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Electromagnetic Field Study

Effects of electromagnetic fields on marine species: A literature review.

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Oregon Wave Energy Trust (OWET) is a nonprofit public-private partnership funded by the Oregon Innovation Council. Its mission is to support the responsible development of wave energy in Oregon. OWET emphasizes an inclusive, collaborative model to ensure that Oregon maintains its competitive advantage and maximizes the economic development and environmental potential of this emerging industry. Our work includes stakeholder outreach and education, policy development, environmental assessment, applied research and market development.

Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
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1. EXECUTIVE SUMMARY

This report summarizes the results of a top-level literature survey on the topic of the electromagnetic (EM) effects on marine biota. The primary driver for this survey was to determine the basic state of knowledge on the topic of potential biological effects that EM fields (EMF) may have on marine species, and then to apply that knowledge to identify EMF sensing requirements. In particular, specific knowledge was sought on species sensitivity to field strength to electric or magnetic fields and on the frequency range of such sensing sensitivity.

It was noted as a result of the survey (Table 1) that EM sensitivities varied significantly by species. Elasmobranchs (sharks and skates) were noted to have extreme sensitivity to low-frequency AC electric fields, including the area between $1/8^{th}$ to 8 Hz, but no notation was made for sensitivity to magnetic fields. Telost fish, including salmonids, also have an electric field sensitivity, but one that is orders of magnitude lower (less sensitive) than sharks. Elasmobranchs provide the most stringent requirement for electric field sensing, with some species sensitive to levels as low as 1 nV/m (1×10^{-9} volts/meter).

On the other hand, benthic species and some marine mammals have been observed to be affected to varying degrees by magnetic fields, but not electric fields. Magnetic sensing requirements appear to be driven by eels, which the literature reports as having sensitivities to magnetic fields on the order of a few µT (1×10^{-6} Tesla). Some benthic species have been shown to be affected by stronger magnetic fields, although there has been little research reported on the subject of certain species native to the Pacific Northwest, including the Dungeness crab.

In summary, a number of species were reported to be sensitive to EM fields, and could potentially be affected by EM fields created by wave energy devices and cables. Thus, instrumentation used to assess the impact of EM fields should provide adequate resolution to allow direct measurement of known sensitivity levels. Furthermore, it would be desirable, but not required, to investigate instrumentation that is capable of measuring levels below the known levels of sensitivity to enable future research on any collected data that may have an observable impact.

2. INTRODUCTION

Oregon's demand for energy continues to increase and the need to develop renewable energy projects remains a high priority for the State. Oregon has been identified as an ideal location for wave energy conversion based primarily on its tremendous wave resource and coastline transmission capacity. However, there are multiple devices, in various stages of development, which convert the power of waves into electricity. Research and development is still required for wave energy to be economically competitive with traditional technologies.

Electromagnetic fields (EMF) originate from both natural and anthropogenic sources. Natural sources include the Earth's magnetic (B) field and different processes (biochemical, physiological, and neurological) within organisms. Marine animals are also exposed to natural EMF caused by sea currents traveling through the geomagnetic field. Anthropogenic sources of EMF emissions in the marine environment include submarine telecommunications (fiber optic and coaxial) and undersea power cables.

Three components of a wave energy conversion project are likely sources of EMF: the wave energy converter (WEC) device itself, the subsea pod, i.e. the power aggregation, control, or conversion housings, and the subsea power transmission cables including the power cable exiting the bottom of each WEC and those cables from the subsea pod to a land-based substation. If part of a WEC design, the enclosed metallic structure of the WEC device and subsea pod designs could potentially serve as Faraday cages, where an enclosure of conducting material results in an electric field shield.

Federal and State agencies, along with other stakeholders have raised the issue of the potential effects of EMF on marine life, including elasmobranchs, including sharks and skates, green sturgeon (Acipenser medirostris), salmonids (Oncorhynchus species), Dungeness crab (Cancer magister), and plankton, with the development of WEC devices and associated infrastructure.

Specific concerns raised suggest that the EMF generated by a WEC project may disrupt migration or cause disorientation of salmon. Recreational and commercial users of the marine environment, such as surfers and fishermen, also suggest that EMF may attract sharks (an electro-sensitive species), and increase the risk of shark attacks in the area. Agency staff are concerned that a WEC project differs from traditional sources of anthropogenic EMF in the ocean. Instead of a single cable lying on or under the seabed, a proposed WEC project represents multiple devices and associated cables running through the entire water column before running along the seabed to connect with the subsea pod. This configuration would increase the potential level of exposure of EMF to marine species.

This report summarizes the existing literature on the EMF effects on marine species, particularly those present in the Pacific Northwest.

3. METHODOLOGY

Over 50 journal articles, abstracts, and reports were reviewed in the course of this research. The sources of literature and information included:

1. Aquatic Sciences and Fisheries Abstracts;
2. Bio One Abstracts and Indexes;
3. University of Washington library system;
4. Toxnet (Toxicology Data Network); and
5. Internet searches.

To ensure a high probability of identifying relevant literature a wide variety of keyword combinations were used in the search, such as “EMF”, “marine”, “aquatic”, and “effects”; or “submarine”, and “cables.”

4. POTENTIAL EFFECTS OF EMF ON MARINE BIOTA

The transmission of electricity from a WEC device to the onshore facilities may involve either a direct current (DC) or an alternating current (AC). DC is characterized by a constant flow of electrical charge in one direction, from high to low potential, while in AC the magnitude of the charge varies and reverses direction many times per second.

The B-fields from these two types of electrical current interact with matter in different ways. While AC induces electric currents in conductive matter, both interact with magnetic material, such as magnetite-based compasses in organisms (Ohman et al. 2007).

Electric (E) fields are produced by voltage and increase in strength as voltage increases, while magnetic fields are generated by the flow of current and increase in strength as current increases.

EMF consists of both E- and B-fields. The presence of magnetic B-fields can produce a second induced component, a weak electric field, referred to as an induced electric (iE) field. The iE-field is created by the flow of seawater or the movement of organisms through a B-field. The strength of E- and B-fields depends on the magnitude and type of current flowing through the cable and the construction of the cable. In addition, shielding of the cable can reduce or in essence eliminate E-fields. Overall, both E- and B-fields, whether anthropogenic or naturally occurring, rapidly diminish in strength in seawater with increasing distance from the source.

The type and degree of observed EMF effects may depend on the source, location, and characteristics of the anthropogenic source, and the presence, distribution, and behavior of aquatic species relative to this source. Since EMF levels decrease in strength with increased distance from the source, it may be surmised that fields emitted by a submerged or buried submarine cable would have more effect on benthic species and those present at depth than on those occupying the upper portion of the water column. While logical in conclusion, this assumption has not yet been validated in an in-situ environment with EMF measurement and observation.

Organisms that can detect E- or B-fields (i.e., electro-sensitive species) are presumed to do so by either iE-field detection or magnetite-based detection, either attracting or repelling an animal.

Electro-sensitive species detect iE-fields either passively (where the animal senses the iE-fields produced by the interaction between ocean currents with the vertical component of the Earth's magnetic field) or actively (where the animal senses the iE-field it generates by its own interaction in the water with the horizontal component of the Earth's B-field (Paulin 1995, von der Emde 1998).

Data on the detection of B-fields by marine species is limited. Research shows that electro-sensitive aquatic species have specialized sensory apparatus enabling them to detect electric field strengths as low as 0.5 microvolt per meter (μV/m). These species use their sensory apparatus for prey detection and ocean navigation (McMurray 2007). For example, members of the elasmobranch family (i.e., sharks, skates, and rays) can sense the weak E-fields that emanate from their prey's muscles and nerves during muscular activities such as respiration and movement (Gill and Kimber 2005).

Magnetosensitive species are thought to be sensitive to the Earth's magnetic fields (Wiltschko and Wiltschko 1995, Kirschvink 1997, Boles and Lohmann 2003, McMurray 2007, Johnsen and Lohmann 2008). While the use of B-fields by marine species is not fully understood and research continues (Lohmann and Johnsen 2000, Boles and Lohmann 2003, Gill et al. 2005), it is suggested that magnetite deposits play an important role in geomagnetic field detection in a relatively large variety of marine species including turtles (Light et al. 1993), salmonids (Quinn 1981, Quinn and Groot 1983, Mann et al. 1988, Yano et al. 1997), elasmobranchs (Walker et al. 2003, Meyer et al. 2005), and whales (Klinowska 1985, Kirschvink et al. 1986), many of which occur in the Pacific Northwest.

4.1 Changes in Embryonic Development and Cellular Processes

The ability to detect E- and B-fields starts in the embryonic and juvenile stages of life for numerous marine species. For example, through controlled experiments it has been shown that B-fields have been found to delay embryonic development in sea urchins and fish (Cameron et al. 1993; Zimmerman et al. 1990, Levin and Ernst 1997). Several studies have found that EM fields alter the development of cells; influence circulation, gas exchange, and development of embryos; and alter orientation.

Research on sea urchins showed that 10 μT to 0.1 T (100 Gauss [G] to 1,000G) static B-fields are able to cause a delay in the mitotic cycle of early urchin embryos. These fields also increase greatly the incidence of exogastrulation, a mental abnormality in sea urchins (Levin and Ernst 1997).

Furthermore, barnacle larvae passed between two electrodes emitting a high frequency AC EMF, caused significant cell damage to the larvae and caused the larvae to retract their antennae, interfering with settlement (Leya et al. 1999).

However, in a study involving chum salmon (O. keta) , Prentice et al. (1998) found no increase in the percentage of egg production/female, fertilization rates, larval mortality or deformity rates, or overall survival in the EMF-exposed fish.

Formicki and Perkowski (1998) exposed embryos of rainbow trout (O. mykiss), a common resident of Oregon, in different development stages to the influence of constant, low B-fields: 5 μT and 10 μT (50 G and 100 G, respectively). An increased oxygen uptake in embryos influenced by the field activity (as compared to those, which develop in a geomagnetic field) was observed. Researchers also noted the effect of a B-field on the breathing process of embryos was more pronounced in periods of advanced morphogenesis.

In addition, Formicki and Winnicki (1998) exposed brown trout (Salmo trutta) and rainbow trout to similar constant, low level magnetic B-fields (0 to 13 mG [0 G to 0.013 G, respectively]) to the aforementioned study. Results showed this exposure slowed the embryonic development of both species. Furthermore, in this same study, Formicki and Winnicki found B-fields also induced change in the circulation of embryos and larvae of pike (Esox lucius) and carp (Cyprinus carpio), as well as in the embryos of brown trout. Formicki and Winnicki concluded that while intensity of breathing processes increase in a magnetic field, they concluded it was dependent on the stage of embryonic development and was especially manifested in the period of an advanced organogenesis.

In another study, embryos of rainbow trout and brown trout exhibited a sense of direction both in natural and artificially created B-field (Tanski et al. 2005). In a controlled experiment, fish embryos in artificially generated 0.5, 1.0, 2.0, and 4.0 μT (5, 10, 20, and 40 G, respectively) horizontal B-fields, superimposed on the geomagnetic field were compared to the orientation in the Earth’s B-field (i.e., the control). The artificially generated constant B-fields were found to induce significantly stronger orientation responses in embryos, compared to those elicited by the geomagnetic field alone.

However, additional research on pike embryo failed to show changes in locomotive responses to varying B-fields (Winnicki et al. 2004).

4.2 Benthic Species

There is little information on benthic species' sensitivity to magnetic fields. No studies on B- or E-field impacts to Dungeness crab, an important commercial and recreational fishery in Oregon, have been conducted. However, several studies have examined the effects and use of B- and E-fields on crustaceans of similar size and the same order (i.e., Decapoda).

In addition to other cues, such as hydrodynamics and visual stimuli, spiny lobster (P. argus) also uses the Earth's magnetic field to orient (Boles and Lohmann 2003). Lohmann et al. (1995) used B-fields to demonstrate that spiny lobster altered their course when subjected to a horizontal magnetic pole reversal in a controlled experiment. However, even under the influence of anthropogenic fields, no negative impacts have been observed in crustacean. For example, no ill effects were detected in western rock lobster (Panulirus cygnus) after electromagnetic tags, emitting a 31 kHz signal, were attached to them (Jernakoff 1987).

Furthermore, when the blue mussel (Mytilus edulis), along with North Sea prawn (Crangon crangon), round crab (Rhithropanopeus harrisii), and flounder (Plathichthys flesus), were all exposed to a static B-field of 3.7 µT (37 G) for several weeks, no differences in survival between experimental and control animals was detected (Bochert and Zettler 2004).

However, an investigation on the blue mussel did show effects of B-fields on biochemical parameters (Aristharkhov et al., 1988). Changes in B-field action of 5.8, 8, and 80 µT (58, 80, 800 G, respectively) lead to a 20% decrease in hydration and a 15% decrease in amine nitrogen values, regardless of the induction value.

4.3 Teleost (Bony) Fish Species

Eels exhibited some sensitivity to EMF (Centre for Marine and Coastal Studies (CMACS) 2003). Magnetosensitivity of the Japanese eel (A. japonica) was examined in laboratory conditions (Nishi et al. 2004). This species was exposed to B-fields ranging from 12,663 to 192,473 nT (0.12663G to 0.192473 G). After 10 to 40 conditioning runs, all the eels exhibited a significant conditioned response (i.e. slowing of the heartbeat) to a 192,473 nT (0.192473 G) B-field. Researchers concluded that the Japanese eel is magnetosensitive.

However, other species of eels have not exhibited the same responses as the Japanese eel. Westerberg and Begout-Anras (2000) investigated the orientation of silver eels (Anguilla anguilla) in the presence of a submarine high voltage, DC power cable. Approximately 60% of the eels crossed the cable, enabling researchers to conclude the cable did not act as a barrier to this species' migration path, although they did concede that further investigation is required. Westerberg (1999) reported similar results after investigating elver (a young stage in the eel life cycle) movement under laboratory conditions. Furthermore, Westerberg and Lagenfelt (2008) found that swimming speed of silver eels was not significantly lowered around AC cables, although more research into eel behavior during passage over the cable is required.

There are a variety of salmonid stocks that pass offshore of Oregon. Threatened or endangered stocks (listed under the Endangered Species Act of 1973) are of particular interest and include southern Oregon/northern California Coast Coho salmon (O. kitsch), Oregon Coast Coho salmon, Lower Columbia River Coho salmon, Lower Columbia River Chinook salmon (O. tshawytscha), Upper Columbia River spring-run Chinook salmon, Snake River spring/summer-run Chinook salmon, and Snake River fall-run Chinook salmon. Furthermore, steelhead (O. mykiss) and cutthroat trout (O. clarkia) originating from the Umpqua River also pass offshore of Oregon. Research suggests salmonid species may be influenced by anthropogenic E-fields, but there is limited support for the influence on B-fields.

Marino and Becker (1977) reported that the heart rate of salmon and eels may become elevated when the fish are exposed to E-field strengths of 0.007 to 0.07 V/m. The "first response", shuddering of gills and fins, is exhibited when the fish are exposed to fields of 0.5 to 7.5 V/m and the anode reaction (i.e., the fish swims towards an electrically charged anode) occurs at field strengths ranging from 0.025 V/m to 15 V/m. Harmful effects on the fish, such as electro-narcosis or paralysis occur only at field strengths of 15 V/m or more (Balayev 1980, and Balayev and Fursa 1980).

There are several potential mechanisms that Pacific salmon use for navigation, including orienting to the Earth's magnetic field, utilizing a celestial compass, and using the odor of their natal stream to migrate back to their original spawning grounds (Quinn et al. 1981, Quinn and Groot 1983, Groot and Margolis 1998). Crystals of magnetite have been found in four species of

Pacific salmon, though not in sockeye salmon (O. nerka; Mann et al. 1988, Walker et al. 1988). These magnetite crystals are believed to serve as a compass that orients to the Earth's magnetic field.

Quinn and Brannon (1982) conclude that while salmon can apparently detect B-fields, their behavior is likely governed by multiple stimuli as demonstrated by the ineffectiveness of artificial B-field stimuli. Supporting this, Yano et al. (1997) found no observable effect on the horizontal and vertical movements of adult chum salmon that had been fitted with a tag that generated an artificial B-field around the head of each fish. Furthermore, research conducted by Ueda et al. (1998) on adult sockeye salmon suggests that, rather than magnetoreception, this species relies on visual cues to locate natal stream and on olfactory cues to reach its natal spawning channel. Blockage of magnetic sense had no effect on the ability of the fish to locate their natal stream.

4.4 Elasmobranchs

Elasmobranchs, such as sturgeons, sharks, skates, and rays utilize natural EM fields in their daily lives and, as a result, are at a higher risk of influence from anthropogenic EMF sources than non-electrosensitive species. These species receive electrical information about the positions of their prey, the drift of ocean currents, and their magnetic compass headings.

In general, elasmobranchs experience sensitivity to E-fields between 5 x 10^{-7} to 10^{-3} V/m. At this level, these species are generally attracted to the source; however, at 1 µV/cm or greater, elasmobranchs typically avoid the source (Kalmijn 1982, Gill and Taylor 2002). However, there are discrepancies between the findings of Gill and Taylor (2002) and Kalmijn (1982) on the lower threshold for elasmobranchs sensitivity to E-fields. Gill and Taylor report this threshold at 5 x 10^{-7} V/m, while Kalmijn reports it to be 5 x 10^{-9} V/m.

Although they are members of one of the oldest classes of bony fishes, the skeleton of sturgeons is composed mostly of cartilage. Hence, they are discussed under "Elasmobranchs." Sturgeons are weakly electric fish that can utilize electroreceptor senses, as well as others, to locate prey. While no research has been conducted on sturgeon species found in Oregon, research on sturgeon has been conducted in Europe. Research found that the behavior of the sterlet sturgeon

(Acipenser ruthenus) and the Russian sturgeon (A. gueldenstaedtii) varies in the presence of different E-field frequencies and intensities (Basov 1999). At 1.0 to 4.0 hertz (Hz) at 0.2 to 3.0 µV/cm, response was searching for the source and active foraging; at 50 Hz at 0.2 to 0.5 µV/cm, response was searching for source; and at 50 Hz at 0.6 µV/cm or greater, response was avoidance of the source.

Sharks typically detect an EM field between the frequencies of 1/8 and 8 Hz. Turning at a constant speed allows shark exploration of the ambient E-field. Acceleration without turning allows exploration of magnetic heading (Kalmijin 2000). This allows sharks to navigate using the Earth's B-field (Walker et al. 2003).

Research has shown responses by skates in a similar frequency range as sharks. The skate, Raja clavata, exhibited cardiac responses to uniform square-wave fields of 5 Hz at voltage gradients of 0.01 µV/cm; and at a voltage gradient of 10^{-6} V/m, their respiratory rhythms were also affected (Kalmijin 1966). At 4 x 10^{-5} V/m, with a 5 Hz square-wave, research showed a slowing down of the heartbeat (Kalmijin 1966).

Elasmobranchs attacking submarine cables has been observed (Marra 1989). In 1982, off the coast of Massachusetts, an experiment determined the sensitivity of dogfish (Mustelus canis), stingray (Urolophus halleri), and blue shark (P. glauca) to E-fields. Each species attacked the E-field sources (Kalmijn 1982). In the case of the dogfish, the E-fields were produced by a current of 8 µA DC passed between two electrodes that were 2 centimeters (cm) apart. Larger dogfish initiated 44 out of 112 attacks from 30 cm and farther, where fields measured less than or equal to 0.010 µV/cm. In 15 of the responses, the distances were in excess of 38 cm where the field measured 5µV/m. For the blue shark a direct current of 8 µA DC was applied to one dipole at a time, producing a full-space field half as strong as the half-space field used for the larger dogfish. In one instance, four to five blue sharks (6 to 8 feet long) repeatedly circled the apparatus and attacked the electrodes 31 times. In training experiments, stingrays showed the ability to orient relative to uniform electric fields similar to those produced by ocean currents.

This aggressive reaction may be age-specific. Naïve neonatal bonnet head sharks (Sphyrna tiburo) less than twenty-four hours post-parturition failed to demonstrate a positive feeding response to prey-simulating weak E-fields, whereas vigorous biting at the electrodes was observed in all sharks greater than thirty two hours post-parturition (Kaijura 2003).

With regards to B-fields, a CMACS (2003) discussion indicated that the strength of the B-fields emitted by submerged AC cables are substantially lower than those associated with the Earth's geomagnetic field. Therefore, they may be undetectable to magneto-sensitive species, such as elasmobranchs, that are attuned to naturally occurring B-field strengths. It should be noted that the Earth's geomagnetic field is essentially DC, and the comparison made in the CMACS report was noted at AC power frequencies (e.g. 50 Hz), thus caution should be employed when describing the relative strength of a EM field at different frequencies.

4.5 Turtles

Several species of sea turtles undergo transoceanic migration; however, limited research has been conducted on these species and their use of magnetic "maps" (Lohmann et al. 2001, Lohmann et al. 2004). What research that has been conducted suggests several species of turtle use the earth's B-fields for migration. Lohmann and Lohmann (1996) noted that Kemps ridley's turtle (Lepidochelys kempi), green sea turtle (Chelonia mydas), and loggerheads (Caretta caretta) all utilize the Earth B-fields, although, the use of these fields is not necessary for these species. Green sea turtle's magnetic cues were found to not be essential for adult females to navigate 2,000 kilometers from Ascension Island to Brazil (Papi, et al., 2000).

4.6 Marine Mammals

Whales and dolphins form a useful "magnetic map" which allows them to travel in areas of low magnetic intensity and gradient ("magnetic valleys" or "magnetic peaks"; Walker et al. 2003).

Many whale and dolphin species are sensitive to stranding when Earth's B-field has a total intensity variation of less than 0.5mG (5×10^{-4} G). Species that are significantly statistically sensitive include common dolphin (Delphinus delphis), Risso's dolphin (Grampus griseus), Atlantic white-sided dolphin (Lagenorhynchus acutus), finwhale (Balaenoptera physalus), and long-finned pilot whale (Globicephala malaena) (Kirschvink et al. 1986).

Live strandings of toothed and baleen whales have also been correlated with local geomagnetic anomalies (Kirschvink et al. 1986). It has been suggested that some cetacean species use geomagnetic cues to navigate accurately over long-distances of open ocean that do not have geological features for orientation. Valburg (2005) suggested that while sharks are unlikely to be impacted by low electric fields immediately around submarine electric cables, shifts in EMF have been significantly correlated to whale strandings.

5. CONCLUSIONS

For WEC devices and their associated infrastructure, the influence of EMF on marine organisms must be closely examined as EMF may have positive or negative implications for a marine organism within the nearby vicinity. (See Table 1 for a summary of observed EM sensitivities found within the literature.)

Varying reactions were observed at an embryo development, depending on species. Research has shown that B-fields delay embryonic development in sea urchins and fish, while several studies have found EM fields alter the development of cells; influence circulation, gas exchange, and development of embryos; and alter orientation. However, eggs of certain species, such as chum salmon, when exposed to EMF appeared to have no effect on the development or survival of salmon zygotes.

Some aquatic species, including spiny lobster and loggerhead turtle, utilize the Earth’s geomagnetic field for navigation and positioning (Lohmann et al. 2001; Boles and Lohmann 2003). In addition, benthic species such as skates, rays, and dogfish use electroreception as their principal sense for locating food.

More open water (pelagic) species, such as salmon, may encounter E-fields near the seabed but spend significant time hunting in the water column. Overall, the potential for an impact is considered highest for species that depend on electric cues to detect benthic prey.

For B-fields, certain teleost fish species, including salmonids and eels, are understood to use the Earth’s B-field to provide orientation during migrations. If they perceive a different B-field to the Earth’s field, there is potential for them to become disorientated. However, experimental evidence is inconclusive regarding whether or not migrating salmon are affected by anthropogenic B-field levels similar in strength to the Earth’s geomagnetic field (Quinn 1981).

Therefore, depending on the magnitude and persistence of the confounding B-field the impact could be a trivial temporary change in swimming direction or a more serious delay to the migration.

While some elasmobranch species can detect and respond to E-fields that are within the range induced by submerged power cables, no studies were found describing whether such EMF levels affect the behavior of elasmobranchs under field conditions.

There is a significant lack of research into the potential impacts of EMF to sea turtles and marine mammals. Sea turtles do not appear to be as sensitive to EMF as marine mammals. Statistical evidence suggests that marine mammals are susceptible to stranding as a result of increased levels of EMF.

Table 1 – Summary of Electromagnetic Field Impacts to Marine Species

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
Benthic Species						
North Sea prawn (*Crangon crangon*) round crab (*Rhithropanopeus harrisi*) *B*lue mussel (*Mytilus edulis*)	Survival	3.7mT (37G)	--	--	No detection	Bochert and Zettler (2004)
Blue mussel (*Mytilus edulis*)	Biochemical parameters	5.8, 8, and 80 mT (58, 80, 800 G)	--	--	20% decrease in hydration and a 15% decrease in amine nitrogen values	Aristharkhov et al., (1988)
Sea urchins	Developmental abnormalities	10 mT – 0.1 T (100G - 1000G)	--	--	Delayed mitotic cycle of early embryos and great increase in the incidence of exogastrulation	Levin and Ernst (1997)
Teleost Fish						
Flounder (*Plathichthys flesus*)	Survival	3.7mT (37G)	--	--	No detection	Bochert and Zettler (2004)
Salmonids (general)	Bradycardia	--	7 µV/cm to 70 µV/cm	--	Elevated heart rate	Marino and Becker (1977)
	First Response	--	0.5 to 7.5 V/m	--	Shuddering of gills and fins	Marino and Becker (1977)
	Anode reaction	--	0.025 V/m to 15 V/m	--	Swims towards an electrically charged anode	Marino and Becker (1977)
	Electro-narcosis or Paralysis	--	15 V/m	--	Electro-narcosis or Paralysis	Balayev (1980), Balayev and Fursa (1980)
Eels (general)	Bradycardia	--	7 to 70 µV/cm (0.007 to 0.07 V/m)	--	Elevated heart rate	Marino & Becker (1977)

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
	First Response	--	0.5 to 7.5 V/m	--	Shuddering of gills and fins	Marino & Becker (1977)
	Anode reaction	--	25 µV/m (0.025 V/m) to 15 V/m	--	Swims towards an electrically charged anode	Marino & Becker (1977)
	Electro-narcosis or Paralysis	--	15 V/m	--	Electro-narcosis or Paralysis	Balayev (1980), Balayev & Fursa (1980)
Silver eels (*Anguilla anguilla*)	Migration	Same order of magnitude as the Earth's geomagnetic field at a distance of 10m	--	--	Approximately 60% crossed the cable	Westerberg & Begout-Anras (2004)
Japanese eel (*Anguilla japonica*)	Magneto-sensitivity	12,663 nT (0.12663G) to 192,473 nT (0.192473 G)	--	--	Exhibited significant conditioned response	Nishi et al. (2004)
Elasmobranchs						
Sharks (general)	AC current sensitivity	All	All	1/8 Hz and 8 Hz	Effects basic function	Kalmijin (2000b), Walker et al. (2003)
Blue shark (*P. glauca*)	Sensitivity to electric fields	--	A full-space field half as strong as the half-space field used for the larger dogfish	--	Repeated circling and attacked apparatus.	Kalmijn (1982)
Small dogfish (*Mustelus canis*)	Sensitivity to electric fields	--	<0.021 µV/cm	--	Attacked from 18 cm or more away from the source	Kalmijn (1982)
Large dogfish	Sensitivity to electric fields	--	5 nV/m	--	Attacked from 38 cm or more away from source	Kalmijn (1982)
Skates (general)	Cardiac response	--	1×10^{-9} V/m	5 Hz (uniform square wave)	Cardiac responses	Kalmijn (1966)

Species	Tested For	B-Field	E-Field	Frequency	Effect	Reference
Skates (*Raja clavata*)	Respiratory and cardiac responses	--	10^{-6} V/m	5 Hz (uniform square wave)	Respiratory and cardiac rhythms are affected	Kalmijn (1966)
	Cardiac response	--	4 x 10^{-5} V/m	5 Hz (uniform square wave)	Slowing down of the heart beat	Kalmijn (1966)
Stingray (general)	Orientation	--	Similar to those produced by ocean currents < 5nV/m (5 x 10^{-9} V/m)	--	Ability to orient relative to uniform electric fields similar to those produced by ocean currents	Kalmijn (1982)
Turtles						
Green sea turtle (*Chelonia mydas*)	Navigation	Variable	--	--	No detection	Papi et al., 2000
Marine Mammals						
Whales and dolphins (general)	Navigation	Earth's magnetic field ±0.5mG	--	--	Use of magnetic maps to travel in areas of low magnetic intensity and gradient	Walker et al. (2003)
Common Dolphin (*Delphinus delphis*) Risso's dolphin (*Grampus griseus*) Atlantic white-sided dolphin (*Lagenorhynchus acutus*) Finwhale (*Balaenoptera physalus*) Long-finned pilot whale (*Globicephala malaena*)	Sensitivity to stranding	Earth's magnetic field ±0.5mG	--	--	Significantly statistically sensitive to stranding	Kirschvink et al. (1986)

APPENDIX A – CONVERSION FACTORS

Magnetic (B-field) Units:

1 Tesla, T = 10,000 Gauss, G

100 microTesla, μT = 1 Gauss, G

1 milliGauss, mG = 1 x 10^{-3} G = 1 x 10^{-7} T = .1 μT = 100 nT

1 milliTesla, mT = 1 x 10^{-3} T

1 microTesla = 1 x 10^{-6} T

1 nanoTesla, nT = 1 x 10^{-9} T

1 picoTesla, pT = 1 x 10^{-12} T

1 femtoTesla, fT = 1 x 10^{-15} T

For reference, the approximate strength of the Earth's magnetic field near Reedsport, OR is 52 μT (.52 G)

Electric (E-field) Units:

1 volt/cm = 100 V/m

1 millivolt/cm, mV/cm = .1 V/m

1 microvolt/cm, μV/cm = .1 mV/m = 100 μV/m

1 nanovolt/cm, nV/cm = .1 μV/m = 100 nV/m

1 millivolt/meter, mV/m = 1 x 10^{-3} V/m

1 microvolt/meter, μV/m = 1 x 10^{-6} V/m

1 nanovolt/meter, nV/m = 1 x 10^{-9} V/m

1 picovolt/meter, pV/m = 1 x 10^{-12} V/m

APPENDIX B – ACRONYMS

AC	alternating current
ASW	anti-submarine warfare
B-field	magnetic field
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research into the Environment
DC	direct current
DoI	Department of Interior
E & E	Ecology and Environment, Inc.
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
G	Gauss
Hz	Hertz, cycles per second
iE-field	induced electric field
µT	micro-Tesla
µV/cm	microvolt per centimeter
µV/m	microvolt per meter
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
SI	International System of Units
SIO	Scripps Institute of Oceanography
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter

APPENDIX C – BIBLIOGRAPHY

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