of off-shore wind farms (Wilhelmsson *et al*., 2006; Linley, 2007).

Commensurately the FAD potential of devices with small footprints such as the buoy type structures and those with smaller device moorings (such as axis turbines) would be predicted to be low. Additionally structures placed in areas with high flow rates would be predicted to attract and aggregate fewer fish. TEC devices will also only have FAD potential out of the current on the sheltered lee of the device and so this exposure to collision risk is much reduced. The FAD potential of various device types has been summarised in Table 24.

Table 24. FAD potential of different device types

Energy Group Type	Device Type	FAD Potential	Confidence
TEC	Horizontal axis turbine	Low	Medium
	Vertical axis turbine	Low	Medium
	Venturi	Low	Medium
	Hydrofoil	Low	Medium
WEC	Attenuator	Medium	Medium
	Point absorber	Low	Medium
	Oscillating wave surge converter	Low-medium	Medium
	Oscillating water column	Low-medium	Medium
	Overtopping devices	Medium	Medium
	Submerged pressure differential	Low-medium	Medium

6.6 Summary

Short range evasion response will vary considerably between different fish species depending on the visual acuity, burst speeds and perception levels of a fish. There are currently very limited monitoring data, which provide information on the 'near-field' interaction of fish with either tidal stream or wave energy devices making an evaluation of evasion response difficult. It is perceived that short range evasion of wave devices should easily be possible for most fish species given the slow movement of device characteristics. For most tidal devices evasion will be feasible for certain species although this may be more difficult particularly at night or in high turbidity when visual cues are reduced.

7. Potential Physiological Damage Caused by Device

Potential impacts of marine renewable devices on fish include injury or mortality through:

- Physical collision with a moving or stationary part of the device;
- Changes in pressure and water flows arising from the hydrodynamic interaction of the device with the water column; and
- Entrapment in part of the device.

Information on the physiological impacts of tidal stream and wave devices on fish is scarce. However, there is extensive information regarding the injury mechanisms and survival rates of fish passing through riverine and tidal hydropower devices and in relation to boat propellers. Although the design, function and hence physiological impact of hydropower turbines or propellers may not always be directly comparable to tidal stream devices, some of the mechanical and pressure mechanisms via which injury occur, may arise from component parts of marine renewable devices, and as such the potential impact of marine renewable devices will be discussed in relation to this information. Given the similarity in function of horizontal axis turbines to hydropower turbines and boat propellers, the discussion will focus on this type of device. Structures which are analogous to wave devices include moored buoys, floating platforms and stationary boats. As discussed in Section 6.5.1, such structures may act as FADs, although none are known to pose a collision risk to fish or cause physiological damage. As such, although it is possible that wave devices located at the sea surface may act as FADs, it is not expected that such devices would result in physiological damage to fish through collision. Entrapment within water collecting or reservoir components of wave devices may be a more likely mechanism via which fish injury or mortality occurs and this is discussed further in Section 7.2.2.

7.1 Information from Hydropower Turbines

In order to consider the relevance of hydropower turbine function to any marine renewable device, the basic structure of hydroelectric turbines is briefly described. All turbines have a basic design consisting of an intake conduit, carrying water into the main casing, a runner blade chamber (the power producing unit of the turbine) and a draft tube directing water out of the turbine. Inside the main casing, ‘stay vanes’ support the casing and ‘guide vanes’ which overlap to direct the water flow into the runner blade chamber and ensure the water jet meets the main turbine with an even distribution of velocity and pressure (Davies, 1988). The four main types of turbine used in most hydropower schemes are the Pelton (designed to operate at a head of water of 300 – 2000m), Francis (40 – 700m head of water), Kaplan/Bulb (a variation of the Kaplan; < 70m head of water) and STRAFLO turbine (up to 40m head of water). Pelton and Francis turbines are not used in tidal power schemes owing to their higher operating head (Davies, 1988).

The largest fishery problem arising from hydropower generation is the passage of fish through hydroelectric turbines. Injuries that fish suffer from passage through turbines include external visible damage such as decapitation, severing of the body, lacerations, abrasions and scale loss in addition to internal injuries including haemorrhage and rupture of the gut and/or swim bladder (Davies, 1988). Injuries which are not immediately fatal may still ultimately result in mortality as fish may die later through predation, disease or physiological stress. Five main mechanisms have been identified as the cause of fish injury/mortality during passage through turbines (Turnpenny, 1998): collision; raid pressure fluxes; cavitation; shear stress and turbulence. Laboratory studies, in which the physiological effects of each of these mechanisms were evaluated separately, have helped to elucidate the relative importance of each one in fish mortality (e.g. Turnpenny *et al*., 1992) and understanding of these impacts has contributed to the ongoing development of ‘fish friendly’ turbines to improve fish passage survival. The physiological impacts of each one of the five main mechanisms via which injury/mortality occurs is considered below.

7.1.1 Collision

'Strike' injuries occur through collision with fixed or moving structures (e.g. rotating blades) or through fish being squeezed/ trapped between moving and fixed structures (grinding). Strike injuries observed from hydroelectric turbines include contusions, abrasions, lacerations, scale loss or complete maceration (Dadswell *et al*., 1986, cited in Davies, 1988). Several studies have highlighted leading edge blade strike as the primary fish injury mechanism in passage through turbines (Turnpenny *et al*., 2000; Hecker and Cook, 2005) and the probability of strike has been shown to be highly dependant on the type of turbine, runner blade diameter, rotation rate, number of blades, operating loads, the size of the fish and its orientation with respect to flow (e.g. Turnpenny *et al*., 2000).

Through investigating the effect of blade strike on fish passing through hydropower turbines, Von Raben (1957; cited in Turnpenny, 1998) proposed that the rate of blade strike could be predicted using the equation:

$$\text{Injury rate} = L \times M/W$$

Where:

L = the fish length;
W = the 'water length';
M = the mutilation rate.

The water length (which is the distance along the turbine axis that a point in the water has moved between successive blade passes) was calculated as:

$$W = U\text{axial}/\cos\alpha\ (n \times s/60)$$

Where:

n = the number of runner blades;
s = rotational speed in rpm;
Uaxial = the axial water velocity (calculated as the discharge / runner swept area);
α = the angle formed between the streamlines and the axis of the turbine at the runners leading edge.

The mutilation rate, M, acknowledges that the blade strikes at some points on the fish's body may be glancing (and hence not cause injury or mortality). Through observation of eels passing through Kaplan turbines, Von Raben determined a value of 0.43 for M, which implies that about half of the fish that were too long to avoid being struck by the blade were uninjured.

Another important factor in the prediction of strike rate, within a hydroelectric turbine, is the orientation and swimming behaviour of fish within the turbine. Fish swimming with the water flow will pass through more quickly and are less likely to sustain injury; alternatively fish resisting the flow through the turbine are at higher risk of injury (Turnpenny, 1998).

The velocity at which the blade strike causes 'mutilation' to the fish has been termed the 'critical impact velocity' and was calculated as 11-14m/s for Kaplan Turbines (Von Raben, 1957, cited in Davies, 1988). Wilson *et al*. (2007) report that collisions with objects moving at velocities over 8m/s will stun fish, whilst turbine tip velocities of 12.5m/s will result in fatal collisions.

There is a competing effect between the fish's momentum carrying it towards a blade and the 'drag force' on the fish exerted by the water that is forced around the side of the blade. The magnitude of drag force on a fish is related to its surface area; greater drag forces will be exerted on small fish with large surface area to mass ratios. Hence, smaller fish are more likely to be drawn unharmed around the blade than a larger fish (Turnpenny, 1998). In addition, small fish are less prone to physical injury as they sustain smaller forces as they have less mass and inertia (Guench *et al*., 2002).

7.1.2 Rapid Pressure Fluxes

Rapid pressure fluxes are exerted on fish as they pass through high then low pressure zones near turbine blades in hydroelectric turbines. Water pressure reaches a peak in the intake casing, typically 5-10 atmospheres (atm.), and then drops abruptly to sub-atmospheric pressure of approx 0.5 atm. as water moves over the turbine. This rapid decompression (over a fraction of a second) can have a damaging effect on gas-filled spaces in the fish's body, rupturing delicate tissue such as small blood vessels, causing gas embolism in the eyes and causing expansion and rupture of the swim bladder, resulting in an inability to adjust buoyancy. The pressure at which swim bladder rupture occurs varies between species depending on whether the swim bladder is connected to the mouth by a duct (physostome fish e.g. clupeids) allowing rapid venting of air if the swim bladder is overinflated, or whether the swim bladder has no external connection and volume changes are achieved through the slower process of gas release/absorption through the blood stream (physoclist fish e.g. bass). Other symptoms of pressure damage include haemorrhaging in the eyes (red eye), bulging eyes (eye popping) and superficial haemorrhages at the base of fins or lateral line (Turnpenny, 1998). Ruptures of the inner ear structures in larval herring have also been observed.

The rate of pressure change and the absolute pressure at which injury occurs have been investigated in several studies. Turnpenny *et al*., (1992) studied the effect of rapid pressure changes, of a magnitude experienced within an operating bulb turbine, in 14 marine and freshwater fish species. The most common symptom observed was swim bladder rupture, although this was limited to the most severe operating condition (6m water head) and to certain species including Atlantic salmon, brown trout, whiting, bass and sand-smelt (*Atherina presbyter*). No swim bladder rupture occurred in clupeids (twaite shad or herring) or eel. The authors concluded that the effects of rapid pressure changes in an operating hydroelectric turbine were relatively minor for most species. Abernethy *et al*., (2002) investigated rates of pressure change that caused injury in salmon and found no significant injury occurred at a pressure rate change of 3,500 kPa/s (500 psi/s) or at an absolute minimum pressure of 0.5 atm. Davies (1988) reports studies that document swim bladder rupture at a minimum absolute pressure of approximately 0.3 - 0.4 atm. in physoclists and 0.5 atm. in physostomes.

7.1.3 Cavitation

Cavitation is the formation of vapour pockets caused by extremely low pressure at the blade tips, which subsequently collapse violently producing local shock waves, and can result in severe haemorrhaging, localised body pulping and injuries to eyes and gill plates (Davies, 1988). Cavitation mainly arises in turbines operating away from their design conditions

(Turnpenny *et al.*, 2000). Experiments in which cavitation was induced in model turbines showed mortality rates of fish increased by 66-85% in Kaplan turbines and by 52-93% in Francis runners (Davies, 1988).

7.1.4 Shear Stresses

Shear stresses are caused by adjacent masses of water moving at different velocities and mainly occur at the leading edge of runner blades in hydropower turbines. Shear stresses can be damaging to a fish if it is caught across two water streams moving at different velocities which may deform and twist the fish causing mucous loss, scale loss, eye damage and internal haemorrhaging, torn operculum, inversion of gill arches and subsequent decapitation likely arising from 'torque' which opens out gill covers with sufficient force to remove the head (Davies, 1988; Turnpenny *et al.*, 1992).

McEwen and Scobie (1992) estimated that the maximum level of shear stress within a bulb turbine was 3,740 N/m² ('on' design operating conditions) and averaged over 500N/m² (cited in Cada and Odeh, 2001). Turnpenny *et al.*, (1992) assessed the effect of exposing fish to equivalent levels of shear stress in laboratory experiments. Their results showed that the resistance to shear stresses varied between species. Clupeids (shad/herring) were the most susceptible with 100% mortality occurring within 1 hour of being exposed to shear stresses of 206 N/m². In contrast, no mortality occurred in salmonids exposed to shear stresses of 206 – 774 N/m² and only small amounts of scale loss occurred at this level. Higher shear stress levels (1,920 - 3,410 N/m²) resulted in injuries including stripping of external mucous in most of the fish, eye removal or corneal rupture in 10% of fish exposed to > 1,920 N/m², red eye or pop eye in 16% of fish exposed to > 1,920 N/m² and torn gill covers in 10% of fish exposed to 3,410 N/m². The immediate survival rate was still 100%, although up to 12% died within 7 days after exposure to the highest shear level (see indirect mortality section below).

The most resistant species were eels, which suffered no evident injury or mortality even when exposed to the highest shear levels. Additional studies have supported the finding that resistance to shear stresses / strain rates (rate of change in water velocity over distance) is species-specific, and possibly also life-stage and size specific (e.g. Cada *et al.*, 2006; Nietzel, 2000). Table 25 indicates how the shear stresses in the study above compares to those in natural and other human-altered aquatic environments.

Table 25. Shear stresses in natural and altered aquatic systems

Environment	Shear Stress (N/m²)	Reference
Water column in trout stream (average flow)	< 1	Fausch and White (1981)
Small streams (near bed)	< 1 - 7	Lancaster and Hildrew (1993)
Medium size stream (near bed)	Most < 30 (some > 200)	Statzner and Muller (1989)
Flash floods (small basin)	61 - 2600	Costa (1987)
Floods (large rivers)	6-10	Costa (1987)
Bulb turbine draft tube	500 – 5421 (off design operation	McEwen and Scobie (1992)
Near ships hulls and wake	7.6 – 40.4	Morgan *et al.* (1976)
Near barge propeller	> 5,000	Killgore *et al.* (1987)

(Source: Cada and Odeh ,2001)

7.1.5 Turbulence

Differences in water speed and direction within a turbine chamber and draft tube can alter the course of fish passage through the turbine or spin fish round. Injuries from turbulence include contusions, abrasions, lacerations and 'sliced' bodies (Davies, 1988). The impact of turbulence on fish is related to the intensity and 'scale' of the turbulence: small scale (acting over distances smaller than the fish) high intensity turbulence may bruise or descale fish. Turbulence scales approximately equal to the size of the fish may bend or twist the fish, possibly leading to injury and/or disorientation. Turbulence scales 5-10 times the length of the fish will transport the fish in random chaotic motion, possibly resulting in disorientation, loss of equilibrium and diminished swimming capacity (Cada and Odeh, 2001).

The magnitude of strike, grinding, pressure fluxes, shear stresses, turbulence and cavitation within a turbine will be related to the geometry of the turbine blade and turbine flow rates. The potential for 'grinding' of fish in gaps between the blades and the hub is lowest at high flows and the potential for grinding between blade tips and turbine housing is smallest at low flows. Generally pressure drops across the blades and the potential for cavitation is greatest at high flows and shear stresses generally (but not always) increase with turbine flow rate (Franke *et al*., 1997, cited in Cada *et al*. 2006). In a study of fish passage through low-head Francis and Kaplan turbines, Turnpenny *et al*. (2000) showed that shear stresses and pressure fluxes were of relatively minor importance in causing fish injury/mortality (accounting for <2% and 6.3% of observed injuries in the field test respectively), whilst runner-strike was identified as the primary cause of injury mortality, being 3-4 times more important than the hydraulic effects.

7.1.6 Mortality of Fish Passing Through Hydropower Turbines

Numerous studies have assessed the injury and mortality rate of fish passing through hydropower turbines and key references and reviews include Von Raben (1957), Monten (1985) Solomon (1988), Davies (1988), Dadswell and Rulifson (1994) and Turnpenny (1998).

Table 26, taken from Dadswell and Rulifson (1994) shows the mortality rates of fish passing through low-head turbines (which include Kaplan propeller turbines, Bulb turbines and axial flow or tube turbines) in relation to the design and operational characteristics of each turbine.

It is important to note that, in comparison to current tidal stream devices, the hydropower turbines are generally smaller (1.5 – 9m diameter) with higher rotational speeds (50 – 100 rpm) and blade tip velocities (18–32 m/s). In addition to the differences in operational characteristics, there are major differences in structural design between the hydropower turbines and tidal stream devices, the fundamental difference being that in unducted-tidal stream devices, the turbines are 'open', potentially enabling fish to exhibit an escape response even in close proximity to the device blades. It should also be highlighted that Dadswell and Rulifson (1994) only reviews studies prior to 1988; since this time many studies have conducted research into improving survival of fish passing through hydropower turbines and into the development of 'fish friendly' turbines. Table 27 summarises some more recent studies on fish injury/mortality rates.

Table 26. Test or observed fish mortality after turbine passage through low-head turbines (studies prior to 1988)

Turbine and Site	Head of Water	Runner Diameter (m)	No. Blades	Rotation Speed (rpm)	Tip Velocity (m/s)	Test Fish	Mortality (%)	Source
Vertical Kaplan – Hadley Falls, Connecticut River.	15.5	4.3	5	129	29	Salmon smolts	12 ± 10	Stier and Kynard (1986); Bell and Kynard (1985), Taylor and Kynard (1985).
						Adult shad	21.5 ± 16	
						Juvenile clupeids	62 - 82	
Vertical Kaplan – Neckarzimmern, Neckar River.	5.3	4.2	Not known in review	83	18	Eels	25 - 50	Berg (1986)
Vertical Kaplan – Tulieres, Dordogne River.	11.5m	2.9	4	167	25	Trout	8 - 7	Larinier and Dartiguelongae (1989).
Tube Turbine – Fourth Lake, Sissibo River.	23	1.6	6	360	32	Trout	18 - 25	Ruggles and Palmeter (1989).
						Clupeids	14 - 66	
						Perch	12 - 100	
STRAFLO – Annapolis Estuary	5.5	7.6	4	50	20	Adult shad	21 - 46	Hogans (1987).
						Juvenile clupeids	52	Stokesbury (1987).
Bulb turbine – Racine, Ohio River.	6.7	7.7	4	62	25	Gizzard shad	41	Wapora Inc. (1987).

(Source: Dadwell and Rulifson, 1994)

Table 27. Injury/mortality rate during fish passage through various hydropower turbines (studies after 1988)

Type of Turbine	Type of Study	Rotation Speed or Velocity	Impact on Fish	Species	Citation
Blade section (not whole turbine).	Laboratory.	5-7 m/s.	40% injury rate.	Adult salmon.	Turnpenny *et al.*, (1992).
			10% injury rate.	Salmon smolt.	
			28% injury rate.	Adult eel.	
			53% injury rate.	Juvenile shad.	
Francis turbine < 30m head, using flow of 2m^3/s.	Field study (dead fish into turbine).	Not given ("standard operating conditions").	17.9% trout had injuries considered to be potentially fatal in live fish (lacerations, spinal fracture, eye injuries) two thirds likely due to blade strike. 33% of live wild smolt (n=9) killed, all by blade strike.	Brown trout (n=56).	Turnpenny *et al.*, (2000).
Kaplan turbine < 30m head, using flow 0.6m^3/s.	Field study (dead fish into turbine).	Not given ("standard operating conditions").	35.4% had potentially fatal injuries (as listed above) – approx 78% likely due to blade strike.	Salmon smolts (n=132).	Turnpenny *et al.*, (2000).
Helical hydraulic turbine (3 helical blades).	Predicted from pilot scale model test.	74 rpm.	Survival up to 98% for fish 100mm length and up to 97% for fish 150mm length.	Rainbow trout (eel, sturgeon had higher survival rates).	Hecke and Cook (2005).
Archimedes hydraulic screw turbine, 2.2m diameter, 11m long, 4.5m head of water.	Field studies.	28-30 rpm, 3.8 m/s max blade speed, shear forces approx. 0.32 N/m^2 within 13mm of helix surface.	Limited and recoverable scale loss in 1.4% of fish.	Brown and rainbow trout.	FISHTEK 2007.

7.1.7 Indirect and Delayed Mortality of Fish Passage Through Hydropower Turbines

Even if fish transit through turbines without suffering major injury, delayed mortality is still a possibility through failing to avoid predators (e.g. if disorientated), succumbing to disease or physiological stress. Disorientation may occur if fish are rotated or generally buffeted by irregular flow patterns (i.e. turbulent flows) (FISHTEK, 2007) and if such disorientation occurs over a prolonged period, it may affect the ability of fish to respond to the presence of predators (the startle response). Groves (1972) exposed juvenile salmon to water velocities of 9 – 37 m/s, and observed that disorientated fish without any sign of injury regained normal 'capacity' within 5-30 minutes. Odeh *et al*., (2002) studied the effect of turbulence on the startle response time (SRT) of juvenile Atlantic salmon and rainbow trout, which were subjected to jets of water. Water velocities of 3.2 m/s, which created a shear stress of 30 N/m² (equivalent to that experienced in fast flowing rivers) had no effect on SRT. Higher levels of turbulence, corresponding to shear stresses of 50 N/m² did begin to influence SRT. Fish exposed to turbulence levels likely to cause disorientation were observed to swim to the bottom and rest, often displaying listing behaviour with bodies tilted by up to 30° from vertical (Odeh *et al*., 2002). Young fish are more prone to behavioural impairment (e.g. disorientation) as they have a smaller mass and therefore sustain larger acceleration (Guench *et al*., 2002, cited in FISHTEK, 2007). With respect to indirect mortality through disease, Turnpenny *et al*., (1992) showed that mortality occurred in 12% of salmonids within 7 days of being exposed to relatively high shear stresses (3,410 N/m²) created within a laboratory environment and that the fish were heavily coated with fungus, possibly due to mucous and scale loss sustained during initial exposure to shear stress making them more susceptible to fungal infection.

7.2 Potential Physiological Damage Caused by Marine Renewable Devices

There are a wide variety of marine renewable device designs, however, whether the devices extract energy from tidal streams or waves, it is the type and movement of the physical structures and their component parts that pose a physical collision or entrapment risk to fish, which may result in physiological damage. Wilson *et al*., (2007) describes the components of marine renewable devices that pose a collision risk to fish and draws parallels between these and existing structures (e.g. oil platforms, fishing nets) for which the collision risk is more clearly understood. Rotating turbines are the most obvious components which pose a significant collision risk to fish, however, fixed submerged structures (e.g. vertical support piles), mooring equipment (e.g. anchor blocks, cables, chains) and surface structures (e.g. static or articulated boxes) also pose collision risks. Some of these structures may occur together and potentially act to 'trap' fish.

Characteristics of tidal stream devices which will influence the likelihood of collision with fish include: frontal turbine sweep area, turbine rotational speed (rpm), blade tip velocity (m/s), the number of blades / foils, efficiency of the device, shape of blade, smoothness/roughness of turbine components and the presence of gaps between moving parts (DTA, 2006). The availability and extent of such information for tidal stream devices is variable (see Table 3, Section 3.2). The risk of injury / mortality to fish through changes in pressure and water flows will depend on the hydrodynamic characteristics of each individual device. However, there is an even greater paucity of information on such characteristics either due to lack of data or due to commercial confidentiality of the data.

With limited data available from demonstration projects of tidal stream devices, potential effects of tidal devices have been inferred based on general design and turbine configuration and comparison to other similar devices, such as boat propellers and hydropower turbines (DTA, 2006). Whilst these devices are similar in principle they operate at greater speeds with higher pressure differentials (Verdant, 2004 cited in DTA, 2006). The slower operating speed of tidal devices and more open nature of non-ducted tidal stream devices compared to hydroelectric turbines may be expected to be less harmful. For example, Fraenkel (2006) states that flow conditions through tidal turbines are 'relatively gentle' and estimates the maximum rotor blade tip velocity of one tidal turbine device, SeaGen, to be 10-12 m/s. Unlike ship or boat propellers, which generate considerable suction when they put energy into the water, a tidal turbine rotor is driven by the water and does not suck or draw anything towards itself. Fraenkel concludes any marine animal entrained in the flow would tend to be swept between the rotor blades rather than into them. Differences between hydropower, propellers and tidal stream devices were summarised by DTA (2006) using data from Verdant Power (2004) and Coutant and Cada (2005):

- For non-ducted tidal devices there are no physical blockages to inhibit the movement of fish (i.e. no confined forebay / penstock into which fish can be drawn) and therefore less potential for abrasion, grinding and pinching injuries;
- Fish may be attracted to accelerated water flows leading into hydroelectric turbines. This may occur to a lesser extent with ducted tidal devices. Flow in front of an non-ducted turbine is slowed by the 'backwater effect', resulting in a slight pressure wave form in front of the turbine which may direct fish outward and away from the turbine blades;
- Rotor speeds and blade tip velocities of tidal devices will be significantly lower than ship propellers and hydroelectric turbines (Table 28);
- The 'solidity' (percentage of rotor swept area occupied by blades) of tidal devices will typically be less than compared to conventional hydropower turbines, resulting in a lower probability of blade strike (Table 28);
- Changes in water pressure across the turbine (pressure differential) will typically be less for tidal devices compared to hydropower turbines, reducing the potential for pressure related injuries (Table 28); and
- The lack of structures such as wicket gates, stay vanes and draft tubes (areas identified as producing potentially lethal shear stresses within operating hydropower turbines by Cada *et al*., 2006), will reduce shear stresses and turbulence in non-ducted tidal devices.

Comparison of the characteristics of boat/ship propellers, hydroelectric turbines and tidal stream devices are shown in Table 28.

Research to investigate the potential impact of tidal stream devices on marine life, using computational modelling, has recently been undertaken by Swansea University. Simulations were used to investigate the 'locations' at which fish would be unable to avoid passing through the rotor (referred to as an 'event horizon') and to assess the risk to fish due to any pressure variations created by the rotating turbine.

Table 28. Comparison of operational speeds and pressures of ship propellers, hydropower turbines and tidal stream devices

Characteristic	Propeller	Hydropower Turbines	Tidal Energy Converter
Rotor speed	Ship propellers 6-9m in diameter typically turns at 80 – 100 rpm.	▪ Conventional hydropower Kaplan or fixed-propeller turbine typically operates at 100 – 200 rpm ▪ 5.35 m diameter Bulb turbine at La Rance 94 rpm. ▪ 7.6m diameter STRAFLO turbine at Annapolis Royal 50 rpm ▪ 28-30 rpm Archimedes Screw Turbine (2.2m diameter)	▪ 23 rpm SeaFlow; ▪ 35 rpm KHPS; ▪ 21 rpm Hydrokinetic turbine; ▪ 20-70 rpm Clean Current Tidal Turbine, dependant on current velocity.
Blade tip speed (m/s)	No information found.	▪ 3.8 m/s Archimedes Screw Turbine.	▪ 12 m/s MCT SeaGen; ▪ 7.6 m/s Verdant Power KHPS; ▪ 12-20 m/s Lunar RTT; ▪ 3.67 m/s at 21 rpm Hydro Green Energy Hydrokinetic turbine; ▪ 2-4 m/s Pulse Generator, Pulse Generation Ltd.
% of rotor-swept area occupied by blades	Variable depending on type of vessel and propeller.	▪ 90%	▪ 4 % MCT Seagen; ▪ 10 % Verdant Power; ▪ 30 % Lunar RTT.
Pressure differential (kPa)	No information found.	▪ 55 horizontal bulb turbine. ▪ 380 vertical Kaplan turbine. ▪ No significant pressure changes, Archimede Screw Turbine.	▪ 2 Verdant Power.
Shear stresses	▪ 627 N/m^2 Towboats in Mississippi river. ▪ > 5,000 N/m^2 near barge propeller.	▪ Average > 500 N/m^2, max 3,740 N/m^2 for Bulb turbine. ▪ 0.32 N/m^2 Archimedes Screw Turbine.	▪ No information.

(Sources: DTA, 2006) Davies, 1988; FISHTEK, 2007; DTI , 2005; Verdant Power, 2008a; http://www.hgenergy.com/technology.html; http://cleancurrent.ca/technology/ ; Fraenkel, 2006; Lewis, 2007; IECS, 2007; Killgore *et al.* 2001; Cada and Odeh, 2001)

The simulations were based on a horizontal axis rotor of 1m diameter, rotating with a blade tip velocity of 6m/s in a current speed of 2m/s. The results showed that the water passing through the simulated turbine originated from a 0.82m disc of water, located 2m upstream of the rotor. Any marine entity within this disc of water would pass through the rotor, unless it was able to propel itself away. The distance (event horizon) at which a marine entity would be unable to avoid passing through the turbine would vary with rotor size, rotational rate and current speed (Nick Croft, University of Swansea pers. comm.) and given the complex relationship between the computational variables, it was not possible to 'extrapolate' and estimate this distance for a larger turbine rotor for the purposes of this report.

The risk of passing through the rotating turbine was also simulated for fish able to swim at various speeds (0.1 – 1.5 m/s). The results showed that the distance (event horizon) at which a fish would be unable to avoid passing through the turbine varied with swimming speed. The unsafe 'event horizon zone' was larger (i.e. started at a greater distance upstream of the rotor and comprised a larger volume of water in front of the rotor) for 'slow' swimming fish compared to faster swimming fish. As such, slower fish had a higher chance of passing through the device. However, just because a fish entered the 'unsafe' event horizon zone, a collision with the blades was not certain as there remained a probability that the fish might pass through the blades without contact occurring. The probability of blade contact was calculated to be 5% based on a 1.5cm fish travelling through a 1m rotor. For a 10m rotor, the chances of contact would be one tenth of the probability calculated for the 1m rotor (i.e. 0.5%) due to the fact that the time between successive blade passes would be 10 times as long. The probability of contact would obviously increase with increasing size of fish passing through the rotor.

The model also showed that there was a maximum pressure drop across the simulated rotating turbine blades of approximately 2,000 Pa, a value which the researchers felt was likely to be of minimal concern with regard to causing pressure-change related damage to marine life (N. Croft, University of Swansea, pers. comm.), although the magnitude of the pressure change across the blades would vary with the rotational rate of the rotor. The results also indicated that the actual time a marine entity spent in the regions of the highest pressure changes was a fraction of that required for pressure related damage to occur (N. Croft, University of Swansea, pers comm.).

7.2.1 Impacts of Tidal Stream Devices

7.2.1.1 Verdant Power - Roosevelt Island Tidal Energy (RITE) Project – hydrodynamic interaction of rotor with water column

Verdant Power conducted both Computational Fluid Dynamics modelling and *in situ* hydrodynamic evaluations of the six KHPS turbines located in the East River, New York to better understand the near-field effect of rotating blades on flow patterns in relation to increased turbulence or creation of small flow disturbances (eddies) which may affect aquatic life predator-prey relationships (Verdant Power, 2008b). The modelling results showed that the 'near-field' hydrodynamic effects around the rotating turbines included helical vortices being shed from the trailing edge tip of each blade and reduced water velocities and wake downstream of the pile, pylon, nacelle and cone. *In situ* field assessments of the 'far-field' effects of the turbines showed that water velocity immediately behind the rotating rotors approached zero whilst velocity direction was up to 90º out of phase, resulting in a 3-D rotating vortex structure that propagated downstream with the potential to interact with the subsequent turbine. With respect to the impact of the turbine hydrodynamics on fish within the river, Verdant Power concluded that the areas of reduced water velocity behind the stationary turbine pylon during ebb and flood flows present a potential area of protection and/or habitation. The results are not discussed in the context of potential impacts on fish passage, although it is highlighted that the preliminary fish survey data indicates that fish are generally not present in the high water velocity zones that the turbines are located in.

7.2.1.2 Marine current turbines – SeaFlow and SeaGen – collision risk

With respect to collision risk, the SeaFlow project ES (summarised in DTI, 2005) states that the blades of the turbine rotate at a relatively slow rate of 23 rpm and have a sweep a diameter of only 10m, so that the chance of collision, and serious injury and mortality arising from any collision, is low.

7.2.1.3 Pulse Generation Ltd – Pulse Device – collision risk

In considering the device's impact on local fish and shellfish, the ES states that it is anticipated that the movement of the hydroplanes during operation will generate a small mobile pressure field and eddies around the device, which may be sensed by fish and result in a behavioural response away from the device. Even if a fish is struck by the device, it is suggested that the slow velocity of the hydroplanes (average 2 m/s) should make it unlikely to lead to serious injury or mortality. The report concludes that impacts from the operation of the device will therefore likely be of negligible magnitude and importance to the fish and shellfish population of the area (IECS, 2007). Quantitative information on the operational pressures and acoustic signature of the device were not given in the ES.

7.2.2 Impacts of Wave Devices

7.2.2.1 LIMPET - Shoreline oscillating water column

The LIMPET device does not have any turbine components in the water column and therefore physiological damage arising from fish colliding with moving components of the device is not applicable. The large water collector chamber (see Table 5) is considered to be no different to a naturally occurring blowhole or cave and therefore the risk to fish of entrapment is likely to be minimal (ABPmer, 2009).

7.2.2.2 Wave Dragon - entrapment risk

The Wave Dragon device allows ocean waves to overtop a ramp that elevates water to a reservoir above sea level. This creates a 'head' of water that is released through a number of turbines, which are the only moving parts of the device. In theory fish could be trapped in the reservoir as waves spill over the ramp into the reservoir. Species such as salmon smolt that swim in the upper water column and pelagic juvenile sprat *(Sprattus sprattus)* and herring may be the most at risk from this impact (PMSS Ltd., 2007). It would not be possible for fish to escape from the reservoir of their own accord, although smaller fish may pass through the turbines if they are small enough to pass through a 50mm grille that would cover the turbines. As there are no moving parts within the reservoir, trapped fish would be unlikely to be injured, although they would clearly be unable to feed and may be subject to predation by pisciverous birds. The experience from the 15,600 hours (650 days) operative experience so far with a prototype device has not identified any accumulation of fish in the reservoir (ABPmer, 2009).

The turbine through which the water passes is a slow rotating (100 to 270 rpm) Kaplan hydro turbine (PMSS Ltd., 2007). The maximum velocity of water through turbines would be 2m/s and the flow volume is predicted to be $75m^3/s$. For any fish passing through the turbines there is potential for injury if fish collide with or get squeezed between moving or stationary parts, or if fish are subjected to sudden pressure fluxes, turbulence, shear stresses or cavitation. Physoclist fish would be more vulnerable to any pressure variations within the turbines.

7.2.2.3 Wave Dragon – Hydrodynamic impacts

Wave Dragon is unlikely to significantly reduce long period swell waves that are largely responsible for influencing benthic and pelagic processes. As for benthic communities there may be implications for fish species from potential reductions in wave energy. The significance of this impact is likely to be minor (ABPmer, 2009).

7.3 Summary

The lack of available information on the operational characteristics of tidal stream and wave devices makes it difficult to assess the potential physiological impacts of these devices on fish. From the limited information that is available, it appears that the operational rotational speeds, blade tip velocities and pressures differentials across the blades of horizontal axis tidal stream devices would be substantially less than those of hydroelectric turbines or propellers. The lack of turbine housing and associated support structures for 'open' horizontal or vertical axis tidal turbines or oscillating tidal devices, ensures there are no structures physically impeding any close range evasion responses of the fish, and removes the areas shown to be associated with potentially lethal shear stresses in hydroelectric turbines. The presence of a water flow accelerating duct in the venturi tidal stream devices makes it likely that operational pressure differentials are likely to be higher for these devices and the duct structure will provide surfaces along which shear stresses will occur. The duct may also physically prevent close range evasion responses of fish which become entrained into the duct. However, given the lack of available data on the operational characteristics of venturi tidal stream devices, it is not possible to quantify the increased risk posed by this device type, only to speculate that the risk of injury or mortality would be higher compared to an non-ducted horizontal axis tidal stream device, but is still likely to be substantially lower than for a low head hydropower turbine. For overtopping wave devices which contain low head hydropower turbines, the injury mechanisms and mortality rate may be similar to that reported in hydropower schemes, however, the probability of fish becoming trapped in the water reservoir and passing through the turbine (which in at least one device is protected by a 50mm grill) appears to be very small. Entrapment and subsequent mortality through inability to feed or predation is more likely although preliminary data from one device indicates that this is also unlikely.

8. Identification of Information Gaps

The literature review and consultations with wet renewable device companies (detailed in Sections 3-7) highlighted the existence of significant information gaps in the knowledge of both environmental factors and device characteristics influencing the overall risk of fish collision. Information gaps where future research would be beneficial to inform further collision risk studies are listed below and have been assigned a 'rating' according to the priority with which it is considered these information gaps should be addressed.

8.1 Device Characteristics

As noted in Section 3, information on the operational characteristics of tidal stream and wave devices is scarce, due in part to being fledging technologies for which monitoring data is not yet available and also due to commercial sensitivity limiting the availability of such information. Specific aspects for which significant information gaps currently exist were identified as follows:

Noise: *In situ* measurements of the operational noise levels emitted by a full-scale renewable device deployed at sea could only be sourced for two tidal stream devices, while no measurements could be sourced for wave devices. Estimates of operational noise levels from two wave devices had been 'estimated' or 'scaled up' from tank tests or proxy information. Furthermore, to the best of our knowledge, only one project has evaluated the operational noise levels emitted by a demonstration 'array' of (tidal stream) devices (Verdant Power RITE project – six turbines). More information on the operational level of noise of different devices would assist with evaluating the distances at which different fish species may detect devices and hence be able to take long-range avoidance behaviour. It would also enable further assessment of the likely noise impact of operational arrays of tidal or wave devices on fish receptors. Collection of information on the acoustic emissions of demonstrator projects has been highlighted as a priority by the Marine Renewable Energy Research Advisory Group (BERR, 2006) and hence is considered as a high priority in this report.

Vibration: No information on the operational vibration levels of any tidal stream or wave devices could be sourced through literature reviews or consultations with development companies. Information on the operational level of vibration of devices would assist with evaluating the distances at which different fish species may detect devices and hence be able to take long-range avoidance behaviour. It would also enable further assessment of the likely impact of operational arrays of tidal or wave devices on fish receptors. Collection of information on the vibration level emitted by demonstrator projects has been highlighted as a priority by the Marine Renewable Energy Research Advisory Group (BERR, 2006) and hence is considered as a high priority in this report.

Hydrodynamic characteristics (tidal stream devices): Very little information on the hydrodynamic impacts of operational tidal stream devices was available, probably due to the commercial sensitivity of this information. Values of the 'pressure differential' across the moving blades of tidal stream devices was only publicly available for one specific device (Verdant Power RITE project). This project also provided the only publicly available detailed information on CFD modelling undertaken to assess the impact of rotating blades on flow patterns and the potential interaction of these affects within an array. Further information on the hydrodynamic effects of operational tidal stream devices will enable better assessment of the likely collision risk (including the likelihood of injury) to fish arising from pressure fluxes, shear stresses and turbulence during 'near-field' encounters. This information is particularly important to obtain for Venturi devices, in which the turbine duct is designed to accelerate flows, which may result in greater pressure fluxes across the blades and shear stresses along surfaces within the turbine housing. Given that more information regarding these characteristics is likely to exist than is publicly available (through CFD modelling and/or tank testing) this information gap has been given a medium priority.

8.2 Environmental Features Associated with Wet Renewable Deployment Locations

Tidal rapid assemblages: Information on fish assemblages within areas suitable for the deployment of wet renewable devices (e.g. tidal rapids) was limited and mainly provided through anecdotal observations from anglers and fishermen due to the fact that the environmental conditions (turbulent flows, high turbidity, rough seabed topography) make quantitative surveys of these areas difficult. More detailed information of the distribution of fish assemblages in tidal rapids within Welsh waters would enable improved assessment of the extent of exposure of fish species (including species which are common, rare, protected and/or migratory species) to renewable devices. This information could be obtained, for example, by undertaking more detailed quantitative surveys (e.g. through the use of questionnaires) of recreational fishing groups (anglers) and fishermen. Dedicated fish surveys in tidal rapids would also be very valuable. This information gap has been given a low/medium priority given that some information (albeit limited) on fish species associated with tidal rapids in Welsh waters was already available.

8.3 Potential Long Range Avoidance Behaviour of Fish

Fish hearing thresholds and behavioural response to noise: Whilst the hearing sensitivity of some species has been extensively studied, there is a lack of information relating to the hearing capability of other species which may potentially be exposed to renewable devices in areas of deployment. In addition, even less is known about the behavioural response of different species to noise stimuli and no monitoring data or published literature was sourced relating to the long range avoidance behaviour of fish towards tidal stream or wave devices (although the Verdant Power RITE project has undertaken some fish monitoring – see below). Further research into the hearing capability of different fish species and behavioural responses to noise stimuli will be required in order to predict the impacts of tidal stream and wave devices with a higher level of confidence. This information gap has been given a low/medium priority as establishing the operational noise and vibration levels of wet renewable devices is of higher priority.

8.4 Close Range Evasion

Near-field fish behaviour in response to renewable devices: To the best of our knowledge, only one project, Verdant Power's RITE Project Fish Monitoring and Protection Plan (FMPP), has published *in situ* monitoring work that investigates the interaction of fish with an operational array of tidal stream devices. The information from the high definition sonar monitoring, however, which would provide such information on the 'near-field' interactions of the fish with the turbines, was not available at the time this report was being prepared. Assessment of the near-field behaviour of fish towards wet renewable devices, and particularly the ability of different fish species, life-stages and sizes to successfully take evasive action to avoid collision with moving components, should be considered a high priority. Such information could be collected during demonstrator projects utilising hydroacoustic technology, although the appropriate monitoring technology is likely to be site and device specific. Examples of such hydroacoustic monitoring include the use of split beam acoustic transducers and high resolution sonar at the Verdant Power RITE project (Verdant Power, 2008 b, c) and a split beam echo sounder to investigate the migration patterns and run size of twaite shad in the River Wye (e.g. Gregory, 2000).

In addition to *in situ* studies it would also be helpful to undertake laboratory studies of the near field interaction of fish and tidal turbine blades. These studies could provide more controlled conditions in which to investigate fish evasion strategies and assess collision damage.

9. Assessment

9.1 Risk Matrices

As discussed in Section 2, collision impact risk of fish can be considered to be a function of the extent of exposure, avoidance response (both long range avoidance and close range evasion) and the potential physiological damage caused by a collision with a wet renewable device.

Risk matrices have been used to present a broad evaluation on the contribution of these factors. The evaluation is based on one device deployed in the water (not an array) using the device groups identified in Section 3.1. Within each of these device groups a considerable diversity of different design types exists and so the evaluation has been based on either generic characteristics or on prototypes where most information is available. Fish receptors used in the matrices were based on the functional groups identified in Section 4.3. Within these groups the assessment has been based on species commonly occurring in Welsh waters in the environments where the devices might be deployed. In general, ecological traits influencing exposure is generally species-specific, showing much variation within each functional group. A matrix for exposure has therefore not been created. In some cases assumptions about some exposure traits can be made for entire functional groups e.g. demersal species will not need to show evasion of overtopping devices (which are at the surface of the water column). A ‘no pathway’ level has been used in the matrices in such instances.

Based on these matrices, conclusions on the overall risk of collision for different device groups has been derived with the aim of identifying those activities that might require further design considerations, monitoring or mitigation measures (see Section 9.3). It should be noted that these conclusions are not based upon an overall collision risk ‘score’ obtained from combining the outputs of the three matrices shown below. Given the significant information gaps relating to many of the collision risk factors, and the subsequent low levels of confidence with which the collision risk factors can be evaluated, it was perceived that combining the matrices to provide a quantitative overall collision risk ‘score’ may lead to outputs which were over simplified and potentially misleading. Instead the matrices have been designed to be used as a potential framework to inform judgement on potential collision risk.

9.1.1 Long Range Avoidance

The evaluation of the extent of long range avoidance in different fish functional groups was made based on the source noise levels typically generated by different tidal stream and wave devices, where this information was available (see Section 3). Given that underwater noise is able to propagate more efficiently as water depth increases, the evaluation was based on the device being in shallow water to determine a potential worst-case risk for fish (i.e. to provide the minimum distances that the devices would be likely to invoke an avoidance response). Within each of the fish functional groups a range of hearing sensitive fish for which audiogram and/or hearing threshold information was available in the literature (namely from Nedwell *et al*. 2004c), was considered in the risk assessment (see Table 16). The different types of hearing sensitive fish (high, medium and/or low) comprising each of the functional groups provided a potential range (maximum to minimum) in the level of risk.

The following levels were used to characterise the long-range ability of fish to avoid a single device:

- **High**: likely to exhibit signs of avoidance at distances >50m from device;
- **Medium:** likely to exhibit signs of avoidance at distances >20m from device;
- **Low**: likely to exhibit signs of avoidance only at distances >10m from device; and
- **Very Low:** likely to exhibit signs of avoidance at distances <10m from device (i.e. at distances at which the device can be seen and near-range evasion mechanisms begin to take place- see Section 6.1).

The analysis of the extent of long range avoidance in fish is presented as a risk matrix in Table 29. There were a number of device types for which no noise source information was available. The risk of these devices to the long range behaviour of fish was, therefore, not possible to evaluate and has been expressed as ‘unknown’ in the matrix. The low level of confidence reflects an appraisal of the specificity of the information available to support the assessment of long range avoidance (see Section 8).

Where source noise information for the devices was available, the level of confidence attributed to the risk assessment was considered to be ‘low’. This was because the evaluation had been derived from limited noise measurements of the devices and only from a general understanding of the fish hearing ability and likely behavioural response to noise. In other words, the assessment had largely been derived by 'informed judgement'.

Table 29. The extent of long range avoidance

Energy Group Type	Device Type	Ability to Avoid Device at Long Range Distances									Confidence
		Pelagic (Bony)		Pelagic (Elasmobranch)	Demersal (Elasmobranch)	Demersal (Bony)		Diadromous			
		High Sensitivity	Medium Sensitivity	Low Sensitivity	Low Sensitivity	Medium Sensitivity	Low Sensitivity	High Sensitivity	Medium Sensitivity	Low Sensitivity	
TEC	Horizontal axis turbine	High	Very Low	Very Low	Very Low	High	Very Low	High	Low	Very Low	Low
	Vertical axis turbine	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
	Venturi	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
	Hydrofoil	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
WEC	Attenuator	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	Very Low	Low
	Point absorber	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
	Oscillating wave surge converter	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
	Oscillating water column	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-
	Overtopping devices	High	Very Low	Very Low	Very Low	Medium	Very Low	High	Low	Very Low	Low
	Submerged pressure differential	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	-

High	Exhibit signs of avoidance at distances >50m from device.
Medium	Exhibit signs of avoidance at distances >20m from device.
Low	Exhibit signs of avoidance at distances >10m from device (i.e. before the device is seen and near-range avoidance mechanisms take place).
Very low	Likely to exhibit signs of avoidance at distances <10m from device.
Unknown	No currently available source noise level information.

9.1.2 Close Range Evasion

The evaluation of the extent of close range evasion due to visual stimuli in different fish functional groups was made based on the data collected in Section 3 and literature reviewed in Section 6 and is presented as a risk matrix in Table 30. The level of confidence attributed to the risk assessment was considered to be ‘low’ throughout. This is because ‘near field’ monitoring and observational data on fish behaviour around devices is limited and so the evaluation has been based on comparable stimuli as well as more general scientific studies on burst swimming speeds, fish vision and fish sensory responses. As described in the model (Figure 2) environmental factors such as light levels and turbidity will modify the level of evasion response possible. This information has been summarised in Section 6.1. For the matrix the following assumptions were made;

- The evaluation is for daylight conditions (collision risk has the potential to be much higher at night); and
- Environmental features such as flow and turbidity were considered to be at levels ‘typical’ for renewable locations based on the literature review.

The following levels were used to characterise the short range ability of fish to evade a single device:

- **High:** Most fish should easily be able to exhibit an evasion response with very few strikes predicted;
- **Medium:** Most fish should easily be able to exhibit an evasion response although some strikes are possible;
- **Low:** Some fish will have difficulty evading the device with strikes possible; and
- **No pathway:** No pathway as an evasion response is not required.

Table 30. The extent of close range evasion

Energy Group Type	Device Type	Ability to Evade Device					Confidence
		Pelagic (Bony)	Pelagic (Elasmobranch)	Demersal (Elasmobranch)	Demersal (Bony)	Diadromous	
TEC	Horizontal axis turbine	Medium-high	Medium-low	No pathway	Medium-high	Medium-high	Low
	Vertical axis turbine	Medium-high	Medium	No pathway	Medium-high	Medium-high	Low
	Venturi	Medium-high	Medium-high	No pathway	Medium-high	Medium-high	Low
	Hydrofoil	High	High	No pathway	High	High	Low
WEC	Attenuator	High	High	No pathway	No pathway	High	Low
	Point absorber	High	High	No pathway	No pathway	High	Low
	Oscillating wave surge converter	High	High	High	High	High	Low
	Oscillating water column	High	High	High	High	High	Low
	Overtopping devices	High	High	No pathway	No pathway	High	Low
	Submerged pressure differential	High	High	High	High	High	Low

High	Most fish should easily be able to exhibit an evasion response with very few strikes predicted.
Medium	Most fish should easily be able to exhibit an evasion response although some strikes are possible.
Low	Some fish will have difficulty evading the device with strikes possible.
No pathway	No pathway as an evasion response is not required.

9.1.3 Potential Physiological Damage

The evaluation of physiological damage was based on device characteristics which have the potential to cause injury or mortality (i.e. through physical collision with a moving or stationary part of the device, changes in pressure and water flows arising from the hydrodynamic interaction of the device with the water column or entrapment in part of the device) where this information was available (see Section 3).

Literature on the physiological impacts of tidal stream and wave devices such as injury on fish is scarce. Extensive information regarding the injury mechanisms and survival rates of fish passing through riverine and tidal hydropower devices and in relation to boat propellers exists (Section 7). Although the design, function and hence physiological impact of hydropower turbines or propellers may not always be directly comparable to tidal stream devices, some of the mechanical and pressure mechanisms via which injury occur, may arise from component parts of marine renewable devices, and as such the potential impact of tidal stream devices was considered in relation to this information. Horizontal axis turbines and venturi turbines have been split into ‘blade tip’ and ‘mid blade’ in the matrices (as damage would be expected to be greater at the tip of the blade based on literature from hydropower turbine studies).

Structures which are analogous to wave devices include moored buoys, floating platforms and stationary boats. As discussed in Section 6.5.1, such structures may act as FADs, although none are known to pose a collision risk to fish or cause physiological damage. As such, although it is possible that wave devices located at the sea surface may act as FADs, it is not expected that such devices would result in physiological damage to fish through collision. Hence, the physiological impact of wave devices is restricted to potential physiological damage arising from entrapment.

Much of the assessment has therefore been largely derived by 'informed judgement' with the level of confidence attributed to the risk assessment considered to be ‘low’ or ‘medium’. The analysis of potential physiological damage is presented as a risk matrix in Table 31.

The following levels were used to characterise the potential physiological damage of a device:

- **High** – High risk of physiological damage and/or mortality to many individuals;
- **Medium** – Moderate risk of physiological damage to some individuals;
- **Low** – Low risk of physiological damage; and
- **No pathway** - No pathway as fish are not exposed to characteristics of the device which could cause physiological damage.

Table 31. Potential physiological damage

Energy Group Type	Device Type	Pelagic (Bony)	Pelagic (Elasmobranch)	Demersal (Elasmobranch)	Demersal (Bony)-	Diadromous	Confidence
TEC	Horizontal axis turbine (blade tip)	Medium-high	Medium-high	No pathway	Medium-high	Medium-high	Low
	Horizontal axis turbine (mid blade)	Low-medium	Low-medium	No pathway	Low-medium	Low-medium	Low
	Vertical axis turbine	Low-medium	Low-medium	No pathway	Low-medium	Low-medium	Low
	Venturi (blade tip)	Medium-high	Medium-high	No pathway	Medium-high	Medium-high	Low
	Venturi (mid blade)	Low-medium	Low-medium	No pathway	Low-medium	Low-medium	Low
	Hydrofoil	Low	Low	No pathway	Low	Low	Medium
WEC	Attenuator	Low	Low	No pathway	No pathway	Low	High
	Point absorber	Low	Low	No pathway	No pathway	Low	High
	Oscillating wave surge converter	Low	Low	Low	Low	Low	High
	Oscillating water column	Low	Low	Low	Low	Low	High
	Overtopping devices	Medium	Medium	No pathway	No pathway	Medium	Medium
	Submerged pressure differential	Low	Low	Low	Low	Low	High

High	High risk of physiological damage and/or mortality to many individuals
Medium	Moderate risk of physiological damage to some individuals.
Low	Low risk of physiological damage.
No pathway-	No pathway as fish are not exposed to characteristics of the device which could cause physiological damage.

9.2 Matrices Application

The matrices can be used as a potential framework to inform judgement on potential collision risk. As discussed in Section 1.2.2 the evaluation is designed as a 'broad-brush' approach, and does not infer that more specific receptors will not be affected by site-specific developments. Examples of the application are given below:

- A dogfish would have a very low ability to avoid a horizontal axis turbine at long range distances (due to poor hearing), a low-medium chance of evasion (because of slow swimming speeds) although due to its bottom dwelling lifestyle is unlikely to come into contact with a horizontal axis turbine (exposure pathway). Therefore a dogfish would be of low/negligible collision risk concern but the confidence in the assessment would be low; and

- A herring has highly sensitive hearing giving it a high ability to avoid a horizontal axis turbine at long range distances, a medium chance of evasion (due to fast burst swimming speeds) although physiological damage at the tip (worst case scenario) is considered high. A mackerel would be of low to moderate collision risk concern but the confidence in the assessment would be low.

- Confidence in the risk matrices was generally low, except in relation to collision damage with wave devices for which confidence is medium or high. These levels of confidence reflect the lack of available information on issues relating to collision risk described in detail in Section 8.

9.3 Summary

In general, it is considered likely that tidal and wave energy devices would not provide sufficient cues for long range avoidance in most fish species. In other words, the devices (tidal horizontal axis turbines, wave attenuators and overtopping devices) are unlikely to result in any modification of a fish's long range behaviour; particularly elasmobranchs and demersal bony fish. This may mean, particularly for hearing insensitive fish, that they would not be aware of the presence of the device before near field 'visual' cues are dominant. Pelagic bony fish comprise species with a wider range of hearing sensitivities, such as hearing specialists (e.g. herring), which would be able to hear the device from the greatest distances and are most likely to be able to avoid any collision. Diadromous fish include species from both pelagic and demersal bony fish groups and, therefore, comprise a wide range of hearing sensitivities and long range behaviours.

It is possible that fish may be able to undertake close range evasion of wave and most tidal stream devices. However, the speed of rotating blades in horizontal axis and venturi turbines combined with very fast flow rates in the surrounding tidal rapids means that strikes could be possible for fish with these devices. Further 'near field' observations and monitoring is recommended for these device groups (Section 8).

Physiological damage would also be expected to be highest in horizontal axis and venturi turbines due to the rotating blades used. The extent of any injury is likely to be less in hydrofoil turbines due to the much slower movement of the blades. Most wave devices have very low or no potential to cause physiological damage to fish. The exception is overtopping devices where if a fish became trapped in the collector the primary exit is through the turbine (although this is protected by a screen through which most fish would not pass). Due to the position of the collector at the very surface of the water and ease of evasion by most fish, entrapment in overtopping devices is unlikely.

The assessment has been focused on the deployment of single devices and not for large arrays where risk could be greater (although greater source noise levels associated with arrays could cause a greater long range avoidance response). Many devices are currently only at a prototype phase and so the size and design of devices are likely to change in the future.

10. Mitigation and Monitoring

Potential mitigation measures which could be tested to reduce risk further include:

- Using bright coloration and high contrast designs on moving parts e.g. blades. This would increase the visual clarity on the device, increasing the potential distance at which fish can see an object and undertake an evasion response;

- Collision risk increases at night, due to poor visibility conditions. The addition of lighting would increase the clarity of a wet renewable device at night. Strobe and fluorescent lighting, for example, have been tested in fish avoidance schemes for power station cooling water extraction plants (McIninch and Hocutt, 1987; Van Anholt *et al*., 1999). The effectiveness and any potential adverse impacts to marine species are largely unknown and would require further research;

- The use of acoustic fish deterrent (AFD) systems placed in the vicinity of a device. Artificial sounds have previously been used to reduce fish impingement by power plant intakes or turbines. For example, Maes *et al*., (2004) used 20 large sound projectors, close to intake pipes, signals vary to limit habituation, range between 20-600 Hz. These reduced entrainment by gobies, herring, sprat, white bream (*Abramis bjoerkna L*.). smelt (*Osmerus eperlanus*), bass (*Dicentrarchus labrax*), perch (*Perca fluviatilis*), sole (*Solea solea*), flounder (*Platichthys flesus*) and gobies of the genus *Pomatoschistus* sp. In particular deflection of clupeids (hearing specialists) was successful, with herring and sprat declining by 94.7 and 87.9% respectively. Reduction in average numbers of sprat was also high at 88%. Deterrence in flatfish species was variable with a significantly reduced catch of sole and flounder and no change in dab, pipefishes, sticklebacks and mullet, which did not show any avoidance reaction to the AFD system. The results from this indicate that the success of an AFD is species-specific and related to hearing ability. Experiments have shown that awareness reactions and avoidance responses are provoked in Atlantic salmon by infrasound frequencies (5-10 Hz) (Knudsen *et al*., 1994). Field tests showed that Atlantic salmon smolt were deterred from entering a river channel by 10 Hz sound but not by 150 Hz sound. Clupeids can also detect ultrasound (Mann *et al*., 1997) and high frequency (120 kHz) sounds have been applied to reduce the occurrence of shad at sites throughout the US (Ross & Dunning, 1993; Ploskey *et al*., 1995; Dunning, 1995). As previous, potential adverse effects (e.g. loss of effective habitat would also need to be considered); and

- Bubble curtains (which fish are less likely to swim through) around a device (McIninch and Hocutt, 1987) could also be employed, although these are likely to be ineffective in areas of strong flow.

11. Conclusions and Recommendations

11.1 Introduction

Wave and tidal stream energy converters are fledgling technologies. There is therefore very little direct evidence on fish collision impacts either positive or negative. Risk assessments based on theoretical considerations identify plausible impact routes. Experiences from hydropower turbines have documented substantial fish impacts (although such turbines are not direct analogues for wave or tidal power converters). The study has postulated a conceptual model which identifies key factors affecting collision risk. This conceptual model has proved helpful in focusing the review on critical areas of uncertainty and has supported the identification of priorities for future research.

11.2 Device Characteristics

The review of wave and tidal stream technologies has identified a general lack of information on environmentally relevant device characteristics that might inform the evaluation of collision risk. Where information is available, it relates to single prototype devices and there is little if any information available on the environmental characteristics of multiple devices, for example, the underwater noise field that might be generated by an array of tidal turbines. However, there is sufficient information available to make an initial analysis for individual devices across device types based on relative assumptions.

11.3 Environmental Characteristics

There is limited information on the environmental characteristics of wave and tidal stream device deployment locations and the associated fish assemblages. In particular, the fish assemblages of tidal stream environments are poorly documented, reflecting the difficulties of quantitative sampling in such areas. The assessment has therefore relied on information on the broad distribution of fish species in Welsh territorial waters and their habitat preferences.

11.4 Collision Risk

The four main factors that have been used in the conceptual model and that contribute to fish collision risk are:

- Exposure;
- Long range avoidance;
- Close range evasion; and
- Collision damage.

11.4.1 Exposure

Ecological factors such as the habitat preferences of a fish, migration routes and the position of a fish in the water column will all influence whether a fish is exposed to features of a wet renewable device which could cause a behavioural avoidance response. For example, demersal species such as blennies and gobies that primarily inhabit the sublittoral fringe for example are unlikely to be seen in the vicinity of tidal stream devices but could be encountered near oscillating wave columns attached to the shoreline.

11.4.2 Long Range Avoidance

The opportunity for fish to engage in long range avoidance is likely to be a function of the source levels of underwater noise associated with wave and tidal devices (particularly during operation), background noise levels (the extent to which device noise levels might be masked by ambient background noise) and the particular hearing sensitivities of different species of fish. The analysis suggests that hearing sensitive fish (such as herring) may be able to detect and avoid individual operational tidal stream devices at distances between approximately 120 to 300m (depending on the depth of the water) even when background noise levels are comparatively high. For wave energy devices, source noise levels are estimated to be lower and thus the distances at which avoidance behaviour might occur would be reduced to around 35 to 200m (depending on the depth of the water). For hearing insensitive fish, the projected source noise levels for wave and tidal devices are likely to be below levels at which these species might exhibit an avoidance reaction.

Significant uncertainties exist concerning the source noise levels of most devices, the ability of fish to differentiate broad spectrum device noise from broad spectrum background noise as well as the precise levels at which fish (both at individual or shoal level) might choose to exhibit an avoidance response. There are no direct observation studies documenting the response of fish to underwater noise associated with wave or energy devices to test the predictions that have been developed, although the predictions are reasonable based on experiences with other human activities generating underwater noise. Overall confidence in these predictions is therefore low.

11.4.3 Close Range Evasion

The extent of close range evasion of wave and tidal stream devices is a function of the 'visibility' of the devices, details of device structure and operation, the visual acuity and maximum swimming speeds ('C-start' or 'burst' speed) of different species of fish and near-field behavioural responses. In relatively shallow water with low turbidity, devices are likely to be visible in the day time at distances of around 5 to 10m. At night time visibility of devices would be significantly lower. Assuming that a normal fish response to the appearance of an unfamiliar object would be avoidance, the scope for fish to actively avoid a device will relate to its maximum swimming speed relative to ambient flow speeds.

Maximum swimming speeds vary significantly between species and with individual size of fish. Adults of pelagic species such as mackerel exhibit burst speeds of up to 5m/s, but the majority of demersal species would have burst speeds of around half of this value. Small fish (including juveniles of larger species) generally have lower burst speeds (which are a function of overall body length). Relatively few UK fish species would be capable of actively swimming upstream against the high flows associated with tidal stream environments or wave surge environments. However, fish would be able to actively swim against the generally lower flows associated with offshore wave deployment environments. Depending on the size of device it may be possible for fish to manoeuvre round the side of a device although given the short distance over which visual cues might operate this may not be feasible for fish encountering tidal stream devices in high flow environments. For example a fish moving passively with a tidal flow of 2.5m/s towards a tidal stream device visible at a distance of 5m would have approximately 2 seconds to swim around the device. For a fish approaching near the centre of a 15m diameter blade this would require it to travel a distance of more than 7.5m in that time period. This is beyond the ability of most fish. There are no direct observation studies on the near-field interaction of fish with wave or tidal stream devices and it remains unclear how fish might respond on encountering such devices, for example whether they might swim towards the tip of a blade or towards the centre. It is noted that fish swimming towards the outer edge of tidal turbine blades will potentially expose themselves to greater risk of collision injury compared to fish swimming towards the proximal part of a blade (which is travelling relatively slowly). The risk assessment has sought to categorise near-field evasion response primarily based on burst swimming speed of different fish species. Given the uncertainties in near-field response the confidence in all the evaluations is low.

11.4.4 Collision Damage

The extent of damage to fish associated with collision with a wave or tidal stream device is largely a function of the characteristics of that device. The position of the device in the water column is also important in governing the exposure of fish to collision risk. For example demersal elasmobranchs and flatfish are unlikely to encounter tidal turbine blades or to interact with floating wave devices.

There are no published direct observation studies relating to fish collision with wave or tidal devices and the assessment has been based on comparisons with analogues. For tidal stream turbines, studies of fish interactions with hydropower turbines have been used to inform possible risks, although in normal operation hydropower turbines introduce much greater environmental changes compared to tidal stream devices. Nevertheless, some of the research studies for hydropower turbines are useful in identifying both the factors causing damage to fish and various thresholds at which particular types of damage occur. This has been particularly useful in informing the assessment of risks associated with tidal stream devices. In general the speed of rotation of most tidal turbine blades is such that towards the terminal end of blades (where velocities may be of the order of 10 to 12m/s) there is a significant risk of physiological damage should a collision occur. However, towards the proximal end of the blades, the relatively lower velocities pose a lesser risk of physiological damage.

For wave devices, the risks of damage associated with a collision are generally much lower. Floating devices might be considered broadly similar to moored vessels or buoys such that any collision, should it occur, might be expected at worst to give rise to minor chafing. For overtopping devices that make use of low head turbines to generate power, there is some risk associated with entrapment of fish within the reservoir, although anecdotal evidence of such devices in operation has not identified any significant entrapment – indeed it is unlikely that fish would enter the reservoir as they are rarely positioned right at the surface. The presence of mesh grilles on the turbine intakes effectively precludes fish from entering the turbines and thus the risk of physiological damage from collision with the turbine blades is negligible.

The lack of direct observation studies means that there are significant uncertainties relating to the magnitude of collision damage for tidal stream devices and confidence in the assessments is low. In contrast, wave devices generally all pose a low risk of collision damage and confidence in this assessment is high.

11.4.5 Overall Assessment of Collision Risk

An overall assessment of collision risk for different types of fish species, devices and locations can be made by considering information on exposure, long range avoidance, short range evasion and collision damage. It is recognised that there is currently a lack of quantified information about some of the factors influencing risk. However, the generic model is considered to be helpful in identifying the factors influencing risk and clarifying the priorities for further research.

In particular, the following priorities for research have been identified:

- Direct observation (e.g. using hydro-acoustic techniques) of near-field behaviour of fish in the vicinity of operation tidal turbines; these studies might also be used to inform effective mitigation measures/strategies;
- Laboratory studies of near-field behaviour of fish in the vicinity of rotating blades and of any collision damage; these studies might also be used to inform effective mitigation measures/strategies; and
- Field measurements of underwater source noise associated with a wider range of wave and tidal stream devices.

It would also be desirable to collect further information on the environmental characteristics of arrays once project scale developments emerge, for example, the underwater noise field associated with an operational array of tidal stream turbines. Additional information on the fish assemblages of tidal stream deployment areas should also be collected as such areas are currently poorly described.

11.5 Mitigation and Monitoring

A limited range of possible mitigation options have been identified, particularly for tidal turbines where collision risks are higher. However, given the current lack of information on impacts, the extent to which such measures might be required is unclear. Possible measures include:

- Acoustic deterrents; and
- Improvements to the visibility of rotating blades (use of lighting, colour).

The monitoring of fish in the marine environment is expensive and any monitoring programmes need to be clearly targeted towards clarifying impacts. General monitoring of fish assemblages in the vicinity of devices is unlikely to provide conclusive data on impacts because the scale of impacts associated with devices is not likely to be large at a population level and variation in the distribution and abundance of fish will mask minor impacts. While general monitoring of fish assemblages is unlikely to significantly improve the scientific knowledge base of wave and tidal stream device impacts, some monitoring may nevertheless be required to address possible concerns of local fishermen or wider public interest.

Direct observation of fish movements and behaviour in the vicinity of devices is likely to be more useful in refining evaluations of risk and impacts, but such studies would be better progressed as part of the wider research on device impacts and it is unlikely to be appropriate to require individual developers to fund such studies.

11.6 Recommendations

Based on the findings of this study we make a number of recommendations concerning the priorities for further research into fish collision risks and impacts and in relation to mitigation measures and monitoring requirements. Key priorities for further research include:

- Direct observation (using hydro-acoustic techniques e.g. sonar) of near-field behaviour of fish in the vicinity of operation tidal turbines; these studies might also be used to inform effective mitigation measures/strategies;
- Laboratory studies of near-field behaviour of fish in the vicinity of rotating blades and of any collision damage; these studies might also be used to inform effective mitigation measures/strategies; and
- Field measurements of underwater source noise associated with a wider range of wave and tidal stream devices.

In addition to any changes in the design of wave or tidal stream devices that may arise from further research into the collision risk with fish as described above, a limited range of possible mitigation measures has been identified, based on the use of acoustic deterrents and improvements to the visibility of rotating blades. The effectiveness of these measures in reducing collision risk and impact is uncertain and would benefit from further research. Given the lack of certainty in effectiveness, we suggest that it would not generally be appropriate to require prototype deployments to apply such measures specifically to seek to reduce fish impacts.

The monitoring of fish assemblages in the vicinity of wave and tidal devices is expensive and, in tidal stream areas, problematic. General studies of fish assemblages are unlikely to significantly improve scientific understanding of fish collision impacts. Direct observation of fish movements and behaviour in the vicinity of devices is likely to be more useful in refining evaluations of risk and impacts, but such studies would be better progressed as part of the wider research on device impacts and it is unlikely to be appropriate to require individual developers to fund such studies.

12. References

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Appendices

Appendix A

Conservation Status of Protected Species Recorded Around Wales

Appendix A. Conservation Status of Protected Species Recorded Around Wales

Group	Scientific Name	Common Name	BAP Species (based on NERC Act Section 42 list)	Hab Dir Annexes	OSPAR Threatened Species	Bern Convention	EC CITES	IUCN Global Red List Status	WACA 1981
Pelagic	*Clupea harengus*	Herring	Yes						
	Scomber scombrus	Mackerel	Yes						
	Trachurus trachurus	Horse mackerel	Yes						
Demersal	*Ammodytes marinus*	Lesser sandeel	Yes						
	Gadus morhua	Cod	Yes		Yes			Vulnerable	
	Hippocampus guttulatus	Long snouted seahorse	Yes			Yes	Appendix II		
	Lophius piscatorius	Sea monkfish	Yes						
	Merlangius merlangus	Whiting	Yes						
	Molva molva	Ling	Yes						
	Osmerus eperlanus	Smelt (Sparling)	Yes						
	Pleuronectes platessa	Plaice	Yes						
	Merluccius merluccius	European Hake							
	Solea solea	Sole	Yes						
Diadromous	*Alosa alosa*	Allis shad	Yes	2, 5	Yes				Sch 5: 9.1, 9.4
	Alosa fallax	Twaite shad	Yes	2, 5					Sch 5: 9.4a
	Anguilla anguilla	European eel	Yes		Yes		Appendix II		
	Lampetra fluviatilis	River lamprey	Yes	2, 5					
	Petromyzon marinus	Sea lamprey	Yes	2	Yes				
	Salmo salar	Atlantic salmon	Yes	2, 5	Yes				
	Salmo trutta	Brown/sea trout	Yes						
Elasmobranch	*Raja brachyura*	Blonde ray	Yes						
	Raja clavata	Thornback ray	Yes					Endangered	
	Rostroraia alba	White or bottle-nosed skate	Yes					Critically Endangered	
	Squatina squatina	Angel shark	Yes						
	Cetorhinus maximus	Basking shark	Yes		Yes	Yes	Appendix II	Vulnerable	Sch 5: 9.1, 9.4
	Dipturus batis	Common skate	Yes		Yes			Critically Endangered	
	Galeorhinus galeus	Tope shark	Yes					Vulnerable	
	Lamna nasus	Porbeagle shark	Yes					Vulnerable	
	Prionace glauca	Blue shark	Yes						
	Raja undulata	Undulate ray	Yes						
	Squalus acanthias	Spiny dogfish	Yes		Yes			Vulnerable	

Appendix B

Fish Species Recorded in Surveys of Tide Influenced Communities by Moore (2004)