APPENDIX F

ASSESSMENT OF LAKE ERIE CONNECTOR PROJECT: STATIC MAGNETIC FIELD AND SELECTED FISH SPECIES

Electrical Engineering & Computer Science Practice and Environmental/Health Practices

Assessment of Lake Erie Connector Project: Static Magnetic Field and Selected Fish Species

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Limitations

At the request of K&L Gates LLP on behalf of its client, ITC Lake Erie Connector LLC (ITC Lake Erie), Exponent calculated the magnetic-field levels from a proposed ±320-kV direct current transmission line that will transmit approximately 1,000 megawatts of electricity. This report summarizes work performed to date and presents the findings resulting from that work. In the analysis, we have relied on information provided to us by ITC Lake Erie and ITC Lake Erie's engineering and technical consultants with respect to parameters and configurations of the transmission line. In addition, Exponent evaluated the potential interaction of the calculated magnetic field with the earth's geomagnetic field and the potential significance for selected fresh water fish species based upon a review of the relevant literature.

The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on review of additional material as it becomes available, through any additional work, or review of additional work performed by others.

The scope of services performed during this analysis may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented here for purposes other than regulatory proceedings relating to this project are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

Introduction

ITC Lake Erie Connector LLC (ITC Lake Erie) is proposing the Lake Erie Connector Project (LEC). The LEC is a direct current (DC) bi-directional electrical transmission interconnection beneath Lake Erie, which will be used to transfer electricity between the Canadian and United States power grids. The line will connect two converter stations across the United States/Canadian border. The Canadian converter station will be located in Haldimand County in the Province of Ontario, and the converter station in the United States will be located in Conneaut Township, Erie County, Pennsylvania.

The purpose of this report is to describe the likely effect of the LEC on the background static geomagnetic field and the potential significance for four fish species of concern identified by the Pennsylvania Fish and Boat Commission (PFBC).

Project Route and Design

The proposed route of the underwater portion of the transmission line is divided into three main segments, as shown in Figure 1.

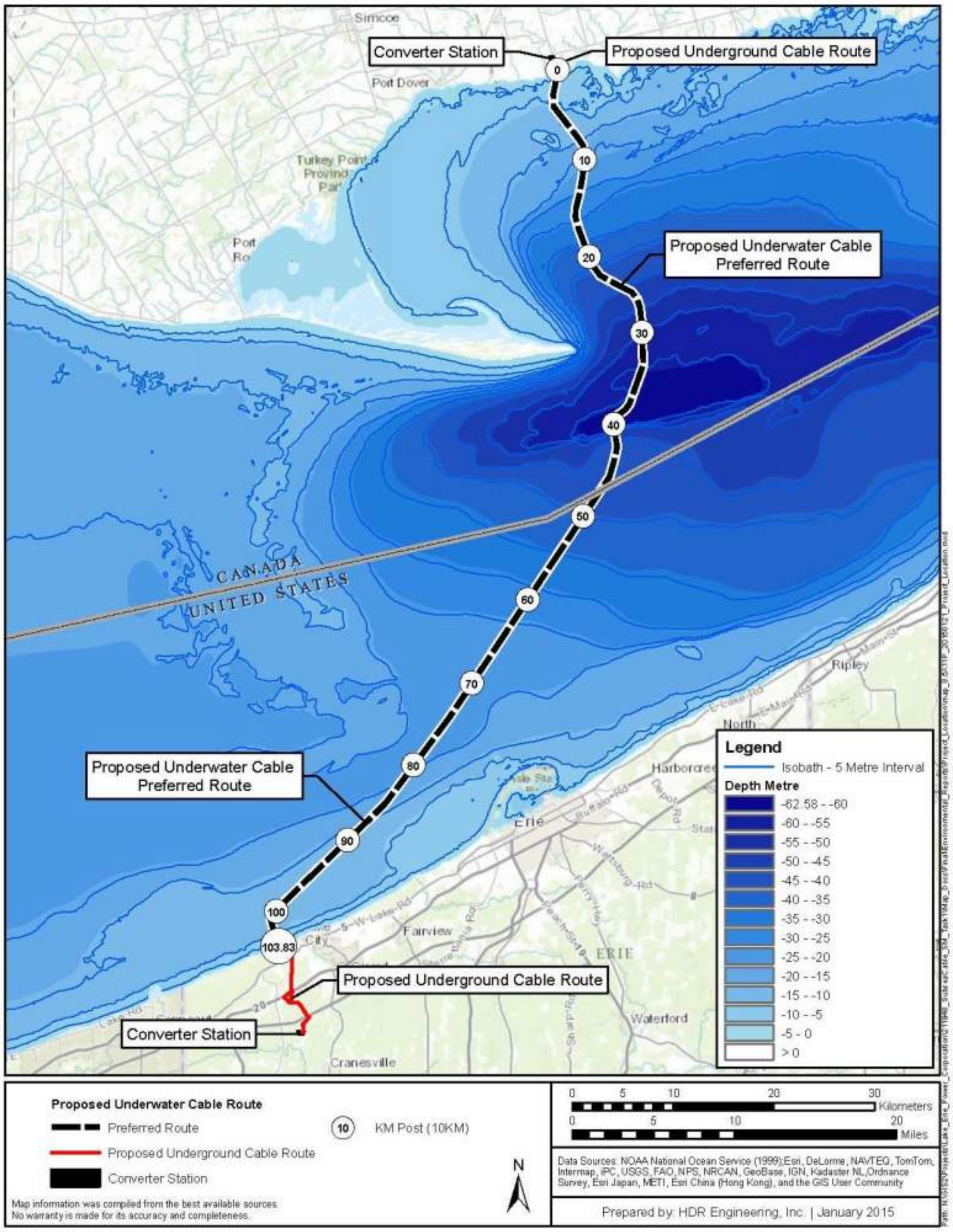

Figure 1. Proposed transmission line route across Lake Erie.

Starting at the shore landing and extending approximately 0.4 miles into Lake Erie (in both Canada and the United States), the transmission line will be installed in borings through bedrock using horizontal directional drilling (HDD). Where the transmission line exits the HDD in the bedrock of the nearshore area, a trench will be excavated out to a distance where softer sediment on the lake bottom will allow the use of a jet plow for the remainder of the route. The approximate length of each segment on the United States is summarized in Table 1.

Table 1. Approximate length of each segment of the LEC in the United States

Jet Plow Burial	34 miles
Trench Burial	0.9-1.2 miles
HDD	0.4 miles

The transmission line will consist of two insulated cables with outside diameters between 130 and 165 millimeters (mm), counter-biased at ±320 kilovolts (kV), and will be capable of delivering 1,000 megawatts (MW) of electricity. The cables will consist of a stranded copper conductor insulated with a solid dielectric material similar to cross-linked polyethylene and shielded with extruded lead or a copper laminate with concentric copper drain wires. The metallic shield will be covered with a polyethylene over-sheath. For the underwater cables, a galvanized steel wire armoring system will cover the cable. No gases or liquids are included in either cable design.

This report summarizes Exponent's calculations of the static magnetic fields[1] and compass deflections associated with the operation of the proposed DC transmission line in Lake Erie. Three separate scenarios, encompassing all proposed configurations of the LEC, are modeled, as described in the following section. These calculations take into account magnetic-field contributions from the transmission line and the earth's geomagnetic field. As such, they represent the total static magnetic field that would be measured around the transmission line.

[1] Magnetic fields associated with the operation of the DC power sources are generally referred to as DC magnetic fields. When produced in nature, these same phenomena are typically referred to as static magnetic fields. While the terminology is different, the phenomena are the same.

Modeling Methodology and Assumptions

Magnetic Field

The flow of DC electricity through the LEC cables will produce a DC magnetic field, commonly referred to as a static magnetic field. Unlike alternating current (AC) electricity that changes magnitude and direction continuously in a cycle that repeats 60 times per second (i.e., 60 Hertz [Hz]), the direction of current flow in the LEC cables is constant (i.e., ~0 Hz).

Calculations of the static magnetic field were performed by application of the Biot-Savart law[2] for specific cable configurations specified by ITC Lake Erie. The Biot-Savart law is derived from fundamental laws of physics and determines the magnetic field, which is generated from the flow of electric current. Application of the Biot-Savart law is particularly well suited when considering long, straight cables, such as those used in the LEC.

Three modeling scenarios were considered and are representative of the most conservative proposed cable configurations for the LEC. The loading of the two cables was assumed to be 1,609 amperes (A), a conservative estimate based on 1,000 MW of delivered power. Case 1 is representative of the HDD sections, where the transmission line enters and exits Lake Erie. Cases 2 and 3 are representative of the remaining trench and jet plow portions of the transmission line route. In the trench and jet plow configurations, the two cables will be strapped together and may be situated in the trench or jet plow such that the two cables are side by side (Case 2, horizontal configuration) or one on top of the other (Case 3, vertical configuration). The configuration of each of the three modeling scenarios is shown in Table 2.

All of the parameters, specified in Table 2 were chosen to produce a conservative (i.e., high) estimate of the magnetic field produced by the transmission line. For example, in Case 1 the separation of the two poles of the cable may vary from approximately 17.5 meters (m) to 22.5 m. For calculation of magnetic-field levels, a smaller separation distance was found to produce higher magnetic-field levels, and therefore the minimum separation distance of 17.5 m was chosen for this study.

[2] See, e.g., Jackson, JD. (1999). Classical Electrodynamics 3rd ed. New York: John Wiley and Sons.

Table 2. Transmission line modeling configuration in Cases 1, 2, and 3

Conditions	Configuration		
	Case 1 (HDD)	Case 2 (Horizontal)	Case 3 (Vertical)
Separation of Cables	17.5 m	Touching	Touching
Cable Orientation	Horizontal	Horizontal	Vertical
Burial Depth (to top of cable)	1 m	0.5 m	0.5 m
Direction of Electrical Current (degrees north of east)	90	20	20
Cable Diameter	165 mm	165 mm	165 mm

Similarly, for both Cases 2 and 3, the target burial depth of the transmission line is 1.5 m in order to protect the cables from damage due to shipping traffic, fishing activity, and other factors. In areas where sufficient depth cannot be reached due to soil conditions or existing facilities, the burial depth may be as little as 0.5 m for both cases.[3] The shallower (0.5 m) depth was used in both cases for the modeling parameter since this will produce a larger calculated magnetic field and therefore represents the more conservative estimate. No effect of ferromagnetic coverings around the cables was accounted for in the calculations.

For Cases 2 and 3, where the cables are strapped together, the cable diameter including insulation determines the separation between conductors and influences the resulting magnetic-field calculation. The precise diameter of the cables is not yet determined and may vary between 135 mm and 165 mm. For calculation of magnetic-field levels, a larger cable diameter was found to produce more conservative magnetic-field levels, and therefore a larger diameter cable of 165 mm was chosen for this study.

Another aspect of the transmission line route shown in Figure 1 is that the direction of the transmission line will vary across its proposed route. The cable direction influences the calculated magnetic field as a result of the interaction between the magnetic field produced by the current-carrying conductors, and the earth's geomagnetic field.

[3] Where the transmission line is buried to a depth of only 0.5 m, however, additional protection in the form of articulated concrete mattresses or reinforced concrete barriers will be required, which would result in greater distance between the buried line and any nearby fish species and therefore a lower magnetic field over the cables.

In order to calculate the total magnetic field, the calculated magnetic-field vector from the transmission line was added to earth's geomagnetic-field vector, and the magnitude of the combination is reported. The geomagnetic field where the transmission line crosses the border was obtained from the International Geomagnetic Reference Field Model. The geomagnetic field at 42.411982 degrees (°) N latitude and 80.032804°W longitude was used in all calculations, and is included in Table 3. At this location, the field has a magnitude of approximately 536 milligauss (mG), a declination of 9.7°W and an inclination of 69.1° downward.

Table 3. Geomagnetic field at coordinates 42.411982°N, 80.032804°W

Component	Geomagnetic field (in nanotesla [nT] and mG)		
Northern Component	18891.7 nT	=	188.92 mG
Eastern Component	-3233.6 nT	=	-3.23 mG
Downward Component	50094.0 nT	=	500.94 mG
Total Geomagnetic Field (norm)			536.35 mG

Source: International Geomagnetic Reference Field Model (IGRF12)
http://www.ngdc.noaa.gov/geomag-web

In the modeling results that follow, the expected north-south orientation of the cables is modeled for Case 1, and discussion is included to characterize the relative insensitivity of the results to small changes in cable direction. In Cases 2 and 3, the direction that produces the most conservative magnetic-field levels (20° north of east) was used for calculations. For the cable oriented in other directions along the route, the maximum magnetic field would be less.

Compass Deflection

The magnetic interaction between the horizontal component of the geomagnetic field and a compass needle causes the needle to point toward the geomagnetic North Pole. To quantify the potential effect on navigation using a compass, Exponent also calculated the compass deviation near the transmission line for each of the three modeling configurations.

Induced Electric Field

Movement of a fish through a magnetic field results in an induced electric field of magnitude:[4]

$$E = vB \sin\theta,$$

where the electric field (E) is the product of the magnitude of the object's velocity (v), the magnitude of the total magnetic field (B), and the sine of the angle (θ) between the velocity and magnetic-field vectors. Induced electric fields for fish moving through water in the vicinity of the transmission line were calculated by inserting the swimming speed of a fish or the speed of local water current into the equation above.

[4] See e.g., Normandeau, Exponent, Tricas T, Gill A. Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species (OCS Study BOEMRE 2011-09). (2011). Camarillo, CA: U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region.

Calculated Static Magnetic Fields

The calculated static magnetic fields and compass deflections for the three cases described above are presented in this section.

Magnetic-Field Deviations

Case 1 pertains to the HDD portion of the proposed route, where cables transition from the underground land-based portion of the LEC into borings within bedrock under the bed of Lake Erie. In this area, the cables are assumed to be buried at a depth of 1 m, separated by 17.5 m, and run primarily north-south. The calculated magnetic field at transects located 0 m, 1 m, and 5 m above the lakebed is shown in Figure 2, which considers the case where the northward current-carrying conductor is on the west side of the pair. The resulting deviations from the geomagnetic field are also tabulated at distances of 5, 10, and 15 m from the centerline of the two cables for each of the three transects and are presented in Table 4.

An alternate scenario, where the northward current is on the east side of the pair, was also considered, but produced smaller fields. Calculation results for the latter scenario are provided in Appendix A.

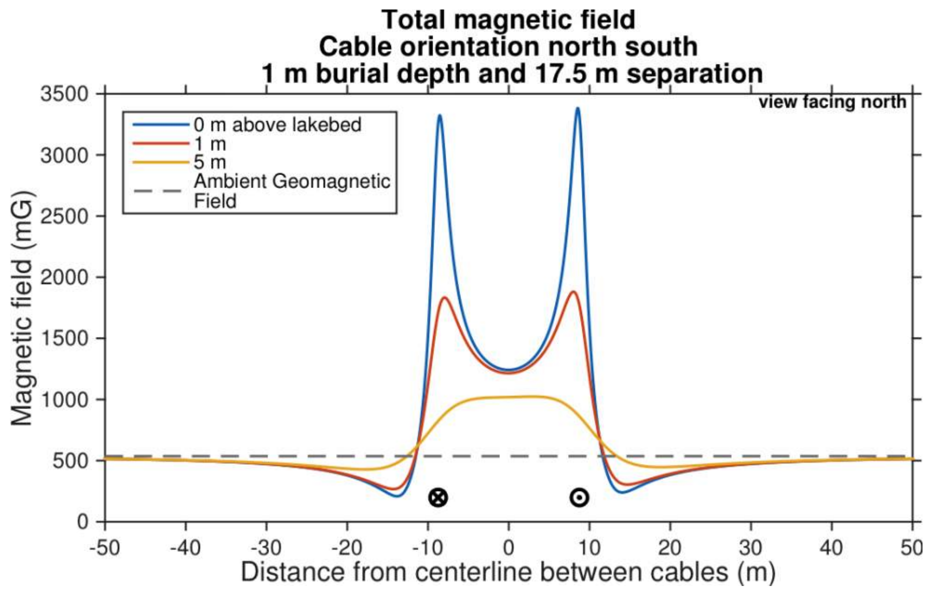

Figure 2. Case 1. Calculated magnetic-field profile for cables oriented north-south, buried at a depth of 1 m, with cables separated by 17.5 m.

While the calculations presented here are for configuration with the transmission line running north-south, the sensitivity of the results to deviations in the cable direction was also examined. For a range of orientations ranging from 80º-100° north of east, the peak total magnetic field was found to vary by less than ±1%.

The trench and jet plow portions of the transmission line, which are not installed by HDD, vary in direction throughout the route, with a bearing ranging from 20º–120° north of east. As the cable orientation varies, the interaction of the cable's magnetic field with the geomagnetic field also varies. For cables oriented horizontally (Case 2) or vertically (Case 3), a range of cable directions within the aforementioned limits were modeled, and the direction that produced the largest total magnetic field is reported here. The reported results therefore represent the most conservative estimate for the magnetic field produced by the LEC.

For the cables laid side by side (Case 2), where the cables are running in a southwest to northeast direction, it was found that the largest total magnetic field was produced when the cable direction was 20° north of east, with the northern conductor carrying northeastward current. In this configuration, the maximum total magnetic field is approximately 2,224 mG, as illustrated in Figure 3. The results for this modeling scenario are also tabulated in Table 5. The magnetic-field profiles for the analog of Case 2 with current flowing in the opposite direction are included in Appendix A.

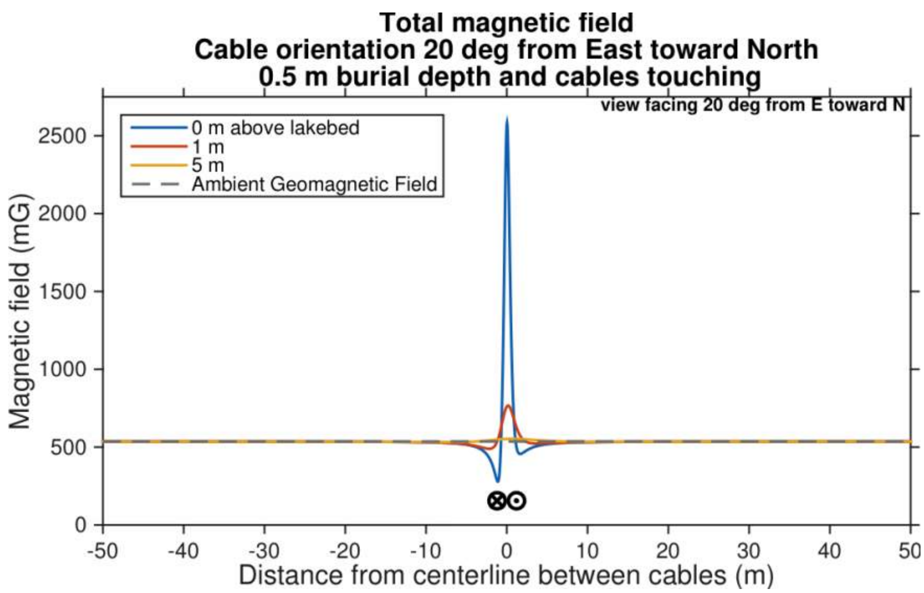

Figure 3. Case 2. Calculated magnetic-field profile for cables strapped together, laid horizontally and oriented at 20° north of east and buried at a depth of 0.5 m.

For cables laid vertically (Case 3), the largest total magnetic field was found for a cable direction of 20° north of east. Transects of the total magnetic field at a height of 0 m, 1 m, and 5 m above the lakebed are shown in Figure 4 for the scenario where the bottom conductor carries the eastward current. The deviations from the geomagnetic field for Case 3 are also presented in Table 5. The alternative scenario of Case 3, where the top conductor carries the northeastward current, was also considered, but found to produce smaller magnetic fields. The results from this scenario are presented in Appendix A.

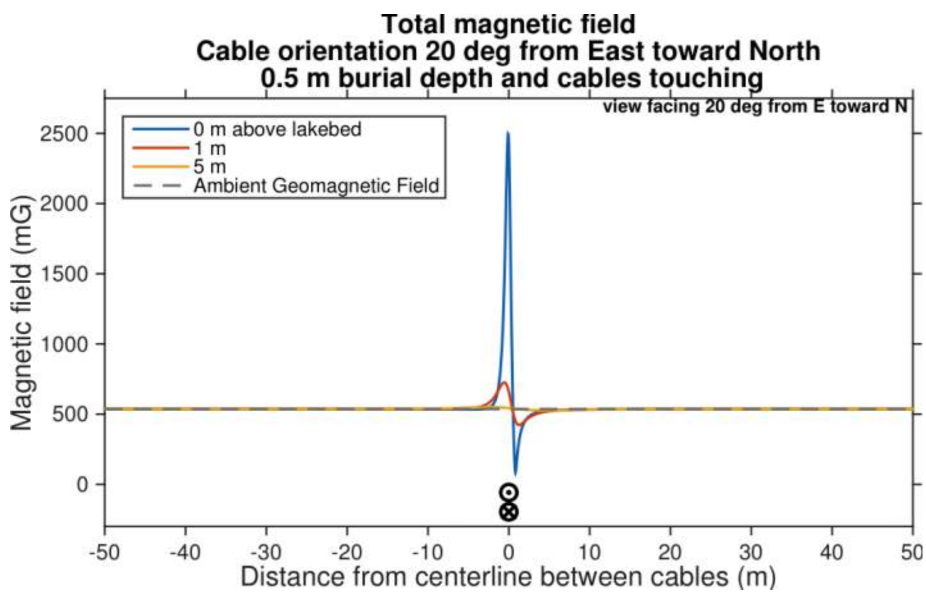

Figure 4. Case 3. Calculated magnetic-field profile for cables strapped together, laid vertically, and oriented at 20° north of east and buried at a depth of 0.5 m.

Table 4. Deviations of the magnetic field (mG) from the geomagnetic field (536.35 mG) for Case 1, above the lakebed and at distances from the centerline of the bipolar DC circuit with cables oriented north-south

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deviation	Max - deviation	+5 m	+10 m	+15 m
Case 1 1 m (northward current, west side)	0	-301	988	1018	2846	-328	1027	1040	-281
	1	-262	589	904	1345	-269	918	652	-231
	5	-86	188	458	488	-108	477	228	-55

Table 5. Deviations of the magnetic field (mG) from the geomagnetic field (536.35 mG) for Cases 2 and 3, above the lakebed and at distances from the centerline of the bipolar DC circuit with cables facing 20° north of east

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deviation	Max - deviation	+5 m	+10 m	+15 m
Case 2 0.5 m (eastward current, north side)	0	-2.2	-5.1	-21	2047	-258	-18	-4.7	-2.1
	1	-2.3	-5.2	-19	231	-47	-11	-4.1	-2.0
	5	-2.0	-3.2	-2.4	17	-3.8	4.3	-0.8	-1.0
Case 3 0.5 m (eastward current, bottom side)	0	-0.7	-1.3	-2.9	1960	-452	-11	-2.3	-1.0
	1	-0.4	-0.3	4.6	189	-113	-16	-3.1	-1.2
	5	0.7	2.5	9.3	14	-8.9	-8.6	-4	-1.8

Compass Deflection

The geomagnetic field in the area of the proposed transmission line has a 9.71°W declination (i.e., the difference between magnetic north relative to geographic north). Compass deflections from this value were calculated for each of the three cases described above.

Figure 5 shows compass deflections for Case 1 along transects 0 m, 1 m, and 5 m above the lakebed with the northward current in the western conductor. This current configuration was chosen because it produces the largest net magnetic field, described above. Tabulated compass deflections for this case are provided in Table 6, below.

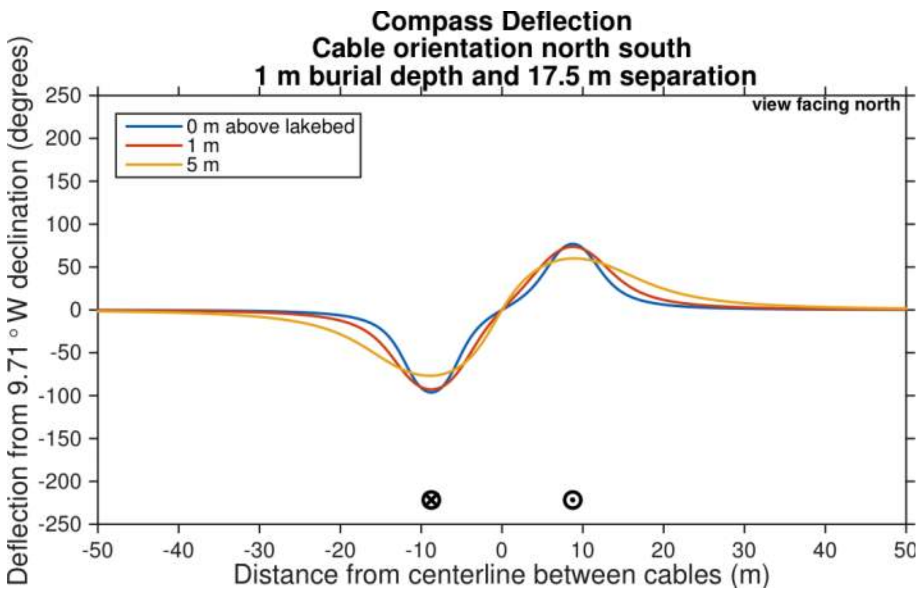

Figure 5. Case 1. Calculated compass deflection (degrees) from 9.71°W declination above cables oriented north-south, separated by 17.5 m in the horizontal direction and with northward current in the western cable.

The compass deflection for Cases 2 and 3 are show in Figure 6 and Figure 7, respectively, and are tabulated in Table 7. The corresponding deflections for each of the three cases with opposite current direction are provided in Appendix A.

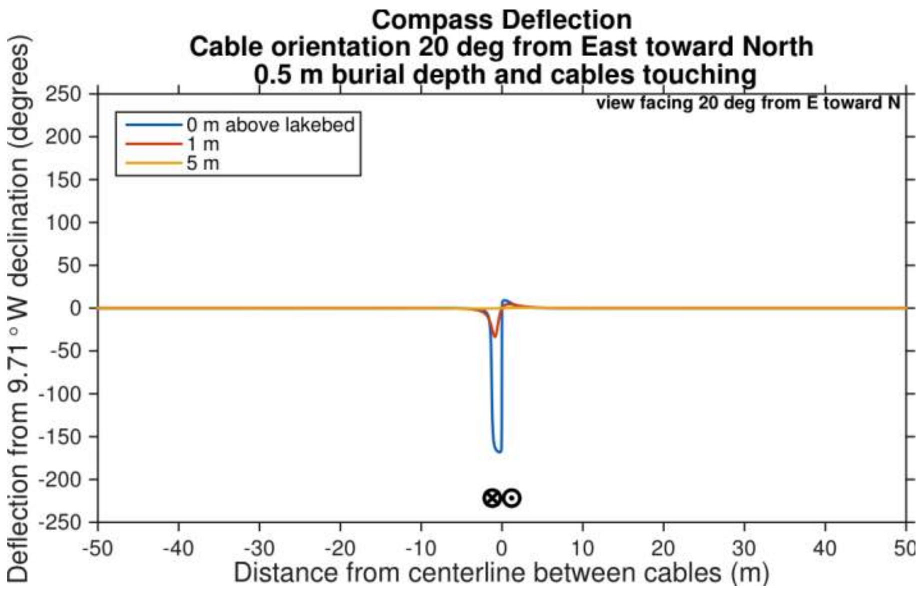

Figure 6. Case 2. Calculated compass deflection (degrees) from 9.71°W declination above cables directed 20° north of east, touching in the horizontal direction, and with northeastward current in the northern cable.

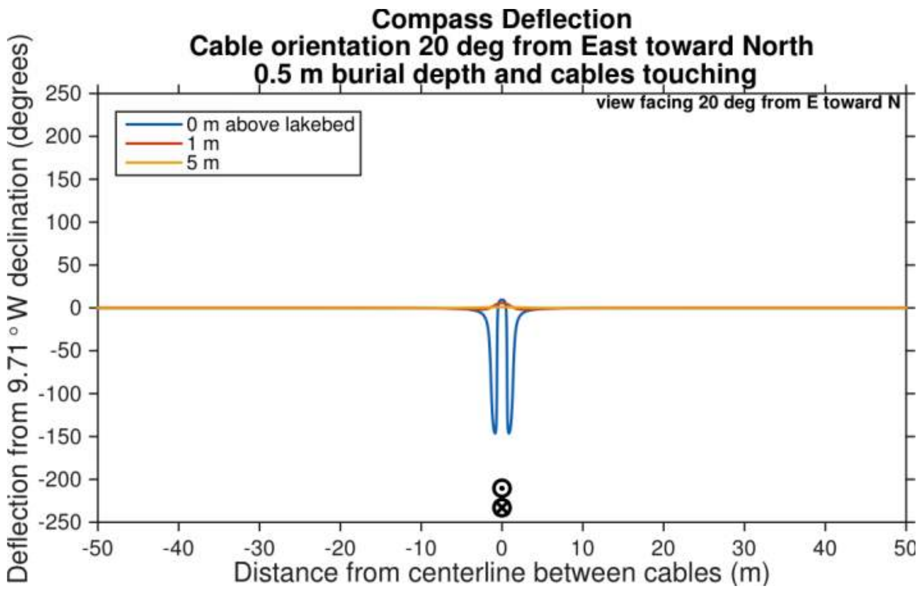

Figure 7. Case 3. Calculated compass deflection (degrees) from 9.71°W declination above cables directed 20° north of east, touching in the vertical direction, and with northeastward current in the bottom cable.

Table 6. Compass deflection (degrees) from 9.71°W declination for Case 1, above lakebed and at distances from centerline of bipolar DC circuit with cables oriented north-south

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deflection	Max - deflection	+5 m	+10 m	+15 m
Case 1	0	-22	-91	-51	77	-96	41	72	20
1 m (northward current	1	-39	-90	-67	74	-93	52	71	32
west side)	5	-55	-76	-65	60	-77	51	60	44

Table 7. Compass deflection (degrees) from 9.71°W declination for Cases 2 and 3, above lakebed and at distances from centerline of bipolar DC circuit with cables oriented 20° north of east

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deflection	Max - deflection	+5 m	+10 m	+15 m
Case 2	0	0.0	0.0	-0.2	9.0	-168	0.2	0.0	0.0
0.5 m	1	0.0	-0.1	-0.6	4.6	-34	0.5	0.1	0.0
(eastward current on north side)	5	-0.1	-0.2	-0.5	0.6	-0.6	0.5	0.2	0.1
Case 3	0	-0.1	-0.3	-1.2	9.5	-146	-1.2	-0.3	-0.1
0.5 m	1	-0.1	-0.3	-0.9	5.7	-1.9	-0.9	-0.3	-0.1
(eastward current on bottom side)	5	-0.1	-0.1	0.0	0.9	-0.1	0.0	-0.1	-0.1

Electric Field Induction

Fish or other animals moving through a magnetic field will experience an induced electric field, which depends on both the speed and direction of movement relative to the magnetic field. The speed of a fish depends on many factors, such as fish species, age, and swim duration. In a recent study (Hoover et al., 2012), the average sustained fish speed of several species of carp was less than or equal to 80 centimeters per second (cm/s). The swimming speed of Atlantic cod was found to be seasonally dependent, but on average was less than 150 cm/s (Cote et al., 2002). As a conservative estimate, in the calculations presented here, a speed nearly 10 times higher (1.38 meters per second [m/s]) is used.

Electric-field induction occurs naturally from movement through the earth's ambient geomagnetic field. For example, a fish or water moving through earth's geomagnetic field (specified in Table 3) in the magnetic north-south direction at a speed of 1.38 m/s will experience an electric field of 69.7 microvolts per meter (µV/m), whereas movement through the earth's geomagnetic field in the geographic east-west direction at the same speed produces an electric field of 73.5 µV/m.

The same effect occurs for movement through the static magnetic field generated by an underwater transmission line. Maximum values of the induced electric field experienced by a fish moving near a transmission line are tabulated in Table 8 for Cases 1, 2, and 3. In each case, the maximum electric field is calculated at the surface of the lakebed when considering parallel, perpendicular, or vertical movement relative to the transmission line orientation.

Table 8. Maximum induced electric field for a fish or water moving at the surface of the lakebed near the transmission line

	Direction of movement at 1.38 m/s relative to transmission line orientation		
	Induced electric field (µV/m)		
	Perpendicular	**Parallel**	**Vertical**
Case 1	319	466	448
Case 2	354	356	213
Case 3	263	344	327

In all cases, the electric field approaches the value associated with movement through the earth's geomagnetic field as the distance from the transmission line is increased. In Case 1, the electric field deviates by less than 10% of this value at a distance of 27 m from the transmission line. For Cases 2 and 3, the electric field drops off more rapidly, reaching less than 10% deviation from the value associated with movement through the earth's geomagnetic field within 5 m of the transmission line.

Discussion

Magnetic fields diminish very rapidly with distance, so it is only in the immediate vicinity of the transmission line that the magnetic-field level will be appreciably different than earth's geomagnetic field.

Case 1 (HDD)

Case 1 represents the typical configuration for the HDD section of the cable route through bedrock in the near shore area of Lake Erie. This section produces larger fields than Cases 2 and 3, but only represents a small length of the overall transmission line. The maximum magnetic-field deviation for Case 1 is 2,846 mG and occurs at the lake bed (0 m) directly over the transmission line. This field is approximately 5.3 times larger than the geomagnetic field, but it diminishes quickly with distance. At a distance of 6.25 m from the cable (15 m from the centerline between the cables), the field deviation drops to -250 mG, representing a decrease in the total magnetic field to a value approximately 50% relative to the earth's geomagnetic field. The field deviation decreases further still at larger distances and the overall field becomes nearly indistinguishable from the geomagnetic field at distances greater than 30 m from the transmission line. Furthermore, as discussed above, the burial depth in the HDD section will vary from approximately 1 to 30 m. For a burial depth of just an additional 1 m (corresponding to the red line shown by the '1 m above lakebed' in Figure 2, above), the magnetic-field level at the lakebed would decrease by a factor of 2; at greater burial depths, the magnetic-field level would be even lower.

Cases 2 and 3

Cases 2 and 3 are representative of two modeling scenarios for either the trench or jet plow portions of the transmission line route in the deeper lakebed areas. For the majority of the underwater route, the cable burial depth is 1.5 m. The scenarios considered in this report, with a 0.5 m burial depth, are therefore highly conservative estimates.

The peak magnetic-field deviation in Case 2 is 2,047 mG, but drops to a value of -18 mG at a distance of 5 m from the cable, which is a 3.3% reduction of the geomagnetic field. Beyond 10 m from the cable, the magnetic-field deviation is less than 5 mG. Case 3, where the cables are vertically oriented, produces magnetic fields largely similar to Case 2, but with magnetic-field deviations consistently smaller in magnitude. Furthermore, as discussed above, a burial depth of at least 1.5 m is expected over the majority of the route. In this case, the maximum magnetic-field level at the lakebed would be approximately 10 times lower (corresponding to the red line shown by the ‘1 m above lakebed’ in Figure 3 and Figure 4, above).

Compass Deflections

A compass is sensitive to the horizontal component of the geomagnetic field. Exponent investigated whether the static magnetic field produced by the proposed transmission line would affect a boater using a compass to navigate. For a boater directly over the transmission line in water 5 m deep, the experienced compass deflection is less than 1º. While the compass deflection would be larger for the HDD section of the line, these sections are at the nearshore areas of the lake, where it is unlikely that a compass would be needed for navigational purposes.

Electric-Field Induction

The LEC cables will not directly produce an electric field that would influence marine life due to shielding around the conductors. An induced electric field, resulting from movement of charges in water or organisms through the static magnetic field will be produced. The maximum induced electric field is calculated to be approximately 466 μV/m, and diminishes quickly with increasing distance from the line.

Standards

While there are no established federal standards for magnetic fields produced by DC transmission lines, the International Commission on Non-ionizing Radiation Protection (ICNIRP) has recommended a limit of 4,000,000 mG for general public exposure, not including persons with implantable medical devices. For individuals with implantable medical devices (such as pacemakers or implantable cardioverter defibrillators [ICD]), the PC69:2007 standard from the Association for the Advancement of Medical Instrumentation specifies that pacemaker and ICD function should not be affected when exposed to magnetic fields smaller than 10,000 mG. When exposed to a magnetic field up to 500,000 mG, after discontinuation of the exposure, a pacemaker or ICD should not remain functionally affected.[5]

As discussed above, the changes in the ambient geomagnetic-field level associated with the LEC will be largely limited to the area in the immediate vicinity of the proposed LEC cables. The highest calculated magnetic-field level anywhere along the portion of the route in Lake Erie is approximately 3,382 mG (a deviation of approximately 2,846 mG from the ambient geomagnetic field). This maximum magnetic-field level (calculated on the lakebed [0 m], directly over the HDD cables) is approximately 0.08% of the general public exposure limit recommended by ICNIRP.

[5] AAMI PC69:2007 has been superseded by 14117:2012, but 14117:2012 is not yet recognized as a consensus standard by the Food and Drug Administration. AAMI PC69:2007 and 14117:2012 do not differ in recommended static magnetic-field limits.

Magnetic-Field Exposures to Fish

Based on the modeling of the magnetic field of the LEC cables summarized above, the field levels relevant to characterizing potential exposures to fish species differ for each section of the route in Lake Erie. The shortest section of the proposed cable route, an approximate 0.37 mile section through bedrock on each side of the lake where the cables are in individual HDD conduits, has the greatest deviation from the earth's background geomagnetic field (2,885 mG) at the lakebed, directly above the cables. The magnetic-field deviation is much lower over the portions of the route (approximately 0.6 miles in the United States) where the cables will be installed by trenching through bedrock (1,688 mG) and the approximately 35.4 miles in the United States of the route where the cables will be installed through lake sediments by jet plow (1,568 mG). It is noteworthy that the change in the static magnetic field for the latter two sections (which comprise all but approximately 0.37 miles from each shore of the route in Lake Erie) diminishes rapidly so that the change in the static magnetic field at 5 m to either side of the cables is insignificant (~3% of the earth's background geomagnetic field). Furthermore, in the HDD portion of the route, modeling was performed assuming a burial depth of 1 m. The burial depth in the HDD section will vary from approximately 1 m to 30 m, and will be at 1 m only for a very short distance where transition to the trench configuration is made. For a burial depth of just an additional 1 m, the magnetic-field level at the lakebed would decrease by a factor of 2; at greater burial depths, the magnetic-field level would be even lower. In addition to calculating the static magnetic field, Exponent estimated the electric field that would likely be induced in fish moving swiftly through the magnetic field is less than 466 µV/m, which is below a reported detection threshold for sturgeon with sensitive electroreceptors as discussed below.

Fish Species of Interest

Exponent's analysis has focused on certain fish species of interest. The PFBC has identified three fish species within Lake Erie that are endangered—cisco, eastern sand darter, and lake sturgeon.[6] PFBC also expressed concern about effects of the LEC on electric and magnetic fields on salmonid (steelhead trout) migration. Given the identified concerns regarding these species, this evaluation has sought to evaluate whether the LEC would pose any additional significant risks to such fish species. This section summarizes the life history and ecology of the four fish species of interest, and provides a review of the relevant literature pertaining to the effects of exposure to static magnetic fields on freshwater fish species.

Cisco

The cisco (i.e., lake herring), *Coregonus artedi*, is a small, pelagic fish that inhabits cold lakes in the upper Midwest. It is a member of the Salmonidae family (salmon, trout, whitefishes, and graylings), which are documented to respond to static magnetic fields (Quinn 1980; Walker et al., 1998). Cisco form large schools in deep, offshore waters, but move into the shallow water and inland shoals to spawn (MNFI, 2014). Spawning occurs in the winter when water temperatures drop below 4 degrees Celsius (°C) and ice forms around shorelines. Adults are pelagic feeders, consuming plankton and crustaceans. Although the cisco has been one of the most important commercially harvested species in the Great Lakes, overfishing, competition with other fish species, and eutrophication has reduced the resident populations (MNFI, 2014). Barring any barriers to movement, cisco populations within a 10 kilometer (km) range are considered a single population occurrence, given what is known about their dispersal (Nature Serve, 2015a).

[6] Letter from Christopher A. Urban, Chief of Natural Diversity Section to HDR, Inc. Re Species Impact Review, September 16, 2014.

Eastern Sand Darter

The eastern sand darter (*Etheostoma pellucida*) is a small demersal fish of the Percidae family (perch) that preferentially inhabits shallow sandy runs in lakes, rivers, and creeks in the upper Midwest. They feed primarily on bottom-dwelling insects and other invertebrates, and adults frequently exhibit a burial behavior where they dive and burrow into the sandy substrate (Nature Serve, 2015b; PNHP, 2014a). Spawning occurs in the summer (PNHP, 2014a). In Lake Erie, most eastern sand darters are found in the sandy shores, bays, and island regions, typically in water depths of 1-5 m; predicted distances the eastern sand darter can traverse are 10 km or less (Nature Serve, 2015b). Agricultural runoff and siltation have reduced the quality of available habitat for the eastern sand darter (PNHP, 2014a).

Lake Sturgeon

The lake sturgeon (*Acipenser fulvescens*) is a large, long-lived freshwater member of family Acipenseridae (sturgeon) that inhabits larger lakes and rivers in Pennsylvania. These fish prefer mud, sand, or gravel bottom habitats at about a depth of 5 to 9 m. Sturgeons are omnivorous benthic feeders, sucking up prey items from the substrate (fishbase.org). Sturgeons are exceptionally long-lived. Spawning begins between 15 to 20 years of age, and occurs every 2 to 3 years for males and 4 to 6 years for females; individual life span might be 80 years or more (PNHP, 2014b). Sturgeon exhibit strong spawning site fidelity and return to the same site year after year (Bemis and Kynard, 1997). Eggs are sticky and anchor to rocks and woody debris in the rocky habitats where sturgeon spawn (PNHP, 2014b). Overfishing and the construction of dams and locks on key waterways have reduced sturgeon populations. Given that the lake sturgeon is potamodromous (i.e., migrating within freshwater systems to spawning sites, usually from a larger lake system up into tributaries), physical barriers to movement may block fish from reaching these sites (Bemis and Kynard 1997). According to United States Fish and Wildlife Service, lake sturgeon populations have largely been extirpated from sites in Lake Erie, with remnant populations in Lake St. Clair and the Niagara River (USFWS, 2003). Data from Nature Serve, however, indicate that nonanadromous sturgeon can swim 100-plus kilometers, if there are no barriers to their movement (Nature Serve, 2015c).

Steelhead trout

A large salmonid species, steelhead trout are the anadromous form of rainbow trout (*Oncorhynchus mykiss*). Native to the cold waters of the western United States, this species has been introduced into cold waters throughout the country (ODNR, no date). The PFBC stocks more than one million steelhead trout into Lake Erie every year (Vargason, 2013). Adult steelhead can inhabit cool lakes, estuaries, or oceanic habitats; in lakes, they feed on various planktonic and benthic invertebrates as well as larval fish and fish eggs (USDA, 2000). Steelhead trout spawn in cobbled and graveled habitat of the cold water tributaries of Lake Erie in the fall, but are found in the lake during the summer months (ODNR, no date). Habitat degradation, including physical barriers to upstream spawning migrations, can have an adverse impact on steelhead populations (USDA, 2000). Available data suggest that both non-anadromous rainbow trout and the anadromous steelhead trout are capable of movements from 10 km to more than 50 km in distance (Nature Serve, 2015d).

Effects of Static Magnetic Fields on Freshwater Fish

Particles of magnetite, the most magnetic of all naturally-occurring minerals on earth (Harrison et al., 2002), are found in many species of fish including salmonids, tuna, herrings, carp, and mackerel. These particles are thought to be a key component of receptors that orient and guide fish via reception of the earth's geomagnetic field (Hanson and Westerberg, 1987; Walker et al., 1998; Öhman et al., 2007; Tanski et al., 2011). This ability to navigate is particularly valuable to fish species that undergo long migrations, such as salmonid species (Quinn, 1980; Quinn and Brannon, 1982) and sturgeon (Cada et al., 2011). Sturgeon and the related paddlefish exhibit sensitive electroreceptors called *ampullae of Lorenzini* on the snout and gills, which allow these fish to detect very low electric-field gradients (Bouyoucos et al., 2013, Basov 1999). These adaptations mean that these fish species, to varying degrees, are capable of detecting and responding to variations in the earth's geomagnetic field or electric fields induced by movement in the magnetic field. A review of the pertinent literature on the effects of static magnetic fields on freshwater aquatic life is provided below.

Behavioral Effects

Cada et al. reported that laboratory exposures of the freshwater snail, *Elimia clavaeformis*, the freshwater clam, *Corbicula fluminea*, and fathead minnows, *Pimephales promelas*, to a static magnetic field of 36.4 millitesla (mT)[7] (equivalent to 364 Gauss [G] or 364,000 mG) showed "no evidence that 3 common freshwater taxa (snail, clam, and fish species) were either attracted to or repelled by the static magnetic field created by the permanent bar magnet" (Cada et al., 2011, p. 35). Data from an additional lab study by Cada et al. of lake sturgeon (*A. fulvescens*), striped bass (*Morone saxatilis*), channel catfish (*Ictalurus punctatus*), and fathead minnows suggested that the presence of the 36.4 mT static magnetic field did not affect the distribution of these fish in the tank but did increase the movement of fathead minnows, but not the other species, during a 46 hour testing period (Cada et al., 2012). The authors concluded "Our results suggest that the predicted EMF [electromagnetic field] that may be created by a

[7] Tesla is another measure of magnetic flux density. For purposes of comparison 1 microtesla (μT) equates to 0.01 G or 10 milligauss (mG); 1 millitesla equates to 10 G, or 10,000 mG

single submerged DC transmission cable from an HK [hydrokinetic] project would not seriously affect the behavior of common freshwater species" (Cada et al.2012, p. 25).

In a series of laboratory experiments, Bevelhimer et al. (2013) exposed a range of freshwater fish species (fathead minnow, redear sunfish, *Lepomis microlophus*, striped bass, lake sturgeon, and channel catfish) to a static magnetic field generated by a permanent magnet. The 36.4 mT (364 G) magnetic field generated by a bar magnet under one end of an aquarium did not affect the preference of striped bass, lake sturgeon, or fathead minnow for the ends of the aquarium with and without magnets, but redear sunfish and channel catfish did spend more time at the end of the aquarium over the magnets. As in previous experiments from this laboratory (Cada et al., 2011, 2012), the presence of the magnetic field increased the movement of fathead minnows during the 46-hour testing period, but did not affect the other species. In contrast, the lake sturgeon exhibited gross variations in swimming behavior during exposure to 60-Hertz AC[8] magnetic fields at 1.5 mT (15 G) (Cada et al., 2012) and 1.65 mT (16.5 G) (Bevelhimer et al. 2014). The LEC is designed to carry DC current and so would not produce any significant AC magnetic field. The results of the Cada et al. and Bevelhimer et al. studies are consistent with a greater sensitivity of electrosensory receptors in sturgeon to AC electric fields produced by the movement of prey. Lake sturgeons were not exposed to static magnetic fields as a part of these studies.

Effects on Migratory Behaviors

Consideration was given to potential impacts of magnetic fields on the migratory behavior of lake sturgeon and steelhead trout.

Barriers to migration that block fish from spawning sites could impact migrating steelhead and sturgeon populations (PNHP, 2014b). To date, the most comprehensive study on the effect of DC cables on fish migration addressed the migratory behavior of marine eels (*Anguilla anguilla*) near high voltage DC cables in the Baltic Sea (Westerberg and Begout-Anras, 2000). The DC cable systems produced a magnetic field of 5 μT (50 mG) at a 60 m distance from the

[8] It should be noted that the proposed LEC is an DC cable system, not an AC cable system

cable, but the authors concluded that there was no evidence that the migrations of tagged eels were affected by the cable, and therefore, they concluded, it "was unlikely to be an obstacle that could influence the escapement of eels" (Westerberg and Begout-Anras, 2000, p. 154). A similar field study conducted by Westerberg and Lagenfelt (2008) at an AC cable site determined that tagged eels swam significantly slower in the cable vicinity. These effects were deemed inconsequential, however, because the delay was estimated to be approximately 40 minutes over a 7,000 km migration (Westerberg and Lagenfelt, 2008). Although comparable tagging studies have not been conducted with lake sturgeon, it can be inferred that, although behavioral changes observed under laboratory exposures to magnetic fields might also occur under field conditions, these are likely to be transitory and minor in nature, since behavior changes are relatively minor and the LEC would affect only a very small portion of Lake Erie.

Like lake sturgeon, steelhead trout and other salmonid species can undergo significant migrations. Laboratory experiments have indicated that salmonids utilize magnetic-field direction and intensity in the absence of ambient light (Hellinger and Hoffman, 2012). This magnetic sense is apparently used in conjunction with other types of cues, including olfactory and visual, to carry out both long-range migration and short-range movements. Putman et al. (2014a) examined the relative importance of geomagnetic and olfactory cues in the long-distance homing behaviors of two salmonid species. It was determined that the much of imprinting behavior resulted from geomagnetic signals, although other factors did contribute to salmon homing. Interestingly, the inland-spawning sockeye salmon (*Oncorhynchus nerka*) responded better to olfactory cues than offshore-spawning pink salmon (*O. gorbuscha*) (Putman et al., 2014a).

Young steelhead trout (*O. mykiss*) reared in distorted magnetic fields (intensities between 42 and 55 μT [0.42 to 0.52 G] with an inclination angle ranging from 62.68° to 70.78°) for 5 to 7 months demonstrated an inability to correctly orient to natural magnetic fields (Putman et al. 2014 b). The authors reported implications for hatchery-reared fish, but not for wild, free-moving populations of fish. It should be noted that chronic exposure to a distorted magnetic field is not predicted under field conditions associated with the LEC. Further, this effect was not documented following transitory exposures to distorted magnetic fields, and salmonids have been observed to regain orienting abilities once removed from the distorted magnetic field (Taylor, 1986).

Physiological Responses

In addition to the study of behavioral effects, effects of magnetic fields on aspects of fish physiology or homeostasis have been studied. Lerchl et al. (1998) reported that a 40 µT (400 mG) magnetic field with a frequency of 1 Hz produced by current pulses of 200 ms on and 800 ms off) increased nocturnal melatonin levels in laboratory-exposed brook trout (*Salvelinus fontinalis*); melatonin governs sleep/wake cycles and other seasonal physiological rhythms in fish. It was suggested that either the magnetic field directly stimulated the pineal gland, causing a release of melatonin, or the magnetic-field exposure resulted in a stress response that eventually caused a release of the melatonin (Lerchl et al., 1998). The possible implications on fish health and fitness, however, were not addressed. Further, because the magnetic field was pulsed, it is possible that the observed responses were produced by electric fields induced in the fish when the field was turned on and off, an exposure scenario that is different from the LEC cables, which would not switch rapidly on or off.

More recently, Woodruff et al. (2012) examined the effects of 0.1-3 mT (i.e., 1-30 G) static magnetic fields on stress indicators of coho salmon (*Oncorhynchus kisutch*). Plasma cortisol levels in fish were unaffected by 80-hour exposures to magnetic fields. Melatonin levels in coho salmon were reduced by exposure to the 3.0 mT strength field, but were unaffected by 0.1 mT field exposures (Woodruff et al. 2012). The authors concluded that there was no evidence that magnetic fields elicited a stress response in exposed fish.

Early Life Stage Effects

Regarding fish early life stages, several studies have indicated that higher intensity static magnetic fields may affect fish eggs and larvae. Constant exposure to a 2 mT (20 G) magnetic field was reported to increase the permeability of salmonid eggs, resulting in a faster sinking rate (Sadowski et al. 2007). Conversely, magnetic-field exposures of 3 mT (30 G) did not affect the fertilization, hatching rates, or average developmental scores of rainbow/steelhead trout (Woodruff et al. 2012). Fertilization success was similar between unexposed eggs and eggs exposed to magnetic fields either 3 or 10 days post-fertilization; hatching success and days to hatch were similarly unaffected by magnetic fields of 3 mT (Woodruff et al. 2012). Salmonid embryos were also found to align to both natural and artificial magnetic fields (Formicki and Tanski, 2000; Formicki et al. 2001; Tanski, 2002). The embryos and larvae of both carp (*Cyprinus carpio*) and pike (*Esox lucius*) exhibited increased heart rates up to about 5% above average for 8-12 minutes when exposed to a constant 50-70 mT (500-700 G) magnetic fields, but then returned to baseline (Formicki and Winnicki, 1996; Winnicki et al., 1993). The authors noted that a weaker magnetic field did not produce the same effect. A similar stimulatory effect on the pectoral fin movement of brown trout (*Salmo trutta*) larvae was observed following exposure to the same strength field; this behavior also stabilized within minutes of exposure (Formicki et al., 1992). Rainbow/steelhead trout (*Oncorhynchus mykiss*) and brown trout eggs exposed to static magnetic fields between 1 and 13 mT (10 and 130 G) in the laboratory resulted in prolonged embryonic development and increased larval weight (Formicki and Winnicki, 1998). Tests with Atlantic halibut (*Hippoglossus hippoglossus*) and California halibut (*Paralichthys californicus*) larvae, however, indicated no adverse effects on larval survival, growth, or development (Woodruff et al., 2012). Given these results, the authors concluded that there was no evidence that exposures to less than 3 mT (30 G) would result in adverse impacts to fish survival, growth, or development. Larger, free-swimming salmonid larvae and fry were observed to preferentially swim towards a static magnetic field of up to 4.2 mT (42 G); older, more mobile fish exhibited a stronger response than yolk-sac larvae, which are weighed down by storage materials contained in the sac (Formicki et al., 2004). The authors surmised that this may have been an “investigative response” behavior triggered in young salmonids.

A summary of reviewed studies is presented in Table 9. It should be noted that the majority of these studies examined the effects of magnetic fields at 10-fold greater than those expected at the LEC (calculated to be between 1.568 and 2.885 G). Many of these studies found no significant effects on fish at these high exposure levels. In fact, only Lerchl et al. (1998) reported a significant physiological effect following exposure to a magnetic field similar to what might be found around the proposed LEC route (0.4 G). It is unclear, however, if increased melatonin levels in fish would cause adverse health effects or even if this effect would occur in a static field as opposed to the pulsed field tested by Lerchl et al.

Table 9. Summary of the observed effects and static magnetic field reported in the reviewed literature

Test Species		Field Strength (G)	Field Type	Endpoint	Significant Effect?	Reference
Eel	***Anguilla anguilla***	**0.05**	**60 m from DC cable**	**Swim behavior**	**No**	**Westerberg and Begout-Anras 2000**
Rainbow/ steelhead trout	***Oncorhynchus mykiss***	**0.4-0.5**	**Static magnetic (5-7 months)**	**Orientation**	**Yes**	**Putman et al. 2014b**
Brook trout	***Salvelinus fontinalis***	**0.4**	**Pulsed 1-Hz magnetic**	**Altered melatonin Levels**	**Yes**	**Lerchl et al. 1998**
Coho Salmon	*Oncorhynchus kisutch*	1–30	Static magnetic	Altered cortisol levels	No	Woodruff et al. 2012
Coho Salmon	*Oncorhynchus kisutch*	1–30	Static magnetic	Altered melatonin levels	At highest exposure	Woodruff et al. 2012
Rainbow/ steelhead trout	*O. mykiss*	10–130	Static magnetic	Altered larval development	Yes	Formicki and Winnicki 1998
Lake sturgeon	*Acipenser fulvescens*	15	60-Hz AC magnetic	Swim behavior	Yes	Bevelhimer et al. 2014
Salmonid eggs	*Salmonidae*	20	Static magnetic	Permeability and sinking	Yes	Sadowski et al. 2007
Rainbow/ steelhead trout	*O. mykiss*	30	Static magnetic	Embryo survival and development	No	Woodruff et al. 2012
Atlantic halibut	*Hippoglossus hippoglossus*	30	Static magnetic	Larval growth and development	No	
California halibut	*Paralichthys californicus*	30	Static magnetic	Larval growth and development	No	Woodruff et al. 2012
Brown trout	*Salmo trutta*	42	Static magnetic	Attraction/repulsion	Yes	Formicki et al. 2004
Snail	*Elimia clavaeformis*	364	Static magnetic	Attraction/repulsion	No	Cada et al. 2011
Clam	*Corbicula fluminea*	364	Static magnetic	Attraction/repulsion	No	Cada et al. 2011
Fathead minnow	*Pimephales promelas*	364	Static magnetic	Attraction/repulsion	No	Cada et al. 2011
Lake sturgeon	*A. fulvescens*	364	Static magnetic	Attraction/repulsion	No	Cada et al. 2012
Striped bass	*Morone saxatilis*	364	Static magnetic	Attraction/repulsion	No	Cada et al. 2012
Channel catfish	*Ictalurus punctatus*	364	Static magnetic	Attraction/repulsion	Potentially	Bevelhimer et al. 2014; Cada et al. 2012
Fathead minnow	*P. promelas*	364	Static magnetic	Movement	Yes	Bevelhimer et al. 2014; Cada et al. 2012
Redear sunfish	*Lepomis microlophus*	364	Static magnetic	Attraction/repulsion	Yes	Bevelhimer et al. 2014
Carp	*Cyprinus carpio*	500–700	Static magnetic	Increased heart rates	Yes (transitory)	Formicki and Winnicki 1996
Brown trout	*S. trutta*	500–700	Static magnetic	Increased pectoral fin movement	Yes (transitory)	Formicki et al. 1992

* Studies in bold reported magnetic-field strengths expected to occur under field conditions on the proposed route of the LEC.

Effects on Food Acquisition

In addition to direct effects on fish species, we considered whether the magnetic field of the LEC cables (as distinct from any physical disturbance due to cable installation) could impact the benthic habitat that supports a key food base for these species. The area of bottom habitat where the geomagnetic field is expected to be altered by the LEC, however, is a very small proportion of the total foraging grounds available to demersal fish (see discussion below). Further, a study conducted of a submarine DC cable in the Baltic Sea determined that benthic macroinvertebrate communities recovered within 1 year following the initial impact of DC cable system construction, indicating no long-term impact to resident invertebrates from the static magnetic field from the cable system (Andrulewicz et al., 2003). A similar conclusion was reached from post-construction monitoring studies of the ±300-kV DC Cross Sound Cable in Long Island Sound (S. Wood, personal communication).

In theory, the movement of fish and other objects through the geomagnetic field and the magnetic field around the DC cables can induce an electric field. The only lake species other than lampreys (order Petromyzontiformes) that may have the means to detect such signals are sturgeon (Normandeau et al., 2011). When exposed to a magnetic field about 100-fold greater than the maximum value predicted to occur above the proposed LEC cables, however, no evidence of behavioral attraction or repulsion of lake sturgeon was observed (Cada et al., 2011). Other sturgeon species have been reported to respond to weak DC and low frequency AC electric signals (Gill et al., 2012). Lake sturgeon, however, are reported to utilize multiple means of detecting benthic prey, including olfactory, tactile, and chemosensory cues, in addition to relying on electric signals from prey movement (Peterson et al., 2007). For instance, sturgeons are able to detect prey *via* taste bud-covered barbels that they drag through the sediment (Boglione et al., 1999). As such, Zhang et al. (2012) noted that although Siberian sturgeon (*A. baerii*) exhibited feeding behaviors in response to an aluminum pole with a peak-to-peak signal of 90 microvolts (µV), similar behaviors were induced though olfactory stimulation only; and a lower electric signal of 15 µV had no effect on sturgeon feeding behavior. In a marine species, an electric field of unreported strength produced by lanthanide metal repelled actively feeding juvenile Atlantic sturgeon (*A. oxyrhynchus*) (Bouyoucos et al., 2014). Other freshwater fish utilize visual and other sensory cues in pursuit of prey; for example, salmonids are primarily visual predators (Mazur and Beauchamp, 2003). In addition, the induced electric field from the LEC was conservatively calculated to be elevated for only 1 m around the cable for a fish swimming at 1.38 m/s, and the reported detection threshold for sturgeon is 20,000 µV/m when produced by a 0.1 Hz AC system (Basov 1999).[9] Sturgeon are expected to have a greater sensitivity to AC electric fields, which are produced by the movement of prey. Since the highest field level directly over the cables is less (466 µV/m) and produced by a DC source, it is not likely that prey detection would be affected by the magnetic field in the vicinity of the proposed LEC. Therefore, it is not expected that the cable would cause any food web related effects on fish populations.

Discussion

Although some behavioral and physiological responses have been noted in laboratory studies of fish exposed to static magnetic fields at high intensity, it is important to note that these effects are far less likely to occur, if at all, at the much lower magnetic-field levels expected around the LEC cables, and are unlikely to result in any significant impact on individual-level fitness or effects at the population-level. The lowest static magnetic-field intensity at which any fish response was reported in the studies described above was 10,000 mG (10 G); this level is well above the maximum static magnetic field modeled using conservative assumptions that will be produced above the LEC cables at the bottom of Lake Erie. Even exposures to magnetic fields 100 times greater than those calculated for the LEC are reported to elicit no response or only a minor response in fish species tested. Observed responses of adult fish to static magnetic fields (e.g., increased movement, variations in swimming behavior, attraction, changes in the hormone melatonin) are not clearly harmful to fish health and fitness, and typically reverse as the fish regains behavioral and physiological homeostasis following removal of exposure to an increased static magnetic field (Formicki and Winnicki, 1996, Bevelheimer et al., 2013) as would occur after the fish swim through the field. Additionally, the electric field induced by movement of sturgeon is calculated to be below the reported threshold of detection.

[9] It should be noted that the proposed LEC is a DC cable system, not an AC cable system.

Responses in early life stages (e.g., increased egg sinking rate, increased heart rate, and prolonged development) have also been shown to return to baseline after exposure ends (Sadowski et al., 2007; Formicki and Winnicki, 1996, 1998; Winnicki et al., 1993). It is unclear, however, how these changes could affect fish health and survival. Fish eggs and larvae are passively dispersed and experience naturally high rates of mortality (Dalhberg 1979); this, coupled with the very small area projected to be impacted by altered magnetic fields, indicates that a population-level impact is highly improbable. In some cases, a magnetic field has been reported to attract young fish through the triggering of an investigative behavioral response (Formicki et al., 2004). Tests were of short duration (2.5 hours), however, and therefore give no indication that young fish would become “ensnared” in fields and fail to respond to other biological cues (i.e., feeding or predator cues). Further, the magnetic fields documented to elicit such effects in fish were at least 10 times stronger than those predicted to occur on the proposed LEC route, and there is no evidence that a similar response would occur following exposure to weaker fields.

Animals (including fish), however, will integrate multiple orientation cues, with prioritization likely depending on environmental conditions (Able, 1991). Since fish behavior and orientation are governed by multiple factors and cues (including visual and olfactory cues), the evidence does not support a conclusion that weak static magnetic fields or induced electric-field signals would override other cues to the detriment of exposed fish. Hence, the investigative response triggered in fish at higher field intensities is unlikely to be prolonged at the expense of feeding, spawning, or other key behaviors.

Furthermore, the volume of water and area projected to be impacted by electric and magnetic fields from the underwater cable are very small in comparison to the total habitat used by the fish species of interest in Lake Erie, which primarily inhabit shoreline habitats to depths of less than 10 m. A single independent population of fish can inhabit all suitable habitats within a multiple kilometer radius; and as reported at Natureserve.org, for these species, all suitable habitats with 10 km will likely support a single interconnected population of fish (NatureServe 2015a-d). Hence, a cable generating increased magnetic field over a 5 m radius over most of the proposed LEC route would affect only 0.1% of the 10 km population range (i.e., 10 m affected over 10,000 m). Consequently, given the small proportion of habitat projected to be associated with a change in the geomagnetic field from the LEC, along with the minor and generally reversible nature of documented effects of static magnetic fields on freshwater fish, it is unlikely that the electric field from the buried cable will constitute any significant threat to resident fish populations in Lake Erie.

Conclusions

The calculations presented in this study describe the change in the background static magnetic field expected from the proposed LEC based on very conservative assumptions selected to yield the highest estimates of the change in the magnetic field. Since magnetic fields diminish rapidly with distance from the source, in all locations, a minimal effect on navigational equipment is expected. Furthermore, even in the direct vicinity of the transmission line, the calculated magnetic field is well below the recommended guidelines for exposure of the general public. Because calculations presented in this report represent conservative estimates, in more typical conditions, the potential change to the background magnetic field environment is expected to be less than described.

Regarding the potential interaction of the change in the magnetic field with fish, a review of the maximum post-construction static magnetic-field exposures and the research on the behavioral, migratory, physiological, and early life-stage responses of freshwater fish to static magnetic fields, including species of concern in Lake Erie—cisco, eastern sand darter, lake sturgeon, and steelhead trout—did not suggest that the LEC would sufficiently change the ambient static magnetic field in the very small portion of Lake Erie habitat around the proposed LEC to threaten the health or performance of these species. Except for one study involving an exposure unlike that associated with the operation of the LEC, other studies reported only no or very minor reactions to static magnetic fields more than 10-fold greater than calculated for the LEC operating at maximum power transfer loads. Regarding potential effects on migration, the change in the magnetic field is not a physical barrier and fish are known to use multiple sensory cues to guide behavior. In the studies reviewed, the responses were readily reversible. As for the electric field induced by fish movement through a static magnetic field, even an assumed high velocity of 1.38 m/s, some 10 times higher than reported, LEC was calculated to induce electric-field levels below the detection threshold of the only species of concern in Lake Erie with electrosensory capabilities.

In summary, the change in the static magnetic field associated with the operation of the proposed LEC is too small to pose a threat to freshwater species of concern in Lake Erie.

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Appendix A – Magnetic-Field Deviation and Compass Deflection Calculations

Each of the results presented in this report for Cases 1-3 represent one of two scenarios, determined by the direction of electrical current flow. For example, in Case 1, the western cable was chosen to carry the northward current and the eastern cable correspondingly carried the southward current. For each case, the polarity of the current was chosen to produce the largest net magnetic field and therefore to represent the most conservative estimate for magnetic-field deviation.

In this Appendix, results for Cases 1-3 with reversed current directions are provided. Magnetic-field deviations are shown in Figures A-1 to A-3 and are tabulated in Tables A-1 and A-2. Compass deviations are shown in Figures A-4 to A-6 and are tabulated in Tables A-3 to A-4.

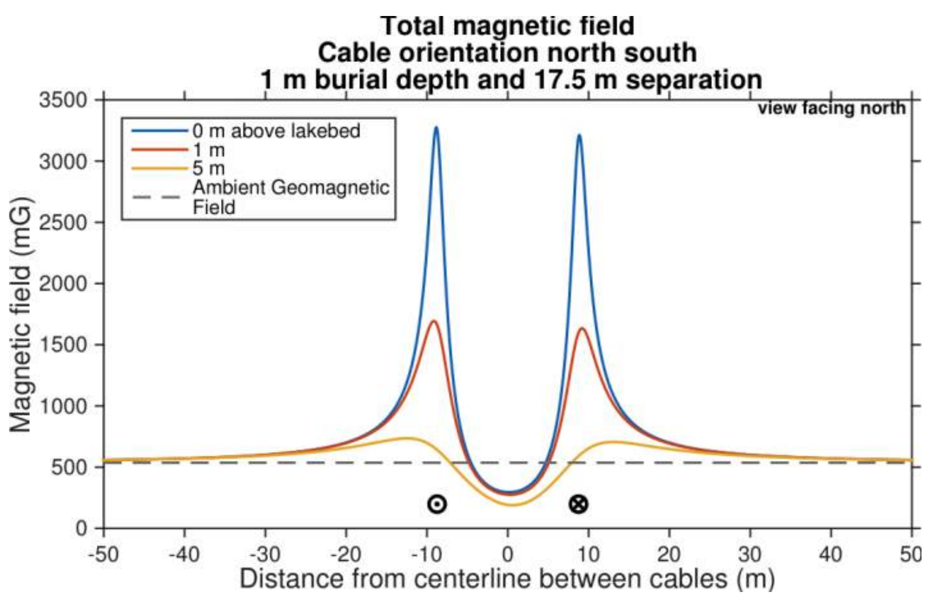

Figure A-1. Case 1. Calculated magnetic-field profile for cables oriented north-south and buried at a depth of 1 m. The cables are separated by 17.5 m.

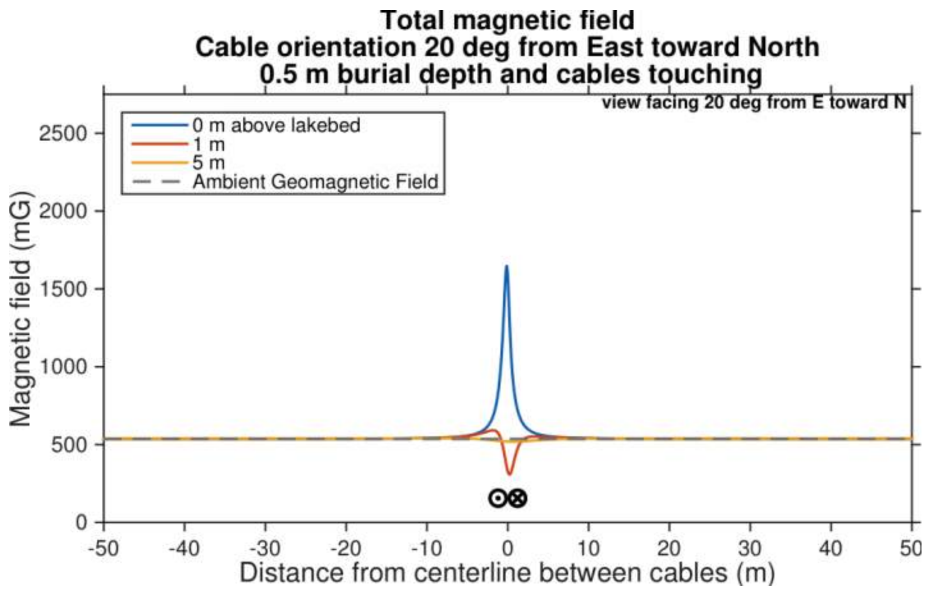

Figure A-2. Case 2. Calculated magnetic-field profile for cables strapped together, laid horizontally, oriented at 20° north of east, and buried at a depth of 0.5 m.

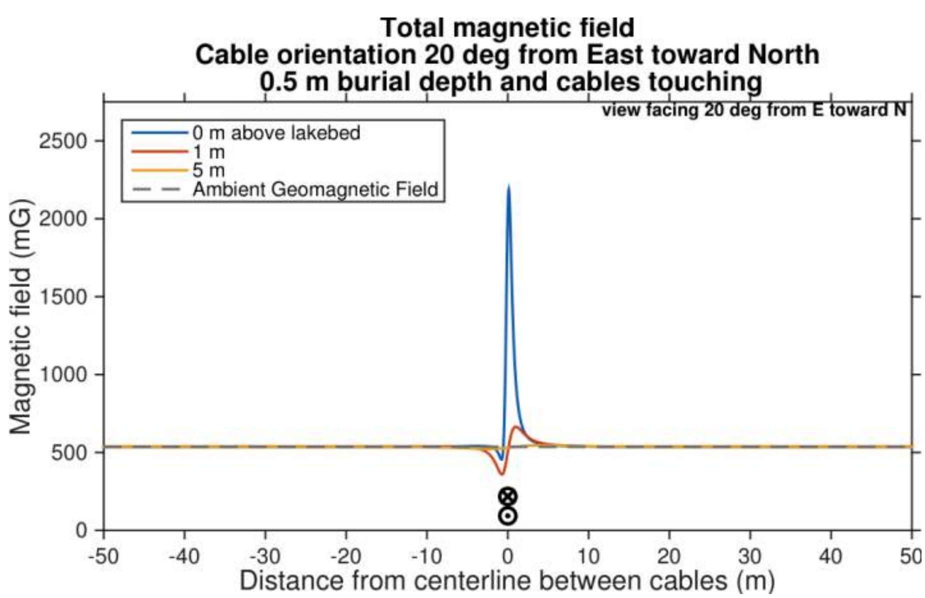

Figure A-3. Case 3. Calculated magnetic-field profile for cables strapped together, laid horizontally, oriented at 20° north of east, and buried at a depth of 0.5 m.

Table A-1. Deviation of magnetic-field (mG) from the geomagnetic field (536.35 mG) for Case 1, above the lakebed and at distances from the centerline of the bipolar DC circuit with cables oriented north-south

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deviation	Max - deviation	+5 m	+10 m	+15 m
Case 1	0	358	1763	73	2739	-241	52	1728	353
1 m (northward	1	335	1051	28	1157	-261	-10	1004	325
current, east side)	5	180	161	-149	199	-347	-203	117	160

Table A-2. Deviations of magnetic-field (mG) from the geomagnetic field (536.35 mG) for Cases 2 and 3, above the lakebed and at distances from the centerline of the bipolar DC circuit with cables facing 20° north of east

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deviation	Max - deviation	+5 m	+10 m	+15 m
Case 2	0	2.3	5.1	21	1109	0.1	18	4.7	2.1
0.5 m (eastward	1	2.3	5.2	19	55	-229	12	4.1	2.0
current, south side)	5	2.0	3.3	2.6	3.8	-17	-4.1	0.8	1.0
Case 3	0	0.7	1.4	3.8	1650	-81	11	2.4	1.0
0.5 m (eastward	1	0.4	0.4	-4.0	129	-177	16	3.2	1.2
current, top side)	5	-0.7	-2.4	-9.2	9.0	-14	8.6	4.0	1.8

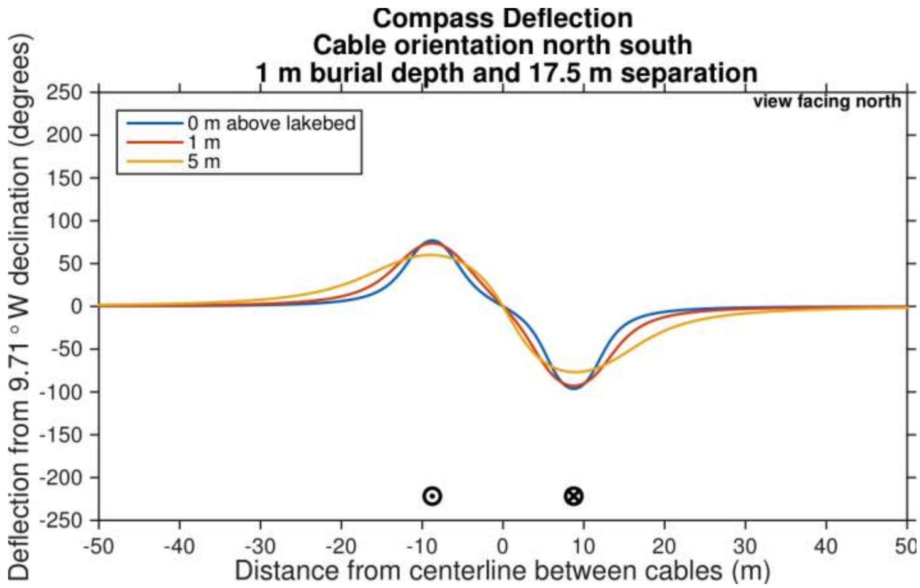

Figure A-4. Case 1. Calculated compass deflection (degrees) from 9.71°W declination above cables oriented north-south, separated by 17.5 m in the horizontal direction and with northward current in the eastern cable.

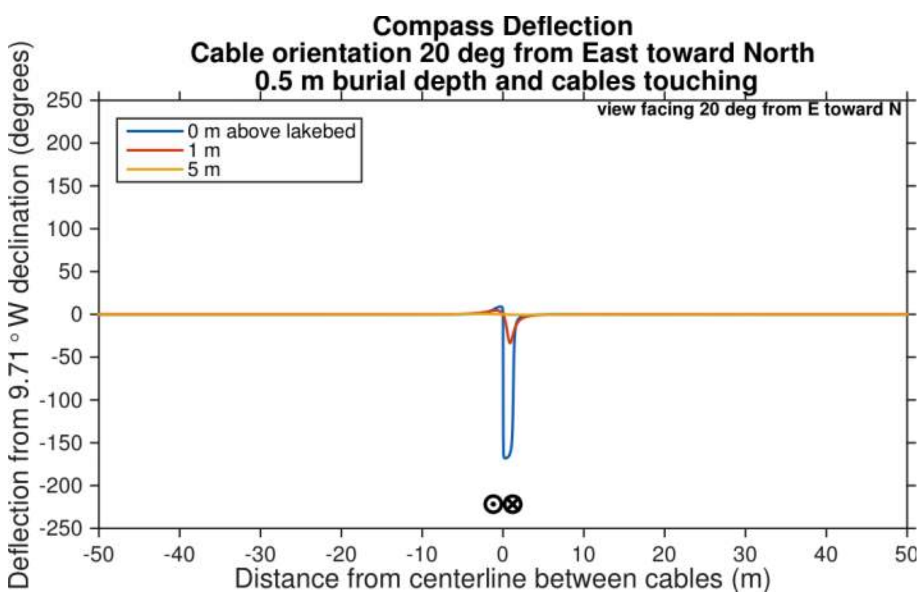

Figure A5. Case 2. Calculated compass deflection (degrees) from 9.71°W declination above cables directed 20° north of east, touching in the horizontal direction, and with eastward current in the southern cable.

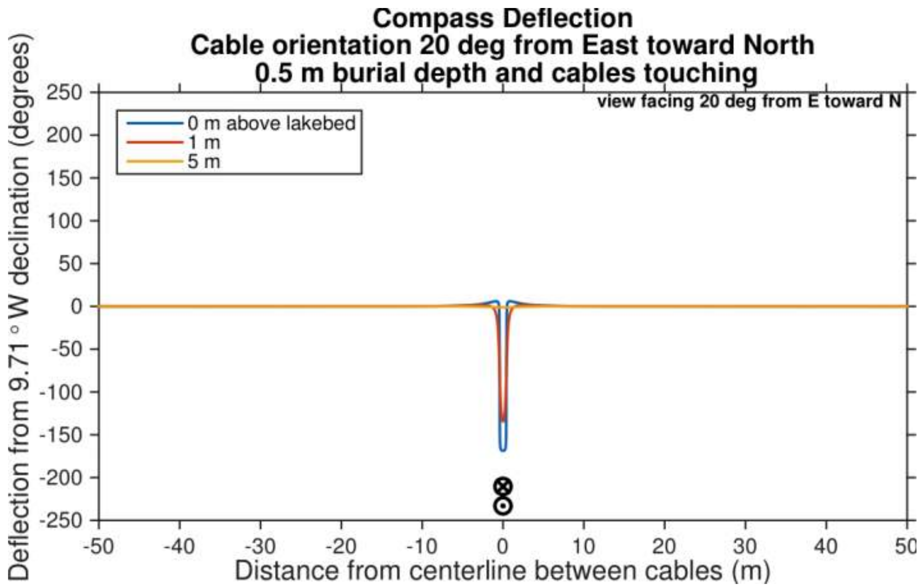

Figure A-6. Case 3. Calculated compass deflection (degrees) from 9.71°W declination above cables directed 20° north of east, touching in the vertical direction, and with eastward current in the top cable.

Table A-3. Compass deviation from 9.71°W declination for Case 1, above the lakebed and at distances from the centerline the of bipolar DC circuit with cables oriented north-south

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deflection	Max - deflection	+5 m	+10 m	+15 m
1 m (northward current, west side)	0	20	72	41	77	-96	-51	-91	-22
	1	32	71	52	74	-93	-67	-90	-39
	5	44	60	51	60	-77	-65	-76	-55

Table A-4. Compass deviation from 9.71 °W declination for Cases 2 and 3, above lakebed and at distances from centerline of bipolar DC circuit with cables oriented 20° north of east

Cable burial depth and phasing	Height above lakebed (m)	Distance from circuit centerline							
		-15 m	-10 m	-5 m	Max + deflection	Max - deflection	+5 m	+10 m	+15 m
0.5 m (eastward current, north side)	0	0.0	0.0	0.2	9.0	-168	-0.2	0.0	0.0
	1	0.0	0.1	0.5	4.6	-34	-0.6	-0.1	0.0
	5	0.1	0.2	0.5	0.6	-0.6	-0.5	-0.2	-0.1
0.5 m (eastward current, bottom side)	0	0.1	0.3	1.0	6.0	-169	1.0	0.3	0.1
	1	0.1	0.3	0.8	1.4	-134	0.8	0.3	0.1
	5	0.1	0.1	0.0	0.1	-1.0	0.0	0.1	0.1