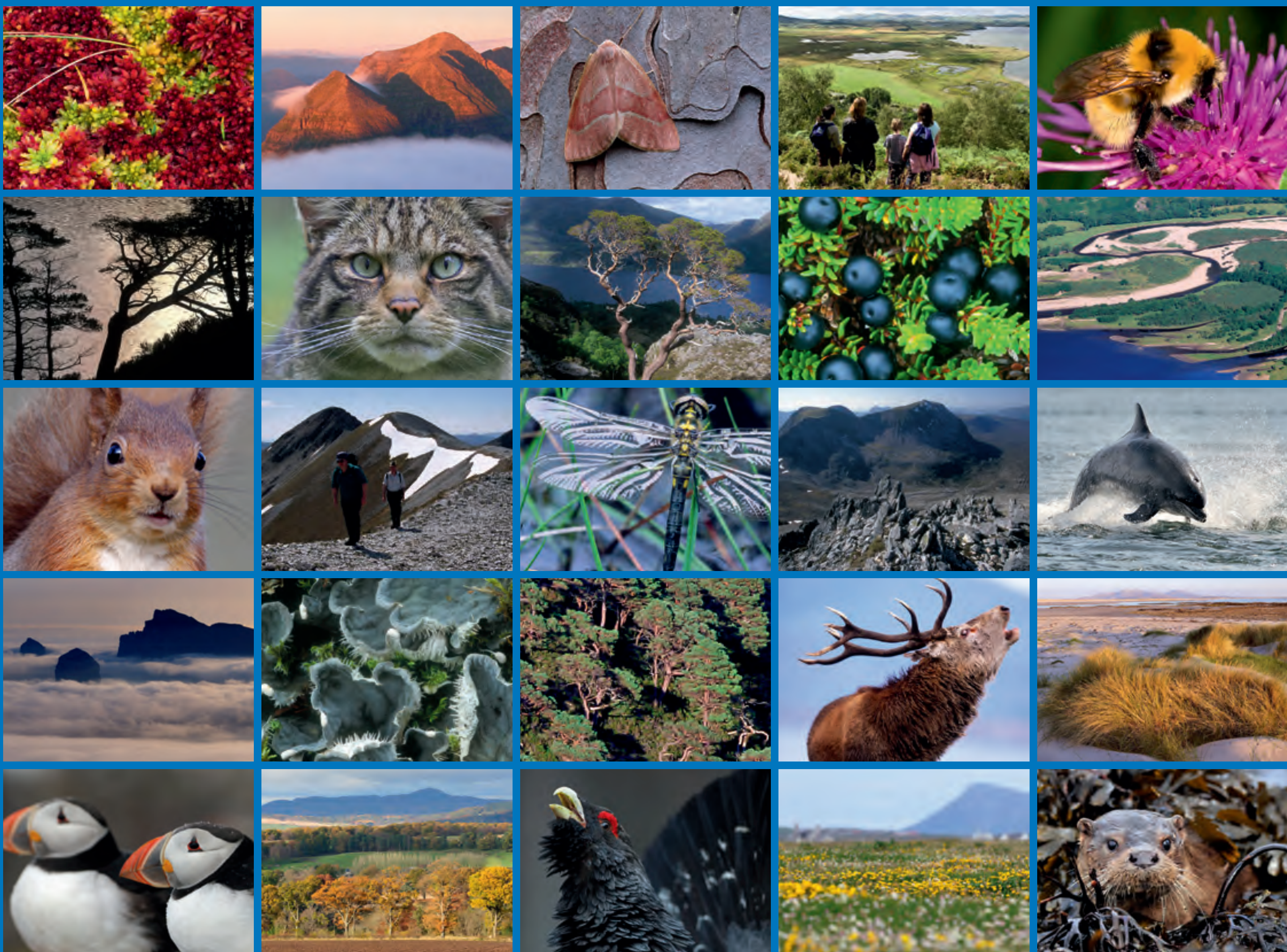
Scottish Natural Heritage
Commissioned Report No. 791

Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments



Scottish Natural Heritage
Dualchas Nàdair na h-Alba
All of nature for all of Scotland
Nàdar air fad airson Alba air fad

COMMISSIONED REPORT

Commissioned Report No. 791

Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments

For further information on this report please contact:

Caroline Carter
Scottish Natural Heritage
Battleby
Redgorton
PERTH
PH1 3EW
Telephone: 01738 444177
E-mail: caroline.carter@snh.gov.uk

This report should be quoted as:

Benjamins, S., Harnois, V., Smith, H.C.M., Johanning, L., Greenhill, L., Carter, C. and Wilson, B. 2014. Understanding the potential for marine megafauna entanglement risk from renewable marine energy developments. *Scottish Natural Heritage Commissioned Report No. 791.*

COMMISSIONED REPORT

Summary

Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments

Commissioned Report No. 791
Project no: 14635
Contractor: Scottish Association for Marine Science Research Services Ltd and the University of Exeter
Year of publication: 2014

Keywords

Marine renewables; marine megafauna; entanglement; moored arrays; qualitative risk assessment.

Background

The global marine renewable energy (MRE) industry (including offshore wind, wave and tidal energy) is developing rapidly, particularly in Scotland where the Scottish Government is driving growth of the industry as part of their sustainable development agenda. As increasing numbers of devices are set to be deployed, concerns have been raised over potential environmental impacts. One such potential impact of marine renewable energy development is the risk of whales, basking sharks and other large animals ("marine megafauna") becoming entangled in mooring systems and associated power cables. Given the widespread occurrence of marine megafauna injury and mortality through entanglement and bycatch in fishing gear, the issue poses potentially serious conservation concerns.

Main findings

The present report set out to review existing information on entanglement risks to marine megafauna posed by moorings. Based on an extensive literature review, it was concluded that moorings such as those proposed for MRE devices will likely pose a **relatively modest risk** in terms of entanglement for most marine megafauna, particularly when compared to risk posed by fisheries. Nevertheless, some circumstances were identified where moorings associated with MRE devices could potentially pose a risk, particularly, 1) in cases involving large baleen whales and, 2) if derelict fishing gears become attached to the mooring, thereby posing an entanglement risk for a wide range of species (including fish and diving seabirds).

In the absence of significant amounts of empirical data, a **qualitative risk assessment** approach was developed to assess **relative** risks to marine megafauna groups on the basis of biological and physical risk parameters. Biological risk factors included body size, animals' ability to detect moorings, animals' body flexibility and general feeding modes. Physical risk factors were defined as mooring tension characteristics, swept volume and curvature. Mooring behaviours were dynamically modelled for six different mooring types (catenary [three different compositions], catenary with accessory buoy, taut, taut with accessory buoy) using OrcaFlex™ software to assess the physical risk factors under different sea states. In order to inform the risk assessment, biological and physical risk factors were combined to populate a relative risk matrix for all modelled moorings.

Results suggest that for most megafauna, MRE device moorings are **unlikely to pose a major threat**; however, it should be remembered that cetaceans (as European Protected Species) and basking sharks are afforded legal protection at the individual level in Scotland and therefore should be considered accordingly. Baleen whales were considered to be at greatest relative risk overall, largely due to their size and foraging habits. Some mooring designs presented a greater relative risk than others, with the greater relative risks generated by catenary moorings, particularly those containing nylon. Taut systems represented the lowest relative risk. Most moorings associated with MRE devices would likely be too strong for animals to easily break free if they became entangled. Entanglement risks among MRE arrays will likely vary substantially based on device spacing, mooring design and array layout.

Currently MRE development proposals often vary in the degree of detail provided about the moorings' physical properties, complicating attempts by regulators to assess different mooring systems for entanglement risk. The qualitative risk assessment approach described in this report enables device developers and regulatory bodies to assess potential entanglement risks at an early stage of the development of a MRE proposal, allowing appropriate risk management and enabling mitigation strategies to be developed if necessary.

Recommendations include the following:

- When submitting a development proposal, developers should be encouraged to follow the relative risk assessment process outlined in this report, and to provide details of existing and planned routine inspection regimes involving moorings.
- During the consent period of devices and arrays, a procedure needs to be put in place which would require developers to report to regulators any significant changes to mooring and MRE device behaviour over time if such changes would increase the risk of marine megafauna entanglement.
- There is a need for the establishment of an official reporting mechanism by which developers can report the presence of marine megafauna entanglement in MRE device moorings to the regulator (e.g. Marine Scotland who will need to be aware for HRA and EPS purposes).
- A formal accident investigation procedure needs to be put in place by the developer, in order that in the event of an entanglement the appropriate authorities are alerted to allow all relevant information to be recorded, and to trigger an assessment by the regulator into whether any emergency measures were required.
- Details of moorings relevant to the risk of entanglement of marine megafauna should be included alongside Marine Licence applications and within Environmental Statements.
- Further investigations are needed to clarify the distribution and abundance of derelict fishing gear in Scottish waters, and the extent to which gear becomes snagged in moorings or other vertical structures in the water column.
- Further research may be required to assess the full range of entanglement mitigation options available to the MRE industry, to minimise any risks of entanglement events occurring.
- Further research may be required to assess the effects of redistribution of fishing effort displaced from MRE development sites, to ensure that marine megafauna entanglement/bycatch risks are not merely displaced or exacerbated elsewhere as a result.

For further information on this project contact:
Caroline Carter, Scottish Natural Heritage, Battleby, Redgorton, Perth, PH1 3EW.
Tel: 01738 444177 or caroline.carter@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

Table of Contents **Page**

Acknowledgements

Numerous individuals and institutes contributed to this report. We wish to thank Dr. Lindsay Porter (SMRU Marine) for providing information and pictures of entanglement of humpbacked dolphins in Hong Kong waters. Wayne Ledwell (Whale Release and Strandings) kindly provided images of entangled humpback whales in Newfoundland, Canada. Dr. Kate Wynne (University of Alaska-Fairbanks) kindly provided notes and impressions of the fin whale entanglement described in the Case Study of Chapter 2. Aleria Jensen (Stranding Coordinator, National Marine Fisheries Service) provided valuable assistance in compiling and revising the Case Study. Dr. David Donnan (Scottish Natural Heritage) provided helpful information on lost and discarded fishing gears around Scotland. Dr. Scott Landry (Provincetown Centre for Coastal Studies), Dr. Simon Northridge (Sea Mammal Research Unit) and Prof. Lionel Carter (Victoria University of Wellington) kindly provided insights and suggestions for this report regarding entanglement risks of large cetaceans. Finally, we wish to thank the various U.S. government agencies for making available without copyright restrictions various images that are used in this report (through the Wikimedia Commons).

1. INTRODUCTION

The global offshore renewable energy industry is developing rapidly, particularly in Scotland where the Scottish Government is driving growth of the industry as part of its sustainable development agenda. Marine renewable energy refers to offshore wind, tidal and wave energy and the commercialisation of projects exploiting these forms of energy are at various stages of development. Offshore wind is the largest sector representing a large proportion of the current and foreseeable installed generation capacity with over 5GW in the planning process, mostly off the East coast. Floating wind projects are currently also in the planning process but have yet to be consented and installed.

Present wave and tidal energy development is at an earlier stage, with test devices and small grid-connected projects comprising a fraction of overall renewable energy capacity. Wave and tidal energy projects are planned across the Pentland Firth and Orkney waters, Shetland and the Western Isles, with a few consents granted. The wave energy sector is the least developed of the offshore renewable energy sectors, with projects not yet approaching full scale commercial deployment (leases have been granted by The Crown Estate for small wave energy development amounting to approximately 660MW of capacity). The Draft Sectoral Marine Plan for Offshore Wind, Wave and Tidal Energy identifies further areas for potential development of commercial scale projects (defined as over 30MW by Marine Scotland) which will be taken forward to the leasing stage (depending on the outcomes of the consultation process; Scottish Government 2013; Figure 1.1, 1.2).

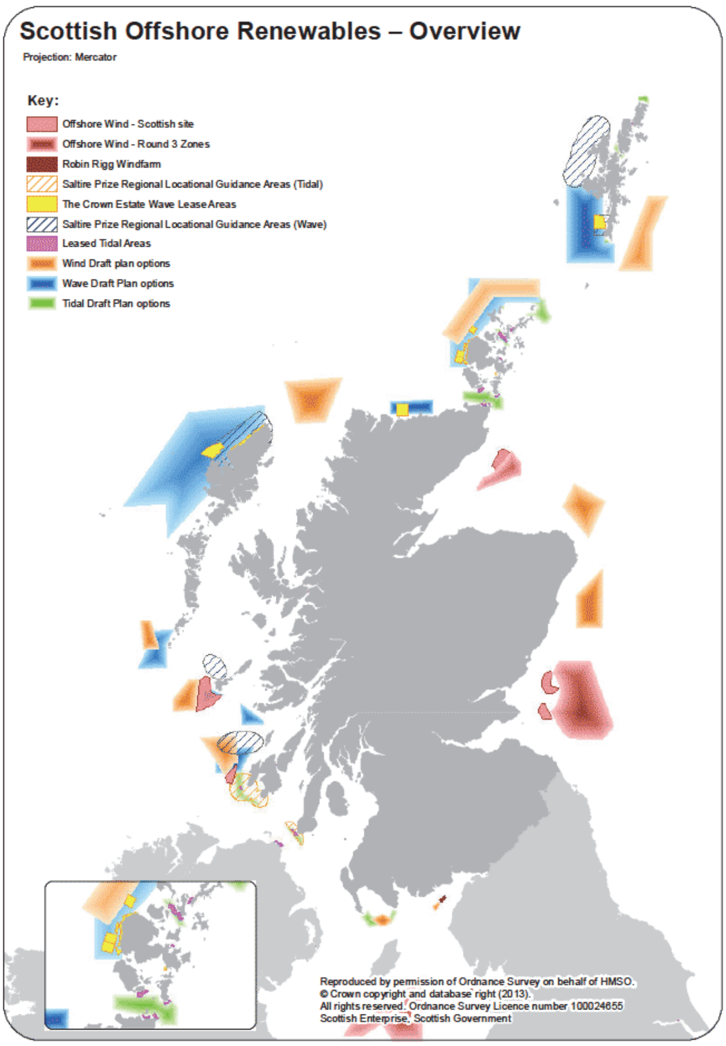


Figure 1.1. An overview of current and planned offshore marine renewable energy projects in Scottish waters. Source: Scottish Government (2013).

Project development is subject to the obtaining of marine licences and associated consents from the relevant authority, including satisfying all legislative requirements relating to the environment and nature conservation. To enable the sector to progress, it is therefore necessary to consider the risks to environmental features and work is progressing at a strategic level and through project-specific investigations to understand possible effects. One potential impact of marine renewable energy development is the risk of whales, basking sharks and other animals becoming entangled in mooring systems and associated power cables. Such entanglement is a serious global conservation problem for many such species of large marine vertebrates (cetaceans [whales, dolphins and porpoises], pinnipeds [seals, sea lions, etc.], sirenians [manatees and dugong], sea turtles, large sharks and large fish, hereafter referred to as "marine megafauna"). The vast majority of reported instances of entanglement, defined in this report as the inadvertent capture or restraint of marine animals by strong, flexible materials of anthropogenic origin, are associated with ropes forming part of fishing gear. To date, there are few reported cases of marine megafauna becoming entangled in moorings or cables of any kind.

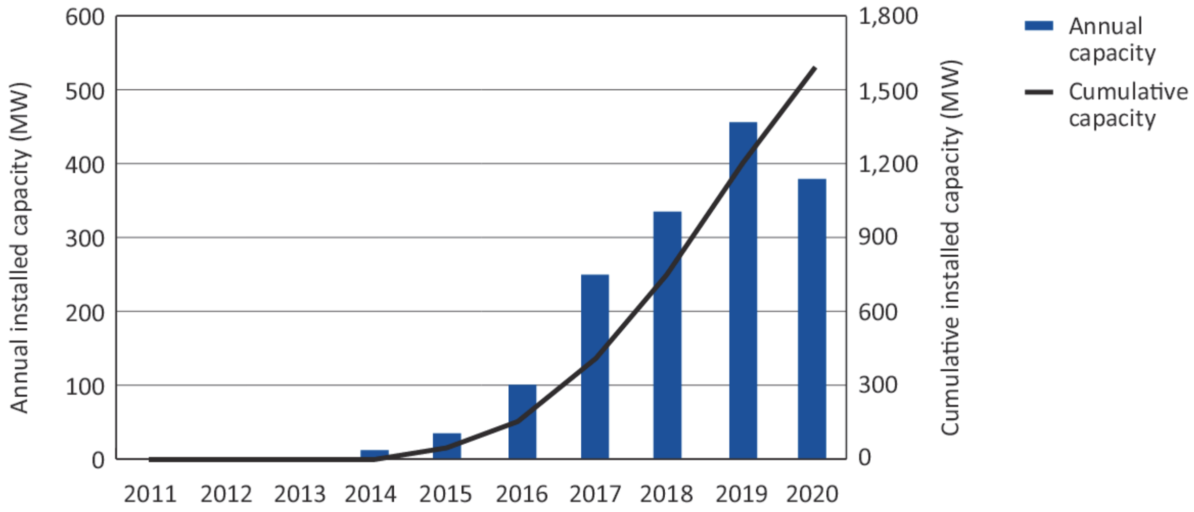


Figure 1.2 Aggregate installation plan for the Pentland Firth and Orkney waters projects (Source: The Crown Estate, 2011)

The proposed future expansion of marine renewable energy (MRE) projects poses a potential risk, particularly in areas where animals' movements may be restricted (tidal channels) or they may be less capable of detecting devices (under energetic tidal or wave conditions). This expected expansion of the industry into more remote and/or offshore sites may also increase the risk of derelict fishing gears becoming caught in moorings and posing a bycatch or entanglement risk. Further (inter)national expansion of the industry may increase the probability of interactions between MRE devices and marine megafauna. This includes development of projects in areas where larger megafauna populations occur (such as the north-west Atlantic, north-east Pacific, and southern oceans) and areas where megafauna recovery from extensive historical exploitation may increase occurrence (e.g. North-east Atlantic ocean). Proper assessment of any risks will have to be based on the most up-to-date and accurate baseline data of marine megafauna presence, distribution and abundance. Such data may not currently be available, in which case additional information will have to be collected. Eventual improvements in our understanding of occurrence of megafauna at development sites will affect the assessment of risks, but the nature of such changes may be difficult to predict. There are likely to be considerable differences between sites, and it may take considerable time before any impacts on animals that are typically long-lived and wide-ranging might become apparent.

Marine megafauna species are protected through specific conservation and protection mechanisms which form part of Scotland's Nature Conservation Strategy. All cetaceans are European Protected Species (EPS) and thus afforded protection against capture, injury, killing and disturbance under the Conservation (Natural Habitats, etc.) Regulations (1994) (as amended in Scotland). Basking sharks are afforded protection through various amendments to the Wildlife and Countryside Act 1981, including most recently the Wildlife and Natural Environment Act 2011. Grey and common/harbour seals are listed in Annex II of the European Habitat Directive and have some protection under the Conservation (Natural

Habitats, etc.) Regulations (1994), and the Marine (Scotland) Act 2010. To enable development to proceed, it needs to be satisfactorily demonstrated that the risk of a negative impact, at either an individual or population level, is sufficiently low as to not compromise nature conservation goals. This process is to be based on scientific evidence as far as possible; there are, however, recognised challenges in addressing uncertainty associated with predicting impacts of new technological proposals on marine species through prescriptive consenting mechanisms.

As a conceivable impact, it is therefore necessary to fully elucidate, using scientific methods, the likely level of risk of impact so that appropriate management measures can be applied to the sector. A level of objectivity is appropriate where it is transparently and pragmatically applied in the form of expert judgement. This report will therefore provide a **qualitative assessment of relative entanglement risk** across different marine megafauna groups, taking into account both biological risk factors such as animal size, sensory capabilities and foraging methods, and physical risk factors such as mooring flexibility, pre-tension and footprint. This outcome will be an independent reference source for assessing the potential risk of entanglement associated with a particular proposal/project design, to provide information on mitigation to be applied to reduce risk where necessary and to enable planners and the regulatory community to consider the risk appropriately when developing strategic plans to support the sector.

2. REVIEW OF EXISTING MARINE MEGAFAUNA ENTANGLEMENT

2.1 Introduction

Incidental mortality of marine megafauna (here defined as marine mammals, marine turtles, sharks, rays and large bony fish; see Table 2.1 for details) caught in subsurface ropes, lines and fishing gears, hereafter referred to as entanglement, is recognised as a significant conservation problem throughout the world (e.g. Laist, 1987; IWC, 1994; Lien, 1994; Laist, 1997; Baum *et al*., 2003; Lewison *et al*., 2004; Read *et al*., 2006; Reeves *et al*., 2013). This process has likely occurred for centuries but has been exacerbated in recent decades by expansion and modernisation of fishing fleets, one important aspect of which has been the widespread use of modern synthetic ropes and nets which are often more difficult to detect and break out of than traditional materials (Henderson, 2001) and decompose at far slower rates. Many marine megafauna species are slow-growing and have low reproductive rates (i.e. produce few young at long intervals), making entanglement-related injuries and mortalities a critical conservation problem for many populations of these species.

There is considerable understanding of how entanglement occurs in fisheries, but much less is known of the potential risks for incidental mortality associated with other offshore industries. The following section will examine entanglement at a global level across all megafauna groups, in order to put into perspective the potential entanglement risks associated with marine renewable energy developments. It is important to realise that entanglement risks associated with marine renewable energy developments are not limited to moorings of MREI devices, as animals may also become entangled in power cables or in smaller moorings associated with marker buoys. Furthermore, mooring structures have the potential to accumulate derelict fishing gears, in which a whole range of species may become entangled, including large whales potentially capable of damaging moorings and other structures whilst trying to break free.

2.2 Scope of marine megafauna entanglement

2.2.1 Definition of entanglement vs. bycatch

Entanglement can be defined as the inadvertent capture or restraint of marine animals by strong, flexible materials of anthropogenic origin. More specifically the term entanglement is typically used to describe animals captured by single or multiple ropes or lines. It is often conflated with bycatch, although this specifically involves animals captured in fishing gears (e.g. gillnets) rather than associated ropes. The two processes are, however, closely related, as many stationary fishing gears include extensive amounts of rope suspended above the seabed or rising vertically towards the sea surface. In the present report, the term '**entanglement**' will be used to specifically describe animals caught in ropes, lines, cables and other mainly linear structures (including lines associated with fishing gears, such as marker buoy lines), while the term '**bycatch**' will be reserved for those cases where animals were caught in actual fishing gears (nets, seines, weirs, etc.), whether active or derelict ('ghost nets'). Many of the issues identified below related to entanglement are also likely to occur in bycaught animals, and it is important to note that this categorisation is to some extent artificial, in that *both entanglement and bycatch result in animals being captured or artificially restrained to the point where injury or death occurs*. In the context of the present report, injury or mortality can happen through entanglement in MRE-device moorings, but potentially also through bycatch in derelict fishing gears that have become attached to moorings or devices. For this reason it is important to review entanglement and bycatch in a fisheries context, given that this problem is particularly prevalent in this sector.

Table 2.1. Overview of megafauna species groups included in the present assessment. Sirenians (manatees and dugong) and seabirds are not explicitly considered here.

Species group		Examples	
Cetaceans	Baleen whales	Humpback whale, fin whale, North Atlantic right whale, minke whale	
	Toothed whales	Sperm whale, beaked whales, pilot whales, killer whales, dolphins, porpoises	
Pinnipeds	Seals	Harbour seal, grey seal	
	Sea lions, fur seals etc.[1]	Steller sea lion, northern fur seal	
Sea turtles		Leatherback turtle, loggerhead turtle, green turtle	
Sharks and rays	Basking sharks	Basking shark	
	Other large sharks and rays	Porbeagle, blue shark, shortfin mako, manta ray	
Bony fish		Ocean sunfish	

Image copyright (from top to bottom): U.S. National Oceanic and Atmospheric Administration (2005); U.S. National Aeronautical & Space Administration (2004); M. Narr (2008); U.S. National Oceanic and Atmospheric Administration (1978); U.S. Fisheries & Wildlife Service (2013); U.S. National Oceanic and Atmospheric Administration (2011); P.Doll (2011); U.S. National Oceanic and Atmospheric Administration (2006). Source: Wikimedia Commons. Images in the public domain or licensed under the Creative Commons Attribution-Share Alike 3.0 Unported licence.

[1] N.B. None of these species occur in the wild in the North Atlantic Ocean.

An important characterization of an entanglement event as defined here is that it typically involves one or more stationary sections of rope, line or other linear structure such as a mooring. Many fisheries-driven entanglements therefore involve stationary fishing gears such as gillnets or pots. Marine megafauna mortality in mobile fishing gears, such as bycatch in purse seines or trawls, will therefore not be considered in this review.

Entanglement is principally a serious problem for individual animals, but it is important to also understand how this risk may materialise at a population level (see Section 2.3.2.5 below for further details). Conservation measures provide protection for individual animals; however the objectives of these measures include maintaining the status of populations, defined as a key aspect of Favourable Conservation Status (FCS) of species protected under the Habitats Directive.

2.2.2 Extent of entanglement

A wide range of marine megafauna have been recorded as entangled worldwide (Northridge, 1991; IWC, 1994). Despite considerable attention being given to the problem in recent decades, it remains a significant source of mortality and injury of marine megafauna in many areas (Reeves *et al*., 2013; see also Section 2.3 below). In light of the above definitions, it is important to note that entanglement records such as those discussed below typically occur against a backdrop of far more prevalent records of bycatch in actual fishing gears.

Many entanglement records involve cetaceans, particularly large whales (e.g. humpback whale [*Megaptera novaeangliae*], North Atlantic right whale [*Eubalaena glacialis*] and minke whale [*Balaenoptera acutorostrata*]; IWC, 1994; Lien, 1994; Knowlton and Kraus, 2001; Northridge *et al*., 2010; Benjamins *et al*., 2012; Reeves *et al*., 2013). Entanglements have been reported across the globe, reflecting the wide distribution of commercial fisheries. Large whales appear to be particularly vulnerable to entanglement in addition to bycatch due to their size and bulk. Fewer comparable records exist of entanglements involving small cetaceans (e.g. dolphins), which are more vulnerable to bycatch in nets than to entanglement due to their smaller size. Entanglement records involving a range of dolphin species do, however, exist, from different areas including the south-eastern U.S.A. (bottlenose dolphins [*Tursiops truncatus*]; Noke and Odell, 2002; McFee *et al*., 2006), Brazil (tucuxis [*Sotalia guianensis*]; Azevedo *et al*., 2008), and Taiwan (Indo-Pacific humpback dolphins [*Sousa chinensis*]; Ross *et al*., 2010). These cases are typically associated with ropes from fishing gears. In Scottish waters, entanglement has been identified as the cause of death in approximately half of all reported baleen whale strandings (Northridge *et al*., 2010), with creel fisheries implicated in many of these cases. There are no current records of dolphins, porpoises or other odontocetes entangled in such gears in Scottish waters. Other static fisheries (e.g. gillnet fisheries) are far less prevalent in Scotland, reducing the potential risk of bycatch to smaller cetaceans.

Like small cetaceans, pinnipeds (seals and sea lions) are often found bycaught in fishing gears (Read *et al*., 2006), and injuries caused by other marine debris are frequently observed (Raum-Suryan *et al*., 2009). Ropes (typically associated with fishing gears) have been reported as a source of entanglement mortality in a wide range of species and localities, including Australian sea lions and New Zealand fur seals off Australia (Page *et al*., 2004), Steller sea lions (*Eumetopias jubatus*) off Alaska (Raum-Suryan *et al*., 2009), Hawaiian monk seals (*Monachus schauinslandi*) in the tropical Pacific (Henderson, 2001), and harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) in the north Atlantic (Lucas, 1992, Allen *et al*., 2012). There are currently no records of entangled seals in Scottish waters, although Allen *et al*. (2012) report rope as one of several types of marine debris found on grey seals at a haul-out site in Cornwall, suggesting that this problem could occur elsewhere in UK waters. Records from the Scottish Marine Animal Strandings Scheme suggest that seal injury and mortality associated with ropes and other marine debris do occur in Scottish waters but may be underreported (Dr. A. Brownlow, Scottish Marine Animal Strandings Scheme, pers. comm.).

Records of sirenian (manatees and dugongs) entanglements and bycatch are rare, possibly because most live in remote areas where monitoring is limited or absent. There have, however, been reports of West Indian manatees (*Trichechus manatus*) being entangled in crab pot lines and other ropes (Beck and Barros, 1991; Northridge, 1991). Given that sirenians are typically found in shallow tropical inshore waters that are unlikely to be developed for MRE generation they will not be discussed in detail in this report.

Sea turtles are often reported as bycatch, typically in demersal gillnets, longlines and pound nets (Gilman *et al*., 2010). Entanglements can occur when turtles encounter even solitary ropes or buoy lines such as those associated with gillnets, creels or traps (Goff and Lien, 1988; Pierpoint, 2000; Zollett, 2009). Entanglement of leatherback turtles (*Dermochelys coriacea*) in fishing gears, particularly creel lines, has been reported in UK waters (Godley *et al*., 1998; Pierpoint, 2000).

Large sharks and rays are often encountered as bycatch in fishing gears (Walker, 1998; Cosandey-Godin and Morgan, 2011). Most of these, however, involve bycatch in hooked longlines, gillnets or trawls rather than entanglements in ropes etc. Basking sharks (*Cetorhinus maximus*) have been recorded in ropes associated with stationary gears, or have been washed ashore entangled in ropes (Lien and Fawcett, 1986; Francis and Duffy, 2002; BBC, 2012). No records of unequivocal entanglement of whale sharks (*Rhincodon typus*) could be found, but such events would not be unexpected given existing bycatch records for this large species (Stevens, 2007). Some large pelagic bony fish species, such as ocean sunfish (*Mola mola*), are also often encountered as bycatch in commercial fisheries (Pope *et al*., 2010) and may be vulnerable to entanglement in ropes. Of all these species, basking sharks are likely to be the species at greatest risk in Scottish waters.

Although marine megafauna species occupy a variety of niches, some common features of the life history of most species include a long lifespan, late maturity, low reproductive output and considerable investment in juvenile development (Lewison *et al*., 2004). As a result, elevated mortality rates due to anthropogenic impacts (such as entanglement of individual animals) are likely to have a disproportionate impact on marine megafauna population sizes, and subsequent recovery may be very slow, on the order of years to decades (Stevick *et al*., 2003; Balasz and Chaloupka, 2004).

2.2.3 Recording entanglement events

By their very nature, entanglement events are difficult to detect from land as they may occur at considerable distances from shore and typically take place underwater. Smaller entangled animals are inherently less likely to be detected than larger ones, but larger animals may subsequently swim off while still entangled, towing lines or fishing gear behind them. The likelihood of witnessing an entanglement event is therefore typically low. In jurisdictions where data collection schemes are in place, reports are provided by fishermen, tourists aboard yachts and/or commercial vessels, but reporting rates are likely to be negatively biased. In addition, casual observers may not recognise an animal is entangled, reporting mechanisms may be lacking, inadequate or insufficiently widely known, or the carcass decays before a full necropsy can be performed to conclusively establish cause of death. All these factors depress reporting rates.

Stranding schemes may provide an additional source of information, although their efficacy will be influenced by numerous factors (Geraci and Lounsbury, 2005). These include distance from the original entanglement event to land, buoyancy of carcasses (variable between species and during decomposition), prevailing currents, the length of the coastline, and accessibility of the coast (Wilkinson and Worthy, 1999). Entanglement in stranded animals is typically diagnosed by the presence of constricting lines or ropes wrapped around one or more body parts, or linear dermal and/or subdermal tissue damage in cases where such ropes have since disappeared (Henry *et al*., 2012), although this becomes increasingly difficult after death as carcasses start to decompose. Details of such tissue damage can help inform what material might have caused the entanglement.

2.3 Processes and impacts of entanglement on marine megafauna

2.3.1 Causes of entanglement

Considerable debate still surrounds the mechanisms by which marine megafauna become accidentally entangled. While an animal's sudden encounter with a rope or line is the proximate cause, it remains unclear in many cases whether an entanglement occurs because of 1) the animal failing to detect the rope; 2) the animal not perceiving the rope as a danger; and/or 3) the animal deliberately making contact with the rope.

The ability of animals to detect ropes or lines in the water (whether by vision, acoustically or by detecting downstream flow disturbances in the water) may be compromised under particular environmental conditions. Although the vast majority of marine megafauna species discussed here possess good eyesight, ropes may be difficult to see in low-light conditions (e.g. in deep water, during high turbidity, or at night) or during storms. Whales and large sharks may have particular problems seeing ropes or cables directly in front of them due to the lateral placement of their eyes on their heads, restricting forward binocular vision (Lien *et al*., 1990; Zhu *et al*., 2001; McComb *et al*., 2009). Trials involving minke whales have indicated that large whales are capable of visually detecting ropes and that white-and-black ropes may be easier to detect (Kot *et al*., 2012). Trials involving simulated ropes of different colours have indicated that North Atlantic right whales responded to red and orange colours at significantly greater distances than green or black ones (Kraus *et al*. 2013). This suggests that the frequency of large whale entanglement might be reduced by changing the colour of commercially available ropes. Sea turtles have been shown to also be sensitive to ultraviolet light, suggesting that ropes reflecting UV wavelengths might help prevent entanglement (Wang *et al*., 2013).

While odontocete cetaceans (toothed whales) possess active acoustic detection abilities (echolocation), most other species rely on passive acoustic detection (hearing) or pressure wave detection to perceive their surroundings. Ropes suspended in flowing water will produce noise in proportion to current flow, and such acoustic cues could be detected by marine mammals, sea turtles and other species (Bartol and Ketten, 2006; Kot *et al*., 2012). Target strengths of ropes used in fisheries have been investigated (Kastelein *et al*., 2000), suggesting that echolocating odontocetes such as harbour porpoises should be able to detect ropes, cables, etc. at distances of tens of metres (Nielsen *et al*., 2012). Pinnipeds also possess acute mechanosensitivity through their vibrissae or whiskers (Dehnhardt *et al*., 2001; Hanke *et al*., 2013) which would likely allow them to detect wakes formed downstream of a rope, mooring or cable. Similarly, sharks and bony fish can be expected to detect underwater objects such as ropes, cables and moorings by means of their dermal mechanoreceptors or lateral line systems (Engelmann *et al*., 2000). Sharks may also be able to detect metallic or electrical elements of cables and moorings at close range by means of their electroreceptors (Haine *et al*., 2001).

Aside from environmental conditions that preclude detection, there may be several reasons why animals fail to detect ropes, cables, moorings etc. in time to avoid entanglement. Marine megafauna are typically long-lived, and juveniles may spend considerable time learning about resources and hazards in their environment. Some species (e.g. whales) exhibit long-lasting relationships that allow juveniles to learn from conspecifics while others (e.g. sea turtles/grey seals) abandon their eggs/young, leaving their young to fend for themselves. Regardless, juvenile animals are typically both inexperienced and inquisitive, and may react inappropriately when confronted with a hazard. This has been reflected in a preponderance of juvenile animals bycaught in certain fisheries (Read, 2013), suggesting that lack of experience around nets contributed to becoming bycaught.

Animals may also be distracted e.g. while feeding on mobile prey species. Filter-feeding and lunge-feeding species, such as North Atlantic right whales, minke whales and basking sharks, are thought to be particularly vulnerable to entanglement because they forage by swimming through or engulfing dense concentrations of prey with their mouths open, thus exposing themselves to entanglement across the mouth (Knowlton and Kraus, 2001; Johnson *et al*., 2005). In baleen whales, ropes can then become captured amongst or behind the baleen (filtering plates in the animal's mouth) and so become difficult to dislodge, particularly since such animals have difficulty reversing direction. Many baleen whale entanglements involve ropes lodged across animal's heads, particularly between the jaws (Johnson *et al*., 2005; Cassoff *et al*., 2011) which appear extremely difficult to remove without human intervention.

Entanglements may also occur when animals are attracted to the vicinity of ropes or lines by novel foraging opportunities. Entanglements apparently resulting from this type of behaviour involving floatlines associated with pot or trap fisheries have been reported for bottlenose dolphins (McFee *et al*., 2006) and loggerhead turtles (NMFS and USFWS, 2008), as animals attempt to obtain either the bait or previously captured target species. Similar situations occur in bottom-set gillnets. The ability of buoys or other floating objects to attract aggregations of fish beneath them is well known and exploited by the use of fish aggregating devices in many areas (Fonteneau *et al*., 2000; Castro *et al*., 2002). Such aggregations of fish beneath moored objects, such as wave energy converters (WECs), could well attract predators that might subsequently become entangled (Brehmer *et al*., 2011). Concerns have also been raised about changes to the benthic environment around long-established extensive mooring systems (development of diverse hard surface communities on moorings and shell middens beneath devices, replacing comparatively species-poor sediment communities) that might attract fish and subsequently marine megafauna (Langhamer *et al*., 2009). Large whales have been anecdotally observed seeking out cables and stationary ships apparently in search of a solid surface against which to scratch themselves, potentially to remove dead skin or parasites (Gentle Giants, 2012). Individual animals' variability in behavioural repertoire, experience and behaviour towards artificial structures are all likely to influence the potential entanglement risks posed by MRE devices towards marine megafauna.

Streamlining is an important consideration when comparing entanglement risk between species. Most marine megafauna have a smooth, streamlined body shape well adapted for fast movement through water. Propulsion, stabilisation and steering are achieved through a range of structures including flippers, tail fins/flukes and/or dorsal fins. As these structures project away from the body into the water, they are often the first body part to become entangled. It therefore follows that animals that have comparatively large appendages relative to their size are at greater risk of becoming entangled. This includes species such as humpback whales, leatherback turtles and basking sharks (see Table 2.1). In some sexually dimorphic species (particularly killer whales), males may possess attributes (in this case a tall dorsal fin and large pectoral fins) that put them at greater risk of entanglement. The presence of rigid dermal structures on the body or extremities (e.g. the callosities on the heads of right whales, bumps on the head and flippers of humpback whales, and external shields of many marine turtles) may also facilitate entanglement. Animals' ability to flex their bodies may be another important factor determining how an entanglement is resolved. Animals with comparatively rigid bodies, like most large whales or marine turtles, may be less capable of escaping entanglement than more flexible species (e.g. basking sharks) which may be able to more easily turn round on themselves and escape. Conversely, animals with more flexible bodies may be more susceptible to accidental entanglement in the first place.

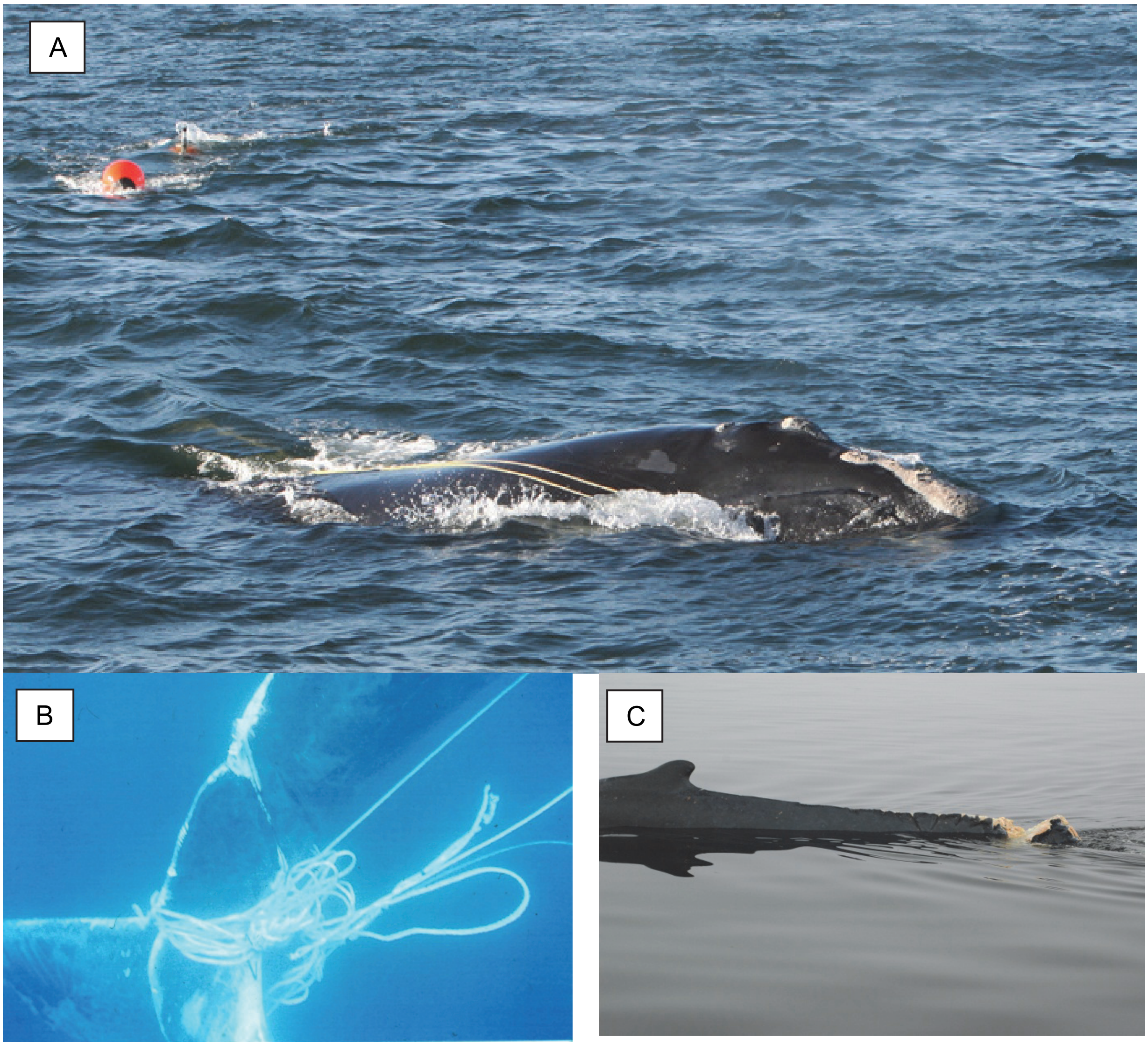


Figure 2.1. Examples of immediate and secondary effects of large whale entanglement in fishing gears, including potentially complex entanglements through the mouth and around the body (A, B), potentially resulting in serious injuries (B, C). Copyright of images A) North Atlantic right whale, Florida Fish and Wildlife Conservation Commission/NOAA News Archive 12272009; B & C) humpback whale, Wayne Ledwell/Whale Release and Strandings, Newfoundland and Labrador, Canada.

Irrespective of the causes of an initial entanglement, once an animal perceives itself to be entangled it may start to roll and turn in an attempt to free itself (Kastelein *et al*., 1995). In many cases, particularly involving fishing gears, this behaviour may only serve to further entangle the animal, resulting in animals that are tightly wrapped in ropes or netting. For obvious logistical and ethical reasons, only limited research has been done to experimentally test the ways in which marine megafauna become entangled, typically involving only a few individuals of smaller, more tractable species (Kastelein *et al*., 1995; Bowles and Anderson, 2012). As a result, our understanding of exactly how entanglements occur remains poor for many megafauna species despite the frequency of such events.

2.3.2 *Effects of entanglement*

Entanglements resulting in stationary animals can either involve carcasses discovered after death, or animals trapped but still alive (e.g. whales able to reach the surface and continue breathing). In addition, larger animals may succeed in towing off all or part of the entangling materials. The following subsection broadly follows the structure of previous reviews of entanglement-related impacts as set out by Cassoff *et al*. (2011) and Moore and van der Hoop (2012).

2.3.2.1 Drowning/lack of oxygen

Air-breathing megafauna (cetaceans, pinnipeds, marine turtles) that cannot reach the surface upon becoming entangled will eventually drown, typically through asphyxiation. This is often the case for smaller animals (e.g. marine turtles) which may subsequently be discovered when equipment is retrieved. Given that many species considered here are excellent divers, the process of drowning following entanglement may take many minutes (Cassoff *et al*., 2011). Larger whales may, however, have the strength to reach the surface or even swim off with equipment still attached. The risk of drowning is increased by the extent of entanglement across multiple different body parts, or circular entanglements around the body. Entangled large sharks (e.g. basking shark) and bony fish (e.g. ocean sunfish), which obtain their oxygen from seawater, may still suffer respiratory distress through restricted gill mobility; this is a particular problem for larger pelagic sharks which often utilise ram-ventilation while swimming (Carlson *et al*., 2004).

2.3.2.2 Infection and tissue damage

Assuming animals remain capable of breathing whilst becoming progressively more tightly entangled, the lines can start to cut into animals' tissues, particularly if an animal is struggling to free itself or is towing gear (Woodward *et al*., 2006; Winn *et al*., 2008; Figure 2.1a-b). Although many animals appear to be able to free themselves of entanglement, tissue damage can be sufficient to induce scarring or subdermal injury. Scarring caused by entanglement is regularly observed amongst baleen whales worldwide, with over 50% of known individuals in some populations (e.g. North Atlantic right whales and humpback whales in the western North Atlantic, humpback whales off southeastern Alaska) experiencing entanglement at least once during their lives (Knowlton and Kraus, 2001; Robbins and Mattila, 2004; Neilson *et al*., 2009; Knowlton *et al*., 2012). The best available data for scarring rates among whales in Scottish waters were described by Northridge *et al*. (2010), suggesting that between 5% and 22% of minke whales in the seas around Mull had experienced at least one entanglement during their lives. As Northridge *et al*. (2010) point out, however, this non-lethal entanglement rate is less important than the lethal entanglement rate, which cannot be estimated without some knowledge of the proportion of entanglement events that end up killing the animal involved. This information is currently unavailable for Scottish waters. As animals drag trailing rope behind them, the force it exerts on adjacent tissues may lead to injury or even death through tissue damage, potentially exacerbated by increased infection risk and septicaemia (Moore *et al*. 2005; Figure 2.1b-c). Such impacts have also been noted in dolphins (see Section 2.4.5 below).

2.3.2.3 Emaciation

Many entanglements, particularly of large whales, involve ropes wrapped around the head region (Cassoff *et al*., 2011). Depending on the extent of the entanglement, animals so restrained may experience difficulty foraging, which will negatively impact their general health. This will lead to accelerated depletion of internal energy reserves (blubber), and may have negative consequences for long-term survival. When emaciated whales eventually die, their carcasses are more likely to sink due to the absence of buoyant blubber, thereby reducing the likelihood of detection (Moore *et al*., 2005). Long-term effects of entanglement on other large species such as basking sharks are unknown, but presumably also include a decreased ability to forage effectively even if the animal remains mobile.

2.3.2.4 Increased drag

Marine megafauna are typically highly streamlined, efficient swimmers and the additional drag imposed on them through towing ropes, fishing gears etc. may be considerable (Moore and van der Hoop, 2012). This may impact animals' ability to forage, dive, migrate and/or invest in reproduction. Recent data on drag forces experienced by an entangled North Atlantic right whale suggest that entangled whales, and presumably also other species, incur significant costs in terms of increased locomotory power output (Van der Hoop *et al*, 2014). This can result in significantly greater demands on stored energy reserves and delay or prevent migration to breeding areas. Large whales released from extended entanglements may experience difficulties in swimming normally for some considerable time following removal of gear (Knowlton and Kraus, 2001).

2.3.2.5 Population-level effects

Low fecundity and a long lifespan mean that many marine megafauna populations are inherently highly vulnerable to adult mortality (Lewison *et al*., 2004). Based on long-term photo-identification studies to assess resighting rates of scarred individuals, humpback whales along the eastern coasts of the U.S. were estimated to suffer a 12.1% annual entanglement rate; annual entanglement mortality rates of this population were estimated to be approximately 3% (Robbins *et al*., 2009). Similarly high annual entanglement and mortality rates have been reported for other large whale populations (Knowlton *et al*., 2012) in those jurisdictions where monitoring schemes are in place. Given the naturally low reproductive rates of many marine megafauna species, such high mortality rates are likely to have a negative impact on population growth. Entanglement-related mortality in fishing gears has been identified as one of the main causes in the lack of recovery of the endangered North Atlantic right whale population in the western North Atlantic (Knowlton and Kraus, 2001; Knowlton *et al*., 2012). Other populations of large whales also suffer from entanglement, but data to accurately quantify annual entanglement and mortality rates are often unavailable. There may be even less information available for other marine megafauna such as basking sharks, for which even reliable population estimates are lacking. As a result, the overall impact of entanglement on populations of these species cannot currently be assessed.

2.4 Sources of entanglement

2.4.1 Fisheries

As indicated in Section 2.1, the vast majority of marine megafauna entanglement events are caused either directly or indirectly by fisheries. In many cases it is difficult if not impossible to distinguish between entanglements involving active fishing gears and those involving gears that were lost. Extrapolating from entanglement data collected in the United States to a global scale on the basis of worldwide fisheries effort data from the United Nations' Food and Agriculture Organisation (FAO, 2013), Read *et al*. (2006) estimated global rates of fisheries-related bycatch and entanglement of marine mammals at hundreds of thousands per year. Given the widespread usage of gillnets worldwide, and the frequency in which marine mammals and other marine megafauna are accidentally caught in well-monitored gillnet fisheries, gillnet fisheries are likely to represent the greatest threat to marine megafauna. Stationary trap fisheries often include extensive mooring systems, and these also may lead to entanglement (e.g. large whales; Benjamins *et al*., 2012).

2.4.2 Aquaculture

There are a limited number of records of marine megafauna (particularly large baleen whales such as humpback and right whales) becoming entangled in mooring lines associated with inshore aquaculture operations (e.g. Pemberton *et al*., 1991; Lloyd, 2003). Recent events in Scottish waters include a juvenile humpback whale becoming entangled and apparently drowning underneath a salmon farm (SRUC 2014). Although current entanglement rates appear low when compared to those associated with fisheries, the global aquaculture industry is expanding at a fast rate and could become a more significant source of entanglement in the future (FAO, 2013).

2.4.3 Offshore petrochemical industry

There are no records of marine megafauna entanglements in moorings or any other infrastructure associated with the offshore petrochemical industry. There are, however, anecdotal observations of large whales seeking out underwater platforms, umbilicals and other structures, apparently as a surface to scratch against. Although absence of evidence of entanglement does not equate to evidence of absence of such events, it would appear that such moorings have not led to large numbers of entanglements to date.

2.4.4 Marine telecommunication cables

There are several historical records involving large whales, particularly sperm whales, found entangled in deep ocean telegraph and telephone cables (Heezen, 1957). No such entanglement has, however, been reported since the 1960s, likely due to improved cable designs, enhanced marine seafloor mapping capabilities and advances in deployment techniques including near-ubiquitous adoption of cable burial procedures (Heezen, 1957; Wood and Carter, 2008; Carter *et al*., 2009).

2.4.5 Vessel moorings

There are numerous reports of large whales (including humpback, right and fin whales) interacting with anchor moorings of yachts and other vessels, towing small yachts from their moorings or becoming entangled in anchor chains, sometimes with lethal consequences (Anonymous, 2012; Richards, 2012; Trekkingthesea, 2012; Kerr, 2013; see also Case Study on p.21). Animals may swim into moorings accidentally whilst moving amongst boats anchored on breeding or feeding grounds; there are, however, anecdotal reports of animals actively seeking out anchor chains or boats as a surface to scratch against (Kimberley Whale Watching, 2012).

Comparatively little information is available on the entanglement risks posed by moorings to smaller megafauna species (dolphins, pinnipeds, sea turtles, etc.). There are several anecdotal references to sea turtles being found entangled in moorings, but details are often unavailable. One well-documented example involves Indo-Pacific humpbacked dolphins (*Sousa chinensis*) in Hong Kong SAR waters, apparently becoming entangled in wire ropes commonly used for anchoring small boats. These entanglements are as yet poorly understood but may result in severe injury over time and appear to be not uncommon in this small population (Dr. L. Porter, pers. comm.; Figure 2.2).

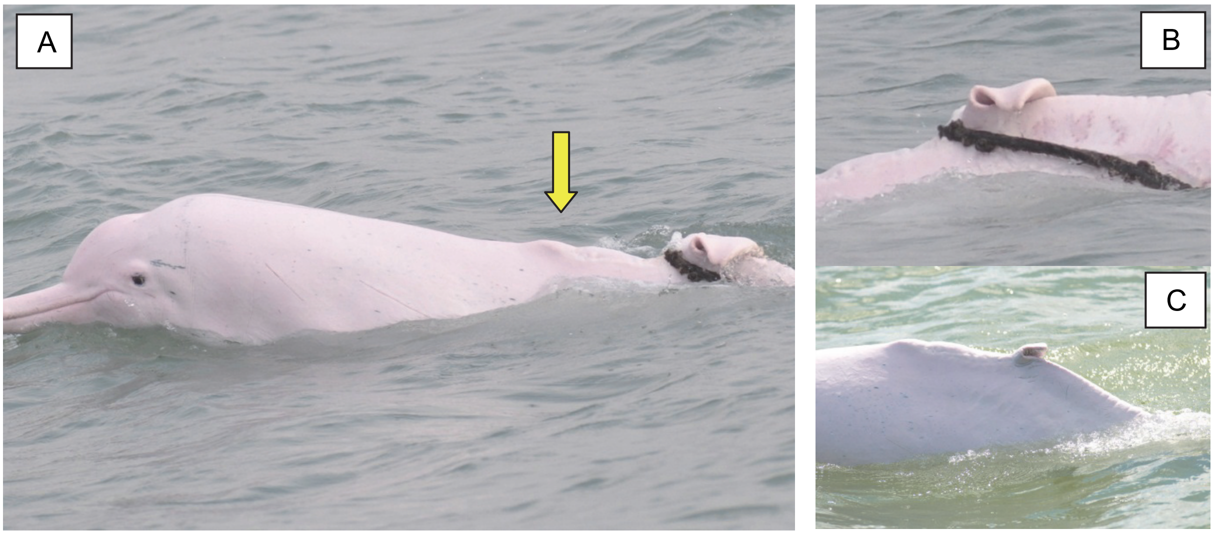


Figure 2.2. Example of entanglement of Indo-Pacific humpbacked dolphin involving wire mooring rope, resulting in loss of the dorsal fin. Pictures A and B (detail) were taken on 11/12/2012 and Picture C (of the same individual) was taken on 08/07/2013, by which time most of the dorsal fin had disappeared. The yellow arrow indicates the likely original frontal end of the dorsal fin prior to entanglement. All pictures © Dr. Lindsay Porter.

Whilst moorings involved in reports to date are typically less substantial than those currently considered for MRE devices, they do suggest that some animals are likely to be unafraid of moorings, may be unaware or indeed attracted to them, and can become severely entangled in them as a result. This clearly has a bearing on assessing the risks surrounding moorings of MRE devices.

2.5 Management of entanglement

Numerous attempts have been made to reduce incidence of marine megafauna entanglement in fisheries worldwide. These range from at-sea disentanglement schemes, to fishing gear modifications, to changes in levels and distribution of fishing effort. Many of these developments have been driven by legislative requirements to reduce fisheries-related mortality in specific groups (e.g., marine mammals, marine turtles; Van der Hoop *et al*., 2012).

Numerous at-sea disentanglement schemes currently operate in various jurisdictions worldwide, typically run by non-governmental organisations or charities. These schemes will attempt to release live entangled whales and other marine megafauna by carefully removing fishing gears, cutting lines, etc. so that the animal can escape. Success rates, in terms of numbers of attended animals successfully released, vary depending on location, logistical difficulties in attending the entanglement (e.g. distance from shore, water depth, etc.), and financial resources. There have been recent moves towards more invasive at-sea release procedures (e.g., partial sedation) in U.S. programmes to further improve entanglement release rates (Moore *et al*., 2010).

Various modifications to fishing gears have been suggested in order to reduce the incidence of entanglement and/or bycatch in them, whilst retaining their ability to effectively capture fish. These include 1) making the gears more easily detectable, either visually or acoustically, by modifying the materials from which they are made (Trippel *et al*., 2003; Cox and Read, 2004; Culik and Koschinsky, 2005; Kot *et al*., 2012; Wang *et al*., 2013); 2) equipping the gears with acoustic alarms, commonly known as “pingers”, that are intended to alert animals or scare animals away (Lien *et al*., 1992 IWC, 1994; Kraus *et al*., 1997; Dawson *et al*., 2013); 3) reducing the amount or extent of potentially entangling ropes and lines in the water column to reduce the probability of entanglement (Johnson *et al*., 2005); and/or 4) deliberately including weak sections in the gears so that entangled animals may break free (Knowlton *et al*., 2012). Multiple methods can be used simultaneously. Other ways in which fisheries can be modified to reduce megafauna entanglement or bycatch include changing gear types used (e.g. from gillnets to fish traps on the seabed), changing fishing effort distribution in space and/or time to reduce overlap (by developing closed areas or changing fishing seasons), and/or an overall reduction in fishing effort (by capacity reduction, fishing licence buy-back, etc.).

Trials of pingers in various fisheries around the world have resulted in considerable declines in small cetacean bycatch rates (Kraus *et al*., 1997; Bordino *et al*., 2002; Barlow and Cameron, 2003; Gönener and Bilgin, 2009; Mangel *et al*., 2013). Some concerns have, however, been raised about the risk of habituation (Cox *et al*., 2001) and local habitat exclusion through disturbance (Carlström *et al*., 2009). Moreover, significant problems remain with ensuring adequate coverage, compliance and device durability (Dawson *et al*., 2013).

In UK waters, bycatch of marine mammals and turtles is recognised as a particularly important conservation problem (DEFRA, 2003). Efforts have to date mainly focused on testing and improving pingers as well as several fisheries closures aimed specifically at the mobile pair trawl seabass fishery off the south coast. There are no present UK initiatives aimed specifically at assessing marine megafauna entanglement in stationary moorings not associated with fisheries.

CASE STUDY – Fin whale entanglement in an anchor chain

On the evening of April 16, 2011, a 58ft fishing vessel anchored in approximately 35 fathoms (64 m) of water in central Uyak Bay, Kodiak Island, Alaska, having spent the day fishing in the area. Waters were reportedly calm and many fin whales were sighted in the vicinity of the bay, apparently feeding on dense aggregations of larval fish. The following morning at ~07:30, the vessel was suddenly forcibly jolted forward as if struck by another ship. Soon thereafter the vessel was pulled sideways with its bow (normally 10ft/3m above the water) being pulled under, and the vessel briefly taking on water. When the skipper finally managed to release the strained anchor line and the vessel straightened itself, there were several more strong tugs on the anchor line before it went slack. The crew then attempted to retrieve the anchor line but was ultimately unable to do so, although a heavy duty winch was used. Some "soft white tissue" was found attached to those sections that were retrieved. The skipper's assumption was that a whale had somehow struck the anchor chain and gotten entangled. No injured whale surfaced and subsequent efforts to recover the anchor chain that day were unsuccessful. The lost anchor line consisted of a solid anchor, ~ 30 fathoms (54 m) of chain (with links approximately 8 cm wide x 12 cm long), and 50-70 fathoms (91 – 128 m) of cable (approximately 2.9 cm in diameter), weighing approximately 450-680 kg in total.

Ten days later, the carcass of a mature fin whale resurfaced in the Uyak Bay area, with the lost anchor chain and cable wrapped around it (Figure 2.3A, B). It appears the chain and possibly the anchor had gotten wedged in the corner of the whale's opened mouth while it was feeding at depth, at which point the whale twisted, knotting the cable in several points around his head, fins, and body. Fin whales typically sink when freshly dead, and decomposition likely contributed to the carcass eventually returning to the surface. The skipper subsequently tried to tow the carcass inshore in an attempt to recover the gear, but was ultimately unsuccessful and the carcass was later lost at sea.

This case is unusual for several reasons, most significantly because it involved a large whale becoming fatally entangled in a comparatively thick anchor line. Similar anchor lines are widely used worldwide and are not generally considered to pose a risk to marine mammals or other megafauna. It appears, however, that under specific circumstances (high concentrations of prey under low light conditions) foraging baleen whales, at least, may have trouble detecting or avoiding large cables and chains suspended vertically in open waters, with potentially fatal results.

This case study was based on information kindly provided by Dr. Kate Wynne (University of Alaska). This case was submitted to the Alaska Marine Mammal Stranding Program maintained by the National Marine Fisheries Service (NOAA) under reference number KW-KOD2012-FW01. Information and photographs were provided courtesy of NOAA Fisheries Alaska Marine Mammal Stranding Program. Photographs were originally collected under NOAA Fisheries permit #932-1905. A brief report of this incident was also published as (Anonymous (2012).

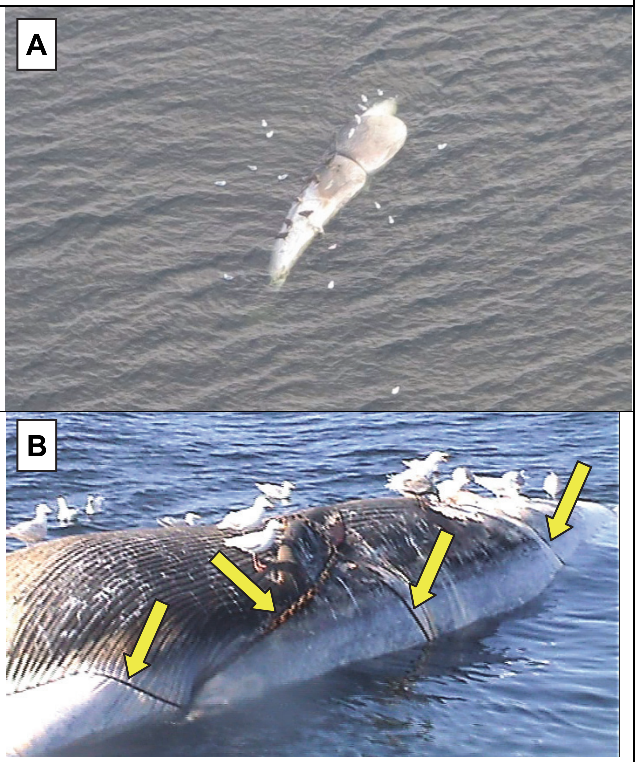


Figure 2.3 A. Aerial picture of the entangled fin whale carcass following resurfacing, with cable visible around the body; B: close-up of the carcass, showing chain and cable wrapped around the body in multiple places (arrows).

2.6 Review of fishing/aquaculture gear loss

Although the key focus of this report is the risk of direct entanglement between marine megafauna and marine energy device mooring or umbilical lines, rates of entanglement may be exacerbated if drifting fishing or aquaculture gear, either lost or discarded, becomes entangled in the MRE device-associated mooring lines. The issue of derelict fishing gear has long been a by-product of commercial fisheries. Commonly referred to as 'ghost nets' or abandoned, lost or discarded fishing gear (Macfadyen *et al*., 2009), this equipment drifts through the sea until it eventually disintegrates or sinks to the seabed, often continuing to trap fish and other marine animals including marine megafauna. Given the slow rate at which such equipment decays, the cumulative impact, in terms of bycatch and entanglement, of derelict fishing gear over time can be substantial.

From the perspective of the MRE industry, derelict fishing gear may pose a risk if it drifts into deployment areas and becomes entangled with devices and mooring infrastructure. With nets potentially tens of metres in width, an entangled net could create a significant barrier to megafauna, in addition to potentially affecting device performance by increasing drag. This risk is particularly acute in energetic waters where MRE devices are likely to be deployed, as strong currents or waves may lift derelict fishing gear off the sea bed and transport it downstream where it may snag on solid structures such as MRE devices and associated moorings. As moorings are likely to remain in place for years at a time, any gear snagged in this way may remain attached and potentially capable of entangling megafauna for a considerable amount of time. Furthermore the range of species susceptible to entanglement or bycatch in derelict gear is far greater than the marine megafauna discussed so far in this report, and includes important groups like diving seabirds (e.g. divers, sea ducks, cormorants, auks) as well as a large number of fish and invertebrate species (e.g. shellfish). When MRE devices are deployed in areas of comparatively soft seabed sediment (i.e. devices with catenary-type moorings using drag embedment anchors) where few obstacles may previously have existed, additional structures will be present on which derelict fishing gear may now snag. As a result, the development of MRE arrays may result in locally enhanced bycatch rates due to the presence of derelict fishing gear on moorings.

2.6.1 Spatial statistical assessment of loss of fishing gear

The phenomenon of drifting derelict fishing gear is largely associated with fishing methods using passive gears, such as gillnets, trammel nets, wreck nets and traps (Brown *et al*., 2005). The causes of lost fishing gear include conflict with towed gear operators, working in deep water, in poor weather conditions or over hard ground, use of very long nets, and working more gear than can be regularly hauled (Brown *et al*., 2005). These factors are largely outside of the control of the fishers (Graham *et al*., 2009), however, gear may also be discarded by illegally operating fishing vessels to avoid enforcement action, and economic pressures can lead to the discarding of nets at sea to avoid the costs of onshore disposal (Macfadyen *et al*., 2009).

Brown *et al*. (2005) suggest that the proportion of nets lost in European fishing waters is low – 'well below one per cent of nets deployed'. The exception is the north-east Atlantic where around 25000 deep water nets are lost or discarded every year, although 'ghost fishing' is not seen as a serious issue in most net fisheries in the EU region. However, the problem is considered serious enough that a number of projects have been established to attempt to quantify the extent of the problem in European waters and propose solutions. These include two EC-funded projects 'FANTARED' (EC Project No 94/095; see Kaiser *et al*. 1996) and 'FANTARED 2' (EC Contract FAIR CT98-4338) (see FANTARED 2, 2003), which worked with national fisheries agencies across Europe to assess the gear loss problem and investigate ecosystem impact and mitigation measures. A further project, DEEPNET, focused on gear loss from the anglerfish fishery to the west and northwest of the British

Isles, attributing the problem to unsustainable fishing practices (Hareide *et al*., 2005). National studies locating and retrieving nets have been performed in Ireland and the UK (Large *et al*., 2009), but these have been geographically limited to specific areas of sea.

Outside Europe, projects such as GhostNets Australia (GhostNets Australia, 2013), and the High Seas GhostNet Project (The High Seas GhostNet Project, 2013) based in the Pacific have set up monitoring programmes to locate and track derelict nets and assess and reduce their impacts. Although these programmes focus primarily on areas of open ocean, a study more relevant to inshore waters where marine energy devices are likely to be deployed has been performed in Puget Sound and the Northwest Straits in the northwestern US (Good *et al*., 2010), a region of sheltered inland marine waters. A single gillnet suspended between rocky outcrops off an island in the sound was found to have thousands of bones piled up to a metre deep along its 30m span, illustrating the risk to marine wildlife of derelict nets becoming trapped in nearshore structures.

However, these projects have all focused almost exclusively on detection and retrieval of nets and assessment of their impacts. Few studies have addressed the question of predicting the paths of drifting nets through numerical modelling in order to assess their possible destinations and the likelihood of encounters with marine wildlife and structures. Exceptions include a study by Wilcox *et al*. (2013), in which a physical model of oceanic drift was combined with ecological data on the distribution of turtle species to quantitatively predict the threat of entanglement to the turtles. Ebbesmeyer *et al*. (2012) used the Ocean Surface Current Simulator model (OSCURS) to simulate potential drift pathways of debris from crab fisheries, and other research has investigated pathways of generic marine debris, e.g. Maximenko *et al*. (2012). However, the issue of modelling the movement of derelict fishing gear was highlighted as an existing data gap in the detection of derelict fishing gear by the ‘Workshop on At-sea Detection and Removal of Derelict Fishing Gear’ held in Honolulu in December 2008 (McElwee *et al*., 2012, McElwee and Morishige, 2010).

2.6.2 Numerical modelling of mean drift patterns

2.6.2.1 Drift motion of floating objects

In 2009, UNEP (United Nations Environment Programme) published a detailed overview of the problems associated with derelict fishing gear (Macfadyen *et al*., 2009). One of the areas highlighted was the fact that discarded fishing gear accumulating in a certain region could have originated from far-field sources, for example derelict gear found in Scottish waters may have been lost in the western Atlantic. An understanding of ocean circulation and drift patterns is therefore essential for understanding the potential movement of such gear. The major circulation patterns in the large oceans are illustrated in Figure 2.4. These are primarily driven by wind, and with the added force of the Coriolis effect tend toward circular patterns, or gyres, which flow around the peripheries of the large ocean basins. With the UK’s position in the Northeast Atlantic, it can be seen how derelict gear from areas such as Greenland, Iceland and the east coast of the US east may eventually drift into UK waters.

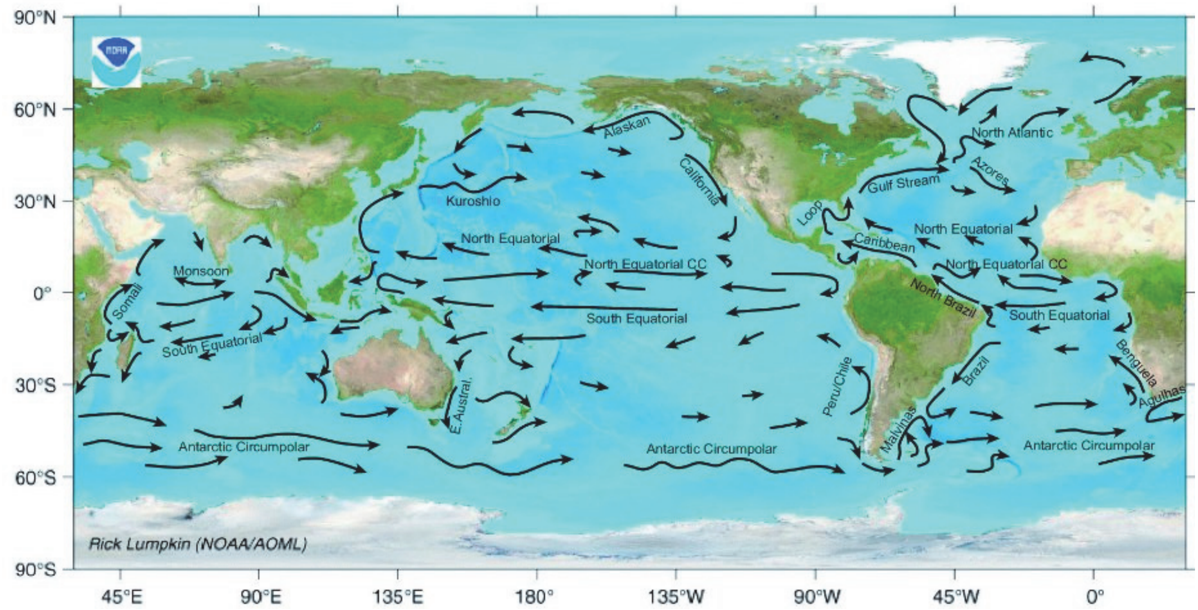


Figure 2.4: Major ocean current circulation patterns (NOAA, 2013).

Techniques have been developed to predict the drift of objects in the ocean. However, this work has usually been approached from the perspective of ship drift, search-and-rescue (SAR) and mapping oil spills. An object drifting in the ocean will be affected by forces due to currents (including tidal, inertial, Ekman drift and wave-induced), wind and wave motion. Its motion will be the net result of these forces, and its position can therefore be estimated by integrating its drift velocity, V_{drift}, where

$V_{drift} = V_{curr} + V_{rel}$ (Hackett *et al.*, 2006).

V_{curr} is the ocean current velocity relative to the earth, and V_{rel} is the object's drift velocity relative to the ambient water, influenced by wave and wind parameters and the geometry of the object.

The drift behaviour of discarded fishing gear is complicated by the fact that different types of nets will be drifting at different depths, depending on factors such as their natural buoyancy, the quantity of fish they are holding (and the state of decomposition of these), and the marine growth on the nets (which will depend on how long the net has been drifting). In deep water areas (>200m), the drift of a net close to the seabed will only be influenced by tidal and ocean circulation currents, while a net closer to the surface will experience wave motion and wave-induced currents and a net at the surface will also experience wind forces. Moving into the nearshore regions where marine energy devices will be deployed, wave motion extends throughout the water column and will therefore play a more significant role on the drift behaviour of nets. A drifting net at the surface will also experience *leeway* drift, where leeway refers to the motion of an object relative to the wind. Most floating objects are asymmetrical, and will therefore drift at a certain angle to the wind.

Experimental studies have been performed to establish leeway characteristics for a range of floating objects (e.g. Allen and Plourde, 1999; Allen *et al.*, 2010), although these mainly consist of ships, boats and objects commonly tracked for search and rescue purposes such as shipping containers. However, there is an example of a particle tracking model adapted to simulate the dynamics of marine debris that allows user-specified leeway values to be input (Hardestry and Wilcox, 2011). The authors apply an equation for the influence of the drag force exerted by the wind based on the horizontal area of the drifting object projected horizontally. Since derelict nets will have minimal area above the water surface, it is expected that this force will be minimal.

2.6.2.2 Approaches to modelling drift patterns of derelict fishing gear

A large number of numerical models to simulate ocean currents have been developed for a range of oceanographic applications, but there are relatively few specific examples of how these have been adapted to specifically address the movements of derelict fishing gear. The Pacific Ocean has seen the largest concentration of efforts to track marine debris (including derelict gear) and much of this work has utilised the model OSCURS. Originally developed by the Alaska Fisheries Science Center as an ocean surface current analysis tool for the Pacific Ocean, it has gained visibility due to its adoption as a debris tracker (NOAA, 2014). However, the application of the OSCURS model is limited to the Pacific. Other programmes involved in the monitoring and tracking of derelict gear have developed their own regional models, such as the GhostNets Australia project (GhostNets Australia, 2013). However, much of the research and tracking work for the North Atlantic has relied on monitoring rather than modelling, so there is a need for development of a more localised model to track gear that may drift into UK waters.

2.6.3 Considering entanglement risk due to derelict fishing gear

The probability of derelict fishing gear accumulating on moorings or MRE devices will be influenced by numerous factors. These include: 1) the presence of source fisheries upstream, which can potentially include areas considerable distances from the moorings, 2) the rate of gear loss from these fisheries, 3) rates of movement or drift by derelict gears downstream, 4) structure of moorings and MRE devices, and 5) the amount of time the mooring has been deployed. Intuitively it can be assumed that structures with complicated shapes, large protrusions or sharp corners will be more likely to retain drifting nets. Also, moorings remaining in the water for extended periods of time are more likely to capture derelict gears than moorings that are regularly lifted and cleaned. Progressive biofouling by seaweeds and sessile invertebrates over time may influence the rate by which moorings accumulate such gears. MRE devices with multiple mooring lines by their very nature offer additional places for derelict gears to become attached. Such gears may stretch between different moorings and thereby affect a greater fraction of the water column. If nets are suspended between moorings, they will resume fishing and pose a risk for a wide range of marine megafauna species, including comparatively small-bodied species such as diving seabirds which would not normally be considered at risk of entanglement in moorings.

Once nets have become captured by a mooring, they may remain there for considerable lengths of time, similar to what is observed on shipwrecks and natural features such as coral heads. This will create additional drag on the mooring, which may eventually affect its performance. Furthermore, the structure of the net will itself become biofouled, adding significantly to the drag (Swift *et al*., 2006), although such biofouling could also make it easier for animals to detect and avoid the net.

A considerable proportion of some populations of large whales have been shown to be towing fishing gears at some point in their lives (Robbins *et al*. 2009; Knowlton *et al*. 2012). Some of these animals are known to have become entangled in multiple different kinds of fishing gear at once (e.g., gillnets and crab pots; Benjamins *et al*., 2012). Similarly, whales already towing fishing gears may be at greater risk of subsequent entanglement among moorings or other structures.

2.7 Summary

Entanglement of marine megafauna in fishing gear (mobile and static; active and lost) is a serious global conservation problem affecting a wide range of marine megafauna. Other sources of entanglement (i.e. in ropes, cables, moorings) may also be an important consideration for conservation, particularly in light of the legislative protection of many of the susceptible species. Entanglement may come about through various means including animals failing to detect an obstacle (e.g. at night, in poor visibility or in stormy conditions), not perceiving the obstacle as a threat (e.g. inexperienced juveniles), or actively seeking out the obstacle (e.g. for foraging purposes). It can lead to serious injury or mortality of individual animals involved, and may result in long-term effects on megafauna populations through reduced adult survival rates.

Although the vast majority of recorded marine megafauna entanglements are directly or indirectly attributable to ropes associated with fishing gears, there are various substantiated reports from around the world of animals (mainly large whales) entangled in other kinds of ropes or structures including moorings. The comparative dearth of reported cases could reflect a genuine ability of animals to avoid entanglement under most conditions, but could also be at least partially explained by the majority of moorings, cables and aquaculture sites currently being situated close inshore where large megafauna species may now be rare or absent. Populations of many megafauna species such as large whales were severely depleted historically and are slowly recovering, suggesting that any interactions are likely to increase as populations re-occupy their ranges. Similarly, expansion of moorings into new areas (e.g. further offshore) may increase the potential for interactions.

Nevertheless, based on existing reports it appears that moorings such as those proposed for MRE devices will likely pose a comparatively modest risk in terms of entanglement for most marine megafauna. Certainly, potential entanglement risks posed by moorings appear far smaller than the documented global risks of entanglement and bycatch associated with fishing gears. Whilst the risks arising from moorings to most megafauna populations appear relatively limited, individual animals may still become entangled in mooring lines, particularly when devices use large numbers of moorings or where many devices are deployed in close proximity as part of an array.

Finally, it is important to note that marine megafauna may face a greater threat from entanglement or bycatch in derelict fishing gear captured by moorings or MRE devices. Little is currently known about the amounts of derelict fishing gear, its propensity to be captured and retained by moorings in exposed energetic areas, or its risk to marine megafauna under such conditions. Although risks of entanglement between derelict fishing gear and MRE moorings and structures clearly exist, further studies are required to quantify the level of risk. This should address not only the volume of derelict gear located in MRE deployment areas, but also the likelihood of entanglement with MRE structures and how this would increase the risk to marine wildlife.

3. REVIEW OF MARINE RENEWABLE ENERGY MOORING SYSTEM DESIGNS

3.1 Introduction

Before installation of Marine Renewable Energy (MRE) devices (here defined as wave, tidal and floating wind energy converters) can proceed, developers are typically required to provide environmental impact studies (e.g. as defined in the EIA Regulations and s36 of the Electricity Act (1989), in order to avoid negatively affecting the environment at the deployment site. The aim of this report is to explore potential injurious interactions between marine megafauna and MRE device moorings, with a particular focus on entanglement. For this to occur, detailed understanding is needed of how moorings behave under variable environmental conditions.

At present, entanglement of marine megafauna in moorings or cabling associated with MRE devices is not typically considered in environmental impact studies. For this reason, recommendations should be developed to allow developers and regulators to make an informed evaluation about proposed mooring and cabling arrangements at the time of application. Such an evaluation needs to be undertaken at an early stage of MRE device mooring configuration design, concurrent with technical design considerations, in order for it to be effective.

Various parameters must be considered in the design of MRE mooring systems (Johanning *et al.*, 2005). Some of these design parameters are similar to offshore installations of moored oil or gas platforms; for example some of the materials are the same (e.g. chains, shackles) and established procedures can be applied. However, the installation of MRE mooring systems requires the consideration of further parameters that are not typically considered within the oil and gas industry. For example, tidal variations and current speed are significant in the relatively shallow waters where MRE devices are expected to be installed, but are often negligible for offshore oil and gas industry applications.

The primary function of any mooring system is the survival and the station keeping of the floating structure, including keeping the anchors in their position, the mooring system intact, and the floating structure attached to the mooring system even in the most severe storm conditions. The cost of the system will be directly related to meeting this requirement, and that of fatigue and abrasion loading, which needs to be assessed over a design life of 30 years for MRE moorings (Harris, 2004). Mooring design calculations will take into account the response of the system to dynamic wave frequency loads, moving the buoy in a dynamic way with large accelerations, and slow low frequency loads, leading to a large horizontal excursion (horizontal amplitude) of the floating structure and consequently tensioning the power cable.

This section will consider various issues relating to mooring system design. An overview of regulatory requirements is presented, followed by a review of various engineering considerations and challenges that form part of the mooring system design process. These include constraints imposed by MRE device motion, considerations surrounding array configuration, generic mooring types, a choice about what materials to use in the mooring, environmental loading considerations, and the overall design process. Subsequently a numerical modelling study is described, utilising different combinations of these parameters to estimate the stiffness characteristics of six different mooring configurations, the total swept volume covered by the device and mooring lines for a range of sea states, and the curvature of the mooring line for the maximum excursion of the floating structure in a given sea state.

On the basis of the modelling study, a risk assessment approach is developed in Section 5, in which appropriate biological and engineering parameters considered to contribute to the risk of entanglement are assigned risk factors. This will form the basis for a risk matrix for the six modelled moorings, described in more detail in Section 6.

3.2 Regulatory requirements and standards

In Scotland, marine life is afforded legal protection under EU Council Directive 92/43/EEC of 21 May 1992, widely known as the Habitats Directive. This legislation is transposed into Scots law through the Conservation (Natural Habitats, &c.) Regulations 1994 (as amended in Scotland). Within this legislation there is specific protection for Annex II species (including grey and common seals, bottlenose dolphin and harbour porpoise) whose conservation requires the designation of Special Areas of Conservation. Seals are also protected under the Marine (Scotland) Act (2010). Also, Annex IV species are classified as European Protected Species (EPS) and include all cetacean species and turtles whose natural range includes UK waters. Under this legislation, it is an offence to deliberately or recklessly disturb, capture, injure or kill such species. Basking sharks have full legal protection under the Wildlife & Countryside Act 1981 (as amended by the Nature Conservation (Scotland) Act 2004). Permission for certain activities that are potentially disturbing may be given under license. Other elasmobranchs in Scotland are afforded protection under the Sea Fisheries Statutory Instrument (The sharks, skates and Rays (Prohibition of fishing, landing, transshipment) Order 2012. No.63). There are no specific Scottish conservation measures in place for ocean sunfish.

There are no current statutory requirements for moorings associated with MRE devices in Scottish waters. As a result, applications for MRE device deployments vary considerably in terms of the level of detail provided of what mooring systems are likely to be used. This complicates efforts by the regulatory agencies to adequately assess the potential risks associated with different mooring configurations.

Several standards and guidelines applicable to moorings for offshore devices have been developed and are currently applied for the design of MRE devices. Most of them refer to existing offshore oil and gas standards such as the API-RP-2SK, of the American Petroleum Institute, DNV-OS-E301 of Det Norske Veritas or the ISO 199901-7 of the International Organisation for Standardization. A guideline focusing specially on MRE devices is at presently in preparation by the TC114 group of the International Electrotechnical Commission (IEC in prep.; see below). A list of guidelines and standards can be found in Table 3.1.

Table 3.1: List of mooring guidelines and standards.

Guideline	Publication Date
Det Norske Veritas	
Design and Installation of Plate Anchors in Clay: DNV-RP-E302	2002
Geotechnical Design and Installation of Suction Anchors in Clay: DNV-RP-E303	2005
Offshore Mooring Chain: DNV-OS-E302	2009a
Offshore Mooring Steel Wire Ropes: DNV-OS-E304	2009b
Position Mooring: DNV-OS-E301	2010a
Environmental Conditions and Environmental Loads: DNV-RP-C205	2010b
Design and Installation of Fluke Anchors: DNV-RP-E301	2012a
Certification of Tidal and Wave Energy Converters: DNV-OSS-213	2012b
Offshore Fibre Ropes: DNV-OS-E303	2013a
Design of Floating Wind Turbine Structures: DNV-OS-J103	2013b
Det Norske Veritas and Carbon Trust	
Guidelines on design and operation of wave energy converters	2005
American Petroleum Institute	
Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring: API RP 2SM *(amended version)*	2007
Mooring Chain. API Spec 2F	1997
American Bureau of Standards	
Guidance Notes on the Application of Fiber Rope for Offshore Mooring	2011
Guidelines for the purchasing and testing of SPM hawsers	2000
Bureau Veritas	
Classification of Mooring Systems for Permanent Offshore Units. NR 493 DT R02 E	2012
Certification of fibre ropes for deep water offshore services. 2nd edition. NI 432 DTO R01E	2007
Rules for the Classification of Offshore Loading and Offloading Buoys NR 494 DT R02 E	2006
International Standards Organisation	
Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 7: Station keeping systems for floating offshore structures and mobile offshore units: ISO19901-7:2013	2013
Shipbuilding and marine structures -- Mooring winches: ISO3730:2012	2012
Fibre ropes for offshore station keeping: Polyester: ISO18692:2007	2007
Fibre ropes for offshore station keeping: High modulus polyethylene (HMPE): ISO/TS14909:2012	2012
Ships and marine technology -- Stud-link anchor chains: ISO1704:2008	2008

The certification of a mooring system will involve determining the mooring line and component performance for different environmental conditions, when the moored system is 1) fully operational (Ultimate Limit State), and 2) during a condition when a part of the mooring system has failed (Accident Limit State). In addition a fatigue analysis (fatigue limit state) of the mooring system is required by the Det Norske Veritas offshore standards (DNV-OS-E301) for a long-term (≥5 years) mooring deployment. Special guidelines and regulations are applicable for the application of mooring components such as ropes and chains that are included in DNV-OS-E303 and DNV-OS-E302, respectively. These standards and regulations have in common that they provide technical guidelines for the safe deployment and station keeping of a moored system, but do not consider any consequence for entanglement.

3.3 MRE mooring system design

3.3.1 Device characterisation

It is fundamentally important to understand the dynamics of the floating structure and mooring system of a single MRE device or of an array of MRE devices. In order to establish a generic design approach for mooring systems for floating MRE devices it is helpful to categorise existing devices based on how they have to respond to the incident wave field. This depends on the method of extracting energy and can be exemplified by the question "does the device need to remain nearly stationary with respect to the mean water level (motion-independent), or should it respond almost freely to wave motion in a resonant fashion (motion-dependent)?". Floating wind and tidal devices, as well as some wave energy devices, fall in the first category, whilst other wave energy devices fall in the second category. Examples of motion dependent and motion independent devices are given in 3.1.

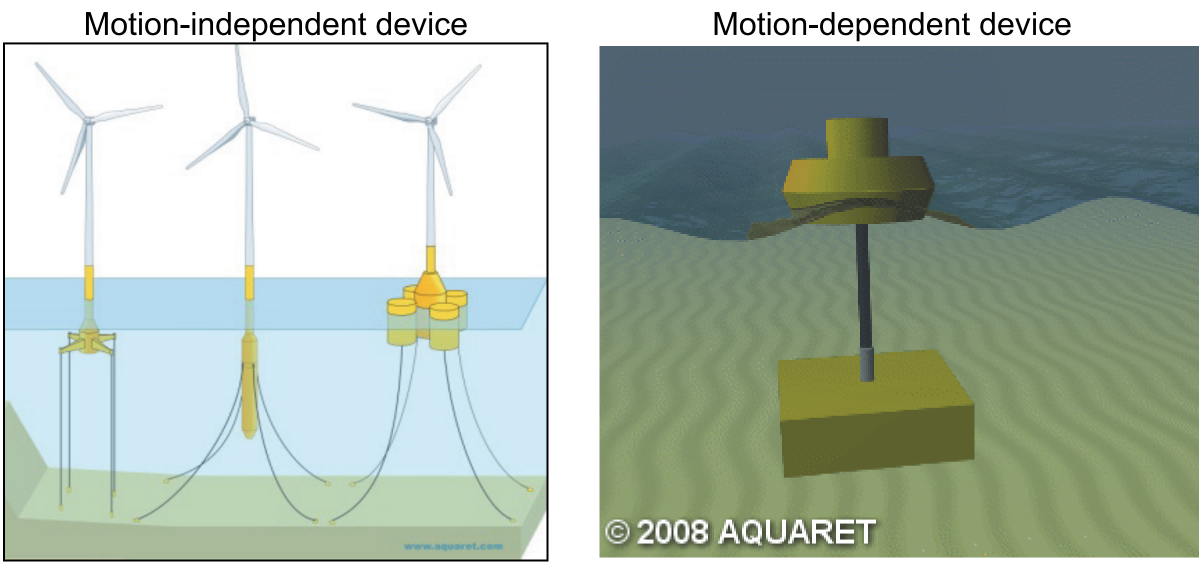


Figure 3.1 Example of motion-independent (floating wind turbines) and motion-dependent devices (wave energy point absorber; source: Aquaret). The motion-dependent device is designed to be far more mobile, with potential entanglement consequences.

A motion-independent device will use a mooring which will act in a conventional manner to keep the device on station. In this case the needs of the mooring are similar to that for a conventional oil and gas floating installation. In particular the resonant period of the mooring (defined as the period where the buoy oscillates with a larger amplitude than at other periods for the same wave amplitude), is designed to fall outside the range of wave periods present at this site. The mooring system should provide a strong restoring force (e.g. horizontal force) to keep the floating structure as stationary as possible. In the context of MRE devices, such a mooring system might be used for floating wind turbines. Motion-dependent devices require the application of a mooring such that the resonant period of the device and mooring system match the wave period as far as is practicable. However, this is difficult to realise for a large range of wave period. The restoring force provided by the mooring system should be sufficiently low in order to let the floating structure move as dynamically as possible. In the context of MRE devices, such a mooring system might be used for some wave energy devices.

3.3.2 Array configuration

Considering the installation of MRE arrays, most currently considered installation locations cover a relatively small area (with the potential exception of future floating wind farms). For example, the Wave Hub (wave) and EMEC (wave and tidal) test sites cover approximately 8-20 km^2. These comparatively small areas would require a relatively dense arrangement of converters to optimise power production, whilst minimising the length of costly power cable and mooring lines. The density of MRE devices within an array is likely to increase the risk of entanglement. Several parameters should be considered for an array:

- Devices in the array should avoid **negative interferences** in power production (Myers *et al*., 2010) through waves radiated or absorbed by the different devices of the array. This would determine the layout and maximum device density of the array.
- The allowable excursion (movement in response to waves or currents) of the floating structures must be small, principally so that adjacent devices **avoid contact.**
- A dense MRE array would require short mooring lines providing a **small footprint area** (area occupied by the mooring lines on the seabed) to allow for the installation of multiple devices. This would be in contrast to typical offshore oil and gas installations where the footprint area is mostly unrestricted, and only obstacles such as pipelines, risers, etc. need to be considered since they are not allowed to touch each other.
- The **removal of a single device** without affecting adjacent devices should be possible.
- Mooring lines and anchors can be shared between several devices.

A small excursion and a small footprint area could be achieved through:

- the use of a heavy catenary mooring arrangement,
- the introduction of a taut configuration,
- a combination of elements, using intermediate buoys or clumps, which would assist in the removal of a single device.

An assessment of different mooring configurations and line materials and their consequences for the excursion of the floating structure will be discussed in the following section.

3.3.3 Mooring types

A variety of mooring configurations have been developed over time for the station keeping of offshore structures, fish farms, etc., and a comprehensive guide can be found in Barltrop (1998). Although single point moorings (SPMs) are often used e.g. for anchoring ships, multiple mooring lines are desirable for reliability, so that devices are not cast adrift in case of the loss of one mooring line. Examples for catenary and single point moorings from the offshore oil and gas industry are shown in figure 3.2A-B, respectively.

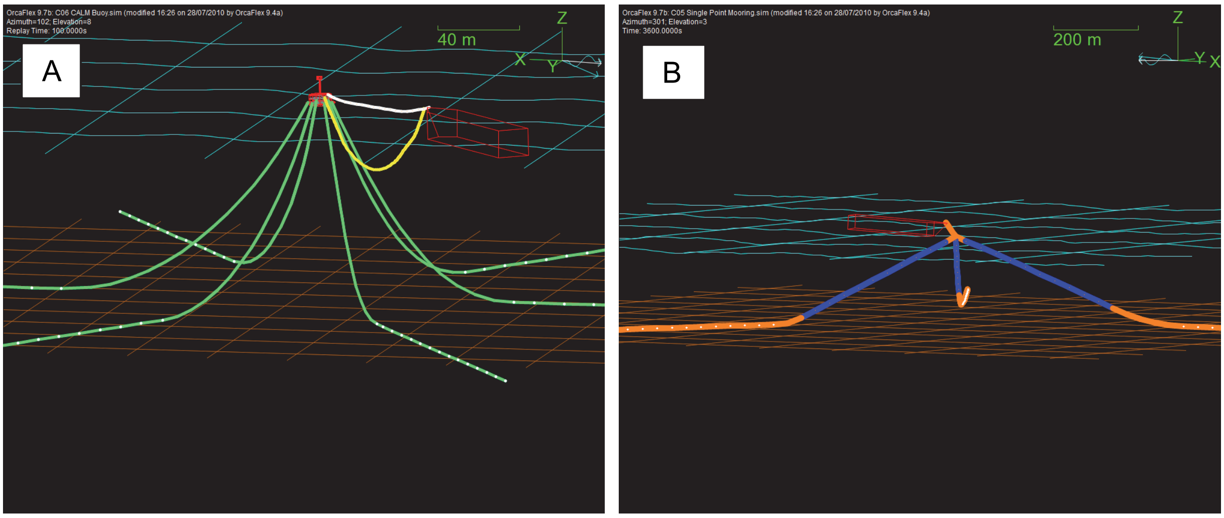


Figure 3.2. Examples of (A) catenary anchor leg moorings (CALMs) and (B) single point moorings (SPMs) used for anchoring production vessels. Source: OrcaFlex™. CALM configurations provide redundancy whereas SPM configurations are connected with only one line to the floating structure.

The two main types of mooring system which are applicable to MRE device systems are slack and taut-moored systems, which each have several variants. Each of these mooring designs can also include subsea buoys, clump weights and/or bend stiffeners to maintain particular configurations.

MRE devices within arrays are likely to be closely spaced, potentially allowing the sharing common mooring attachment points. The compliance of a slack mooring system will allow a connected device to move in several degrees of freedom in response to wave, current and wind forces. Whilst large motions in one degree of freedom (i.e. heave for a WEC point absorber) may be desirable, a mooring system which is too compliant may lead to large horizontal motions as well as a large spatial footprint of the mooring lines with the possibility of 1) collision with adjacent devices at surface, and 2) entanglement of megafauna species in the water column. Additional loadings due to variations in tide height need to be considered as they will result in cyclical variations in load, contributing to rope pre-tension (tension when non-dimensional excursion equals zero) increasing during tide floods and conversely allowing relaxation as the tide ebbs.

MRE devices will require some form of energy export system, which will often take the form of power cables that are ultimately connected to the onshore electricity grid, adding further obstacles into the water column. The power cables would most likely be deployed in standard (e.g. ‘lazy-S’, ‘steep-S’ or ‘Chinese lantern’) configurations, using clump weights and subsea buoys. Examples of a lazy-S and a steep-S configuration are shown in Figure 3.3. The configuration and number of power cables will vary significantly between different devices and arrays. These cables present additional obstacles in the water column and could conceivably also cause entanglement, either directly (e.g. foraging large whales) or indirectly (by acting as an anchor point for derelict fishing gears). The extent of interconnector cables, and the volume of water impacted under different sea states, could be quantified using a similar modelling procedure to the one discussed in Section 4.3.

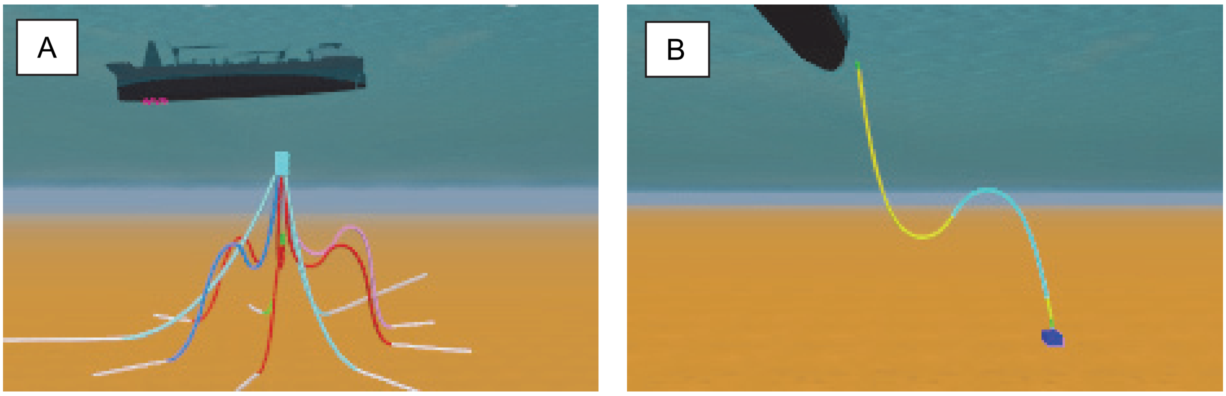


Figure 3.3. Examples of power cable configurations: A) lazy-S configuration; B) steep-S configuration. The lazy S uses catenary chains lying on the seabed, whereas the steep-S uses a clump weight to connect with the seabed. Source: OrcaFlex™.

Two main types of mooring configurations are considered for this entanglement study, namely slack catenary moorings and taut moorings. Modified versions of both these configurations are also investigated by incorporating accessory buoys into the model, thereby altering the top end motion characteristics. Concepts of the mooring configurations included in the mooring parameter study (Section 4 of this report) are shown in Figure 3.4.

- Catenary mooring configuration

Catenary lines provide restoring forces when the heavy chains lying on the seabed are lifted (Figure 3.4a). When the excursion of the device is increasing, tensions in the mooring line increase non-linearly, until the chains are fully lifted and tensions increase in a linear way thereafter. Fibre ropes can be used in the section between the surface and the seabed to reduce the weight and cost of the mooring and to allow the floating structure to move more freely, because the weight of the mooring lines may limit the dynamics of the floating structure. However, fibre ropes should avoid contact with the seabed because of the risk of damage through abrasion. Cost-effective drag embedment anchors can be used because the mooring tensions near the anchors are nearly horizontal. However, the footprint of such a system can be large. Vertical loaded anchors (VLAs) can then be used to reduce the mooring footprint because they allow vertical loads, thereby reducing the need for extensive lengths of chain lying on the seabed.

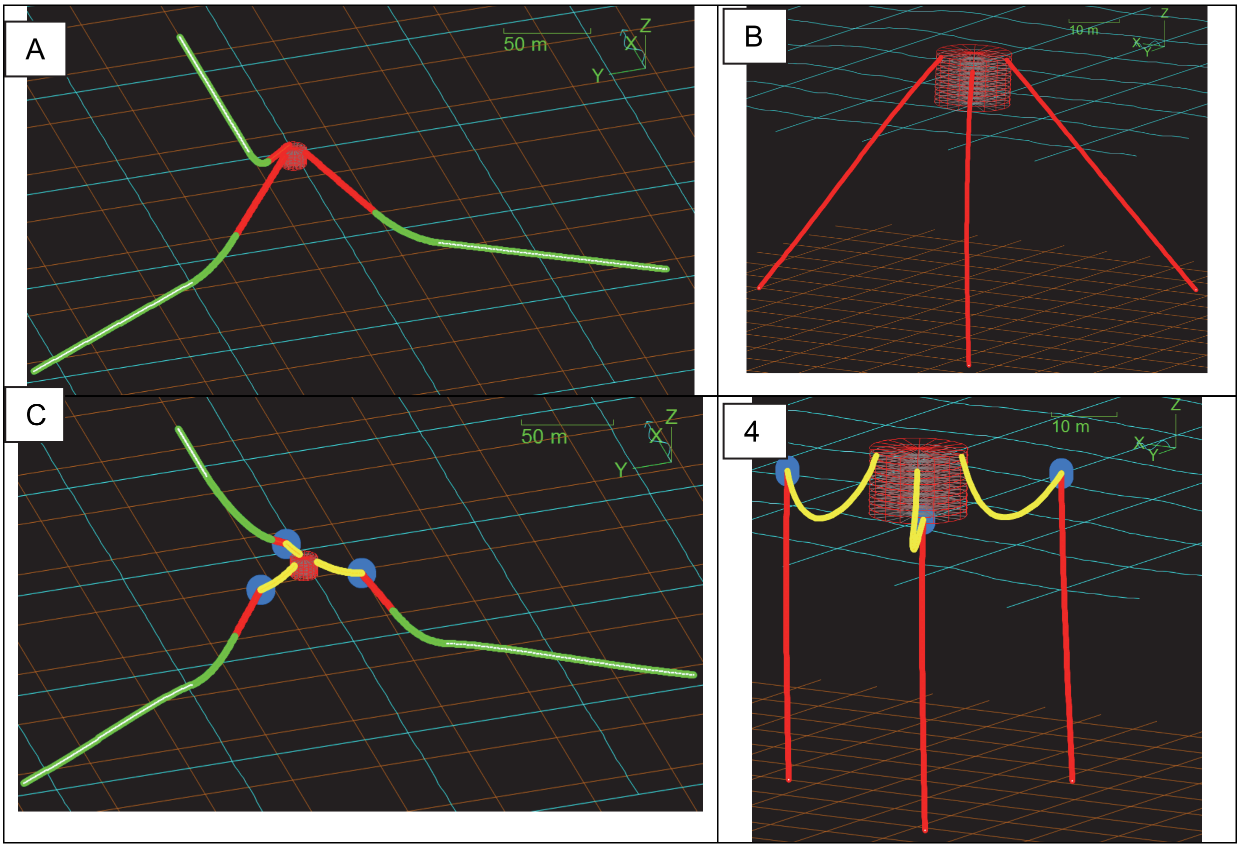


Figure 3.4 Mooring configurations used for the present mooring parameter modelling study. A) Catenary mooring configuration; B) Taut mooring configuration; C) Catenary mooring configuration with accessory buoys; D) Taut mooring configuration with accessory buoys.

- Taut mooring configuration

Taut mooring systems (Figure 3.4b) provide restoring forces from the axial strength of the lines, with tensions in the mooring line increasing linearly when the excursion of the device is increasing. Consequently, a taut configuration will have a small footprint and a small excursion. Fibre ropes are commonly used as they provide elastic properties which are often desirable. Anchors have to be able to resist vertical loads; piles or deadweight anchors can be used in such cases. These anchors may be expensive to install, requiring expert installation vessels. However, because of their high pre-tension (tension when non-dimensional excursion is equal to zero), taut configurations also restrain motions of small amplitude, which may reduce the power production in the case of a motion-dependent device.

- Catenary mooring configuration with accessory buoys

In this configuration, each catenary line is connected to a surface buoy, and a connector links the accessory buoys and the floating structure (Figure 3.4c). This allows a reduction of the weight of mooring chains attached to the floating structure which may be an issue in a standard catenary configuration. One drawback of the use of an intermediate buoy is that moorings are less able to limit the excursion of the floating structure, which may be undesirable in an array.

- Taut mooring configuration with accessory buoys

In this configuration, each taut line is connected to a surface buoy, and a connector links the surface buoys and the floating structure (Figure 3.4d). This allows a reduction of the pre-tensions of the mooring lines attached to the floating structure which is an issue for a taut configuration.

3.3.4 Mooring materials

The following components are commonly used in mooring configurations, with details of their materials provided in Table 3.2.

Typical mooring lines:
Chain and/or synthetic fibre ropes: Properties of these components are presented in

- Table 3.2, although these will vary slightly depending on type, construction and manufacture. Diameters of chain available for commercial usage range from 6 to 175 mm but commonly used chain types in the marine renewables industry tend towards the more robust end of that range. In a catenary line, the decision on what chain diameter to use is typically informed by the resulting total weight, in order to avoid excessive vertical loads on drag embedment anchors.
  Fibre ropes available for commercial purposes range from 16mm and 240mm in diameter (Bridon manufacturer catalogue, 2011). The main parameter on which to base the selection of rope diameter is the minimum breaking load (MBL), which represents the smallest load capable of breaking the rope (typically provided by the manufacturer). The MBL is divided by a factor of safety (FOS) value. The choice of fibre rope diameter depends on demands for both strength and elasticity: the stronger the rope, the less elastic it is, and the higher the mooring loads it can sustain.

Typical mooring connectors and weight/buoyancy components:

- Shackles or swivels (Vryhof, 2000): Shackles are a commonly used connector, made of a bow and a pin. Different types are available, depending on the application. Swivels are used to relieve the twist and torque that build up in a mooring line, close to the anchor point, or between chains and a rope.

- Intermediate clump weights or floating buoys are used to locally modify the weight of the mooring line or to reduce the weight/pre-tension on the floating structure.

Typical anchors:

- Drag embedment anchors which cannot accommodate large vertical loads;
- Vertically loaded anchors (VLAs) which can accommodate larger vertical loads;
- Deadweight anchors, which can be very large and heavy and therefore difficult to install, and
- Pile or suction anchors, which require a designated (and expensive) installation methodology.

Table 3.2. An indication of basic physical parameters of commonly used mooring materials, where d (mm) is the rope diameter, D (mm) is the bar diameter of the chain, and C is a coefficient parameter depending of the material grade (equal to 22.3 for Grade 3). All data are from Barltrop (1998) except for the Nylon (Bridon, 2011) data. Properties will vary depending on exact type, construction and manufacturer. Technical terms are further defined in the glossary.

	Strength	Stiffness	Weight	Main properties	Use
	Minimum Breaking Load (MBL),	Axial stiffness per unit length	Submerged weight		
Unit	N	N	N/m		
Nylon (Superline)	228 d^2	~115d^2 (linear behaviour for small extension)	0.00050 d^2	Very compliant, light	In the water column of a compliant mooring configuration
Polyester	250d^2	5000 d^2 to 13000 d^2	0.0067 d^2	Compliant, light	In the water column
Aramid	450d^2	15000 d^2 to 52000 d^2	0.00565 d^2	Stiff, light	In the water column
High Modulus PolyEthylene (HMPE)	575d^2		0.0062 d^2	Very stiff, light	In the water column of a taut mooring configuration
Chain Grade 3	C x D^2 x (44 – 0.08D)	90000 D^2	0.1875 D^2	Strong, heavy, good abrasion and bending properties	Catenary

3.3.5 Environmental considerations

A moored structure is subject to various environmental loadings and can be characterised as a dynamic system responding to these loadings at high and low frequency excitations in the form of wave-frequency motion (motion caused at wave frequencies), high-frequency motions (due to e.g. structural vibration), slow-drift motion (motion caused by tidal current) and mean drift (motion caused by mean wave or wind forces). These types of responses are the result of different environmental loading mechanisms due to the combined action of wind, current and waves acting on the structure.

For the analysis of a suitable mooring the environmental loadings have to be identified at a given location, and are typically characterised for an extreme weather condition defined by the most unfavourable combination of wind, wave and current. In design terms this is done for permanent moorings by considering the worst combination for a 10 min average wind speed, a sea state corresponding to a 100-year return period and a 10-year return period current (Det Norske Veritas, 2010a). From this most unfavourable loading condition the behaviour of the body must be determined, from which all the resulting mooring line tensions can be calculated.

Other requirements must also be taken into account for the design of MRE moorings:

- The mooring should be designed for a range of tidal elevations at the MRE site. Because MRE sites are close to the shore, tidal ranges are relatively high compared to the water depths.

- MRE moorings should interact in a positive way with the power production, or at least try not to disturb it. That is why the mooring should be designed for production sea states, i.e. frequently occurring sea states with low or moderate wave elevations, for which the power take-off (PTO) is optimised.

3.4 Mooring design approach/considerations

It is necessary to choose mooring materials and arrangements at an early stage of the moored structure design in order to assess the coupled behaviour as well as providing information regarding potential entanglement possibilities, before proceeding with any necessary design iteration.

First, data are required on MRE converter properties, installation location and environmental loading (wave, wind and tidal forces). Based on this, a preliminary mooring design needs to be assessed using a static analysis method. The main outcome of this approach is to assess anticipated system properties, including device footprint, excursion limits, etc. If the outcomes are acceptable, a detailed dynamic analysis needs to be performed using either a quasi-static or a fully dynamic approach. The detailed dynamic analysis needs to be conducted in accordance with relevant standards such as DNV-OS-E301.

As discussed in Weller *et al*. (2012), several commercial modelling programmes exist which can be used to conduct static, quasi-static and dynamic analysis of complete mooring systems, including (but not limited to) *Orcaflex*™ by Orcina, *Optimoor*™ by TTI and *Deeplines*™ by Principia. Although these tools are sophisticated, it is not possible to model all distinct features of MRE devices, such as PTO systems, using existing mooring system software. *WaveDyn*™ by GL-Garrad Hassan is one of the first commercially available simulation tools that has been specifically designed for the dynamic response of WECs.

4. MOORING CONFIGURATION PARAMETER ASSESSMENT

4.1 Introduction: Mooring design concepts and entanglement risk

Understanding of the exact sequence of events in a marine megafauna entanglement event is still comparatively limited. Nevertheless, in this report it is assumed that a number of key mooring characteristics, such as mooring tension, mooring stiffness and mooring radius, could enhance the probability of marine megafauna entanglement. These characteristics have an important influence on the spatial footprint of an individual mooring line and hence on the potential entanglement risk posed by the overall mooring system. Quantifying the entanglement risk on an individual application is rather complicated as various factors would need to be considered, such as mooring materials, mooring configuration, device buoyancy, etc. However, using the key mooring characteristics a generic risk assessment can be undertaken that would allow individual assessment of technical design criteria to inform the wider entanglement assessment.

A detailed study of differences in mooring behaviours of taut and slack configurations was conducted by Johanning and Smith (2008), with a particular focus on variation in tension for different surge positions of these configurations. Assessments were undertaken for four different slack configurations and two different taut configurations (Figure 3.8a-b), each based on a three-leg mooring configuration. The study identified that slack configurations could have chaotic non-linear tension characteristics, meaning that the tension in mooring lines increased in a non-linear way for a given displacement of the floating structure. This can be explained by the lifting of chain off the seabed and the changing shape of the catenary line (Figure 4.2). In strong contrast, tension characteristics for taut configurations were found to behave linearly. This is because the restoring force is provided directly by the elasticity of the mooring line as shown in Figure 4.2.

In the following sections different mooring configurations will be assessed based on the tension characteristics and the consequent behaviour of the mooring lines to assess their spatial footprint. This will aid in the development of the entanglement risk assessment.

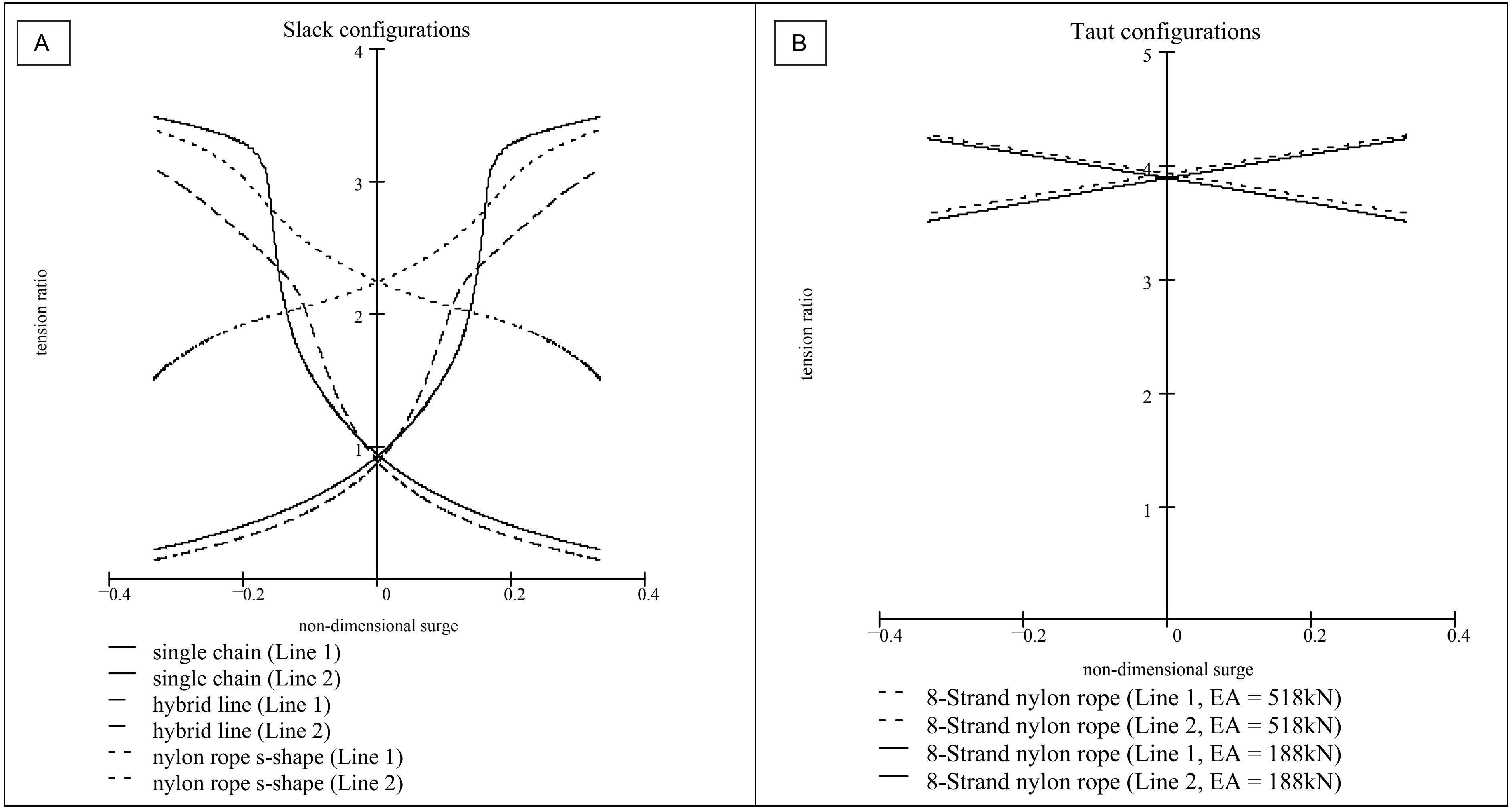


Figure 4.1. Examples of tension characteristics for different slack (A) and taut (B) mooring configurations with 2 opposite lines (from Johanning and Smith, 2008). Tension ratio (the ratio of vertical to horizontal tensions T_H/T_V) in the mooring line is plotted against mooring motion (expressed as a non-dimensional surge parameter).

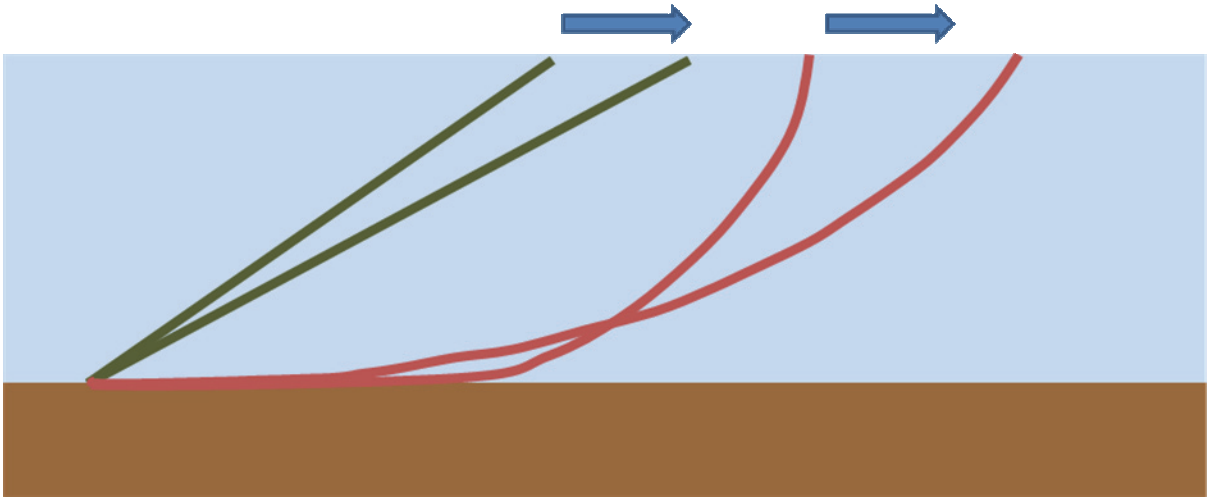


Figure 4.2. Change in the shape of a taut (green) and catenary (red) mooring lines due to surge of the floating structure.

In Section 3 the parameters which should be taken into account during mooring design were identified. For this report, a numerical model was built in Orcaflex™ to assess the importance for entanglement of each parameter relative to each other. The tension characteristics of each mooring configuration were calculated. If the buoy had a large excursion without large restoring forces being observed in the mooring line, the risk of entanglement was increased. The model calculated the total swept volume occupied by the mooring lines. If this occupied volume was high, this meant that the mooring lines and the floating structure behaved highly dynamically, potentially increasing the risk of marine megafauna entanglement. The model also estimated the maximum curvature of the mooring lines in order to assess the potential entanglement risk due to curvature criteria such as the consequence of forming a loop, especially when animals are in contact with the lines. For the swept volume assessment, the model was run over a range of sea states and for different mooring configurations, thereby allowing the development of a generic coverage assessment tool over a range of conditions, which will inform the entanglement assessment for MRE devices. For the curvature assessment, only one sea state was used for analysis.

4.2 Methodology

Simulations were run for regular waves with periods (T) from 1 to 10s (in 1-second steps), and for wave heights (H) of 1, 5 and 10m, as shown in Table 4.1. Particular combinations of periods and wave heights which resulted in unrealistic sea state conditions (i.e. waves which were too steep) were removed. A simulation was also run for extreme sea states (H~10m and T~10s), to quickly check the order of magnitude of the maximum mooring loads and compare these with the allowable minimum breaking loads (MBL) of the mooring lines. Other points to note include:

- A more detailed analysis would be required for the detailed design of a mooring system. Tidal elevation, current and wind were not considered in these calculations in order to simplify them.
- The water depth for the modelling study was defined as 50m, typical of floating wave and tidal deployment depths. Because of this relatively shallow depth compared to the wave height during extreme sea states, mooring design should ensure that mooring lines stay under tension and snatch loads do not occur, especially for the taut configuration.
- The numerical model compared several mooring configurations in a range of scenarios. The six mooring arrangements presented in the previous section were assessed: catenary (three different versions), taut, catenary with accessory buoy and

taut with accessory buoy. Moorings considered had three symmetrical mooring lines (i.e. arranged at 120° intervals around the central buoy). The catenary arrangements were assessed with different materials: a) chains only, b) chains (on the seabed) and nylon (in the water column), and c) chains (on the seabed) and polyester (in the water column). Mooring lines were attached on the side of the central buoy, at the mean water level.

Table 4.1 Sea states used for mooring assessment

H (m)	T (s)
1	3-10
5	6-10
10	7-10

The mooring configurations included in the following mooring parameter study are shown in figure 3.4A-D, and the full range of variables considered in the modelling study and the mooring configurations are presented in Table 4.2. The configurations were designed to have a pre-tension of 50kN except for the taut configuration, where the pre-tension was defined as 1000kN.

Environmental parameters such as tidal elevation, current and wind were not considered in these simulations to simplify the process. The inclusion of these parameters would change the pre-tension (mean tension) and equilibrium position of the mooring system. Consequently, the dynamics of the mooring system would be slightly modified, and the results for tension characteristics, swept volume ratio and mooring line curvature would also slightly vary. However, the mooring configuration remains the main driver of mooring dynamics.

Table 4.2. Mooring properties for numerical model. Components absent from particular designs are indicated by "-". All chains are Grade 3 and studlink. Minimum breaking loads (MBLs) were calculated in Orcaflex™ for this study.

Parameters	Catenary			Taut	Catenary with accessory buoy	Taut with accessory buoy
Material top lines	Chain	Nylon	Polyester	Nylon	Nylon	Nylon
Length top lines (m)	57.5	52.8	54.25	64.8	28.5	46.6
Diameter top lines (m)	0.045	0.140	0.200	0.19	0.140	0.19
MBL top line (kN)	1603	2731	6818	5030	2731	2007
Material bottom lines	Chain	Chain	Chain	-	Chain	-
Length bottom lines (m)	175	175	175	-	175	-
Diameter bottom lines (m)	0.064	0.064	0.064	-	0.064	-
MBL bottom line (kN)	3121	3121	3121	-	3121	-
Material connector	-	-	-	-	Chain	Chain
Length connector (m)	-	-	-	-	25	25
Diameter connector (m)	-	-	-	-	0.05	0.04
MBL connector (kN)	-	-	-	-	1960	1279
Central Buoy volume (m^3)	-	-	-	-	3	5.3
Distance centre buoy-anchor (m)	220	220	220	50	220	50
MBL mooring (kN)	1603	2731	3121	5030	1960	1279
Pre-tension (kN)	50	50	50	1000	50	50
Pre-tension/MBL %	3.1%	1.8%	1.6%	19.9%	2.6%	3.9%

4.3 Calculation of tension characteristics, volume and curvature

The concept of **tension characteristics** in moorings is likely to have a significant effect on entanglement risk. Intuitively, taut moorings (under high tension, by definition) are much less likely to cause entanglement than flexible ones (under low tension). This can be investigated more quantitatively by assessing how mooring components perform under increasing tension. One way this can be done is to assess the relationship between tension and minimum breaking load (MBL). The ratio of these two factors results in a fraction, here referred to as Tension/MBL. Where this fraction reaches unity, the tension in the mooring line is equal to the MBL, and the mooring will break according to the manufacturer's specifications.

The tension characteristics were obtained by slowly moving the buoy in the horizontal direction (along the X axis), without any environmental loads (no wave, wind or current), and by obtaining the given mooring loads for the different buoy position, as shown in Figure 4.3. The tension on a mooring is mainly dependent on the amount of surge (motion on the same axis as the wave direction) encountered by the mooring. Because three mooring lines were used, the stiffness characteristics were expected to be asymmetrical: when movement was positive, two mooring lines were tensioned, but when movement was negative, only one mooring line was tensioned.

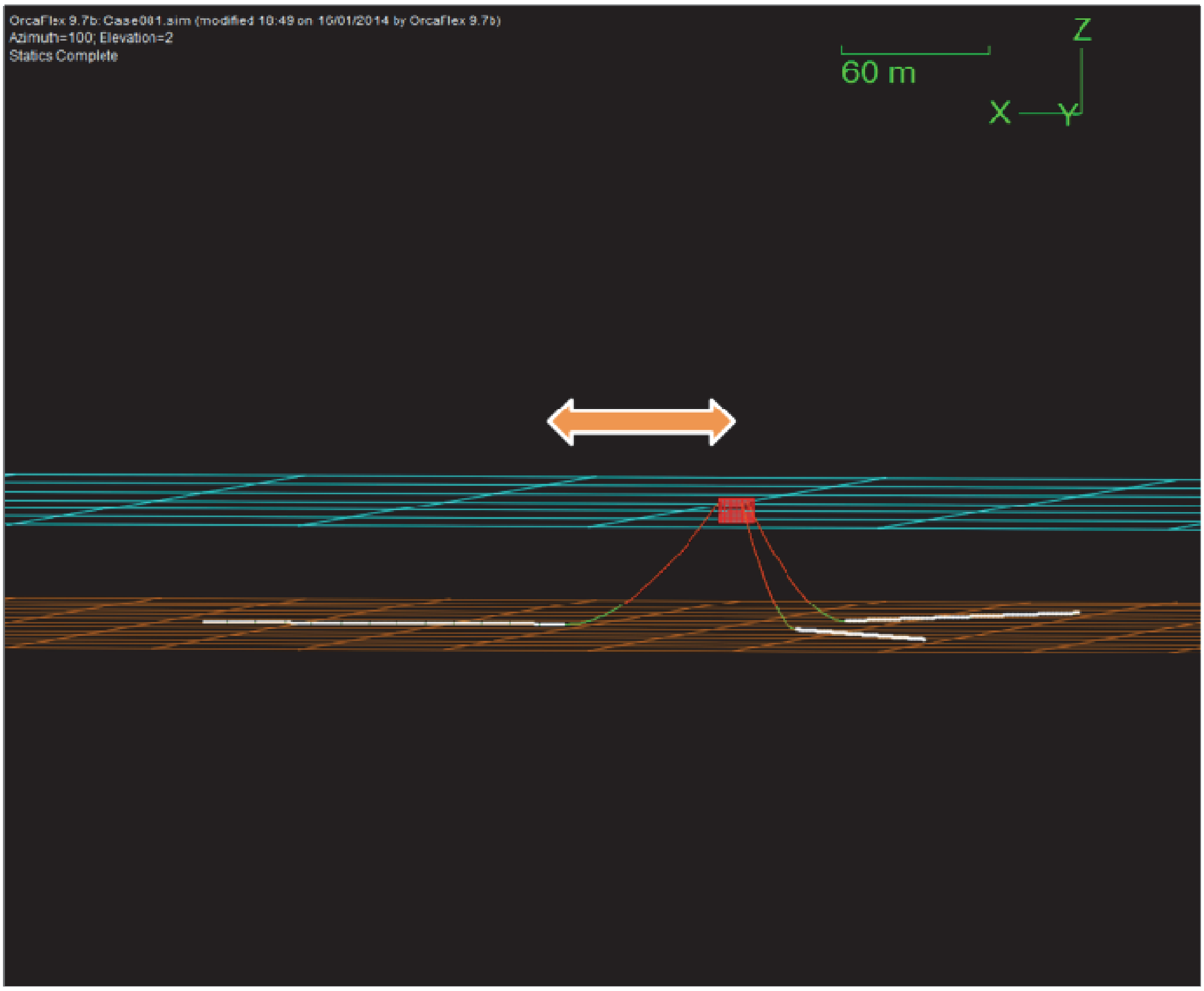
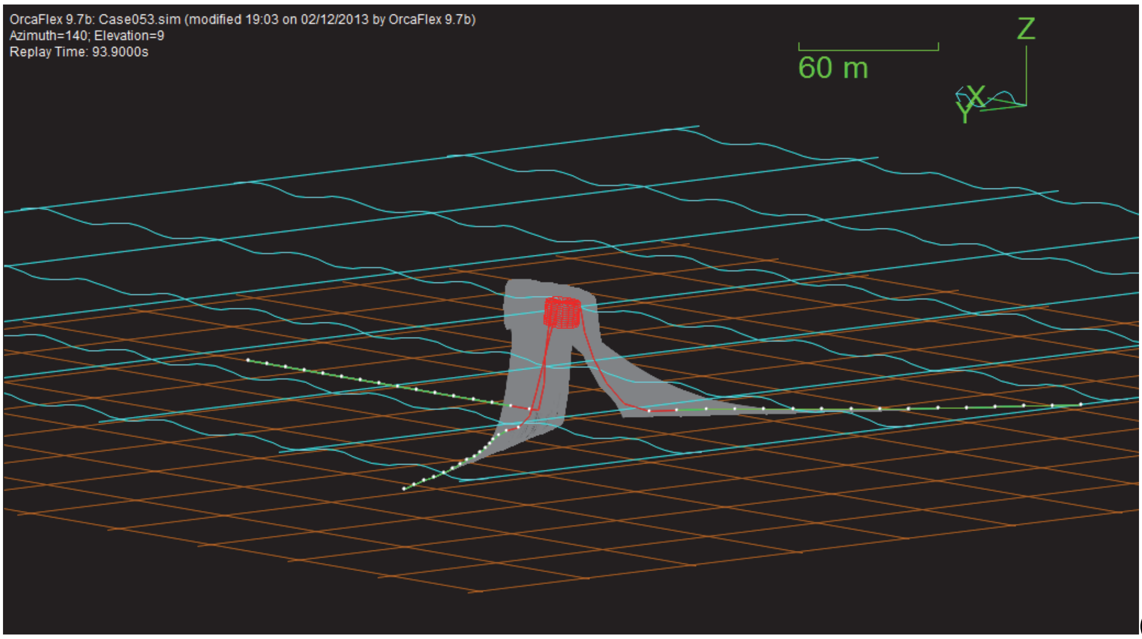


Figure 4.3. Example of OrcaFlex™ simulations to assess tension characteristics of different moorings.

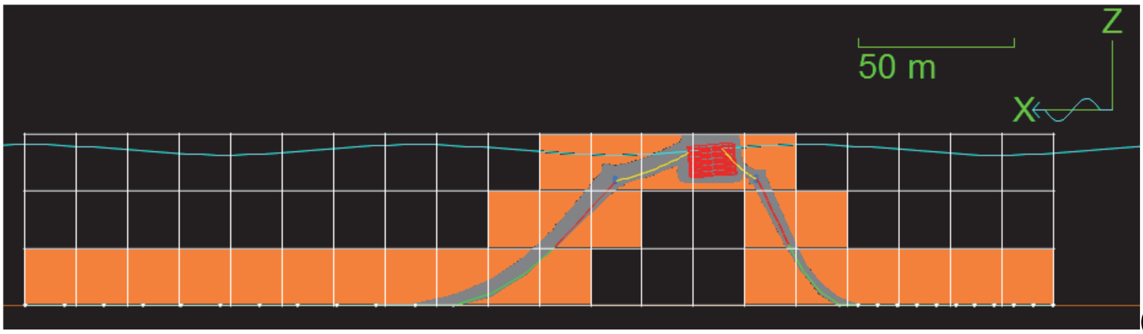
The concept of **swept volume** attempts to capture the potential impact of dynamic moorings in terms of the volume of the water column that can potentially be occupied by the mooring lines under energetic conditions. The volume occupied by the moving mooring lines (as shown in grey in Figure 4.4a) was calculated for the different mooring arrangements and sea states. The methodology used to estimate the volume was as follows:

- The time histories of the positions of ten nodes of each mooring lines were output (the mooring lines were modelled with segments connected with nodes). This limited resolution was chosen to reduce computation time and the size of the Orcaflex™ output files of the time series. The maximum and minimum x, y and z positions for the mooring lines were calculated. Between these two points, a large rectangular cuboid was built. This large cuboid was divided into 200x200x200 small rectangular cuboids. The size of these cuboids varied between simulations, depending on sea-state conditions and mooring designs. For example, for H=1m and T=3s, for the taut configuration, the size of a cuboid was 0.36m x 0.41m x 0.25m while for the catenary configuration the size of a cuboid was 1.5m x 1.7m x 0.27m.
- The time series of mooring line positions were analysed. If a mooring line occupied a small cuboid at any time during the simulation, the small cuboid was marked as occupied.
- The total volume occupied (in m^3) was obtained by adding up the volumes of the occupied small cuboids.

A simplified 2D example of this process is provided in Figure 4.4b, where the orange cells correspond to occupied small rectangular cuboids. With a high resolution this method allows an accurate estimation of the volume occupied. The volume of water swept by the mooring (V_{swept}), divided by the volume of the mooring line itself (V_{lines}), could then be used to provide a ratio (V_{swept}/V_{lines}) to describe the mobility of the mooring in the water column.



(a)



(b)

Figure 4.4 Example of volume occupied (grey) by mooring systems, (a) in three dimensions and, (b) as a cross-section. In the latter, cells occupied by a section of mooring are coloured orange.

The concept of **curvature** aims to evaluate the bending of the mooring lines. Curvature was calculated directly by OrcaFlex™ by dividing the angle change at any node by the sum of the half-segment lengths on each side of the node. Nodes were defined to be 0.5m apart resulting in varying node numbers for different moorings, from 92 nodes in a 46m-mooring to 466 nodes in a 233m mooring. Only nodes capable of rising off the seabed (≤300 nodes, depending on mooring configuration) were analysed in this study. An example of curvature along a line is given in Figure 4.5. Curvature was calculated for H=1m and T=5s.

4.4 Modelling results

First, the tension characteristics were plotted for all mooring configurations. Then the model was run for all scenarios presented in Table 4.1, for a full range of wave height and wave period values (Table 4.2). Swept volume and curvature were then evaluated. Results for all scenarios are summarised in this section for single devices.

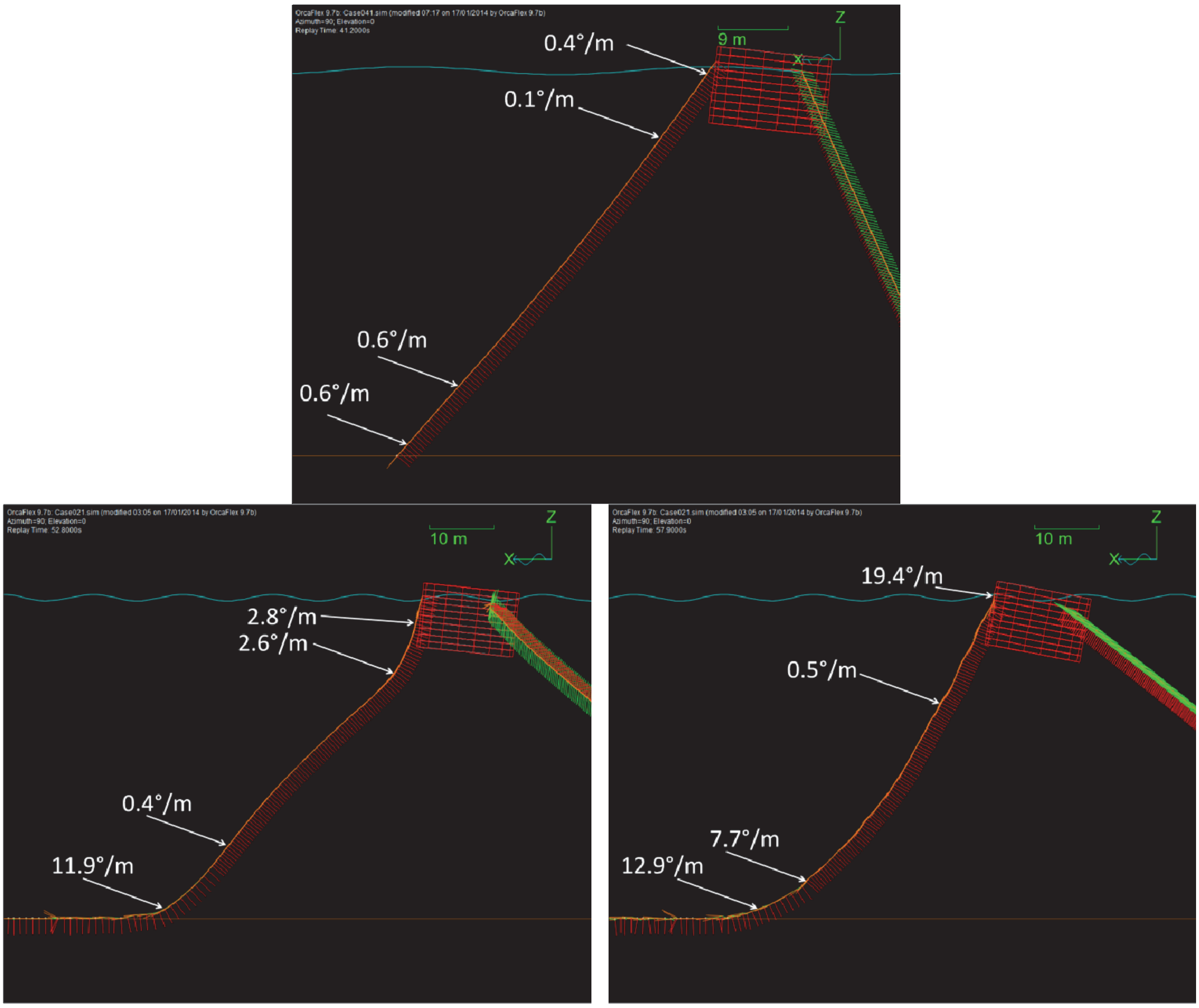


Figure 4.5. Example of curvature calculation in Orcaflex™ for the taut configuration (top) and for a catenary configuration (bottom).

4.4.1 Tension characteristics

The tension characteristics of the different mooring arrangements are illustrated in Figure 4.6. The red line indicates the tension in the two mooring lines facing into the waves (front lines), while the blue line indicates the tension in the mooring line facing away from the waves (back line). Because there were two mooring lines facing the waves, the mooring load was shared and consequently reduced, compared to the load in the backwards-facing mooring line. This explains the asymmetrical shape of the stiffness characteristics. The behaviour of the different mooring arrangements was noticeably different in terms of their behaviour under horizontal surges. Most mooring arrangements (with the notable exception of the taut mooring) displayed comparatively low Tension/MBL values for small to medium surge ranges, indicating considerable flexibility and thus increased potential risks of entanglement. In the case of the catenary moorings, there were distinct differences in the Tension/MBL ranges when using different material components (Figure 4.6.a-c) and the configuration using nylon rope shows a significantly higher flexibility. The taut mooring configuration (Figure 4.6.d) had a high pre-tension without surge, around 20% of its MBL, and the mooring loads increased steeply for a small range of surge. The catenary mooring with accessory buoys (Figure 4.6.e) showed a similar behaviour to the catenary configurations. The taut mooring with accessory buoys (Figure 4.6f) displayed near-constant Tension/MBL values across the surge range, indicating that such moorings would allow considerable flexibility. These results are overlaid in Figure 4.7 to allow direct comparison between different mooring configurations.

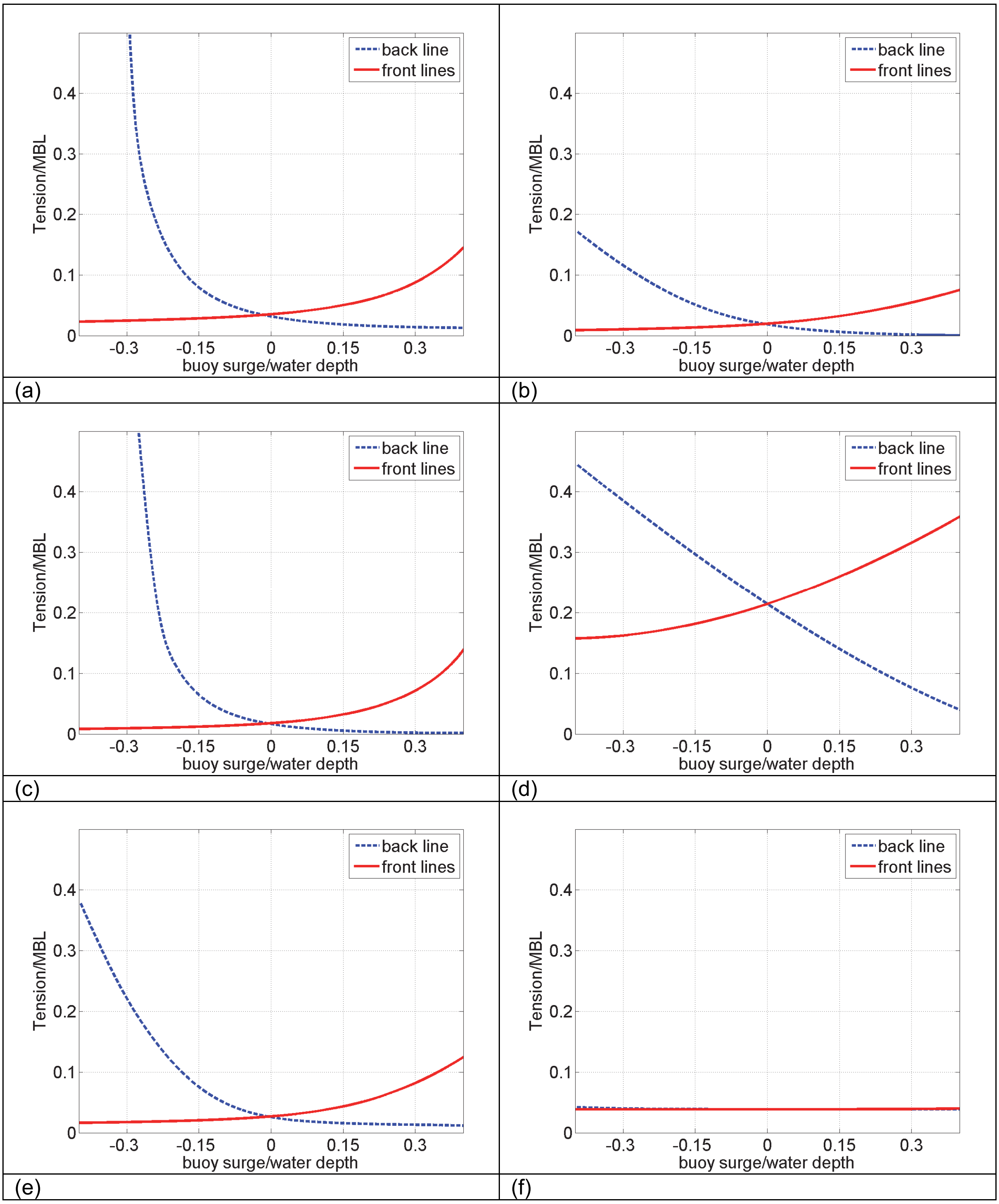


Figure 4.6. Modelled tension characteristics for the six modelled mooring configurations. a) catenary with chain; b) catenary with chain and nylon; c) catenary with chain and polyester; d) taut; e) catenary with accessory buoys; f) taut with accessory buoys.

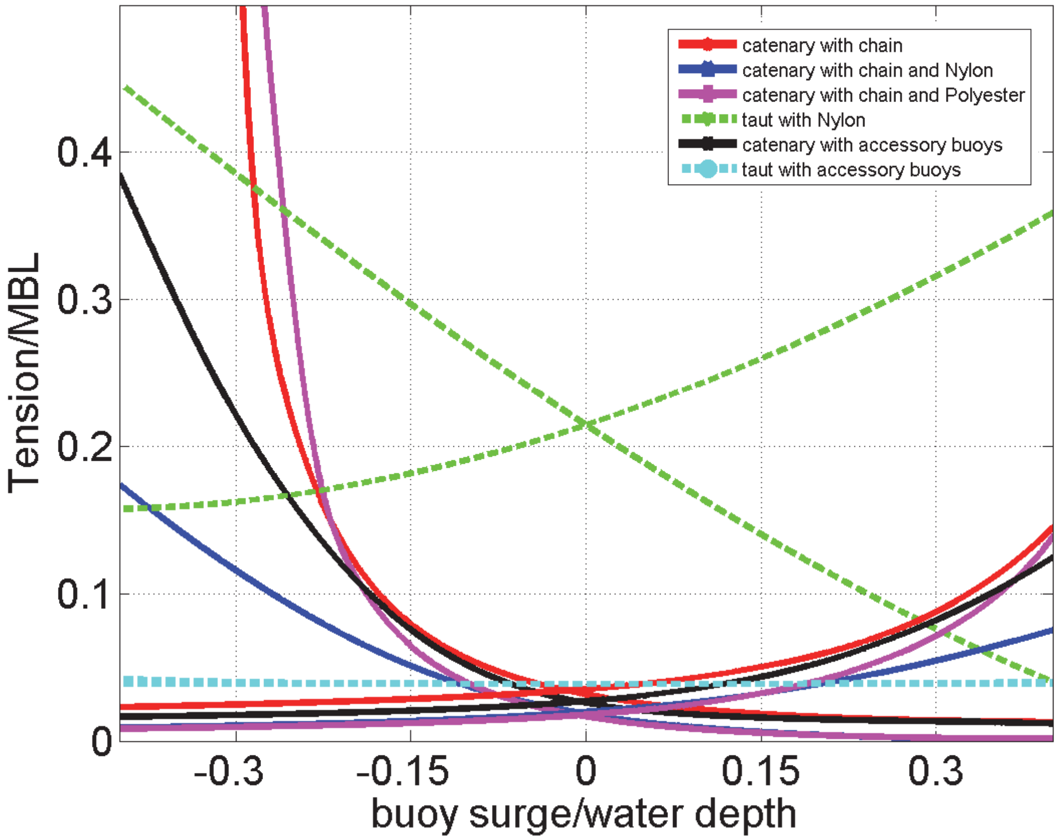
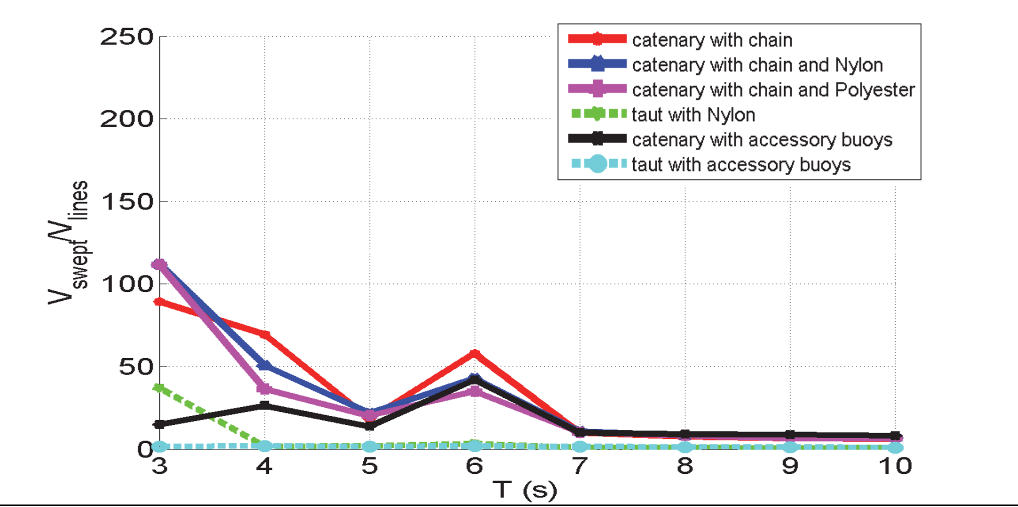


Figure 4.7. Summary and comparison of the different mooring arrangement modelled tension characteristics: catenary with chain (red), catenary with chain and Nylon (blue), catenary with chain and Polyester (magenta), taut with Nylon (green), catenary with accessory buoys (black), taut with accessory buoys (cyan). Catenary configurations are represented by solid lines while taut configurations used dashed lines.

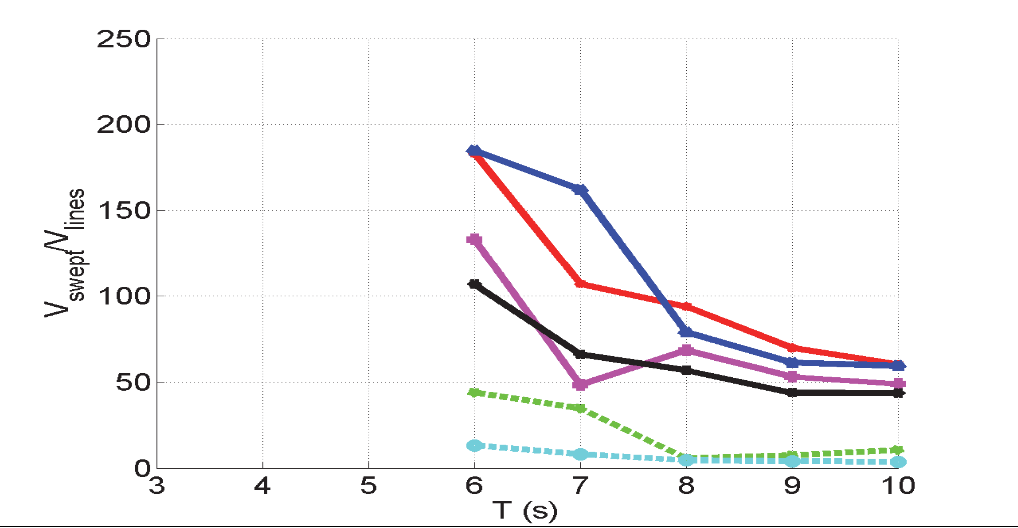
4.4.2 Swept volume

Results indicated that the higher values of swept volume (V_{swept}/V_{lines}) ratios occurred for the catenary configurations at all wave heights considered (Figure 4.8 and Table 4.3). For wave heights H = 1 and 5 m, there was a general trend towards declining swept volume ratios for greater wave periods, because of the decreasing steepness of the waves, but such a trend was not evident for H = 10 m because sea states are highly energetic for such wave heights. Catenary moorings containing either solely chain or chain and Nylon exhibited particularly large swept volume ratios. The taut configurations (both with and without accessory buoys) displayed significantly lower swept volume ratios across sea states.

Wave height H = 1 m



Wave height H = 5 m



Wave height H = 10 m

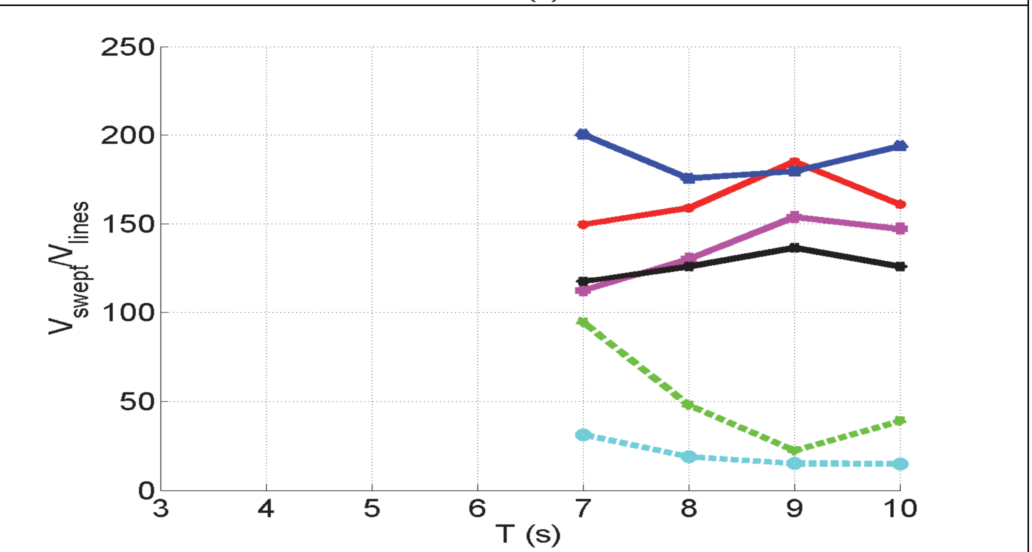


Figure 4.8. Swept volume ratio (V_{swept}/V_{lines}) for the different mooring configurations at different sea states. Sea states were considered unrealistic if the waves were too steep, therefore datasets start at wave period=3 s for H = 1 m, 6 s for H = 5 m and 7 s for H =10 m: catenary with chain (red), catenary with chain and Nylon (blue), catenary with chain and Polyester (magenta), taut with Nylon (green), catenary with accessory buoys (black), taut with accessory buoys (cyan). Catenary configurations are represented by solid lines while taut configurations used dashed lines.

The actual maximum swept volumes encountered for all mooring configurations during the modelling exercise were summarised in Table 4.3. The figures indicate that the volume potentially occupied by moorings may differ across two orders of magnitude (from 55m^3 to 1934m^3), depending on the mooring design.

Table 4.3. Maximum volume occupied for the different mooring configurations and corresponding sea states.

Configuration	Max. swept volume (m^3)	T for max volume (s)	H for max volume (m)
Catenary with chain	1436	6	4
Catenary with chain and Nylon	1934	7	7
Catenary with chain and Polyester	1665	6	3
Taut with Nylon	311	7	10
Intermediate buoys with catenary	1061	9	10
Intermediate buoy with tether	55	7	9

4.4.3 Curvature

Mooring curvature was modelled in OrcaFlex™ for the maximum excursion of the floating structure for a given sea state. Results showed that the response (expressed in degrees per meter) varied considerably between different mooring configurations (Figure 4.9). For the taut configurations, curvatures were very small (under 0.01°/m), but for the catenary configurations they were considerably greater (between 0.01 and 10°/m). There could be considerable variability between the individual nodes. To capture this variability, curvatures at maximum horizontal excursion were plotted as boxplots (Figure 4.9). Catenary moorings consistently displayed considerably greater variability in curvature across the mooring than taut moorings (note the logarithmic vertical axes).

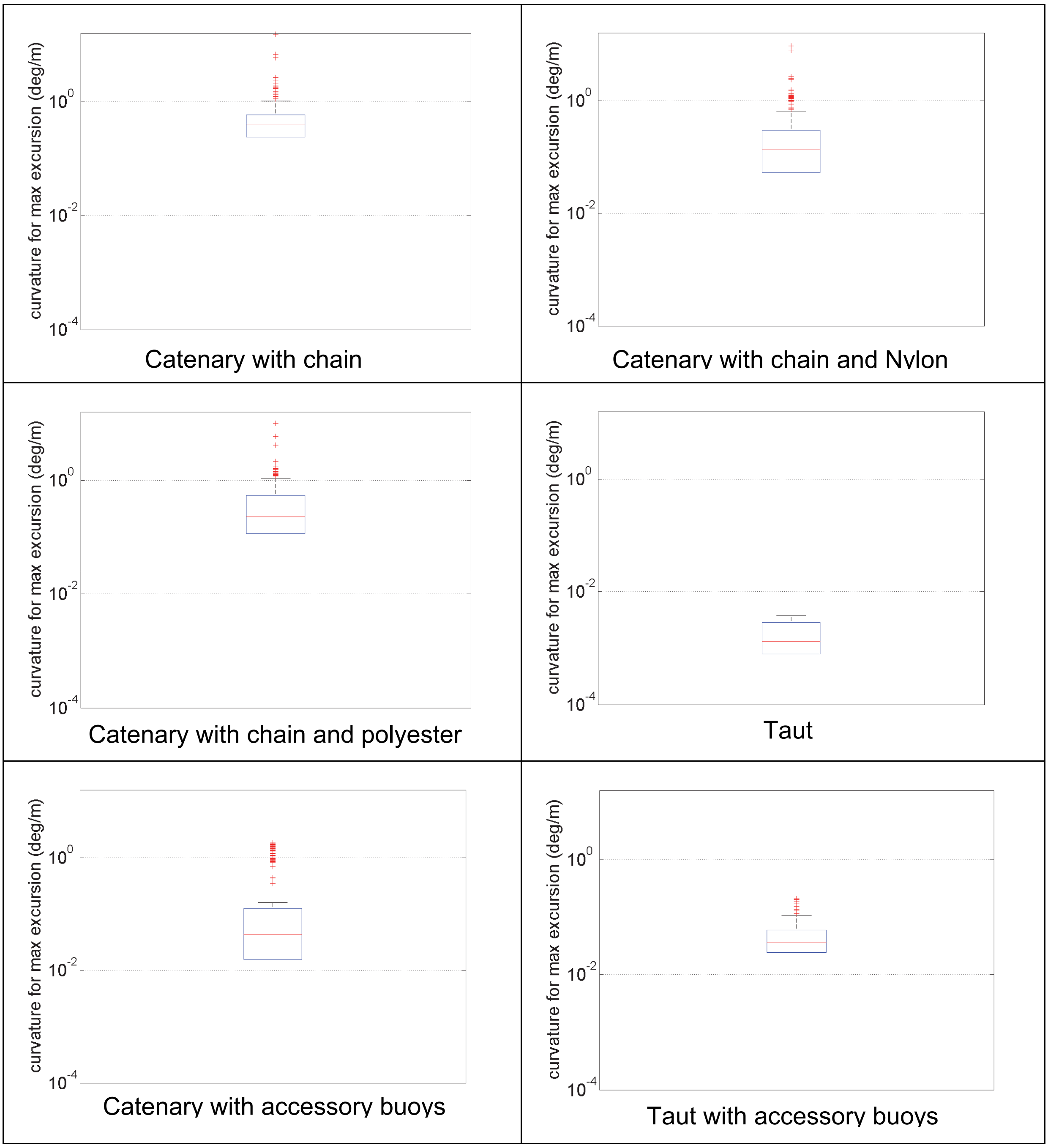


Figure 4.9. Boxplots of modelled mooring curvatures of the six configurations considered in this report. These plots were created from the local curvatures calculated for each node across the mooring. There are obvious differences in terms of scatter and outliers around the mean curvature value. See text for details. Note the logarithmic vertical axes.

4.5 Summary

Six different mooring configurations were modelled in OrcaFlex™ under varying environmental conditions, generating data on mooring tension characteristics, swept volume ratio and curvature. Catenary moorings exhibited a compliant behaviour, a large swept volume and large curvatures. Using accessory buoys on catenary moorings made the mooring system less compliant, with a smaller swept volume and curvatures. Taut moorings consistently displayed a stiffer behaviour, a smaller swept volume and more reduced curvatures than all other mooring configurations, sometimes by an order of magnitude. Using accessory buoys on a taut mooring system made the mooring system the most compliant, with the smallest swept volume and with very small curvatures. These different responses have implications for the potential relative risk to marine megafauna posed by these different mooring designs. Given that the derivation of the parameters identified above can be done at an early stage of the mooring design process, it would not be unrealistic for developers to take potential entanglement risks into account as an integral part of the mooring design process.

Finally, it is important to note that mooring line characteristics such as thickness are linked to the stiffness properties of a specific line. The analytical method applied here is based on mooring line stiffness characteristics considering variables specific to the lines. However, a correlation between line diameter and average body size of a species will also specify criteria towards entanglement risk that is considered through the generic assessment of species size. A detailed analysis of correlation between line diameter and species size would be outside the framework of this work and would require a detailed research programme.

5. BIOLOGICAL AND MOORING RISK PARAMETERS

5.1 Introduction

Marine megafauna entanglement risk may be influenced by the biological characteristics of different species, as well as the various aspects of the mooring design. In this section, an attempt has been made to qualitatively compare risk of entanglement between different megafauna groups. Individual risk factors (whether biological or physical) were scored against a qualitative binary (0-1) or factorial (1-2-3) scale, on the basis of pre-existing knowledge of biological characteristics or physical parameters. Biological risk parameters were scored against megafauna groups as identified in Section 2. Physical risk parameters were scored against modelled mooring configurations described in Section 4. Subsequently Biological Risk Scores (BRS) and Physical Risk Scores (PRS) were calculated by summing risk scores of all relevant parameters. BRS and PRS were then multiplied to provide a Total Risk Score (TRS), which described the relative significance of entanglement risk for each combination of megafauna group and modelled mooring configuration.

Risk was evaluated on the level of *probability* of an entanglement event occurring if an animal is in close proximity to a mooring, rather than on the level of *significance* to the individual if the entanglement event does occur. Entanglement was defined as serious and undesirable whenever it occurred, so the significance of any entanglement would be considered high. *The aim of this approach is to assess how different factors might modify entanglement probability*.

- **In the following section, it is important to note that the figures assigned throughout the risk assessment process are not to be taken quantitatively but simply provide an index of risk relative to each other.**

5.2 Biological risk parameters

Biological risk parameters discussed here include body size, sensory capabilities, flexibility and typical feeding mode. For classification purposes, megafauna were aggregated into broad groups based on taxonomic relationships as well as body size (see Table 5.1).

Table 5.1. Overview of megafauna species groupings considered in the present assessment.

Species group			Examples
Cetaceans	Baleen whales	Large whales	Humpback whale, fin whale, North Atlantic right whale
		Medium-sized whales	Minke whale
	Toothed whales	Sperm whale	Sperm whale
		Medium-sized whales and dolphins	Beaked whales, pilot whales, killer whales
		Small whales, dolphins and porpoises	Harbour porpoise, bottlenose dolphin, pygmy sperm whale
Pinnipeds	Seals (phocids)		Harbour seal, Grey seal
	Sea lions, fur seals etc. (otariids)		Steller sea lion, Northern fur seal
Sea turtles			Leatherback turtle
Sharks	Basking sharks		Basking shark
	Other large sharks		Porbeagle, blue shark
Ocean sunfish			Ocean sunfish

5.2.1 Body size

MRE devices are often large, and their associated moorings often consist of comparatively thick components. Generally speaking, moorings may pose less of a risk to small animals than to large ones simply because smaller animals cannot physically become entangled in such moorings. For this reason, many species are intuitively at less risk of becoming entangled in MRE device-related moorings. Table 5.2 summarises the likely entanglement risk of various megafauna groups purely on the basis of body size. Other groups (e.g. seabirds, most bony fish) are too small to be considered at risk of entanglement.

Table 5.2. Entanglement risk associated with different species' body sizes.

Species group			Entanglement risk based on total body length (TL) TL <5m = 1 TL = 5-10m = 2 TL >10m = 3
Cetaceans	Baleen whales	Large whales	3
		Medium-sized whales	2
	Toothed whales	Sperm whale	3
		Medium-sized whales and dolphins	2
		Small whales, dolphins and porpoises	1
Pinnipeds	Seals		1
	Sea lions, fur seals etc.		1
Sea turtles			1
Sharks	Basking sharks		2
	Other large sharks		1
Ocean sunfish			1

5.2.2 Flexibility

As detailed in Section 2, different megafauna groups can be distinguished by means of their flexibility, i.e. the degree to which they flex their bodies while swimming. For the purposes of this report, no attempt was made to subdivide different groups quantitatively. Instead a broad categorisation was applied on the basis of groups' known swimming behaviours to distinguish swimmers with comparatively rigid bodies from those with comparatively flexible ones (see Table 5.3 below). The assumption was that flexible animals would be able to avoid entanglement more easily than animals with more rigid bodies.

Table 5.3. Entanglement risk associated with body flexibility of different megafauna groups.

Species group			Entanglement risk based on body flexibility: Relatively flexible = 1 Relatively rigid = 2
Cetaceans	Baleen whales	Large whales	2
		Medium-sized whales	2
	Toothed whales	Sperm whale	2
		Medium-sized whales and dolphins	2
		Small whales, dolphins and porpoises	2
Pinnipeds	Seals		1
	Sea lions, fur seals etc.		1
Sea turtles			2
Sharks	Basking sharks		1
	Other large sharks		1
Ocean sunfish			2

5.2.3 Ability to detect moorings

The ability of marine megafauna to detect moorings at sufficient distance to avoid a collision or entanglement (defined here as within 10 body lengths), using different sensory modalities, has been discussed in Section 2. Moorings typically consist of large cables that are likely to be detectable at considerable distances (tens of metres) for echolocating odontocete cetaceans, and are likely far more detectable than nylon or monofilament fishing gears. Animals that rely more on sight (e.g. sea turtles) would have to approach closer before detecting the mooring, although the possibility that water flow noise around the mooring is audible at greater distances cannot be discounted. Different mooring components are likely to influence audibility; chain, for example, is likely to be inherently noisier than fibre rope, both due to metal-on-metal movement and a larger surface area along which turbulence can be generated. Surface smoothness of mooring elements will also be a factor in the amount of turbulence produced. Turbulence itself will be detectable downstream by pinnipeds, sharks and bony fish. Detectability at distance is, however, likely to change under inclement conditions (e.g. storms, turbid waters), whatever the sensory modality used or the extent of device motion.

Table 5.4 summarises the ability of different megafauna groups to detect moorings at distance (where 10 body lengths was assumed to be a sufficiently long-range distance to potentially allow evasive action). This detection distance criterion was primarily used to distinguish toothed whales (with their well-understood long-range echolocation capability) from other megafauna groups, the long-range sensory capabilities of which are less well understood. This assumption was considered conservative (particularly given that animals may well be able to avoid obstacles within closer distances) but there are very few data available on detection capabilities of any marine megafauna in these energetic habitats. **Note** that these scores also assumed that animals were actively investigating their environment and were not distracted by prey, predators, etc.

Table 5.4. Entanglement risk associated with different species' ability to detect mooring components. Note that the division at 10 body lengths is based on the notion that animals need a minimum detection distance to avoid colliding with the mooring, principally to allow a distinction between echolocating toothed whales and other species groups.

Species group			Ability to accurately detect object at distances of: >10 body lengths = 1 1-10 body lengths = 2	Likely main sensory modality used at close range
Cetaceans	Baleen whales	Large whales	2	Vision, hearing
		Medium-sized whales	2	Vision, hearing
	Toothed whales	Sperm whale	1	Active acoustics (echolocation), vision
		Medium-sized whales and dolphins	1	Active acoustics (echolocation), vision
		Small whales, dolphins and porpoises	1	Active acoustics (echolocation), vision
Pinnipeds	Seals		2	Mechanoperception, vision, hearing
	Sea lions, fur seals etc.		2	Mechanoperception, vision, hearing
Sea turtles			2	Vision, hearing
Sharks	Basking sharks		2	Mechanoperception, electroperception, vision
	Other large sharks		2	Mechanoperception, electroperception, vision
Ocean sunfish			2	Mechanoperception, vision

5.2.4 Mode of feeding

Foraging appears to be an important risk factor leading to entanglement in fishing gears. Many entanglements in ropes proceed with the rope becoming wrapped around animals' extremities or through the mouth, apparently whilst foraging. The considerable thickness of moorings and cables associated with marine offshore renewables, when compared to ropes associated with fishing gears, may preclude such entanglement in all but very specific cases. Large baleen whales may, however, become entangled by swimming into the mooring with their mouths open. Many species of large whales (e.g. blue and fin whales) feed by rapidly lunging into dense prey aggregations while opening their mouths wide (out to ~ 80 degrees) to actively engulf both water and prey (Brodie, 1993). With jaws of 5+ metres long and correspondingly large gapes, these animals clearly do have the capacity to envelop a section of mooring if they were to engulf a dense school of prey in its immediate vicinity. Any resulting collision would result in a rapid deceleration of the animal, although these animals are anatomically adapted to withstand such forces as a natural consequence of their lunge-feeding habits (Goldbogen *et al*., 2006, 2011). An example of the potential effects of such a collision is described in the Case Study in Section 2 (p.21) of this report.

Large whales have been shown to be attracted to fish and other species shoaling below fish aggregation devices (Brehmer *et al*., 2011), and similar responses by prey fish species may occur underneath floating MRE devices. This suggests that foraging baleen whales may be attracted to prey aggregations beneath such devices, potentially increasing the risks of entanglement. Basking sharks are smaller than the largest whales and do not feed in a similarly energetic fashion; although they appear capable of engulfing some elements of a mooring based on their large gape they would likely be able to avoid doing so except under extreme circumstances (Table 5.5).

Table 5.5. Risk associated with foraging styles for different megafauna groups. Note that baleen whales include both filter feeders and lunge feeders.

Species group				Entanglement risk based on foraging style Pursuit hunters = 1 Filter feeders = 2 Lunge feeders = 3
Cetaceans	Baleen whales	Large whales	Lunge feeders	3
			Filter feeders	2
		Medium-sized whales	Lunge feeders	3
	Toothed whales	Sperm whale		1
		Medium-sized whales and dolphins		1
		Small whales, dolphins and porpoises		1
Pinnipeds	Seals			1
	Sea lions, fur seals etc.			1
Sea turtles				1
Sharks	Basking sharks			2
	Other large sharks			1
Ocean sunfish				1

5.2.5 Summary of biological risk parameters

The four tables above were amalgamated into Table 5.6 in order to assess the perceived relative risks to different marine megafauna groups (Biological Risk Scores, or BRS). Scores from tables 5.2-5.5 were summed in order to achieve a total BRS score. The resulting scores reflect differences in animal size, swimming and foraging styles and sensory capabilities, but should nevertheless be considered a comparatively crude measure by which to rank such diverse groups.

On the basis of BRS scores, small and medium-sized toothed whales, pinnipeds, sea turtles, large sharks, and ocean sunfish appear to be at least risk of inadvertently becoming entangled in moorings associated with MRE devices. Basking sharks and sperm whales are considered to be at somewhat greater potential risk, albeit for different reasons. Baleen whales appear to be at greatest risk, due to their size and distinctive foraging techniques.

This analysis is based on best available data from the scientific literature. It is, however, open to further improvement as new information becomes available. At present, it is considered that the four parameters used here offer an acceptable degree of resolution between different groups. It would certainly be possible, however, to add additional biological parameters to further differentiate risk between different groups. It is furthermore possible that certain parameters are more significant than others when determining entanglement risk for different megafauna groups. The present approach does not apply weighting factors to indicate any such differentiation, but this could be considered if further information became available. Given the diversity of mooring configurations currently under consideration it is, however, presently unclear whether sufficient evidence exists to justify such an approach.

Table 5.6. Summary of entanglement risk for different megafauna groups based on biological risk parameters.

Species group			Entanglement risk based on total body length (TL) TL <5m = 1 TL = 5-10m = 2 TL >10m = 3	Entanglement risk based on body flexibility: Relatively flexible = 1 Relatively rigid = 2	Ability to accurately detect object at distances of: >10 body lengths = 1 1-10 body lengths = 2	Entanglement risk based on foraging style Pursuit hunters = 1 Filter feeders = 2 Lunge feeders = 3	TOTAL (A+B+C+D; min. = 4, max. = 10)
Cetaceans	Baleen whales	Large whales	3	2	2	2, 3	**9, 10**
		Medium-sized whales	2	2	2	3	**9**
	Toothed whales	Sperm whale	3	2	1	1	**7**
		Medium-sized whales and dolphins	2	2	1	1	**6**
		Small whales, dolphins and porpoises	1	2	1	1	**5**
Pinnipeds	Seals		1	1	2	1	**5**
	Sea lions, fur seals etc.		1	1	2	1	**5**
Sea turtles			1	2	2	1	**6**
Sharks	Basking sharks		2	1	2	2	**7**
	Other large sharks		1	1	2	1	**5**
Ocean sunfish			1	2	2	1	**6**

5.3 Physical risk parameters of mooring elements

In the same way that certain biological characteristics of marine megafauna may lead to a greater or lesser risk of entanglement, the physical characteristics of mooring lines can also be assessed by the risk that they pose to large marine animals and risk parameters can be assigned accordingly. In the present report, relative risk was evaluated by assessing the tension characteristics, swept volume and curvature for a given mooring configuration. These are discussed in the following sections. As before, **it is important to reiterate that the values in relative risk categories used here were based on the authors' assessment of their relative significance, and should not be over-interpreted.**

5.3.1 Tension characteristics

The tension on a mooring is mainly dependent on the amount of surge encountered by the floating structure. This can be described by the ratio of surge divided by the mean water depth to facilitate comparison between moorings. The relationship between tension and the position in surge of the floating structure can be described by tension characteristics of the type shown in Figure 4.1. The risk of entanglement will vary according to a combination of mooring tension and surge, as indicated by the simple colour scheme used in Figure 5.1. Colours were assigned on the basis of multiplying predefined surge scores (blue numbers) by tension scores (red numbers). These numeric risk scales are indicative and used as examples only.

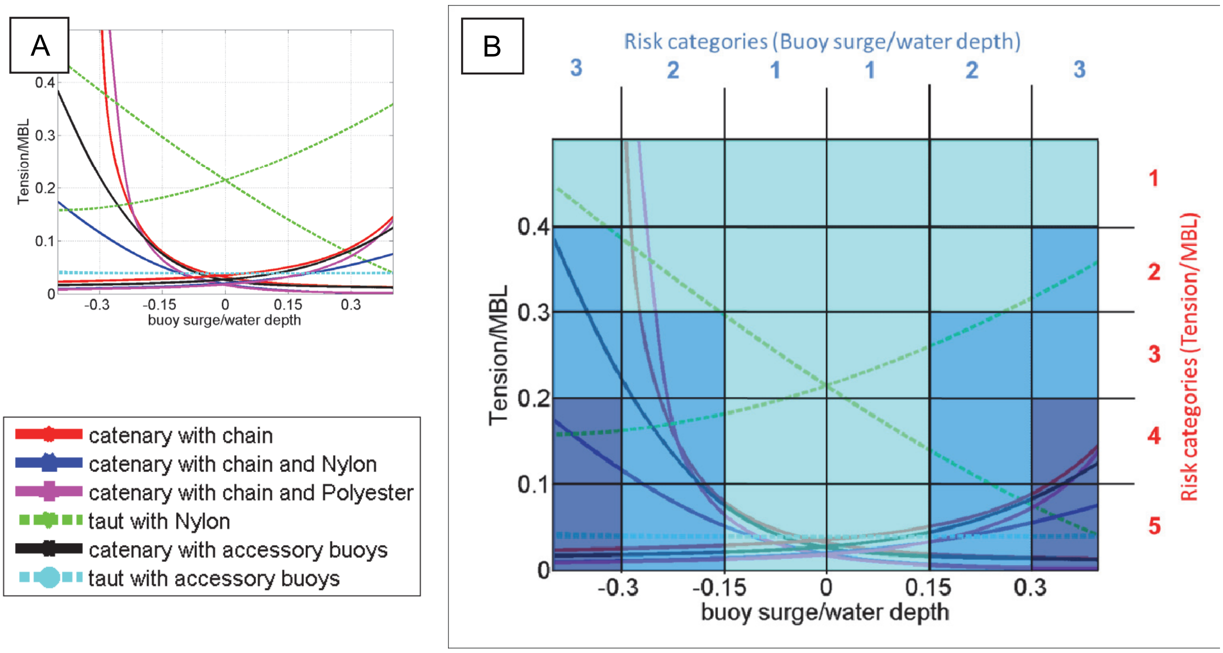


Figure 5.1. A) The modelled relationship between Tension/MBL and normalised buoy surge for various mooring configurations (reproduced from Figure 4.6): catenary with chain (red), catenary with chain and Nylon (blue), catenary with chain and Polyester (magenta), taut with Nylon (green), catenary with accessory buoys (black), taut with accessory buoys (cyan). Catenary configurations are represented by solid lines while taut configurations used dashed lines. B) The parameterised risk pattern for these same curves, calculated on the basis of multiplying Tension and Surge risk categories. Colours represent least (1-5; cyan:), medium (6-10; azure:) and greatest (11-15; navy blue:) relative entanglement risk. Greatest risk (navy blue) is the result of particularly low tensions at particularly high surges.

From Figure 5.1, the tension characteristics risk parameter for each modelled mooring was calculated by the following process:

- For each mooring, the number of cells of different colours that were intersected by the curve was counted;
- For each mooring, the total number of intersected cyan cells was multiplied by 1 (low risk), the total number of intersected azure cells was multiplied by 2 (moderate risk), and the total number of intersected navy blue cells was multiplied by 3 (high risk). These values were subsequently summed for each mooring;
- The summed values were divided by the total number of intersected cells to generate an average risk score for each mooring.
- Values <1.75 were designated an overall tension risk score of 1, values between 1.75-<2.00 were designated a score of 2, and values ≥2.00 were designated an overall score of 3 (Table 5.7). This parameter was carried forward in subsequent analyses.

Table 5.7. Summary of risk assessment process for the tension characteristics risk parameter.

Mooring type	# Cyan cells (1)	# Azure cells (2)	# Navy blue cells (3)	Total # of cells	Average score	Final Tension risk parameter score
Catenary with chain	6	6	3	15	1.80	2
Catenary with chain & Nylon	4	5	4	13	2.00	3
Catenary with chain & Polyester	6	6	4	16	1.88	2
Taut with nylon	9	6	2	17	1.59	1
Catenary with accessory buoys	4	8	4	16	2.00	3
Taut with accessory buoys	4	4	4	12	2.00	3

Results indicated a higher risk of entanglement based on mooring stiffness for the most compliant mooring arrangements, specifically catenary with chain and Nylon, catenary with accessory buoys and taut with accessory buoys. The risk was reduced for the catenary configuration with chain, and catenary configuration with chain and polyester. The risk was lowest for the stiffer taut configuration.

5.3.2 Swept volume

A volume ratio V_r can be calculated between the swept volume of water in the water column (V_{swept}) and the volume of the mooring lines themselves (V_{lines}) to generate a dimensionless parameter that can be compared between different moorings. The greater this parameter, the larger the swept volume is relative to the dimensions of the mooring, and the greater the potential risks of entanglement. Results are presented in Figure 5.2.

The response of each mooring configuration to different sea states was defined on the basis of wave period and volume ratio V_r. For the purposes of this report, V_r values ≤100 were defined as having a risk value of 1 (low risk), V_r values >100 but ≤200 were defined as having a risk value of 2 (medium risk), and V_r values >200 were defined as 3 (high risk). Because not all combinations of wave height and wave period produced sensible sea states (because the waves are too high for the period and are breaking), the wave period was further subdivided into two categories, namely 3-6 seconds and 7-10 seconds (Figure 5.2).

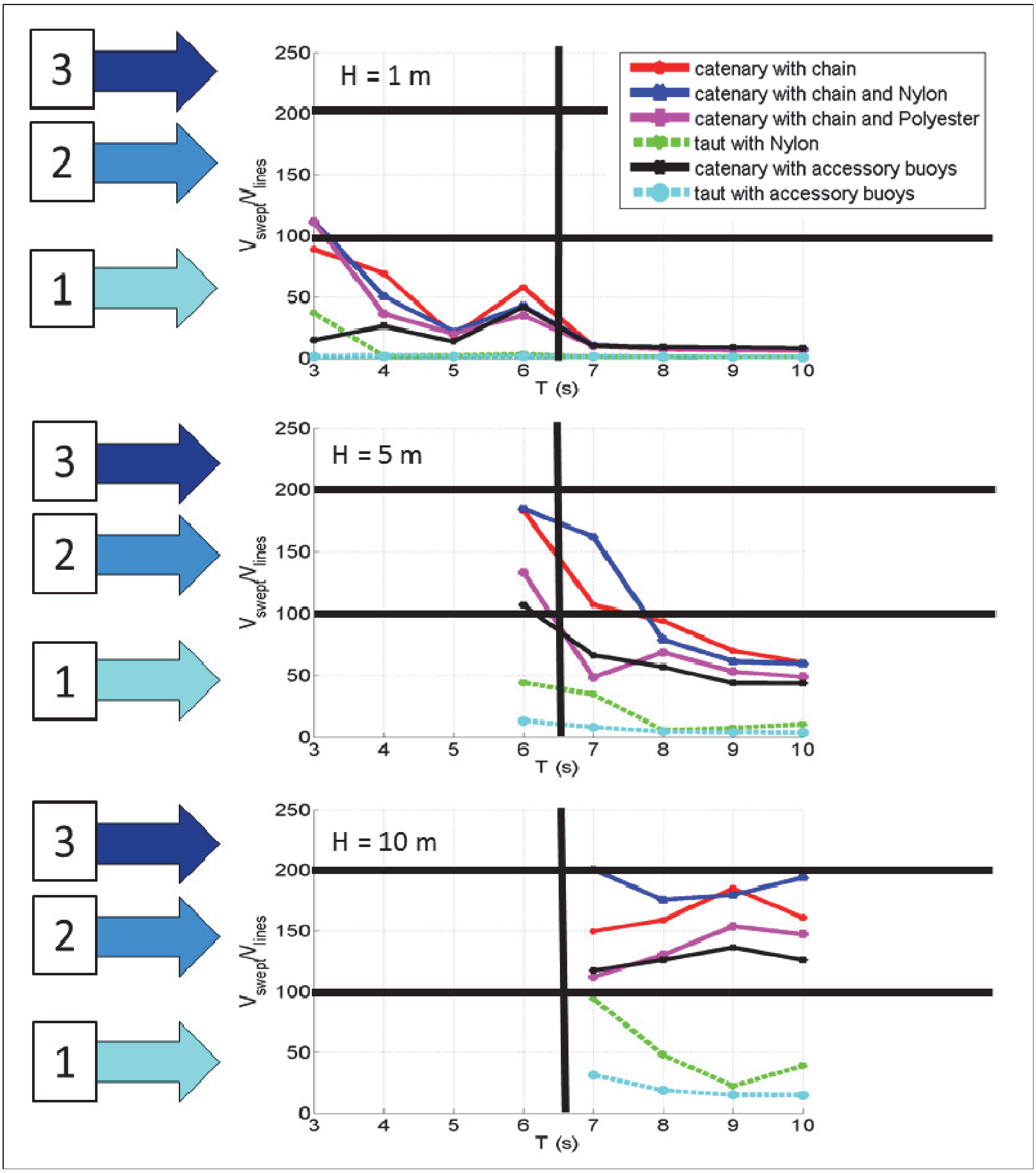


Figure 5.2. Swept volume ratio ($V_r = V_{swept}/V_{lines}$) for different mooring configurations: catenary with chain (red), catenary with chain and Nylon (blue), catenary with chain and Polyester (magenta), taut with Nylon (green), catenary with accessory buoys (black), taut with accessory buoys (cyan). Catenary configurations are represented by solid lines while taut configurations used dashed lines. Results are given for various sea states (derived from Figure 4.7), illustrating how risk values were associated with different V_r values.

The highest V_r score of each mooring for each of the two wave period categories was used to determine the overall relative risk score of the mooring (Table 5.8), with relative risk parameters of 1 (least risk), 2 (medium risk) and 3 (greatest risk) assigned on the basis of the average of the five scores (no data were available for the combination of wave height = 10 m and wave period = 3-6 seconds; see Section 4.1.2 for details).

Table 5.8. Risk associated with swept volume ratio (V_{swept}/V_{lines}) for different mooring configurations at various sea states. Data were divided by wave height (in m) and wave period (in seconds).

Mooring type	Wave period (seconds)	Wave height (m)			Average score across sea states	Final Swept Volume score
		1	5	10		
Catenary with chain	3-6	1	2	-	1.6	2
	7-10	1	2	2		
Catenary with chain & Nylon	3-6	1	2	-	1.6	2
	7-10	1	2	2		
Catenary with chain & Polyester	3-6	2	2	-	1.6	2
	7-10	1	1	2		
Taut with nylon	3-6	1	1	-	1.0	1
	7-10	1	1	1		
Catenary with accessory buoy	3-6	1	2	-	1.4	2
	7-10	1	1	2		
Taut with accessory buoy	3-6	1	1	-	1.0	1
	7-10	1	1	1		

Results indicated that the risk of entanglement based on mooring swept volume was higher for all catenary configurations, with different materials, with or without accessory buoys, while the risk was lower for the taut configurations, with or without accessory buoys.

5.3.3 Mooring curvature

The ability of ropes to bend back upon themselves and form loops in which animals can inadvertently get themselves caught is a well-known feature of many entanglement cases involving fishing gears (see Section 2). In OrcaFlex™, the curvature of the mooring can be obtained at each predefined mooring node (see Section 4.1.3 for details). The mean (global) curvature relative to a predefined vertical axis can also be obtained. The amount of within-mooring variability in curvature (i.e. scatter around the mean) is also likely to vary considerably between different mooring configurations, and this parameter can be used to rate moorings in terms of entanglement risk, using boxplots as in Figure 5.3. On each box plot, the red central line represents the median value, the edges of the box are the 25th and 75th percentiles, respectively, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually in red.

For the present report, subdivisions of the curvature risk parameter were defined as follows: Any model for which the mean curvature value was $<10^{-2}$ was given a score of 1, while models with mean curvature values between 10^{-2} and 10^{0} were given a score of 2 and models with mean curvature values $> 10^{0}$ were given a score of 3 (indicated by the coloured arrows). It should be emphasized that these **cut-off values were chosen arbitrarily** and further work is needed to provide further underpinning of these parameters. For the present report these values served to separate mooring configurations whose mean curvature values differed by multiple orders of magnitude.

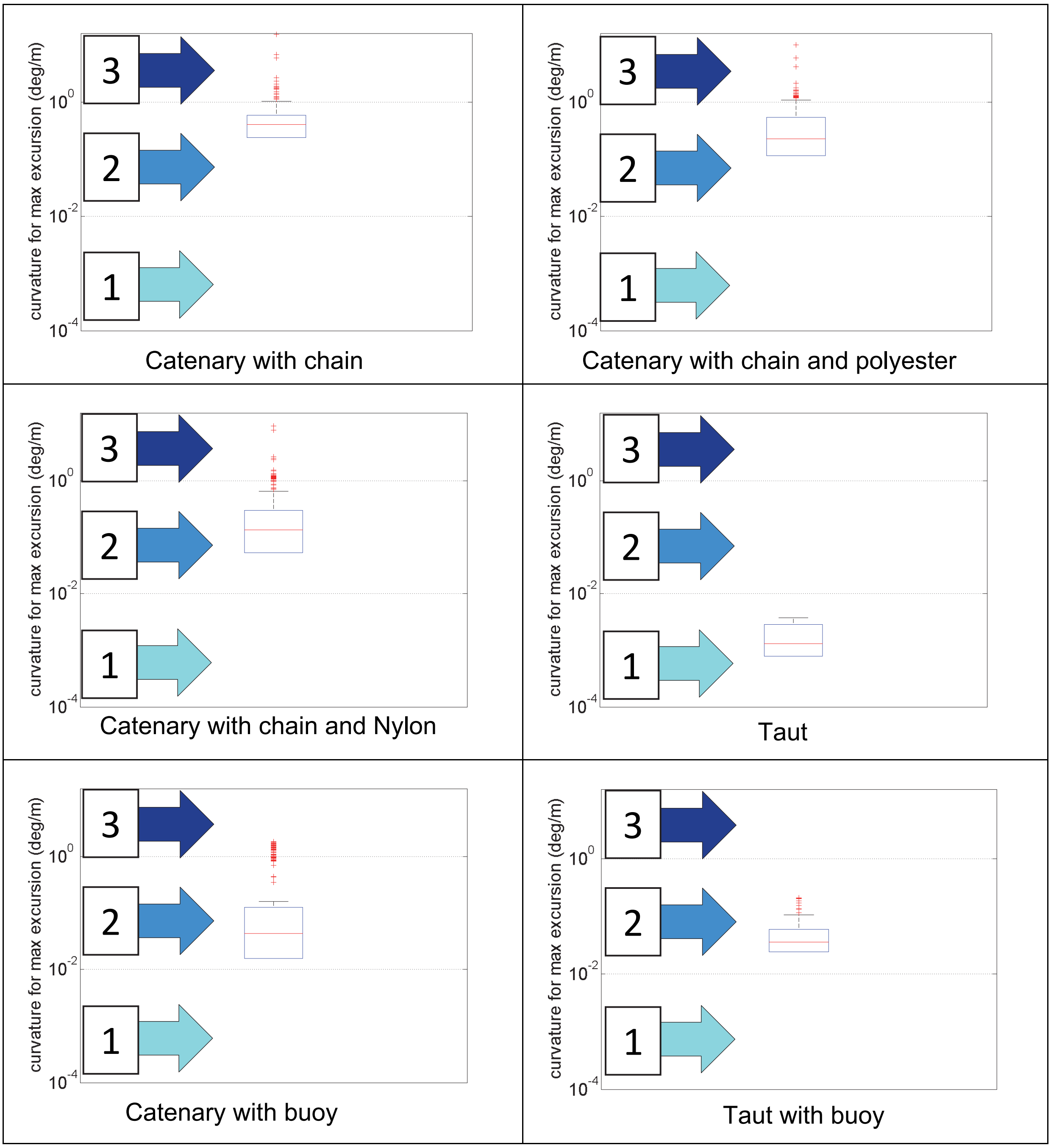


Figure 5.3. Boxplots of modelled mooring curvatures of the six configurations considered in this report illustrating how risk values were associated with different curvature values. Red lines within boxplots indicate median values.

The mean curvatures were summarised in Table 5.9. Results indicate that the risk of entanglement based on curvature is similar for all configurations, except the taut configuration where the risk is lower. It is worth noting that such curvature values are far less than might be encountered in, for instance, fishing gears.

Table 5.9. Summary of curvature scores for the different modelled mooring configurations. The configurations with accessory buoys did not consider the floating lines in the curvature calculation, therefore their curvature score has been increased to take these lines into account.

Mooring type	Median curvature (degrees per m) at maximum excursion of the buoy	Mean curvature (degrees per m) at maximum excursion of the buoy	Curvature score
Catenary with chain	0.4062	0.5715	2
Catenary with chain & Nylon	0.1364	0.3465	2
Catenary with chain & Polyester	0.2292	0.4572	2
Taut with nylon	0.0013	0.0018	1
Catenary with accessory buoy	0.0441	0.2822	2
Taut with accessory buoy	0.0360	0.0520	2

5.3.4 Summary of mooring element risk parameters

Similarly to the calculation of the Biological Risk Score for each marine species, a Physical Risk Score can also be calculated for each of the moorings scenarios considered in the numerical modelling study. This is illustrated in Table 5.10.

Table 5.10: Summary of entanglement risk based on the physical characteristics of the mooring for the modelled mooring scenarios.

Mooring type	Tension characteristics	Swept volume	Curvature	Total score (A + B + C)
Catenary with chain	2	2	2	6
Catenary with chain & Nylon	3	2	2	7
Catenary with chain & Polyester	2	2	2	6
Taut with nylon	1	1	1	3
Catenary with accessory buoy	3	2	2	7
Taut with accessory buoy	3	1	2	6

These results indicate that the taut configurations presented the lowest entanglement risk, based on the 3 parameters considered in this study: tension characteristics, swept volume and curvature. The risk was comparable for the other mooring arrangements, and slightly higher for the catenary configuration using chain and Nylon, as well as the catenary configuration using accessory buoys.

5.4 Other considerations

It should be noted that other parameters than the ones considered so far may influence relative entanglement risk. These include MRE device mass and buoyancy as well as mooring strength and spacing of devices within arrays.

5.4.1 Device mass and buoyancy

The mass and buoyancy of MRE devices can vary considerably between different designs, for example between a small point absorber and a large overtopping device. For this reason, it is difficult to assess these parameters in detail in the present report. However, given that large whales are known to be capable of moving small vessels at anchor (Section 2), light and buoyant devices or accessory buoys could potentially be comparatively easily moved by the largest marine megafauna. This could potentially lead to an enhanced risk of entanglement.

5.4.2 Mooring strength

As described earlier, the minimum breaking load (MBL) of a mooring component describes the force (in N) required to break that component. Due to the demanding environmental conditions such moorings are expected to encounter, mooring components have been designed to have high MBL values (see Table 3.1). Depending on the diameter of components used, the force required to break them can increase dramatically. Biophysical models suggest that foraging blue whales regularly overcome drag forces of $>1x10^5$ N during lunge feeding (Goldbogen *et al*., 2011). It is therefore likely that $1x10^5$ N represents a reasonable upper limit for the amounts of force that marine megafauna species would be able to generate while trying to escape an entanglement, with smaller species capable of much less force.

An attempt was made to estimate the approximate amount of force required by representative megafauna species to achieve burst speeds as reported in the scientific literature (Table 6.11). The assumption was made that entangled animals would attempt to rapidly accelerate to their maximum speed in an attempt to break free. Animal body shapes were represented as cylinders to estimate surface area. Assuming burst speeds are achieved over short timeframes (10 seconds), forces required to achieve burst speeds range between $3.5x10^1$ – $8.8x10^4$ N (harbour porpoise vs. blue whale, respectively). As the present calculations do not include drag or lift, actual forces can be expected to deviate somewhat from these results, which are only intended to provide a basic assessment of the relative orders of magnitude of force required to accelerate to burst speeds.

Comparing these estimates to published MBL values suggests that even the thinnest of ropes and chains (d=16mm and 6 mm, respectively) would be able to restrain animals the size of a bottlenose dolphin. The ropes and chains under consideration in this study (with diameters ranging between d = 140mm – 240mm [rope] and between 40mm – 175mm [chain]; see Table 5.11) would appear to be impossible to break by animals according to their MBL values as indicated in Table 5.12. This indicates that, based on a simplistic model, most mooring components in use today are sufficiently strong to restrain entangled animals, should entanglement take place. Similarly, in the Case Study in Section 2 (p.21) of this report a commonly used anchor chain proved sufficient to restrain an adult fin whale, although loops of chain formed around this individual which also contributed to its entanglement.

Table 5.11. Summary of approximate force (F, in N) required to accelerate a cylinder with dimensions comparable to representative megafauna species from zero to maximum recorded speeds in 10 seconds. A = acceleration. Marine mammal mass and length values taken from National Audubon Society (2002).

Species	Length (m)	Max. speed (m/s)	Mass (kg)	A_{10sec} (m/s^2)	F (N)	Source
Blue whale	24.7	10.0	88000	1.00	8.8E+04	Sears & Calambokidis 2002
Sperm whale (male)	15.9	8.3	44000	0.83	3.65E+04	Aoki *et al*. 2012
Humpback whale	13.5	7.5	32000	0.75	2.40E+04	Noad & Cato 2007
Right whale	15	3.6	47000	0.36	1.69E+04	Tomilin 1957
Minke whale	8	8.3	7000	0.83	5.81E+03	Ford *et al*. 2005
Killer whale (male)	8.2	12.5	4100	1.25	5.13E+03	Williams 2002
Bottlenose dolphin	2.9	8.0	360	0.8	2.88E+02	Rohr *et al*. 2002
Harbour porpoise	1.5	6.1	50	0.61	3.05E+01	Nowak 1991
Grey seal	2.6	3.2	350	0.32	1.12E+02	Gallon *et al*. 2007
Leatherback turtle	2.6	2.8	900	0.28	2.52E+02	Eckert *et al*. 2002
Basking shark	7	1.1	5000	0.11	5.50E+02	Shepard *et al*. 2006

Table 5.12. Minimum breaking load for chains and Nylon ropes with the highest available diameters, and with the minimum diameters used in this study.

	Chain		Nylon rope	
	Largest available diameter	Minimum diameter in this study	Largest available diameter	Minimum diameter in this study
Diameter (mm)	175	40	240	140
MBL (N), based on data in Table 3.2	20E+6	1.5E+6	13E+6	4.5E+6

5.4.3 Spacing of devices within arrays

In the interest of energy capture, MRE devices and their associated moorings within arrays will be placed in an energetically optimal configuration while minimising inter-device distance for efficient subsea cabling. Array design depends heavily on various factors including the type of device used, mooring footprint, site conditions and distance to shore. Risk of entanglement will vary depending on whether single mooring elements are shared between multiple MRE devices in the same array, or whether individual devices each have their own independent mooring system. If it is assumed that individual devices do not share moorings, then the total number of mooring lines can be calculated in a straightforward manner by multiplying the number of mooring lines for individual devices by the total number of devices planned for an array.

MRE arrays can be classified in terms of what fraction of the water column within the entire array will be affected by moving moorings. The volume of the array itself (V_{Array}) can be calculated by multiplying the water depth by an area defined by the maximum lateral excursions of the outermost devices in the array, or the mooring footprint on the seabed, whichever is greater. As indicated by modelling results discussed in Section 4, the volume of water affected by the moorings of an individual device (V_{swept}) can be estimated. The volume of water affected by all devices within a given array (V_{all}), therefore, can be obtained by multiplying V_{swept} by the total number of devices in the array (N). The ratio of V_{all} over V_{Array} can then provide a metric by which different arrays can be compared to each other, in terms of volume of water impacted by the entire array.

6. RELATIVE ENTANGLEMENT RISK ASSESSMENT

6.1 Results

This report has highlighted various risk factors, including biological characteristics of animals involved and physical features of the moorings themselves, which can influence entanglement risk. At present, no large-scale arrays of moored MRE devices exist anywhere in the world, although several projects are currently in the pre-construction phase. In the resulting absence of direct evidence of entanglement in such arrays, this report has by necessity taken a theoretical approach to assess the relative risks such arrays might pose to marine megafauna. The authors are conscious that the approach presented here makes several key assumptions (e.g. regarding animals' abilities to detect moorings, or risks posed by particular physical parameter scores; see Sections 4, 5.2 and 5.3), which may need to be revised as additional data become available.

In this section we draw together the results of this investigative report, including empirical evidence and theoretical material, to present a risk assessment matrix which may support impact assessment and the communication of risk to species of entanglement in MRE devices. This approach presents a guide based on relative risk, which would be refined upon the availability of more detailed project-specific information.

Section 5 identified the key elements of entanglement risk relating to both the physical design of the moorings and biological characteristics of marine megafauna. Each of these elements had risk parameters assigned, ranging from 1 (smaller relative risk) to 3 (greater relative risk). This enabled a total risk parameter to be calculated for each species or sub-species by summing the individual risk parameters (see Table 5.6). A similar risk parameter was calculated for the mooring, based on the mooring type and its component elements (see Table 5.9). An overall risk of entanglement parameter could therefore be calculated for a particular type of animal interacting with a specific type of mooring by multiplying these two values (biological risk and physical risk; see Table 6.1).

The mooring behaviour modelling approach undertaken in this report is a standard part of the mooring design process and would therefore be undertaken by developers as a matter of course. The present report suggests that developers could take relative-risks of entanglement into account in the manner reported here, in the course of modelling expected mooring behaviours. This would allow them to put their results into the context of relative risks posed by the various mooring designs described in this report.

Table 6.1 combines the results of the biological and physical risk assessments for different megafauna groups and mooring configurations to provide a total overview of entanglement risk for the mooring configurations, as modelled in this report.

Table 6.1: Total RELATIVE risk assessment for each megafauna group and mooring scenario (based on biological and physical risk parameters from Tables 5.6 and 5.10). Baleen whales have been subdivided into filter-feeders (FF) and lunge-feeders (LF). Cyan-coloured cells ( ) indicate lowest relative risk, azure-coloured cells ( ) indicate moderate relative risk, and navy blue-coloured cells ( ) indicate greatest relative risk. These relative risk assessments are in themselves not quantitative but are intended to compare relative degrees of risk posed by different mooring configurations to different megafauna groups.

Species group			Catenary & chain	Catenary & chain & nylon	Catenary & chain & polyester	Taut & nylon	Catenary & accessory buoy	Taut & accessory buoy
Cetaceans	Baleen whales	Large whales (LF)	[navy]	[navy]	[navy]	[cyan]	[navy]	[navy]
		Large whales (FF)	[navy]	[navy]	[navy]	[cyan]	[navy]	[navy]
		Medium-sized whales (LF)	[navy]	[navy]	[navy]	[cyan]	[navy]	[navy]
	Toothed whales	Sperm whale	[azure]	[azure]	[azure]	[cyan]	[azure]	[azure]
		Medium-sized whales and dolphins	[azure]	[azure]	[azure]	[cyan]	[azure]	[azure]
		Small whales, dolphins and porpoises	[cyan]	[azure]	[cyan]	[cyan]	[azure]	[cyan]
Pinnipeds	Seals		[cyan]	[azure]	[cyan]	[cyan]	[azure]	[cyan]
	Sea lions, fur seals etc.[2]		[cyan]	[azure]	[cyan]	[cyan]	[azure]	[cyan]
Sea turtles			[azure]	[azure]	[azure]	[cyan]	[azure]	[azure]
Sharks	Basking sharks		[azure]	[azure]	[azure]	[cyan]	[azure]	[azure]
	Other large sharks		[cyan]	[azure]	[cyan]	[cyan]	[azure]	[cyan]
Ocean sunfish			[azure]	[azure]	[azure]	[cyan]	[azure]	[azure]

[2] NB: These species do not occur in Scottish waters.

Key points:

- Although some parameters were informed by quantified evidence and values were assigned in generating the risk parameters, these are in themselves **not quantitative** parameters but are intended to compare **relative** degrees of risk posed by different mooring configurations to different megafauna groups.
- For many species of megafauna, MRE device moorings are **unlikely** to pose a major threat due to the moorings' size and mass. This is in line with the apparent absence of entanglement records in similar moorings associated with other offshore industries (e.g. oil and gas). However, even if the threat is small, it should be remembered that cetaceans (as European Protected Species) and basking shark are afforded legal protection at the individual level in Scotland and therefore should be considered accordingly. Baleen whales were considered to be at greatest relative risk overall, largely due to their size and foraging habits.
- Some mooring designs present a greater relative risk than others. The greater risks were generated by catenary moorings, particularly those containing nylon. Taut systems represented the lowest risk, with the caveat that pre-tension should be designed to be high enough to prevent slack mooring lines.
- The range of uncertainty varies amongst the risk parameters (Table 6.1). As projects are deployed and empirical evidence is collected this uncertainty in the risk parameters can be refined through appropriate monitoring studies (if deemed necessary).
- Modelling results indicate that moorings may show considerable swept volume under moderate to severe wave conditions which would increase entanglement risk. These findings have additional relevance when considering arrays of devices because of the increased numbers of moorings within arrays.
- Based on analyses discussed in previous sections of this report (Sections 5.2.4 and 5.4.2), it appears that most moorings associated with MRE devices would likely be too strong for animals to easily break free if they became entangled. This is also a problem for animals becoming entangled in derelict fishing gears that become attached to moorings.
- Curvature of mooring lines can be high, especially in the top sections of the mooring. Although not modelled in this study, it is important to note that the power cables will also have a high curvature and therefore should be considered in future studies. However, power cables are less strong than mooring lines (see Section 5.4.2), which means there is the possibility that an entangled animal may be able to break free.
- The risks for arrays will vary. For example, catenary moorings consistently displayed greater swept volume than taut moorings, which would suggest that arrays of devices using catenary moorings would end up occupying a larger area than an array of devices using taut moorings. These differences should be taken into consideration when reviewing future applications for MRE device array developments.
- There are no records of marine megafauna entanglements in moorings or any other infrastructure associated with the offshore petrochemical industry, the closest parallel to marine renewables moorings. There are, however, anecdotal observations of large whales seeking out underwater platforms, umbilicals and other structures, apparently as a surface to scratch against.
- This investigative report has addressed the risk of entanglement of marine megafauna through analysis of the physical characteristics of the mooring configurations along with biological parameters of individual species. At the project level, it is necessary to combine this with the likely biological use of the area by these species, in order to draw conclusions on the significance of impacts. This information will also be useful for the understanding of collision risk (such as with the blades of tidal energy devices), animal displacement due to noise, etc.

The assessment of entanglement risk could be integrated into the EIA reporting process in a relatively straightforward manner, as illustrated by the Risk Analysis flow chart below (Figure 6.1):

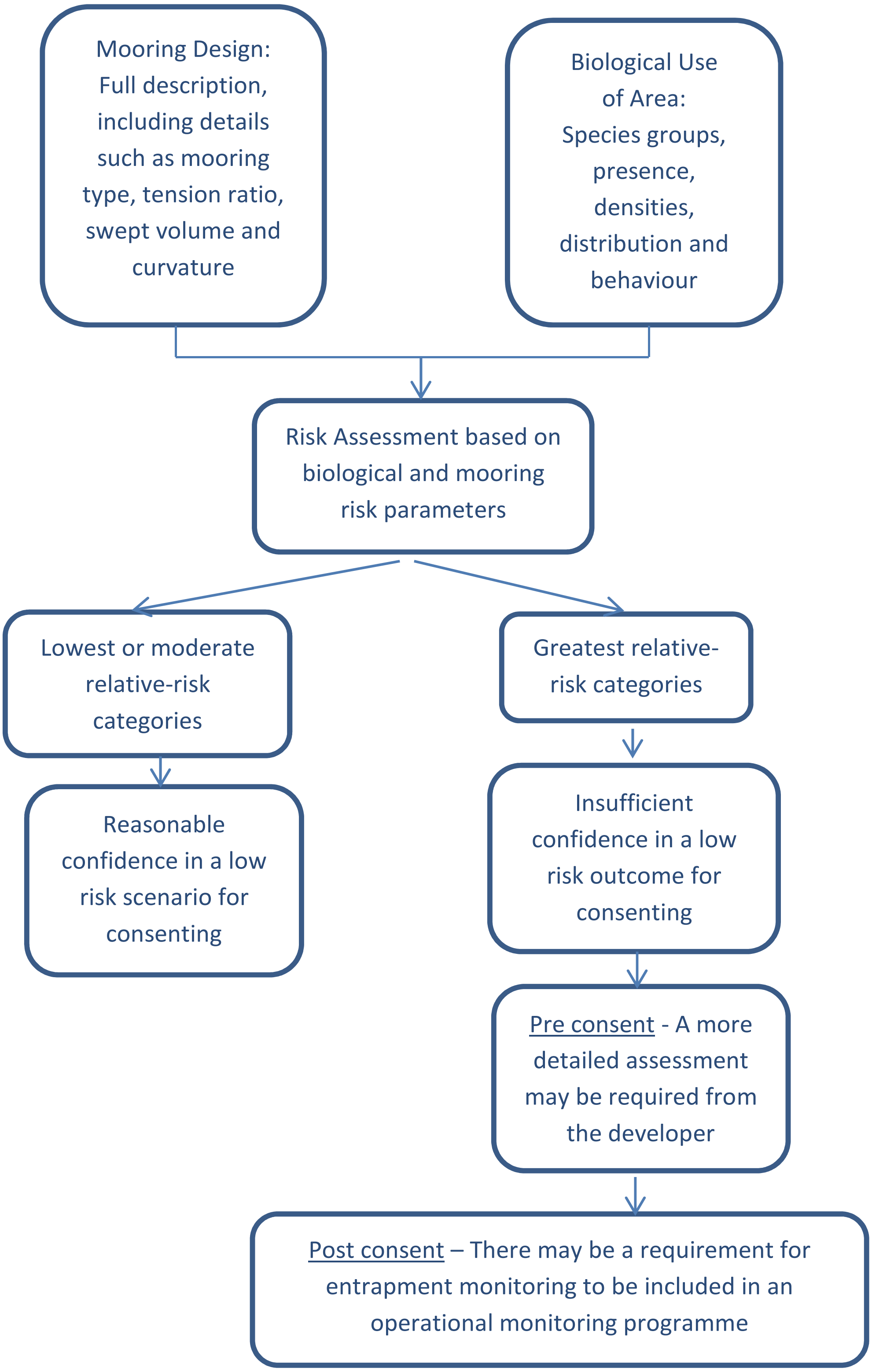


Figure 6.1. Flowchart displaying the general risk assessment process for entanglement.

6.2 Implications of entanglement

If an animal becomes caught in a mooring or cable of any kind, there are expected to be two broad potential outcomes:

1. The mooring line or cable does not break, in which case an animal may remain stuck if it is unable to disentangle itself. This may result in the animal dying while still entangled.
2. The mooring or cable breaks, in which case it becomes important to identify where the break might occur. If the break occurs at the point where the animal is touching the mooring line, it will most likely be able to escape.

It is important to stress that such breakage is considered both unlikely and highly undesirable from the developers' point of view. This suggests that entanglement of marine megafauna amongst MRE devices, should it occur, is likely to be injurious or fatal to the animals involved. As many future MRE developments can be expected to be located in remote or offshore areas, opportunities for live release of any entangled animals would appear to be unlikely. The presence of a large carcass may negatively affect mooring or device performance, particularly once the buoyancy of the carcass changes through decomposition. Whether, and when, such a carcass would eventually decompose sufficiently to fall away from the mooring is not clear and would likely depend on particular factors of each specific case.

6.3 Monitoring of entanglement risk

Future studies on actual devices and arrays are required to improve upon the approach presented in this report. In particular, there is scope for improving and focusing the various biological and physical risk parameters of the model used here. As more devices are deployed in the future, careful monitoring will be essential to adequately assess whether or not entanglement is occurring. This may be difficult to achieve at remote or offshore sites where access by inspection vessels may only be possible at wide intervals. Remote sensing technologies may therefore be required.

In the early phase of marine renewable development, there will be a need to validate the risk assessment processes in an iterative manner based on the results of monitoring as deemed appropriate by the regulators. Due to the particular challenges in monitoring novel impacts to marine megafauna from developments with confidence, there is a need to balance the feasibility (time and cost) of monitoring relative to the predicted risk. It would be more cost- and time-efficient if monitoring were focused on the 'greater relative risk' developments based on the risk assessment process presented above, including focusing on the sites that may have a greater species presence and therefore a higher potential encounter rate. Nevertheless, it is probable that developers will routinely monitor their development for other reasons, such as device performance; there may, therefore, be the opportunity to check for entanglement, animal behaviour/presence around the site and trapped derelict fishing gear.

It is important to note that the risk assessment process as described in this report (Table 6.1) indicates degrees of **relative** entanglement risk, based on a number of key parameters. We note in particular that a critical parameter in determining overall actual risk for individual projects is the occurrence and behaviour of megafauna species in and around the proposed array. Following consideration of project-specific information regarding mooring characteristics and species occurrence, entanglement rates directly associated with MRE devices are likely to be low in most areas, taking into account the various caveats outlined above. Although entanglements of most smaller megafauna species in moorings are considered to be comparatively unlikely, baleen whales are expected to be at greatest risk given what is known about their anatomy, behaviour and recorded entanglement events in other moorings, anchor chains, aquaculture facilities etc. These risks should be considered by developers based on the results of monitoring as deemed appropriate by the regulators.

7. FURTHER RECOMMENDATIONS

This report has considered the entanglement risk to marine megafauna from MRE developments and presented a method of assessing relative risk. This is one part of the MRE development overall risk assessment that should be undertaken at a project level. As highlighted in the previous section, the presence of animals in the area is of key importance; as is how the animals are using the site and if/how their use is altered for other reasons (e.g. barrier due to presence of development, or attraction due to increase prey presence should the development act as Fish Aggregation Device).

This report should therefore be considered as a first step in this process (i.e. could entanglement happen and what are the consequences - see Risk analysis flow chart - Figure 6.1). There is currently a large degree of uncertainty surrounding the potential impacts of all marine renewable developments, and adaptive management approaches (which may include potential entanglement amongst other impacts considered) may therefore be appropriate.

Research undertaken for this report has indicated a comparative lack of empirical data on marine megafauna entanglement events involving moorings and other vertical structures in the water column, in contrast to frequent entanglement reports involving fishing gear. As the marine renewable energy industry expands, care needs to be taken to ensure any entanglement event is correctly reported to the relevant regulators.

Potentially, of greater concern than the entanglement risk presented by the moorings themselves is entanglement with derelict fishing gear which becomes caught / snagged amongst the moorings and devices. If such gears are being held erect in the water column for extended periods, they would present a novel entanglement or bycatch risk for a wide range of species, including those otherwise too small to be adversely affected (e.g. seabirds). This means that there is a need for more in-depth assessment of the snagging risk and subsequent presence of derelict gears among moorings and cables associated with MRE devices or analogous structures across multiple offshore industries.

This present report has provided a method to describe qualitatively the variation that exists between different mooring designs in terms of potential entanglement risk to marine megafauna. Currently development proposals vary in the degree of detail provided about the moorings' physical properties. As such it may be difficult for the regulator to assess different mooring systems in relation to entanglement risk.

MRE devices are expected to remain in the marine environment for the operational lifetime of proposed projects, currently up to 25 years, before either being replaced or decommissioned. During this time, their surfaces will be colonised by many different species of marine algae and invertebrates unless stringent antifouling measures are taken. Assuming that such biofouling communities are able to establish themselves and are allowed to develop, the combined mass of such communities may influence the behaviour of such moorings and devices over time. Such changes could modify existing entanglement risks to marine megafauna. Moreover, the presence of biofouling communities will increase the surface roughness of both devices and moorings, and could increase opportunities for derelict fishing gears becoming attached.

Underwater visual inspection of the conditions of moorings, interconnector cables, etc. is likely to be required for operational reasons. Such inspections are likely to be carried out by remotely operated vehicles (ROVs) or comparable platforms equipped with cameras. Such inspections can be used to detect entanglements and/or derelict fishing gears. Inspections are likely to occur at wide intervals, typically after significant construction activity, heavy storms, etc. The frequency of inspections may differ between developments and is unlikely to be fixed across the industry, and moreover may change over time.

Our recommendations are detailed below and are grouped into recommendations regarding reporting (for both developers and regulators), and wider research questions.

Reporting

- *Recommendation 1:* When submitting a development proposal, developers should be encouraged to follow the relative risk assessment process outlined in this report, and to provide details of existing and planned routine inspection regimes involving moorings. This includes specifying the monitoring methodology (ROVs, etc.), the fraction of moorings/mooring lengths expected to be monitored, and the expected frequency of inspection, details of whether/how derelict fishing gear snagged on moorings or MRE devices might be recovered, and how any such gear would be disposed of. The regulator should be informed if any significant changes are made to this inspection regime.

- *Recommendation 2:* During the consent period of devices and arrays, a procedure needs to be put in place which would require developers to report to regulators any significant changes to mooring and MRE device behaviour over time (e.g. through replacement of mooring components) if such changes would increase the risk of marine megafauna entanglement.

- *Recommendation 3:* There is a need for the establishment of an official reporting mechanism by which developers can report the presence of marine megafauna entanglement in MRE device moorings to the regulator (e.g. Marine Scotland who will need to be aware for HRA and EPS purposes). This includes reporting on the presence/absence of snagged derelict fishing gear. For developments deemed of lowest or moderate risk and where a high level of monitoring is not deemed necessary, developers should ensure that visual surveys are undertaken during routine maintenance and any entanglement issues reported. More frequent assessment may be required for higher risk developments.

- *Recommendation 4:* A formal accident investigation procedure needs to be put in place by the developer, in order that in the event of an entanglement the appropriate authorities are alerted to allow all relevant information to be recorded, and to trigger an assessment by the regulator into whether any emergency measures were required.

- *Recommendation 5:* Details of moorings relevant to the risk of entanglement of marine megafauna should be included alongside Marine Licence applications and within Environmental Statements. Such parameters include the spatial scale of the mooring configuration (surface footprint, swept volume), the length, diameter and composition and particular metrics associated with each component such as mooring tension characteristics and curvature (under normal and extreme conditions). Other relevant metrics include strength (MBL), axial stiffness per unit length, weight per unit length of components in the mooring and the range of sea states at a particular project site. Similar data need to be provided for power cables associated with devices, both single and in arrays (see developer checklist in Annex 1).

Wider recommendations

If marine megafauna entanglement were shown to occur in moorings associated with MRE devices some modifications to current and future moorings may be required. If entanglement or bycatch in snagged derelict fishing gear were found to be the main problem, other approaches such as gear removal programmes could be considered. Any such potential options should be considered carefully to ensure that no further impacts occur as a result.

Given the potential importance of derelict fishing gear in terms of entanglement risk, further work is necessary to assess how serious a bycatch risk derelict fishing gear might pose around moorings associated with MRE devices and other industries. This information would assist in the assessment of impacts to protected species / populations across all sectors.

In the context of entanglement risks associated with MRE, it is also important to consider the displacement of existing fishing activities due to MRE developments. Most MRE developments as currently foreseen will require a zone from which mobile fishing activities are effectively excluded to prevent active fishing gears interfering with the devices. Although most fishing effort may not be displaced far, there is the potential for subsequent concentration of fishing effort outside the exclusion zone which could increase the risk of bycatch and/or entanglement in these fishing gears in new areas.

- *Recommendation 6:* Further investigations are needed to clarify the distribution and abundance of derelict fishing gear in Scottish waters, and the extent to which gear becomes snagged in moorings or other vertical structures in the water column. Potential data sources include ROV survey data from the oil and gas industry, Northern Lighthouse Board surveys of navigational buoys, etc. This will allow regulators to make informed decisions on how best to assess and mitigate entanglement and bycatch risks associated with snagging derelict fishing gear.

- *Recommendation 7:* Further research may be required to assess the full range of entanglement mitigation options available to the MRE industry, to minimise any risks of entanglement events occurring.

- *Recommendation 8:* Further research may be required to assess the effects of redistribution of fishing effort displaced from MRE development sites, to ensure that any marine megafauna entanglement/bycatch risks posed by the MRE development are not inadvertently exacerbated by increased entanglement/bycatch rates in displaced fisheries.

8. GLOSSARY

Term	Definition
Anthropogenic	An effect or object resulting from human activity.
Axial stiffness per unit length	Mooring line resistance to being elongated to a given length by an axial force.
Autonomous Underwater Vehicle (AUV)	Robotic underwater vehicle capable of operating autonomously or otherwise untethered.
Benthic zone	The ecological region at the deepest level of a body of water, including the surface and subsurface sediment or rocky substrate.
Bony fish	A taxonomic group of fish possessing bony skeletons. It is the largest class of vertebrates in existence today, containing over 28,000 species including nearly all commonly encountered fish.
Bycatch	The inadvertent capture or retention of undesirable marine species as part of normal fisheries operations. (NB: this term may be conflated with entanglement in the scientific literature).
Catenary mooring	Suspended mooring line with a curve shape between the floating structure and the seabed, and with horizontal lines on the seabed. Much of the restoring forces are provided by the weight of the mooring line.
Compliant mooring	Flexible mooring, allowing freedom of motion for the floating structure it is connected to.
Coupled behaviour	Reciprocal influence of the mooring system on the floating structure behaviour.
Entanglement	The inadvertent capture or retention of marine megafauna in linear structures in the marine environment such as, but not limited to, ropes, lines, cables etc. (NB: this term may be conflated with bycatch in the scientific literature).
Excursion	Horizontal motion of the floating structure.
Footprint	Space used by the mooring system on the seabed.
Invertebrates	A generic term of convenience used to describe all animals without backbones (>98% of all known animals).
Mooring Load	Tension, force in the mooring system.
Marine megafauna	A term used to describe all large marine vertebrate species including marine mammals, seabirds, marine turtles, sharks and large bony fish.
Marine Renewable Energy (MRE) devices	Wave, tidal and floating wind energy converters.
Mean drift:	Mean horizontal motion of a floating structure.
Mean zero up-crossing period	Average time between successive crossings of the mean water level in an upward direction.
Minimum Breaking Load (MBL; [N], also called	Force which will break a mooring material, according to the manufacturer’s specifications.

Catalogue Break Strength [CBL])	
Motion-dependent device	Device in which its dynamics and its primary mode of energy extraction require the application of an interactive mooring system – the mooring must be designed such that the resonant period of the device and mooring system should match the wave periodicity (Johanning & Wolfram, 2005).
Motion-independent device	Device in which the mooring will act in a conventional manner to restrain the device to remain on station while providing minimum restraints on its motions (example: floating Oscillating Water Column (OWC) Wave Dragon device, floating wind turbine; Johanning & Wolfram, 2005).
Pre-tension	Tension in the mooring system without any external forces, when non-dimensional surge is equal to zero.
Restoring force	Force provided by the mooring system to bring the floating structure back to equilibrium.
Remotely Operated underwater Vehicle (ROV)	Tethered underwater vehicle.
Significant wave height (Hs)	Mean wave height (trough to crest) of the highest third of the waves ($H_{1/3}$).
Second order wave load	Low or high frequency wave loads, proportional to the square of the wave elevation. The sea state can be represented by a sum of i regular waves at frequencies ωi. Second order loads occur at ωi + ωj or ωi - ωj
Sessile	A condition describing animals that are permanently attached to a substrate or otherwise immobile. Many such species have a free-swimming larval stage.
Slow-drift motion	Slow (second-order) oscillatory horizontal motion of the floating structure.
Surge	Motion of a floating structure on the same axis as the wave direction.
Taut mooring	Mooring line with a straight shape between the floating structure and the seabed. The restoring forces are provided by elastic deformation of mooring lines.
Wave frequency loads	Forces applied by the waves on the floating structure at the same frequency than the waves.

9. REFERENCES

Allen, A.A. and Plourde, J.V., 1999. *Review of Leeway; Field Experiments and Implementation*, USCG R&D Center Report CG-D-08-99.

Allen, A., Roth, J-C., Maisondieu, C., Breivik, Ø. and Forest, B., 2010. *Field Determination of the Leeway of Drifting Objects*. Met.no Report no. 17/2010 SAR/HAZMAT/Leeway.

Allen, R., Jarvis, D., Sayer, S. & Mills, C. 2012. Entanglement of grey seals *Halichoerus grypus* at a haul out site in Cornwall, UK. *Marine Pollution Bulletin,* 64**,** 2815-2819.

American Bureau of Standards 2000. Guidelines for the purchasing and testing of SPM hawsers.

American Bureau of Standards 2011. Guidance Notes on the Application of Fiber Rope for Offshore Mooring.

American Petroleum Institute 1997. Mooring Chain API Spec 2E.

American Petroleum Institute 2007. Recommended Practice for Design, Manufacture, Installation and Maintenance of Synthetic Fiber Ropes for Offshore Mooring: API RP 2SM (amended version).

Anonymous 2012. Whale drowns after getting hooked on ship's anchor chain. *Anchorage Daily News*, May 17, 2012.

Aoki, K., Amano, M., Mori, K., Kourogi, A., Kubodera, T, & Miyazaki, N. 2012. Active hunting by deep-diving sperm whales: 3D dive profiles and maneuvers during bursts of speed. *Marine Ecology Progress Series,* 444, 289-301.

Azevedo, A.F., Lailson-Brito, J., Dorneles, P.R., Van Sluys, M., Cunha, H.A. & Fragoso, A.B.L. 2008. Human-induced injuries to marine tucuxis (*Sotalia guianensis*) (Cetacea: Delphinidae) in Brazil. *Brazilian Journal of Oceanography,* 56**,** 313-316.

Balasz, G.H. & Chaloupka, M. 2004. Thirty-year recovery trend in the once depleted Hawaiian green sea turtle stock. *Biological Conservation,* 117**,** 491-498.

Barlow, J. & Cameron, G.A. 2003. Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. *Marine Mammal Science,* 19**,** 265-283.

Bartol, S.M. & Ketten, D.R. 2006. Turtle and tuna hearing. *U.S Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-07***,** 98-103.

Barltrop, N. 1998. Floating Structures: A guide for design and analysis CMPT/OPL.

Baum, J.K., Myers, R.A., Kehler, D.G., Worm, B., Harley, S.J. & Doherty, P.D. 2003. Collapse and conservation of shark populations in the northwest Atlantic. *Science,* 299**,** 389-392.

BBC. 2012. Basking shark caught in creels in Loch Broom. Available online at http://www.bbc.co.uk/news/uk-scotland-highlands-islands-13604986.

Beck, C.A. & Barros, N.B. 1991. The impact of debris on the Florida manatee. *Marine Pollution Bulletin,* 22(10), 508-510.

Benjamins, S., Ledwell, W., Huntington, J. & Davidson, A.R. 2012. Assessing changes in numbers and distribution of large whale entanglements in Newfoundland and Labrador, Canada. *Marine Mammal Science,* 28**,** 579-601.

Bordino, P., Kraus, S.D., Albareda, D., Fazio, A., Palmerio, A., Mendez, M. & Botta, S. 2002. Reducing incidental mortality of Franciscana dolphin *Pontoporia blainvillei* with acoustic warning devices attached to fishing nets. *Marine Mammal Science,* 18**,** 833-842.

Bowles, A.E. & Anderson, R.C. 2012. Behavioral Responses and Habituation of Pinnipeds and Small Cetaceans to Novel Objects and Simulated Fishing Gear With and Without a Pinger. *Aquatic Mammals,* 38**,** 161-188.

Brehmer, P., Josse, E. & Nøttestad, L. 2011. Evidence that whales (*Balaenoptera borealis*) visit drifting fish aggregating devices: do their presence affect the processes underlying fish aggregation? *Marine Ecology,* 33**,** 176-182.

Bridon. 2011. Fibre brochure (3rd edition). Available online at http://www.bridon.com/x/downloads/fibre/Fibre.pdf.

Brodie, P. 1993. Noise generated by the jaw actions of feeding fin whales. *Canadian Journal of Zoology,* 71**,** 2546-2550.

Brown, J, Macfadyen, G., Huntington, T., Magnus, J. and Tumilty, J., 2005. *Ghost Fishing by Lost Fishing Gear*. Final report to DG Fisheries and Maritime Affairs of the European

Commission. Fish/2004/20. Institute for European Environmental Policy / Poseidon Aquatic Resource Management Ltd joint report.

Bureau Veritas 2006. Rules for the Classification of Offshore Loading and Offloading Buoys. NR 494 DT R02 E.

Bureau Veritas 2007. Certification of fibre ropes for deepwater offshore services. 2nd edition. NI 432 DTO R01E.

Bureau Veritas 2012. Classification of Mooring Systems for Permanent Offshore Units. NR 493 DT R02 E.

Carlson, J.K., Goldman, K.J. & Lowe, C. G. 2004. Metabolism, Energetic Demand, and Endothermy. *Biology of Sharks and their Relatives.* Boca Raton, FL: CRC Press.

Carlström, J., Berggren, P. & Tregenza, N.J.C. 2009. Spatial and temporal impact of pingers on porpoises. *Canadian Journal of Fisheries and Aquatic Sciences,* 66**,** 72-82.

Carter L., Burnett D., Drew S., Marle G., Hagadorn L., Bartlett-McNeil D., and Irvine N. 2009. Submarine Cables and the Oceans – Connecting the World. UNEP-WCMC Biodiversity Series No. 31. ICPC/UNEP/UNEP-WCMC.

Cassoff, R.M., Moore, K.M., Mclellan, W.A., Barco, S.G., Rotstein, D.S. & Moore, M.J. 2011. Lethal entanglement in baleen whales. *Diseases of Aquatic Organisms,* 96**,** 175-185.

Castro, J.J., Santiago, J.A. & Santana-Ortega, A.T. 2002. A general theory on fish aggregation to floating objects: An alternative to the meeting point hypothesis. *Reviews in Fish Biology and Fisheries,* 11**,** 255-277.

Cosandey-Godin, A. & Morgan, A. 2011. Fisheries bycatch of sharks: Options for mitigation. Washington, D.C.

Cox, T.M. & Read, A.J. 2004. Echolocation behavior of harbor porpoises *Phocoena phocoena* around chemically enhanced gill nets. *Marine Ecology Progress Series,* 279**,** 275-282.

Cox, T.M., Read, A.J. & Tregenza, N.J.C. 2001. Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? *Journal of Cetacean Research and Management,* 3**,** 81-86.

Culik, B.M. & Koschinsky, S. 2005. Warning sounds at reflective nets: triggering and improving echolocation in harbour porpoises *Phocoena phocoena*. *Document AC12/Doc.9(S) presented to the 12th ASCOBANS Advisory Committee Meeting, Brest, France, 12-14 April 2005***,** 25 pp.

Dawson, S.M., Northridge, S., Waples, D. & Read, A.J. 2013. To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. *Endangered Species Research,* 19**,** 201-221.

Department of Environment, Food and Rural Affiars (DEFRA) 2003. UK Small cetacean bycatch response strategy. A consultation paper outlining the proposed strategy by the Department for Environment, Food and Rural Affairs; the Scottish Executive; the Welsh Assembly Government and the Department of Agriculture and Rural Development in Northern Ireland to reduce the incidental capture of small cetaceans in UK fisheries.

Dehnhardt, G., Mauck, B., Hanke, W. & Bleckmann, H. 2001. Hydrodynamic trail-following in harbor seals (*Phoca vitulina*). *Science,* 293**,** 102-104.

Det Norske Veritas 2002. Offshore standard DNV-RP-E302: Design and Installation of Plate Anchors in Clay.

Det Norske Veritas 2005. Offshore standard DNV-RP-E303: Geotechnical Design and Installation of Suction Anchors in Clay.

Det Norske Veritas 2009a. Offshore standard DNV-OS-E302: Offshore Mooring Chains.

Det Norske Veritas 2009b. Offshore standard DNV-OS-E304: Offshore Mooring Steel Wire Ropes.

Det Norske Veritas 2010a. Offshore standard DNV-OS-E301: Position Mooring.

Det Norske Veritas 2010b. Offshore standard DNV-RP-C205: Environmental Conditions and Environmental Loads.

Det Norske Veritas 2012a. Offshore standard DNV-RP-E301: Design and Installation of Fluke Anchors.

Det Norske Veritas 2012b. DNV-OSS-213: Certification of Tidal and Wave Energy Converters.

Det Norske Veritas 2013a. Offshore standard DNV-OS-E303: Offshore Fibre Ropes.

Det Norske Veritas 2013b. DNV-OS-J103: Design of Floating Wind Turbine Structures.

Det Norske Veritas and Carbon Trust 2005. Guidelines on design and operation of wave energy converters.

Ebbesmeyer, C.C., Ingraham, W.J., Jones, J.A. and Donohue, M.J., 2012. Marine debris from the Oregon Dungeness crab fishery recovered in the Northwestern Hawaiian Islands: Identification and oceanic drift paths. *Marine Pollution Bulletin*, 65, 69-75.

Eckert, S.A. 2002. Swim speed and movement patterns of gravid leatherback sea turtles (*Dermochelys coriacea*) at St Croix, US Virgin Islands. *Journal of Experimental Biology*, 205(23), 3689-3697.

Engelmann, J., Hanke, W., Mogdans, J. & Bleckmann, H. 2000. Neurobiology: hydrodynamic stimuli and the fish lateral line. *Nature,* 408**,** 51-52.

FANTARED-II. 2003. *A study to identify, quantify and ameliorate the impacts of static gear lost at sea*. EU Study Contract FAIR CT98-4338. ISBN 0 903941 97 X.

Fonteneau, A., Pallarés, P. & Pianet, R. 2000. A worldwide review of purse seine fisheries on FADs. *In:* LE GALL, J.-Y., CAYRE, P. & TAQUET, M. (eds.) *Peche thoniere et dispositifs de concentration de poissons.* IFREMER.

Food and Agriculture Organization of the United Nations (FAO). 2013. Global Aquaculture Production Statistics for the year 2011. Available online at ftp://ftp.fao.org/FI/news/GlobalAquacultureProductionStatistics2011.pdf.

Ford, J.K.B., Ellis, G.M., Matkin, D.R., Balcomb, K.C., Briggs, D. & Morton, A.B. 2005. Killer whale attacks on minke whales: prey capture and antipredator tactics. *Marine Mammal Science*, 21, 603–618.

Francis, M.P., & Duffy, C. 2002. Distribution, seasonal abundance and bycatch of basking sharks (*Cetorhinus maximus*) in New Zealand, with observations on their winter habitat. *Marine Biology,* 140**,** 831-842.

Gallon, S.L., Sparling, C.E., Georges, J.Y., Fedak, M.A., Biuw, M., & Thompson, D. 2007. How fast does a seal swim? Variations in swimming behaviour under differing foraging conditions. *Journal of Experimental Biology*, 210(18), 3285-3294.

Gentle Giants. 2012. Top Encounter 2012. *Gentle Giants - Visit the Gentle Giants of Husavik - Probably the best place in Iceland for whale watching - NEWS* [Online]. Available from: http://www.gentlegiants.is/news/nr/658/top-encounter-2012/.

Geraci, J.R., & Lounsbury, V.J. 2005. *Marine mammals ashore - A field guide for strandings,* Baltimore, MD, Baltimore Aquarium.

GhostNets Australia. 2013. GhostNets Australia [online]. Available at: http://www.ghostnets.com.au/ [accessed 22/10/13].

Gilman, E., Gearhart, J., Price, B., Eckert, S., Milliken, H., Wang, J., Swimmer, Y., Shiode, D., Abe, O., Peckam, S.H., Chaloupka, M., Hall, M., Mangel, J., Alfaro-Shigueto, J., Dalzell,

P. & Ishizaki, A. 2010. Mitigating sea turtle by-catch in coastal passive net fisheries. *Fish and Fisheries,* 11**,** 57-88.

Godley, B.J., Gaywood, M.J., Law, R.J., Mccarthy, C.J., Mckenzie, C., Patterson, I.A.P., Penrose, R.S., Reid, R.J. & Ross, H.M. 1998. Patterns of marine turtle mortality in British waters (1992-1996) with reference to tissue contaminant levels. *Journal of the Marine Biological Association of the United Kingdom,* 78**,** 973-984.

Goff, G.P. & Lien, J. 1988. Atlantic leatherback turtle, *Dermochelys coriacea*, in cold water off Newfoundland and Labrador. *Canadian Field-Naturalist,* 102**,** 1-5.

Goldbogen, J.A., Calambokidis, J., Oleson, E., Potvin, J., Pyenson, N.D., Schorr, G. & Shadwick, R.E. 2011. Mechanics, hydrodynamics and energetics of blue whale lunge feeding: efficiency dependence on krill density. *Journal of Experimental Biology,* 214**,** 131-146.

Goldbogen, J.A., Calambokidis, J., Shadwick, R.E., Oleson, E.M., Mcdonald, M.A. & Hildebrand, J.A. 2006. Kinematics of foraging dives and lunge-feeding in fin whales. *Journal of Experimental Biology,* 209**,** 1231-1244.

Good, T.P., June, J.A., Etnier, M.A. and Broadhurst, G., 2010. Derelict fishing nets in Puget Sound and the Northwest Straits: Patterns and threats to marine fauna. *Marine Pollution Bulletin*, 60, 39-50.

Gönener, S. & Bilgin, S. 2009. The effect of pingers on harbour porpoise, *Phocoena phocoena* bycatch and fishing effort in the turbot gill net fishery in the Turkish Black Sea coast. *Turkish Journal of Fisheries and Aquatic Sciences,* 9**,** 151-157.

Graham, N., Hareide, N-R., Large, P.A., MacMullen, P., Mulligan, M., Randall, P.J., Rihan, D. and Peach, D., 2009. *Recuperation of fishing nets lost or abandoned at sea*. Final report to DG Fisheries and Maritime Affairs of the European Commission. FISH/2006/15/Lot No. 5.

Hackett, B., Breivik, Ø. and Wettre, C., 2006. *Forecasting the drift of objects and substances in the oceans*. In: Chassignet, E.P. and Verron, J. (Eds.), Ocean Weather Forecasting: An Integrated View of Oceanography. Springer, 507–524.

Haine, O.S., Ridd, P.V. & Rowe, R. 2001. Range of electrosensory detection of prey by *Carcharhinus melanopterus* and *Himantura granulata*. *Marine and Freshwater Research,* 52**,** 291-296.

Hanke, W., Wieskotten, S., Marshall, C. & Dehnhardt, G. 2013. Hydrodynamic perception in true seals (Phocidae) and eared seals (Otariidae). *Journal of Comparative Physiology A,* 199**,** 421-440.

Hardestry, B.D. and Wilcox, C., 2011. *Understanding the types, sources and at-sea distribution of marine debris in Australian waters*. Final Report to the Department of Sustainability, Environment, Water, Population and Communities.

Hareide, N-R., Rihan, D., Mulligan, M., McMullen, P., Garnes, G., Clark, M., Connolly, P., Tyndall, P., Misund, R., Furevik, D., Newton, A., Høydal, K. Blasdale, T., and Humborstad, O.B. 2005. *A Preliminary Investigation on Shelf Edge and Deepwater Fixed Net Fisheries to the West and North of Great Britain, Ireland, around Rockall and Hatton Bank*. ICES working paper ICES CM 2005/ N:07: 11 pp. Available online at: http://brage.bibsys.no/xmlui/handle/11250/103720.

Harris, R.E., Johanning, L., & Wolfram J. 2004. Mooring systems for wave energy converters: A review of design issues and choices. *3rd International Conference on Marine Renewable Energy*, Blyth, UK, MAREC 2004.

Heezen, B.C. 1957. Whales entangled in deep sea cables. *Deep Sea Research (1953),* 4**,** 105-115.

Henderson, J.R. 2001. A Pre- and Post-MARPOL Annex V Summary of Hawaiian Monk Seal Entanglements and Marine Debris Accumulation in the Northwestern Hawaiian Islands, 1982–1998. *Marine Pollution Bulletin,* 42**,** 584-589.

Henry, A.G., Cole, T.V.N., Garron, M., Hall, L., Ledwell, W. & Reid, A. 2012. Mortality and Serious Injury Determinations for baleen whale stocks along the Gulf of Mexico, United States East Coast and Atlantic Canadian Provinces, 2006-2010. US Department of Commerce, Northeast Fisheries Science Centre Reference Document 12-11; 24 pp. Available online at http://www.nefsc.noaa.gov/nefsc/publications/.

High Seas GhostNet Project, 2013. The High Seas GhostNet Project [online]. Available at http://www.highseasghost.net/ [accessed 22/10/13].

International Electrotechnical Commission – Technical Specifications (IEC/TS) 2013. Marine energy - Wave, tidal and other water current converters - Part 10: The assessment of mooring system for marine energy converters (MECs). IEC/TS 62600-10 Ed. 1.0 *In preparation.*

International Standards Organisation (ISO) 2007. Fibre ropes for offshore stationkeeping: Polyester: ISO18692:2007

International Standards Organisation (ISO) 2008. Ships and marine technology -- Stud-link anchor chains: ISO1704:2008

International Standards Organisation (ISO) 2012. Fibre ropes for offshore station keeping: High modulus polyethylene (HMPE): ISO/TS14909:2012

International Standards Organisation (ISO) 2012. Shipbuilding and marine structures -- Mooring winches: ISO3730:2012

International Standards Organisation (ISO) 2013. Petroleum and natural gas industries – Specific requirements for offshore structures – Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units: ISO19901-7:2013

International Whaling Commission (IWC) 1994. Report of the Workshop on Mortality of Cetaceans in Passive Fishing Nets and Traps. *Reports of the International Whaling Commission***,** 6-57.

Johanning, L., and Smith, G.H. 2008. Station keeping study for WEC devices including compliant chain, compliant hybrid and taut arrangement. *27th International Conference on Offshore Mechanics and Arctic Engineering.* Estoril, Portugal, 15th Jun – 20th Jun 2008, OMAE 2008.

Johanning, L., Smith, G.H. & Wolfram, J. 2005. Towards design standards for WEC moorings. *6th European Wave and Tidal Energy Conference.* Glasgow, UK, 29th Aug - 2nd Sep 2005, EWTEC2005.

Johanning, L., Wolfram, J. 2005. Challenging tasks on moorings for floating WECs, *International Symposium on Fluid Machinery for Wave and Tidal Energy: State of the Art and New Developments*, London, UK

Johnson, A., Salvador, G., Kenney, J., Robbins, J., Kraus, S., Landry, S. & Clapham, P. 2005. Fishing gear involved in entanglements of right and humpback whales. *Marine Mammal Science,* 21**,** 635-645.

Kaiser, M.J., Bullimore, B., Newman, P., Lock, K. and Gilbert, S., 1996. Catches in 'ghost-fishing' set nets. *Marine Ecology Progress Series*,145:11-16.

Kastelein, R.A., Au, W.W.L. & De Haan, D. 2000. Detection distances of bottom-set gillnets by harbour porpoises (*Phocoena phocoena*) and bottlenose dolphins (*Tursiops truncatus*). *Marine Environmental Research,* 49(4)**,** 359-375.

Kastelein, R.A., De Haan, D., Staal, C., Nieuwstraten, S.H. & Verboom, W.C. 1995. Entanglement of harbour porpoises (*Phocoena phocoena*) in fishing nets. *In:* Nachtigall, P.E., Lien, J., Au, W.W.L. & Read, A.J. (eds.) *Harbour porpoises/Laboratory studies to reduce bycatch.* Woerden, The Netherlands: De Spil Publishers.

Kerr, A. 2013. Happy Whale Day! *Ocean Alliance: Conserving whales and our Ocean through research and education* [Online]. Available from: http://www.whale.org/happy-whale-day/ [Accessed September 26, 2013].

Kimberley Whale Watching. 2012. Kimberley Whales & Reefs expedition 10 August 2011. Uploaded October 22, 2012. Available from: http://kimberleywhales.com.au/trip-reports/kimberley-whales-reefs-expedition-10-august-2011/].

Knowlton, A.R., Hamilton, P.K., Marx, M.K., Pettis, H.M. & Kraus, S.D. 2012. Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. *Marine Ecology Progress Series,* 466.

Knowlton, A.R. & Kraus, S.D. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. *Journal of Cetacean Research and Management,* 2**,** 193-208.

Kot, B. W., Sears, R., Anis, A., Nowacek, D.P., Gedamke, J. & Marshall, C.D. 2012. Behavioral responses of minke whales (*Balaenoptera acutorostrata*) to experimental fishing gear in a coastal environment. *Journal of Experimental Marine Biology and Ecology,* 413**,** 13-20.

Kraus, S.D., Read, A.J., Solow, A., Baldwin, K., Spradlin, T., Anderson, E. & Williamson, J. 1997. Acoustic alarms reduce porpoise mortality. *Nature,* 388**,** 525.

Kraus, S.D., Hagbloom, M., Marx, M., Zani, M.A., & Fasick, J.I. 2013. Can color be used to reduce right whale entanglements in fishing gear? Oral presentation presented at the 20th Biennial Conference on the Biology of Marine Mammals, Dunedin, New Zealand, 9013 December 2013.

Laist, D.W. 1987. Overview of the Biological Effects of Lost and Discarded Plastic Debris in the Marine Environment. *Marine Pollution Bulletin,* 18**,** 319-326.

Laist, D.W. 1997. Marine debris entanglement and ghost fishing: a cryptic and significant type of bycatch? Alaska Sea Grant Program Report AK-SG-96-03, pp.33-40.

Langhamer, O., Wilhemsson, D. & Engström, J. 2009. Artificial reef effect and fouling impacts on offshore wave power foundations and buoys – a pilot study. *Estuarine, Coastal and Shelf Science,* 82**,** 426-432.

Large, P.A., Graham, N.G., Hareide, N-R., Misund, R., Rihan, D.J., Mulligan, M.C., Randall, P.J., Peach, D.J., McMullen, P.H. and Harlay, X., 2009. Lost and abandoned nets in deep-water gillnet fisheries in the Northeast Atlantic: retrieval exercises and outcomes. *ICES Journal of Marine Science*, 66(2), 323-333.

Lewison, R.L., Crowder, L. B., Read, A. J. & Freeman, S. A. 2004. Understanding impacts of fisheries bycatch on marine megafauna. *Trends in Ecology and Evolution,* 19**,** 598-604.

Lien, J. 1994. Entrapments of large cetaceans in passive inshore fishing gear in Newfoundland and Labrador (1979-1990). *Reports of the International Whaling Commission, Special Issue,* 15**,** 149-157.

Lien, J., Barney, W., Todd, S., Seton, R. & Guzzwell, J. 1992. Effects of adding sounds to cod traps on the probability of collisions by humpback whales. *In:* Thomas, J.A., Kastelein, R.A. & Supin, A.Y. (eds.) *Marine mammal sensory systems.* New York, NY: Plenum.

Lien, J. & Fawcett, L. 1986. Distribution of basking sharks, Cetorhinus maximus, incidentally caught in inshore fishing gear in Newfoundland. *Canadian Field-Naturalist,* 100**,** 246-252.

Lien, J., Todd, S. & Guigne, J. 1990. Inferences about perception in large cetaceans, especially humpback whales, from incidental catches in fixed fishing gear, enhancement of nets by "alarm" devices, and the acoustics of fishing gear. *In:* Thomas, J. A. & Kastelein, R. A. (eds.) *Sensory abilities of cetaceans/Laboratory and field evidence.* New York, NY: Plenum.

Lloyd, B.D. 2003. Potential effects of mussel farming on New Zealand's marine mammals and seabirds: a discussion paper. Department of Conservation, Wellington, NZ: vii + 34 pp.

Lucas, Z. 1992. Monitoring persistent litter in the marine environment on Sable Island, Nova Scotia. *Marine Pollution Bulletin,* 24**,** 192-199.

Macfadyen, G., Huntington, T., & Cappell, R. 2009. Abandoned, lost or otherwise discarded fishing gear. Food and Agriculture Organization of the United Nations (FAO) Technical Paper No.523: 139 pp.

Mangel, J.C., Alfaro-Shigueto, J., Witt, M.J., Hodgson, D.J. & Godley, B.J. 2013. Using pingers to reduce bycatch of small cetaceans in Peru's small-scale driftnet fishery. *Oryx***,** 47(04), 595-606.

Maximenko, N., Hafner, J. and Niiler, P., 2012. Pathways of marine debris derived from trajectories of Lagrangian drifters. *Marine Pollution Bulletin*, 65, 51-62.

McComb, D.M., Tricas, T.C. & Kajiura, S.M. 2009. Enhanced visual fields in hammerhead sharks. *Journal of Experimental Biology,* 212**,** 4010-4018.

McElwee, K. and Morshige, C., 2010. *Proceedings of the Workshop on At-sea Detection and Removal of Derelict Fishing Gear, Honolulu, HI, December 9-10, 2008*. National Oceanic and Atmospheric Administration Technical Memorandum NOS-OR&R-34.

McElwee, K., Donohue, M.J., Courtney, C.A., Morishige, C. and Rivera-Vicente, A., 2012. A strategy for detecting derelict fishing gear at sea. *Marine Pollution Bulletin*, 65, 7-15.

McFee, W.E., Hopkins-Murphy, S.R. & Schwacke, L.H. 2006. Trends in bottlenose dolphin (*Tursiops truncatus*) strandings in South Carolina, USA, 1997-2003: implications for the Southern North Carolina and South Carolina Management Units. *Journal of Cetacean Research and Management,* 8**,** 195-201.

Moore, M., Walsh, M., Bailey, J., Brunson, D., Gulland, F., Landry, S., Mattila, D., Mayo, C., Slay, C., Smith, J. & Rowles, T. 2010. Sedation at sea of entangled North Atlantic Right Whales (*Eubalaena glacialis*) to enhance disentanglement. *PLoS One,* 5**,** e9597.

Moore, M.J., Knowlton, A.R., Kraus, S.D., Mclellan, W.A. & Bonde, R.K. 2005. Morphometry, gross morphology and available histopathology in Northwest Atlantic right whale (*Eubalaena glacialis*) mortalities (1970 to 2002). *Journal of Cetacean Research and Management,* 6**,** 199-214.

Moore, M.J. & Van der Hoop, J.M. 2012. The painful side of trap and fixed net fisheries: Chronic entanglement of large whales. *Journal of Marine Biology,* 2012**,** 1-4; http://dx.doi.org/10.1155/2012/230653.

Myers, L., Bahaj, A.S., Retzler, C., Ricci, P. and Dhedin, J.-F. 2010. Inter-device spacing issues within wave and tidal energy converter arrays. *Third International Conference and Exhibition on Ocean Energy,* Bilbao, Spain, 06 - 08 Oct 2010. 6pp.

National Audubon Society. 2002. Guide to Marine Mammals of the World. Alfred A. Knopf, Inc., New York, NY, USA.

Neilson, J.L., Straley, J.M., Gabriele, C.M. & Hills, S. 2009. Non-lethal entanglement of humpback whales (*Megaptera novaeangliae*) in fishing gear in northern Southeast Alaska. *Journal of Biogeography,* 36**,** 452-464.

Nielsen, T.P., Wahlberg, M., Heikkilä, S., Jensen, M., Sabinsky, P. & Dabelsteen, T. 2012. Swimming patterns of wild harbour porpoises *Phocoena phocoena* show detection and avoidance of gillnets at very long ranges. *Marine Ecology Progress Series,* 453**,** 241-248.

NMFS & USFWS 2008. Recovery Plan for the Northwest Atlantic Population of the Loggerhead Sea Turtle (*Caretta caretta*), Second Revision. Silver Spring, MD.

NOAA, 2013. NOAA's Adopt a Drifter Program. Available online at: http://www.adp.noaa.gov/images/oceancurrents.jpg. [23/1/14].

NOAA, 2014. Southwest Fisheries Science Center.OSCURS Model. Available online at http://www.pfeg.noaa.gov/products/las/OSCURS.html. [24/1/14].

Noad, M.J., & Cato, D.H. 2007. Swimming speeds of singing and non-singing humpback whales during migration. *Marine Mammal Science*, 23(3), 481-495.

Noke, W.D. & Odell, D.K. 2002. Interactions between the Indian River lagoon blue crab fishery and the bottlenose dolphin, *Tursiops truncatus*. *Marine Mammal Science,* 18**,** 819-832.

Northridge, S., Cargill, A., Coram, A., Mandleberg, L., Calderan, S. & Reid, R. 2010. Entanglement of minke whales in Scottish waters: an investigation into occurrence, causes and mitigation. *Contract Report. Final Report to Scottish Government CR/2007/49*.

Northridge, S.P. 1991. An updated world review of interactions between marine mammals and fisheries. Rome: FAO.

Nowak, R.M. 1991. Walker's Mammals of the World. Johns Hopkins University Press, Baltimore, MD.

Page, B., Mckenzie, J., Mcintosh, R., Baylis, A., Morrissey, A., Calvert, N., Haase, T., Berris, M., Dowie, D., Shaughnessy, P.D. & Goldsworthy, S. D. 2004. Entanglement of Australian sea lions and New Zealand fur seals in lost fishing gear and other marine debris before and after Government and industry attempts to reduce the problem. *Marine Pollution Bulletin,* 49**,** 33-42.

Pemberton, D., Brothers, N. & Copson, G. 1991. Predators on marine fish farms in Tasmania. *Papers and Proceedings of the Royal Society of Tasmania,* 125**,** 33-35.

Pierpoint, C. 2000. Bycatch of marine turtles in UK and Irish waters. JNCC Report No. 310.

Pope, E.C., Hays, G.C., Thys, T.M., Doyle, T.K., Sims, D.W., Queiroz, N., Hobson, V.J., Kubicek, L. & Houghton, J.D.R. 2010. The biology and ecology of the ocean sunfish *Mola mola*: a review of current knowledge and future research perspectives. *Reviews in Fish Biology and Fisheries,* 20**,** 471-487.

Raum-Suryan, K.L., Jemison, L.A. & Pitcher, K.W. 2009. Entanglement of Steller sea lions (*Eumetopias jubatus*) in marine debris: Identifying causes and finding solutions. *Marine Pollution Bulletin,* 58**,** 1487-1495.

Read, A.J. 2013. Development of conservation strategies to mitigate the bycatch of harbor porpoises in the Gulf of Maine. *Endangered Species Research,* 20**,** 235-250.

Read, A.J., Drinker, P. & Northridge, S. 2006. Bycatch of marine mammals in U.S. and global fisheries. *Conservation Biology,* 20**,** 163-169.

Reeves, R.R., Mcclellan, C.M. & Werner, T.B. 2013. Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research,* 20**,** 71-97.

Richards, S. 2012. Niue: Whale in a tangle with visiting yacht's mooring. Available online at: http://www.noonsite.com/Members/sue/R2012-09-08-4.

Rohr, J.J., Fish, F.E. & Gilpatrick, J.W. 2002. Maximum swim speeds of captive and free-ranging delphinids: Critical analysis of extraordinary performance. *Marine Mammal Science,* 18(1), 1-19.

Robbins, J., Landry, S. & Mattila, D.K. 2009. Estimating entanglement mortality from scar-based studies. *Scientific Committee Meeting of the International Whaling Commission, 2009, SC/61/BC3.*

Robbins, J. & Mattila, D.K. 2004. Estimating humpback whale (*Megaptera novaeangliae*) entanglement rates on the basis of scar evidence. Final report to the US National Marine Fisheries Service (unpublished). Available from the Center for Coastal Studies, Box 1036, Provincetown, MA 02657.

Ross, P. S., Dungan, S.Z., Hung, S.K., Jefferson, T.A., Macfarquhar, C., Perrin, W.F., Riehl, K.N., Slooten, E., Tsai, J., Wang, J.Y., White, B.N., Würsig, B., Yang, S.C. & Reeves, R.R. 2010. Averting the baiji syndrome: conserving habitat for critically endangered dolphins in Eastern Taiwan Strait. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 20**,** 685-694.

Scottish Government. 2013. Planning Scotland's Seas. Sectoral Marine Plans for Offshore Wind, Wave and Tidal Energy in Scottish Waters.Consultation Draft. Available online at www.scotland.gov.uk/Resource/0042/00428241.pdf (last accessed 15/01/2014).

Sears, R. & Calambokidis, J. 2002 Update COSEWIC status report on the blue whale *Balaenoptera musculus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON, Canada.

Shepard, E.L., Ahmed, M.Z., Southall, E.J., Witt, M.J., Metcalfe, J.D., & Sims, D.W. 2006. Diel and tidal rhythms in diving behaviour of pelagic sharks identified by signal processing of archival tagging data. *Marine Ecology-Progress Series*, 328, 205.

Scottish Rural Agricultural College (SRUC). 2014. Humpback whale post mortem suggests entanglement in salmon farm. SRUC News Release Number 14R102, Friday 4 July 2014. Available online at: http://www.sruc.ac.uk/news/article/898/humpback_whale_post_mortem_suggests_entanglement_in_salmon_farm (last accessed 8/07/2014).

Stevens, J.D. 2007. Whale shark (*Rhincodon typus*) biology and ecology: A review of the primary literature. *Fisheries Research,* 84**,** 4-9.

Stevick, P.T., Allen, J., Clapham, P.J., Friday, N., Katona, S.K., Larsen, F., Lien, J., Mattila, D.K., Palsbøll, P.J., Sigurjûnsson, J., Smith, T.D., Øien, N. & Hammond, P.S. 2003. North Atlantic humpback whale abundance and rate of increase four decades after protection from whaling. *Marine Ecology Progress Series,* 258**,** 263-273.

Swift, M.R., Fredriksson, D.W., Unrein, A., Fullerton, B., Patursson, O. & Baldwin, K., 2006. Drag force acting on biofouled net panels. *Aquacultural Engineering*, 35(3), 292-299.

The Crown Estate 2011. Wave and tidal energy in the Pentland Firth and Orkney waters: how the project could be built. Available online at: http://www.thecrownestate.co.uk/media/71431/pentland_firth_how_the_projects_could_be_built.pdf.

Tomilin, A.G. 1957. Mammals of the USS.Royal. and Adjacent Countries, Vol. IX. Cetacea. Nauk USSR, Moscow, Russia. (English translation, 1967, Israel Program for Scientific Translations, Jerusalem).

Trekkingthesea. 2012. Whale pulled my chain.. *trekkingthesea - the continuing sailing adventures of Jen and Glenn* [Online]. Available from: http://trekkingthesea.blogspot.co.uk/2013/08/whale-pulled-my-chain.html [Accessed Tuesday, August 13, 2013].

Trippel, E.A., Holy, N.L., Palka, D.L., Shepherd, T.D., Melvin, G.D. & Terhune, J.M. 2003. Nylon barium sulphate gillnet reduces porpoise and seabird mortality. *Marine Mammal Science,* 19**,** 240-243.

Van der Hoop, J.M., Moore, M.J., Barco, S.G., Cole, T.V.N., Daoust, P.-Y., Henry, A.G., Mcalpine, D.F., Mclellan, W.A., Wimmer, T. & Solow, A.R. 2012. Assessment of management to mitigate anthropogenic effects on large whales. *Conservation Biology,* 27**,** 121-133.

Van der Hoop, J., Moore, M., Fahlman, A., Bocconcelli, A., George, C., Jackson, K., Miller, C., Morin, D., Pitchford, T., Rowles, T., Smith, J. and Zoodsma, B. 2014. Behavioral impacts of disentanglement of a right whale under sedation and the energetic cost of entanglement. Marine Mammal Science, 30: 282–307. doi: 10.1111/mms.12042.

Vryhof 2000. Anchor manual. Available online at: http://www.vryhof.com/anchor_manual.pdf.

Walker, T.I. 1998. Can shark resources be harvested sustainably? A question revisited with a review of shark fisheries. *Marine and Freshwater Research,* 49**,** 553-572.

Wang, J., Barkan, J., Fisler, S., Godinez-Reyes, C. & Swimmer, Y. 2013. Developing ultraviolet illumination of gillnets as a method to reduce sea turtle bycatch. *Biology Letters,* 9**,** 20130383.

Weller, S., Johanning, L., & Davies, P. 2012. Best practice report - mooring of floating marine renewable energy devices; deliverable 3.5.3; INTERREG IV MERiFIC report.

Wilcox, C., Hardesty, B.D., Sharples, R., Griffin, D.A., Lawson, T.J. and Gunn, R., 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. *Conservation Letters*, 6(4), 247-254.

Wilkinson, D. & Worthy, G.A.J. 1999. Marine Mammal Stranding Networks. *In:* TWISS, J. & REEVES, R. R. (eds.) *Conservation and Management of Marine Mammals.* Washington D.C.: Smithsonian Press.

Williams, T.M. 2002. Swimming. In: *The Encyclopedia of Marine Mammals* (Ed. by W.F. Perrin, B. Würsig & J.G.M. Thewissen), pp. 1213–1222. Academic Press, San Diego, CA, USA.

Winn, J.P., Woodward, B.L., Moore, M.J., Peterson, M.L. & Riley, J.G. 2008. Modeling whale entanglement injuries: An experimental study of tissue compliance, line tension, and draw-length. *Marine Mammal Science,* 24**,** 326-340.

Wood, M.P. & Carter, L. 2008. Whale entanglements with submarine telecommunication cables. *IEEE Journal of Oceanic Engineering,* 33**,** 445-460.

Woodward, B. L., Winn, J. P., Moore, M. J. & Peterson, M. L. 2006. Experimental modeling of large whale entanglement injuries. *Marine Mammal Science,* 22**,** 299-310.

Zhu, Q.A., Hillmann, D.J. & Henk, W.G. 2001. Morphology of the eye and surrounding structures of the bowhead whale, *Balaena mysticetus*. *Marine Mammal Science,* 17(4), 729-750.

Zollett, E.A. 2009. Bycatch of protected species and other species of concern in US east coast commercial fisheries. *Endangered Species Research,* 9, 49-59.

ANNEX 1 - MARINE RENEWABLE ENTANGLEMENT RISK CHECKLIST

This is intended to provide developers with a checklist of relevant information for incusion in their submission. It is suggested that developers use the broad risk categories outlined in the present report to undertake their own relative risk assessments on the basis of available engineering and biological data. The information used to inform this relative risk assessment should be readily available as these data will be required for a variety of other purposes surrounding mooring design. For example detail on mooring design would be necessary for engineering and Health and Safety reasons. Data on species presence and use would be available from site characterisation and marine life monitoring surveys.

□ **Description of the mooring design to be used**
  - Include detail of mooring type and proposed layout, number of moorings/devices and spacing between (if array) plus detail on inter-array and export cabling.
  - Include detail on the tension characteristics, swept volume and curvature parameters appropriate for this project, as well as other relevant metrics include strength (MBL), axial stiffness per unit length, weight per unit length of components in the mooring and the range of expected sea states at a particular project site.
  - Detail whether this assessment has been made on the worst case scenario and/or has accounted for all potential design permutations (e.g. array layout).

□ **Description of the species groups found in the development area**
  - To include species groups likely to be present and respective relative-risk factors.

□ **Total relative risk parameters noted**
  - Using Benjamins *et al* Relative-Risk Approach (Sections 4, 5 and Table 6.1 in the present report).

□ **If in the Smaller/Intermediate relative risk category**
  - No further detail required.

□ **Or if in the Greater relative risk category**
  - Include an estimation of species encounter rate.
  - Include potential mitigation or adaptive management approaches.

□ **Conclusion as to the relative risk of the project, including any mitigation and monitoring considerations.**

www.snh.gov.uk

ISBN: 978-1-78391-189-9

Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

You can download a copy of this publication from the SNH website.

recycle

Scottish Natural Heritage
Dualchas Nàdair na h-Alba
All of nature for all of Scotland
Nàdar air fad airson Alba air fad