Potential Ecological Impacts of Crude Oil Transport in the Great Lakes Basin

Prepared by the
Great Lakes Science Advisory Board
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Energy Transport and Water Quality Work Group

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Executive Summary

Environmental threats associated with the transport of crude oil[1] in the Great Lakes basin are drawing increasing attention. Issues of potential relevance include extensive use of pipelines and rail transport within or near the Great Lakes basin, several high profile oil spills in or near the region over the past decade, and increasing oil production in source regions such as North Dakota, Montana and Alberta, much of which is transported through or near the Great Lakes basin to meet energy demands across the continent and beyond. This ongoing transport of crude oil has highlighted the need to better understand potential threats to regional aquatic ecosystems and the region's preparedness to respond to spills.

Accordingly, the International Joint Commission's Science Advisory Board (SAB) Science Priority Committee undertook a synthesis of the science related to observed and potential impacts of crude oil on Great Lakes water quality and ecosystem condition and identified additional research, monitoring and information needs, including recommendations associated with high priority science gaps.

This science synthesis includes a focus on ecological exposures and effects and vulnerabilities to oil spills in the region, but did not include an analysis of risk - i.e., including the likelihood of a crude oil release and subsequent exposures and effects. This project was completed with the assistance of an expert work group (including SAB and external members), a contractor, LimnoTech, that produced a technical report[2], and International Joint Commission (IJC) staff.

For crude oil in general, three key physical properties are density, viscosity (or "thickness" of the oil), and flash point (or the lowest temperature at which the oil will catch fire with an ignition source). In addition to these physical properties, chemical composition can vary between crude oil types, and both physical and chemical attributes can influence oil transport, potential ecological impacts, and in turn, choices of preparedness and response actions. Crude oil can be extracted via "conventional" and "unconventional" production, with increasing North American production in the past two decades of the latter, including from low permeability oil formations and oil sands.

Assessments of the exposure to oil requires consideration of the locations and potential magnitudes of spills, and hence transport modes. Based on available data, pipelines are the dominant mode of crude oil transport through or near the Great Lakes basin, followed by rail transport. No crude oil is transported by ship on the Great Lakes, although barge transport occurs downstream on the St. Lawrence River. Though shipping of refined products such as fuel oils occurs on the lakes, impacts of such spills are not considered in this review.

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[1] A formal definition of crude oil is "A mixture of hydrocarbons that exists in liquid phase in natural undergrounds reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities" (EIA 2018a). This report uses "crude oil" as synonymous with "unrefined liquid hydrocarbons," in either case umbrella terms for various types of crude oils and their mixtures (e.g. light crude, heavy crude, diluted bitumen, synthetic crude oil, etc.) The report does not consider refined hydrocarbons (e.g. fuel oil, gasoline, diesel, etc.), nor natural gas liquids.

[2] The technical report, LimnoTech, 2018. Impacts of Unrefined Liquid Hydrocarbons on Water Quality and Aquatic Ecosystems of the Great Lakes Basin, is available at www.ijc.org.

In assessing potential ecological effects of oil spills and potential approaches to response, it is critical to first understand the transport and fate of spilled oil. Once released, oil can be subject to many processes, including spreading, evaporation, dispersion, dissolution, sedimentation (including via attachment to particles) and biodegradation, with the potential for multiple processes acting on the same spill material. An additional important phenomenon is "weathering" of oil, or physical, chemical, or biological processes affecting the oil after a spill; for example, evaporation of lighter oil components can eventually lead to an increase in density of the remaining oil sufficient to lead to sinking in water. Additional issues of concern in the Great Lakes include the potential for riverine spills to move into the lakes, complex currents that can change over short time spans (e.g. in the Straits of Mackinac), as well as seasonal factors including winter ice cover. All of these issues must also be considered in response planning.

This study assessed potential ecological impacts of oil spills in the Great Lakes basin. Much of what is known derives from major spills in ocean/coastal areas, including the Exxon Valdez tanker spill in Prince William Sound in Alaska in 1989 and the Deepwater Horizon offshore drilling rig accident in the Gulf of Mexico in 2010. Both accidents released large quantities of crude oil into marine systems and impacted various aquatic habitats and species, with research (including on more subtle impacts) continuing to this day. Though spills of similar magnitude have not happened in the Great Lakes basin, one of the largest freshwater inland oil spills on record in North America occurred in July 2010, when a pipeline rupture released approximately 24,000 barrels of crude oil into a tributary of the Kalamazoo River near Marshall, Michigan. This led to a cleanup effort costing over $1 billion. A major rail accident and spill in July 2013 took place in Lac-Mégantic, Quebec (close to the broader Great Lakes – St. Lawrence region), with the accident and resulting fire leading to fatalities and significant damage to the town, along with downstream transport of spilled oil.

The toxicity of oil to aquatic species depends on a number of factors including the chemical and physical characteristics of the oil, the type, extent and duration of exposure to oil (or individual components), and the sensitivity of the organisms themselves. Exposure must account for multiple potential pathways and consider lethal and sublethal endpoints. While for a number of years the focus of research was on exposure to bulk oil (e.g., as quantified through total petroleum hydrocarbons), more recent work has focused on groups of compounds in oil, including aliphatic compounds (such as pentane), aromatic compounds (such as benzene and polycyclic aromatic hydrocarbons, or PAHs), resins, and asphaltenes. Increasing research has involved use of biomarkers as indicators of oil exposure and effects. An additional important factor in assessing oil exposures is time and the potential for acute or chronic exposures and impacts, as well as the potential for those to change following weathering (leading to changes in composition of the remaining oil).

Based on a review of limited research in the Great Lakes basin and more extensive work in the case of other spills and studies, key findings from this assessment on potential oil spill impacts on groups of organisms of relevance in the Great Lakes include:

- Lower food web: Phytoplankton can be affected by shading of light (from oil on the water surface) as well as direct toxicity from PAHs and other compounds. Some studies on zooplankton have shown oil can cause acute toxicity, while other studies have suggested some zooplankton can metabolize PAHs.

- Bottom sediment organisms: Benthic invertebrates can exhibit direct toxicity from oil, and some studies have documented changes in relative abundance of individual species.
- Fish: Issues of concern for fish include multiple exposure routes, impacts of bulk oil versus components, and age, with impacts such as deformities and developmental delays possible following early life stage exposures.
- Amphibians and reptiles and semi-aquatic mammals: There has been very limited research in general on these groups of animals in freshwater environments, though some research in marine systems has shown impacts on sea turtle embryo survival following oil exposure.
- Birds: Oil exposure for birds can occur via multiple routes, including direct contact and ingestion in particular during early stages following a spill, and larger ocean/coastal oil spills have resulted in significant mortality for certain birds. As is the case with other organism groups, there is much less research on impacts from freshwater spills.

In addition to impacts to individuals and populations within the above groups, there is also the potential for more far-reaching (e.g. food web) impacts associated with oil spills, as was seen in the case of both the Exxon Valdez and Deepwater Horizon spills, whether resulting from changing human management (e.g. fishing restrictions) or decreased predation on certain fish populations.

The size and complexity of the Great Lakes basin makes identifying areas of greatest vulnerability to a crude oil spill challenging. This assessment used the proximity or intersection of key ecological features with oil transportation corridors or likely spill movement pathways to develop a preliminary and qualitative list of more vulnerable locations. Key ecological resources were identified based on tributary locations, biodiversity reports and maps, and the knowledge that much of the biological productivity and diversity within the Great Lakes basin is concentrated in the coastal zones. Oil transportation corridors, refining locations and storage sites are well documented in the region. Based on this information on ecological features and oil transport or processing infrastructure, 15 areas of higher ecological vulnerability to crude oil spills were identified. All water (including tributary) crossings by any transport mode, as well as downstream reaches scaled by spill volume hazard, would also be considered vulnerable. For example, oil transport via rail (crossing several tributaries) along the southern shore of Lake Erie indicates greater vulnerability of habitats in that area as compared to the north shore of Lake Erie, without a similar rail corridor. Similarly, areas with pipelines crossing through or under connecting waters (e.g. Straits of Mackinac, Huron-Erie Corridor) would be considered vulnerable. It is important to note that this vulnerability analysis was not a quantitative risk assessment, but rather based on spatial correlation of sensitive or important habitats with potential oil sources. Furthermore, though the 15 areas were all considered more vulnerable in this assessment, they should not be considered equivalent in terms of vulnerability.

Monitoring and modeling are both important in assessing potential impacts of and effectively responding to oil spills in the Great Lakes basin. Monitoring can be done for bulk oil and constituents, and technologies for both (including *in situ* monitoring of oil via fluorometers) have advanced in recent years. Modeling has also advanced, with increasing use of hydrodynamic models to predict potential transport and fate of hypothetical oil spills over multiple scales (e.g., in the Straits of Mackinac). Though available, ecological exposure and effects models have not been used extensively in addressing oil spill threats and there is a need to couple these models with hydrodynamic models.

In addition to the many factors influencing the transport, fate, exposure and effects of oil following a spill, an important consideration influencing ultimate impacts is the human response. Oil spill response planning occurs in the United States and Canada under statutes such as the US Oil Pollution Act and the Canadian Fisheries Act, and there is also binational coordination, including via the Joint Marine Pollution Contingency Plan. Even in the case of spills within one country, extensive coordination between multiple entities is important; for example, the Kalamazoo River oil spill entailed coordination between the pipeline owner (Enbridge Energy), multiple federal and state agencies, and local and tribal governments.

The success of a given response will depend on varying factors, including the nature of the spill itself (type of oil, specific location, subsequent weathering, etc.) and the efficiency of the response actions. Multiple potential response actions can be pursued (often in combination), including use of booms, skimmers, in situ burning, dispersants, solidifiers, and sorbents. Given specific considerations in the Great Lakes (in particular use of the waters as drinking water supply for millions of people), Great Lakes governing bodies do not currently promote the use of dispersants in the case of an oil spill.

Another issue of regional relevance is the potential for spills in winter (and ice cover), which is considered in planning and spill response exercises. Other aspects of response include cleaning and rehabilitating affected individual organisms, which has had relatively high success rates (concerning animals treated) in some spills. Finally, there is increasing research examining the issue of ecological resiliency, or the capacity of ecosystems to respond to disturbances while maintaining some semblance of original structure and function. Some research following oil spills has found evidence of resiliency for individual species or habitats, though more research is needed.

A comprehensive assessment of ecological risk from crude oil transport was beyond the scope of this analysis. Such a risk assessment would require detailed and quantitative consideration of types of hydrocarbons; amounts transported by various transportation modes and volume, location, and likelihood of release; modeling of transport and fate of released oil; and a fine-scale spatial analysis of potential spill impacts, considering post-spill weathering and response actions. A broader impact assessment would also consider other components, including socioeconomic impacts and traditional/indigenous knowledge. This report presents a science synthesis of ecosystem vulnerability to oil spills in the Great Lakes, drawing on the technical report for this project (LimnoTech 2018) to identify key types of oils of concern in the region, major transportation modes and locations, sensitive organisms, habitats, and locations of greater vulnerability. While a number of questions remain on risks from crude oil spills in the Great Lakes basin, the topic is receiving increasing attention from a number of organizations and governments concerned with the health of the Great Lakes, and this analysis can help inform other work, including more comprehensive risk assessments.

Recommendations

Recommendations to improve understanding of potential impacts of crude oil spills on water quality and ecosystems of the Great Lakes basin region, and application to management decisions on oil transport, including approaches to prevent and/or respond to spills, include the following:

- **Recommendation #1**: To increase the ability to identify areas potentially vulnerable to oil spills, the Parties (i.e., federal governments) should identify opportunities to increase availability of data on petroleum infrastructure, including spatial data and transport and storage volumes, whether broadly to the public (as security requirements allow) or to researchers and other interested parties with appropriate disclosure agreements.

- **Recommendation #2:** To enhance spill response planning and preparedness, researchers should carry out further analysis and modeling on the potential transport and fate of the multiple crude oil types transported in the region, with particular emphasis on the vulnerable areas identified in this report.

- **Recommendation #3:** To address the relative paucity of scientific knowledge on the potential impacts of crude oil on freshwater environments, agency program managers should encourage, and researchers should pursue, additional emphasis on investigations into exposures and effects of the multiple crude oil types that are currently transported in the region on ecosystems and organisms. This includes investigations on the toxicity of oil components (such as PAHs and chemicals in diluents), in particular those found in dilbit and other blends, and further exploration of the use of biomarkers in assessing exposures and effects.

- **Recommendation #4:** To appropriately site future oil transportation developments/infrastructure and for species conservation purposes, agency program managers should encourage and researchers should pursue assessments with regards to exposure, sensitivity and adaptive capacity (and hence vulnerability) that include a focus on species of particular cultural and/or conservation concern in the Great Lakes (e.g., fish species such as walleye, lake trout and lake sturgeon), especially those species that may be present in vulnerable areas.

- **Recommendation #5:** In order to better understand the vulnerability to direct and indirect oil exposure for all life stages of less-well-studied freshwater taxa, agency program managers should encourage and researchers should pursue further work on toxicological assessments of amphibians and reptiles, and semi-aquatic mammal populations in Great Lakes tributaries.

- **Recommendation #6:** To support spill response activities and manage for short- and long-term exposure to fish and other organisms following an oil spill, agency program managers should ensure development (or updating, as appropriate) and sharing of detailed habitat and biological sensitivity maps, including baseline surveys, on a binational basis.

- **Recommendation #7:** To reduce vulnerabilities of higher value habitats and inform spill response planning and preparedness, agency program managers should support assessments of how spills from pipeline and rail crossings and nearshore routes might impact river ecosystems and downstream Great Lakes habitats, including seasonal variation, on a binational basis.

- **Recommendation #8**: Agencies in both countries should expand coordinated monitoring for oil and its components in the Great Lakes ecosystem, including development of real-time systems to ensure early identification of spills. An effort similar to the earlier Huron to Erie Drinking Water Monitoring Network could serve as a pilot, and any such effort should consider opportunities to inform both ecological and human exposures to oil as well as response actions.

- **Recommendation #9**: Agencies should continue to support development of oil spill models, including with application for vulnerable areas and species identified in this assessment. Furthermore, agency program managers and researchers should expand development of ecotoxicological and food web models to accompany existing hydrodynamic models, and to help in identifying both more vulnerable areas and species as well as preventative and response actions.

- **Recommendation #10**: All relevant agencies as well as industrial oil spill response teams should continue their oil spill response planning, training and action coordination through respective Coast Guards, and ensure planning is taking into account various contingencies possible in the Great Lakes, including related to seasonal factors such as ice cover as well as complications related to oil weathering and potential submergence.

- **Recommendation #11:** Further research is needed on potential vulnerability of Great Lakes habitat and species to oil spills in light of other (including interacting) ecosystem stressors, and any potential implications for ecosystem resiliency.

- **Recommendation #12:** To inform spill planning and preparedness and spill response activities, basinwide monitoring and modeling should be coordinated to maximize integration of geospatial data on lake and watershed ecosystems with hydrodynamic models and ecotoxicological/food web models.

1.0 Introduction

Crude oil[3] is one of the key primary sources of energy for a variety of sectors in North America, and refined products are widely used in the chemicals, plastics and other industries. The rapid increase in oil production in the central northern United States and western Canada since 2010, and ongoing transport of crude oil and related material through or near the Great Lakes region[4] have emphasized the need to understand the environmental hazards posed by crude oil transportation. Petroleum can enter the aquatic environment in multiple ways, including via natural seeps (not known to be present in the Great Lakes), accidental release of oil during extraction, and accidental release of oil while in transport, storage or processing. Oil spills can occur on land and in water. Oil spills on land can spread into wetlands, rivers, lakes and streams, or contaminate underlying aquifers (GLC, 2015).

Potential ecological impacts of oil spills in the Great Lakes region have been of interest to policymakers and researchers for several decades, and recent work has included projects focused on oil transport by the Great Lakes Commission (GLC, 2015), contracted assessments through the Michigan Pipeline Safety Advisory Board, and scientific review of ecological impacts of oil spills (Perhar and Arhonditsis, 2014). In 2006, the International Joint Commission (IJC) released a report on oil and other hazardous materials spills, with a focus on the Lake Huron – Lake Erie Corridor (HEC) (IJC, 2006). The report made six recommendations concerning broad information sharing between parties, discharge data reporting, monitoring, spill prevention and response approaches, public communications, and coordination of programs, including through the Great Lakes Water Quality Agreement (GLWQA).

A well-established approach to examining human disturbances to ecosystems, including oil spills, is via ecological risk assessment. In ecological risk assessment, a common approach uses a problem formulation step, an analysis step, and a risk characterization step (see Figure 1-1 below for approach used by U.S. Environmental Protection Agency (USEPA)). The analysis step characterizes exposure and ecological effects for the substance of interest (in this case oil or its components). A determination was made in the earliest stages of this project to focus on the potential impacts posed by crude oil spills – so for example, characterizing the stressor (crude oil), the components of the ecosystem in the Great Lakes, and relevant effects information (including from releases elsewhere). As part of this work, a qualitative assessment of ecological vulnerability to oil spills in the region was carried out by the contractor. Components of such assessments typically include exposure, sensitivity, and adaptive capacity (of organisms or habitats). Table 1-1 provides definitions for several terms used in this report.

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[3] As indicated in footnote 1, the term “crude oil” is used synonymously with “unrefined liquid hydrocarbons,” and includes normal crudes, shale oil, diluted bitumen and synthetic crude/bitumen blends.

[4] Consistent with International Joint Commission’s responsibilities under the Great Lakes Water Quality Agreement, the geographic scope of this analysis includes the Great Lakes and upper St. Lawrence river to the international boundary between Canada and the United States (approximately located at Cornwall, Ontario and Massena, New York), the region alternatively referenced as “Great Lakes basin” or “Great Lakes region” in this report. Note occasional reference in this report to the broader Great Lakes-St. Lawrence region (which as defined here, extends further downstream to Montreal).

Accordingly, the focus of this assessment is on the potential impacts of oil spills on Great Lakes habitats and organisms. This review did not consider potential human health concerns, socioeconomic impacts, or impacts otherwise to First Nations/Tribes associated with oil spills. Furthermore, other components that would be part of a comprehensive ecological risk assessment, such as the probability of a spill from specific transportation infrastructure in the region, were not considered.

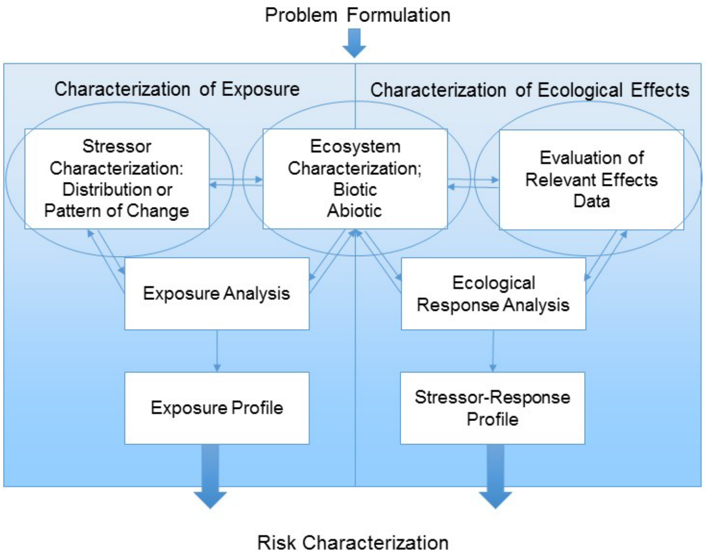

Figure 1-1. Components of ecological risk assessment (adapted from US EPA, 1992). This project emphasized the top three circled boxes.

Table 1-1. Key terms involving exposures and effects of environmental substances*

Term	Definition
Hazard	Threatening event, or potential for occurrence of a damaging phenomenon
Exposure	Contact of an organism with a chemical, physical, or radiological agent.
Toxicological sensitivity	Extent to which species (or processes) experience the effect of substances
Vulnerability	Degree to which a system is susceptible to, and unable to cope with, harm
Risk	Expected losses due to a particular hazard for a particular area and reference period
Resilience	Capacity of a system to resist a disturbance, and return to an “equilibrium” state of the system.

*: Drawn from De Lange et al. (2010). Note “adaptive capacity” is considered synonymous with “resilience” or “recovery potential” in De Lange et al. (2010). Note also that all of these terms can be applied to oil or its components (as done in LimnoTech, 2018). Also note potentially different definitions for some of these terms in the ecological risk assessment literature. A recent white paper briefly reviews risk in the context of Great Lakes oil spills (Polich et al. (2017).

This report, drawing heavily on the technical report for this project (LimnoTech, 2018), provides an overview of the science related to observed and potential impacts of crude oil releases on Great Lakes water quality and ecosystem condition, and identifies additional research, monitoring and information needs. This synthesis consists of a number of related elements, each of which is addressed in subsequent sections of the report:

- Overview of crude oil, its properties, transport modes in the Great Lakes region,[5] and environmental cycling of oil,
- Crude oil ecological exposures and effects
- The Great Lakes basin, and areas potentially vulnerable to oil spills
- Monitoring, modeling, oil spill response and ecosystem resiliency
- Overall assessment of potential oil spill impacts in the Great Lakes basin
- Summary of recommendations.

This project included meetings of the Work Group, comprised of 22 subject matter experts from diverse sectors (see Acknowledgments), development of the contract technical report (LimnoTech, 2018), and development of this synthesis report. This report is intended to help inform IJC advice to the Parties to the GLWQA on issues involving oil spills, including highlighting potential impacts from oil spills to components of the Great Lakes ecosystem, informing management decisions related to spill prevention planning and preparedness and spill response, and highlighting knowledge gaps that deserve attention from the science community through ongoing and new research activities.

2.0 Crude oil, its properties, transport modes in the Great Lakes region and environmental cycling

Crude oil is a natural or moderately altered (diluted or blended) mixture of hydrocarbons which is typically liquid, but can include gasses, waxes, solids or tars (see Table 2-1 for definitions of crude oil and related terms). Liquid hydrocarbons extracted from geological formations by drilling, mining or other means are referred to as natural gas. Though the distinction changes with time, oil production can be divided into conventional means (e.g. traditional vertical drilling into a relatively permeable formation in which oil flows naturally to a wellbore) and unconventional approaches developed in more recent decades (e.g., *in situ* processing of oil sands, and the combination of horizontal drilling and hydraulic fracturing). Unconventional oil production also often entails use of additional hydrocarbon liquids to facilitate product transport (see Table 2-1).

Crude oil is commonly refined into more useful products such as gasoline, diesel fuel, kerosene, and liquefied petroleum gas. This report does not consider the potential ecological impacts of refined products, including heavy oils, which are used as fuels for heavy industry adjacent to the lakes, used in marine transportation, and shipped in bulk on the lakes. In addition, natural gas liquids, with multiple uses, including as diluent for oil sand bitumen, were also not considered in this report.

Crude oil is primarily comprised of hydrocarbons (molecules consisting of only carbon and hydrogen) and to a lesser extent, compounds which include nitrogen, oxygen or sulfur. Additionally, small amounts of metals, minerals and dissolved gases (e.g., hydrogen sulfide) are often present in crude oil. Most oil is derived from organic matter in geological formations that originated as the remains of aquatic plants, animals and microbes.

Crude oil can be composed of thousands of compounds. In addition to variable characteristics of different crudes, the many crude oil constituents themselves can have highly variable physical-chemical properties, which in turn have implications for their environmental behavior, fate and effects (Lee et al., 2015, Mayer et al., 2013; NASEM, 2016). Three key physical properties of crude oil are density, viscosity and flash point, and ranges of values for each property for several types of oil are given in Table 2-2. Density determines whether oil will float or sink in water and can vary by oil type and with time (e.g., following a spill). A related parameter is API gravity, which is a measure of density commonly used in the oil industry (see Table 2-1). Viscosity is a measure of the fluid's ability to resist shear or tensile (stretching) forces; higher viscosity fluids would be both more challenging to transport and less readily spread on a surface (e.g. following a spill). Flash point is the lowest temperature at which a substance will ignite in the presence of an ignition source. As indicated in Table 2-2, "light crude" has generally lower density, viscosity

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[5] As noted in footnote 4, the focus of this report is the Great Lakes basin, though given broader issues involving oil transport and potential spill impacts, the broader Great Lakes – St. Lawrence region is occasionally referenced.

and flash point than “heavy crude.” Diluted and synthetic bitumen generally are more similar to heavy crudes in physical characteristics. All three physical properties are important in affecting the transport and fate of bulk oil following a spill, as well as response approaches. In addition, as discussed later, it is important to note all three parameters can change with time following a spill (e.g., as lighter components evaporate, the remaining oil would typically become more viscous and dense, and potentially sink in some scenarios).

2.1 Crude oil production in North America

In North America, oil production has increased substantially in the last decade, and production is predicted to continue to increase in the near-medium term in the United States and Canada (EIA, 2017; NEB, 2017). Production has increased in both countries in particular due to advances in extracting and processing unconventional oil (e.g., oil shale and oil sands).

In Canada, oil production is now dominated by heavy oil from the oil sands of Alberta, which is recovered as bitumen (see definition in Table 2-1) by surface mining or subsurface *in situ* methods. The bitumen extracted is upgraded to synthetic crude oil or diluted with lighter oils or other hydrocarbons to facilitate transport. Much of the crude oil produced in Canada is either sent to the United States via pipeline and rail for further refining, or passes through the country on its way to back to Canadian refineries in Ontario, Quebec and New Brunswick. Oil sands production has more than doubled since 2006 and is expected to continue to grow through 2030 (Capp, 2017).

Table 2-1. Selected terms related to crude oil*

Term	Definition
Crude oil	Mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities; can also include other components
Conventional oil and natural gas production	Crude oil and natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore
Unconventional oil and natural gas production	Umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production; at any particular time, multiple factors influence what is considered “unconventional”
API gravity	Arbitrary scale (developed by American Petroleum Institute) expressing density of petroleum products (expressed as “degrees API gravity”). The higher the API gravity, the lighter the oil
Light crudes	Crude oil with API gravity above approximately 30 degrees
Heavy crudes	Crude oil with API gravity below approximately 22 degrees
Bitumen	Naturally occurring viscous mixture, mainly of hydrocarbons heavier than pentane, that may contain sulphur compounds and that, in its natural occurring viscous state, is not recoverable at a commercial rate through a well
Diluent	Lighter viscosity petroleum products used to dilute bitumen for pipeline transport
Diluted bitumen (or dilbit)	Bitumen reduced in viscosity via addition of a diluent (e.g. naphtha) to facilitate transport

Synthetic crude oil (SCO) or syncrude	Upgraded bitumen that resembles light, sweet crude oil
Synbit	A syncrude and dilbit mixture
Neatbit	Nearly pure bitumen (with small fraction diluent), transported by rail
Railbit	Bitumen with larger fraction diluent (and moderate viscosity), transported by rail
Tight oil	Oil produced from petroleum-bearing formations with low permeability such as the Eagle Ford, the Bakken, and other formations that must be hydraulically fractured to produce oil at commercial rates; shale oil is a subset

* Drawn from LimnoTech, 2018; Birn et al., 2014; CAPP, 2017; Fingas, 2011; Lee et al., 2015; EIA, 2018a; EIA, 2018b. Note that some terms have overlapping scope and definitions can vary slightly by source (e.g., categorization of crudes based on API gravity).

Table 2.2. Physical properties of crude oil

	Light Crude	**Heavy Crude**	**Diluted and Synthetic Bitumen**
Viscosity (cSt)*	5 to 50	50 to 50,000	200 to 350
Density (g/mL)	0.78 to 0.88	0.88 to 1.00	0.91 to 0.94
API gravity (degrees)**	30 to 50	10 to 30	19 to 22
Flash Point (degrees C)	-30 to 30	-30 to 60	<-5

From LimnoTech (2018), compiled by Fingas et al. (2011) and other sources. *: Kinematic viscosity, with units in centistokes (water at 20° C (or 68°F) has a kinematic viscosity of about 1 cSt); **: See definition in Table 2-1. Note that other terms can be used as well, e.g., “medium crude” for oil with characteristics intermediate between light and heavy crudes.

In the United States, while the Gulf of Mexico region has been a significant source of crude oil for many years, the use of horizontal drilling and hydraulic fracturing has significantly increased crude oil production in shale rock formations elsewhere, such as the Eagle Ford (Texas) and Bakken (Montana and North Dakota) that were previously not economical to exploit (EIA, 2017). The most recent EIA forecasts project that this “tight oil” production will continue to dominate domestic production until 2050, with production stabilizing between 11 and 12 million barrels per day by the mid-2020s (EIA, 2018c). In the Great Lakes states, there are also small oil reserves in Ohio, Pennsylvania, New York, and limited oil production in northern Michigan (GLC, 2015). However, virtually all crude oil transported to and through the Great Lakes basin originates from outside of the basin.

2.2 Crude oil transport modes

The growth in North American oil production has led to substantial increases in infrastructure investments to provide ways to transport more oil over long distances, including construction of new pipelines and reversal of flow configurations in existing pipelines. Oil transport to or through the Great Lakes basin has been increasing in the past two decades given the recently developed sources of oil to the west, as noted above, and major refineries, terminals, and markets to the east and south of the basin (see Figure 2-1 on following page) (also see review in Graziano et al., 2017). Though much of this oil is refined outside the Great Lakes basin, major refineries are present in the basin, including in Superior, Wisconsin; in the Illinois-Indiana region south of Chicago; in Sarnia, Nanticoke, and near Toronto, Ontario; in the Detroit-Toledo region; in Lima, Ohio; and in Montreal, Quebec (Figure 2-1).

In total there are 11 refineries in the Great Lakes basin and another dozen within the broader Great Lakes-St. Lawrence region (Hull, 2017) that have a combined crude oil refining capacity of over 3 million barrels (480,000,000 L) per day. In addition to considering transport modes (with varying potential spill volumes, and thus risk implications), refineries, terminals, and storage facilities can generate large-volume spills, including unrefined and refined hydrocarbons. These facilities are also often located in areas that are already extensively developed and subject to many other stressors.

Due to varying reporting requirements and practices, exact oil quantities shipped by various modes in the region are not readily available (especially for rail), though a recent assessment indicated pipeline shipment of crude oil is likely more than double that of rail (Hull, 2017; see further discussion in Section 2.2.2), which is consistent with data at a broader scale on oil transport compiled by the Energy Information Administration (EIA, 2018d). Multiple factors can influence the actual amounts of oil shipped via pipelines in the region, including pipeline capacity both in and out of the region, regional refining capacity, potential redirection of transport in some lines, and additional changes in supply and demand (see e.g. Hull, 2017). An additional challenge in quantifying oil transport more comprehensively is limited public availability of spatial (i.e. GIS) data on oil transportation infrastructure (Graziano et al., 2017).

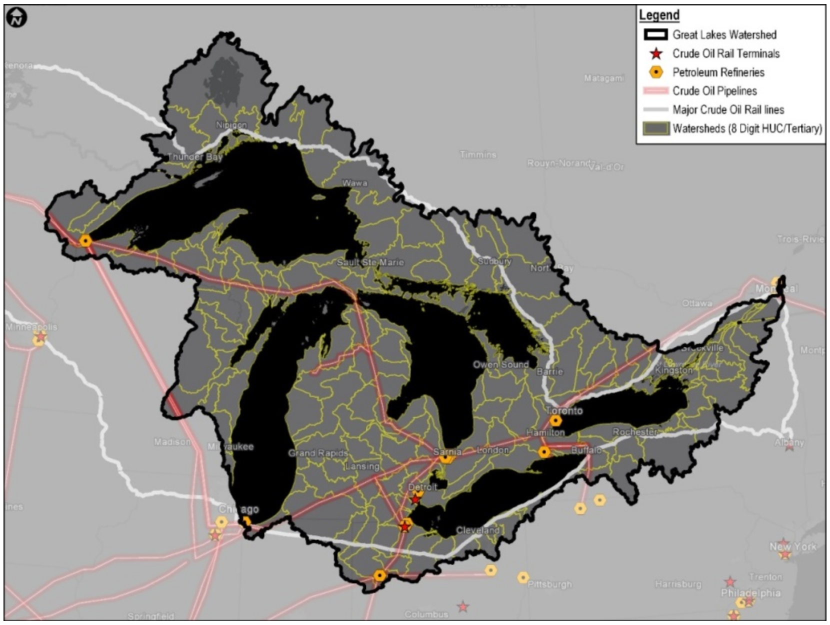

Figure 2-1. Crude oil pipelines, major rail lines, terminals, and refineries in the Great Lakes basin and surrounding areas, along with watersheds (8 digit HUC in United States, tertiary in Canada). The basin is approximately 1,610 kilometers (1,000 miles) wide from east to west. Note map includes several watersheds downstream of Massena, New York and Cornwall, Ontario. (LimnoTech 2018)

2.2.1 Pipelines

Pipelines are the main method of transporting crude oil to and across the Great Lakes region. Crude oil enters the Great Lakes region via pipelines at three main locations: at Clearbrook, Minnesota/Superior, Wisconsin; at Whiting, Indiana near Chicago; and near Lima, Ohio (Figure 2-1).

An important pipeline segment within the basin runs under the Straits of Mackinac, the narrow waterway connecting Lake Michigan and Lake Huron. Concerns about potential spills from the twin underwater pipelines spurred the creation of the Michigan Pipeline Safety Advisory Board, which has coordinated several assessments of spill risks (e.g. Dynamic Risk Assessment Systems, Inc. 2017; Meadows et al. 2018). Other pipelines pass under Great Lakes tributary or connecting channels, including Line 5 and Line 6b[6] pipelines buried under the St. Clair River from Michigan to Sarnia, Ontario.

In addition to existing pipelines, there have been proposals to expand the oil pipeline network, including pipelines running north of Lake Superior and Lake Huron, south from Canada to Texas, and west to terminals in British Columbia and Oregon (CAPP 2017). In addition to potential expansions of the pipeline network, there have been proposals for oil transfer terminals involving ship or rail (e.g. Superior, Wisconsin and Thunder Bay, Ontario) (LimnoTech, 2018).

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[6] Pipelines owned by Enbridge Energy.

2.2.2 Railways

Rail shipment volumes of crude oil to and through the region are difficult to estimate due to the complexity of switching, routing, loading/unloading, and limited readily available data. In considering several factors (including rail loading capacity for Bakken and Canadian oil sand crude), Hull (2017) estimated an upper bound value of about 30 percent rail transport – and thus 70 percent pipeline transport – in the region. Though the fraction of oil transported via rail in the region is smaller than via pipelines, the railway system within the Great Lakes basin is one of the busiest in North America, in particular due to the extensive rail line transfer facilities in Chicago. In addition to crossing major metropolitan centers, rail lines also move through relatively undisturbed and unpopulated areas of the basin. Though rail transports smaller volumes of crude oil than pipelines, the transportation of crude oil via rail has expanded in recent years due to its flexibility with routing, load capacity and the higher speed at which oil can move by rail relative to pipelines (Hull, 2017). In addition to potential spill volumes, other factors (e.g. volatility and potential to ignite) must be considered in assessing potential risks from a rail spill (LimnoTech, 2018).

2.2.3 Marine shipping

A third potential transport mode in the Great Lakes is marine shipping (or waterborne transport). No crude oil is presently transported by vessel on the Great Lakes proper, due in particular to economics and presumably to concerns with adequately addressing recovery of oil in vessel response plans required in Canada and the United States (Polich, 2017).

Additional logistical issues would be winter ice and seasonal lock closures. However, crude oil is currently transported on the St. Lawrence River, and oil transported via pipeline or rail can be transferred to barges for river transport, including in the Chicago area and other locations outside the basin. In addition, refined petroleum products are transported by ship on the lakes (LimnoTech, 2018).

2.3 Releases of crude oil into the aquatic environment

Much of what is known about crude oil impacts on aquatic ecosystems stems from the combined knowledge generated from previous spill events and laboratory studies. Although they occurred in marine (saline) environments, both the Exxon Valdez tanker spill in Prince William Sound in Alaska in 1989 and the Deepwater Horizon offshore drilling rig accident in the Gulf of Mexico in 2010 released large quantities of crude oil. These spills led to several studies representing a large fraction of knowledge on oil exposure and effects today.

The 1989 Exxon Valdez oil spill, which released an estimated 260,000 barrels (41.3 million liters) of oil into Prince William Sound, Alaska, was one of the largest oil spills to date. Though various spill response actions were implemented, the size of the spill and its remote location made cleanup efforts difficult and tested existing plans for dealing with such an event. A number of studies have been carried out on ecological impacts of the spill, including more recently by Li and Boufadel (2010) and Nixon and Michel (2015) (LimnoTech, 2018). Following the spill, the US Oil Pollution Act was adopted in 1990, including a framework for approaches to oil spill response.

The Deepwater Horizon oil spill occurred over three months from April – July 2010 in the Gulf of Mexico, following explosion of a drilling rig that killed 11 workers, and led to what is considered the largest marine oil spill in the history of the petroleum industry. Approximately 3.19 million barrels was ultimately released into the aquatic environment. The spill responders used several methods to contain and remove the oil including skimmers and floating booms to remove the thin layers from the surface, *in situ* burning, and chemical dispersion via two types of dispersants deployed at the surface and below the surface. As with the Exxon Valdez spill, many studies have been completed (with several others ongoing) to understand the impacts to the complex aquatic ecosystem of the Gulf of Mexico (e.g. Beyer et al., 2016; summary in LimnoTech, 2018).

Though no spills of similar magnitude have happened in the Great Lakes, there have been large spills in tributaries and connecting channels associated with oil transportation accidents via multiple modes. In addition, it is important to note that studies of smaller spills can still offer insights concerning potential ecological impacts of spills.

A major freshwater inland oil spill occurred near Marshall, Michigan, in July 2010, when a pipeline ruptured and released Canadian crude oil (dilbit) into a tributary of the Kalamazoo River (Dollhopf and Durno, 2011; NASEM, 2016). The spill was one of the largest inland oil spills at ~24,000 barrels [3.8 million liters] and most costly (over one billion dollars in cleanup costs) in the United States. Oil traveled up to 63 kilometers (39 miles) down the river and was particularly difficult to clean up for that portion of the oil that interacted with river sediments or weathered and sank to the river bed. The spill and response activities provided lessons and led to changes in response protocols after the spill (LimnoTech, 2018).

Rail spills typically involve smaller crude oil volumes compared to pipeline spills, but can still cause significant injury to life, property, and ecosystems depending on the volume of oil, accident character, and spill location. For example, a major rail accident and spill took place in July 2013 in the town of Lac-Mégantic, Quebec (east of Montreal), with the derailment and resulting fire leading to numerous fatalities. In addition, over 619 barrels (98,000 liters) of oil spilled into the Chaudière River, a tributary of Lake Mégantic, which was the main drinking water source for the town (Brunke et al., 2016). While rail spills have decreased substantially in normalized frequency relative to pipeline transport (spill volume per ton mile) since the early 1990s (Frittelli et al., 2014), the Lac-Mégantic accident has resulted in some policy changes. Canada plans to phase out oil transport in cars of the type involved in the accident, and a 2015 US rule that strengthens safety standards for rail transport of oil and other flammable liquids (Shea et al., 2015).

2.4 Crude oil behavior and fate

Assessing the potential impacts of oil released in the environment requires an understanding of the behavior and fate of oil, which itself is complex. As with other substances released in the environment, oil can be subject to physical, chemical, and biological processes. Two issues of particular importance in examining the cycling of oil in the aquatic environment include time (and changes in location and character of oil after a release) and the behavior of bulk oil versus individual chemical components of oil. A related issue is “weathering,” which has been described as the combination of physical, chemical, and biological processes involving spilled oil in the environment (Hollebone, 2011).

In general, oil released to the environment can be subject to a number of individual processes, which include the following (Fingas, 2011; Hollebone, 2011; LimnoTech, 2018; also see Figure 2-2):

- Spreading, which begins immediately following a spill, and will be affected by factors such as oil viscosity, water and air temperatures, and physical conditions (wind, waves, etc.), with potential results of widely varying thickness of surface slicks following a spill.
- Dispersion, a mixing process caused by turbulence in the water, which is also dependent on characteristics of the oil and physical factors in the environment. This process can be enhanced following a spill by application of chemical dispersants.
- Evaporation, or loss of components to the air, which will also vary depending on oil or component characteristics (e.g. vapor pressure of individual compounds) as well as other factors (such as oil thickness). In general, the lighter, more volatile components (e.g. benzene) evaporate the most readily, leading to remaining oil being enriched in less volatile, generally higher molecular weight compounds.
- Dissolution, or movement of individual oil compounds into the dissolved phase in water, allowing for subsequent direct uptake of these compounds by organisms.
- Entrainment, or driving of oil droplets into water column (e.g., via wave motion), which can be temporary, depending on the droplet density.
- Emulsion formation, or dispersion (e.g. of droplets) of one liquid in another immiscible liquid (e.g. oil in water or vice-versa).
- Biodegradation, or partial or complete degradation of oil into basic components (ultimately carbon dioxide and water) through the activity or microorganisms. This process depends on both microorganisms and their contact with oil, and oil compound types, with generally greater biodegradability of alkanes and unsubstituted aromatic hydrocarbons.
- Photo-oxidation, or light-mediated degradation of oil, which increases with solar intensity. Ecological implications of the process are complicated, depending on the material acted upon, with products that can range from generally more water soluble and less toxic compounds, to tar ball formation (e.g. following transformation of viscous oil), to enhanced toxicity following light action on polycyclic aromatic hydrocarbons (PAHs).
- Sedimentation, or movement of oil downward through the water column, potentially reaching the bottom. Sedimentation and sinking can be enhanced as oil interacts with other particles in the water, potentially increasing density.

As shown in Figure 2-2 below, additional processes can occur affecting oil transport and fate, including cycling processes within bottom sediments and between those sediments and the water column.

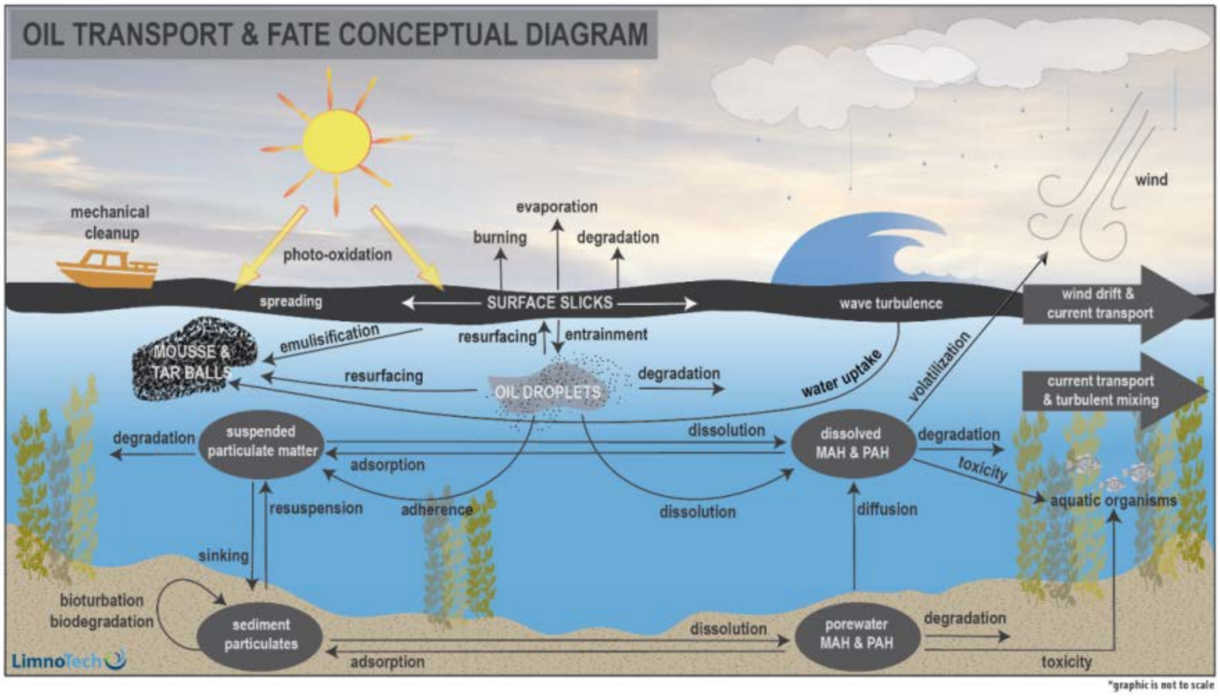

Figure 2-2. Major processes involving crude oil transport and fate in the aquatic environment. MAH refers to monocyclic aromatic hydrocarbon, and PAH refers to polycyclic aromatic hydrocarbon, important compound classes within crude oil. Note dispersion (e.g. of oil droplets, as discussed above) is not explicitly shown, but is an important component of transport following an oil spill, which can lead to other processes in figure. (LimnoTech, 2018)

An important issue affecting all these processes is the potential for changes with time, in particular with weathering of oil following a spill. For example, evaporation of lighter components in the days following a spill will generally lead to increased density of the remaining oil. Coupled with any increased entrainment and dispersion (e.g. with wave action) could lead to increased density of the oil aggregates, potentially leading to sedimentation, with both ecological and spill response implications (LimnoTech, 2018; Hollebone, 2011). Indeed, changes in characteristics in the diluted bitumen that leaked during the Kalamazoo River spill in 2010 led to sinking of some oil (as noted above), complicating clean-up efforts (LimnoTech, 2018). Additional issues in assessing transport and fate of oil in the Great Lakes include ice (e.g., potential for spills on or below ice-covered rivers or lakes) as well as locations (e.g. at or near a tributary, or below the water surface).

2.5 Summary of state of knowledge and gaps related to crude oil characteristics, transport, behavior, and fate

Crude oil is made up of mainly liquid hydrocarbons, with potential presence of smaller quantities of other constituents (including natural gas). Three key properties of crude oil are density, viscosity, and flash point, which can differ appreciably between crudes (e.g., light versus heavy), and which also has implications for approaches to extraction and transport. Unconventional oil production (e.g., from oil sands, and tight oil) continues to be important in the source regions for oil transported in or near the Great Lakes region, and projections show continued importance of these oils in coming years.

Information on the locations and capacities of current transportation infrastructure is partially accessible, particularly for pipelines. Though available data preclude a complete assessment, pipeline transport is the dominant mode for crude oil in the region, with most of the remainder moving via rail. Though no crude oil currently moves via ships on the Great Lakes, barge transport occurs on the St. Lawrence River and other connecting waterways outside the Great Lakes basin. Predicting future crude oil shipping routes, quantities, and composition in the region is characterized by substantial uncertainty due to multiple factors, including fluctuating prices, production levels, alternative pipeline and terminal construction, regulatory changes, and variable regional and global demand.

Transport and fate of oil is understood well in aggregate, with a number of physical, chemical, and biological processes affecting spilled oil. Much of this understanding is based on spills in ocean/coastal ecosystems, though freshwater spills (e.g., the 2010 Kalamazoo River spill) have led to additional insights. Both the behavior of bulk oil as well as individual compounds (e.g., PAHs) must be considered in assessing transport and fate of oil spills, and an important consideration is the potential for weathering, which can lead to changes in characteristics of oil and subsequent transport and fate in the period following a spill. Issues requiring further exploration include potential transport and fate of oil during winter/ice conditions, following a spill across or near a tributary or connecting channel, and for dilbit and other blends resulting from unconventional production, including implications for formation of oil mineral aggregates (e.g. O’Laughlin et al. 2017).

Recommendation: To increase the ability to identify areas potentially vulnerable to oil spills, the Parties (i.e., federal governments) should identify opportunities to increase availability of data on petroleum infrastructure, including spatial data and transport and storage volumes, whether broadly to the public (as security requirements allow) or to researchers and other interested parties with appropriate disclosure agreements.

Recommendation: To enhance spill response planning and preparedness, researchers should carry out further analysis and modeling on the potential transport and fate of the multiple crude oil types transported in the region with particular emphasis on the vulnerable areas identified in this report.

3.0 Crude oil ecological exposures and effects

As is the case with other potentially toxic substances, the toxicity of oil to aquatic species depends on a number of factors, including the chemical and physical characteristics of the oil, the type, extent and duration of exposure (including to individual components), and the sensitivity of the organism itself. Exposure can be either over shorter periods (acute) or longer periods (chronic), and endpoints can be lethal and sublethal. Exposure must account for multiple potential pathways, including via external coating of organisms, ingestion (direct or indirect), inhalation (for air-breathers), or via gill uptake.

A key issue in assessing oil exposure and effects is the consideration of the bulk oil itself (which can be characterized as “total petroleum hydrocarbons”) and individual compounds (or groups) within the oil. For a number of years, the bulk oil itself was typically used to characterize exposures to oil, much of which may not be available for organism uptake. More recently there has been increasing research on exposure and effects of individual compounds (or classes of compounds) in crude oil. These compounds can be grouped into four categories (Lee et al. 2015):

- Aliphatic compounds, sometimes termed “saturates,” such as pentane and n-hexadecane. These compounds tend to be the most biodegradable among the oil fractions, and generally less toxic.
- Aromatic compounds, including monocyclic aromatic hydrocarbons (MAHs) such as benzene, and polycyclic aromatic hydrocarbons (PAHs) such as anthracene and pyrene (i.e., with two or more fused benzene rings). These compounds vary in their water solubility, and in general can cross biological membranes. PAHs tend to be more persistent than MAHs.
- Resins, or compounds that are not formally hydrocarbons, due to the presence of other atoms (e.g. nitrogen, sulfur, and/or oxygen) in the chemical structures, which in many cases have not been identified. They tend to be the smallest polar compounds in oil.
- Asphaltenes, or diverse groups of compounds with the highest molecular weight in petroleum, and, as with resins, they are not formally hydrocarbons. They are the least susceptible to biodegradation, and while comprising a small proportion of light oils, can be more significant in heavy oils and bitumens

In addition, other non-hydrocarbon components found in oil can include metals (such as iron, vanadium, copper and nickel), organometallic compounds, sulfur, naphthenic acids, mineral particles and water (Lee et al., 2015).

Time is an important consideration in assessing exposures to oil and effects (i.e., toxicity), and as with other substances, there can be concern with acute and chronic exposures and effects. Because of the potential for significant weathering of oil, both types of exposure can arise with a given spill, such as organism acute exposures to less persistent compounds such as benzene and toluene in the early period after a spill, and longer term exposures to other constituents, such as more persistent PAHs and other degradation products in weeks and months after a spill.

An increasingly used approach to understand exposures and non-lethal effects of toxicants (including crude oil) is via biomarkers (den Besten, 1998, Connon et al., 2012). A biomarker is molecular or cellular indicator of an event or a condition in a biological system or sample

(USEPA, 2018).[7] One of the most commonly used approaches to indicate fish and wildlife exposure to oil has been with indicators of induction of cytochrome P450 1A (CYP1A) (e.g., Ji et al., 2011; Alexander et al., 2017; Esler et al., 2017). These biomarkers have been useful in documenting exposure of organisms to crude oil, though further research is needed to clarify association with effects in individuals, and broader implications (e.g. to a population) (reviewed in Lee et al., 2015 and LimnoTech, 2018).

The general term describing uptake of chemicals by an organism is bioaccumulation, whether this uptake is direct from the surrounding medium (e.g. direct uptake from water) or via ingestion of food (USEPA, 2012). A substance bioaccumulates when its rate of intake in the organism is higher than the rate of elimination (e.g., via excretion). A related term is biomagnification, in which case a substance bioaccumulates in certain regions of the organism (e.g. lipid-rich cells) and also increases in concentration at higher trophic levels in the food web (discussed below). Concerning petroleum, much research on bioaccumulation has focused on PAHs, with documented bioaccumulation in multiple organism groups, but generally not biomagnification, due to transformation/elimination at higher trophic levels. While many crude oil compounds can be metabolized in organisms, it is important to note that in some cases, the breakdown products can be more toxic than the parent compounds (e.g. PAHs). Furthermore, a significant fraction of studies on cycling and toxicity of crude oil compounds has focused on conventional PAHs, whereas closely related chemicals such as alkylated derivatives – while also more common in crude oil – can also be more toxic (Bornstein et al., 2014; Hodson, 2017).

As indicated above, exposures to oil and its components must include consideration of the totality of the ecosystem. In the Great Lakes, this means consideration of all trophic levels in the food web, ranging from the primary producers (e.g. attached algae, phytoplankton – small, freely-floating plants) to primary consumers (e.g. benthic macroinvertebrates, zooplankton – small, freely-floating animals) to other consumers (e.g. forage fish, piscivorous fish, wildlife) (see Figure 3-1 on following page). Organisms at each trophic level can potentially be exposed to bulk oil following a spill, and even though crude oil compounds do not tend to biomagnify, bioaccumulation at all levels must be considered following a spill. The technical assessment for this project reviewed potential impacts of crude oil on multiple taxonomic groups of interest in the Great Lakes (LimnoTech, 2018), and also references several other recent indepth reviews on the matter (e.g., Perhar and Arhonditsis, 2014, Lee et al., 2015, Dew et al., 2015, Dupuis and Ucan-Marin, 2015). A summary of potential ecological impacts organized by different taxonomic groups follows.

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[7] Note this use of biomarker in the toxicology sense, as distinct from biomarker in petroleum chemistry. The latter references a poorly or nonbiodegradable chemical that can indicate the material origins.

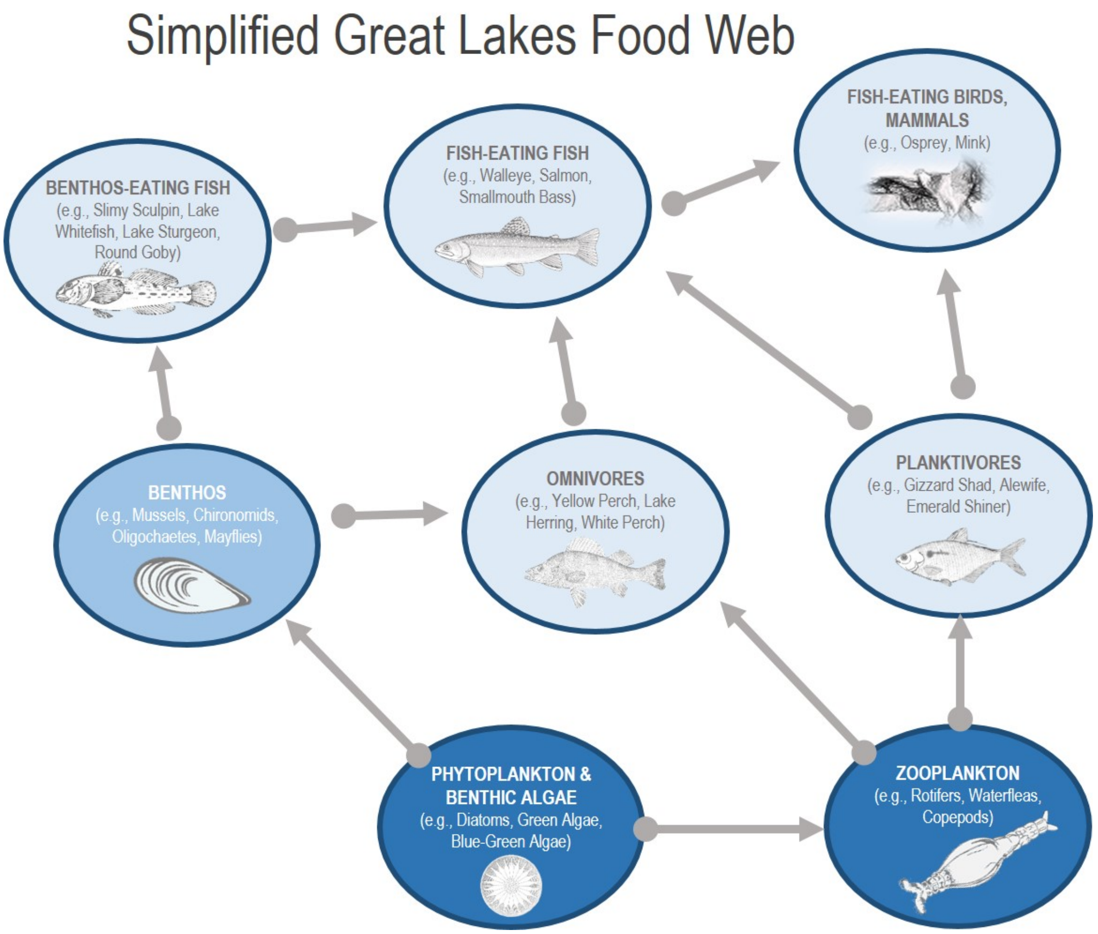

Figure 3-1. Simplified Great Lakes food web, showing trophic levels ranging from primary producers (phytoplankton and benthic algae) to increasing levels of consumers. Benthos refers to organisms living on or in the bottom sediments of the lakes and tributaries, with the plankton (in darker blue) in the water column, and lightest blue representing fish, birds, and mammals. (LimnoTech, 2018)

3.1 Lower food web

The lower food web includes phytoplankton and zooplankton (as shown in Figure 3-1) as well as bacteria and other decomposers, which are considered together in this assessment. Given limited motility, species in these organism groups can potentially be heavily impacted by an oil spill in their vicinity. However, turnover and recovery tend to be relatively rapid, so given their wide distribution and recruitment from other areas and short generation times, long-term effects from oil may be less pronounced than for other organism groups (Batten et al., 1998).

Bacteria are relatively unique concerning oil spill impacts given that they can be either inhibited by crude oil or utilize it as a resource, thereby contributing to microbial decomposition (biodegradation) (e.g. Kostka et al. 2011). Indeed a large bloom of hydrocarbon-degrading bacteria was present following the Deepwater Horizon oil spill, which may have contributed to subsequent lower diversity in the bacterial community (Rivers et al., 2013). Limited information is available on the effects of crude oil on freshwater microbial communities.

Phytoplankton impacts from crude oil and its constituents have been explored in multiple studies, and varying (sometimes contradictory) results have been obtained (e.g. Batten et al. 1998; Sargian et al. 2009; Parsons et al. 2015; reviewed in Perhar and Arhonditsis 2014). Two mechanisms by which oil spills can affect phytoplankton include via shading (preventing phytosynthesis) and through toxic action of oil components (e.g. PAHs) (reviewed in LimnoTech, 2018). In addition, factors such as temperature, organism size and nutrient concentrations can affect toxicity (reviewed in Perhar and Arhonditsis, 2014). One of the few studies on Great Lakes plankton reported photo-induced toxicity on Lake Erie phytoplankton communities following short duration exposure to realistic PAH concentrations (Marwood et al., 1999, 2003). Given the importance of phytoplankon at the base of aquatic food webs, any significant oil spill-related impacts to populations can lead to other food web impacts (LimnoTech, 2018).

Zooplankton are an important energy transfer link between lower and upper trophic levels. Zooplankton can take up oil and its constituents via direct diffusion, food ingestion and ingestion of oil directly. As observed in some studies of oil exposure and effects with phytoplankton, toxicity tests have shown varying results for zooplankton, though high mortality has been seen in some studies (e.g. Federle et al., 1979; Barata et al., 2005). One of the modes of oil or oil constituent removal from zooplankton is via transfer to eggs, and some research has shown impacts of hydrocarbons on eggs, including production and/or hatching success (reviewed in Perhar and Arhonditsis, 2014). Some research in marine and estuarine systems appears to show that some zooplankton can metabolize PAHs, though the mechanism is not clear (Berrojalbiz et al., 2009, Cailleaud et al., 2009).

3.2 Benthos

Following an oil spill, sediments can act as a major sink for oil depending on the oil type and subsequent weathering, as discussed above. Due to the fact that benthic (bottom) organisms (or benthos, commonly referring to bottom-dwelling animals) are relatively immobile and may reside in a particular location for long time periods, benthos may be both impacted by nearby spills and used as indicators of broader sediment and water quality conditions. Benthic organisms can be affected by both bulk oil and compounds. Acute toxicity following the Kalamazoo River oil spill was demonstrated with benthic invertebrates in toxicity tests using contaminated sediment compared to controls (Great Lakes Environment Center, 2012; Dew et al., 2015; cited in LimnoTech, 2018). Concerning oil components, as with zooplankton, benthos can take up PAHs via ingestion or direct transfer from the environment, and toxicity appears to vary across species, habitats and even life stage for a given species (e.g., embryonic stages are more sensitive).

Other studies have explored impacts of oil spills on benthic organism communities, sometimes finding changes in the community composition or structure. For example, it took over 10 years following the Amoco Cadiz oil spill off the coast of Brittany, France for the previously dominant amphipod to regain its relative numbers in the community. Other marine studies have shown relatively few longer term impacts of oil spills on benthic communities, including a review of coastal benthic communities following the Deepwater Horizon oil spill (Beyer et al., 2016; LimnoTech, 2018). In the aftermath of an oil spill in a Missouri Ozarks stream, there was a persistent reduction in abundance of sensitive benthic macroinvertebrates nine months following the spill (LimnoTech, 2018).

Understanding of impacts of bulk oil or its components can also be assessed through broader synoptic studies (i.e., not specific to a specific spill). For example, a study of sediments at 250 connecting channel locations in the Great Lakes showed 3.5-fold lower *Hexagenia* (burrowing mayfly) densities in areas with higher oil concentrations. The potential for multiple stresses affecting the mayflies and issues of multiple possible sources (including legacy) of crude oil compounds highlights the value of baseline data and comprehensive monitoring programs in assessing impacts following an oil spill (LimnoTech, 2018).

3.3 Fish

As with other taxonomic groups, issues of concern in assessing oil impacts on fish include acute versus chronic (including sublethal) toxicity, oil type and characteristics (including compounds present, and changes with time), and species sensitivity (Lee et al., 2015). Fish can be exposed to oil or components via diffusion across gills, directly through ingestion (e.g. of oil droplets), and via food. Acute toxicity of oil is typically associated with lower molecular weight hydrocarbons, which are taken up more quickly following a spill, and which cause death by narcosis (general disruption of functions of lipid membranes). As noted in Section 2.4, these lighter hydrocarbons tend to be lost from the water relatively quickly after a spill (e.g., via evaporation/volatilization), so toxicity typically decreases with time. The moderately larger hydrocarbons, though generally persisting longer in water and having a greater tendency to bioaccumulate in fish tissue, tend to have lower toxicity. In contrast, alkyl PAHs are known to cause chronic toxicity, in particular to fish embryos (Lee et al. 2015). A recent review noted fish physiology and life history were important in toxicity assessments, as well as the particular laboratory method used (Barron et al. 2013), highlighting an ongoing need for further work, including in using more standardized methods (LimnoTech, 2018).

Consideration of fish age (in particular early life versus juveniles and adults) is important in assessing potential impacts from oil exposure. Recent research has shown that crude oil (and in particular PAH constituents) can directly or indirectly impact the physiology, health, growth, and reproduction of adult and juvenile fish. Researchers have noted in this work the importance of biomarkers (e.g., CYP1A, as discussed at the start of this section) indicating expression of enzymes involved in transforming PAHs (or alkyl PAHs) following exposure. Studies following the Deepwater Horizon oil spill have reported presence of these biomarkers; for example, several studies on Gulf killifish identified these biomarkers reflecting gene responses indicative of physiological and reproductive impairment (Lee et al., 2015; LimnoTech, 2018).

An important consideration in assessing oil exposure and effects in fish is the early life stages (eggs and larvae or ichthyoplankton), which are important both to population recruitment and in some cases as food for other fish. Unlike their adult and juvenile counterparts, embryos and larvae are mostly unable to avoid exposure to oil spills. Several studies have found early life stages of fish to be sensitive to oil spills, including high rates of deformities, developmental delays, impaired cardiac function and anemia when compared to controls/cleaner environments (LimnoTech, 2018). An additional concern is delayed toxicity, with effects including swimming impairment in juveniles and lower survival rates in some adults following early life stage oil exposure. In addition to numerous early life stage studies in the lab, there have been studies in field settings following spills. For example, a number of studies showed embryos were particularly sensitive to oil following the Exxon Valdez spill, though salmon spawning habitat and embryo condition in Prince William Sound had appeared to recover within five years after the spill (LimnoTech, 2018).

Though generally less studied than marine and anadromous (migratory into freshwaters) systems, studies on the early life stages of freshwater fish have observed similar results. For example, larval lake whitefish (*Coregonus clupeaformis*) from areas of Wabamun Lake (Alberta) exposed to a fuel oil spill (via a train derailment) showed incidences of deformities associated with oil exposure, even in a historically contaminated environment with relatively higher background deformity rates (DeBryun et al., 2007).

There has been increasing research into impacts of unconventional oils (e.g. dilbit) on fish. The chemical composition of dilbit will depend on both the original bitumen (which may have a higher fraction of higher molecular weight PAHs) and the diluting material (or diluent) with lighter hydrocarbons, and as with other oil mixtures, the composition can change with weathering and time following a spill (reviewed in Alsaadi et al. 2018). Recent research on Japanese medaka (a common species used in fish toxicity studies) report impacts of dilbit on fish embryos, including blue sac disease, impaired development and impaired swim bladder development, with biochemical measurements consistent with response to PAH exposures (Madison et al., 2015). Additional research from the same group found increasing malformations and toxicity to fish embryos with dilbit exposure – including oil enhanced with chemical dispersant – with toxicity varying depending on the type of dilbit (Madison et al., 2017). A number of questions remain regarding dilbit toxicity in fish, including on variations in sensitivity in early life stages, relationship of oil biomarkers of exposure and effects in various fish species, and the implications for exposed fish of transformation of PAHs to either more readily excreted degradation products or more toxic metabolites (Alsaadi et al. 2018).

An additional issue with fish impacts of oil spills is the potential for broader community and/or food web impacts, as well as the need to consider multiple factors affecting fish populations. For example, reduced fishing of sockeye salmon following the Exxon Valdez oil spill led to increases in adult spawning numbers, and negative impacts on juvenile salmon growth and abundance. Pacific herring populations in the region declined dramatically after the Exxon Valdez spill, and researchers attributed the decline to multiple factors (overharvesting, natural factors, changes in food supply, etc.), but with some arguing a key role for direct or indirect effects of the oil spill (reviewed in Lee et al., 2015). Following the Deepwater Horizon oil spill, widespread impacts to fish populations in either offshore or coastal waters were not observed, which was surprising in light of laboratory toxicity studies. Researchers have noted multiple factors that could explain these findings, including high spatial and temporal variability in population demographics, movement of fish into and out of affected areas, fisheries closures, food web impacts (e.g., potential enhanced productivity with oil-derived carbon), and delayed impacts (Fodrie et al., 2014, cited in Lee et al., 2015).

3.4 Amphibians and reptiles

In contrast to relatively extensive work on the impacts of oil in fish, there has been less research on impacts of oil exposure on amphibians and reptiles. Studies have explored impacts of oil on early life stages of amphibians, with one study finding impacts to metamorphosis and overall size in tiger salamanders, and another study exploring impacts of crude oil on the endocrine system in tadpoles of the African clawed frog (commonly used in toxicity studies) (reviewed in LimnoTech, 2018). Oil spills near coastal habitats can contaminate areas used by aquatic turtles for nesting. In one study, an oil spill in Tampa Bay, Florida, resulted in survival rates of sea turtle embryos on the impacted nesting beach of 5 percent compared to the normal rate of 50-90 percent, while a lab study on snapping turtle eggs showed no impacts of dispersed crude oil on hatching success or hatchling/juvenile traits (reviewed in LimnoTech, 2018).

It should be noted that rescue and rehabilitation efforts following oil spills can help reduce impacts for certain taxonomic groups; for example, efforts following the Kalamazoo River oil spill resulted in a 97 percent survival rate for rescued turtles (LimnoTech 2018). Research on understanding the effects of crude oil spills and their implications on amphibians, especially during critical periods in their life history (e.g., metamorphosis, overwintering) is limited and further study is warranted.

3.5 Semi-aquatic mammals

Semi-aquatic mammals at risk for oil exposure in the Great Lakes include the river otter, beaver, mink, and muskrat. A major concern with a spill would be external coating from contact with surface slicks of oil, leading to direct ingestion with grooming. There appears to be limited research on crude oil impacts to semi-aquatic mammals (in particular in freshwater), and additional research is needed (LimnoTech, 2018).

3.6 Birds

With over 450 documented bird species, the Great Lakes support a wide variety of birds that depend on the waterways for seasonal or year-round habitat. Coastal wetlands and beaches in particular provide food, shelter and nesting sites for resident and migratory species. Types of birds at particular risk for direct oil exposure are shorebirds (e.g., wading birds) and those that inhabit the water surface (e.g., diving ducks). Following any contact with oil, the instinct to groom or preen in birds leads to ingestion of oil, redistribution of oil in the plumage, and loss of thermal insulation. Birds can also be exposed to volatile components of oil through inhalation.

Large-scale bird mortality has been observed in large spills in the marine environment. For example, following the Exxon Valdez oil spill mortality of adult birds was accompanied by a reduction in body mass, condition, and survival in nestlings, and in the case of the Deepwater Horizon oil spill, one estimate indicated 600,000 – 800,000 over-wintering birds were killed (reviewed in LimnoTech 2018). Similar data are not available for freshwater spills, which have been smaller in magnitude to date. Though not crude oil, a 2005 spill of heavy fuel oil to Wabamun Lake, Alberta resulted in observations of dead birds (Birtwell, 2008).

An additional issue of concern is broader ecological implications of bird mortality following an oil spill. For example, widespread mortality of fish-eating birds following the Deepwater Horizon oil spill may have had ‘top-down’ effects on the marine ecosystem of the Gulf of Mexico, changing the abundance and age structure of fish populations that supported the birds, with unclear longer-term implications (Short 2017). As with other taxonomic groups, there is a need for baseline surveys of population density and assessment of species sensitivities to help in spill assessment, including assessing any damages following a spill (e.g., on the United States side through provisions in the Migratory Bird Treaty Act and Oil Pollution Act) (Haney et al., 2017; LimnoTech, 2018).

3.7 Summary of state of knowledge and gaps related to exposure and effects concerning crude oil and aquatic organisms

Laboratory and field studies have shed light on a number of questions related to the ecological impacts of crude oil. A high-level summary of the state of knowledge specific to particular taxonomic groups based on the technical assessment for this project is shown in Table 3-1. As discussed above and indicated in the table, we have a better understanding of oil spill impacts to fish and birds, and very limited research to date on impacts to amphibians and reptiles as well as semi-aquatic mammals, with lower food web groups falling in between. There is a good understanding of exposure pathways of both bulk oil and components (in particular PAHs and some derivatives) as well as potential effects to fish and birds, with less information available (in particular on effects) for lower food web groups. Possibly in part because of the history of larger ocean/coastal spills, the scientific literature in general is more developed on exposures and effects of oil in ocean/coastal ecosystems as compared to freshwater ecosystems, in particular the Great Lakes. An area of research that has increased significantly in just the past few years concerns potential toxicity of crude oil mixtures (e.g. dilbit), in particular to fish. There remain a number of knowledge gaps to better understand crude oil risks to organisms in the Great Lakes, including:

- Better understanding of species-specific sensitivity to oil spills, especially of species that are of greatest importance to tribal subsistence, culture and commerce, species listed as threatened or endangered, and key commercial and recreational species
- Better understanding of sensitivity of amphibians, reptiles, and semi-aquatic mammals to oil, and more research on sensitivity of freshwater fish (in particular early life stages) to oil spills
- More comprehensive toxicity information for a broader range of oil types, including dilbit and other blends resulting from unconventional oil extraction, which should include consideration of lighter and heavier component hydrocarbons, a wider range of species and life stages, and further exploration of mechanisms of action
- Linking biomarkers of oil (whether exposure or effect) to broader impacts or implications, including at the population level
- Broader baseline data through monitoring programs on oil and components (in particular PAHs, including alkylated PAHs)

- Further research on both potential for oil to act as one amongst many stressors affecting organisms as well as the potential for broader community or food web impacts of oil spills
- Further research on implications of seasonal timing for oil spills (e.g. in winter with ice cover, or in a tributary during spring runoff).

Table 3-1. Qualitative summary of state of knowledge of oil spill impacts on major taxonomic groups*

Taxonomic Group	State of Knowledge	Notes
Zooplankton and Phytoplankton	Fair	Marine species better studied
Benthic Invertebrates	Fair	Best information on primary components of fish diets
Fish	Good	Focus on high-value species and common prey fish; still limited data on early life stages
Reptiles and amphibians	Poor	River and wetland species and habitats are understudied
Semi-aquatic Mammals	Poor	River and wetland species and habitats are understudied
Birds	Good	Focus on waterfowl, piscivores, and gulls; limited data compared to marine species

*: From LimnoTech, 2018.

To address these knowledge gaps, the following actions should be pursued.

Recommendation: To address the relative paucity of scientific knowledge on the potential impacts of crude oil on freshwater environments, agency program managers should encourage, and researchers should pursue, additional emphasis on investigations into exposures and effects of the multiple crude oil types that are currently transported in the region on ecosystems and organisms. This includes investigations on the toxicity of oil components (such as PAHs and chemicals in diluents), in particular those found in dilbit and other blends, and further exploration of the use of biomarkers in assessing exposures and effects.

Recommendation: To appropriately site future oil transportation developments/infrastructure and for species conservation purposes, agency program managers should encourage, and researchers should pursue assessments with regards to exposure, sensitivity, and adaptive capacity (and hence vulnerability) that include a focus on species of particular cultural and/or conservation concern in the Great Lakes (e.g., fish species such as walleye, lake trout and lake sturgeon), especially those species that may be present in vulnerable areas.

Recommendation: In order to better understand the vulnerability to direct and indirect oil exposure for all life stages of less-well-studied freshwater taxa, agency program managers should encourage, and researchers should pursue further work on toxicological assessments of amphibians and reptiles, and semi-aquatic mammal populations in Great Lakes tributaries.

4.0 The Great Lakes basin and areas potentially vulnerable to oil spills

With a total area of over 244,000 km^2 (94,000 mi²) and with over approximately 17,000 km (10,000 miles) of shoreline, the Laurentian Great Lakes hold approximately one-fifth of the world's surface fresh water. The varieties of habitats within the broader Great Lakes-St. Lawrence region support a wide range of aquatic species. Consideration of factors related to oil exposure (in particular locations of oil transport), species and habitat sensitivity, and adaptive capacity together can indicate areas that are potentially vulnerable to oil spills within the region.

4.1 Overview of the Great Lakes basin

The Great Lakes basin includes a number of rivers, streams, and inland lakes in the eight states and one province that border and underlie the Great Lakes and Upper St. Lawrence River. In addition to its diversity of species, fisheries, wetlands, and wide variety of ecosystem types (Pearsall et al, 2013; Riseng et al., 2018), approximately 40 million people depend on waters of the Great Lakes – St. Lawrence region for their drinking water supply. The basin and surrounding area is also a vibrant and important economic region that serves as a critical corridor for transport and infrastructure serving energy commodities, such as oil and gas products, as well as a strong tourism economy and productive fisheries. Crude oil is a commodity that is deserving of attention because of documented impacts identified from the past spills within the region, and from high-profile spills outside the region (Marty and Nicoll, 2017).

The major water bodies of the Great Lakes region consist of the five lakes themselves (Superior, Michigan, Huron, Erie, and Ontario) along with the three connecting channels (St. Marys River, Huron-Erie Corridor [including Lake St. Clair], and Niagara River) and the outlet through the Upper St. Lawrence River. As discussed in Section 2.2, potential sources of crude oil release to the lakes include pipelines that flow near and under the lakes and connecting channels, and rail lines, terminals, and refineries located along their shores. Important habitats that are vulnerable to spills in the lakes include coastal wetlands, beaches, and spawning and nursery areas.

In addition to spills directly into Great Lakes or connecting channel waters from pipelines, refineries, or other sources at the shoreline, there is also a history and future potential of crude oil releases into Great Lakes tributaries that may or may not impact the lakes or St. Lawrence River. Two examples include the pipeline rupture near Marshall, Michigan in 2010, which released dilbit into a tributary of the Kalamazoo River (itself a tributary to Lake Michigan), and the Lac-Mégantic, Quebec rail accident in 2013, which released Bakken light crude oil into the nearby lake and the Chaudière River (a tributary to the St. Lawrence River, downstream of the Great Lakes basin).

4.2. Vulnerable ecological areas in the Great Lakes basin

The size and complexity of the Great Lakes basin creates challenges in identifying priority ecological resources, including habitats and species, because habitat types, sizes, distributions and relative significance vary within and among the lakes. To identify key ecological resources located in proximity to or intersecting with crude oil transportation modes in the Great Lakes basin, LimnoTech (2018) drew upon Great Lakes biodiversity reports (Franks et al., 2010; Pearsall et al., 2012a; Pearsall et al., 2012b; Pearsall et al., 2013; LOBSWG, 2009; LSLAMP, 2015).[8]

For each of the five lakes, Table 4-1 lists lake-specific plants, animals and habitats that may be vulnerable to future oil spills for seven distinct habitat types and for migratory fish, which typically use multiple habitats. Coastal habitats are of particular concern because much of the biological productivity and biodiversity within the Great Lakes basin is concentrated in coastal zones and particularly within coastal wetlands, which provide sites for critical life history needs for many of the species inhabiting or migrating through the basin. Tributaries and embayments also serve a wide range of life history needs across the basin and increase the intersections of transportation and transfer modes with habitats and/or organisms of concern across the basin (LimnoTech, 2018).

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[8] In addition, though beyond the scope of this project, a biodiversity atlas that ranked biodiversity status within and along the St. Lawrence River (Tardif et al., 2005), ranking categories of condition and threats to habitats amd species, could be used to idntify areas along the St. Lawrence River where oil transportation corridors and refineries threaten areas of high biodiversity.

Table 4-1. Selected lake-specific habitats, plants and animals of concern in the Great Lakes that could be impacted by future oil spills*

Lake	Nearshore (zones and reefs)	Migratory fish	Coastal habitats
Erie	Native submerged aquatic vegetation, shore birds, waterfowl, amphibians and reptiles, benthic macroinvertebrates (e.g., Hexagenia), mussels, nearshore reefs and dependent species (e.g., walleye), and other fishes (e.g., emerald shiner)	Lake sturgeon, walleye, suckers, sauger	Emergent marshes, wet meadows, sedge communities, submergent/emergent/floating native aquatic plants, migratory waterbirds, wetland obligate nesting birds, amphibians and reptiles, wetland dependent fishes, aquatic macroinvertebrates and mussels
Michigan	Native submerged aquatic vegetation, shore birds, waterfowl, reptiles and amphibians, benthic invertebrates (e.g., Hexagenia spp.), mussels, nearshore reefs and dependent species (e.g., lake trout), and other fishes (e.g., spottail shiner)	Lake sturgeon, walleye, suckers, northern pike, lake whitefish	Emergent marshes, wet meadows, sedge communities, submergent/emergent/floating native aquatic plants, migratory waterbirds, wetland obligate nesting birds, amphibians and reptiles, wetland dependent fishes, aquatic macroinvertebrates and mussels
Huron	Walleye, yellow perch, lake herring, Blandings turtle	Lake sturgeon, suckers, redhorse, walleye	Emergent marshes, coastal cedar swamps, alvars, migrating water birds, eastern

			fox snake, northern pike
Superior	Walleye, Lake Sturgeon, Brook Trout, Siscowet Lake Trout, Humper Lake Trout, Lean Lake Trout, Burbot, Cisco, Lake Whitefish, Round Whitefish, Ninespine Stickleback, Trout-perch, Pygmy Whitefish, Slimy Sculpin, Deepwater Sculpin, Longnose Sucker, White Sucker, shorebirds, waterfowl, benthic macroinvertebrates, native mussels, forage fishes, spawning habitat for deepwater fishes (e.g., deepwater ciscoes and sculpins)	NA	All Coastal wetland types, spawning and larval fish, amphibians, breeding and migratory birds, invertebrates
Ontario	Submerged aquatic vegetation critical for waterfowl and many fishes such as smallmouth bass and yellow perch	Native migratory fish include lake sturgeon (lake to tributaries), American eel (lake to ocean), lake trout (deep lake to reefs), white sucker (lake to tributaries), walleye (lake to tributaries), and northern pike (lake to shallow wetlands)	Many natural communities, shaped by the long- term hydrologic periodicity of the lake and river, provides breeding, nursery, and migratory habitat for many species of native fish, birds, amphibians and reptiles

* From LimnoTech, 2018. Note technical report includes additional habitat types – open water, embayments and inshore, tributaries and watersheds, connecting channels, islands and coastal terrestrial, most of which had assigned species or components of value. In addition, for some conservation categories for individual lakes, descriptions were not provided in the original biodiversity conservation strategies assessed by LimnoTech, reflected as “NA” in table.

Combining information from biodiversity reports with the rail, pipeline and refinery data layers provides a first approximation of the spatial configuration of vulnerable ecosystems. One such qualitative presentation is shown in Figure 4-1. Table 4-2 summarizes potential oil sources and critical habitats at each of the 15 areas indicated in Figure 4-1. As an example of screening for vulnerability in Lake Erie, a rail line used for transporting crude oil runs along the lake’s southern shore, with a terminal on the eastern end of the lake. This rail line is situated close to the southern shore of the lake and crosses a number of tributaries that enter Lake Erie in habitat zones of fair to good coastal wetland quality. In contrast, the northern part of the Lake is relatively free of such transport corridors and thus less vulnerable to rail spills that would affect coastal habitats along that shore. In addition, tributary oil spills can have potential impacts on rivers and the lakes proper, with increasing risk to the Lakes for closer stream crossings; as noted in LimnoTech (2018), oil was transported up to 64 kilometers (40 miles) downstream following the Kalamazoo River oil spill.

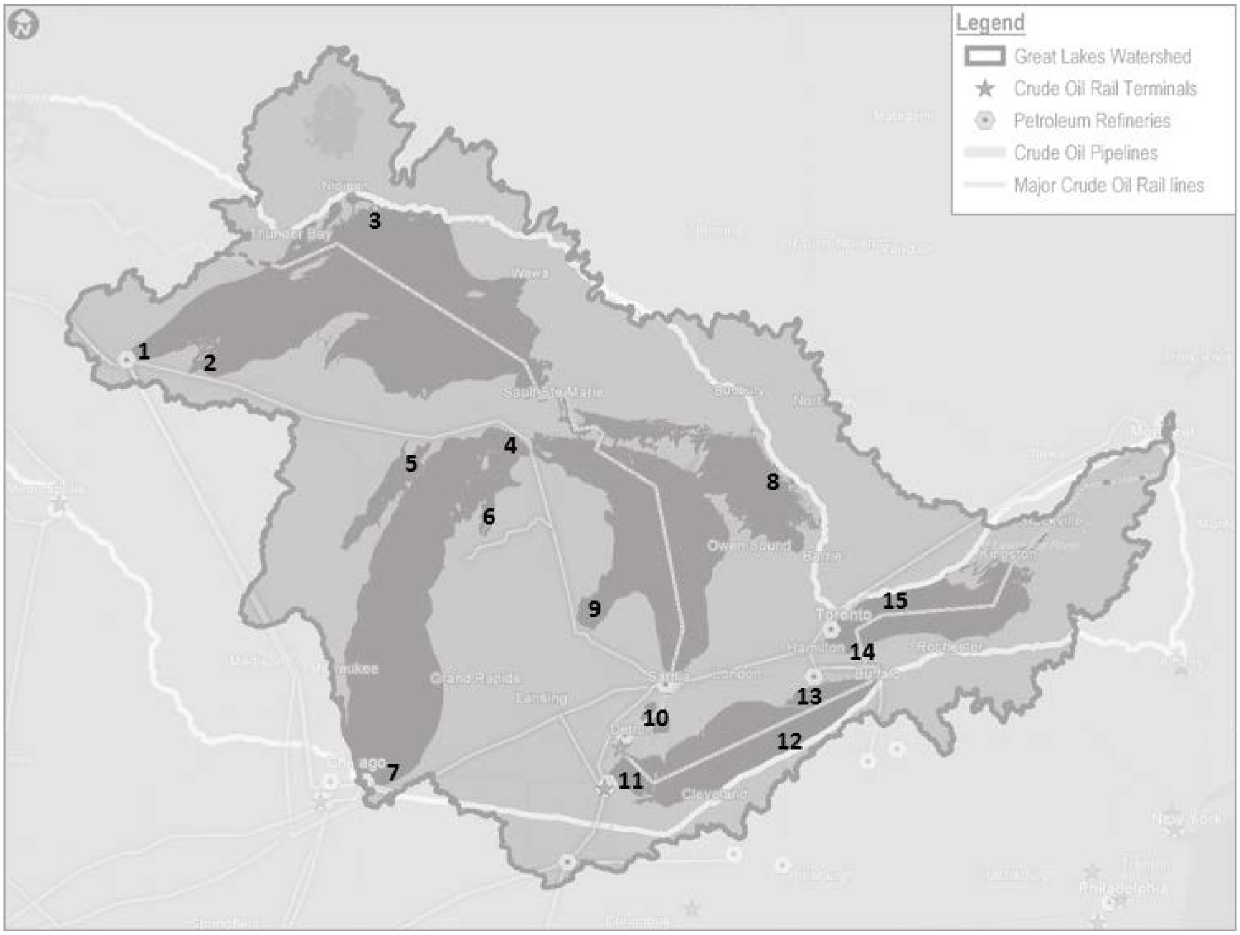

Figure 4-1. Schematic representation of results of a qualitative assessment showing 15 areas of higher ecological vulnerability to crude oil spills from transportation and related infrastructure in the Great Lakes basin based on proximity to sources and habitat quality or significance. All tributary crossings by any transport mode, as well as downstream reaches, would also be considered vulnerable, with factors such as spill volume being important. Note these results do not reflect a quantitative analysis of risk, or any ranking of vulnerability— numbers are used for identification purposes only, and correspond to Table 4-2 entries below. (LimnoTech, 2018)

Table 4-2. Description of 15 areas of ecological vulnerability to oil spills in the Great Lakes basin, as shown in Figure 4-1

Area of Vulnerability	Potential Source of Crude Oil	Vulnerable Habitat or Species
1. St. Louis River Estuary	Refinery, pipeline crossing	Sturgeon, wild rice
2. Chequamegon Bay, Apostle Islands National Lakeshore	Nearshore pipeline	Wild rice, waterfowl, colonial water birds, lake trout spawning
3. Thunder Bay, Lake Superior National Marine Conservation Area	Nearshore rail	Lake trout spawning, sturgeon spawning (rivers)
4. Northern Lake Michigan and Straits of Mackinac	Nearshore pipeline and pipeline crossing	Lake trout spawning, coastal wetlands, alvars
5. Northern Green Bay	Nearshore pipeline	Walleye, coastal wetlands
6. Grand Traverse Bay	Nearshore pipeline (small)	Trout streams, lake trout, lake whitefish, salmon spawning
7. Southern Lake Michigan, Indiana Dunes National Lakeshore	Refinery, rail, pipeline	Coastal wetlands, dunes
8. Georgian Bay Biosphere Reserve	Nearshore rail	Coastal wetlands, spawning
9. Saginaw Bay	Nearshore pipeline	Walleye, yellow perch, waterfowl
10. Huron-Erie Corridor	Refineries, pipeline crossings	Sturgeon, wetlands, waterfowl
11. Maumee Bay	Refineries, pipelines	Coastal wetlands, walleye
12. South Lake Erie, Presque Isle	Nearshore rail	Nearshore spawning, wetlands
13. Long Point Bay	Refinery	Wetlands, migratory waterfowl
14. Niagara River	Pipelines, nearshore rail	Sturgeon spawning
15. North Lake Ontario	Nearshore rail	Coastal wetlands, spawning

* In potential source of crude oil column, “nearshore” references potential sources that could readily impact the nearshore waters, even if on land, due to proximity to the shoreline (J. Bratton, personal communication).

The likelihood of exposure to an oil spill and the vulnerability of species and ecosystems may vary among broad ecological zones of the Great Lakes basin. Exposure to crude oil of pelagic (open water column) food webs (Figure 3-1) would come from pipelines that span open waters or connecting channels in the lakes (assuming ongoing restrictions on oil shipping on the lakes). Most fishes are likely to move away from dispersed hydrocarbons, while phytoplankton and zooplankton may experience greater harm due to their limited mobility, but also may show more rapid population recovery. As a first approximation, impacts on pelagic food webs may be most severe in localized areas such as embayments, or from a large release of crude oil.

Benthic food webs are populated by a variety of invertebrates, including larvae of a number of families of aquatic insects, such as the mayfly *Hexagenia*, historically a diverse assemblage of freshwater mussels and the amphipod *Diporeia*, and increasingly over the past two decades, the invasive zebra and quagga mussels (*Dreissena* spp). Benthic habitat is also important to the spawning and early life stage rearing of a number of Great Lakes fishes. Many areas vulnerable to oil spills (Figure 4-1) coincide with Areas of Concern (designated under the GLWQA), more localized areas that typically include sediment impairments, such as habitat degradation or contaminated sediments, that have been subject to restoration efforts over several decades (LimnoTech, 2018).

Coastal habitats (in particular coastal wetlands) are of particular concern both because of their proximity to oil transport modes in at least parts of the basin as well as the important habitats and ecosystem services they provide. Great Lakes coastal wetlands often have high physical and hydrological connectivity to their associated Great Lake. These diverse ecosystems provide habitat for hundreds of species of birds, fish and amphibians, and a significant portion of all lake fish species spawn in coastal wetlands and in some cases use through most or all of their life cycle (Ludsin et al. 2014). In addition to inherent threats from oil spilled directly into a coastal wetland, wind and current-driven upwelling, downwelling and seiches have the potential to produce large onshore-offshore transport of oil constituents (processes similar to what occurred in some Gulf of Mexico coastal areas following the Deepwater Horizon oil spill (reviewed in LimnoTech, 2018)).

Other Great Lakes habitats that are potentially vulnerable to oil spills include coastal terrestrial habitats (following upland spills close to the lakes, with shorebirds and other species at risk), nearshore zones (including reefs, with important fish species and some amphibians and reptiles at risk of injury), and islands (with colonial nesting waterbirds and some migratory land birds at risk).

Great Lakes tributaries are important habitats for many species, including a number of fish species that use them for spawning. Flow conditions would be expected to influence impact of a tributary spill, including extent to which it may be transported quickly downstream. Given the typically shallower depth of tributaries, some oil spills may reach and penetrate sediments, in which case recovery can take several years (Hoff et al., 1993). As noted in Section 2.4, an additional important factor in assessing oil transport and fate is oil characteristics – for example, the dilbit involved in the Kalamazoo River spill weathered and much of the oil sank. While this meant less downstream transport than otherwise would have occurred, it also complicated recovery in the affected areas (reviewed in LimnoTech, 2018).

4.3. Summary of vulnerable ecological areas in the Great Lakes basin and knowledge gaps

As with any vulnerability analysis, the vulnerability of ecological areas in the Great Lakes basin to oil spills will be determined by the exposure to oil, the sensitivity of the areas/habitats, and adaptive capacity of those systems. In this case, the exposure is a function of the type of oil transport infrastructure, associated crude oil volumes, type of oil, and transport and fate of released oil. Information on transport infrastructure is reasonable well known, in particular for pipelines. Ecological area sensitivity was assessed through compilation of data through multiple sources, in particular The Nature Conservancy-led efforts at development of biodiversity conservation strategies for each of the Great Lakes, with relatively complete information on habitat quality and significance ranging from upland areas to open waters of the Lakes. Adaptive capacity (to oil spills) is less studied, and others have noted the need to study longer-term response of systems (including wetlands) to oil spills (e.g. Lee et al., 2015).

Integration of the available exposure and ecological sensitivity information for this project led to the qualitative identification of 15 areas of higher ecological vulnerability to spills in the Great Lakes basin. One common element among all areas was a coastal or nearshore location, including areas such as the St. Louis River Estuary (Minnesota), the Straits of Mackinac (Michigan), and Maumee Bay (Ohio), with most areas involving nearby oil transport via pipeline or rail (or a combination), and with five areas involving refineries as potential oil sources. Coastal wetlands were a common vulnerable habitat type and fish spawning sites (including for lake trout and sturgeon) were also identified as vulnerable at several locations. Wild rice cultivation was also identified as among the vulnerable resources at two areas in the northern portion of the Great Lakes basin (LimnoTech, 2018). It is important to note the human dimensions aspect of prioritizing areas or species for consideration in these vulnerability analyses, and the importance of considering both areas and species of direct human use as well as other cases with separate ecological values.

Pursuing a more quantitative analysis of ecological vulnerability in the Great Lakes basin could be done, using for example numerical thresholds of proximity, spill volume and spill frequency from individual sources to areas with, for example, higher quality habitat (e.g. coastal wetland habitats, spawning reefs or waterbird nesting colonies). Such an analysis could be done for rivers in the basin based on similar criteria. A numerical system quantifying parameters such as ecosystem value, vulnerability, and/or resilience could be coupled with oil infrastructure spill threat values, with weighting as appropriate. As noted above, adaptive capacity (of both organisms and habitats) to oil is not well known, though individual studies have shown some potential (e.g., degradation of oil compounds in some organisms). Finally, it would be important to consider temporal aspects as well (e.g. related to seasonality and life history influences on ecological vulnerability, any changes in oil transport infrastructure), as well as spill response challenges based on natural or management factors (LimnoTech, 2018).

Other recent work could aid in such an analysis. For example, vulnerability assessments for oil spills have been carried out recently in other regions of the world, in particular coastal marine areas (e.g. Santos et al. 2013; Rosenberger et al. 2017). Canada has developed a framework for ship-source oil spills (DFO 2017) with potential regional application. On the US side, the National Oceanic and Atmospheric Administration (NOAA) has utilized an environmental sensitivity index for several decades to assist in spill planning, where habitat types are prioritized in coastal areas based on likely oil persistence as well as sensitivity of plants and animals to the oil (Scott et al. 2013). Habitat and species updates for the Great Lakes basin are warranted, given significant changes in many ecological aspects of the lakes from the period 1985 – 1994 with data available for the lakes (https://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html). Updated sensitivity maps could be coupled with more detailed exposure considerations to provide a more robust assessment of vulnerability in the Great Lakes region.

Recommendation: To support spill response activities and manage for short- and long- term exposure to fish and other organisms following an oil spill, agency program managers should ensure development (or updating, as appropriate) and sharing of detailed habitat and biological sensitivity maps, including baseline surveys, on a binational basis.

Recommendation: To reduce vulnerabilities of higher value habitats and inform spill response planning and preparedness, agency program managers should support assessments of how spills from pipeline and rail crossings and nearshore routes might impact river ecosystems and downstream Great Lakes habitats, including seasonal variation, on a binational basis.

5.0 Monitoring, modeling, oil spill response and ecosystem resiliency

Assessing the potential ecological impacts of oil spills in the Great Lakes basin requires considering all relevant information, including monitoring multiple aspects of the environment, and output from modeling, including predictive modeling on potential transport and fate following a particular oil spill. In addition, with any spill in the region, there will be some type of response, and in general it would be expected that the response would ultimately lessen the ecological impacts of the spill that would have otherwise occurred, due in part to recovery of some oil and with fraction recovered varying widely for individual spills (e.g. Lee et al., 2015). Finally, an important consideration in any disturbance to Great Lakes ecosystems is the potential ecosystem resiliency, or the capacity for the system to absorb change and maintain similar structure and processes in place before the change (as discussed above in the context of species or habitat vulnerability). This section briefly reviews these components relevant to oil spill impacts in the region.

5.1 Oil spill monitoring

Monitoring oil spills in the environment entails multiple aspects, ranging from direct measurement of affected matrices to remote sensing, and technologies continue to evolve. Direct measurement can include measurements of bulk oil and chemical constituents in the oil, and has included field sampling followed by subsequent laboratory analysis. Use of optical instruments such as fluorometers to measure *in situ* oil in water has increased in recent years, with extensive deployment during the Deepwater Horizon oil spill to measure oil within the water column. A more difficult task is monitoring sunken oil (e.g., in sediments), as was evidenced following the Kalamazoo River spill, when manual methods (e.g. involving probing sediment) were utilized (NASEM, 2016; LimnoTech, 2018).

Remote sensing entails gathering data from a land, water, or subsurface area without direct contact, through means that can include satellites, piloted aircraft, and drones (Li et al., 2017). Though not used extensively in oil response monitoring traditionally, it was utilized in the Deepwater Horizon spill, and in general is a viable technique for detecting and monitoring oil spills, with the caveat of limitations in assessing oil slick thickness (Leifer et al., 2012; LimnoTech, 2018).

The 2006 IJC report on oil and other hazardous material spills included two recommendations regarding monitoring in the region relevant to this assessment (IJC, 2006). One recommendation called for binational data sharing and reporting of spills from vessels, discharges from onshore and offshore facilities, and other discharges from shipping sources. There is coordination between the U.S. and Canadian Coast Guards on these issues through the Canada-United States Joint Marine Contingency Plan (CANUSLAK Annex). Another recommendation called for binational work (including with agencies at other levels) in development of a real-time monitoring and biomonitoring system that is also integrated with hydraulic models. Subsequently, a Huron to Erie Drinking Water Monitoring Network was established between 2006 and 2010. Though the system degraded due to funding limitations, there are current efforts to reactivate a similar network (LimnoTech, 2018).

5.2 Oil spill model capabilities

In addition to direct observation and measurement of water quality and ecosystem impacts following a spill, numerous models have been developed to predict spill movement and their potential impacts. This review found that the literature is dominated by models addressing marine systems. Predominant models developed for freshwater environments (or modified from marine environments) are summarized in Table 5-1, and discussed in detail in LimnoTech (2018).

Table 5-1. Summary of oil spill models and applications for freshwater environments

Model	Description	Applications
FVCOM	Coastal ocean hydrodynamic model that uses variable density grids from higher resolution near shore and in channels; simulates oil as particles.	Operational model currently being used in Great Lakes by NOAA to replace Princeton Ocean Model; recent Straits simulations by Schwab and Anderson.
Lagrangian Model	Two-layer model that represents advection, dispersion, evaporation and dissolution.	Developed in 1980s for application to Lake St. Clair.
ROSS3	Next generation model building on prior Lagrangian model with more processes.	Developed in 1990s for St. Clair River and Lake St. Clair; includes ice.
ROSS2 and MICROSS2	Simpler models than ROSS3, with lower resolution grids.	Applied to Upper St. Lawrence River for spill hindcasting, and Ohio-Monongahela-Allegheny River System in early 1990s.
GNOME	Operational NOAA spill trajectory model; simulates 2-D Eulerian/Lagrangian movement.	Used in Great Lakes and coastal ocean during spill response for projecting spill movement.
ADIOS® System	Set of tools developed for NOAA; focus is on weathering up to five days, using a database of over 1,000 crude oil and refined product types.	Requires only limited field data because of large database; applied rapidly in many spill responses.
Ecotoxicological and food web models: AQUATOX, PETROTOX, CATS-5 GBMBS, QWASI, FISHRAND	More recently developed models include the application of probabilistic, spatially explicit and dynamic bioaccumulation formulations, but only simple food chains have been simulated.	These models are primarily used in research and contaminated sediment cleanup applications. Their use in guiding operational response or early recovery following oil spills has been limited.

From LimnoTech 2018 (see references therein).

In general, modeling the transport and fate of oil spills incorporates hydraulic and hydrodynamic transport of water and associated particles (e.g., numerical oil droplet surrogates), and potentially includes processes such as dissolution and evaporation, with a focus on open-water spills.

Several of these models have been developed and/or applied to select locations in the Great Lakes basin, as follows:

- Straits of Mackinac - NOAA has developed a set of three-dimensional hydrodynamic (FVCOM) models for the Great Lakes to simulate currents, water temperatures, short-term water level fluctuations (e.g., seiche, storm surge), ice, and waves. Lakes Michigan and Huron are simulated as one water body, which allows simulation of the complex, bidirectional flow and high energy mixing between the lakes through the Straits of Mackinac (Anderson and Schwab, 2013). In a recent study, Schwab (2016) simulated different hypothetical spill scenarios from Line 5 in the Straits of Mackinac during ice-free conditions, which found that in the worst case scenario (assumed to be 25,000 barrels), the released oil could affect approximately 15 percent of Lake Michigan's open waters and 60 percent of Lake Huron's surface.[9]
- St. Clair River-Lake St. Clair - Shen et al. (1987) developed a Lagrangian model for Lake St. Clair to represent various processes occurring following an oil spill. The model simulated oil slick movement and fate for a hypothetical spill near the mouth of the St. Clair River under varying ice conditions, and results found with ice, the spilled oil accumulates near the edge of the ice and does not spread as far as in the ice-free scenario. Yapa et al. (1994) adapted a more complex model (ROSS3) to simulate oil spill fate and transport in the St. Clair River and Lake St. Clair and demonstrated that the model accurately predicts transport patterns in several areas of the system, based on device tracking data.
- Kalamazoo River - Zhu and Garcia (2016) developed a hydrodynamic model of sediment resuspension and transport to evaluate the risk of remobilization of sedimented oil in the Kalamazoo River system.

There has been generally less work (in particular in the Great Lakes) on application of exposure and effect modeling of oil spills, though work on ecotoxicological and food web models is developing (as summarized in Table 5-1, and reviewed briefly in LimnoTech, 2018).

5.3 Oil spill response

Oil spills can cause a wide range of impacts in the aquatic environment, and improved understanding of potential impacts at the ecosystem level is an important part of effective spill response. Adequate response to an oil spill to minimize damage is critical (NASEM, 2016). An oil spill response plan details what actions should be taken in the event of an oil spill, and the success of a response plan is related to a number of factors including the size and location of a spill, conditions affecting transport and fate, and the efficiency of the spill response. Spill response involves coordination among many entities, including federal, tribal/First Nations, state and provincial agencies as well as local response organizations and any party involved. In general, United States and Canadian Coast Guard staff and vessels oversee spill response in Great Lakes waters (Canadian Coast Guard, US Coast Guard, 2016). In the United States, the

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[9] Note that recent work for the Michigan Pipeline Safety Advisory Board has included an independent risk analysis of the Straits pipeline, with additional modeling of hypothetical spills in the Straits (Meadows et al. 2018).

USEPA is the lead for spills in tributaries and inland waters, while NOAA provides science support during spill response, and covers natural resource damage assessment responsibilities during spill recovery phases (with the US Fish and Wildlife Service involved for inland spills within the region). In Canada, Environment and Climate Change Canada (ECCC) advises the Canadian Coast Guard on spills from ships and is the lead agency for spills to waters that start on federal lands (First Nations reservations, federal airports, etc.). The National Energy Board is typically the lead government agency for spills originating from pipelines. For land-based spills that impact a water course the provincial Ministry of Environment, Conservation and Parks is typically the lead agency.

During a spill response, various types of equipment and tactics are used to limit the contact of oil with sensitive areas (NOAA, 2017), recognizing that some natural processes can lead to degradation or loss of oil from the spill site (Lee et al., 2015). Management response actions that can be pursued are summarized in Table 5-2. In general, an initial goal is to contain/remove as much oil as possible from the water surface following a spill, with decisions on response methods considering multiple factors, including oil characteristics, water and weather conditions, and human and environmental exposure and sensitivities (Bejarano et al., 2014). Although dispersants have been increasingly used in marine environments, they are not typically deployed in freshwater due to the threat posed to drinking water, some evidence of reduced efficacy in cold water, and concern about whether dispersants may enhance the exposure, uptake and toxicity of oil to organisms. Presently, the Canadian and United States governing bodies (through the Joint Marine Pollution Contingency Plan) do not promote the use of dispersants on surface waters within the Great Lakes. Better quantification of the relative benefit versus risk of dispersant use remains an area of uncertainty, and further research is necessary to determine potential dispersant effectiveness in large cold-water systems like the Great Lakes (reviewed in LimnoTech, 2018).

This assessment found that oil spill response activities in the region have involved planning for shoreline, open-lake, and tributary spills. Challenging winter spill response conditions have been recognized, particularly for ice-covered waters, and exercises have been conducted in the Great Lakes and connecting channels to prepare for such spills. Planning for all types and seasons of spills can benefit from enhanced understanding of ecosystem vulnerabilities, including submerged and shoreline habitats. Additional challenges can occur in situations of heavier oil – i.e., inherently heavy oil, or oil that becomes heavier following weathering, as occurred following the Kalamazoo River oil spill (LimnoTech 2018). Furthermore, there can be challenges when particular habitats (e.g. wetlands) are impacted, with the potential that response actions (e.g. heavy equipment) can degrade the habitat in other ways, even if some oil is recovered (Lee et al. 2015).

Table 5-2. Common oil response actions

Response Action	Notes
Containment and recovery	Includes booms or physical barriers to oil which slow the spread of oil and keep it contained. Skimmers are boats and other devices that can recover oil from the water surface.
Sorbents	Larger pieces of equipment or loose material used to aid in cleanup and recovery of oil-contaminated shorelines, sensitive habitats, or small spills, through absorption, adsorption, or both.
Oil removal from shorelines	Various beach washing techniques, ranging from low to high pressure settings, and chosen based on shoreline sediment type (e.g. sand beaches versus bedrock shoreline with no beach).
Vegetation cutting	Cutting of shoreline vegetation, such as in a coastal wetland, with factors such as time of year considered.
Removal of oiled sediment/ Reworking of sediment	Used for shoreline sediments that cannot be easily cleaned otherwise. Reworking of sediment is done to enhance natural degradation processes.
Physical dispersion	Can enhance removal of oil-mineral aggregates, through means such as injecting air into sediment to lift aggregates to surface.
***In situ* burning**	Technique to rapidly reduce the mass of oil at spill site, often done following boom containment. Issues of concern include the air pollution (soot, carbon monoxide, sulfur and nitrogen oxides, etc.), and potential for sinking of residue material.
Bioremediation	This natural process (degradation of oil by microorganisms) can be enhanced either by adding nutrients, or by adding particular microorganisms.
Phytoremediation	Natural process by which some plants (and/or associated microorganisms) can degrade oil, with potential for enhancement.
Chemical dispersion	Chemicals are added to reduce the oil-water interfacial tension, promoting droplet breakup and mix into the water column (and consequently reduce exposure of surface organisms or sensitive coastal habitats). (Not currently recommended in response planning in Great Lakes due to drinking water concerns.)

Drawn from Lee et al. 2015. Note several other techniques are described, including solidifiers and herding agents.

In addition to activities to recover oil following a spill, wildlife rehabilitation is required. As with other response components, success will be based on having a rehabilitation plan prior to an oil spill, as well as being able to work from site-specific knowledge, coordination among the various parties (including any contractors), and utilizing appropriate feeding, hydration and other techniques for affected wildlife. While the outcomes from oil spill rehabilitation efforts have varied significantly, given the varying factors affecting success (e.g., related to organisms sensitivity, physiology, and duration and amount of exposure), some rehabilitation actions following spills have been relatively successful (e.g. following the 2010 Kalamazoo River oil spill (Winter 2013, Dew et al. 2015), and wildlife care and rehabilitation is an important component to the oil spill response strategy.

5.4 Resilience and recovery

Ecosystem resilience has been conceptualized as the capacity of a system to absorb change and maintain a similar set of processes and structure. When an ecosystem exceeds this capacity, the system can shift into a new regime characterized by a different set of processes and structures (Allen et al. 2014). In addition to recognition of the large number of variables that can change and affect a system, the scientific literature around resilience is helping to identify the need to consider whole ecosystems in management decisions rather than simply concentrating on individual species or populations in isolation (e.g., NYOGLECC 2007).

Studies of actual oil spills have identified the potential for resilience and recovery. For example, studies investigating effects of oil spills on marshes indicate that regrowth of plants can overcome the negative impacts of an oil spill once the oil has been degraded (Silliman et al. 2012), and other research has shown resilience in upper trophic levels (e.g. freshwater fish in years following a spill in Brazil), with factors such as spill location and specific population of concern being important (LimnoTech 2018). At the same time, resistance and resilience can vary among different communities, or even the same types of communities in different locations. As noted above in Section 3.3, other human changes to an affected ecosystem (e.g. changes in fishing pressure) also need to be considered in the overall response of ecological communities to oil spills. Given the complexities of Great Lakes ecosystems (with multiple components and multiple stressors), research needs will continue on ecosystem resilience in light of oil spills.

5.5. Summary of oil spill monitoring, modeling, oil spill response, ecosystem resiliency considerations and knowledge gaps

Monitoring of oils spills has continued to advance in recent years. In addition to direct measurement of bulk oil via traditional means, more recently developed *in situ* devices (e.g. fluorometers) can provide near real-time information on oil presence in water, which can help identify the spill extent and inform response strategy. Remote sensing has been increasingly used to monitor oil spill transport and fate, and would be applicable in the case of a major Great Lakes spill, though issues such as cloud cover may prevent acquisition of continuous data following a spill.

As noted in Sections 3 and 4, there is a need for more baseline monitoring in a number of Great Lakes locations to assess potential impacts from oil spills, especially for organisms at particular risk. In addition, in terms of oil spill monitoring, though there is good binational coordination through the Canada-United States Joint Marine Contingency Plan (CANUSLAK Annex), it is important to incorporate any additional recommendations arising through work under the GLWQA, including Annex 5 as appropriate. In addition, since the emphasis here is on ecological impacts, it would be fruitful for managers involved in a new binational Huron to Erie Drinking Water Monitoring Network to consider if the network could also provide information useful in addressing potential ecological impacts of oil spills in the area.

Modeling of oils spills has advanced significantly in the past two decades. There have been significant efforts involving hydrodynamic modeling of potential transport and fate of oil spills in the Great Lakes, including in the Straits of Mackinac. There has been less effort at developing and using models to estimate ecological exposures and effects, and some existing models have had a focus on contaminated sediments and similar environments (e.g., subject to legacy contamination by toxic chemicals). Further development of ecological models specifically applicable to oil spills is an ongoing need, including considering the individual constituents of particular concern in crude oil. In addition, there is a need to couple such models with hydrodynamic/transport and fate models, both to better understand potential vulnerabilities of particular species and locations in general, as well as aid in oil spill response following an actual oil spill.

Oil spill response has received increasing attention in the Great Lakes basin, including through the Canada-United States Joint Marine Contingency Plan, with the Great Lakes Annex most recently updated in 2016 (Canadian Coast Guard, U.S. Coast Guard, 2016). Two key ongoing issues concerning response actions include potential challenges depending on the season (e.g., spills involving ice-covered waters, tributary spills during high flow periods), as well as planning for potential challenges with sinking oil (e.g., following weathering of an oil blend that may be relatively heavy from the start). Finally, it is important that lessons learned in wildlife rehabilitation (including via the major spills of the last decade) be applied in planning for any potential future spill.

Ecological resilience and recovery has received increasing attention in the past two decades, with some oil spill research indicating the potential for populations and/or habitats to recover following oil spills. It is important that the broader ecosystem (including structure and function) be considered in assessing ecological resiliency in light of stressors (including oil spills), rather than just individual species. Given the complexities of the Great Lakes ecosystem (with a diversity of habitat types and species and multiple stressors present), further research is needed on factors that may contribute to ecosystem resilience to oil spills.

Recommendation: Agencies in both countries should expand coordinated monitoring for oil and its components in the Great Lakes ecosystem, including development of real-time systems to ensure early identification of spills. An effort similar to the earlier Huron to Erie Drinking Water Monitoring Network, could serve as a pilot, and any such effort should consider opportunities to inform both ecological and human exposures to oil, as well as response actions.

Recommendation: Agencies should continue to support development of oil spill models, including with application for vulnerable areas and species identified in this assessment. Furthermore, agency program managers and researchers should expand development of ecotoxicological and food web models to accompany existing hydrodynamic models, and to help identifying both more vulnerable areas and species as well as in preventative and response actions.

Recommendation: All relevant agencies as well as industrial oil spill response teams should continue their oil spill response planning, training, and action coordination through respective Coast Guards, and ensure planning is taking into account various contingencies possible in the Great Lakes, including related to seasonal factors such as ice cover as well as complications related to oil weathering and potential submergence.

6.0 Overall assessment

This project entailed a broad review of ecological threats to the Great Lakes basin ecosystem from oil spills, with an emphasis on oil transport sources. In considering potential ecological impacts from oil spills, it is important to consider multiple issues, including exposure aspects such as the type of unrefined oil, the release location (function of the oil transport infrastructure), its bulk characteristics and chemical composition, transport processes following release (including as affected by response actions), sensitivity of affected areas (whether habitats or species), seasonality, and any adaptive capacity of the system.

In terms of species sensitivity to oil spills, this assessment found that while all taxonomic groups have been studied to some extent, the knowledge base is uneven. There is a decent understanding of risks of oil to plankton, and while significant local impacts are possible following a spill, the shorter reproductive cycles may mean the potential for relatively rapid recovery of these organism groups. For fish, there is a good understanding of impacts from oil spills, and early life stages in particular are sensitive to oil, including individual compounds (e.g. PAHs) in the oil. This assessment did find the need for further research on impacts of oil and individual compounds on Great Lakes fish species. Finally, amphibians and reptiles can be heavily impacted by oil spills, but there is a dearth of information available, in particular for freshwater systems like the Great Lakes.

Concerning areas of vulnerability to oil spills in the Great Lakes, a high-level qualitative assessment of vulnerable areas was done, based in particular on oil transport infrastructure locations and ecologically sensitive areas (drawing in particular on recent lake-based conservation assessments). This assessment indicated 15 areas of particular vulnerability, with a common element being a shoreline or nearshore location. Most areas involved nearby oil transport via pipeline or rail (or a combination), and five areas involved refineries as potential oil sources. A common vulnerable habitat type was coastal wetlands, and fish spawning sites (including for lake trout and sturgeon) were also identified as vulnerable at several locations. Wild rice cultivation was also identified as among the vulnerable resources at two areas in the northern portion of the Great Lakes basin (LimnoTech 2018).

Both monitoring and modeling capabilities for oil spills have advanced in recent decades. For monitoring, there is a need for increased baseline monitoring in the region (including potentially vulnerable organisms, and for oil or oil compounds), as well as consideration of any challenges in applying remote sensing to study Great Lakes oil spills. Modeling of oil spills has been an active area of research, with hydrodynamic models of hypothetical spill transport and fate having been applied in the Great Lakes basin, in particular the Straits of Mackinac. While ecological exposure and effects models have been developed, there has been less application to scenarios in the Great Lakes, and there remains a need to integrate fate and transport and ecotoxicological/food web models.

Oil spill response has developed extensively in the past few decades, informed by major marine/coastal spills, and there is binational coordination of response planning in the Great Lakes. There is recognition that oil spill response should lessen the ultimate environmental impact of a spill (compared to no action at all), and multiple response actions can be pursued in the Great Lakes (though there remains a policy against use of chemical dispersants in the lakes).

Issues to consider in spill response in the Great Lakes include potential challenges depending on the season (e.g., spills involving ice-covered waters, tributary spills during high flow periods), as well as potential challenges with sinking oil (e.g., following weathering). Finally, wildlife rehabilitation has been carried out following major spills in the past decade, and insights gleaned can be applied in planning for any potential future spill in the region.

Ecosystem resilience and recovery are important factors that can be relevant to environmental response to oil spills, with some research indicating the potential for populations and/or habitats to recover following oil spills. Better understanding this adaptive capacity (whether of organisms or habitats), coupled with improved understanding of potential oil exposures and sensitivity to oil can lead to more comprehensive vulnerability assessments. Furthermore, given the complexities of the Great Lakes ecosystem, including the presence of multiple stressors which in some cases can interact, there is a need for further research on ecosystem resiliency and oil spills.

Recommendation: Further research is needed on potential vulnerability of Great Lakes habitat and species to oil spills in light of other (including interacting) ecosystem stressors, and any potential implications for ecosystem resiliency.

Recommendation: To inform spill planning and preparedness, and spill response activities, basin-wide monitoring and modeling should be coordinated to maximize integration of geospatial data on lake and watershed ecosystems with hydrodynamic models and ecotoxicological/food web models.

7.0 Summary of recommendations

Through the body of this report 12 recommendations for improved understanding of potential impacts of crude oil spills on water quality and ecosystems of the Great Lakes basin, many with application to oil spill prevention and/or response, are presented. Recommendations include:

- **Recommendation #1**: To increase the ability to identify areas potentially vulnerable to oil spills, the Parties (i.e., federal governments) should identify opportunities to increase availability of data on petroleum infrastructure, including spatial data and transport and storage volumes, whether broadly to the public (as security requirements allow) or to researchers and other interested parties with appropriate disclosure agreements.

- **Recommendation #2:** To enhance spill response planning and preparedness, researchers should carry out further analysis and modeling on the potential transport and fate of the multiple crude oil types transported in the region, with particular emphasis on the vulnerable areas identified in this report.

- **Recommendation #3:** To address the relative paucity of scientific knowledge on the potential impacts of crude oil on freshwater environments, agency program managers should encourage, and researchers should pursue, additional emphasis on investigations into exposures and effects of the multiple crude oil types that are currently transported in the region on ecosystems and organisms. This includes investigations on the toxicity of oil components (such as PAHs and chemicals in diluents), in particular those found in dilbit and other blends, and further exploration of the use of biomarkers in assessing exposures and effects.

- **Recommendation #4:** To appropriately site future oil transportation developments/infrastructure and for species conservation purposes, agency program managers should encourage and researchers should pursue assessments with regards to exposure, sensitivity and adaptive capacity (and hence vulnerability) that include a focus on species of particular cultural and/or conservation concern in the Great Lakes (e.g., fish species such as walleye, lake trout and lake sturgeon), especially those species that may be present in vulnerable areas.

- **Recommendation #5:** In order to better understand the vulnerability to direct and indirect oil exposure for all life stages of less-well-studied freshwater taxa, agency program managers should encourage and researchers should pursue further work on toxicological assessments of amphibians and reptiles, and semi-aquatic mammal populations in Great Lakes tributaries.

- **Recommendation #6:** To support spill response activities and manage for short- and long-term exposure to fish and other organisms following an oil spill, agency program managers should ensure development (or updating, as appropriate) and sharing of detailed habitat and biological sensitivity maps, including baseline surveys, on a binational basis.

- **Recommendation #7:** To reduce vulnerabilities of higher value habitats and inform spill response planning and preparedness, agency program managers should support assessments of how spills from pipeline and rail crossings and nearshore routes might impact river ecosystems and downstream Great Lakes habitats, including seasonal variation, on a binational basis.

- **Recommendation #8**: Agencies in both countries should expand coordinated monitoring for oil and its components in the Great Lakes ecosystem, including development of real-time systems to ensure early identification of spills. An effort similar to the earlier Huron to Erie Drinking Water Monitoring Network could serve as a pilot, and any such effort should consider opportunities to inform both ecological and human exposures to oil as well as response actions.

- **Recommendation #9**: Agencies should continue to support development of oil spill models, including with application for vulnerable areas and species identified in this assessment. Furthermore, agency program managers and researchers should expand development of ecotoxicological and food web models to accompany existing hydrodynamic models, and to help in identifying both more vulnerable areas and species as well as preventative and response actions.

- **Recommendation #10**: All relevant agencies as well as industrial oil spill response teams should continue their oil spill response planning, training and action coordination through respective Coast Guards, and ensure planning is taking into account various contingencies possible in the Great Lakes, including related to seasonal factors such as ice cover as well as complications related to oil weathering and potential submergence.

- **Recommendation #11:** Further research is needed on potential vulnerability of Great Lakes habitat and species to oil spills in light of other (including interacting) ecosystem stressors, and any potential implications for ecosystem resiliency.

- **Recommendation #12:** To inform spill planning and preparedness and spill response activities, basinwide monitoring and modeling should be coordinated to maximize integration of geospatial data on lake and watershed ecosystems with hydrodynamic models and ecotoxicological/food web models.

8.0 References cited

Alexander, C.R., Hooper, M.J., Cacela, D., Smelker, K.D., Calvin, C.S., Dean, K.M., Bursian, S.J., Cunningham, F.L., Hanson-Dorr, K.C., Horak, K.E. and Isanhart, J.P. 2017. CYP1A protein expression and catalytic activity in double-crested cormorants experimentally exposed to deepwater Horizon Mississippi Canyon 252 oil. *Ecotoxicology and environmental safety*, 146, 68-75

Allen, C.R., D.G. Angeler, A.S. Garmestani, L.H. Gunderson, and C.S. Holling. 2014. Panarchy: Theory and application. *Ecosystems*, 17:578-589.

Anderson, E.J., and D.J. Schwab. 2013. Predicting the oscillating bi-directional exchange flow in the Straits of Mackinac. *Journal of Great Lakes Research*, 39(4):9.

Barata, C., Calbet, A., Saiz, E., Ortiz, L., Bayona, J.M., 2005. Predicting single and mixture toxicity of petrogenic polycyclic aromatic hydrocarbons to the copepod *Oithona davisae*. *Environmental Toxicology and Chemistry*, 24, 2992–2999.

Barron, M.G., Hemmer, M.J. and Jackson, C.R. 2013. Development of aquatic toxicity benchmarks for oil products using species sensitivity distributions. *Integrated Environmental Assessment and Management*, 9(4), 610-615.

Batten, S.D., Allen, R.J.S., and Wotton, C.O.M. 1998. The effects of the Sea Empress oil spill on the plankton of the Southern Irish Sea. *Marine Pollution Bulletin*, 36(10), 764–774.

Bejarano, A.C., Clark, J.R. Coelho, G.M. 2014. Issues and Challenges with Oil Toxicity Data and Implications for Their Use in Decision Making: A Quantitative Review, *Environmental Toxicology and Chemistry*, Vol. 9999, 1-11, 2014.

Berrojalbiz, N., Lacorte, S., Calbet, A., Saiz, E., Barata, C. and Dachs, J. 2009. Accumulation and cycling of polycyclic aromatic hydrocarbons in zooplankton. *Environmental Science & Technology*, 43(7), 2295- 2301.

Beyer, J., Trannum, H.C., Bakke, T., Hodson, P.V. and Collier, T.K. 2016. Environmental effects of the Deepwater Horizon oil spill: a review. *Marine Pollution Bulletin*, 110(1), 28-51.

Birn, K., Osuna, J., Velasquez, C., Meyer, J. Owens, S., and Cairns, M. 2014. Crude by rail: The new logistics of tight oil and oil sands growth. *IHS Energy*, 25 p., https://www.ihs.com/pdf/IHS-Oil-Sands- Dialogue-Crude-by-rail-dec-2014_210390110913052132.pdf

Birtwell, I.K. 2008. *Comments on the effects of oil spillage on fish and their habitat - Lake Wabamun, Alberta*. Report submitted to the Department of Fisheries and Oceans, Edmonton, AB.

Bornstein, J.M., Adams, J., Hollebone, B., King, T., Hodson, P.V. and Brown, R.S. 2014. Effects-driven chemical fractionation of heavy fuel oil to isolate compounds toxic to trout embryos. *Environmental Toxicology and Chemistry*, 33(4), 814-824.

Brunke, S., Aubé, G., Legaré, S. and Auger, C. 2016. Analysis and remediation of the 2013 Lac-Mégantic train derailment. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 41(B8):17-23, XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic.

Cailleaud, K., Budzinski, H., Menach, K.L., Souissi, S. and Forget-Leray, J. 2009. Uptake and elimination of hydrophobic organic contaminants in estuarine copepods: an experimental study. *Environmental Toxicology and Chemistry*, 28(2), 239-246.

Canadian Association of Petroleum Producers (CAPP), 2017. *Crude Oil Forecast, Markets and Transportation*, 54 p., http://www.capp.ca/publications-and-statistics/publications/303440

Canadian Coast Guard, U.S. Coast Guard, 2016. Great Lakes Operational Supplement to the Canada-United States Joint Marine Contingency Plan (CANUSLAK Annex), available from http://www.rrt5.org/Portals/0/ResponsePlans/2016_CANUSLAK_JCP_Annex.pdf

Connon, R.E., Geist, J. and Werner, I. 2012. Effect-based tools for monitoring and predicting the ecotoxicological effects of chemicals in the aquatic environment. *Sensors*, 12(9), 12741-12771.

De Lange, H.J., Sala, S., Vighi, M. and Faber, J.H., 2010. Ecological vulnerability in risk assessment—a review and perspectives. *Science of the Total Environment*, 408(18), 3871-3879.

Den Besten, P.J. 1998. Concepts for the implementation of biomarkers in environmental monitoring. *Marine Environmental Research*, 46(1-5), 253-256.

Department of Fisheries and Oceans Canada (DFO), Canadian Science Advisory Secretariat, 2017. A Framework for Assessing Vulnerability of Biological Components to Ship-Source Oil Spills, Science Advisory Report 2017/032, 10 p.

Dew, W.A., Hontela, A., Rood, S.B. and Pyle, G.G. 2015. Biological effects and toxicity of diluted bitumen and its constituents in freshwater systems. *Journal of Applied Toxicology*, 35(11), 1219-1227.

Dollhopf, R. and Durno, M. 2011. Kalamazoo River Enbridge Pipeline Spill 2010. In International Oil Spill Conference Proceedings (IOSC) (Vol. 2011, No. 1, p. abs422). American Petroleum Institute.

Dupuis, A. and Ucan-Marin, F. 2015. A literature review on the aquatic toxicology of petroleum oil: An overview of oil properties and effects to aquatic biota, Fisheries and Oceans Canada, Science Advisory Secretariate. Fisheries and Oceans Canada, Science Advisory Secretariate, Doc, 7.

Dynamic Risk Assessment Systems, Inc., 2017. *Alternatives Analysis for the Straits Pipeline - Final Report*, Final Report, Revision 2, October 26, 2017, 379 p. https://mipetroleumpipelines.com/document/alternatives-analysis-straits-pipeline-final-report

Energy Information Administration (EIA), 2017. Annual Energy Outlook 2017 with Projections to 2050, 64 p. https://www.eia.gov/outlooks/aeo/

EIA, 2018a. Glossary, available from https://www.eia.gov/tools/glossary/index.php

EIA, 2018b. Petroleum Marketing Monthly, Glossary (not dated), available from https://www.eia.gov/petroleum/marketing/monthly/pdf/glossary.pdf

EIA, 2018c. Annual Energy Outlook 2018 with Projections to 2050, 64 p. https://www.eia.gov/outlooks/aeo/

EIA, 2018d. Petroleum Supply Annual, Volume 1, available from https://www.eia.gov/petroleum/supply/annual/volume1/

Esler, D., Ballachey, B. E., Trust, K. A., Iverson, S. A., Reed, J. A., Miles, A. K., Henderson, J.D., Woodin, B.R., Stegeman, J.J., McAdie, M., Mulcahy, D.M., Wilson, B. W. (2011). Cytochrome P4501A biomarker indication of the timeline of chronic exposure of Barrow's goldeneyes to residual Exxon Valdez oil. *Marine Pollution Bulletin, 62*(3), 609-614. doi: https://doi.org/10.1016/j.marpolbul.2010.11.015

Federle, T.W., Vestal, J.R., Hater, G.R., Miller,M.C., 1979. Effects of Prudhoe Bay crude oil on primary production and zooplankton in arctic tundra thaw ponds. *Marine Environmental Research*, 2, 3–18.

Fingas, M. 2011. *Introduction to Oil Chemistry and Properties.* In *Oil Spill Science and Technology*. Edited by M. Fingas. Gulf Professional Publishing, Boston. 51-59.

Fodrie, F.J., Able, K.W., Galvez, F., Heck, K.L., Jensen, O.P., Lopez-Duarte, P.C., Martin, C.W., Turner, R.E. and A. Whitehead. 2014. Integrating organismal and population responses of estuarine fishes in Macondo spill research. *Bioscience* 64: 778-788.

Franks Taylor, R., A. Derosier, K. Dinse, P. Doran, D. Ewert, K. Hall, M. Herbert, M. Khoury, D. Kraus, A. Lapenna, G. Mayne, D. Pearsall, J. Read, and B. Schroeder. 2010, June. The Sweetwater Sea: An International Biodiversity Conservation Strategy for Lake Huron: Technical Report. The Nature Conservancy, Environment Canada, Ontario Ministry of Natural Resources, Michigan Department of Natural Resources and Environment, Michigan Natural Features Inventory Michigan Sea Grant, and The Nature Conservancy of Canada, Lansing, MI, 264 with appendices.

Frittelli, J., Parfomak, P.W., Ramseur, J.L., Andrews, A., Pirog, R. and Ratner, M., 2014. *U.S. rail transportation of crude oil: Background and issues for Congress*. Congressional Research Service, Report R43390, 25 p.

Graziano, M., Gunther, P., and Lema, E., 2017. The Economic Impact of Crude Oil Transportation in the Great Lakes- St. Lawrence Region: A Preliminary Study, available from https://www.glc.org/work/oil-transportation/publications/

Great Lakes Commission (GLC), 2015. Issues and trends surrounding the movement of crude oil in the Great Lakes-St. Lawrence River Region, available from https://www.glc.org/work/oil-transportation/publications/

Great Lakes Environment Center, 2012. *Chironomus dilutus* and *Hyalella azteca* 10-day Whole Sediment Toxicity Testing Results, Kalamazoo River Sediment Sampling, Line 6B Oil Spill Marshall, Michigan.

Haney, J.C., Jodice, P.G., Montevecchi, W.A. and Evers, D.C. 2017. Challenges to oil spill assessment for seabirds in the deep ocean. *Archives of Environmental Contamination and Toxicology*, 1-7.

Hodson, P.V. 2017. The toxicity to fish embryos of PAH in crude and refined oils. Archives of *Environmental Contamination and Toxicology*, 1-7.

Hoff, R.Z., 1993. Bioremediation: an overview of its development and use for oil spill cleanup. *Marine Pollution Bulletin*, 26(9), 476-481.

Hollebone, B.. 2011. *Measurement of Oil Physical Properties*, In *Oil Spill Science and Technology*. Edited by M. Fingas. Gulf Professional Publishing, Boston. 63-86.

Hull, B. 2017. *Status of Infrastructure Related to Crude Oil Transportation in the Great Lakes-St. Lawrence River Region*. Prepared for the Great Lakes Commission.

International Joint Commission (IJC), 2006. Report on Spills in the Great Lakes Basin, available from http://www.ijc.org/files/publications/ID1594.pdf

Ji, K., Seo, J., Liu, X., Lee, J., Lee, S., Lee, W., Park, J., Khim, J.S., Hong, S., Choi, Y. and Shim, W.J. 2011. Genotoxicity and endocrine-disruption potentials of sediment near an oil spill site: two years after the Hebei Spirit oil spill. *Environmental Science & Technology*, 45(17), 7481-7488.

Kostka, J.E., Prakash, O., Overholt, W.A., Green, S.J., Freyer, G., Canion, A., Delgardio, J., Norton, N., Hazen, T.C. and Huettel, M. 2011. Hydrocarbon-degrading bacteria and the bacterial community response in Gulf of Mexico beach sands impacted by the Deepwater Horizon oil spill. *Applied and Environmental Microbiology*, 77(22), 7962-7974.

LOBSWG - Lake Ontario Biodiversity Strategy Working Group. 2009. *The Beautiful Lake: A Binational Biodiversity Conservation Strategy for Lake Ontario*. The Nature Conservancy, Nature Conservancy Canada, and US–Canada Lake Ontario Lakewide Management Plan. Nature Conservancy of Canada, Toronto, 40 pp.

Lee, Kenneth (chair), Michel Boufadel, Bing Chen, Julia Foght, Peter Hodson, Stella Swanson, Albert Venosa. (2015). *Expert Panel Report on the Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments*. Royal Society of Canada, Ottawa, ON. ISBN: 978-1-928140-02-3

Leifer, I., Lehr, W.J., Simecek-Beatty, D., Bradley, E., Clark, R., Dennison, P., Hu, Y., Matheson, S., Jones, C.E., Holt, B. and Reif, M., 2012. State of the art satellite and airborne marine oil spill remote sensing: Application to the BP Deepwater Horizon oil spill. *Remote Sensing of Environment*, 124, 185-209.

Li, H. and Boufadel, M.C. 2010. Long-term persistence of oil from the Exxon Valdez spill in two-layer beaches. *Nature Geoscience*, 3(2), 96-99.

LimnoTech, 2018. Impacts of unrefined liquid hydrocarbons on water quality and aquatic ecosystems of the Great Lakes Basin, available at http://www.ijc.org/

LSLAMP - Lake Superior Lakewide Action and Management Plan - Superior Work Group. 2013, updated March 2015. *Lake Superior Biodiversity Conservation Assessment*. 130 p. Available from https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/wholesystems/greatlakes/basin/biodiversity/Documents/BCASuperiorUpdatedMarch2015.pdf

Madison, B. N., Hodson, P. V., & Langlois, V. S. (2015). Diluted bitumen causes deformities and molecular responses indicative of oxidative stress in Japanese medaka embryos. *Aquatic Toxicology, 165*, 222-230. doi:10.1016/j.aquatox.2015.06.006

Madison, B. N., Hodson, P. V., & Langlois, V. S. (2017). Cold Lake Blend diluted bitumen toxicity to the early development of Japanese medaka. *Environmental Pollution, 225*, 579-586. doi:10.1016/j.envpol.2017.03.025

Marwood, C.A., Smith, R.E.H., Solomon, K.R., Charlton, M.N., and Greenberg, B.M. 1999. Intact and photomodified polycyclic aromatic hydrocarbons inhibit photosynthesis in natural assemblages of Lake Erie phytoplankton exposed to solar radiation. *Ecotoxicology and Environmental Safety*, 44(3), 322–327.

Marwood, C.A., Smith, R.E.H., Charlton, M.N., Solomon, K.R., and Greenberg, B.M. 2003. Photoinduced toxicity to Lake Erie phytoplankton assemblages from intact and photomodified polycyclic aromatic hydrocarbons. *Journal of Great Lakes Research*, 29(4), 558–565.

Marty, J. and Nicoll, A., 2017. *Environmental Sensitivity to Oil Exposure in the Great Lakes Waters: A multimodal approach*. Prepared for the Great Lakes Commission.

Mayer, L.A., et al. 2013. *An Ecosystem Services Approach to Assessing the Impacts of the* Deepwater Horizon *oil spill in the Gulf of Mexico*. National Academies Press, Washington, DC. https://doi.org/10.17226/18387

Meadows, G. et al. 2018. *Independent Risk Analysis for the Straits Pipelines*, Final Report, September 15, 2018, Michigan Technological University, available from https://mipetroleumpipelines.com/document/independent-risk-analysis-straits-pipelines-final-report

National Academies of Sciences, Engineering, and Medicine (NASEM), 2016. *Spills of Diluted Bitumen from Pipelines: A Comparative Study of Environmental Fate, Effects, and Response*. Washington, DC: The National Academies Press.

National Energy Board (NEB). 2017. *Canada's Energy Future 2017*, 90 p. Government of Canada. https://www.neb-one.gc.ca/index-eng.html

Nixon, Z. and J. Michel. 2015. Predictive Modeling of Subsurface Shoreline Oil Encounter Probability from the Exxon Valdez Oil Spill in Prince William Sound, Alaska. *Environmental Science & Technology*, 49: 4354-4361.

New York Ocean and Great Lakes Ecosystem Conservation Council (NYOGLECC), 2007. *Transitioning the Ocean and Great Lakes to a Sustainable Future: Implementation of Ecosystem-Based Management in New York State*, 22 p. http://www.esf.edu/glrc/documents/OGLECC_Implementation%20of%20EBM%20Report%20Sept200 7.pdf

O'Laughlin, C. M., Law, B. A., Zions, V. S., King, T. L., Robinson, B., & Wu, Y. S. (2017). Settling of dilbit-derived oil-mineral aggregates (OMAs) & transport parameters for oil spill modelling. *Marine Pollution Bulletin, 124*(1), 292-302. doi:10.1016/j.marpolbul.2017.07.042

Pearsall, D., P. Carton de Grammont, C. Cavalieri, P. Doran., L. Elbing, D. Ewert, K. Hall, M. Herbert, M. Khoury., S. Mysorekar., S. Neville., J. Paskus., and A. Sasson. 2012a. Michigami: Great Water. Strategies to Conserve the Biodiversity of Lake Michigan. Technical Report. A joint publication of The Nature Conservancy and Michigan Natural Features Inventory. 309 p. with Appendices.

Pearsall, D., P. Carton de Grammont, C. Cavalieri , C. Chu, P. Doran, L. Elbing, D. Ewert, K. Hall, M. Herbert, M. Khoury, D. Kraus, S. Mysorekar, J. Paskus and A. Sasson. 2012b. Returning to a Healthy Lake: Lake Erie Biodiversity Conservation Strategy, Technical Report. A joint publication of The Nature Conservancy, Nature Conservancy of Canada, and Michigan Natural Features Inventory, Lansing, Michigan, 340 p. with Appendices.

Pearsall, D.R., Khoury, M.L., Paskus, J., Kraus, D., Doran, P.J., Sowa, S.P., Taylor, R.F. and Elbing, L.K. 2013. "Make no little plans": Developing biodiversity conservation strategies for the Great Lakes. Environmental Practice: *Environmental Reviews and Case Studies*, 15(4), 462-480.

Perhar, G and G.B. Arhonditsis, 2014. Aquatic ecosystem dynamics following petroleum hydrocarbon perturbations: A review of the current state of knowledge, Journal of Great Lakes Research 40(3): 56-72.

Polich, M., 2017. Oil Transportation Regulatory Framework, Great Lakes Commssion, available at https://www.glc.org/work/oil-transportation/publications/

Polich, M., Bergeron, D., Leduc-Lapierre, M., 2017. *Using and Understanding the Term RISK*, Great Lakes Commission, available from https://www.glc.org/work/oil-transportation/publications/

Riseng, C.M., Wehrly, K.E., Wang, L., Rutherford, E.S., McKenna Jr, J.E., Johnson, L.B., Mason, L.A., Castiglione, C., Hollenhorst, T.P., Sparks-Jackson, B.L. and Sowa, S.P., 2017. Ecosystem classification and mapping of the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, https://doi.org/10.1139/cjfas-2017-0242

Rivers, A.R., Sharma, S., Tringe, S.G., Martin, J., Joye, S.B. and Moran, M.A. 2013. Transcriptional response of bathypelagic marine bacterioplankton to the Deepwater Horizon oil spill. *The ISME Journal*, 7(12), 2315.

Rosenberger, A. L. J., MacDuffee, M., Rosenberger, A. G. J., & Ross, P. S. (2017). Oil Spills and Marine Mammals in British Columbia, Canada: Development and Application of a Risk-Based Conceptual Framework. *Archives of Environmental Contamination and Toxicology, 73*(1), 131-153.

Santos, C. F., Carvalho, R., & Andrade, F. (2013). Quantitative assessment of the differential coastal vulnerability associated to oil spills. *Journal of Coastal Conservation, 17*(1), 25-36.

Sargian, P., Mostajir, B., Chatila, K., Ferreyra, G.A., Pelletier, É., Demers, S., 2005. Nonsynergistic effects of water-soluble crude oil and enhanced ultraviolet-B radiation on a natural plankton assemblage. Mar. Ecol. Prog. Ser. 294, 63–77.

Scott, G. I., Fulton, M. H., DeLorenzo, M. E., Wirth, E. F., Key, P. B., Pennington, P. L., Kennedy, D.M., Porter, D., Chandler, D.T., Scott, C.H., and Ferry, J. L. (2013). The Environmental Sensitivity Index and Oil and Hazardous Materials Impact Assessments: Linking Prespill Contingency Planning and Ecological Risk Assessment. *Journal of Coastal Research*, 100-113.

Shea, D., Hartman, K., Qiu, S. 2015. *Transporting crude oil by rail: State and federal action*, National Conference of State Legislatures, available from http://www.ncsl.org/research/energy/transporting-crude-oil-by-rail-state-and-federal-action.aspx

Short, J.W. 2017. Advances in understanding the fate and effects of oil from accidental spills in the United States beginning with the Exxon Valdez. *Archives of Environmental Contamination and Toxicology*, 1-7.

Schwab, D.J. 2016. *Statistical Analysis of Straits of Mackinac Line 5: Worst Case Spill Scenarios*. University of Michigan Water Center. Ann Arbor, MI.

Shen, H.T., Yapa, P.D., Wang, D.S., Yang, X.Q. 1993. A mathematical model for oil slick transport and mixing in rivers. Cold Regions Research and Engineering Lab, Hanover, NH, No. CRREL-SR-93-21.

Silliman, B.R., van de Koppel, J., McCoy, M.W., Diller, J., Kasozi, G.N., Earl, K., Adams, P.N. and Zimmerman, A.R., 2012. Degradation and resilience in Louisiana salt marshes after the BP–Deepwater Horizon oil spill. *Proceedings of the National Academy of Sciences*, 109(28), 11234-11239.

U.S. Environmental Protection Agency (USEPA), 1992. *Framework for Ecological Risk Assessment*, EPA/630/R-92/001.

USEPA, 2018, *Report on the Environment, Glossary* (not dated), available from https://www.epa.gov/report-environment/roe-glossary#b

Winter, J. 2013. *Assessing Natural Resource Impacts from the Enbridge Pipeline Spill into the Kalamazoo River, Oil sands products forum and working group*. NOAA Office of Response and Restoration.

Yapa, P.D., Shen, H.T., Angammana, K.S. 1994. Modeling oil spills in a river—lake system. *J. Mar. Syst*. 4, 453–471.

Zhu, Z. and García, M.H. 2016. Numerical modeling of sediment traps after the 2010 Kalamazoo River oil spill, Michigan, USA. *River Flow* 2016, 1383-1389. CRC Press.