Impacts of Unrefined Liquid Hydrocarbons on Water Quality and Aquatic Ecosystems of the Great Lakes Basin

Final Report

Prepared for:
The International Joint Commission

January 31, 2018

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ADIOS®	Automated Data Inquiry for Oil Spills
AHR	Aryl Hydrocarbon Receptor
AOPL	Association of Oil Pipelines
AWB	Access Western Blend
CAPP	Canadian Association of Petroleum Producers
CATS-5	Contaminant in Aquatic and Terrestrial ecoSystems
CCG	Canadian Coast Guard
CLB	Cold Lake Blend
Dilbit	Diluted Bitumen
DOE	Department of Energy
EC	Effective Concentration
EC50	Effective Concentration, 50% organism response
EIA	U.S. Energy Information Administration
ELS	Early Life Stage
EPA/U.S. EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency (U.S.)
FVCOM	Finite Volume Community Ocean Model
GBMBS	Green Bay Mass Balance Study
GLC	Great Lakes Commission
GLCFS	Great Lakes Coastal Forecasting System
GLSLR	Great Lakes-St. Lawrence Region
HEC	Huron-Erie Corridor
HMW	High Molecular Weight
IFEM	Integrated Fates and Effects Model

IJC	International Joint Commission
K_{OW}	Octanol-Water Partitioning Coefficient
LC50	Lethal Concentration, 50% mortality
LMW	Low Molecular Weight
MAH	Monoaromatic Hydrocarbons
MBD	Thousand Barrels Per Day
MEDSLIK	Mediterranean oil spill model
MPA	Marine Preservation Association
NIMS	National Incident Management System
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NOAA-GLERL	NOAA's Great Lakes Environmental Research Laboratory
OMA	Ohio-Monongahela-Allegheny River System
OPA	Oil Pollution Act
PAHs	Polycyclic Aromatic Hydrocarbons
PPM	Parts Per Million
QWASI	Quantitative Water, Air, Sediment Interaction
RRT	Regional Response Team
SIMAP	Spill Impact Modeling Application
SSCs	Scientific Support Coordinators
SST	Scientific Support Team
Synbit	Synthetic crude oil mixed with bitumen
TIR	Thermal Infrared

1 Executive Summary

This assessment of potential impacts of unrefined liquid hydrocarbons (crude oil) on water quality and aquatic ecosystems of the Great Lakes was conducted in cooperation with members of the International Joint Commission Science Advisory Board's Energy Transport and Water Quality Work Group. This report 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. Crude oil includes normal crudes, shale oil, diluted bitumen, and synthetic crude/bitumen blends.

This synthesis consists of the following elements:

- Overview of unrefined liquid petroleum (crude oil) transported in the region, and a summary of major releases over the last few decades;
- Overview of the methods of transportation, specific to the Great Lakes Region;
- Discussion of oil in the Great Lakes, with an overview of the sources of oil and relevant characteristics of different lakes and tributaries in the region;
- Evaluation of ecologically important regions that overlap with oil transportation corridors or likely spill movement pathways;
- Summary of the fate and behavior of oil in waterways with a focus on Great Lakes processes;
- Summary of effects of oil on aquatic organisms;
- Discussion of oil spill response, mainly focused on ecological aspects and modeling efforts in the Great Lakes and other regions, and
- Identification of knowledge gaps and recommendations for future research.

Findings

Results of the assessment include the following:

- A rapid increase in oil production in North Dakota, Montana, and Alberta since 2010, and the lack of sufficient infrastructure to transport, refine, and deliver crude oil to refineries and markets from the central northern U.S. and south-central Canada to the east, west, or south, without passing through the Great Lakes watershed, have created the need to understand potential changes to ecosystem threats and vulnerabilities in the Great Lakes and their tributaries;
- Pipelines can release substantial amounts of crude oil into river or lake habitats; rail accidents may present less of an environmental hazard due to smaller volumes of worst-case releases,

although spill volumes can still be quite large; refineries, terminals, and storage facilities can generate large-volume spills, but they are often located in areas that are already ecologically degraded and perhaps less sensitive to exposure; spills from ships or barges of persistent oil in the Great Lakes are outside the scope of this crude oil study;

- Detailed ecological analyses and geodatabases of Great Lakes coastal and watershed habitats have been recently developed by binational teams; they were created to guide habitat protection and restoration planning, without specific consideration of oil spill threats and vulnerabilities;

- Previous oil-related assessments have concentrated on potential human exposure via drinking water and bi-national coordination in the Huron-Erie Corridor (e.g., IJC 2006), as well as considerations regarding spills from pipelines that cross the Straits of Mackinac;

- 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, and exercises have been conducted in the Great Lakes and connecting channels to prepare for such spills, although planning for all types and seasons of spills can benefit from enhanced understanding of ecosystem vulnerabilities, including both submerged and shoreline habitats,

- Particular attributes such as the volatility and flammability of Bakken light crude oil, and the time-variant density of released heavy crude oil that can sink in water need to be considered when ecosystem vulnerabilities and threat mitigation are assessed,

- Acute spill impact effects on larger birds and aquatic organisms, and their responses to rehabilitation, as well as fish impacts, are reasonably well known based on experience with prior spills, such as the Kalamazoo River spill in 2010; longer term ecological impacts and effective remediation techniques, especially for benthic and wetland habitats and for aquatic invertebrates and early life stages of vertebrates, are less well understood,

- Hydrodynamic models have proven useful for simulating physical processes that influence the rates of movement and dispersion of oil from various hypothetical release locations in the Great Lakes system, and under various weather conditions, although they require additional development and validation, as well as better linkage with models that simulate oil fate and ecological effects.

Data and Knowledge Gaps

Important gaps in information, technology, and process understanding that may impact the ability to respond to oil spills in the Great Lakes-St. Lawrence Region, and which merit further research, include the following topics and areas where enhanced capabilities are needed;

- Numerical models that can perform large-scale, multi-dimensional, high-resolution analysis representing both physical and ecological conditions expected in large lakes or rivers, over significant time periods;

- Understanding of species-specific sensitivity to oil spills, especially of species that are of greatest importance to tribal subsistence, culture, and commerce, as well as for federal or state/provincial species listed as threatened or endangered, and for key commercial and recreational species;

- Understanding of the sensitivity to oil of amphibians, reptiles, and semi-aquatic mammals, and the food web consequences of the loss or impairment of their populations;

- Knowledge of the links between biomarkers of oil exposure in individual organisms and their significance for whole populations, as well as for long-term community-level and ecosystem-scale impacts of oil spills;

- Information on specific behavior and toxicity in the environment of diverse crude oil types, especially for the suite of diluted and blended bitumen mixtures;

- More complete analysis of how variable and transient environmental conditions affect spill behavior and ecological vulnerability (e.g., spills during high flow caused by spring snow melt, ice formation and breakup, or migratory waterbird stopover and nesting);

- Understanding and identification of future crude oil shipping routes, quantities, and composition in the region based on fluctuating prices, declining production from the Bakken Formation, alternative pipeline and terminal construction, regulatory changes, and variable regional and global demand.

Recommendations

Recommendations for improved understanding of potential impacts of crude oil spills on water quality and ecosystems of the Great Lakes region include the following:

- There is a need for investigations into the effects of the various crude oil types that are currently transported in the region on ecosystems and organisms; studies of single constituents (e.g., PAHs) are critical to understanding the toxicity of hydrocarbon mixtures in crude oil, but they may not fully capture potential impacts of bitumen on aquatic organisms and ecosystems in the region; application the PETROTOX model (Redman et al. 2012) to prediction of toxicity of crude oil types transported through the Great Lakes region may be valuable,

- Based on the very limited information available, baseline assessments of semi-aquatic mammal populations in Great Lakes tributaries and research on their sensitivity to direct and indirect oil exposure at all life stages are needed; similarly, research on the effects of crude oil spills and their implications for amphibians is also needed, especially focusing on critical periods in their life histories (e.g., egg development, metamorphosis, overwintering).

- Detailed and updated spawning and biological sensitivity maps are needed to assess reproductive outcomes of potentially impacted organisms; baseline surveys in general are valuable to document impacts of spills, particularly of widespread indicators of sediment and water quality such as benthic invertebrates.

- Better assessment of how spills from pipeline and rail crossings and nearshore routes might impact river ecosystems and downstream Great Lakes habitats, including consideration of seasonal variation in ecological vulnerability (e.g., a spill during river spawning) is needed to properly identify and mitigate vulnerabilities in infrastructure, operating procedures, and potential spill response.

- A coordinated basin-wide monitoring and modeling program, which integrates existing geospatial data on lake and watershed ecosystems with data assimilation in operational models (e.g., FVCOM) of dynamic conditions (wind, currents, wave height, water temperature, operating conditions of crude oil transport and storage systems), and oil fate and transport capabilities, would position the region for informed reduction of spill threats, and prudent decision-making during incidents regarding minimization of ecosystem impacts.

2 Project Description

2.1 Project Tasks

The following three project task descriptions were developed by the work group and provided guidance on the objectives and scope of this assessment project at the point of proposal solicitation in early 2017. This report constitutes the Task 1 deliverable, the Science Synthesis.

Task Descriptions:

Task	Description/Deliverable*
1	Science Synthesis: LimnoTech will complete a detailed report that synthesizes the science related to observed and potential impacts of unrefined liquid hydrocarbons on Great Lakes water quality and ecosystem condition, and identify additional research, monitoring and information needs. This synthesis will include (1) current knowledge on potential environmental impacts to water quality and the ecosystem in the Great Lakes Region, addressing surface water quality and ecological impacts in the water column, benthic environment, and coastal habitats, including food web considerations; and issues around spill modeling (including modeling of bulk hydrocarbon transport as well as modeling of exposure and effects of bulk hydrocarbons and constituents). The review will aim to expand on other major recent reviews (e.g., Lee et al. 2015; Perhar and Arhonditsis, 2014), including through an emphasis on organism groups of particular relevance in the Great Lakes; address particularly sensitive habitats (drawing on recent Great Lakes mapping and other work); and consider the various types of unrefined liquid hydrocarbons transported in the region (light and heavy crude, diluted bitumen, etc.). Impacts to human health will not be considered, though the overall assessment will inform such considerations. The synthesis will also (2) identify research, monitoring, and information needs around hydrocarbon hazards to organisms and habitats in the region, consider status of implementation of recommendations from the 2006 IJC spill report, and include science and policy recommendations that could form the basis of advice to the Parties. LimnoTech will complete the science synthesis using refereed and grey literature covering the Great Lakes (or otherwise applicable regions), with consultations (email or telephone interviews) with experts from multiple sectors as needed to ensure a comprehensive assessment.
2	Assistance in development of summary report, including recommendations: LimnoTech will assist in development of the summary report (including recommendations, based on the science synthesis report), and will also assist with any subsequent work and discussions, involving collaboration of the Work Group members, IJC's advisory board members, IJC staff, and subject matter experts identified by IJC.
3	Communication with Work Group members and other individuals: LimnoTech will coordinate on this project with the Work Group and with other IJC boards, including Science Advisory Board's Research Coordination Committee, and as appropriate the Water Quality Board, as well as other individuals/stakeholders, including industry representatives, non-government organizations, agencies including but not limited to contingency planning personnel for designated

	sectors/regions of U.S. Coast Guard and Canadian Coast Guard spill response, the Great Lakes Commission, Great Lakes Fishery Commission and Great Lakes Sea Grant Network. A subgroup of the Work Group will have the lead role in these coordinating efforts. LimnoTech will have an initial meeting with Work Group members (or a subset) to discuss details of the project work, including scope, approach, potential information sources, and periodic updates. LimnoTech will participate in at least three additional meetings (some or all by conference call, as appropriate) – (1) a mid-project status update, (2) following submission of the draft technical report, and (3) following preparation of the draft summary report. There will be periodic conference calls and email correspondence between LimnoTech and Work Group members as needed through the course of the project.

2.2 Project Communication

Project kickoff call, April 25, 2017

A project kickoff call organized by IJC was conducted to introduce the Work Group and LimnoTech team members, provide an overview of the project objectives, project approach and expectations of the team members. The meeting provided value in clarifying the spatial extent of the project focus within the Great Lakes Region, key researchers and efforts within the region, the general types of information to be used in the project, spatial data sources, and information on regional and national meetings that could serve to support the project. The call concluded with a description of the literature review and compilation that will form the science-based foundation for the project.

Follow-up call, August 8, 2017

A call organized by IJC was conducted to update the Work Group and LimnoTech team members, provide an overview of the project objectives, project approach and expectations of the team members. The meeting provided value in clarifying the project focus within the Great Lakes Region, key researchers and efforts within the region, the general types of information to be used in the project, and information on regional and national meetings that could serve to support the project.

Follow-up call, October 16, 2017

This call consisted of an overview of the first draft of the final report and associated discussion.

Follow-up call, December 11, 2017

This call included sharing of some recent developments and upcoming events related to the topic of the assessment, as well as an overview and discussion about some of the major changes incorporated into the 2nd draft of the final report.

Follow-up call, January 19, 2018

This call included Work Group, IJC, and LimnoTech leadership, and served as a status update for the final round of revisions of the assessment report.

2.3 Project-related Workshops and Symposia

Crude Move Symposium, June 8-9, 2017

In Cleveland, Ohio, the Great Lakes and Gulf Coast Sea Grant Networks, the Great Lakes Commission, and the IJC hosted the workshop titled, "Crude Move Symposium: Oil Transportation Infrastructure, Economics, Risk, Hazards and Lessons Learned". The symposium assembled a range of regional experts conducting research and implementing activities related to oil resource transportation, economics, hazard and risks, and emergency response activities in the Great Lakes Region. The symposium included experiences from the Gulf of Mexico as well as panel discussions covering a range of topics. John Bratton and Jen Daley (LimnoTech) both attended the conference and recorded key findings from the event.

28th Annual No-Spills Conference, January 3-5, 2018

This annual conference was held in Acme, Michigan and is described as "a premier environmental and emergency response event focused on preventing hazardous material spills into the Great Lakes and its tributaries". [The]…"conference encourages and facilitates interaction between agencies, industry professionals, subject matter experts and the public". Presenters at the 2018 conference included representatives from the U.S. Coast Guard, Sea Grant, USEPA, NOAA's Thunder Bay National Marine Sanctuary, state agencies, the energy industry, the marine salvage industry, universities, environmental non-profit groups, and environmental consulting companies.

2.4 Project Deliverables

2.4.1 Draft Literature Compilation, May 25, 2017

Following the April 25 kickoff call, LimnoTech conducted a synthesis of the available knowledge and literature relevant to the aquatic impacts of oil spills. These sources include peer-reviewed articles, conference proceedings, government publications, books, other published articles, and industry reports and databases provided by the supporting members. The compiled sources were organized into primary topic areas of Biological Impacts, Environmental Fate and Behavior, Ecological Impacts, Oil Spill Response, Monitoring, Modeling, Policy, Dispersants, Non-Peer Reviewed and Other Literature, and Spatial Data Resources. On May 25, this 21-page compilation was sent to Work Group leads to distribute to other members for feedback on the assembled resources, and get comments and suggestions on other resources not identified, that support the project.

2.4.2 Interim Progress Report, June 30, 2017

LimnoTech provided a progress report which summarized updates of activities that supported the project and highlighted key findings. The key areas of project activities were outlined and described in a draft format similar to that envisioned for the final report.

2.4.3 Literature Review Update, July 20, 2017

Following the interim report, LimnoTech updated the literature review which compiled additional sources organized into primary topic areas of Biological Impacts, Environmental Fate and Behavior, Ecological Impacts, Oil Spill Response, Monitoring, Modeling, Social Science, Dispersants, Non-Peer Reviewed and Other Literature, and Spatial Data Resources. On July 20, the 25-page compilation was sent to Work Group leads to distribute to other members for feedback on the assembled resources, and get comments and suggestions on other resources not identified, that support the project.

2.4.4 First Draft Final Report, September 15, 2017

LimnoTech provided a draft of the final report that included narrative text, figures, tables, and references for review by the work group members, co-chairs, and IJC staff. Additional review comments were solicited and received from external subject matter experts, specifically regarding proper industry terminology to describe forms of crude oil that were unrefined but still partially processed (e.g., diluted or mixed) for transport. The outside industry reviewers also commented on other aspects of the report based on their expertise, including toxicology sections and descriptions of prior crude oil releases and accidents.

2.4.5 Second Draft Final Report, December 6, 2017

This draft report addressed comments received on the first draft and included modified and additional text, tables, figures, and references. The work group requested an expansion of the initial project scope to include an addition round of review and comments, and preparation of a responsive third and final draft of the report in January of 2018.

2.4.6 Final Report (version 3), January 31, 2018

This final revision incorporated additional comments received between December 6, 2017, and January 19, 2018.

3
Science Synthesis

The purpose of this science synthesis is to provide an overview of the science related to observed and potential impacts of unrefined liquid hydrocarbons, subsequently referred to as crude oil, on Great Lakes water quality and ecosystem condition, and identify additional research, monitoring and information needs. Crude oil includes normal crudes, shale oil, diluted bitumen, and synthetic crude/bitumen blends. This synthesis includes current knowledge on potential environmental impacts to water quality and the ecosystem in the Great Lakes Region, addressing surface water quality and ecological impacts in the water column, benthic environment, and coastal habitats, including food web considerations; and issues around spill modeling. For the purposes of this report, the Great Lakes Region or the Great Lakes-St. Lawrence Region (GLSLR), refers to the Great Lakes watershed and tributaries, the lakes themselves, the connecting channels, and the upper St. Lawrence River above the dam at Cornwall, Ontario. Some discussion will necessarily include regions outside of this area in description of crude oil sources to the west, and transportation destinations to the east of the basin.

The review aims to expand on other major recent reviews (e.g., Lee et al. 2015, Perhar and Arhonditsis 2014, McKnight et al. 2016), and addresses organism groups of ecological relevance; particularly sensitive habitats (drawing on recent Great Lakes mapping and other work); and considers the various types of crude oil transported in the region (light and heavy crude, diluted bitumen, etc.). The synthesis also briefly identifies research, monitoring, and information needs around hydrocarbon hazards to organisms and habitats in the region, and considers the status of implementation of recommendations from the 2006 International Joint Commission (IJC) spill report. This synthesis was completed following a detailed literature review, which included relevant refereed and gray literature covering an array of topics including biological impacts, environmental fate and behavior, and spill modeling.

This report provides an overview of the science related to observed and potential impacts of unrefined liquid hydrocarbon releases on Great Lakes water quality and ecosystem condition, and identifies additional research, monitoring, and information needs. This synthesis consists of the following elements:

- Overview of unrefined liquid petroleum products transported in the region (with a focus on crude oil), and a summary of major releases over the last few decades,
- Overview of the methods of transportation, specific to the Great Lakes Region,
- Discussion of oil in the Great Lakes, with an overview of the sources of oil and relevant characteristics of different lakes and tributaries in the region,
- Evaluation of ecologically important regions that overlap with oil transportation corridors or likely spill movement pathways,
- Summary of the fate and behavior of oil in waterways with a focus on Great Lakes processes,
- Summary of effects of oil on aquatic organisms,
- Discussion of oil spill response efforts, mainly focused on modeling efforts in the Great Lakes and other regions, and

- Identification of knowledge gaps and recommendations for future research.

3.1 Previous Great Lakes Oil Spill Studies

Prior to the current report, several other research efforts related to the threat of oil spills in the Great Lakes Basin have been undertaken in recent years or are underway. A subset of the products generated from these includes the following:

- 2006 (July), IJC, Report on Spills in the Great Lakes Basin with a Special Focus on the St. Clair-Detroit River Corridor
- 2013 (June), U.S. Coast Guard (Yankielun et al.), Great Lakes Oil-in-Ice Demonstration 3 Final Report
- 2014 (November), Cornell's Community and Regional Development Institute (Christopherson and Dave), A New Era of Crude Oil Transport: Risks and Impacts in the Great Lakes Basin
- 2015 (February), Great Lakes Commission (GLC), Issues and Trends Surrounding the Movement of Crude Oil in the Great Lakes-St. Lawrence River Region
- 2015 (July), Michigan Petroleum Pipeline Task Force Report
- 2017 (June 8-9); Sea Grant, GLC, and IJC: Crude Move Symposium: Oil Transportation Infrastructure, Economics, Risk, Hazards and Lessons Learned, Cleveland, Ohio
- 2017 (July), GLC (3): Status of Infrastructure Related to Crude Oil Transportation in the Great Lakes-St. Lawrence River Region (Hull 2017); The Economic Impact of Crude Oil Transportation in the Great Lakes (Graziano 2017); Environmental Sensitivity to Oil Exposure in the Great Lakes Waters: A Multimodal Approach (Marty 2017)
- 2017 (November), Dynamic Risk Assessment Systems, Inc., Alternatives Analysis for the Straits Pipeline - Final Report
- 2018 (planned completion by August), team led by Michigan Technological University, Independent Risk Analysis for the Straits Pipeline; no drafts were available for review during preparation of the present assessment report

Additional related activity has included revision of existing operating procedures by industries and regulatory agencies, and preparation of new legislation at municipal, state, provincial, and federal levels (including tribes), related to pipeline, rail, and proposed vessel transport of crude oil in the Great Lakes Basin. Environmental advocacy groups have also underwritten new studies; proposed new policies, regulatory actions, and legislation; and filed lawsuits related to oil transportation in the region.

The six recommendations from the prior IJC report on spills (2006) follow, along with brief status summaries:

IJC (2006) Recommendation #1
The responsible agencies at all levels of government in Canada and the United States should develop a shared regional database for the Great Lakes Basin that can be used to produce a comprehensive binational spill trend analysis that identifies patterns, and to focus regulatory efforts. This database should be based on common, well-defined terms, reporting criteria and comparable information.

***Status*:** Transport Canada, the Transportation Safety Board of Canada, the U.S. Department of Transportation (e.g., Pipeline and Hazardous Materials Safety Administration, Federal Railroad Administration), and the U.S. Department of Commerce (National Oceanic and Atmospheric

Administration Office of Response and Restoration) maintain national databases that contain information on pipeline, rail, and other crude oil incidents, but the agencies generally do not link, harmonize, or regionalize these data across the international border. The functionality, resolution, accessibility, and timeliness of these databases has generally improved over time due to periodic investments in upgrades and the evolution of information technology. Recent information on U.S. spills and associated tracking systems was compiled by the U.S. Congressional Research Service (Ramseur 2017).

IJC (2006) Recommendation #2

The U.S. and Canadian Coast Guards should consult and work cooperatively with other relevant federal, state, provincial and local agencies to

• exchange information and data and report biennially on discharges from vessels (including oil and hazardous substances and wastes), discharges from onshore and offshore facilities, and discharges in the Great Lakes watershed that impact Great Lakes water quality and pollution from shipping sources;
• identify problems or areas of concern;
• determine necessary actions; and
• review and modify the Joint Maritime Contingency Plan as required.

***Status*:** The U.S. and Canadian Coast Guards collaborate on an ongoing basis in these shared areas of interest and responsibility. One example is in the preparation of the 2016 revision of the Great Lakes Operational Supplement to the Canada-United States Joint Marine Contingency Plan (CANUSLAK Annex), http://www.atlanticarea.uscg.mil/Portals/7/Ninth%20District/Documents/2016_CANUSLAK_JCP_Annex.pdf?ver=2017-06-14-134141-797 . Additional operational supplements cover the Niagara River and upper St. Lawrence River (CANUSCENT, last updated in 2013), as well as the Quebec-U.S. border region from Cornwall on the St. Lawrence River to northern Maine (CANUSQUE, last updated in 2013).

IJC (2006) Recommendation #3

To prevent chemical spills to the Great Lakes and their connecting channels, particularly the St. Clair–Detroit River corridor, the Canadian and U. S. federal governments should work cooperatively with state, provincial and local governments to develop and implement effective, coordinated spills prevention approaches that:

• harmonize U.S. and Canadian prevention and enforcement programs;
• provide consistent approaches to prevent and contain spilled substances, including provisions for secondary and tertiary containment;
• establish effective real-time monitoring to ensure compliance;
• ensure enforcement of discharge permits and regulations at all industrial facilities; and
• facilitate public outreach and education programs to reduce illicit spills by businesses and households.

***Status*:** The State of Michigan and the operator of pipelines that cross the Straits of Mackinac and the St. Clair River signed an agreement on November 27, 2017 covering coordination of enhanced operation and maintenance. Commitments regarding pipeline replacement and changes in operations were designed to reduce related hazards and enhance transparency of crude oil transmission in the state via the company's pipelines. In May 2015, the U.S. Transportation Secretary and Canada's Minister of Transport jointly announced new coordinated rules for the safe transportation of flammable liquids by rail. The new provisions were designed to prevent and mitigate consequences of accidents by upgrading of tank car containment design and braking systems, increasing operating and routing restrictions, and requiring better information sharing, among other provisions. Amendments by the U.S. Environmental Protection Agency (USEPA) to the Spill Prevention, Control, and Countermeasures Rule became effective in 2010 and clarified or refined some aspects of prior legislation; Compliance Assistance Guides are available for many industries. The USEPA also proposed several regulatory revisions and updates to the Clean Water Act's National Pollutant Discharge Elimination System in 2016. The U.S. Coast Guard announced updated

National Preparedness for Response Exercise Program (PREP) Guidelines in 2016 that covered spill response drills for oil storage facilities that are required to maintain Facility Response Plans. Various public outreach activities related to raising awareness of spill impacts and reducing discharges from businesses and households have included storm drain labeling programs (e.g., "Drains to Lake" markings) and release by the Sea Grant Oil Spill Outreach Team in 2017 of the brochure, *A Boater's Guide to Handling Oil and Fuel Spills*. Regarding pipelines, the 2014 Joint Forward Plan of the United States – Canada Regulatory Cooperation Council states (p. 22; https://obamawhitehouse.archives.gov/sites/default/files/omb/oira/irc/us-canada-rcc-joint-forward-plan.pdf):

"Transport Canada and the U.S. Pipeline and Hazardous Materials Safety Administration will strive to more closely align their regulatory regimes for the transportation of dangerous goods, including working to align national standards and regulations; sharing data, analyses and research; and synchronizing consultations with industry when feasible."

IJC (2006) Recommendation #4
The two federal governments should work cooperatively with state, provincial and local governments to establish and conduct joint testing of government-supported, real-time monitoring and biomonitoring systems that would:
• monitor for a broad suite of potential chemical and biological contaminants;
• be supported by a back-up source of power, maintained to the highest standards, and designed to protect all U. S. and Canadian water intakes in the St. Clair–Detroit River corridor and other strategic sites in the basin; and
• be integrated with state-of-the-art hydraulic models of the rivers (such as that proposed for the St. Clair River under the Commission's Upper Lakes Study) to provide improved assessment of relative risks and forecasting capability in the event of a spill.

***Status*:** The sophisticated Huron to Erie Drinking Water Monitoring Network was developed and installed at 13 stations in the Huron-Erie Corridor between 2006 and 2010 to detect changes in water quality and spills that could impact the drinking water intakes along the corridor. Over time, a lack of ongoing investment in operating and maintenance costs has resulted in degradation of the system. Efforts to reactivate the full network are underway, under the leadership of the Michigan Office of the Great Lakes, Wayne State University, and the Southeast Michigan Council of Governments (Beaulac 2016). An operational hydrodynamic model known as the Huron-Erie Corridor Waterways Forecast System and spill reference tables were developed by the NOAA Great Lakes Environmental Research Laboratory (Anderson et al. 2010; Anderson and Schwab 2012). Model output is accessible via the Great Lakes Observing System Data Portal (http://portal.glos.us/).

IJC (2006) Recommendation #5
Ontario and Michigan should improve their spill risk communication to communities on both sides of the St. Clair River and the Detroit River by establishing:
• common risk assessment criteria to discern relative risk;
• stream-lined, standardized procedures to trigger responsible agency and public notification; and
• joint communication procedures that differentiate levels of risk and specify action levels for downstream and transboundary communities, including water plant operators, business and industry, and the public.

***Status*:** Although there have been improvements in monitoring and modeling of spills in the corridor (see status of Recommendation #4 above), risk communication within countries and across the border remains an issue of concern, particularly communication from Canada to the U.S. (see, for example, Selweski 2017). The Community Awareness and Emergency Response (CAER) organization in Sarnia, Ontario supports communication and preparedness for emergencies related to the petrochemical facilities in the area through many activities including an annual Emergency Preparedness Day (http://www.caer.ca/).

IJC (2006) Recommendation #6
The U.S. and Canadian governments should resolve the conflict between the terms of the Great Lakes Water Quality Agreement [GLWQA] and the Joint Marine Contingency Plan [JMCP] regarding compensation for cleanup costs of major spills that impact both countries.

Status: Article 4 of the 2012 Amendment of the GLWQA references the following principle: the "polluter pays" principle, as set forth in the Rio Declaration on Environment and Development, "that the polluter should, in principle, bear the cost of pollution". Section V, precept b) of the 2016 CANUSLAK Annex revision to the JMCP states: The "polluter pays principle," with regard to marine spills, is entrenched in the Canadian Marine Liability Act and the U.S. National Contingency Plan as amended by the Oil Pollution Act 1990. Each country maintains oil spill trust funds that are generated by fees assessed on oil transportation and used to cover initial event response costs and responses to "mystery spills" where sources or responsible parties are not identified, or where they are unable to pay the associated costs of a spill.

Based on this review, there has been partial implementation of the six recommendations from the IJC (2006) report on spills, although work remains in most areas, including rebuilding of a spill monitoring network that was previously more robust but has since degraded.

3.2 Introduction to Crude Oil in and around the Great Lakes-St. Lawrence Region

Crude oil is a natural or moderately altered (diluted, blended, "upgraded") mixture of hydrocarbons, which contains organic compounds consisting of hydrogen and carbon which can be gases (e.g., methane), liquids (e.g., octane), waxes, solids, or polymers. Liquid hydrocarbons extracted from geological formations by drilling, mining, or other means are referred to as petroleum, whereas those extracted in the gaseous form are referred to as natural gas. Crude oil is commonly refined into various types of fuels and includes both naturally occurring unprocessed crude oil and petroleum products that are made up of refined crude oil. Petroleum refineries are industrial process plants where crude oil is processed and refined into more useful products such as gasoline, diesel fuel, kerosene, and liquefied petroleum gas. For the purposes of this report, the focus will be on unrefined petroleum, herein referred to as crude oil.

Crude oil is made up of complex mixtures of thousands of compounds, but primarily comprised of hydrocarbons (molecules consisting of only carbon and hydrogen) and to a lesser extent, compounds in which heteroatoms (non-carbon atoms) replace the carbon in the molecule's carbon backbone or ring structure (e.g., nitrogen, oxygen, or sulfur). Additionally, small amounts of metals, minerals, and dissolved gases (e.g., hydrogen sulfide) are often present in crude oil. The majority of oil components are derived from organic matter in geological formations that originated as the remains of aquatic plants, animals, and microbes.

Natural gas liquids (NGLs) or condensates comprise a number of light hydrocarbons that are produced in conjunction with methane, or as a byproduct of crude oil refining, and which are liquid at room temperature when compressed. Component hydrocarbons include ethane, propane, butane, isobutane, and natural gasoline. They are becoming an increasingly important commercial product and are used as a feedstock for other manufactured chemicals and plastics, as well as in fuel mixtures. They are generally not persistent in the environment in the event of a pipeline or containment vessel leak and do not pose comparable environmental threats to those of crude oil; they will not be considered further in this assessment with respect to environmental hazards. Note that they have become important as diluents in the processing of oil sand bitumen for shipment, and have driven investment in new pipelines to transport them from their shale source regions to processing and manufacturing plants in the East and the West (see: https://www.brookings.edu/wp-content/uploads/2016/07/Natural-Gas-Briefing-1-pdf.pdf).

3.2.1 Crude Oil

Crude oil can be composed of thousands of constituents, making their chemical and physical properties vary significantly across products. This chemical composition is important in understanding oil spills, as the chemistry impacts the physical properties which subsequently impacts the environmental fate and behavior (Lee et al. 2015, Mayer et al. 2013; McKnight et al. 2016). Crude oil can be categorized into light, medium, heavy, and extra heavy based on its density. However, for the purposes of this synthesis, oil will only be distinguished, when appropriate, between light and heavy, the type of blended or upgraded bitumen (e.g., diluted bitumen, synthetic bitumen), or between shale oil and oil sands oil. Crude oil that is less viscous and flows more easily is referred to as "light," while more viscous crudes that may require heating or diluent to flow are considered "heavy." These diluted crudes are discussed below. Light crudes require less processing at a refinery, whereas heavier crudes tend to have higher production costs and fewer refineries can process them. Additionally, certain impurities in crudes make them more difficult to process effectively into refined products which meet current standards. Still, many U.S. refineries, especially those in the Gulf Coast, are configured to handle large amounts of heavy crude and this production is expected to increase over time.

A detailed examination of the physical and chemical characteristics of crude oil is beyond the scope of this synthesis but a brief overview of these properties (especially those important to the ecological effects) is presented below (Table 1). It should be noted that the values or ranges listed in Table 1 are general estimates compiled from multiple sources; properties will also change with varying temperature and pressure.

Table 1. Physical property ranges of crude oil, compiled from Fingas et al. (2011) and other sources.

	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) [= (141.5/specific gravity) - 131.5]	30 to 50	10 to 30	19 to 22
Flash Point (degrees C)	-30 to 30	-30 to 60	<-5

Oil properties important in characterizing behavior in the event of a spill include:

- **Density,** which determines whether crude oil will sink or float in water; this also depends on whether the water is fresh or salty (see the example of the 2010 Kalamazoo River spill below). In general, most crude oil is less dense than water (floats). While density is important in controlling the buoyancy of the oil in water, many other factors impact its fate and behavior. For example, mixing with sediments can cause a buoyant oil to sink in the water-column when sediment-oil aggregations are formed. Weathering can also cause evaporation or degradation of lighter oil components and diluents, resulting in increasing density with time. If more oil sinks to the bottom, cleanup response options become more complicated (McKnight et al. 2016).

- **Viscosity,** which controls both the rate of spreading and the depth of permeation into the substrate once on shore. Oil viscosity is important in understanding dispersion because while lighter viscosity oils are readily dispersible, higher viscosity crudes are not. For example, the oil sands of Alberta, Canada, contain large deposits of bitumen or very heavy crude oil (King et al. 2017) but this material is too viscous to transport via pipelines. Pipelines can only carry oil with a maximum density of 0.940 g cm^{-3} and a viscosity of 350 cSt, so Alberta crude must be diluted to adjust its properties to meet pipeline specifications (King et al. 2017). Weathering of diluted or undiluted crude oil can change its viscosity as well, typically resulting in higher viscosity as more volatile and less viscous components, such as diluents, are lost to the atmosphere, dissolved, or degraded.
- **Flash point,** which is the lowest temperature at which vapors will ignite, when given an ignition source. This can be an important property in spill cleanup operations; whereas lighter oil fuels like gasoline can ignite under most ambient conditions, heavier oils have higher flash points. Weathering, dispersion, and water temperatures limit the window of opportunity for responding to a spill with an *in situ* burn event. Freshly spilled crude oils can have low flash points, until the lighter components have evaporated or dispersed.

3.2.2 Crude Oil Production in North America

Oil production is an important source of energy, chemicals, plastics, and other products in North America. The petrochemical industry provides both jobs and revenue to Canada and the United States. In North America, oil production has increased substantially in the last decade, and production is predicted to continue to increase through at least the middle of the next decade in the U.S. (EIA 2017) and through the mid-2030s in Canada (NEB 2017). Canada still has abundant resources of unconventional crude oil (oil sands, oil shale, etc.), with an estimated 340 billion barrels available for use (NEB 2017). Note that the distinction between “conventional” versus “unconventional” oil shifts over time as once-novel extraction and processing methods such as hydraulic fracturing or directional drilling become more routine (Speight 2011; Gordon 2012). There are two major producing regions in Canada, the Western Canada Sedimentary Basin, which includes Alberta, Saskatchewan, and parts of British Columbia and Manitoba; and offshore eastern Canada. To a lesser extent, oil is also produced in Ontario and the Northwest Territories. A wide majority of Canadian oil production is exported to the United States, with only 2% going to other foreign markets (NEB 2017). Although Canada is an oil exporter, due to the cost constraints of moving crude oil across the country, it also imports oil. In 2017, approximately half of its imports or about 374,000 barrels per day came from the U.S. (National Energy Board).

Canadian oil production is now dominated by heavy oil from the oil sands of Alberta, and has been on the rise over the last decade. The majority of crude oil in Canada is extracted from three major deposits of bitumen; the Athabasca, the Cold Lake and the Peace River deposits (CAPP 2017). In general, this bitumen is upgraded to synthetic crude oil or diluted with lighter oils (gas condensate) or other hydrocarbons prior to transport. This is mostly due to the high viscosity of natural bitumen, which would be difficult to transport by pipeline or to load and unload with other transportation methods (e.g., rail cars, barges). Bitumen blended with synthetic crude oil is referred to as synbit. Dilbit is

Common Blends of Bitumen from Oil Sands (Birn et al. 2014)

- **Neatbit** (1-2% diluent), almost pure and highly viscous bitumen, transported by rail
- **Railbit** (12-18% diluent), moderate viscosity blend for rail transport
- **Dilbit** (30% diluent), lower viscosity bitumen blended for pipeline transport
- **SCO (synthetic crude oil) or Syncrude**, upgraded bitumen that resembles light, sweet crude
- **Synbit**, a Syncrude-bitumen mixture

produced by combining bitumen with natural gas condensates, such as naphtha, whereas synbit contains a mixture of bitumen and a synthetic light crude oil (Dew et al. 2015). As such, dilbit contains more organic solvents whereas synbit is entirely composed of oil products (Dew et al. 2015). Synthetic crude or syncrude is a type of partially refined crude oil that consists of bitumen that has been thermally “upgraded” by fluid coking and other processes into a less viscous form prior to transportation to other refineries for further processing into finished products. The large syncrude production facility outside of Fort McMurray, Alberta has a capacity of 350,000 barrels per day.

In 2016, the U.S. produced an average of 8.9 million barrels of crude oil each day, imported 7.9 million barrels of crude, and imported 2.2 million barrels per day of refined petroleum products to support total average consumption of 19.6 million barrels a day (U.S. Energy Information Administration (EIA) 2017). Petroleum imports (crude and refined products combined) dropped below 25 percent of average annual U.S. needs in 2015 and have remained low, at values last seen in the early 1970s (EIA 2017). In the U.S., crude oil production has risen as horizontal drilling and hydraulic fracturing have allowed access to oil resources from shale rock formations that were previously not economical to exploit (EIA 2017). Shale oil is found in low-permeability sedimentary formations. The largest shale and light oil production in the U.S. is from the Eagle Ford (Texas), Bakken (Montana and North Dakota), and Permian (West Texas) shale formations. In the Great Lakes states, there are also small oil reserves in Ohio, Pennsylvania, New York, and limited shale oil production in northern Michigan (GLC 2015). The Gulf of Mexico region, both land-based and offshore, supplies more than half of the crude oil production in the United States. Much of the crude oil produced in Canada is sent to the U.S. via pipeline and rail for further refining, or at least passes through the U.S. on its way back to Canadian refineries in Ontario, Quebec, and New Brunswick.

An oil spill is the release of liquid petroleum hydrocarbons into the environment. Petroleum can enter the aquatic environment in multiple ways, including via natural seeps, accidental release of oil during extraction, and accidental release of oil while in transport or storage. While the term is usually applied to aquatic oil spills, spills can occur both on land and in water. Oil spills on land near waterbodies can spread into wetlands, rivers, lakes, and streams, or contaminate underlying aquifers (Great Lakes Commission 2015). Some of the largest historical oil spills in North American are discussed briefly below.

3.2.3 Releases of Petroleum Products into the Aquatic Environment

Two previous North American oil spill events that point out our need to understand the potential for ecosystem impacts are: the Exxon Valdez tanker spill in Prince William Sound in Alaska in 1989, and the Deepwater Horizon offshore drilling rig accident and well release in the Gulf of Mexico in 2010. Both released huge amounts of crude oil into marine systems, fouled long stretches of coastline with oil, and filled the news with images of oiled birds and other animals. The details of these events are highlighted below:

Important Terms Used in Discussion of Impacts of Oil Spills

Threat or **Hazard** – potential for occurrence of a damaging spill within a given time period and area
Exposure - contact with oil or its constituents
Toxicity – the degree to which oil can harm or kill an organism
Sensitivity – degree of negative response to oil exposure by an organism
Vulnerability – exposure and sensitivity above the organism level to damage from an oil spill threat
Risk – relative likelihood of exposure to oil and effects of exposure
Disturbance – perturbation of a system from a reference state
Damage – negative impact from oil
Resilience - capacity of a system to adapt to changing conditions (e.g., oil exposure) without collapsing, or to effectively resist change

Developed from De Lange et al. 2010

- The Deepwater Horizon Oil Spill occurred on April 20, 2010 in the Gulf of Mexico when a drilling rig exploded and sank. The spill is considered the largest marine oil spill in the history of the petroleum industry, with approximately 3.19 million barrels ultimately being released into the aquatic environment, after estimation of recovered or burned oil was considered (U.S. District Court ruling in 2015; McNutt et al. 2012; note that one barrel = 42 gallons, 159 liters, or 0.16 cubic meters so this spill released over 168 million gallons or 636 million liters). The spill responders used several methods to contain and remove the oil including the use of 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. A number of remote sensing technologies were implemented to track the spill and there was continuous video coverage of the wellhead provided by underwater cameras on remotely operated vehicles for over five months. Since the spill, a huge number of studies have been completed (with many ongoing), to understand the impacts to the complex aquatic ecosystem of the Gulf of Mexico, including Kostka et al. 2011, McCall and Pennings 2012, Whitehead et al. 2012, Brewton et al. 2013, Gutierrez et al. 2013, Hall et al. 2013, Aeplli et al. 2013, 2014, Dubanksky et al. 2013, 2017, Crowe et al. 2014, Gros et al. 2014, Haney et al. 2014a,b, Murawski et al. 2014, Hayworth et al. 2015. Recent or ongoing studies have been organized as Oil Spill Response Joint Industry Projects, Joint Industry Task Force studies, and investigations supported by the Gulf of Mexico Research Initiative.
- Prior to the Deepwater Horizon oil spill, one of the largest marine spills had been the Exxon Valdez oil spill in 1989, which spilled an estimated 260,000 barrels (41.3 million liters) of oil into Prince William Sound, Alaska. The spill was caused by collision of the ship that was carrying a large oil load bound for California with a rocky outcrop. The spill responders used various methods to remove the oil and to slow down its dispersion, including chemical dispersants, skimmers, booms, and burning. The size of the spill and its remote location made cleanup efforts difficult and tested existing plans for dealing with such an event. Since the spill, many studies have been completed (a few are still ongoing), to understand the impacts to the complex aquatic ecosystem of the Alaskan coast (e.g., Feder et al. 1998, Heintz et al. 1999, Page et al. 2002, Marty et al. 2003, Bowyer et al. 2003, Ruggerone and Rogers 2003, Peterson et al. 2003, Hailong and Boufadel 2010, Li and Boufadel 2010, Nixon and Michel 2015).

No spills of similar magnitude have happened in the Great Lakes. There is an absence of crude transport by oil tankers in the Great Lakes (does not apply to the lower St. Lawrence River), and a binational ban on offshore oil drilling (since 2005 in the U.S.). Large spills in tributaries and connecting channels, however, associated with oil transportation accidents via other modes, have also occurred in recent years. One of the largest freshwater inland oil spills occurred in Marshall, Michigan, in July 2010, when a pipeline ruptured and released Canadian crude oil into a tributary of the Kalamazoo River (Dollhopf and Durno, 2011; McKnight et al. 2016). The six-foot break in the pipeline resulted in one of the largest and most costly inland oil spills in the United States (~24,000 barrels [3.8 million liters] spilled and over one billion dollars in cleanup efforts were incurred; Dollhopf et al. 2014, Zhu and Garcia 2016). The spill resulted in a large portion of the river being closed during the cleanup. Oil traveled roughly 39 miles (63 kilometers) down the river before it was contained by the Morrow Dam. The spill was particularly difficult to clean up as a portion of the oil quickly interacted with river sediments or weathered and sank to the river bed, requiring the development and implementation of new approaches for the detection and recovery of oil mixed with river sediment (Dollhopf et al. 2014, Fitzpatrick et al. 2015; McKnight et al. 2016). Changes regarding spill response procedures, line operations, and other provisions to prevent similar future events were implemented after the spill (www.enbridge.com/~/media/Enb/Documents/Factsheets/FS_WhatsChangedSinceMarshall.pdf).

Rail spills typically involve smaller crude oil volumes compared to the above, and have decreased substantially in normalized frequency relative to pipeline transport (spill volume per ton mile) since the early 1990s (Frittelli et al. 2014). (Note that for true risk comparison purposes, which are outside the scope of this assessment, modes of transportation must be normalized by considering volume and distance transported when examining spill histories by number of incidents or volumes released.) Rail accidents, however, can still cause significant injury to life, property, and ecosystems depending on where they occur and how much crude oil is released. A major rail accident and spill took place on the outskirts of the Great Lakes-St. Lawrence Region in July 2013. The accident involved a train with 72 tank cars, each loaded with 711 barrels (113,000 liters) of Bakken crude oil from the North Dakota formation, and occurred in Lac-Mégantic, Quebec (Brunke et al. 2016). The train derailment and resulting fire caused numerous fatalities and significant damage to the town. The accident also caused a spill of over 619 barrels (98,000 liters) of oil into the Chaudière River, a tributary of Lake Mégantic, which was the main drinking water source for the town. Restrictions on potable water from the river remained in place for over two months from the date of the accident. Following the incident, crew procedures, operating guidelines, and tank car specifications for trains transporting crude oil have been substantially modified by coordinated efforts in the U.S. and Canada.

3.3 Fate and Behavior of Crude Oil

The fate and behavior of crude oil are dependent on a number of physical, biological, and chemical processes, collectively referred to as "weathering". These weathering processes are extremely important with respect to the fate and behavior of oil in the environment after a spill, including where and how ecosystems and organisms become exposed to spill-derived products. For example, King et al. (2014, 2015), tested the effects of weathering on the physical properties of several types of dilbits (Cold Lake Blend (CLB) vs. Access Western Blend (AWB)) and found that while all the oils tested initially had densities less than freshwater at 15 °C, the density of dilbits, such as the CLB or AWB, increased rapidly within 48 h. As a general rule, processes can be divided into two chronological categories in terms of when they are most significant: the early stage of a spill and the later stage of a spill. Processes such as spreading, evaporation, dispersion, emulsification, and dissolution happen rather quickly while longer term processes such as oxidation, sedimentation, and biodegradation determine the ultimate fate of the heavier fractions of the oil spilled (Fingas 2016). A graphical representation of the various fate and behavior processes is shown in Figure 1, and general summaries are presented below.

Understanding the toxicity of crude oil derived from oil sands in particular is complicated by the complexity of their formulations and the combined impact of diluents such as naphtha and other light hydrocarbons, or blending with heavy oil derivatives. Polycyclic aromatic hydrocarbons (PAHs) are a complex class of organic pollutants found in crude oil that contain two or more fused aromatic rings (deBruyn et al. 2007). Note that technically PAHs are structurally distinct from heterocyclic aromatic hydrocarbons (e.g., polynuclear), but the acronym "PAH" is more familiar to most as a loose shorthand for this broad class of large hydrocarbon molecules with ring structures, and will be used subsequently in this report, even if it is technically imprecise. In general, light oils, made up of mostly monoaromatic compounds (MAH; e.g., benzene, toluene) are more acutely lethal than heavy oils (McGrath and Di Toro 2009). However, these compounds are highly volatile and evaporate rapidly following a spill, limiting the duration of exposure and resultant toxicity (Neff and Stubblefield 1995, Neff et al. 2000).

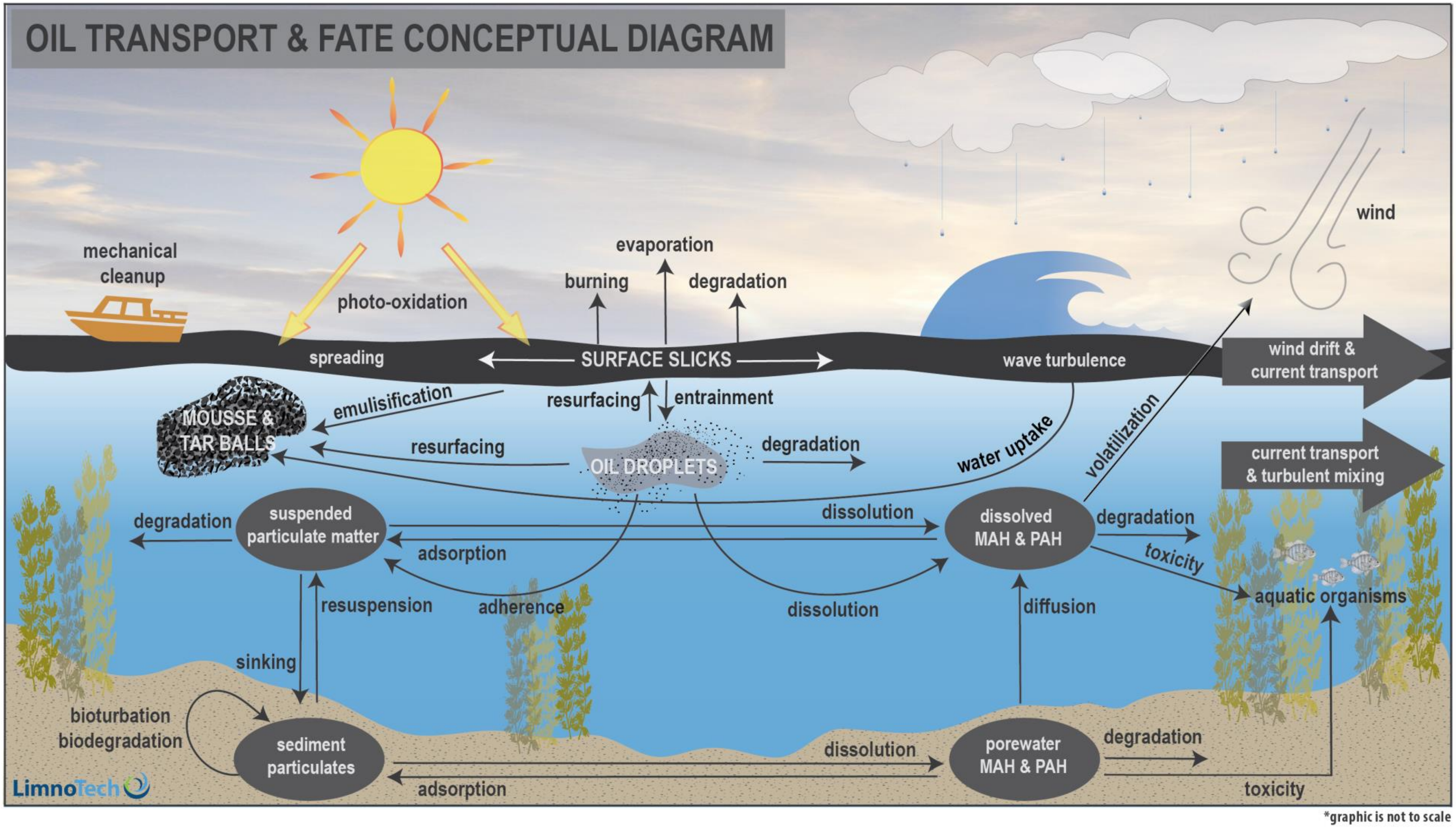

Figure 1. Crude oil transport and fate processes in an aquatic environment.

3.3.1 Spreading

Spreading begins as soon as the oil is spilled but the speed at which it spreads depends on factors such as the oil viscosity, water and air temperature, and physical conditions (e.g., wind, waves, and currents). Low viscosity oils tend to spread more quickly than those with a higher viscosity and oil tends to be more viscous at low temperatures than at higher temperature (viscosity is inversely proportional to temperature).

Following an oil spill, oil moves away from the source where the oil layer is thickest (Chebbi 2014). This causes a reduction in the average thickness of the oil layer, but increases the spatial area over which adverse effects could occur. Slick thickness and area are key variables in oil weathering and transport models but spreading is rarely uniform and large variations in thickness are typical. The spreading and thinning of oil can also enhance other surface-dependent fate processes such as evaporation, degradation and dissolution.

3.3.2 Dispersion

Dispersion is a mixing process caused by the turbulence field in the water and increases with increasing surface turbulence (Delvigne and Sweeny 1988). Dispersion originates from eddies of various scales, Langmuir circulation, boundary-layer shear (e.g., wind gusts blowing on the water surface), and other random turbulence (Le Henaff et al. 2012). Similar to spreading, the speed at which an oil disperses into progressively smaller droplets is largely dependent upon the nature of the oil and the physical conditions of the environment. There is also an important distinction between physical and chemical dispersion. While this section describes the physical process of natural dispersion of oil in the water column, the addition of chemical dispersants can enhance and accelerate this process.

3.3.3 Evaporation

Evaporation is the primary mechanism for loss of low molecular weight constituents and light oil products (Blumer et al. 1973). The rate and speed at which evaporation occurs depends upon the volatility of the oil. As lighter components evaporate (e.g., benzene), the remaining petroleum becomes denser and more viscous. In general, the components with the highest vapor pressures will evaporate the most rapidly. The thickness of the oil layer (see above) can also affect the rate of evaporation, with thinner oil sheens tending to evaporate more quickly than thicker oil slicks (Fingas 2015).

Although evaporation can also increase acute toxicity to air-breathing organisms at the site of the oil spill, eventually hydrocarbons that volatilize into the atmosphere are broken down by sunlight into smaller compounds (Gros et al. 2014). In general, evaporation tends to reduce oil acute toxicity but enhance persistence as progressively less volatile components in the original crude oil become concentrated in the remaining residue (Lee et al. 2015).

3.3.4 Dissolution

Dissolution is the chemical stabilization of oil components in water. While it is not a significant process controlling the fate of many low-solubility oil constituents in the environment, crude oil is made up of a complex mixture of organic compounds of varying solubilities that can control the toxic effects of a spill. Evaporation and dissolution are generally considered competing processes but both contribute to the reduction in acute toxicity of residual oil (Lee et al. 2015). With evaporation the oil components are released into the atmosphere from the surface of the spill, while in dissolution they are dissolved in the water column. Although dissolution accounts for a much smaller portion of oil loss compared to evaporation, it is still considered important because the soluble components of oil (e.g., monoaromatic compounds) tend to be more toxic to adult aquatic organisms than the larger molecules, and may transfer more readily across membranes such as gill surfaces into the tissues or blood streams of organisms.

3.3.5 Entrainment

Oil can be temporarily entrained/driven into the water column by wind and wave turbulence. However following these events, droplets above a certain size range generally resurface after the turbulence diminishes. The greater the entrainment, there is less oil floating on the water surface, and hence less is available for evaporation.

3.3.6 Emulsification

An emulsion is a dispersion of one liquid in another immiscible liquid. With respect to crude oils, it is the incorporation of water into oil and is the opposite of dispersion. The formation of the emulsion depends on the environmental and on the composition of the oil. In general, the heavier oils emulsify quicker than lighter oils. Emulsification occurs by physical mixing supported by turbulence at the water surface. Although oils generally take up water once spilled, emulsions don't always form. Water can be simply "entrained" by the oil due to viscous forces, without forming a more stable emulsion. The emulsion formed is usually very viscous and more persistent and can cause the volume of pollutant to increase several fold. This slows and delays other oil weathering processes, and can complicate the response to an oil spill.

3.3.7 Biodegradation

The biodegradation of oil is considered a key mechanism in breaking down oil in aquatic environments (Kostka et al. 2011). Some microorganisms can partially or completely degrade oil to water-soluble compounds and eventually to carbon dioxide and water. Rates of biodegradation are dependent on a number of factors including the ability of microorganisms to contact hydrocarbons (surface area available) as well as on the bacterial metabolic processes operating within the cell (Chikere et al. 2011). In general, alkanes and unsubstituted aromatic compounds tend to be broken down more easily while alkyl substituted aromatic compounds are more resistant and may not readily degrade (Das and Chandran 2010). The process of bioremediation is defined as the introduction of new biodegrading microorganisms or the enhancement of the biodegradation activity of naturally occurring microorganisms by humans to detoxify or remove pollutants, whereby microbial enzymatic activity transforms or degrades oil constituents (Chikere et al. 2011).

3.3.8 Photo-oxidation

Photo-oxidation is generally considered a significant process of degradation of crude oil following a spill. A group of light-catalyzed reactions oxidize the reduced carbon in petroleum hydrocarbons and as such the process increases with greater solar intensity. While it can be a significant process during sunny days it becomes less important during cloudy days. Photodegraded products tend to be more soluble and less toxic than parent compounds. Greater size and increasing alkyl substitution increase the sensitivity of aromatic compounds to photochemical oxidation. Photo-oxidation may also result in higher-molecular-weight products through the condensation of peroxide intermediates. For example, tarballs are caused by the oxidation of thick layers of viscous oil or emulsions. Tarballs, which are often found on shorelines, tend to be relatively resistant to weathering processes.

In contrast, photo-oxidation can also lead to photo-enhanced toxicity to organisms. Photo-enhanced toxicity is a mechanism of toxicity that is mediated by the interaction of solar radiation with specific PAH compounds in oil (Barron et al. 2017). Laboratory studies have shown that after exposure to solar radiation some PAHs can become more toxic by 50,000-fold (Giesy et al. 2010). Several studies have discussed photo-enhanced toxicity to zooplankton (Duesterloh et al. 2002, Wernersson 2003), aquatic invertebrates (Pelletier et al. 1997, Ho et al. 1999), and fish (Barron et al. 2003, Incardona et al. 2012), although some question the ecological significance of this process (e.g., McDonald and Chapman 2002).

3.3.9 Sinking

Oil droplets or masses that are denser than water to sink below the surface and are eventually transported to the bottom. Although most crude oil has a density less than that of water and few fresh oils sink in the aquatic environment, oil may weather sufficiently or incorporate enough sediment to become denser than water and sink. Sinking of oil is generally disadvantageous for oil removal (Fitzpatrick et al. 2015, Fingas 2016). Because fresh water is less dense than saltwater, some types of oil that would float in the ocean would sink in the Great Lakes and tributaries. The presence of ice in the winter in GLSLR water bodies can complicate transport, weathering, and spill response, as oil can become frozen in ice and released later when the ice melts, or become trapped under ice, slowing or preventing volatilization of lighter constituents (Yankielun et al. 2013).

Sorption of oil to suspended sediments can change its density and cause it to sink as oil-particle aggregates, especially in rivers or shallow waters (Dachs et al. 1996, Fitzpatrick et al. 2015, McKnight et al. 2016). Another mechanism of downward oil transport is via the ingestion of oil droplets dispersed in the water column by zooplankton and the excretion of oil in fecal pellets, which then sink to the bottom (Prahl and Carpenter 1979). For example, *Calanus finmarchicus* copepods were estimated to ingest and then excrete substantial masses of oil in fecal pellets per day, which then sink to the sediment surface (Muschenheim and Lee 2002). This process was documented during the *Arrow* spill in Chedabucto Bay in Nova Scotia, Canada (Conover 1975), where it was estimated that 10% of the oil in the water column was ingested by zooplankton. Another method of density enhancement of oil is via mixing with phytoplankton blooms, where the flow of detritus to the sediment surface carries with it oil constituents (Skei et al. 2000). When floating oil gets close to the shore, it often interacts with suspended solids in shallow waters and sinks prior to impacting the shore. It should be noted that during sediment disturbances (e.g., bioturbation, storm events), oil may become re-suspended and re-enter the water column.

3.4 Methods of Crude Oil Transportation in the Great Lakes-St. Lawrence Region

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 (e.g., change from westward to eastward flow). A relatively small amount of crude oil is actually produced within the Great Lakes Basin (e.g., approximately 4 million barrels per year (640,000,000 L) in Michigan and 220,000 barrels (35,000,000) per year in Ontario; https://www.eia.gov/state/rankings/?sid=MI#series/46 ; https://www.neb-one.gc.ca/nrg/sttstc/crdlndptrlmprdct/stt/stmtdprdctn-eng.html).

The Great Lakes are a transportation barrier between recently developed sources of oil in the West—the Bakken Formation and the Alberta oil sands—and major refineries, terminals, and markets in the East, among other destinations. The Bakken Formation, which is present in North Dakota, Montana, and southern Manitoba and Saskatchewan, is a set of oil-rich subsurface shale and dolomite units. As previously mentioned, it had produced small amounts of oil for decades, but market and technology changes led to an oil boom in the region beginning in approximately 2010, which peaked at a production level of almost 1.2 million barrels of oil per day in December 2014 (https://www.dmr.nd.gov/oilgas/stats/historicalbakkenoilstats.pdf).

Production from the Alberta oil sands, recovered as bitumen by surface mining or subsurface heating and other means, also jumped up around 2010, with current production of about 3 million barrels per day. This rate is predicted to rise gradually over the next 10 to 20 years (CAPP 2017). Mined bitumen from the oil sands is too viscous to transport easily in its natural form, so it is processed into modified diluted products. The combined *daily* production from the Bakken Formation and oil sands is comparable to total *annual* production from Michigan and Ontario near and within the Great Lakes Basin.

Much of the oil from the western sources is transported east by pipeline and rail to or through the Great Lakes watershed (Figure 2). Production has exceeded transportation capacity at times leading to construction of new terminals and pipelines. Some of the shale oil and oil sand oil is refined in the Great Lakes Basin 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 (Figure 2; https://www.eia.gov/petroleum/refinerycapacity/table3.pdf; http://www.canadianfuels.ca/Facts/). A substantial quantity of unrefined petroleum also passes through the region to other Midwest refineries outside the basin, or to rail-to-ship terminals in Albany, New York and the large refinery in St. John, New Brunswick (>300,000 barrels per day processing capacity; http://www.canadianfuels.ca/Facts/); transit through Portland, Maine has been halted since 2014 by local ordinance. The decline in crude oil prices beginning in 2014 impacted development and production in both source regions, but prices have generally risen since a January 2016 low, which may spur more production in the West and increase demand for transport east if the trend continues.

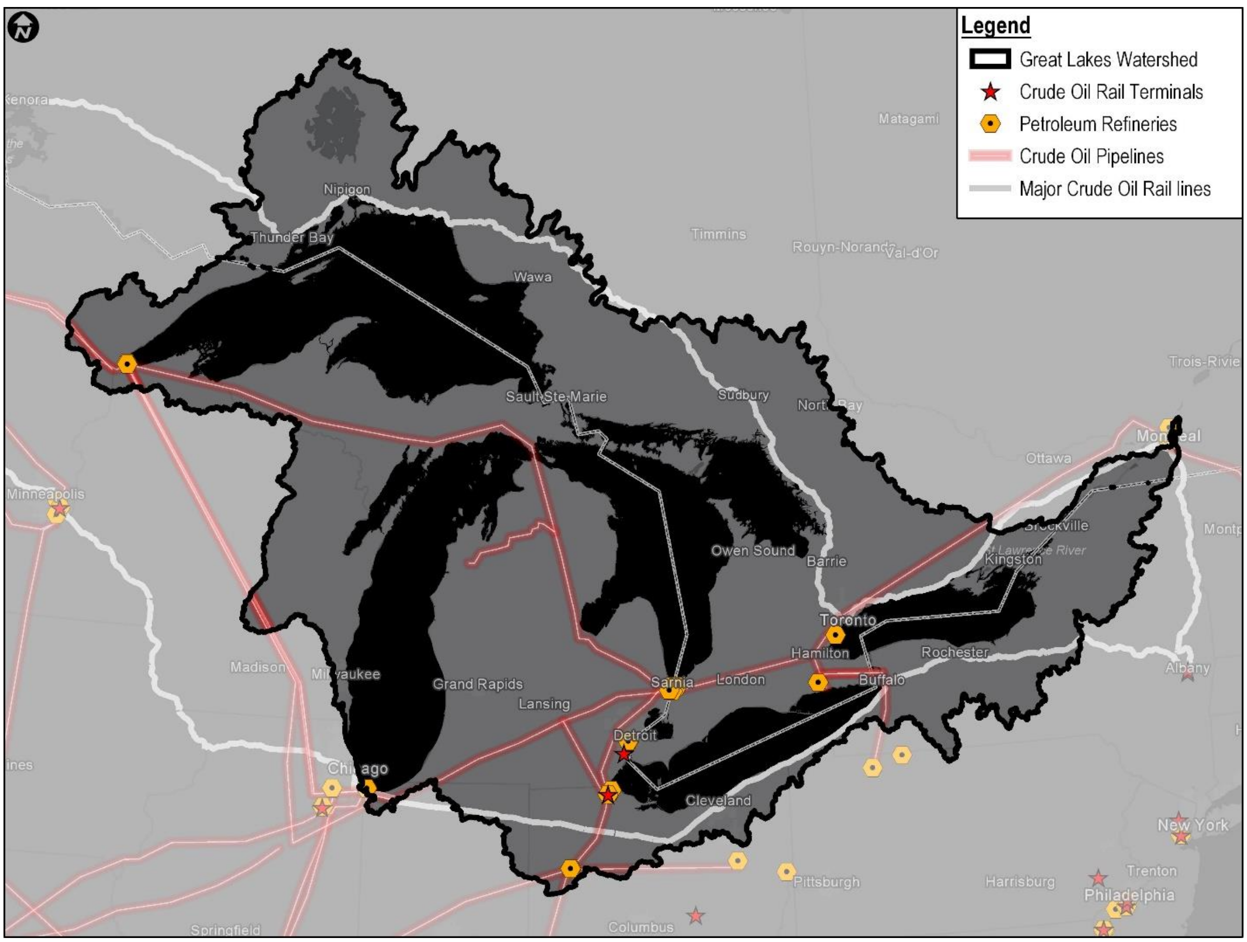

Figure 2. Crude oil pipelines, major rail lines, terminals, and refineries in the Great Lakes Basin and surrounding areas. The basin is approximately 1,000 miles (1,610 kilometers) wide from east to west.

Oil transportation modes and activities vary depending on several factors including where oil is originating and ending up, the type of oil, and the overall amount of oil being transported. In the GLSLR, there is a vast network of pipelines, terminals, and rail lines to meet the energy demands across North

America. This network moves oil to some of the region's largest refineries in the Sarnia, Ontario area, and one of the largest U.S. refineries located on Lake Michigan in Whiting, Indiana (~15 miles or 24 kilometers south of Chicago) (Table 2). Facilities like these (~23 refineries in the broad GLSLR and 11 in the basin proper; Hull 2017) combine for over 3 million barrels (480,000,000 L) per day of crude oil refining capacity in the region. Large amounts of crude oil are also moved through the region to refineries outside the watershed (Great Lakes Commission 2015). A recent oil transport overview for the GLSLR was prepared by Hull (2017) on behalf of the Great Lakes Commission; more information can be found in that report.

Table 2. Refineries and crude oil capacity (thousand barrels per day, MBD) in the broad Great Lakes-St. Lawrence Region (adapted from Hull 2017), including some facilities outside the basin.

Great Lakes-St. Lawrence Region	Number of Refineries (Capacity in MBD)
Illinois	5 (1,371)
Indiana	2 (448)
Michigan	1 (132)
Minnesota	2 (437)
Ohio	4 (585)
Pennsylvania	2 (76)
Wisconsin	1 (45)
Ontario	4 (392)
Quebec	2 (367)
TOTAL IN GLSLR	23 (3,853)

Recent developments in the Great Lakes-St. Lawrence Region include the first transfer of Alberta dilbit to a large tanker in Quebec on the lower St. Lawrence River (September 2014), and the development of proposals for oil transfer terminals from pipeline to ship or rail to ship at Superior, Wisconsin and Thunder Bay, Ontario, for shipment through Lake Superior to the lower lakes, East Coast refineries, and foreign ports. These proposals were followed by strong opposition from environmental groups and legislative initiatives by politicians in the region, but the need remains to link oil production in the West to refining capacity in the Midwest and the East utilizing transportation through the Great Lakes Region. Other proposals for new pipelines running north of Lake Superior and Lake Huron (TransCanada Energy East, terminated in October 2017), south from Canada to Texas, and west to terminals in British Columbia and Oregon have been considered or are in development (CAPP 2017).

In addition to the large spill events described previously, a small release of oil (18 barrels) to Lake Michigan took place in March of 2014 from a recently upgraded refinery in Whiting, Indiana that attracted media attention. The refinery's processing capacity is 420,000 barrels (67,000,000L) per day.

Also, it was discovered in 2015 that a barge that sank in Lake Erie in 1937, the *Argo*, still contained some of its chemical cargo—reportedly 4,762 barrels (760,000 L) of crude oil and benzoyl when first loaded—and was slowly leaking. The barge was offloaded by salvage divers and recovery vessels in late October through mid-December of 2015 without incident.

3.4.1 Pipelines

A large network of pipelines delivers crude oil to the Great Lakes and other regions, as well as transporting some refined oil products. Crude oil enters the Great Lakes Region via pipelines at three main locations: at Clearbrook, MN/Superior, WI; at Whiting, IN near Chicago; and near Lima, OH. Besides the crossing at the Straits of Mackinac, oil also flows in pipelines under the St. Clair River from Michigan to Sarnia, Ontario and beyond. A general map with the existing pipelines in the GLSLR is shown in Figure 2; Figure 3 also shows subwatershed boundaries and a buffer zone around the lakes (green) where a spill that impacts a tributary might also reach the lakeshore.

Pipelines are the main method of transportation for crude oil across the GLSLR, at a transmission rate that is likely more than double that of rail (Hull 2017). The incoming pipeline capacity of approximately 5.3 million barrels (840,000,000 L) per day exceeds regional refining capacity, so over 800,000 barrels (130,000,000 L) per day must move beyond the region when the system is operating at capacity (Hull 2017). As previously mentioned the lighter crude oils (Bakken and West Texas Intermediate) have lower viscosity and are easier to move, whereas the heavier Canadian oil is very viscous and needs to be thinned out before pumping.

Pipelines are classified as batch or common, where the batch pipelines move different crude oil types in "batches" back-to-back in the same pipeline. Common-stream pipelines (e.g., the Dakota Access Pipeline which carries Bakken crude; Hull 2017; AOPL, http://www.aopl.org/pipeline-basics/pipeline-101/) move a single type of oil, and so the identification of oil type is not as important, although oil quality from different fields and within different parts of the same field can vary substantially, affecting value and properties. Crude oil and refined products are generally not transported in the same pipelines. Different types of refined products can also be "batched" in refined product pipelines, like in crude oil pipelines.

One important pipeline segment runs under the Straits of Mackinac, a narrow waterway connecting Lake Michigan and Lake Huron. Spill hazards associated with these paired pipelines include exposure to ship anchor strikes, among other factors (Dynamic Risk Assessment Systems, Inc. 2017). The pipeline owner and operator, Enbridge, reached an agreement with the State of Michigan in November 2017 to address certain concerns about this pipeline segment and another pipeline segment that spans the St. Clair River (https://mipetroleumpipelines.com/sites/mipetroleumpipelines.com/files/document/pdf/SOM-Enbridge-Agreement_11-27-17.pdf).

3.4.2 Railways

The railway system within the Great Lakes Basin is one of the busiest in North America, especially due to the large and complex rail line transfer facilities in Chicago. More than a quarter of all freight trains move through Chicago, with over 1300 freight and passenger trains per day (Hull 2017). While rail transport includes routes that cross these major metropolitan centers, they also include routes through relatively undisturbed and unpopulated areas of the GLSLR (Figures 2 and 3). 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). Additionally, rail is advantageous because it can deliver crude oil to intermodal transfer terminals or to appropriately equipped refineries that do not have pipeline access. Within the GLSLR, Bakken shale crude oil (mostly from North Dakota but to a lesser extent from Montana, Manitoba and Saskatchewan) moved primarily via rail until the Dakota Access Pipeline came on line in 2017. This oil is more volatile and prone to ignition than heavier crude oils, due to its lower flash point (the lowest temperature at which ignition can occur) and often greater concentration of dissolved gases than heavy crude.

Estimating rail shipment volumes of crude oil to and through the GLSLR is difficult due to the complexity of switching, routing, and loading/unloading. A direct comparison with pipeline transmission is not possible, but an upper bound is dictated by the rail loading capacity for Bakken crude and oil sand crude in the West, which totals approximately 2.2 million barrels per day (Hull 2017). This represents an upper limit because these facilities are not operating at capacity, especially since the opening of the Dakota Access Pipeline. Likewise, not all rail cars loaded with crude oil in these regions are routed through the Great Lakes Basin. That said, a comparison with pipeline transport based on capacity alone, using values of 2.2 versus 5.3 million barrels per day, yields an upper bound value of about 30% rail transport of crude in the GLSLR compared with 70% pipeline transport; the actual rail value may be substantially lower and shrinking due to expanding pipeline capacity and other factors. In terms of potential spill volume, unit trains, made up entirely of crude oil tanks cars, tend to carry larger total volumes of oil per train than do mixed trains.

3.4.3 Marine Shipping

Besides binational prohibitions, impediments to marine shipping of crude oil in the GLSLR include the winter ice conditions and the seasonal closure of locks during winter months. While at present no crude oil is transported by vessel to or from the Great Lakes, the first tankers moved dilbit crude oil for export down the St. Lawrence River from Quebec in 2014. Cargoes of 4 to 5 million tons per year of refined petroleum products (not crude oil) are moved on the lakes by U.S.-flagged vessels (USDOT 2013); additional refined products are transported in Canada. Large quantities of rail-transported crude oil that pass through the Great Lakes Basin to Albany, NY terminals are then loaded onto barges and transported down the Hudson River to refineries in New Jersey and elsewhere (Hull 2017).

3.5 Hydrology and Ecology of the Great Lakes-St. Lawrence Region

The Laurentian Great Lakes hold a significant portion of the world's fresh water and cover a total area of 244,000 km^2 with over 16,000 km of coastline. The total drainage area of the Laurentian system, including the Saint Lawrence River, comprises roughly 4% of the surface area of North America. Though the five major lakes are separate basins, they are naturally connected and water flows in one direction from Lake Superior and Lake Michigan to Huron (there is some movement from Huron to Michigan at times, but no net transport), and then southward to Erie and northward to Lake Ontario, and finally into the outlet at the Saint Lawrence River. The larger Great Lakes watershed includes a number of rivers, streams, and inland lakes in the eight states and two provinces that border and underlie the Great Lakes and St. Lawrence River. Over 40 million people depend on the GLSLR for their drinking water supply. Due to its central location in North America, the GLSLR is considered a major transportation hub, connecting different regions of North America. It is a busy trade intersection, serving many agricultural, commercial, and manufacturing interests, and is thereby a central location for the crude oil supply chain. Clean water in the Great Lakes, however, is fundamental to sustain both human health and ecological health in the bi-national region.

3.5.1 Lakes Overview

The major water bodies of the Great Lakes 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. 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 areas. More details are provided in Table 3.

3.5.2 Tributaries Overview

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 themselves. Two examples discussed above include the pipeline rupture near Marshall, Michigan in 2010, which released dilbit into a tributary of the Kalamazoo River, and the Lac-Mégantic, Quebec rail accident in 2013, which released Bakken light crude oil into the nearby lake and the Chaudière River. The Michigan incident caused petroleum to flow up to 39 miles (63 kilometers) downstream, to within 115 miles (185 kilometers) of Lake Michigan. Oil from the much smaller Lac-Mégantic spill was carried 50 miles (80 kilometers) downstream on the Chaudière River to within 60 miles (97 kilometers) of the St. Lawrence River.

These incidents illustrate the potential for crude oil to impact GLSLR tributary habitats, and possibly river mouths and open lake shorelines where the spill is close enough and/or large enough to make it all the way to the mouth of the river. The phenomenon of lake seiches means that spilled oil in the lake, whether originating there or carried to the lake by a tributary spill, may be transported along the shore and into multiple river mouths by temporary reversals of flow from the lake into rivers by wind setup and subsequent oscillations.

Ecological impacts of tributary spills may include acute or chronic toxicological or physical impairment of organisms in riparian wetlands, as well as year-round or seasonal stream populations of native mussels, trout and other resident fish, migratory spawning fish, semi-aquatic mammals, turtles and snakes, frogs and other amphibians, and migratory water birds. In addition to volume and type of spill, other non-biological factors that can influence spill impacts include river stage (e.g., during spring snowmelt, storm flow, or drought), river valley geomorphology, thermal regime of the river (groundwater-dominated or runoff-dominated), ice cover, the presence of engineering modifications such as dams, and the presence of pre-spill stressors in the watershed and river such as urban runoff or other pollution sources.

3.5.3 Vulnerable Ecosystems in the Great Lakes-St. Lawrence Region

North America's Great Lakes are a vital ecological and economic resource containing the largest source of surface freshwater in the world, 10,000 miles (16,000 kilometers) of freshwater coastline, and unique ecological features such as the largest system of freshwater dunes in the world, endemic coastal ecological communities, and deepwater fishes (Koslow et al 2014; Pearsall et al, 2013). The region 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 ecological resources within the Great Lakes Basin are complex and expansive across the region, as well as among and within the lakes, bays and connecting channels themselves, providing a wide range of ecosystem services (Allan et al. 2017, Steinman et al. 2017). As such, critical ecological resources that are vulnerable to oil spills should be identified by analyzing their locations relative to corridors of primary transport modes within the basin (discussed below).

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. By defining groups of key ecological resources located in proximity to or intersecting with crude oil transportation modes, a clearer picture emerges of specific vulnerable locations, habitat types, and species emerges.

For the purpose of this binational project, the ecological diversity within the Great Lakes Basin is summarized primarily using binational reports. Between 2009 and 2015, The Nature Conservancy (TNC) led the development of a set of Great Lakes biodiversity reports, in collaboration with a broad range of agencies and entities including Canadian, U.S., First Nation and Native American tribes from across the region (Franks et al. 2010; Pearsall et al. 2012a; Pearsall et al. 2012b; Pearsall et al. 2013; LOBSWG 2009; LSLAMP 2015). These reports summarize key biodiversity targets (categories), with relative biodiversity significance and condition ratings, identification of priority species, and priority locations at the lake and connecting channels level. The collaborative assessment, findings and maps contained within these reports can be used to identify the intersection of valued features within the region, and the proximity or intersection of oil transportation modes.

Tardif et al. (2005) developed a biodiversity atlas that ranked biodiversity status within and along the St. Lawrence River, ranking categories of condition and threats to habitats and species. Its spatial rankings can be used to identify areas along the St. Lawrence River where oil transportation corridors and refineries threaten areas of high biodiversity.

Using the reports developed by TNC (Pearsall et al. 2013) and Tardif et al. (2005), biodiversity categories for the Great Lakes Basin are established and described in Table 4. These categories include: open water and pelagic systems, nearshore zones, native migratory fish, islands, coastal wetlands, aerial migrants, coastal terrestrial systems, rivers, estuaries, and connecting channels (Pearsall et al. 2013). Although the specific definitions of the categories may vary among lake reports, the categories capture primary resources of concern for the majority of the region, when located in the proximity of existing oil transport modes.

Within the Great Lakes Basin, much of the biological productivity and diversity are concentrated in the coastal zones (Table 4, Vadeboncoeur et al. 2011), both aquatic and terrestrial, particularly within the coastal wetlands, which provide sites for critical life history needs for many or most of the species inhabiting or migrating through the basin (Pearsall et al. 2012a, 2012b, 2013). Tributaries and embayments also serve a wide range of life history needs across the basin and increase the intersections of transportation and transfer modes across the basin. Table 5 describes the details of key features and species contained within each lake.

Table 3. Overview of major lakes and channels throughout the Great Lakes-St. Lawrence Region, highlighting important characteristics, transport modes, and major receiving waters/shorelines.

Lake or Channel	Characteristics	Key Crude Oil Transport Modes/Sources	Key Habitats or Resource Areas
Lake Superior	Cold, deep, easterly flow of currents along south shore, counterclockwise current gyre in east basin, maximum ice cover commonly >80%, few stressors except mining (localized)	Pipelines, rail, refinery (Superior, Wisconsin)	Duluth-Superior Harbor, Thunder Bay, Chequamegon Bay, Apostle Islands, Isle Royale, National Marine Conservation Area (Canada)
St. Marys River	Cold, strong currents, concentrated vessel activity, locks and dams	Limited--mostly rail	North Channel, Georgian Bay, including aquaculture pens
Lake Huron	Cold, complex shoreline and bathymetry with multiple basins and ridges, complex currents, maximum ice cover commonly >60%, little development in north	Limited--mostly rail	Georgian Bay, Saginaw Bay, National Marine Sanctuary (U.S.)
Lake Michigan	Upwelling on west shore, strong counterclockwise gyre in south basin, mid-lake plateau, urban and industrial impacts in southeast (Chicago area), maximum ice cover typically <50%	Pipelines, rail, refinery (Whiting, Indiana)	Green Bay, Grand Traverse Bay, proposed marine sanctuary (Wisconsin)
Straits of Mackinac	Strong bi-directional flow, concentrated ice for 3-4 months	Pipelines	Lake Huron and Lake Michigan bays and islands
Huron-Erie Corridor	High flow velocities in rivers, armored shorelines, concentrated year-round vessel activity, drinking water intakes, urban and industrial impacts (Detroit-Windsor)	Refineries (Sarnia, Detroit), pipelines, rail	St. Clair River, St. Clair Delta, Lake St. Clair, urban beaches, Detroit River
Lake Erie	Warm, shallow in west with summer algal blooms (agricultural impacts), hypoxic in central basin in summer, clockwise gyre in central basin, maximum ice cover usually >90%	Rail, pipelines, refineries (Toledo, Nanticoke)	Toledo Harbor, Maumee Bay, islands between western and central basins
Niagara River	Strong currents, urban impacts (Buffalo), hydropower facilities	Rail, pipeline	Lower Niagara River and Western Lake Ontario
Lake Ontario	Upwelling and current to east along north shore, urban impacts in west (Toronto), Niagara River plume follows south shore to east, limited winter ice cover (maximum <30%)	Rail, pipeline, refinery (near Toronto)	Small embayments and harbors
St. Lawrence River	Strong and variable currents due to dam regulation, concentrated vessel activity, multiple locks and hydropower dams	Rail, pipelines; refineries (Montreal), terminals, and oil tankers in lower section	Pools above dams, Thousand Islands area, Gulf of St. Lawrence

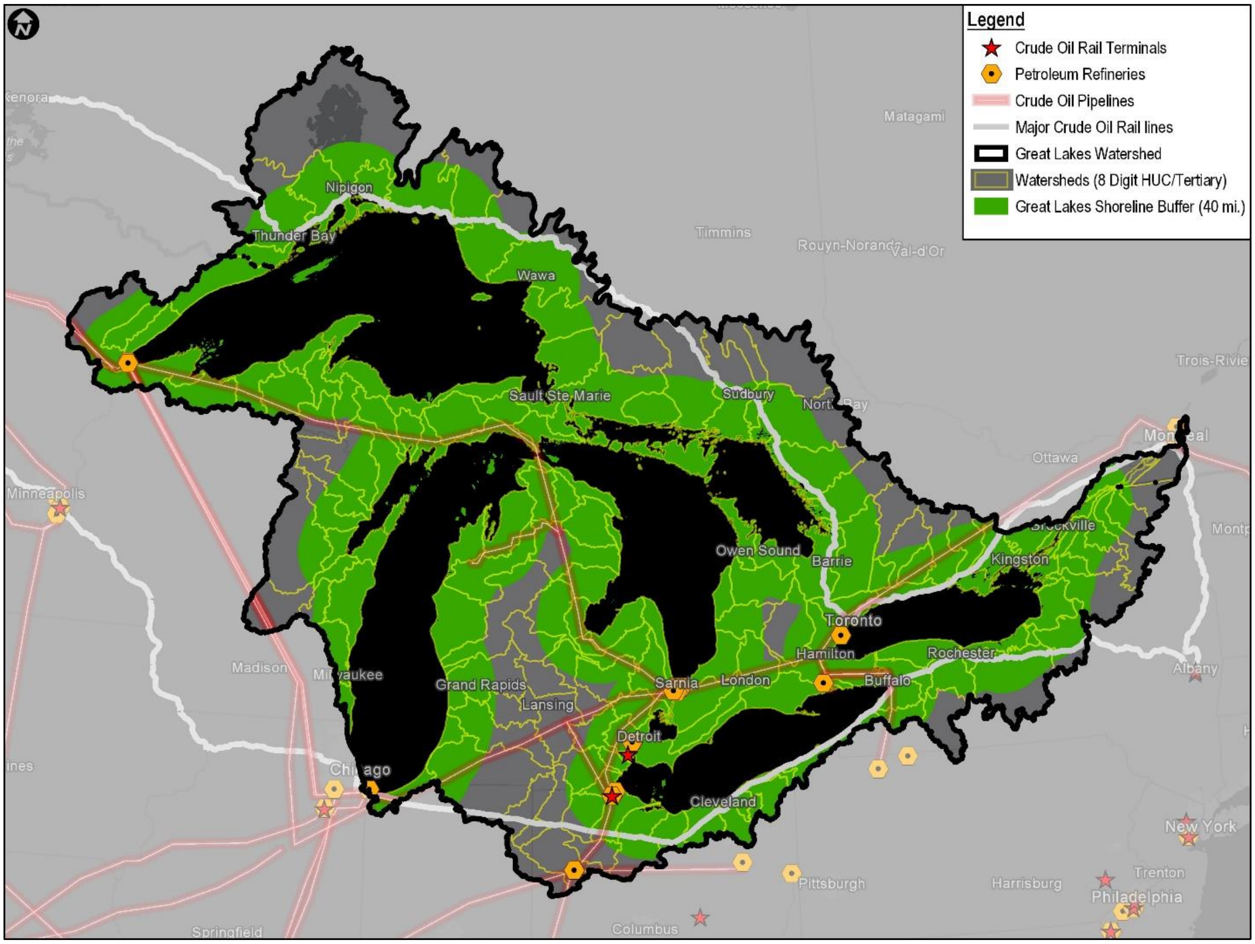

Figure 3. Great Lakes Basin showing crude oil infrastructure along with sub-watershed boundary lines (yellow), and a 40-mile (64-km) buffer inland from the shoreline to illustrate the complexity of the drainage basins relative to the oil transport modes. Transportation network crossings in the upper watersheds (upstream of green buffer zone) pose greater threats to river ecosystems, while those in the lower watersheds (green zone) would be more likely to impact river mouths and Great Lakes shorelines in the event of a spill. The 40-mile distance represents the approximate downstream transport during the Kalamazoo River oil spill in 2010 (which did not reach Lake Michigan).

Table 4. Summary of biodiversity conservation categories (Franks et al. 2010, Pearsall et al. 2012a, Pearsall et al. 2012b, LOBSWG 2009, LSLAMP 2015).

Biodiversity Conservation Categories	Definitions					
	Lake Erie	Lake Superior	Lake Huron	Lake Michigan	Lake Ontario	St. Lawrence River
Deepwater and Offshore Waters	> 15 m depth	>80 m depth	Open water ecosystem > 30-meter deep from mainland or islands, including reefs and shoals	Offshore; waters > 30 m deep	Open waters and bottom of the lake in permanently cold water greater than 20 m in depth	NA
Nearshore Zone and Reefs	< 15 m depth	15-80 m depth	Submerged lands and water column of Lake Huron starting at (shoreline) and extending to 30 meters depth, not including areas upstream from river mouths and riverine coastal wetlands.	Waters <30 m	20 m depth contour to the high water mark along the coast	Included in assessment but not specifically defined
Embayments and Inshore	NA	<15 m depth	NA	NA	NA	Included but not specifically defined
Coastal Wetlands	Wetlands with historic and current hydrologic connectivity to and directly influenced by Lake Erie	Wetlands within 2 km of the coast	All wetlands (lacustrine, riverine, barrier protected, plus subcategories including estuaries and island coastal wetlands) with historic and current hydrologic connectivity to, and directly influenced by Lake Huron	Wetlands with historic and current hydrologic connectivity to, and directly influenced by Lake Michigan	Hydrologic link to Lake Ontario as their water levels are directly related to the water level in the lake.	Included but not specifically defined
Islands	Natural formed and artificial	Natural and artificial islands	Land masses within Lake Huron that are surrounded by water, including both naturally formed and artificial islands	Both naturally formed and artificial islands	Provide nesting habitat for colonial water birds	Included but not specifically defined
Coastal Terrestrial Habitats	Upland systems within 2 km of the shoreline	Natural habitats within 2 km of the coast	Shoreline up to 2 km inland or to the extent of the delineated Great Lakes coastal communities.	Upland and wetland systems within ~2 km of the shoreline	Natural habitats that occur from the line of wave action to 2 km inland	10 km strip along shores
Tributaries and Watersheds	NA	Entire drainage area of Lake Superior including all tributaries and inland waters	NA	NA	Streams and rivers that flow into Lake Ontario	Included but not specifically defined
Native Migratory Fish	Fishes that migrate as part of their life cycle (e.g., lake sturgeon, walleye, suckers)	NA	Native fish that migrate to and depend on tributaries, nearshore areas, or wetlands as part of their natural life cycles	Lake Michigan fish with populations that require tributaries for a portion of their life cycle, including lake sturgeon, walleye, and suckers	Species that migrate to rivers (e.g., walleye), coastal wetlands (e.g., yellow perch and northern pike) and even the Atlantic Ocean (American eel)	Included but not specifically defined
Connecting Channels	Lake Erie Corridor and Upper Niagara River	St. Marys River	St. Marys River, Straits of Mackinac, St. Clair River	Straits of Mackinac	Streams and rivers that flow into Lake Ontario	NA
Aerial Migrants	All types of migrating birds, insects, and bats	All types of migrating birds, insects, and bats; few cross the open lake	Migrants that have high fidelity to Lake Huron, and for which migratory corridors associated with the lake are crucial to their survival	All types of migrating birds, insects, and bats dependent on Lake Michigan	All types of migrating birds, insects, and bats dependent on Lake Ontario	Included but not specifically defined

The biodiversity reports offer a valuable spatial representation of these features, broken into regions, depicted in the maps at the lake level of resolution. For example, Figure 4 (upper panel) provides an example of the condition of coastal wetlands in Lake Erie (Pearsall et al. 2012b). If combined with the rail, pipeline, and refinery data layers, these maps could depict areas where coastal wetland biodiversity conditions could be compared with oil infrastructure to evaluate the proximity and level of potential vulnerability of ecosystems. For example, examining rail infrastructure in Lake Erie, a rail line used for transporting crude oil runs along the southern shore of Lake Erie, with a terminal on the eastern end of the lake (Figure 4, lower panel). This rail line is situated close to the southern shore of Lake Erie and crosses a number of tributaries that enter Lake Erie in habitat zones of fair to good coastal wetland quality (although wetland areas are small). 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.

This type of evaluation is possible across all the lakes and would allow a more precise look at the distribution and quality of species biodiversity, communities, and habitat types across the Great Lakes Basin. Summarized spatial data sources are available for a range of species (e.g., sturgeon, migratory birds) and lake and inland habitats (e.g., fish spawning reefs and spawning tributaries). The unique spatial data sets used by The Nature Conservancy and the Great Lakes Aquatic Habitat Framework (Riseng et al. 2017) would be valuable in conducting a more quantitative assessment of ecological risk from crude oil transport, which is beyond the scope of this assessment. Use of these data and similar data would allow a more detailed look into priority areas across the basin to better understand within-lake and among-lake conditions and areas of potential exposure and vulnerability relative to particular oil transport modes and corridor segments.

Figure 5 shows a schematic and qualitative version of the type of synthesis that could be developed. A more quantitative analysis of ecological oil hazard locations would be based on numerical thresholds of proximity, spill volume, and spill frequency from pipelines, refineries, terminals, and rail lines to lake areas with significant coastal wetland habitats, or other high-value shoreline or nearshore habitat, such as spawning reefs or waterbird nesting colonies. A comparable analysis could be done for rivers in the basin based on related criteria. A numerical system for quantifying ecosystem value, vulnerability, and/or resilience would also be needed to weight infrastructure spill threat values with ecological factors. Consideration of seasonality and life history influences on ecological vulnerability should also be considered, along with related changes in infrastructure threat and changing spill response challenges based on weather and other non-ecological factors.

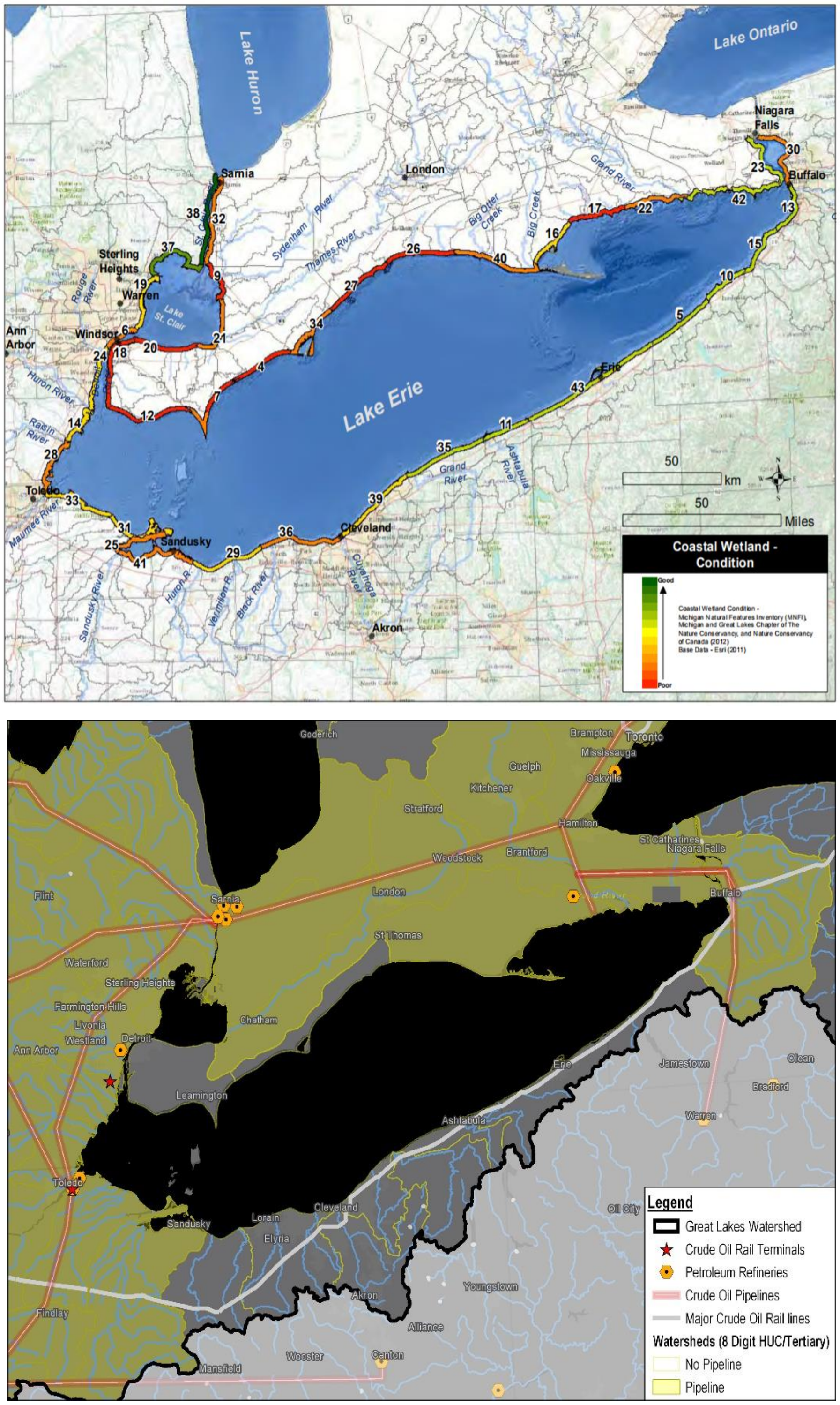

Figure 4. Coastal wetland condition segments surrounding Lake Erie (Pearsall et al. 2012b, top; red = poor, yellow = fair, green = good), compared with Lake Erie subwatersheds (bottom) that contain crude oil pipelines and refineries (yellow shading), but not major crude oil rail transport lines (dark gray); tributaries are shown by blue lines and subwatersheds by yellow lines.

Table 5. Lake-specific animals, plants, and habitats of concern based on Table 4 references that could be impacted by future oil spills.

Lake	Open Water	Nearshore (Zones and Reefs)	Embayments and Inshore	Tribs and Watersheds	Migratory Fish	Connecting Channels	Coastal Habitats	Islands	Coastal Terrestrial
Erie	Benthic invertebrates, forage fishes (benthic and pelagic), fish and bird piscivores (benthic, pelagic, avian), shoals and reefs, phytoplankton and zooplankton	Native submerged aquatic vegetation, shore birds, water-fowl, herpetofauna, benthic macroinvertebrates (e.g., Hexagenia), mussels, nearshore reefs and dependent species (e.g., walleye and fishes (e.g., emerald shiner)	No assignment	No assignment	Lake sturgeon, walleye, suckers, sauger	Erie Corridor, Upper Niagara River (above Niagara Falls), freshwater mussels, big river fishes (e.g., mooneye, lake sturgeon)	Emergent marshes, wet meadows, sedge communities, submergent/emergent/floating native aquatic plants, migratory waterbirds, wetland obligate nesting birds, herpetofauna, wetland dependent fishes, aquatic macroinvertebrates and mussels	Colonial nesting waterbirds, imperiled species (e.g., Lake Erie Watersnake, lakeside daisy), all natural communities that occur on islands (e.g., island forests, alvars, cobble lakeshores), stopover habitat for migrating birds, bats, and insects	Plants: Eastern white-fringed orchid, Sullivan's milkweed Pumpkin ash, Lakeside daisy, Bushy cinquefoil, and Beach peavine; Animals: Eastern fox snake, Blazing star borer, Elusive clubtail, and Duke's skipper; Natural Communities: Forested wetland, Emergent marsh, Beach-dune systems, alvar/bedrock communities
Michigan	Benthic invertebrates (e.g., Diporeia), forage fishes (benthic and pelagic), piscivorous fish (benthic, pelagic), shoals and reefs, phytoplankton, zooplankton	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 fishes (e.g., spottail shiner)	No assignment	No assignment	Lake sturgeon, walleye, suckers, northern pike (Esox Lucius), lake whitefish	No assignment	Emergent marshes, wet meadows, sedge communities, submergent/emergent/floating native aquatic plants, migratory waterbirds, wetland obligate nesting birds, herptiles, wetland dependent fishes, aquatic macroinvertebrates and mussels	Colonial nesting waterbirds, imperiled4 species (e.g., Pitcher's thistle), all natural communities that occur on islands (e.g., island forests, alvars, cobble lakeshores), stopover habitat for migrating land birds	Plants and animals: Lake Huron locust, Piping plover, Hines emerald dragonfly, Caspian tern, Common tern, Land snails (various species), Karner blue butterfly, and eastern massasauga rattlesnake. Natural Communities: Open dunes, Interdunal wetland, Wooded dune and swale complex, Coastal forests (boreal forest, rich conifer swamp, hardwood swamp), Limestone bedrock shoreline, Sand and gravel beach, Cobble beach, Alvar, Great Lakes barrens, Northern wet meadow, and Emergent marsh
Huron	Diporeia, lake trout, lake whitefish	Walleye, yellow perch, lake herring, Blandings turtle	No assignment	No assignment	Lake sturgeon, suckers, redhorse, walleye	No assignment	Emergent marshes, coastal cedar swamps, alvars, migrating water birds, eastern fox snake, northern pike	Colonial nesting waterbirds	Sand or cobble beaches, alvars, piping plover, Pitcher's thistle

Lake	Open Water	Nearshore (Zones and Reefs)	Embayments and Inshore	Tribs and Watersheds	Migratory Fish	Connecting Channels	Coastal Habitats	Islands	Coastal Terrestrial
Superior	Bloater, Burbot, Cisco, Siscowet Lake Trout, Humper Lake Trout, Deepwater Sculpin, Kiyi, Shortjaw Cisco, phytoplankton and zooplankton, benthic invertebrates, forage fishes	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)	Walleye, Lake Sturgeon, Brook Trout, Burbot, Cisco, Lake Whitefish, Round Whitefish, Ninespine Stickleback, Pygmy Whitefish, Longnose Sucker, White Sucker, Shorebirds, Waterfowl, Benthic macroinvertebrates, Aquatic plant communities, Native mussels, Forage fishes, Spawning habitat for some deepwater and nearshore fishes (e.g., Lake Whitefish and Lake Trout)	Nutrient and sediment processes, Watershed characteristics and health, Migratory fishes, Lake Sturgeon, Brook Trout, River spawning Lake Trout, White Sucker, Longnose Sucker, Silver Redhorse, Shorthead Redhorse, Walleye, Northern Wild Rice	No assignment	No assignment	All Coastal Wetland Types, Spawning and larval fish, Amphibians, Breeding and migratory birds, Invertebrates	Migratory birds and stopover habitat, Colonial nesting waterbirds, Arctic-alpine disjunct communities and plants, Landbirds (songbirds and raptors), Shorebirds, Waterfowl, Aerial migrants (e.g., migratory insects, bats), Ring-billed Gull, Herring Gull, Common Tern, Caspian Tern, American White Pelican, Unique plant and animal communities (e.g., populations of Beaver and Woodland Caribou in predator-free environments)	Sand beaches and dunes, Cobble beaches, Shoreline cliffs, Rocky shores, Bluffs, Arctic-alpine disjunct species, Coastal forests, Many plant species, Piping Plover, Peregrine Falcon, Bald Eagle, Woodland Caribou, Wide-ranging mammals Landbirds (songbirds and raptors), Shorebirds, waterfowl and waterbirds, Migratory bats· Sand beaches and dunes, Cobble beaches, Shoreline cliffs, Rocky shores, Bluffs, Arctic-alpine disjunct species, Coastal forests, Lake Huron Tansy, Houghton's Goldenrod, Dune Thistle, Piping Plover, Peregrine Falcon, Bald Eagle, Woodland Caribou, Wide-ranging mammals (e.g., Lynx), Endemic coastal insects and migratory insects, Landbirds (songbirds and raptors), Shorebirds, waterfowl and waterbirds, Migratory bats

Lake	Open Water	Nearshore (Zones and Reefs)	Embayments and Inshore	Tribs and Watersheds	Migratory Fish	Connecting Channels	Coastal Habitats	Islands	Coastal Terrestrial
Ontario	*Diporeia* and *Mysis*, in addition to other important benthic invertebrates, and prey fish such as the deep-water sculpin. Lake trout and burbot are the native top predators. A diverse array of native Coregonid fishes previously dominated pelagic waters, with the Atlantic salmon as the top predator	Submerged aquatic vegetation critical for waterfowl and many fishes such as smallmouth bass and yellow perch	No assignment	Streams and rivers that flow into Lake Ontario. These systems and their associated riparian areas provide habitat for many fishes and other aquatic species, and have a significant influence on the diversity and health of nearshore waters	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)	No assignment	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	Islands of Lake Ontario are important for colonial nesting waterbirds, migratory birds and support many rare species. Islands in the eastern basin and the upper St. Lawrence River provide “stepping stones” in the linkage between Ontario’s Algonquin Park and the Adirondacks in New York	Dunes and beaches that protect inshore lagoons and major wetlands in the Prince Edward peninsula and eastern shore of the lake in Jefferson and Oswego Counties, New York. Remnant barrier beaches and cobble bars still shelter embayments and ponds along the southern shore of the lake

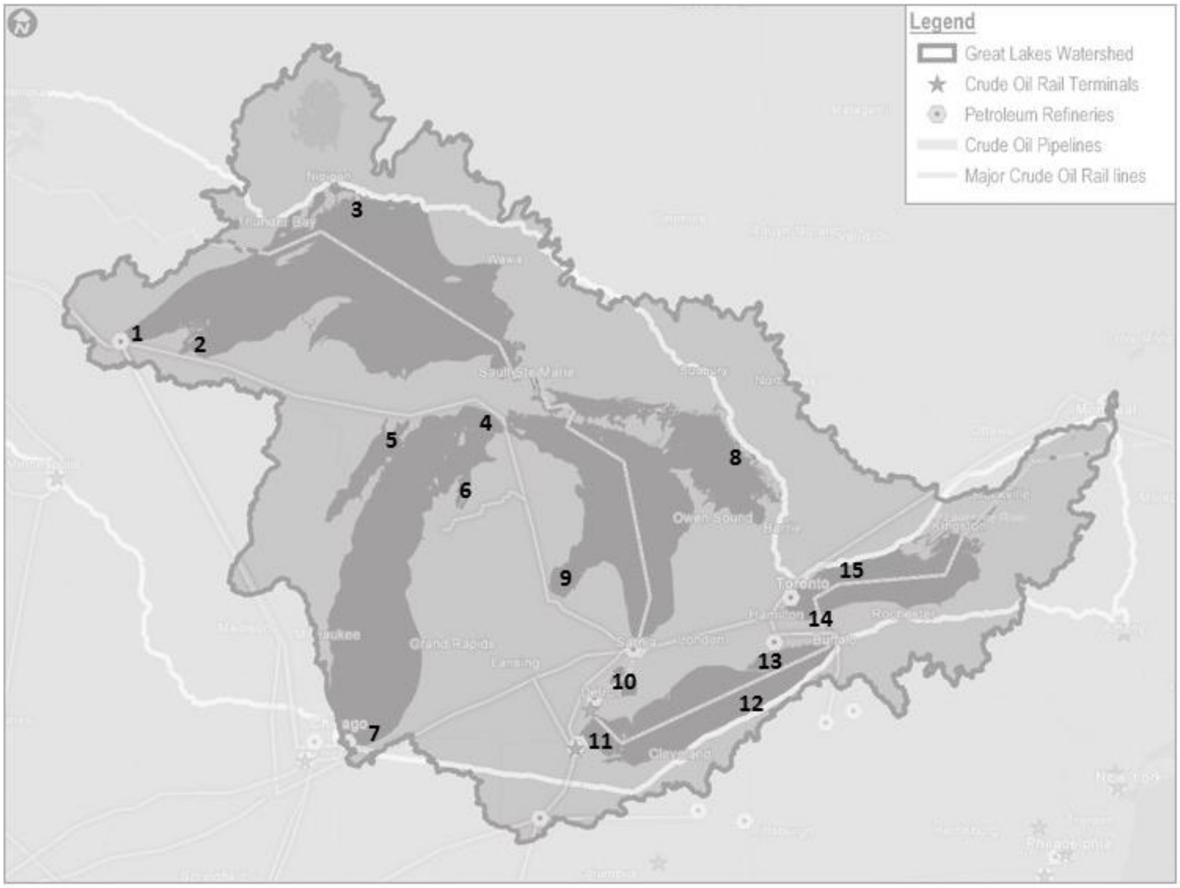

Figure 5. Schematic representation using Figure 2 base map of results of a qualitative assessment showing 15 areas of higher ecological vulnerability to crude oil spills from pipelines, rail lines, terminals, or refineries in the Great Lakes based on proximity to potential hazard(s) and habitat quality or significance. All tributary crossings by either transport mode, as well as downstream reaches scaled by spill volume hazard, would also be considered vulnerable (see Figure 3). Note that these results do not reflect a quantitative analysis of risk, or any sort of ranking of vulnerability—numbers are used for identification purposes only, and correspond to Table 6 entries below.

Table 6. Descriptions of 15 areas of ecological vulnerability shown in Figure 5.

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, L. Superior Nat. 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, and salmon spawning
7. Southern Lake Michigan, Indiana Dunes Nat. Lakeshore	Refinery, rail, pipeline	Coastal wetlands, dunes
8. Georgian Bay Biosphere Res.	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 summary, the Great Lakes Basin supports a vast array of ecosystem services as well as critical energy transportation infrastructure. The local regions of potential impact can be identified using spatial data queries and overlays. This would provide an important initial framework for understanding transportation mode vulnerabilities of species and habitats, but such a quantitative analysis is beyond the scope of this assessment.

3.5.4 Great Lakes Food Web

The GLSLR supports a rich and diverse composition of nearly 180 fish species (Schroeder and Dann 2003), including commercial, recreational and subsistence fisheries for important stocks such as lake trout, walleye, cisco, whitefish, and yellow perch. Despite the high variability in communities within and among lake and tributary areas, the main aquatic food web can be split into several groups of organisms (Figure 6). Crude oil can alter the structure and function of the food web. The structure of the aquatic food web and population dynamics of its member species determine how energy flows throughout the food web. The components of a food web are closely linked, such that changes to a single component can affect the entire food web (Ludsin and Hook 2013). It is therefore important to understand both the upper food web components (i.e., fish) as well as the lower trophic levels (e.g., benthos, zooplankton, phytoplankton), as changes at the lower levels can have a significant impact on both the composition and productivity of fisheries communities within the Great Lakes Basin. Ecologically, a crude oil spill can lead to a trophic cascade, where both top-down or bottom-up cascades may occur (Bunnell et al. 2014, Dew et al. 2015). If the upper trophic level (e.g., predatory fish in the Great Lakes), is impacted by an oil spill, it could result in population-level effects in the prey population, whereby a reduction in a predator can lead to increases in lower trophic level numbers. In a bottom up scenario, a reduction in the primary producers could affect all levels above the primary producer (Dew et al. 2015). The magnitude of this potential impact is, of course, dependent upon the severity or size of the spill.

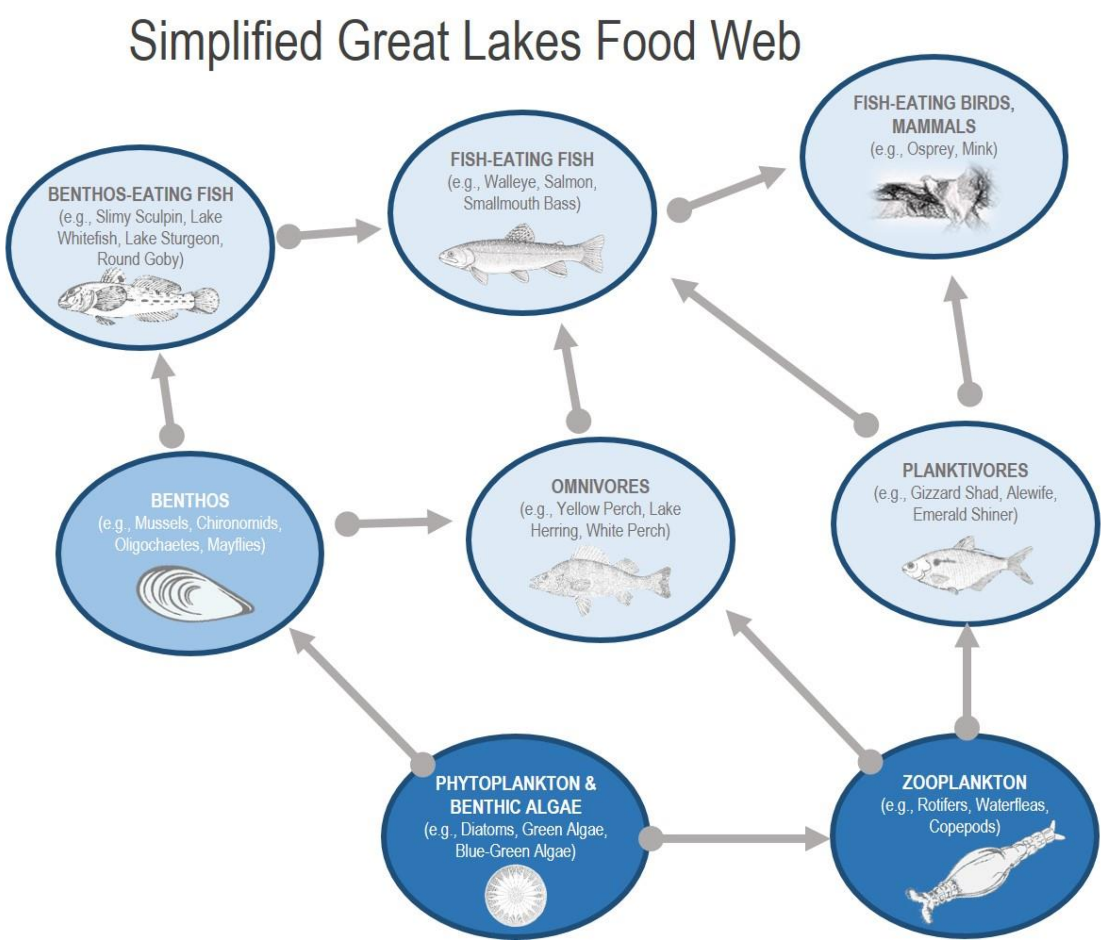

Figure 6. Simplified Great Lakes food web; darker shading represents lower parts of food web.

The main groups presented are the primary producers (e.g., phytoplankton), primary consumers (e.g., zooplankton, macroinvertebrates), secondary consumers (e.g., small fish) and top predators (e.g., salmon lake trout, walleye). While this simplification does not represent the full complexity of Great Lakes food webs, it does provide context for how energy moves throughout the system and the different positions of food groups.

The Great Lakes ecosystems are subjected to multiple stressors where chemical mixtures and interactions with environmental factors are contributing to organism declines (Allan et al. 2013, 2017). Anthropogenic stressors such as chemical and oil discharges can interact or be compounded by habitat degradation, invasive species, and other site-specific stressors (e.g., nutrients, flow alterations, turbidity). In the Great Lakes watershed, stressors differ greatly in their spatial scale.

3.5.4.a Benthic Environment

According to recent and historical data, the Great Lakes benthic community has experienced significant changes during the last half-century (except Lake Superior). Many regions of the GLSLR have experienced structural and functional changes with the introduction of Dreissenid mussels in the mid-1980s (Burlakova et al. 2014). The zebra mussel (*Dreissena polymorpha*) and the quagga mussel (*D. bugensis*) were introduced to the Great Lakes in ship ballast water and have nearly eliminated the native mussel communities in the Great Lakes (Bunnell et al. 2014). Although the colder temperatures of Lake Superior have limited the expansion of the zebra and quagga mussels (zebra mussels became established in 1989 and quagga in 2005), they remain a threat because they compete with the native mussels and planktivorous fish for food.

Contamination of sediments contributes to the exposure and effects on aquatic species that typically inhabit sediments, particularly the early life stages (ELS) of fish that spawn in sediments. Bottom-dwelling adult fish have been shown to have higher incidences of abnormal skin lesions following exposure to oil (Murawksi et al. 2014). Intensive sediment cleanup activities have been carried out since 2010 in many areas of historical sediment contamination, including areas of oil impacts, at Great Lakes Areas of Concern (AOCs) under the U.S. Great Lakes Restoration Initiative. These activities have been undertaken to restore sediment quality, remove Beneficial Use Impairments, and move toward de-listing of AOCs (https://www.glri.us/pdfs/fy2016-glri-progress-report-to-congress-and-president-20170803-35pp.pdf). Important sediment cleanups have also taken place at similar Canadian sites.

3.5.4.b Pelagic Environment

The open water column of the Great Lakes is dominated by phytoplankton, zooplankton, and fish, with some interactions at certain times of the year with offshore piscivorous water birds. Direct pelagic sources of crude oil are limited to the pipelines that span open waters or connecting channels in the lakes. The larger animals in the pelagic realm, mostly fish like lake trout and walleye, are generally capable of avoiding parts of the water column that contain irritating substances such as dispersed hydrocarbons, except under the conditions of a large spill. Therefore the interaction of most pelagic species with crude oil in the event of a spill, except in embayments or near the surface or bottom where oil may be concentrated, will be minimal. Zooplankton and phytoplankton, which are less mobile if at all, are more likely to be impacted by spilled oil in the water column, but their populations are abundant and resilient enough that impacts would likely be relatively short-lived.

3.5.4.c Coastal Habitats

This terrestrial component of this synthesis is mainly limited to the water-land interface such as coastal shorelines. The behavior of oil on shorelines depends on the specific properties of the shoreline including the substrate type (e.g., sand, gravel), the porosity of the substrate, the topography, etc. Specifically, riverine shorelines are affected by stream order, flow rate morphology and the nature of the riparian zone. A spill occurring during high flow conditions will likely be transported farther downstream than would a spill of the same volume during a low flow period.

The coastal zone is defined as the zone that begins at the shoreline or the lake side edge of wetlands and extends offshore to where the thermocline intersects with the lake bottom (in summer or fall; Rao and Schwab 2007). One of the main habitat features of coastal waters of the Great Lakes is their shallow depth, typically 0-20 m, compared with lake-average depths of 60-150 m, except for Lake Erie (Rao and Schwab 2012). During the stratified season, significant wind events cause upwelling and downwelling along the shore and within the coastal region, and can set up seiches that move water (or oil) into and out of coastal wetlands. Upwelling is the process where deep cold water rises towards the surface, whereas downwelling occurs when the wind causes surface water to build up along a coastline and sink toward the bottom. Upwelling and downwelling have the potential to produce large onshore-offshore transport of oil constituents. Following the Deepwater Horizon oil spill, studies found that regions which were initially thought to be free of contamination, appear to have been subsequently impacted by upwelling (Weisberg et al. 2014, Hu et al. 2011).

Great Lakes marsh ecosystems are coastal wetlands that are dominated by emergent vegetation, and have high physical and hydrological connectivity to their associated Great Lake (Figure 7). Classification schemes for Great Lakes wetlands based on geomorphology, biological integrity, and other factors have been developed (e.g., Maynard and Wilcox 1997; Wilcox and Whillans 1999). Coastal wetlands are strongly influenced by the lakes and their processes, such as wave action, seiches, and seasonal and interannual water level fluctuations. Wetlands in the Great Lakes Basin are diverse ecosystems in their form and function and are critical habitats to many wildlife. Wetlands act as a bridge between terrestrial and aquatic systems. The interconnection between physical and biological components with other land and aquatic resources causes them to be vulnerable and fragile in nature (Pennings et al. 2014). The vegetation in a wetland ecosystem provides the structure and function on which many important ecosystem services rely (Mendelssohn et al. 2012). Understanding impacts of crude oil on wetland vegetation may be particularly important, and was a topic of research focus after the Deepwater Horizon spill (API 2013).

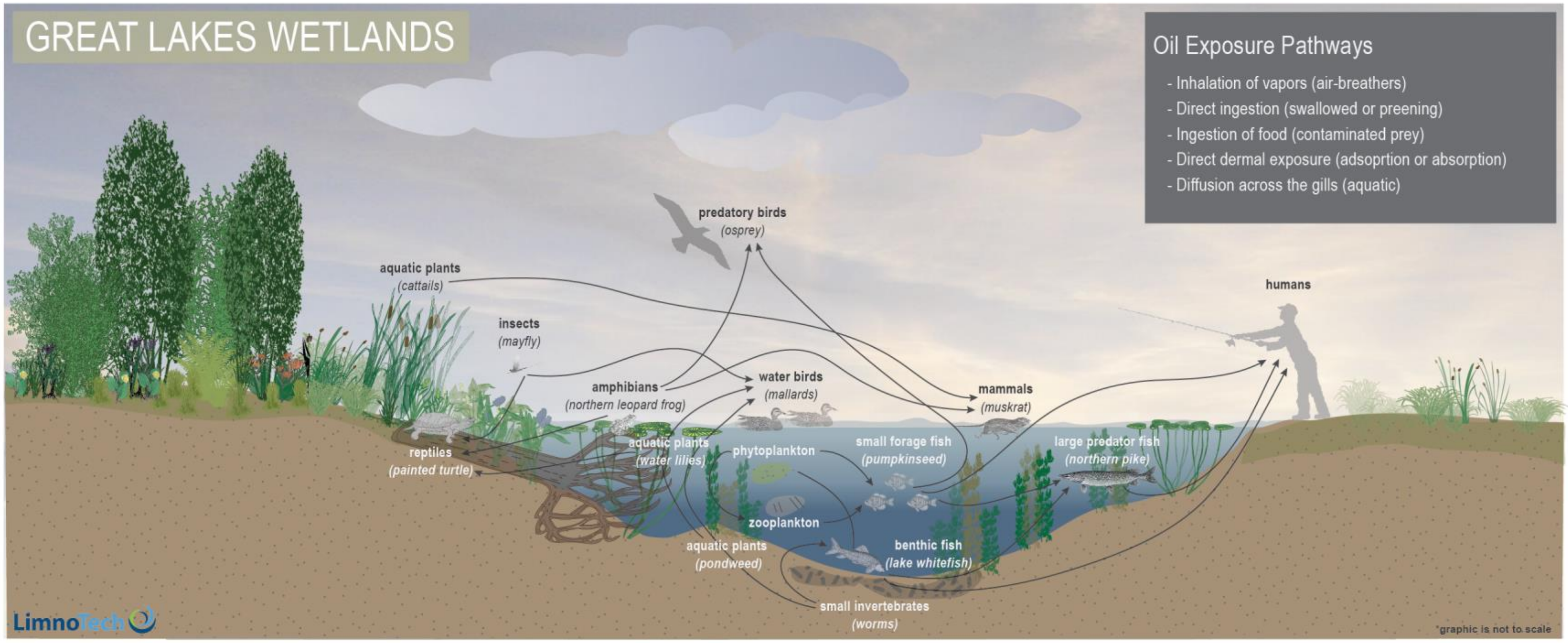

Figure 7. Great Lakes Coastal Habitat (wetlands) food web representation showing oil exposure pathways via food ingestion (arrows).

Oil cleanup is another important controller of oil spill impacts. In situations where oil only impacts the surface shoots and leaves of wetland plants, recovery may be rapid and effective. However, when oil penetrates the soil or sediments, recovery can take several years (Hoff et al. 1993). Additionally the manual removal of oil must be executed carefully and with consideration of local conditions, because these actions can sometimes lead to breaks in plant shoots, which may do more harm to the vegetation than the oil itself, or cause oil to penetrate more deeply into the soil (Hoff et al. 1993, Hester and Mendelssohn 2000).

Coastal wetlands provide habitat for hundreds of species of birds, fish and amphibians (Table 4, Table 5) and a significant portion of all lake fish species spawn in coastal wetlands. Ludsin et al. (2014), presented the spawning habitats for 24 Lake Erie fish species, including the most harvested commercial and/or recreational fish as well as important prey species, and all of the fishes had spawning preferences in the nearshore coastal environment. As discussed above, these early life stages are particularly susceptible to the toxic effects of petroleum hydrocarbons. Although, fish utilize coastal wetlands at all stages of their life cycle including egg, larval, immature and adult stages, making the coastal wetlands extremely important to the health of a fisheries community.

3.6 Exposure and Effects of Crude Oil on Aquatic Receptors

The toxicity of oil to aquatic species depends on a number of factors including the type, extent and duration of exposure to the toxic components of oil, the chemical and physical characteristics of the oil substance, as well as the sensitivity of the organism itself. Exposure can occur when oil is absorbed or adsorbed (e.g., externally coat organisms) by the organism, ingested (directly or indirectly), inhaled (air-breathers) or the bioavailable components of oil diffuse across respiratory membranes via the gills. Exposure may be acute or chronic, and understanding both lethal and sublethal endpoints following crude oil exposure is important.

Traditionally, total petroleum hydrocarbons were used to characterize exposures to oil which includes both dissolved and undissolved fractions (mostly unavailable for uptake). Thus, total petroleum hydrocarbons are likely to be a poor predictor of adverse effects (Carls et al. 2008, Letinski et al. 2014). A number of studies published on the toxicity of crude oil to aquatic organisms have focused on the major constituents, specifically PAHs (Manzetti 2012, Ball and Truskewycz 2013), naphtenic acids (Clemente and Fedorak 2005, Headley and McMartin 2004, Brown and Ulrich 2015), or metals (Gautheir et al. 2014), with less information on the effects of different crude types (e.g., dilbit vs. synbit or Bakken shale vs. oil sand derivatives; see Dew et al. 2015, Green et al. 2016, Alsaadi et al. 2018). Models have recently been developed, validated and published which allow for the prediction of toxicity of different crude types based on knowledge of the composition and fraction of the oil (see Redman et al. 2012, 2017). An example model, PETROTOX, which includes a quantitative framework for describing the toxicity of dissolved hydrocarbon mixtures, will be briefly addressed in section 3.7.5.

During the initial stages (e.g., 24-48 hours) of an oil spill, organisms are vulnerable to acute exposure. This period is generally brief, as the loss of acutely lethal components of oil from weathering occurs rapidly. However, it should be noted that if the spill is continuous and distributed in an area with minimal dispersion, organisms could experience acute and prolonged exposure. Weathered, heavier oils with varying amounts of PAHs with 3 to 5 rings tend to be more persistent and exposures may occur over longer time frames and effects will depend on nature and magnitude of exposures. There are several approaches to better understand exposures, including the use of biomarkers.

Acute Toxicity - adverse effects of a toxicant that results from either a single exposure or multiple exposures over a short time period (often 24-96hrs)
Chronic Toxicity – adverse effects of a substance resulting from long term exposure to a toxicant
Cytochrome P450 – hemoproteins of a superfamily of enzymes which can metabolize potentially toxic compounds
Bioaccumulation – describes the general process by which chemicals are taken up and retained by organisms from their environment and diet

Reference: USEPA (2012)

Biomarkers can provide sensitive information on chemical exposures and potentially of effects (den Besten 1998, Connon et al. 2012). One of the most commonly used approaches to indicate fish and wildlife exposure to oil has been using indicators of induction of cytochrome P450 1A (CYP1A). In vertebrates, CYP1A1, a member of a large family of cytochrome P450 genes, is a xenobiotic-metabolizing enzyme whose expression can be induced by exposure to a variety of arylhydrocarbon receptor (AHR) agonists such as PAHs (Esler et al. 2017, Hodson et al. 2017, Incardona et al. 2017). Indicators of induction of CYP1A messenger RNA, protein or activity is one of the more commonly reported responses to crude oil exposure of fish (Ji et al. 2011) and to a lesser extent in birds and mammals (Alexander et al. 2017, Esler et al. 2017). While the following sections identify biomarkers that are excellent for documenting exposure of organisms to crude oil, their value in establishing ecologically significant impairments to aquatic biota is an area of active research. It is anticipated that their diagnostic capabilities will continue to improve in the coming years.

Another potential exposure pathway are bioaccumulation processes which can impact the amount of crude oil constituents, mainly PAHs, in the organism. Bioaccumulation describes the process by which anthropogenic chemicals (e.g., PAHs) are taken up by organisms from their environment and diet and are subsequently assimilated into tissues (Arnot and Gobas 2003; Mackay and Fraser 2000). Due to the tendency of hydrophobic compounds, such as PAHs, to partition into lipid, the K_{OW} (octanol water partition coefficient) has also been used as a surrogate measure to predict bioaccumulation. High molecular weight (HMW) PAHs have a range of log K_{ow} from 5 to greater than 6 whereas low molecular weight (LMW) PAHs range from 3 to greater than 4 (Environment Canada 1998). Because PAHs are often readily metabolized in upper trophic levels, predictive models such as these are rarely accurate in determining PAH bioaccumulation (Landrum 1988, Johnson et al. 2008). Due to the higher rate of biotransformation, PAH tend to have limited trophic magnification (Gewurtz et al. 2011) and often undergo trophic dilution (Wan et al. 2007, Khairy et al. 2014). Large differences exist in biotransformation capacity among different organisms (McElroy et al. 2000). While upper trophic level organisms (fish and mammals) tend to have higher rates of transformation, even closely related species can differ considerably in the degree to which they are capable of biotransformation of PAHs (Bach et al. 2005; Palmqvist et al. 2006). And while many species can metabolize PAHs, in some cases the breakdown products can be more toxic than the parent PAH (Neff 1979).

Most studies on toxicity, bioaccumulation and/or bioavailability focus on conventional PAHs with only fused aromatic rings in their chemical structure, even though the majority of PAHs in crude oils are alkylated derivatives (Lee et al. 2015; Barron et al. 2004; Bornstein et al. 2014). In addition to being the major constituents, several studies have shown that the alkyl derivatives can also be more toxic (Page et al. 2002, de Santiago-Martin et al. 2015, Barron et al. 2004, Bornstein et al. 2014, Hodson 2017).

The effects (both lethal and sublethal) of an oil spill can span the aquatic ecosystem including plankton, invertebrates, fish, amphibians, reptiles, or mammals and as such, each will be briefly discussed below. Several recent reviews have highlighted impacts of crude oil and its constituents on several of these taxa groups and they should be reviewed for additional information (e.g., Perhar and Arhonditsis, 2014, Lee et al. 2015, Dew et al. 2015, Dupuis and Ucan-Marin 2015).

3.6.1 Basal Food Web

For the purposes of this review, partially based on the relative paucity of information on crude oil impacts on these groups, bacteria, biofilms, phytoplankton, and zooplankton will be discussed together. Primary producers and heterotrophs form the basal food web of both marine and freshwater ecosystems, providing food for upper trophic levels (Debenest et al. 2012). While many species in these groups have some motility, currents and waves heavily influence their location and many are unable to avoid unfavorable conditions (Batten et al. 1998) so they will likely be influenced 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 taxa groups (Batten et al. 1998).

3.6.1.a Bacteria and Microbial Biofilms

Bacteria can be either inhibited by crude oil or provide a significant means of decomposition. Microbial decomposition (biodegradation) is discussed above, with a focus on natural attenuation, where oil-degrading microbes naturally present in the environment break down oil particles, as well as bioremediation, which accelerates the rate of decomposition by stimulating or augmenting the oil-degrading microbial communities (Kostka et al. 2011). This section will briefly review the potential biological impacts on microbial communities.

One of the earliest mesocosm studies observed changes to nitrogen fixation in bacteria when exposed to Alaskan crude oil in a stream (Baker et al. 1983). Following the *Agip Abruzzo* oil spill (1991, Italy), there was an increase in bacterial abundance with a subsequent increase in biomass (Danovaro et al. 1995). Similar increases in bacterial community abundance have been observed (Head et al. 2006, Yakimov et al. 2007, Jung et al. 2012, Fefilova 2011). Rivers et al. (2013) found that bacterial communities were less diverse following the Deepwater Horizon oil spill, which the authors attributed to a large bloom in hydrocarbon degrading bacteria. Yergeau et al. (2013) studied the impacts of naturally occurring bituminous compounds from Athabasca River sediment on biofilms and found that impacted tributaries had less biomass and lower productivity compared to control tributaries. They also identified an increase in some specific microbial taxa that appeared to be less sensitive to the compounds or able to degrade and utilize the bitumen for production. Limited information is available on the effects of crude oil on freshwater microbial communities.

3.6.1.b Phytoplankton

Phytoplankton are primary producers that form the base of many food webs. They are a major component of the lower trophic levels and critical in sustaining and maintaining healthy food webs. Given their importance to the entire food web, as previously mentioned (e.g., trophic cascades), negative impacts to the phytoplankton community can propagate throughout other trophic levels. However, they exhibit significant transient and/or episodic variability, often making it difficult to track population changes due to stressors. Additionally, phytoplankton are susceptible to all types of stressors and exploring the interaction between these stressors is complicated (Interlandi 2002).

It has been known for several decades that crude oil and its constituents (mainly PAHs) are phytotoxic (Bate and Crafford 1985). However, understanding the toxicities of complex mixtures of PAHs to different species of phytoplankton and aquatic plants across variable environmental conditions is difficult (Perez et al. 2010). Varying temperatures, organism size, illumination and nutrient concentrations have been shown to elicit different toxic responses to the water soluble fractions of crude oil (McCauley 1966, Kong et al. 2010, Halling-Sorensen et al. 2000, Echeveste et al. 2010). A complete evaluation of aquatic ecosystems requires the understanding and examination of multiple stressors that affect those ecosystems. Indeed, the immediate effects from an oil spill on phytoplankton appear to be related to both the physical interference from surface slick induced light attenuation, which prevents access to sunlight, oxygen as well as essential nutrients (P, N).

There are several recent reviews that have looked at the effects of crude oil on phytoplankton and aquatic plants (e.g., Perhar and Arhonditsis 2014; Lewis and Pryor 2013). Perher and Arhonditsis (2014) did a thorough review of the effects of crude oil on phytoplankton communities while Lewis and Pryor (2013) provided a comprehensive review of the toxicity of 41 different crude oils on aquatic plants including algae and wetland plants. The information will be briefly summarized below, highlighting new studies that expand upon their reviews.

The inhibition of photosynthesis of phytoplankton has been well documented (Bate and Crafford 1985, Marwood et al. 1999, 2003, Gin et al. 2001, Gonzalez et al. 2009, Perez et al, 2010). However, the toxicity of crude oil can vary widely across species (Bate and Crafford 1985, Ostgaard et al. 1984) and crude oil type (Doerffer 1992) and the effective concentration (EC) can vary by several orders of magnitude (Lewis and Pryor 2013). In general, three main approaches have been used to study the effects of crude oil on phytoplankton: single species toxicity tests, mescocosms with natural or lab cultured plankton and/or *in situ* field studies. While many studies (lab and field) have identified that exposure to crude oil can reduce plankton growth (Tukaj et al. 1987, Kong et al. 2010, Perez et al. 2010), some studies have reported a stimulatory effect at lower concentrations (El-Sheekh et al. 2000; Parab et al. 2008), or reported no observed effects (Varela et al. 2006).

On a similar note, while a decrease in chlorophyll-a and biomass may be common following an oil spill (Gilde and Pinckney 2012, Gonzalez et al. 2009, Marwood et al. 1999, 2003), some studies (Sheng et al. 2011, Sargian et al. 2005) have observed a resurgence to normal levels or above within a few weeks to a month. Sheng et al. (2011), observed a decrease in chlorophyll *a* followed by an increase above control levels, and proposed that this could be due to solar radiation initially negatively impacting plankton levels, followed by a proliferation of bacteria groups which decomposed the hydrocarbons. Hu et al. (2011) observed a similar phenomenon three weeks after the Deepwater Horizon oil spill event. The toxicity of PAHs on phytoplankton appears to be linked to nutrient levels in the system, but this is a complex interaction, and while some researchers have found a reduction in toxicity to crude oil in systems with low nutrient levels (Kong et al. 2010), others did not (Jung et al. 2012). Early studies suggested that a decrease in phytoplankton following an oil spill may be due in part to a reduction in nutrient levels from the increase in hydrocarbon-reducing bacteria monopolizing the nutrients (Miller et al. 1978), or that an increase in phytoplankton might be driven by a decrease in zooplankton grazing caused by oil toxicity (Johansson et al. 1980).

While significantly more research has been done on marine and estuarine systems, Marwood et al. (1999, 2003), published results of a study from Lake Erie samples. They elicited photo-toxicity of natural phytoplankton communities after short durations at realistic PAH concentrations. The results showed that exposures of freshwater phytoplankton to PAHs at the surface can be toxic after very short durations, but depending on the kinetics of mixing of the water column, recovery of photosynthesis is possible if there is sufficient time for repair from the damage. Additional freshwater studies on plankton communities are warranted.

3.6.1.c Zooplankton

Zooplankton are a vital component of freshwater food webs. Along with other plankton they are critical to maintaining a healthy and diverse community and represent an important energy transfer link between lower and upper trophic levels. While acute toxicity of crude oil on zooplankton has been documented (Calbet et al. 2007, Hansen et al. 2008, Lennuk et al. 2015), less information is available on the effects of chronic exposures to zooplankton communities (Federle et al. 1979, Bejarano et al. 2006).

As observed with phytoplankton, standard acute toxicity tests varied significantly across species and feeding regime (Ikenaka et al. 2013). While some studies have reported differences in uptake by zooplankton depending on feeding regime (Magnusson et al. 2007), others (Berrojalbiz et al. 2009) observed no significant differences in the accumulation between fed and unfed copepods exposed to various PAHs. While studies have observed zooplankton ingesting oil directly (Lee et al. 2012), feeding and passive diffusion tend to dominate accumulation of PAHs in zooplankton (Jensen et al. 2008, 2012). There is evidence to suggest some zooplankton can metabolize PAHs (Berrojalbiz et al. 2009, Cailleaud et al. 2009), but while the mechanism could be related to cytochromes P450 enzymes, further research on lower trophic levels is needed to verify this (Jensen et al. 2012). In general it appears the initial exposure of crude oil to zooplankton is followed by rapid dilution until a steady state is reached with the environment (Landrum et al. 2003, Bhattacharyya et al. 2003).

3.6.2 Benthos

Following an oil spill, sediments can act as a major sink for oil, and due to their close interaction with bottom sediments, benthic fauna are more vulnerable to dense hydrocarbon exposure. For the purposes of this synthesis, benthic fauna will be collectively referred to as “benthos”, with a focus on both macroinvertebrates and shellfish. Unlike fish, they are relatively immobile and are continuously exposed to their environments; many reside in the aquatic area long enough (months to years) to reflect changing environments. Consequently, benthos represent an important biotic category frequently used in biological monitoring programs. While most of the studies discussed below are sublethal endpoints, toxicity testing with sediment collected from the Kalamazoo River oil spill showed a significant increase in mortality compared to control sediments (Great Lakes Environment Center 2012, Dew et al. 2015). While limited in scope, these studies suggest that crude oil can be acutely toxic to benthic invertebrates, but more research is needed.

PAHs are mostly hydrophobic (3-5 ringed PAHs have log K_{ow} = 4 to >6) and bind to organic carbon in the sediment. Unlike upper trophic level groups (e.g., fish, birds), some invertebrates do not metabolize or excrete PAHs at a fast rate and can bioaccumulate PAHs (Crunkilton and Duchrow 1990, Lotufo 1998, Olivia et al. 2017). Though the immune system appears to be more primitive than in vertebrates, immunotoxicity has been identified as a response to oil exposure in benthic invertebrates. Specifically in marine bivalves, several exposure routes have been shown to produce immunotoxicity (Galloway and Depledge 2001). Phagocytosis, the main mechanism of immunity in bivalves has been reduced following exposure to oil (Grundy et al. 1996, Frouin et al. 2007, Hannan et al. 2009, 2010). Experiments exposing bivalves to PAHs via contaminated phytoplankton, oiled sediments and fine residues from combustion of fuels caused a reduction in activity and efficiency of phagocytosis (Frouin et al. 2007). Hannan et al. (2009, 2010) studied the effects of crude oil and PAHs on scallops in Arctic temperature environments and found a reduction in membrane stability and phagocytosis with an increase in hemocytes (blood cells of invertebrates). Understanding lipid utilization and lipid catabolic pathways appears to also be important following an oil spill. In a study with marine shrimp, both eggs and adults had increased energy demands following exposure to hydrocarbons (Lavarias et al. 2006), but less is known about freshwater benthos.

Benthos can take up PAHs directly via ingestion or contact with sediments. For example, several studies have shown filter-feeding bivalves are vulnerable to exposure via diet by consuming oil-bound particles or oil droplets (Payne and Driskell 2003, Olivia et al. 2017). Bioavailability of dissolved hydrocarbons is much greater than those bound to particles, as the freely dissolved fraction of chemicals in the water is able to diffuse across biological membranes and enter organisms (Suedel et al. 1994, Allan et al. 2012) while the bound particles do not. Similar to other taxa groups, toxicity in benthic invertebrates varies across species and habitats. For example, Lee et al. (2000) found differences in sensitivity between the mystery snail (*Viviparus georgianus*) and the mimic pondsnail (*Pseudosuccinea columella*) in a wetland experiment along the St. Lawrence River. These differences were attributed to feeding habits as the more sensitive mystery snail, which is a detritivore, assimilated contaminants directly from sediments, while the pondsnail, an herbivore, assimilated contaminants indirectly, presumably from oiled vegetation. Life stage can also be particularly important with respect to toxicity, as studies have shown the embryonic stages are more sensitive. Exposure of adult amphipods to water column oil particles did not affect population but a high frequency of abnormalities in the embryos was reported (Casmus and Olsen 2008). Early studies on oil, found the larval stages of the American lobster (*Homarus americanus*) exposed to a sublethal concentration of crude oil, resulted in changes to lipid storage, utilization and synthesis along with delayed molting and reduced growth (Capuzzo et al. (1984).

Effects on population and communities in the field include a change in the dominant taxa following an oil spill. For example, immediately following the Amoco Cadiz oil spill, there was no change in the subtidal sediment community structure but as concentrations increased, the more tolerant polychaetes emerged as the dominant class. When sediment concentrations reached threshold levels, very low species diversity was observed, with the exception of opportunistic polychaetes (Dauvin, 1998). It took in excess of ten years for the originally displaced amphipod *Ampelisca* to regain its dominance in the community, likely because of its low dispersal, low fecundity, and lack of a nearby unpolluted population from which emigration could occur, suggesting the impacts of oil spills need to be tracked for multiple years. A study in a Missouri Ozark stream following a large oil spill showed a reduction of up to 99% in benthic fauna abundance, 25 days post-spill (Crunkilton and Duchrow 1990). The more sensitive taxa (e.g., Emphemeroptera, Plecoptera, and Trichoptera) were still reduced nine months post-spill. Following a tanker spill in 1992, Northwest of Spain, a change in community structure was observed (Gesteira and Dauvin 2005). They found a short period of high mortality in some species, especially amphipods, followed by a period of low abundance and then recovery in later years.

In contrast to the above, some marine studies have reported minimal long-term changes in community structure (Burns et al. 1993, Feder and Blanchard 1998). Burns et al. (1993) reported the results from a NOAA sponsored assessment following the oil spill from the 1991 Gulf War off the coast of Saudi Arabia. They measured benthic respiration rates and primary production at sites along the shallow subtidal basin near heavily oiled coastlines. Measured benthic ecosystem respiration rates were in the range reported for shallow marine sediments and concluded after one year the levels had decreased enough to minimize benthic community stress, and long term damage appear limited to enclosed bays adjacent to the most heavily oiled coastlines. Likewise, Feder and Blanchard (1998), reported minimal disturbances of the benthic community in deeper waters (40-100m), 16 months following the Exxon Valdez oil spill. While a marine shipping spill in Ibiza, Spain resulted in enhanced antioxidant and detoxification defense systems in the wild mussel *Mytilus galloprovincialis*, normal levels were apparent within six months post-spill (Sureda et al. 2011). Beyer et al. (2016) reviewed the effects on invertebrates following the Deepwater Horizon oil spill and found few reported impacts and no mass mortalities in the coastal waters. Additionally, caged *in situ* mussels and oysters that were exposed to oil showed no evidence of assimilation into their tissues (Lee et al. 2015). While many of these spills identified a short-term impact on the benthic community, the impacts appeared transient in nature.

Understanding the long-term impact of oil spills in large ecosystems like the Great Lakes can be difficult as PAHs are found in sediments across the Great Lakes from a number of legacy sources including past industrial and municipal discharges (Schloesser et al. 1991). In the Great Lakes, the benthic mayfly *Hexagenia* has long been used to study the health of sediments. In the early 1990s a large-scale study (250 stations) throughout the Great Lakes compared mean mayfly density with oil in sediments (Schloesser et al. 1991). The authors showed that average *Hexagenia* densities were roughly 3.5-fold lower in connecting channel sediment with oil present in sediments (46 sites), compared to sites without oil. It is important to keep in mind that many parts of the Great Lakes are subjected to multiple stressors that contribute to reduction of density and diversity in benthos besides residual oil in sediment (e.g., competition with dreissenid mussels, low bottom-water dissolved oxygen), but the strong correlation of oil with low *Hexagenia* densities in this study indicates a causative linkage. Disentangling the relationship of various PAH sources following an oil spill represents a significant challenge (Murawksi et al. 2014). Overall, it is important to have a detailed understanding of the baseline benthic community to accurately assess effects of crude oil following a spill, which is justification for ongoing benthic monitoring programs throughout the basin.

3.6.3 Fish

The large and diverse Great Lakes fish fauna (Schroeder and Dann 2003) is important ecologically, economically, and culturally. Important stocks include lake trout, walleye, lake whitefish, yellow perch, and lake sturgeon-. During the first 24-48 hours of an oil spill, fish are vulnerable to acute exposure. This period is generally brief, as the loss of acutely lethal components of oil due to weathering occurs rapidly. While the acute toxicity of crude oil on adult fish is often minimal and localized following a spill (Vosyliene and Kazlauskiene 2005), long-term sublethal impacts can occur depending on the nature of spill and resulting site-specific exposures. As previously mentioned, acute lethality is mostly associated with LMW compounds such as mono- or diaromatics. Fish can take up these components from passive diffusion across the gills, directly through ingestion or indirectly through food (Figure 7). Mortality is often expressed as the lethal concentration, 50% (LC50), where 50% of the organisms die. Sublethal effects are expressed as the effective concentration, 50% (EC50), where 50% of organisms show a response other than mortality.

The mode of action for acute toxicity in fish from oil exposure, is mostly attributed with narcosis. Narcosis results from a general and reversible disruption of the cell membrane which depresses biological activity. It involves a number of biochemical reactions in the organism and although the exact mechanism behind the narcotic-membrane interaction is not fully understood, it is dependent on the concentration of toxicant. Larger oil constituents, such as PAHs with 3-5 rings, are taken up more slowly and contribute less to acute toxicity. Barron et al. (2013), provided a review of the toxicity literature for a wide range of crude oils across 67 species of fish and invertebrates (as measured by total PAH concentrations). These data were expressed across a species sensitivity distribution and found a wide range of sensitivities depending on physiological and life history traits as well as differences in the laboratory method used. This report has led to recent attempts to standardize procedures to increase reproducibility among studies (e.g., Echols et al. 2016) but more comprehensive studies are needed to better understand toxicity to fish, especially in freshwater ecosystems (Redman et al. 2017). Fish toxicity is variable across life stages (larval vs. adult) and will be discussed separately in the following sections.

3.6.3.a Adults and Juveniles

The effects of contaminants on fish (along with other taxa groups) are often sublethal (e.g., changes in physiological processes, growth, reproduction, development, behavior), and can have a negative effect on the fitness of individuals. Recent research has shown that crude oil, especially PAH constituents, can directly or indirectly impact the physiology (Alderman et al. 2017a, Crowe et al. 2014, Kochhann et al. 2015, Murawski et al. 2014, Dubansky et al. 2013, Jung et al. 2012, Whitehead et al. 2012), health (Alderman et al. 2017b, Bauer et al. 2017, Nunes et al. 2017, Vosyliene and Kazlauskiene 2005), growth (Brewton et al. 2013, Claireaux et al. 2013, Ruggerone and Rogers 2003), and reproduction (Ruggerone and Rogers 2003, Turscott et al. 1992, Kocan et al. 1996a,b). A preliminary review of specific information on dilbit toxicity to aquatic organisms was recently published (Alsaadi et al. 2018).

A number of laboratory studies have established sublethal impacts from crude oil on adult and juvenile fishes, including early studies on the direct ingestion of oil, leading to suppressed appetite in fishes (Luquet et al. 1983, 1984). The direct ingestion of oil was confirmed during a migration of juvenile salmon

(Sturdevant et al. 1996), which subsequently impaired their growth (Willette 1996; as summarized in Short et al. 2017). The most common biomarker attributed to exposure of fish is measuring levels of enzymes involved in detoxification (e.g., CYP1A1, Section 3.6) via the Cytochrome P450 system (Ribecco et al. 2012). Aas et al. (2000) used the biomarker approach to study the effects of chronically exposed Atlantic cod to North Sea crude oil for a 30 day period at comparable concentrations to spilled oil slicks (e.g., Neff and Stubblefield, 1995). While the highest oil concentrations produced a number of biomarker changes (DNA adduct formation, induction of CYP1A1 in liver estimated by enzymatic activity), changes were also noted at very low exposure concentrations. The authors suggested that the presence of PAH metabolites in bile and DNA adduct formation at low concentrations, shows the use of these tools as sensitive indicators of recent PAH exposure. Vosyliene and Kazlauskiene (2005), exposed adult rainbow trout to crude oil for four days to evaluate changes in biological parameters. Even after this short duration they found a number of changes to the hematological indices in adult fish, most notably a significant decrease in the gill ventilation frequency (Vosyliene and Kazlauskiene, 2005).

Following the Deepwater Horizon oil spill incident, several studies have demonstrated activation of the AHR pathway in organisms exposed to the spill (Dubansky et al. 2017). The Gulf killifish (*Fundulus grandis*) was identified as a sentinel species for the study of site-specific effects of crude oil contamination on biological function and a number of studies on killifish have identified gene responses indicative of physiological and reproductive impairment (Garcia et al. 2012, Whitehead et al. 2012). Whitehead et al. (2012) observed changes in the genome expression and tissue morphology),), over two months following the initial exposure period. In laboratory studies, comparable results were observed following oil exposures with killifish (Pilcher et al. 2014) and spotted sea-trout (*Cynoscion nebulosus*) (Brewton et al. 2013). CYP1a1 gene expression was associated with growth depression in sea-trout (Brewton et al. 2013) and the gene expression in killifish were indicative of changes in gene transcription, cell cycle progression, RNA processing, DNA damage, oxidative stress and apoptosis (Crowe et al. 2014; Pilcher et al. 2014).

Other secondary impacts on fish communities have been observed. Following the Exxon Valdez oil spill, there was reduction in fishing of sockeye salmon. This allowed large numbers of sockeye to enter spawning ground (up to 4-fold increases) (Ruggerone and Rogers 2003). These larger densities had multi-year impacts on the juvenile size and subsequent adult abundances, as juvenile salmon growth was negatively related to the greater number of parent spawners (Ruggerone and Rogers 2003). Additionally, following the loss of hundreds of thousands of seabirds from the Deepwater Horizon oil spill, there was a strong increase in the recruitment of coastal fishes the following year (Scaefer et al. 2016). These predatory-prey interactions are not well understood at this time, but could have important ecological ramifications (Short et al. 2017).

In contrast to the above, some studies have also found minimal long-term impacts following large oil spills (e.g., Masnik et al. 1976, Able et al. 2014). Able et al. (2014), studied the impacts of oiled and non-oiled regions in Louisiana marshes following the Deepwater Horizon oil spill, and observed no differences in species composition, assemblage or abundance, two-three years after the oil spill reached the marshes (Able et al. 2014). This finding, however, was not consistent with other research which identified impacts (de Soysa et al. 2012), on *F. grandis* following the spill (Whitehead et al. 2012; Garcia et al. 2012; Dubansky et al. 2013; Crowe et al. 2014).

In the Great Lakes, lake sturgeon are generally listed as a Species of Special Concern with strict regulations for harvest. Substantial investments have been made in restoration of sturgeon stocks over decades, sometimes in rivers where populations had been entirely extirpated (e.g., St. Louis River in Minnesota/Wisconsin, Maumee River in Ohio). They are also a species of high cultural significant to many Native American tribes and First Nations. Sturgeon are cool-water fish that prefer large shallow lakes and rivers, and are commonly found in the shoal waters of the Great Lakes shorelines, but they also spawn and spend their early years in river habitats. Lake sturgeon populations have been dramatically reduced or extirpated as a result of overfishing, habitat loss, dam construction and pollution in the GLSLR. Their population status and life history makes sturgeon especially vulnerable to oil spills in both tributaries and coastal waters. A spill in one of the few remaining rivers where lake sturgeon spawn and spend their early years could be a major setback for restoration of the species.

3.6.3.b Early Life Stages

The early life stages of fish (eggs and larvae; ichthyoplankton) contribute both to population recruitment and to the food base of adult fish population as they age and mature. These life stages of fish are a highly dynamic period with respect to tissue differentiation and animal development, whereby a large number of genetic and molecular processes are occurring. Moreover, unlike their adult and juvenile counterparts, embryos and larvae are mostly unable to avoid exposure to oil spills, due to their minimal swimming capacity (Dettmers et al. 2005).

Several studies have found early life stages of fish to be sensitive to oil spills (e.g., Barron et al. 2003, 2004; Carls and Thedinga, 2010; Carls et al. 2005; Heintz et al. 1999; Rice et al. 2001; Short, 2003; Incardona 2017). In particular studies have identified high rates of deformities (Hose and Guilette 1995, Hose et al. 1996, Carls et al. 1999, 2002, Shen et al. 2012), developmental delays (Carls and Thedinga, 2010), impaired cardiac function (Incardona et al. 2004, Hicken et al. 2011, Zhang et al. 2012) and anemia (Carls and Thedinga) when compared to controls/cleaner environments. Heavy fuel oils with high proportions of 3- to 5-ringed alkyl PAHs are generally more chronically toxic than light oils due to the disruption of embryonic development by alkyl PAHs. Bornstein et al. (2014) isolated different groups of PAHs to determine which were the most toxic to trout embryos. Indeed, the most toxic fractions were richest in PAHs and alkyl-PAHS, which was consistent with other studies which identified increased toxicity with heavier oils.

In addition to standard acute and chronic toxicity, some studies on early life stages have observed delayed toxicity (Mager et al. 2014). Heintz et al. (2000), saw a decrease in adult survival rates of pink salmon (*Oncorhynchus gorbuscha*) exposed to PAHs, and Mager et al. (2014) found swimming impairment in juveniles, following embryonic exposure. Also notable is that embryo development in most salmonids is characterized by a dependence on maternally-provided food resources. Bue et al. (1998) found significantly higher mortality rates in embryos collected from adult pink salmon which resided in more contaminated environments. These delayed effects are often not accounted for but can affect recruitment, growth, reproduction and survival in later months or years (post-exposure) and require additional long-term monitoring studies to fully assess (Lee et al. 2015).

Although most studies to date on the sublethal effects of early life stages from crude oil exposure have been completed in the laboratory (Barron et al. 2003, 2004), there a several instances following large oil spills (Exxon Valdez, Deepwater Horizon) in which effects have been assessed on wild fish embryos and larvae. In particular, following the Exxon Valdez spill a number of studies noted that fish embryos were particularly sensitive to oil exposure even at relatively low concentrations of PAHs (Carls et al. 1999, 2002, Hose et al. 1996, Kocan et al. 1996, McGurk and Brown 1996). That said, recovery of salmon spawning habitat and associated embryos in Prince William Sound appeared to be complete or nearly so by 1994, five years after the Exxon Valdez spill (Bue et al. 1998, Murphy et al. 1999).

While there is more research on marine and anadromous fish, studies on the early life stages of freshwater fish have observed similar results. DeBryun et al. (2007) studied the effects of an oil spill (via a train derailment) in Wabamun Lake (Alberta) on the early life stages of whitefish. They compared deformities in larval Lake Whitefish (*Coregonus clupeaformis*) from areas of Wabamun Lake exposed only to “background” PAH contamination with larvae from sites additionally exposed to PAHs from the oil spill. All sites in the lake (including reference areas) showed incidences of deformity higher than typically observe in laboratory studies, but a small number of oil-exposed sites showed higher incidences and severity of some deformities than sites not exposed to oil. After consideration of incidence, severity, and pattern of deformity, the authors were able to detect a consistent response to the oil, despite high variability and background deformity rates in this historically contaminated environment.

Recent spills of diluted bitumen (dilbit; Kalamazoo River) have raised concerns about toxicity (McKnight et al. 2016). In general, the high molecular weight components of bitumen are considered less toxic due to their low solubility in water and inability to readily cross biological membranes compared to lower molecular weight (LMW) components. Lower solubility, however, may result in greater bioaccumulation potential for some lipophilic compounds. Diluents added to bitumens contain LMW compounds (often including benzene) that can dissolve in water and contribute to acute aqueous toxicity before they are lost by weathering. In addition, 3-to-5-ringed alkyl PAHs detected in dilbit are derived from bitumen. Their concentrations in dilbit are similar to those of conventional crude oils and are thought to be the components causing chronic toxicity to fish embryos (Madison et al. 2015).

More recently the impacts of diluted bitumen on early life stages have been investigated (Madison et al. 2015, Philibert et al. 2016, Madison et al. 2017, Alderman et al. 2017). Alderman et al. (2017) recently looked at the impacts of diluted bitumen on the early life stages of sockeye salmon (*Oncorhynchus nerka*). They exposed parr to the water-soluble fraction and looked at molecular, morphological and organismal endpoints related to cardiotoxicity. The authors observed significant changes in liver biomarkers in response to the PAH exposure at levels of 3.5 µg/L, while much higher levels resulted in changes to biomarkers in the heart. Madison et al. (2015, 2017) observed the effects of two types of dilbit, CLB and AWB on medaka embryos and found that while the effects were similar across the two types, the onset of toxicity was 6-10-fold lower in CLB solution than AWB. The authors suggested this could be due to the rate of weathering for each dilbit (Madison et al. 2017).

3.6.4 Amphibians and Reptiles

Most research on the impacts of crude oil spills on vertebrates has focused on marine mammals, fish, and sea birds and mammals. The impacts of oil exposure on other freshwater vertebrates, such as amphibians and reptiles, are less studied. The GLSLR is home to a number of reptiles and amphibians, such as the Northern Leopard Frog (*Rana pipiens*) and Painted Turtle (*Chrysemys picta*). Oil spills near coastal habitats in temperate regions such as the GLSLR can contaminate areas used by aquatic turtles for nesting (Milton et al. 2003). There is also evidence that turtles can ingest oil directly and they have limited means of avoiding a spill (Lutcavage et al. 1995). Turtles reproduce by internal fertilization and produce shelled eggs deposited on land. The female leaves the water and will seek sand or mud to dig a shallow cavity. An oil spill in Tampa Bay, Florida resulted in survival rates of sea turtle embryos on the impacted beach of 5% compared to the normal rate of 50-90% (Yender and Mearns, 2003). On the other hand, Rowe et al. (2009) completed a lab study on snapping turtle eggs to determine if exposure via percolation through nest material of physically dispersed and chemically dispersed crude oil resulted in embryonic or juvenile toxicity. Hatchlings were raised for 13 months and while eggs accumulated up to 560 µg/kg of total PAHs, no effects were observed on hatching success or hatchling/juvenile traits (DNA integrity, survival, growth, metabolism, energy storage or behavior).

A team of researchers from Nigeria and Italy (Luiselli and Akani 2003, Akani et al. 2004) completed an indirect assessment of the potential impacts to amphibian and reptile diversity in Nigeria from oil exposure. The authors compared the abundance and diversity of turtles in two areas with similar environments, one that had been impacted by an oil spill in 1988 and one that had not. The authors found a reduction in species diversity (from 4 species to 2 species) and abundance (510 individuals to 88) in the unpolluted area compared to the polluted area, respectively. Additionally, they indirectly studied the potential impacts of oil to amphibians across 6 locations in the Niger Delta (Nigeria) from 1996-2002 in two pristine environments compared to four sites that had been influence by the oil industry. While all sites had a wide diversity of amphibian species (28 species total), there was a general decrease in total species at the oil-impacted locations. However, it should be noted that the four developed sites used for the amphibian study, were also impacted by a number of other factors (habitat alteration, human development), and oil may not have been a main contributor.

While limited in scope, a few studies have looked at the effects of crude oil and its components on amphibians. Amphibians undergo a major life history change from their aquatic tadpole life stage to their adult semi-aquatic stages. Lefcort et al. (1997) studied the effects of oil exposure on larval tiger salamanders (*Ambystoma tigrinum*) and identified a change in metamorphosis timing and a reduction in the overall size, compared to salamanders kept in an oil-free environment. During metamorphosis, several changes to an animal's biochemical, metabolic, and physiological functions may occur. Endocrine function is sensitive to a number of PAHs in vertebrates (Zhang et al. 2016) including amphibians and reptiles (Bishop et al. 1998). Recently, Truter et al. (2017) exposed *Xenopus laevis* tadpoles to crude oil and found down-regulation of endocrine-disrupting biomarkers in the exposed animals. The authors suggested that exposure of amphibians to crude oil may result in altered endocrine signaling, but further research is necessary to fully understand these alterations.

While research suggests there is no single overarching cause linked to declines in amphibians, several multiple stressors, including contaminants are likely interacting (Gutleb et al. 2000, Hayes et al. 2002). 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 warranted.

3.6.5 Semi-Aquatic Mammals

The GLSLR is home to number of semi-aquatic mammals such as the river otter, beaver, mink, and muskrat. While research is limited on these animals, the greatest concern with respect to semi-aquatic mammals following a spill are the external coatings, particularly in those which cannot avoid contact with surface slicks of oil. They instinctively groom their fur following exposure, which leads to direct ingestion of oil and redistribution on their fur. Additionally, they are vulnerable to inhalation of the aerosols that evaporate from the spill.

During and after spills semi-aquatic mammals are vulnerable to exposure to oil. Fortunately, if the spill is small and does not impede their movement, they are mobile enough to move away from the spill and can access the area outside the core impacted region. As a top predator in the GLSLR, river otters (*Lutra and Lontra canadensis*) serve as a keystone species (Estes and Duggins 1995; Roemer et al. 2009) and a sentinel species for freshwater health (Peterson and Schulte 2016). Yet, limited information is available on semi-aquatic mammals in freshwater systems. Following the Exxon Valdez oil spill, twelve river otter carcasses were found (Bowyer et al. 2003), but no direct mortality estimates were made (Harwell and Gentile 2006). The marine cousin of the river otter, the sea otter, has been studied more frequently, due to their presence in coastal environments. Survival of sea otter pups in areas impacted by the spill, was lower than for those in control regions (Monnett and Rotterman, 1992; Ballachey et al. 1994). Unfortunately, it is difficult to assess reproductive outcomes of impacted mammals in large scale field studies without the use of telemetry for detailed monitoring (Mazet et al. 2001). Additional research on understanding the effects of crude oil spills on freshwater semi-aquatic mammals is needed.

3.6.6 Birds

The Great Lakes support a wide variety of birds that depend on the waterways for seasonal or year-round habitat. There are over 450 bird species that have been documented in the GLSLR. In particular, the coastal wetlands, and beaches provide food, shelter and spawning grounds for both resident and migratory species. Historically, organic contaminants were linked to a number of adverse effects on bird populations including eggshell thinning, failed reproductive success, deformities, and population declines

(Hebert et al. 2011). While the Great Lakes bird populations appear to be recovering from these effects, they are still vulnerable to oil spill impacts.

The most obvious effect of an oil spill on birds is the direct contact of oil with shorebirds (e.g., wading birds) and those that inhabit the water surface (e.g., diving ducks). Waterfowl such as scaup use coastal wetlands as stopover sites and shorebirds, including the endangered piping plover, fly thousands of miles to nest on mainland and Great Lakes island beaches. Birds are immediately vulnerable following an oil spill, as oil will stick to their feathers, but shorebirds are particularly vulnerable because they spend much of their time foraging in shoreline habitat and many nest in colonies on beaches or low-lying islands and sand bars (Henkel et al. 2012). Like mammals, the natural instinct of birds is to groom or preen their outer covering of feathers following exposure, which leads to direct ingestion of oil by the bird, redistribution of oil in the plumage, and loss of thermal insulation and hypothermia.. Birds are also vulnerable to the acute toxicity of light constituents via inhalation of these volatiles from air during preening.

While Great Lakes research specific to oil spill impacts on birds is limited, several large-scale studies have shown significant mortality from oil spills in areas frequented by aquatic birds. For example, Haney et al. (2014a, b) estimated that 600,000 to 800,000 over-wintering birds were killed following the Deepwater Horizon oil spill. Similar effects were observed following the Exxon Valdez oil spill, where in addition to mortality of adults, there was a reduction in body mass, body condition, and nestling survival (Golet et al. 2002). For freshwater spills, data are not readily available for effects on aquatic birds and spills of this magnitude are not anticipated based on crude oil transportation modes and exploration restrictions. Smaller numbers of dead birds were observed, however, in shoreline areas following the 2005 spill of heavy fuel oil to Wabamun Lake, Alberta (Birtwell 2008); estimates of total numbers killed have not been published. The ecological significance of widespread bird mortality from oiling is also poorly understood. Experience with the Deepwater Horizon spill indicates that widespread mortality of fish-eating birds 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 (Short 2017), although the duration of such an impact is not yet fully known.

In the United States, assessing injury from oil spills to wildlife includes monetization of the mortality (Migratory Bird Treaty Act) or the lost uses of injured resources and services (Oil Pollution Act; Sperduto et al. 2003). Baseline surveys of population density and an understanding of species most sensitive to exposure are high priorities for spill assessment (Haney et al. 2017). To cover damage assessment needs, Irons (1996) recommended the immediate collection of data on oil exposure, distribution, abundance and behavior of birds at spill sites where baseline data are lacking. While surveys (offshore and onshore) can be used to estimate the impacts on birds following a spill, long term research on the distribution and habitat use of Great Lakes birds is necessary to fully understand potential impacts. The Great Lakes Commission has been coordinating related avian resources activities over the last several years (https://www.glc.org/work/avian-resources), including aerial surveys (lakes Michigan, Huron, Erie, and St. Clair; 20012-2014), an open water bird workshop in March 2016, a webinar in November 2017, and promotion of the Midwest Avian Data Center as a data repository and decision-support resource (https://data.pointblue.org/partners/mwadc/index.php?page=home).

3.6.7 Summary of knowledge gaps related to exposure to crude oil of aquatic receptors

Although much has been learned from laboratory and field studies related to the impacts of crude oil on various organisms, many questions remain. A high-level summary of the state of knowledge specific to particular taxonomic groups is shown in Table 7. In the Great Lakes and tributaries, important research questions and knowledge gaps remain. Among these is a need for better understanding of species-specific sensitivity to oil spills, especially of species that are of greatest importance to tribal subsistence, culture, and commerce; for federal or state/provincial aquatic species listed as threatened or endangered; and for key commercial and recreational species. The sensitivity to oil of amphibians, reptiles, and semi-aquatic mammals, and the food web consequences of the loss or impairment of their populations is not well understood. This was recognized as an issue during the response and restoration activities following the Kalamazoo River oil spill. Linking the measurement of biomarkers of oil exposure in organisms to population, community, and ecosystem-level impacts on longer timescales has proven challenging. The unevenness of toxicity information that is available for specific types of crude oil that are transported in the GLSLR has been an obstacle for preparing for and responding to spills, especially for the diverse suite of diluted, blended, and upgraded types of bitumen. More complete analysis of how variable and transient environmental conditions affect spill behavior and ecological vulnerability (e.g., spills during high flow caused by spring snow melt, during ice formation and breakup, or during migratory bird stopovers) would also be valuable.

Table 7. Qualitative summary of the state of knowledge of oil impacts on major taxonomic groups.

Taxonomic Group	State of Knowledge			Notes
	Poor	Fair	Good	
Zooplankton and Phytoplankton		●		Marine species are better studied
Benthic Invertebrates		●		Best information is on primary components of fish diets
Fish			●	Focus has been on high-value species and common prey fish
Reptiles and Amphibians	●			River and wetland organisms and habitats are understudied
Semi-Aquatic Mammals	●			River and wetland organisms and habitats are understudied
Birds			●	Focus has been on waterfowl, piscivores, and gulls

3.7 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 (McKnight et al. 2016). An oil spill response plan details what actions should be taken in the event of an oil spill. In 1990, following the Exxon Valdez spill, the U.S. enacted the Oil Pollution Act (OPA), which requires the development of Area Contingency Plans to prepare and plan for oil spill response on a regional scale. The U.S. Congressional Research Service prepared two reports on oil spills and response in recent years (Bearden and Ramseur 2014, Ramseur 2017). Canadian legislation also governs potential oil spills, with oil pollution prevention regulations found in a number of acts including the Fisheries Act, Oceans Act, Arctic Waters Pollution Prevention Act, and the Canada Shipping Act.

The success of a response plan is related to a number of factors including the efficiency of the spill response as well as the speed at which the oil is diluted or dissipated by weathering processes. Federal, tribal, state, and provincial as well as local response organizations and mechanisms are in place to deal with natural or man-made disasters. Examples of some of these plans and organizations related to oil spills are listed in Table 8. In general, U.S. and Canadian Coast Guard staff and vessels oversee spill response in Great Lakes waters. The USEPA is the lead for spills in tributaries and inland waters. In the United States, NOAA provides science support during spill response, and covers natural resource damage assessment responsibilities during spill recovery phases.

3.7.1 Oil Spill Response Options

During a spill response, various types of equipment and tactics are used to limit the contact of oil with sensitive areas (NOAA 2017, https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/spill-containment-methods.html). One major difference in spill response in the Great Lakes Basin, in contrast to responses to spills in saltwater systems, is concern about impacts of response actions, such as dispersant use, on drinking water that is sourced from the lakes. In general, the most common response to a spill is to quickly remove as much oil as possible from the water surface, either mechanically or by other means (Table 9). The decision to use a particular response method is carefully considered, while taking into account oil characteristics, water and weather conditions, and human and environmental exposure and sensitivities (Bejarano et al. 2014). Indeed, some of these response mechanisms could result in adverse consequences if not used appropriately. Dispersants are often considered in ocean spill response because their use can lessen the near-term environmental impacts of a spill by moving concentrated oil from the water surface into the top few meters of the water column in dispersed form, facilitating oil dilution and microbial degradation (Jung et al. 2012, Bejarano et al. 2014). In particular this approach can be used to reduce the amount of oil contacting shorelines and surface species, such as aquatic birds and marine wildlife (amphibians, reptiles, semi-aquatic mammals) (Barron et al. 2013).

Besides the threat posed to drinking water, there is concern that in cold water chemical dispersants may not be as effective. There is active debate about the effectiveness of dispersants at freezing temperatures. Venosa and Holder (2013) studied the effectiveness of dispersants at 5 and 25°C and found that the differences were not as significant as expected, and that they may be effective in cold environments as long as there is not a significant increase in viscosity. To date, most of the research on dispersant effectiveness has tested them in marine conditions (high salinity), with few freshwater tests being performed (Ramachandrann et al. 2006). Additionally, there is concern about whether dispersants may enhance the exposure, uptake, and toxicity of oil to organisms. In the sub-surface water column, concentrations of dispersed oil may be increased to levels that are toxic to fish and invertebrate embryos, where even brief exposures could be harmful. Several studies have shown that dispersants can enhance toxicity to fish (Vosyliene and Kazlauskiene 2005, Yu et al. 2015), invertebrates (Salehi et al. 2017), and plankton communities (MacNaughton et al. 2003, Hook and Osborn 2012, Jung et al. 2012). Due to these toxicity concerns, most regions in the U.S. (13 Regional Response Teams) do not allow the use of oil dispersants in shallow coastal waters or estuaries, or in freshwater settings.

Presently, the U.S. and Canadian governing bodies do not promote the use of dispersants on surface waters within the GLSLR. According to the Joint Marine Pollution Contingency Plan, “this policy is necessary to protect the fragile aquifers, sensitive ecosystems, and numerous potential and existing surface and subsurface water intakes (potable and non-potable) in the region”. Better quantification of the relative benefit versus risk of dispersant use remains an area of uncertainty, and further research is necessary to determine dispersant effectiveness in large cold-water systems like the Great Lakes.

Table 8. Federal organizations and agencies responsible for oil spill response and oversight.

Group/Act	Organization/Agency	Details
Joint Marine Pollution Contingency Plan, 2016 CANUSLAK, 2013 CANUSCENT and CANUSQUE Annexes	Canadian Coast Guard and U.S. Coast Guard, with supporting federal agencies	Covers coordinated binational planning, preparedness, and response to a spill in the contiguous waters of Canada and the U.S., defines the Joint Response Team (JRT), and is regularly tested and improved upon in an ongoing series of tabletop and field exercises. http://www.atlanticarea.uscg.mil/Our-Organization/District-9/Ninth-District-Staff/Response-Division/CANUSLAK-Joint-Response-Team/CANUSLAK-Plans/
Regional and Area Contingency Plans	U.S. Region 5 Regional Response Team (RRT), co-chaired by U.S. Coast Guard 9th Dist. and USEPA Region V; PA served by RRT 3 and NY by RRT 2	Comprised of members from local, state, tribal, and federal agencies committed to working efficiently to minimize the adverse effects of oil and chemical incidents that affect safety, human health and the environment in the Upper Midwest region including the Great Lakes. http://www.rrt5.org/
Michigan Pipeline Safety Advisory Board	15-member board including state, tribal, NGO, law enforcement, university, tourism, and public representatives	The board provides oversight of activities related to pipeline safety technical studies, develops policy recommendations, hosts public meetings, and promotes information exchange. https://mipetroleumpipelines.com/
Emergency Response Division	U.S. National Oceanic and Atmospheric Administration, Office of Response and Restoration	Scientific Support Coordinators (SSCs) and the Scientific Support Team (SST) respond to virtually every significant marine and Great Lakes release in the country. https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/
Robert T. Stafford Disaster Relief and Emergency Assistance Act	U.S. Federal Emergency Management Agency	FEMA established the national incident management system (NIMS) to guide departments and agencies at all levels of government to work together seamlessly and manage incidents involving all threats and hazards. https://www.fema.gov/robert-t-stafford-disaster-relief-and-emergency-assistance-act-public-law-93-288-amended
Emergency Management Framework for Canada	Public Safety Canada	The Framework builds a shared approach for cooperative emergency management. https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/mrgnc-mngmnt-frmwrk/index-en.aspx
National Preparedness Plan and Environmental Response Plan	Canadian Coast Guard (CCG) and Transport Canada	Transport Canada lays out the overall framework for the national preparedness capacity to combat marine oil pollution incidents in Canada. Similarly, the CCG has a National Response Plan that identifies how CCG will manage the response to a marine oil spill, including the deployment of personnel and response resources. https://www.tc.gc.ca/eng/marinesafety/tp-tp13585-procedures-EPRNPP-3091.htm
No-Spills	Northern Michigan Waterways Hazardous Materials Spill Planning Committee	The group is a regional industry-government-media partnership based in Northern Michigan that seeks to build awareness and cooperation around the topic of oil spills and environmental response by organizing annual workshops, among other activities. http://www.no-spills.org/

Table 9. Common oil response actions (Cojocaru et al. 2011).

Response Action	Notes
Booms	Floating, physical barriers to oil which slow the spread of oil and keep it contained. Especially common in places where the boom can keep oil away from sensitive areas such as spawning grounds.
Skimmers	Boats and other devices that can remove oil from the water surface before it reaches sensitive areas along a coastline.
In situ burning	This technique works best when the oil is fresh with a low flash point and the weather is relatively calm.
Dispersants	Mixture of emulsifiers and solvents that helps break oil into small droplets following an oil spill, although potential drinking water impacts must be considered before use in freshwater systems.
Solidifiers	Chemical agent which is composed of porous high molecular weight polymers which can form a physical bond with the oil.
Sorbents	Inert and insoluble materials which are used to remove oil from water through adsorption, absorption, or both.

3.7.2 Rehabilitation and Biological Cleaning

Effective rehabilitation efforts require coordination among local, State/Provincial, Federal, and private agencies. Under the OPA, the responsible party, is required to hire and fund trained groups to handle the many jobs required by a spill, including wildlife rehabilitation. The importance of establishing a rehabilitation plan prior to an oil spill is critical to their success. With site-specific knowledge at hand, these groups collect oiled wildlife (most often this includes birds, amphibians, reptiles, and mammals), in the contamination area. The animals are warmed, fed, hydrated and rested before they are washed in a series of tubs filled with a mixture of diluted cleaning agents and water.

While the results of post-rehabilitated wildlife varies significantly because the species and oil exposure levels involved are rarely consistent (Saba and Spotila 2003), there have been many organisms successfully rehabilitated back into the wild. Following an oil spill in Pennsylvania, a group studied the survival, home range and temperature preferences for turtles that had been rehabilitated versus non-exposed turtles. The study concluded that the rehabilitation was effective in restoring the animals back to normal behavior in the wild (Saba and Spotila 2003). Mignucci-Giannoni (1998) found that of the 5687 organisms representing 152 species recovered alive from an oil spill in San Juan, Puerto Rico, 63% were successfully rehabilitated. Following the Kalamazoo River spill, turtles, birds and mammals were rehabilitated with a survival rate of 97%, 84% and 68% respectively (Winter 2013, Dew et al. 2015). But as mentioned, mixed results are often observed depending on species and location. Following the Exxon Valdez spill, rehabilitation survival rates were reported as 67% among sea otters (n=347; Rebar et al. 1995), yet most of the recovered sea birds did not survive rehabilitation (n=1888; Piatt and Ford, 1996). Survival rates were as high as 95% among cleaned and translocated little penguins (*Eudyptula minor*) (n=1894; Hull et al. 1998) for a 1995 spill in Tasmania, Australia; many penguins returned to the spill site within four months after translocation.

Although the success of rehabilitation depends on a number of factors (e.g., organism sensitivity, physiology, duration of exposure, dosage and oil type, geography), wildlife care and rehabilitation can have significant biological and conservation value and is an important component to the oil spill response strategy.

3.7.3 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 or 'the magnitude of disturbance that a system can experience before it shifts into a different state' (Holling, 1973). Additionally, resilience has been defined as 'the capacity of a system to absorb disturbance and reorganize' (Walker et al. 2004). Ecosystems that exhibit this dynamic behavior are characterized by multiple regimes (Holling and Gunderson 2002) and have the capacity for nonlinear change (Garmestani et al. 2009). Yagi et al. (2010) provided a helpful example where a lake's resilience will define the capacity of the lake to receive additional phosphorus inputs, while still remaining relatively clear. 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). Ecological systems are naturally variable but still tend toward stability over timescales of years to decades. With the number of changing variables, the value of consideration of resilience theory has been recognized for better understanding how large-scale changes in ecosystem function will alter the distribution of species (Benson 2012). This has resulted in more consideration of whole ecosystems in management decisions rather than simply concentrating on individual species or populations in isolation (e.g., NYOGLECC 2007). For some, resiliency is primarily viewed as a theoretical concept, which is generally approximated in practice by measuring recovery rates after a disturbance incident such as an oil spill, and then applying those observations to similar future situations as they are encountered.

Past studies investigating effects of oil spills on marshes indicate that re-growth of plants can overcome the negative impacts of an oil spill once the oil has been degraded (Silliman et al. 2012). Silliman et al. (2012) studied the resilience of marshes following the Deepwater Horizon oil spill and found that despite a number of harmful effects of the oil spill on marsh vegetation, there was clear evidence for recovery processes. Similar results were observed by other marsh researchers, who found that marsh plants and marsh animals (e.g., meiofauna) may be somewhat resilient to oil pollution, supporting their recovery from spills (Roth and Baltz 2009, DeLuane and Wright 2011, McCall and Pennings 2012, Moody et al. 2013, Able et al. 2014, Fleeger et al. 2015).

Upper trophic levels may also display resilience. A study on several freshwater species 14 years following an oil spill in southern Brazil found no impact on the genetic variability of fish populations in the impacted region compared to controls. This was consistent with other studies which identified fish population recoveries two years after the Exxon Valdez oil spill (Barber et al. 1995) and on duck populations (Lanctot et al. 1999). The results suggest that depending on the population and location, upper trophic level taxa can exhibit resilience and recovery from oil spill impacts over time.

While resilience is considered a fundamental component of ecosystems that can be useful in predicting the overall response to an anthropogenic change, such as an oil spill, resistance and resilience to anthropogenic disturbance varies among different communities or even among similar communities in different locations. This variation makes it difficult to predict community responses and recovery times following an additional stressor, such as an oil spill. There is an inherent bias that results following a major anthropogenic event that often results in economically important or charismatic species receiving special attention under the Natural Resource Damage Assessment (NRDA) regulations of the United States (Newman and Clements 2008).

Some scientists have argued, however, that failing to account for the response of all taxa, including those resilient to oil, may provide an incomplete picture. For example, the Exxon Valdez oil spill had a dramatic impact on seabird populations, causing mortality in the hundreds of thousands, but seabirds in the region showed unexpected resilience (Weins et al. 1996) in the year following the event. Understanding and predicting acute and chronic ecosystem responses to spills is an inexact science, but each new incident provides an opportunity to learn new lessons and to test understanding developed from successes, mistakes, and surprises experienced during and after previous spills. Each spill is unique in some ways, but hopefully some commonalities can emerge from thoughtful analysis and synthesis.

3.7.4 Oil Spill Monitoring

In addition to direct observation from shore, vessels, and aircraft, additional techniques are commonly used to monitor the surface and subsurface locations, concentrations, and changing properties of spilled oil, as well as impacts of remedial actions on the oil. In addition to laboratory instruments such as gas chromatographs that can analyze concentrations of oil constituents in field samples, optical instruments such as fluorometers (Conmy et al. 2014) proved useful to track *in situ* oil in the subsurface water column during the Deepwater Horizon spill and other events. Monitoring of sunken oil in the water column or on the sediment surface has proven very difficult in the case of events such as the Kalamazoo River spill (McKnight et al. 2016), where manual methods such as probing sediment and looking for a surface sheen were employed in lieu of other options.

Remote sensing is the science of gathering data on a land or water surface or subsurface area without being in direct physical contact with it (Li et al. 2017). Remote sensing has the ability to provide surprisingly fine-scale spatial data that is increasingly useful for a multitude of water related studies (Jha et al. 2008). Remote sensing can be used for detecting and monitoring oil spills but traditionally has played a secondary role in oil response monitoring (Leifer et al. 2012). However, recent advancements and sensor availability along with the scale and urgency of the Deepwater Horizon oil spill elevated the role for remote sensing (Leifer et al. 2012) in spill monitoring, particularly using thermal infrared imaging. Equipment used to capture remote sensing data includes satellites, piloted aircraft, balloons, and drones. One major limitation of most remote sensing methods is their inability to provide information about the thickness of oil slicks.

3.7.5 Oil Spill Modeling

This section provides a summary of existing models that are relevant to oil spills and their potential impacts. While the review is intended to focus on modeling analysis in freshwater system, the literature is dominated by studies in marine systems. We include both freshwater and marine models for completeness, and the review is organized by waterbody or hydrologic system.

In general, the modeling analyses of oil spills incorporate hydraulic and hydrodynamic transport of water and associated particles (e.g., numerical oil droplet surrogates), and potentially include processes such as dissolution and evaporation, with a focus on open-water spills. 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. Fewer modeling studies have incorporated food web dynamics into the fate and transport of oil spills. The operational spill model currently used by NOAA in the Great Lakes and coastal ocean is GNOME v. 1.3.10 (General NOAA Operational Modeling Environment). The models and applications described in more detail in the following sections are summarized in Table 10.

Table 10. Summary of oil spill models and applications.

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 1000 crude oil and refined product types.	Requires only limited field data because of large database; applied rapidly in many spill responses.
OILTRANS	Similar in formulations to the ROSS2 and ROSS3 models, but it operates on fully 3-D grids.	Applied to Celtic Sea spill in 2009 near the coast of Ireland.
MEDSLIK	Well-documented 3-D model that predicts the fate and weathering of oil spills in marine systems.	Applied operationally in the Mediterranean Sea.
SIMAP	Estimates the three-dimensional trajectory, fate, and biological exposure and effects of oil spills.	Applied to Deepwater Horizon spill response and natural resources damage assessment.
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.

3.7.5.a Freshwater Modeling Analyses

Straits of Mackinac

NOAA has developed a set of three-dimensional hydrodynamic models for the Great Lakes as part of the Great Lakes Coastal Forecasting System (GLCFS). The next generation of the models is using the unstructured-grid model FVCOM (Finite Volume Community Ocean Model) to simulate currents, water temperatures, short-term water level fluctuations (e.g., seiche, storm surge), ice, and waves. As part of the GLCFS, Lakes Michigan and Huron are simulated as one water body, which allows simulation of natural bidirectional flow between the lakes through the Straits of Mackinac.

The ability to simulate the complex flow in the Straits of Mackinac is important for estimating the potential transport pathways of oil spills in the region. Anderson and Schwab (2013) modeled the oscillating flow in the region, demonstrating high energy mixing throughout the Straits. They also found that the area of influence of the Straits extends up to 70 km in each of Lake Michigan and Huron (Figure 8), representing the potential zone of impact if an oil spill were to occur in the Straits.

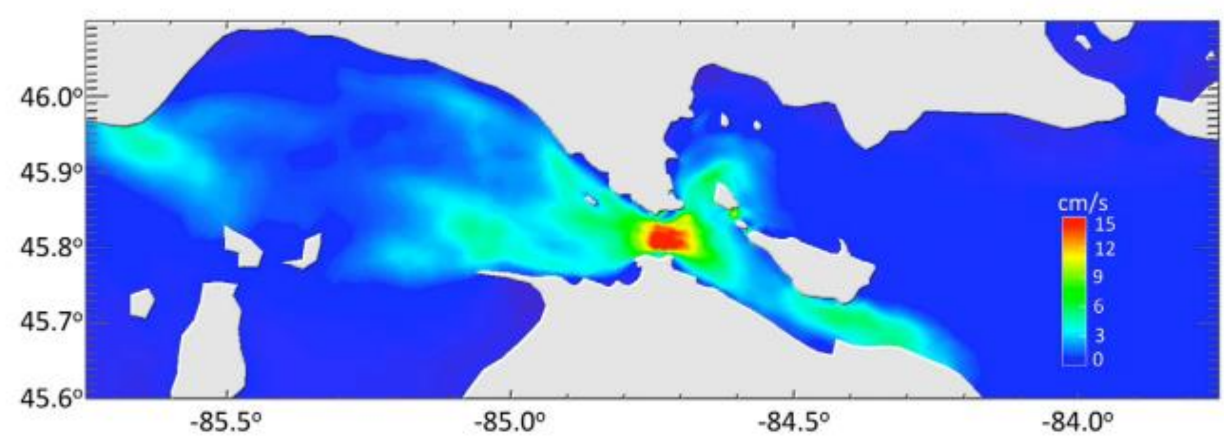

Figure 8. Modeled area of influence of Straits of Mackinac.

Additionally, NOAA's Great Lakes Environmental Research Lab (NOAA-GLERL) has applied a conservative tracer to the model to demonstrate the high energy mixing that occurs in the Straits. Animations of the tracer simulation can be found on the GLCFS website (https://www.glerl.noaa.gov/res/straitsOfMackinac/). An example of the tracer simulation comparing the level of mixing in the Straits with that in the Western Basin of Lake Erie and Lake Michigan is shown in Figure 9, indicating that a potential spill in the Straits would be spread far more quickly and further than in other locations in the Great Lakes.

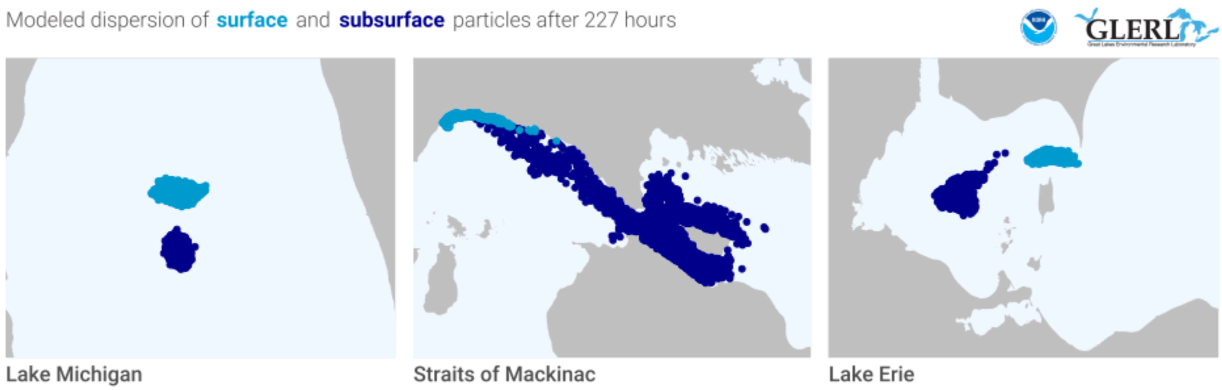

Figure 9. Comparison of simulated dispersion in Lake Michigan (left), Straits of Mackinac (center) and Western Lake Erie (right). Light blue indicates location of a conservative tracer in the surface, dark blue indicates location of the tracer in the subsurface layers of the model.

Schwab (2016) used the GLCFS model and the particle tracking sub-model to simulate 840 different hypothetical spill scenarios from Line 5 in the Straits of Mackinac. Spill volumes were 5,000, 10,000, and 25,000 barrels with simulated release at the surface. Actual overlapping 60-day windows of hydrodynamic conditions from March through October 2014 were also used. Winter was excluded because of the limited knowledge of oil spill behavior under ice. A statistical analysis of the simulations determined that the worst case scenario of a spill in the Straits could affect approximately 15% of Lake Michigan's open waters and 60% of Lake Huron's surface (Table 11). At least 60% of the cases affected an area of 207 km² in Lake Michigan and 1,953 km² in Lake Huron. This is also depicted graphically in Figure 10.

Table 11. Offshore lake area affected by simulated spill scenario cases, grouped into five bins of 20% of the total or 168 scenarios each (Schwab 2016).

Percent of cases	Total area (km^2)	L. Michigan area (km^2)	L. Huron area (km^2)
>0 %	44,405	9,141	35,264
>20%	12,931	1,688	11,243
>40%	5,684	518	5,166
>60%	2,160	207	1,953
>80%	635	64	571

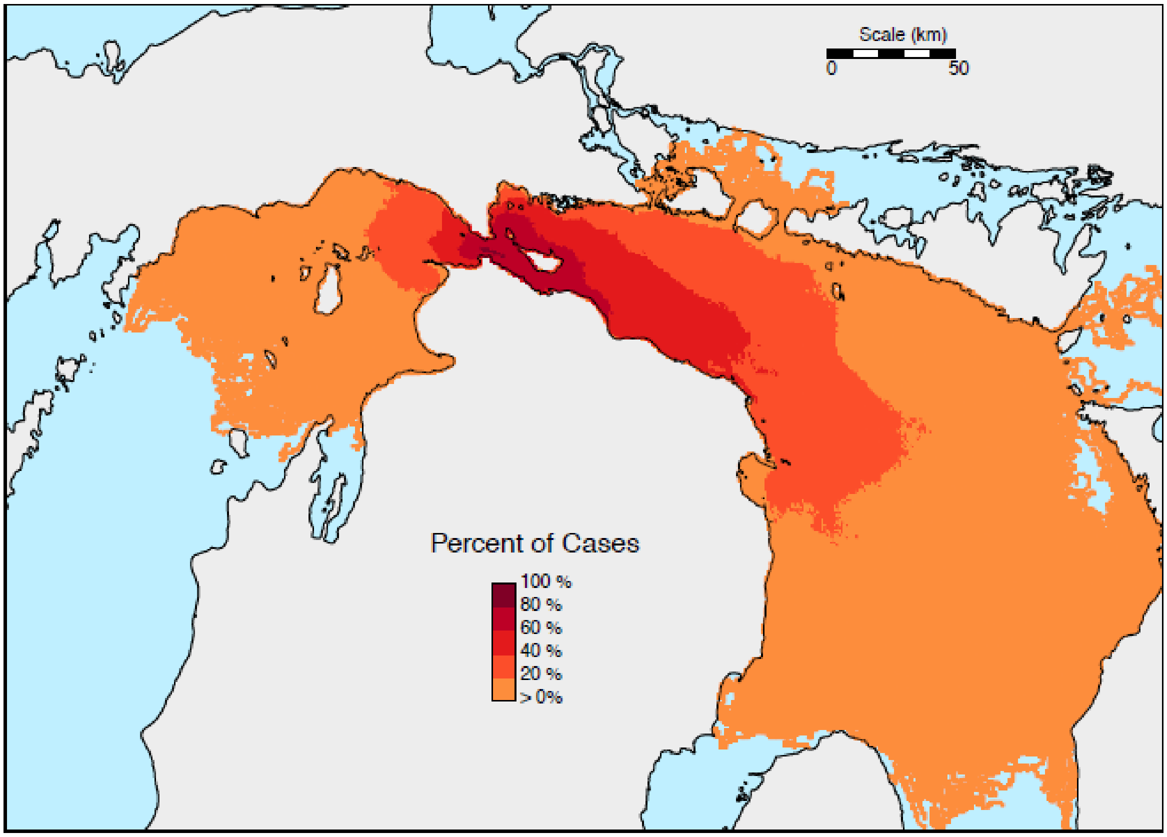

Figure 10. Percent of cases in which oil is present at *any* time after initial release.

St. Clair River – Lake St. Clair System

This region is directly downstream from multiple pipeline crossings and refineries that were the subject of the 2006 IJC spill study. Shen et al. (1987) developed a Lagrangian Model for Lake St. Clair to represent advection, dispersion, evaporation and dissolution of oil slicks. This model utilized a pre-existing transport model of Lake St. Clair developed by Schwab et al. (1984), and applied the oil slick kinetic algorithms to the transport pathways. The model simulated oil slick movement and fate under both ice-covered and ice-free conditions. The impact of ice cover in the model is applied by adjusting current advection via ice-roughness coefficients. The authors used this model to simulate two scenarios of an oil spill occurring near the mouth of the St. Clair River; in ice-free conditions (Case 1) and with ice coverage over the southern portion of the lake (Case 2). Figure 11 shows the tracking of the simulated oil spill for Case 1, while Figure 12 shows Case 2. The simulation for Case 2 demonstrates the impact of ice coverage, as the spill accumulates near the edge of the ice and does not spread as far as in the ice-free scenario (Case 1).

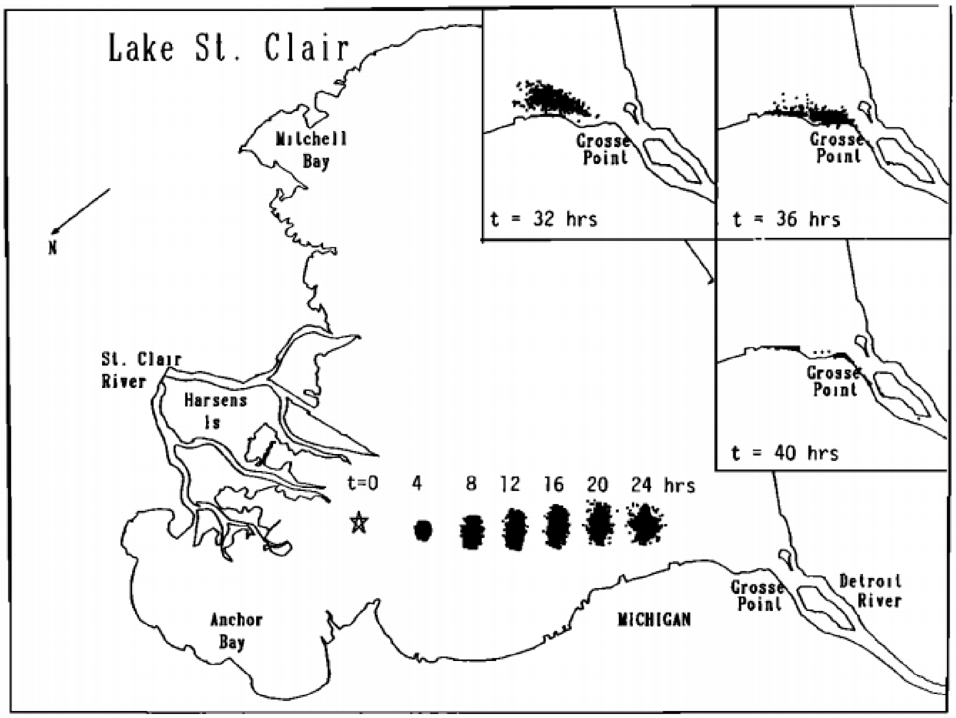

Figure 11. Simulated oil slick transport for Case 1: ice-free condition, in Lake St. Clair. The St. Clair River enters at the delta ("Harsens Island") on the left side, and north is to the lower left.

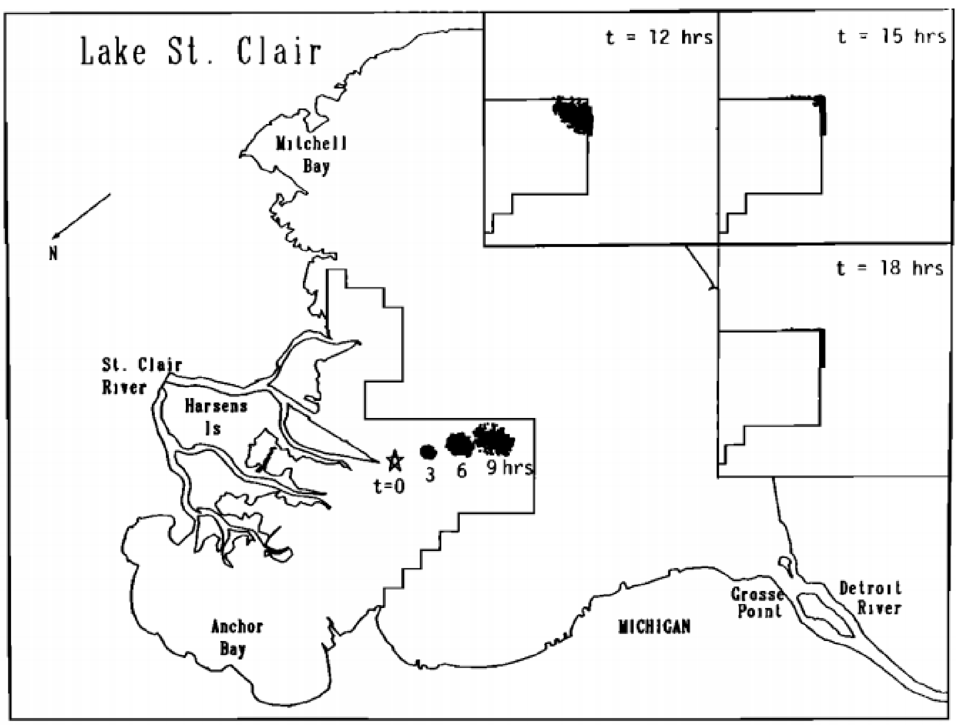

Figure 12. Simulated oil slick transport for Case 2 in Lake St. Clair: partial ice coverage condition. Ice coverage is depicted by delineation shown in the map, with the right hand portion covered in ice. Figure orientation is the same as in Figure 11.

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. The model is a two-layer two-dimensional model that includes advection, horizontal diffusion, mechanical spreading, shoreline deposition, evaporation, dissolution, vertical mixing, resurfacing and sinking processes. The model can also be used in an ice-covered system or ice free conditions and includes an improved under-ice spreading algorithm, comparted to that of Shen et al. (1987). ROSS3 also contains an internal hydraulic transport sub-module to simulate flow in the system. Additionally, the model is not constrained to a standard rectangular gridding system, and therefore allows much more realistic delineation of complex river systems. Yapa et al. (1994) demonstrated that the model accurately predicts transport patterns in several areas of the system (Figure 13) and used the corroborated flow model to simulate a potential oil spill in the Upper St. Clair River.

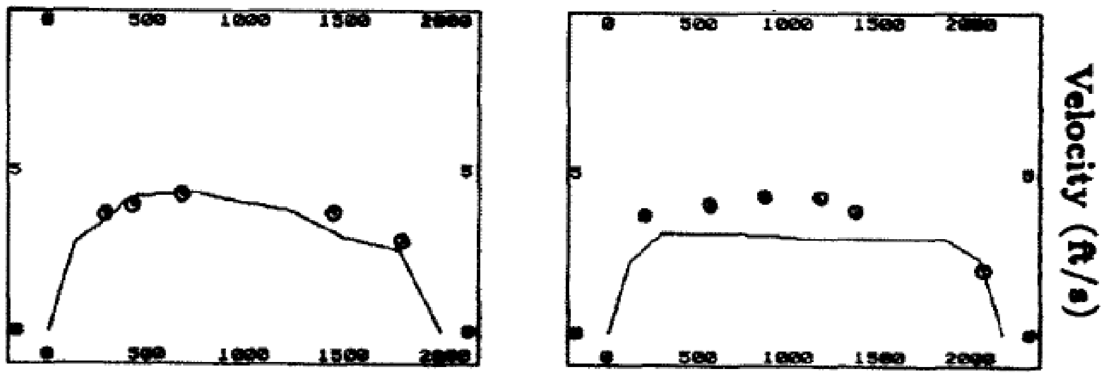

Figure 13. Modeled (solid line) and observed (points) velocity distributions at two cross-sections near Marysville, Michigan on the St. Clair River.

The hypothetical oil spill scenario was designed to simulate a light crude oil spill upstream of Fawn Island in summer conditions. A map depicting the time-variable location of the spill is shown in Figure 14. The simulation shows how advection would transport and spread the spill down the St. Clair River and into the St. Clair Delta within approximately 8 hours.

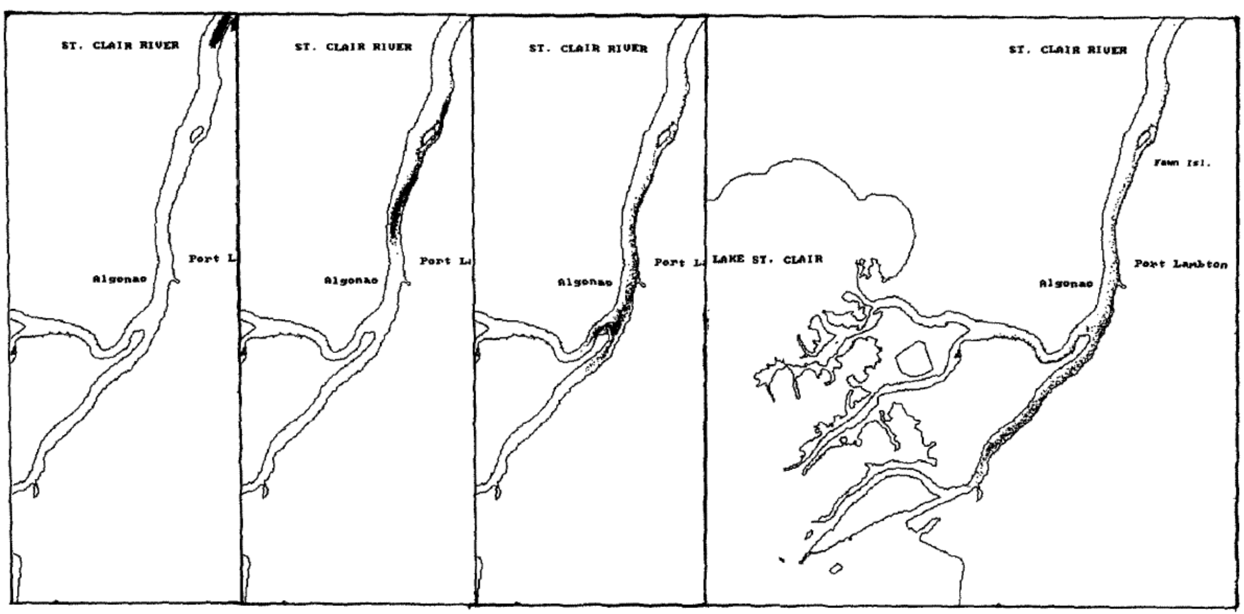

Figure 14. Simulated hypothetical light crude oil spill upstream of Fawn Island and Lake St. Clair at 1 hour, 4 hours, 6 hours, and 8 hours after release.

St. Lawrence River System

Yapa et al. (1992) also applied an earlier version of their oil spill model (ROSS2 and MICROSS2) to the Upper St. Lawrence River. This version of the model uses the same mechanistic algorithms (advection, horizontal diffusion, mechanical spreading, shoreline deposition, evaporation, dissolution, vertical mixing, resurfacing and sinking processes) as the ROSS3 model that was applied in the St. Clair system, however the grid formulation is simpler. In this application, the ROSS2 model utilized an existing hydrodynamic model of the St. Lawrence River (Potok and Quinn 1979), and interpolated the current output over a 500 ft. x 500 ft. horizontal grid. Yapa et al. (1992) then used these currents as inputs into the ROSS2 model to hindcast the spill from the ship *Imperial Sarnia* on April 14th, 1974 near Oak Point, NY. The model produced results that are generally agreeable with the qualitative description of the actual oil spill. The model was then used to conduct two hypothetical spill scenarios each using different wind conditions. The model showed that winds from the west would quickly push the oil near shore into low energy zones, and therefore booms may be effective in containing the spill. However, winds from the east kept the spill mostly in the high current channel of the river, and therefore a dispersant would likely be more effective. These analyses demonstrate the value of the model in helping managers and decision makers decide on appropriate response actions.

Ohio-Monongahela-Allegheny System

Another example from outside the basin but in a setting similar to winter conditions in larger Great Lakes tributaries and connecting channels was published in the early 1990s. The ROSS2 model was applied to the Ohio-Monongahela-Allegheny (OMA) river system (Shen et al. 1993). The OMA system is highly complex geomorphically, containing over 300 miles (483 kilometers) of meandering river channels, as well as navigational locks. The configuration for the model simulation was a two-dimensional, two vertical layer system that accounted for advection, horizontal diffusion, mechanical spreading, shoreline deposition, evaporation, dissolution, vertical mixing, resurfacing and sinking. A hindcast scenario was created to simulate the January 2, 1988 Ashland diesel fuel tank spill (not crude oil) of approximately 15,000 barrels, which entered the Monongahela River upstream of Pittsburgh and was carried over 35 miles downstream including the upper Ohio River (Laskowski and Voltaggio 1988). Particles were tracked in a Lagrangian reference frame. While ice was present in the system and hindered cleanup, the model simulation ignored the impact of the ice, as it was estimated to reduce oil slick movement by only 10-15% in the system. The simulated “leading edge” of the spill was compared spatially with observations of the spill movement, tracked for eight days following the spill. A comparison of model and observations is shown in Figure 15 demonstrating general agreement in the location and timing of the spill transport.

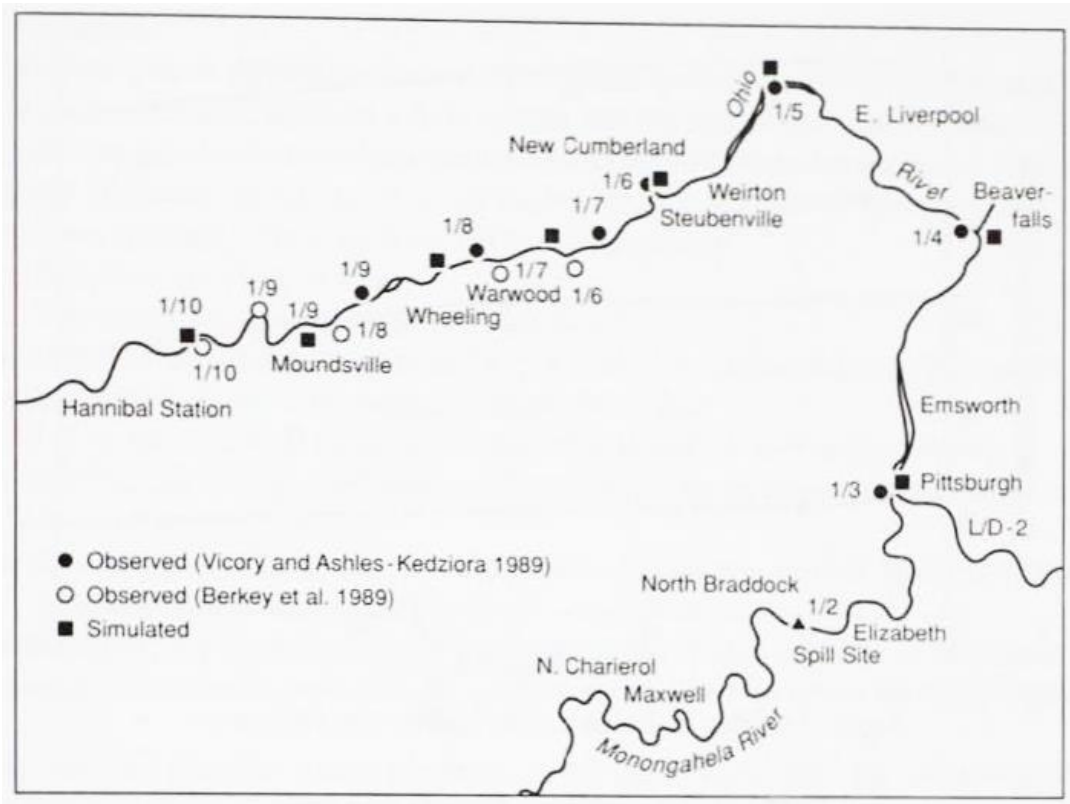

Figure 15. Comparison of simulated and modeled leading edge positions. Dates are indicated on map.

3.7.5.b Marine Systems and Other Models

ADIOS® System

NOAA (2016) has developed the Automated Data Inquiry for Oil Spills (ADIOS®) system for estimating the physical and chemical changes that oil spills are expected to undergo in marine environments. The model uses an extensive database in addition to user inputs on type of oil spill and environmental conditions to estimate the behavior of the spill to aid managers in deciding the best approach to mitigate damages and remediate the site. ADIOS® is a high level screening model that supports quick estimation of impacts with very little site-specific data, such as wind speed, wave height, water temperature, and water salinity, as well as the type and amount of oil released. However, the tool cannot accurately account for spatial distribution along local shorelines or complex geomorphic characteristics of rivers and lakes. Additionally, the model predictions are only reliable for up to five days after the spill, at which time biodegradation and photo-oxidation may occur, which are not represented in the forecasts.

OILTRANS Model

Similar to the linked hydraulic/hydrodynamic and particle tracing models described above for the Great Lakes, Berry et al. (2012) describe the development of OILTRANS, a model capable of simulating water flow and transport, as well as advection, diffusion, evaporation, emulsification and dispersion processes of oil slicks. This model is very similar in mechanistic formulations as the ROSS2 and ROSS3 models described above, however it operates on fully three-dimensional grid, while the ROSS2/3 models include only two vertical layers. A schematic showing the relationship between meteorological forcings (e.g., wind, waves, and temperature) and the oil slick transport are shown in Figure 16. The OILTRANS model has been applied to the Celtic Sea to simulate the impact of a spill resulting from an accidental release during a ship-to-ship fuel transfer to a Russian aircraft carrier, the *Admiral Kuznetsov*, which occurred at sea on February 14, 2009. Over a 10-day simulation, the model accurately represented the path and location of the observed oil slick (Figure 17).

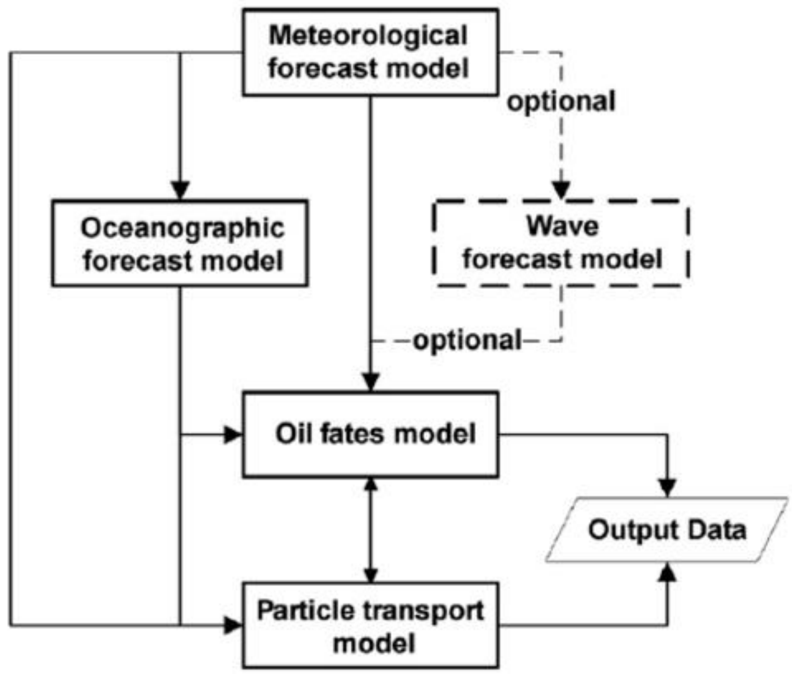

Figure 16. OILTRANS model and sub-model schematic.

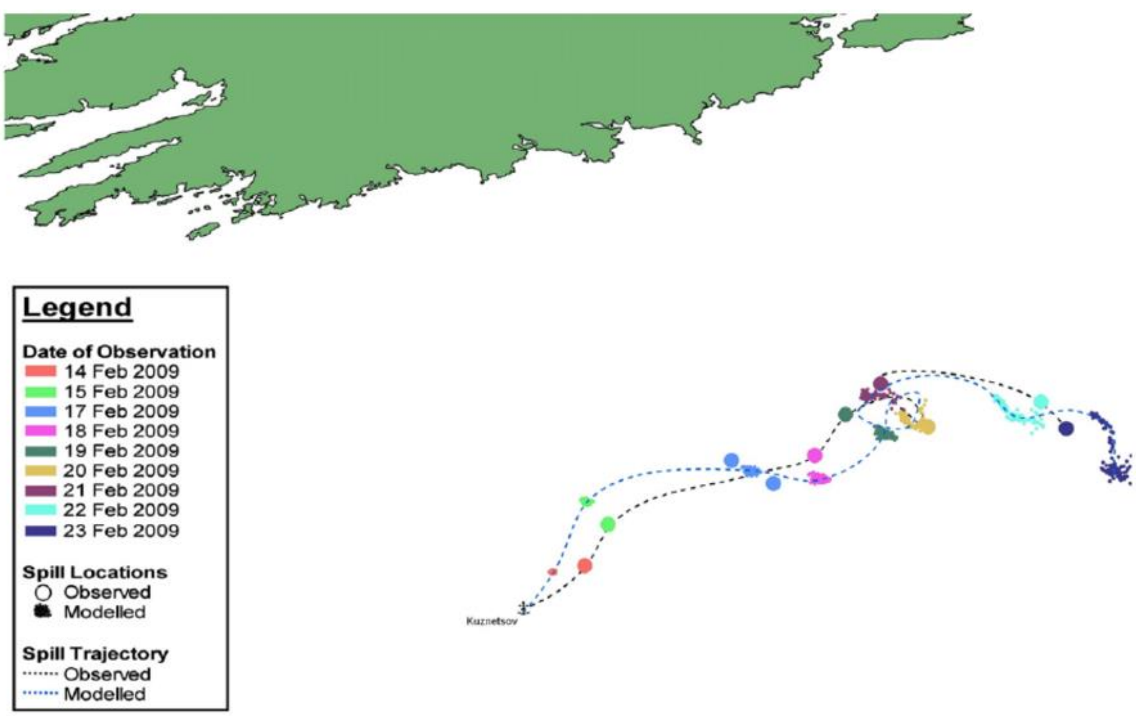

Figure 17. Comparison of observed and simulated oil slick location using OILTRANS in the Celtic Sea south of County Cork, Ireland.

MEDSLIK Model

Alves et al. (2014) combined the operational Mediterranean oil spill model (MEDSLIK) with detailed bathymetric and geomorphic mapping data to estimate potential hazards to regions of the southern Aegean Sea. The MEDSLIK model (Lardner and Zodiatis, 1998) is a well-documented three-dimensional model that predicts the fate and weathering of oil spills in the Mediterranean region, given information related to the type of product spilled, and environmental conditions such as water temperature, waves, and meteorological data. Fate and weathering processes included in the model are evaporation, emulsification, viscosity changes, dispersion, coast adhesion and sedimentation. Alves et al. (2014) designed a process for created impact hazard maps around oil spills by mapping the MEDSLIK model forecasts onto detail bathymetric and geomorphological data.

Spill Impact Modeling Application (SIMAP)

French McCay (2004) developed the Spill Impact Modeling Application (SIMAP) to estimate the three-dimensional trajectory, fate, biological effects, and other impacts of spilled oil and fuels. Similar to the AXIOS tool, it can estimate the effectiveness of response and remediation efforts. As with the other reviewed models in the report, the SIMAP tool relies mainly on physical conditions (e.g., winds, currents, ice conditions, temperature, and salinity) and geomorphological attributes of the system as inputs. The model is capable of simulating transport and dispersion of entrained oil and dissolved aromatics in the water column, dissolution and adsorption of entrained oil and dissolved aromatics to suspended sediments, sedimentation and resuspension, natural degradation, shoreline entrainment and dispersant effectiveness. Additionally, SIMAP includes predictions of the affected area exposed to contaminant levels above EPA guidelines, as well as estimated toxicity and mortality rates of the event and selected response activities.

3.7.5.c Integrated Contaminant and Food Web Models

Food web modeling is recognized as a critical component of understanding the movement of contaminants through ecosystems. While several models are capable of simulating the combined impact of food web processes (e.g., eutrophication, biological productivity) with contaminant fate and transport mechanisms, no such models have been applied in large-scale multi-dimensional analysis representing conditions expected in large lakes or rivers, over significant time periods. One complication of this type of analysis is that accurate simulation of the transport of oil spill material requires fine spatial and temporal model resolution, while the impacts on the ecosystem and food web may operate on monthly to annual or longer timescales. Further, simulating food web impacts at the same spatial scale required for oil spill analysis could be computationally expensive.

Food chain models that are specific to oil spills have been developed, but have not been rigorously tested. Gin et al. (2001) presented an oil spill-food chain interaction model, composed of a multi-phase oil spill model (MOSM) and a food chain model to assess impacts of oil spills on several key marine organisms. While the model was able to provide temporal and spatial estimates of concentrations of hydrocarbons in marine organisms, it was limited in its prediction power and by a lack of field data for verification (Gin et al. 2001). Additionally, the model used a simplified food chain construct which had a unidirectional mass flow (Perhar and Arhonditsis et al. 2014). This resulted in a very static framework, which cannot be used to address ecosystem impacts beyond immediate uptake of unweathered oil following a spill.

Koelmans et al. (2001) compiled a summary of the models that are capable of simulating the interactive effects of food web and contaminant modeling including the models AQUATOX, CATS-5 (Contaminant in Aquatic and Terrestrial ecoSystems), GBMBS (Green Bay Mass Balance Study), IFEM (Integrated Fates and Effects Model), and QWASI (Quantitative Water, Air, Sediment Interaction). All of the models that were summarized in the Koelmans et al. (2001) review operated on spatially course domains, which make integration with highly localized and spatially variable oil spill modeling difficult.

Gobas et al. (2016) compiled a summary of models that integrate terrestrial and aquatic ecosystems with contaminant processes. Models reviewed included RAIDAR (Risk Assessment IDentification And Ranking) and KABAM (K_{OW} Based Aquatic BioAccumulation Model). More recently developed models such as FISHRAND include the application of probabilistic, spatially explicit, and dynamic bioaccumulation formulations. The FISHRAND model simulates foraging behavior over GIS-defined spatially-variable sediment and water exposure concentrations using a dynamic (time-varying) mathematical framework. It more realistically captures organism life histories that impact aquatic food web exposures and potential risks (von Stackelberg et al. 2017). While integrated food web and contaminant models continue to evolve in ecotoxicology research, the use of such models in guiding operational response following an oil spill remains limited.

PETROTOX Model

The PETROTOX Model was developed by Redman et al. (2012), in order to assess the aquatic toxicity of complex petroleum substances based on their composition. The model uses the hydrocarbon block method, which defines fine-scale blocks of hydrocarbons on the basis of the physiochemical and degradation properties which affect their fate and distribution. In addition to the composition, the model incorporates a multimedia model of water-accommodated fraction fate, and the target lipid model, which provides a quantitative framework for predicting the toxicity of hydrocarbons individually and in mixtures.

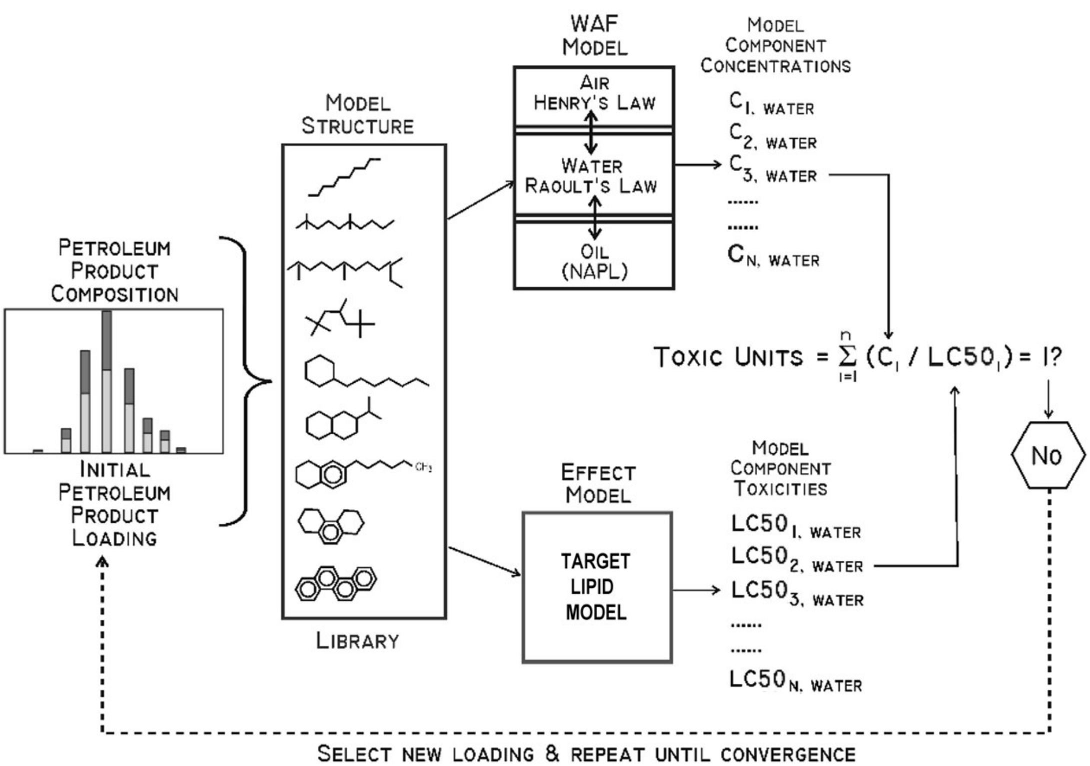

Figure 18. A schematic diagram of the PETROTOX model and sub-models presented in Redman et al. (2012).

Redman et al. (2017) further evaluated the PETROTOX model by using a wider range of acute and chronic toxicity data than were available in the original calibration and validation (Redman et al. 2012). The validation data sets included invertebrate, algal and fish toxicity data. The model performed well, and predictions compared favorably with measured toxicity data across a range of petroleum substances. The model can be used as a computational tool which relates the composition of petroleum products to the acute and chronic toxicity.

3.8 Summary of Findings, Knowledge Gaps, and Recommendations

Findings

Results of the assessment include the following:

- A rapid increase in oil production in North Dakota, Montana, and Alberta since 2010, and the lack of sufficient infrastructure to transport, refine, and deliver crude oil to refineries and markets from the central northern U.S. and south-central Canada to the east, west, or south, without passing through the Great Lakes watershed, have created the need to understand potential changes to ecosystem threats and vulnerabilities in the Great Lakes and their tributaries;

- Pipelines can release substantial amounts of crude oil into river or lake habitats; rail accidents may present less of an environmental hazard due to smaller volumes of worst-case releases, although spill volumes can still be quite large; refineries, terminals, and storage facilities can generate large-volume spills, but they are often located in areas that are already ecologically degraded and perhaps less sensitive to exposure; spills from ships or barges of persistent oil in the Great Lakes are outside the scope of this crude oil study;

- Detailed ecological analyses and geodatabases of Great Lakes coastal and watershed habitats have been recently developed by binational teams; they were created to guide habitat protection and restoration planning, without specific consideration of oil spill threats and vulnerabilities;

- Previous oil-related assessments have concentrated on potential human exposure via drinking water and bi-national coordination in the Huron-Erie Corridor (e.g., IJC 2006), as well as considerations regarding spills from pipelines that cross the Straits of Mackinac;

- 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, and exercises have been conducted in the Great Lakes and connecting channels to prepare for such spills, although planning for all types and seasons of spills can benefit from enhanced understanding of ecosystem vulnerabilities, including both submerged and shoreline habitats,

- Particular attributes such as the volatility and flammability of Bakken light crude oil, and the time-variant density of released heavy crude oil that can sink in water need to be considered when ecosystem vulnerabilities and threat mitigation are assessed,

- Acute spill impact effects on larger birds and aquatic organisms, and their responses to rehabilitation, as well as fish impacts, are reasonably well known based on experience with prior spills, such as the Kalamazoo River spill in 2010; longer term ecological impacts and effective remediation techniques, especially for benthic and wetland habitats and for aquatic invertebrates and early life stages of vertebrates, are less well understood,

- Hydrodynamic models have proven useful for simulating physical processes that influence the rates of movement and dispersion of oil from various hypothetical release locations in the Great

Lakes system, and under various weather conditions, although they require additional development and validation, as well as better linkage with models that simulate oil fate and ecological effects.

Data and Knowledge Gaps

Important gaps in information, technology, and process understanding that may impact the ability to respond to oil spills in the Great Lakes-St. Lawrence Region, and which merit further research, include the following topics and areas where enhanced capabilities are needed;

- Numerical models that can perform large-scale, multi-dimensional, high-resolution analysis representing both physical and ecological conditions expected in large lakes or rivers, over significant time periods;

- Understanding of species-specific sensitivity to oil spills, especially of species that are of greatest importance to tribal subsistence, culture, and commerce, as well as for federal or state/provincial species listed as threatened or endangered, and for key commercial and recreational species;

- Understanding of the sensitivity to oil of amphibians, reptiles, and semi-aquatic mammals, and the food web consequences of the loss or impairment of their populations;

- Knowledge of the links between biomarkers of oil exposure in individual organisms and their significance for whole populations, as well as for long-term community-level and ecosystem-scale impacts of oil spills;

- Information on specific behavior and toxicity in the environment of diverse crude oil types, especially for the suite of diluted and blended bitumen mixtures;

- More complete analysis of how variable and transient environmental conditions affect spill behavior and ecological vulnerability (e.g., spills during high flow caused by spring snow melt, ice formation and breakup, or migratory waterbird stopover and nesting);

- Understanding and identification of future crude oil shipping routes, quantities, and composition in the region based on fluctuating prices, declining production from the Bakken Formation, alternative pipeline and terminal construction, regulatory changes, and variable regional and global demand.

Recommendations

Recommendations for improved understanding of potential impacts of crude oil spills on water quality and ecosystems of the Great Lakes region include the following:

- There is a need for investigations into the effects of the various crude oil types that are currently transported in the region on ecosystems and organisms; studies of single constituents (e.g., PAHs) are critical to understanding the toxicity of hydrocarbon mixtures in crude oil, but they may not fully capture potential impacts of bitumen on aquatic organisms and ecosystems in the region; application the PETROTOX model (Redman et al. 2012) to prediction of toxicity of crude oil types transported through the Great Lakes region may be valuable,

- Based on the very limited information available, baseline assessments of semi-aquatic mammal populations in Great Lakes tributaries and research on their sensitivity to direct and indirect oil exposure at all life stages are needed; similarly, research on the effects of crude oil spills and their implications for amphibians is also needed, especially focusing on critical periods in their life histories (e.g., egg development, metamorphosis, overwintering).

- Detailed and updated spawning and biological sensitivity maps are needed to assess reproductive outcomes of potentially impacted organisms; baseline surveys in general are valuable to document impacts of spills, particularly of widespread indicators of sediment and water quality such as benthic invertebrates.

- Better assessment of how spills from pipeline and rail crossings and nearshore routes might impact river ecosystems and downstream Great Lakes habitats, including consideration of seasonal variation in ecological vulnerability (e.g., a spill during river spawning) is needed to properly identify and mitigate vulnerabilities in infrastructure, operating procedures, and potential spill response.

- A coordinated basin-wide monitoring and modeling program, which integrates existing geospatial data on lake and watershed ecosystems with data assimilation in operational models (e.g., FVCOM) of dynamic conditions (wind, currents, wave height, water temperature, operating conditions of crude oil transport and storage systems), and oil fate and transport capabilities, would position the region for informed reduction of spill threats, and prudent decision-making during incidents regarding minimization of ecosystem impacts.

References

Aas, E., Baussant, T., Balk, L., Liewenborg, B., Andersen, O.K. 2000. PAH metabolites in bile, cytochrome P4501A and DNA adducts as environmental risk parameters for chronic oil exposure: a laboratory experiment with Atlantic cod. *Aquatic Toxicology*, 51(2), 241–258.

Able, K.W., López-Duarte, P.C., Fodrie, F.J., Jensen, O.P., Martin, C.W., Roberts, B.J., Valenti, J., O'Connor, K., and Halbert, S.C. 2014. Fish assemblages in Louisiana salt marshes: effects of the Macondo oil spill. *Estuaries and Coasts*. doi: 10.1007/ s12237-014-9890-6.

Akani, G.C., Politano, E., and Luiselli, L. 2004. Amphibians recorded in forest swamp areas of the River Niger Delta (southeastern Nigeria), and the effects of habitat alteration from oil industry development on species richness and diversity. *Applied Herpetology*, 2(1), 1-22.

Alderman, S.L., Dindia, L.A., Kennedy, C.J., Farrell, A.P. and Gillis, T.E. 2017. Proteomic analysis of sockeye salmon serum as a tool for biomarker discovery and new insight into the sublethal toxicity of diluted bitumen. *Comparative Biochemistry and Physiology Part D: Genomics and Proteomics*, 22, 157-166.

Alderman, S.L., Lin, F., Farrell, A.P., Kennedy, C.J. and Gillis, T.E. 2017. Effects of diluted bitumen exposure on juvenile sockeye salmon: from cells to performance. *Environmental Toxicology and Chemistry*, 36(2), 354-360.

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

Allan, J.D., McIntyre, P.B., Smith, S.D., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton, G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J. and Doran, P.J. 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. *Proceedings of the National Academy of Sciences*, 110(1), 372-377.

Allan, J.D., Nathan F. Manning, Sigrid D.P. Smith, Caitlin E. Dickinson, Christine A. Joseph, and Douglas R. Pearsall. 2017. Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services. *Journal of Great Lakes Research* 43 (2017) 678–688.

Allan, S.E., Smith, B.W. and Anderson, K.A. 2012. Impact of the Deepwater Horizon oil spill on bioavailable polycyclic aromatic hydrocarbons in Gulf of Mexico coastal waters. *Environmental Science & Technology*, 46(4), 2033-2039.

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.

Alsaadi, F., Hodson, P.V. and Langlois, V.S., 2018. An embryonic field of study: The aquatic fate and toxicity of diluted bitumen. *Bulletin of Environmental Contamination and Toxicology*, 100(1), 8-13.

Alves, T., Kokinou, E., and Zodiatis, G. 2014. A three-step model to assess shoreline and offshore susceptibility to oil spills: The South Aegean (Crete) as an analogue for confined marine basins. *Marine Pollution Bulletin*, 86(1), 443-457.

Anderson, E.J., Schwab, D.J., and Lang, G.A. 2010. Real-Time hydraulic and hydrodynamic model of the St. Clair River, Lake St. Clair, Detroit River System. *Journal of Hydraulic Engineering*, 136(8), 507-518.

Anderson, E.J., and Schwab, D.J. 2012. Contaminant transport and spill reference tables for the St. Clair River. *Marine Technology Society Journal*, 46(5), 34-47.

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.

API (American Petroleum Institute). 2013. Oil Spills in Marshes: Planning and Response Considerations. Technical Report 1146, API, 1220 L Street, NW, Washington, DC 20005, 102 p., http://oilspillprevention.org/~/media/Oil-Spill-Prevention/spillprevention/r-and-d/shoreline-protection/1146-oil-spills-in-marshes.pdf

Arnot, J.A. and Gobas, F.A. 2003. A generic QSAR for assessing the bioaccumulation potential of organic chemicals in aquatic food webs. *Molecular Informatics*, 22(3), 337-345.

Bach, L., Palmqvist, A., Rasmussen, L.J. and Forbes, V.E. 2005. Differences in PAH tolerance between Capitella species: underlying biochemical mechanisms. *Aquatic Toxicology*, 74(4), 307-319.

Baker, J.H., Morita, R.Y. 1983. A note on the effects of crude oil on microbial activities in a stream sediment. *Environmental Pollution Series A, Ecological and Biological*, 31, 2, 149

Ball, A. and Truskewycz, A. 2013. Polyaromatic hydrocarbon exposure: an ecological impact ambiguity. *Environmental Science and Pollution Research*, 20(7), 4311-4326.

Ballachey, B.E., Bodkin, J.L. and DeGange, A.R. 1994. An overview of sea otter studies. *Marine Mammals and the Exxon Valdez*, 47-59.

Barber, W.E., McDonald, L.L., Erickson, W.P. and Vallarino, M. 1995. Effect of the Exxon Valdez oil spill on intertidal fish: a field study. *Transactions of the American Fisheries Society*, 124(4), 461-476.

Barron, M.G., Carls, M.G., Short, J.W. and Rice, S.D. 2003. Photoenhanced toxicity of aqueous phase and chemically dispersed weathered Alaska North Slope crude oil to Pacific herring eggs and larvae. *Environmental Toxicology and Chemistry*, 22(3), 650-660.

Barron, M.G., Carls, M.G., Heintz, R. and Rice, S.D. 2004. Evaluation of fish early life-stage toxicity models of chronic embryonic exposures to complex polycyclic aromatic hydrocarbon mixtures. *Toxicological Sciences*, 78(1), 60-67.

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.

Barron, M.G. 2017. Photoenhanced toxicity of petroleum to aquatic invertebrates and fish. *Archives of Environmental Contamination and Toxicology*, 1-7.

Bate, G. C., and Crafford, S. D. 1985. Inhibition of phytoplankton photosynthesis by the WSF of used lubricating oil. *Marine Pollution Bulletin*, 16(10), 401–404.

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.

Bauer, A.E., Frank, R.A., Headley, J.V., Peru, K.M., Farwell, A.J. and Dixon, D.G. 2017. Toxicity of oil sands acid-extractable organic fractions to freshwater fish: *Pimephales promelas* (fathead minnow) and *Oryzias latipes* (Japanese medaka). *Chemosphere*, 171, 168-176.

Bearden, D. M., and Ramseur, J. L. 2014. Oil and chemical spills: Federal emergency response framework. *Congressional Research Service Report R43251*, 22 p.

Beaulac, M. 2016. Water monitoring in southeast Michigan: Research conducted to coordinate reactivation of Huron-Erie Corridor water monitoring system, *in Michigan State of the Great Lakes 2016*, Office of the Great Lakes, Michigan Department of Environmental Quality, 43 p.

Bejarano, A.C., Chandler, G.T., He, L., and Coull, B.C. 2006. Individual to Population Level Effects of South Louisiana Crude Oil Water Accommodated Hydrocarbon Fraction (WAF) on a Marine Meiobenthic Copepod, *Journal of Experimental Marine Biology and Ecology*, Vol. 332, Is. 1, 49-59.

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.

Benson, M.H., 2012. Intelligent tinkering: the Endangered Species Act and resilience. *Ecology and Society* 17 (4): 28, 2012

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.

Berry, A., Dabrowski, T., and Lyons, K. 2012. The oil spill model OILTRANS and its application to the Celtic Sea. *Marine Pollution Bulletin*, 64(11), 2489–2501.

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.

Bhattacharyya, S., Klerks, P.L. and Nyman, J.A. 2003. Toxicity to freshwater organisms from oils and oil spill chemical treatments in laboratory microcosms. *Environmental Pollution*, 122(2), 205-215.

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.

Bishop, C.A., Ng, P., Pettit, K.E., et al. 1998. Environmental contamination and developmental abnormalities in eggs and hatchlings of the common snapping turtle (*Chelydra serpentina serpentina*) from the Great Lakes-St. Lawrence River Basin (1989-91). *Environmental Pollution*, 101:143–156.

Blumer, M., Ehrhardt, M., and Jones, J. 1973. The environmental fate of stranded crude oil. *Deep Sea Research and Oceanographic Abstracts*, 20(3), 239–259.

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.

Bowyer, R.T., Blundell, G.M., Ben-David, M., Jewett, S.C., Dean, T.A. and Duffy, L.K. 2003. Effects of the Exxon Valdez oil spill on river otters: injury and recovery of a sentinel species. *Wildlife Monographs*, 1-53.

Brewton, R., Fulford, R., and Griffitt, R. 2013. Gene expression and growth as indicators of effects of the BP Deepwater Horizon oil spill on spotted seatrout (*Cynoscion nebulosus*). *Journal of Toxicology and Environmental Health*, 76(21):1198-209.

Brown, L.D. and Ulrich, A.C., 2015. Oil sands naphthenic acids: a review of properties, measurement, and treatment. *Chemosphere*, 127, 276-290.

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.

Bue, B.G., Sharr, S. and Seeb, J.E. 1998. Evidence of damage to pink salmon populations inhabiting Prince William Sound, Alaska, two generations after the Exxon Valdez oil spill. *Transactions of the American Fisheries Society*, 127(1), 35-43.

Bunnell, D.B., Barbiero, R.P., Ludsin, S.A., Madenjian, C.P., Warren, G.J., Dolan, D.M., Brenden, T.O., Briland, R., Gorman, O.T., He, J.X. and Johengen, T.H. 2013. Changing ecosystem dynamics in the Laurentian Great Lakes: bottom-up and top-down regulation. *BioScience*, 64(1), 26-39.

Burlakova, L.E., Karatayev, A.Y., Pennuto, C. and Mayer, C. 2014. Changes in Lake Erie benthos over the last 50 years: Historical perspectives, current status, and main drivers. *Journal of Great Lakes Research*, 40(3), 560-573.

Burns, K.A., Ehrhardt, M.G., Howes, B.L., and Taylor, C.D. 1993. Subtidal benthic community respiration and production near the heavily oiled Gulf coast of Saudi Arabia. *Marine Pollution Bulletin*, 27, 199–205.

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.

Calbet, A., Saiz, E. and Barata, C. 2007. Lethal and sublethal effects of naphthalene and 1, 2-dimethylnaphthalene on the marine copepod Paracartia grani. *Marine Biology*, 151(1), 195-204.

Camus, L. and Olsen, G.H. 2008. Embryo aberrations in sea ice amphipod Gammaruswilkitzkii exposed to water soluble fraction of oil. *Marine Environmental Research*, 66(1), 221-222.

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

Capuzzo, J.M., Lancaster, B.A., and Sasaki, G.C. 1984. The effects of petroleum hydrocarbons on lipid metabolism and energetics of larval development and metamorphosis in the American lobster (Homarus americanus Milne Edwards). *Marine Environmental Research*, 14(1), 201–228.

Carls, M.G., Rice, S.D. and Hose, J.E. 1999. Sensitivity of fish embryos to weathered crude oil: Part I. Low-level exposure during incubation causes malformations, genetic damage, and mortality in larval pacific herring (Clupea pallasi). *Environmental Toxicology and Chemistry*, 18(3), 481-493.

Carls, M.G., Heintz, R.A., Marty, G.D. and Rice, S.D. 2005. Cytochrome P4501A induction in oil-exposed pink salmon Oncorhynchus gorbuscha embryos predicts reduced survival potential. *Marine Ecology Progress Series*, 301, 253-265.

Carls, M.G., and Thedinga, J.F. 2010. Exposure of pink salmon embryos to dissolved polynuclear aromatic hydrocarbons delays development, prolonging vulnerability to mechanical damage. *Marine Environmental Research*, 69(5), 318–325.

Chebbi, R. 2014. Spreading of oil on water in the surface-tension regime. *Environmental Fluid Mechanics* 14(6), 1443-1455.

Chikere, C.B., Okpokwasili, G.C. and Chikere, B.O. 2011. Monitoring of microbial hydrocarbon remediation in the soil. *3 Biotech*, 1(3), 117-138.

Claireaux, G., Théron, M., Prineau, M., Dussauze, M., Merlin, F.-X., and Le Floch, S. 2013. Effects of oil exposure and dispersant use upon environmental adaptation performance and fitness in the European sea bass, *Dicentrarchus labrax*. *Aquatic Toxicology*, 130, 160–170.

Clemente, J.S. and Fedorak, P.M., 2005. A review of the occurrence, analyses, toxicity, and biodegradation of naphthenic acids. *Chemosphere*, 60(5), 585-600.

Cojocaru, C., Macoveanu, M. and Cretescu, I., 2011. Peat-based sorbents for the removal of oil spills from water surface: Application of artificial neural network modeling. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 384(1), 675-684.

Collier, T.K., Anulacion, B.F., Arkoosh, M.R., Dietrich, J.P., Incardona, J.P., Johnson, L.L., Ylitalo, G.M. and Myers, M.S. 2013. Effects on fish of polycyclic aromatic hydrocarbons (PAHs) and naphthenic acid exposures. *Fish Physiology: Organic Chemical Toxicology of Fishes: Fish Physiology*, 33, 195-255.

Conmy, R.N., Coble, P.G., Farr, J., Wood, A.M., Lee, K., Pegau, W.S., Walsh, I.D., Koch, C.R., Abercrombie, M.I., Miles, M.S. and Lewis, M.R., 2014. Submersible optical sensors exposed to chemically dispersed crude oil: wave tank simulations for improved oil spill monitoring. *Environmental Science & Technology*, 48(3), 1803-1810.

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.

Conover, S.A.M. 1975. Nitrogen utilization during spring blooms of marine phytoplankton in Bedford Basin, Nova Scotia, Canada. *Marine Biology*, 32(3), 247-261.

Crowe, K.M., Newton, J.C., Kaltenboeck, B. and Johnson, C. 2014. Oxidative stress responses of gulf killifish exposed to hydrocarbons from the Deepwater Horizon oil spill: Potential implications for aquatic food resources. *Environmental Toxicology and Chemistry*, 33(2), 370-374.

Crunkilton, R.L., and Duchrow, R.M. 1990. Impact of a massive crude oil spill on the invertebrate fauna of a Missouri Ozark stream. *Environmental Pollution*, 63(1), 13-31.

Dachs, J., Bayona, J. M., Fowler, S. W., Miquel, J.-C., and Albaigés, J. 1996. Vertical fluxes of polycyclic aromatic hydrocarbons and organochlorine compounds in the western Alboran Sea (southwestern Mediterranean). *Marine Chemistry*, 52(1), 75–86.

Danovaro, R., Fabiano, M., and Vincx, M. 1995. Meiofauna response to the Agip Abruzzo oil spill in subtidal sediments of the Ligurian Sea. *Marine Pollution Bulletin*, 30(2), 133–145.

Das, N. and Chandran, P., 2010. Microbial degradation of petroleum hydrocarbon contaminants: an overview. *Biotechnology Research International*, 2011.

Dauvin, J.-C. 1998. The fine sand Abra alba community of the bay of morlaix twenty years after the Amoco Cadiz oil spill. *Marine Pollution Bulletin* (Vol. 36).

Debenest, T., Turcotte, P., Gagne, F., Gagnon, C. and Blaise, C. 2012. Ecotoxicological impacts of effluents generated by oil sands bitumen extraction and oil sands lixiviation on Pseudokirchneriella subcapitata. *Aquatic Toxicology*, 112, 83-91.

deBruyn, A., Wernick, B.G., Stefura, C., McDonald, B.G., Rudolph, B.L., Patterson, L. and Chapman, P.M. 2007. In situ experimental assessment of lake whitefish development following a freshwater oil spill. *Environmental Science & Technology*, 41(20), 6983-6989.

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.

DeLaune, R.D. and Wright, A.L., 2011. Projected impact of Deepwater Horizon oil spill on U.S. Gulf Coast wetlands. Soil Science Society of America Journal, 75(5), 1602-1612.

Delvigne, G.A.L. and Sweeney, C. 1988. Natural dispersion of oil. *Oil and Chemical Pollution*, 4(4), 281-310.

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

de Santiago-Martín, A., Guesdon, G., Díaz-Sanz, J. and Galvez-Cloutier, R., 2015. Oil spill in Lac-Mégantic, Canada: Environmental onitoring and remediation. *International Journal of Water and Wastewater Treatment*, 2(1): http://dx.doi.org/10.16966/2381-5299.113bacteria

de Soysa, T.Y., Ulrich, A., Friedrich, T., Pite, D., Compton, S.L., Ok, D., Bernardos, R.L., Downes, G.B., Hsieh, S., Stein, R. and Lagdameo, M.C. 2012. Macondo crude oil from the Deepwater Horizon oil spill disrupts specific developmental processes during zebrafish embryogenesis. *BMC Biology*, 10(1), p.40.

Dettmers, J.M., Janssen, J., Pientka, B., Fulford, R.S. and Jude, D.J. 2005. Evidence across multiple scales for offshore transport of yellow perch (*Perca flavescens*) larvae in Lake Michigan. Canadian *Journal of Fisheries and Aquatic Sciences*, 62(12): 2683-2693.

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.

Doerffer, J. 1992. *Oil Spill Response in the Marine Environment*. BPCC Wheatons Ltd., Great Britain, UK, 125–135.

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.

Dollhopf1, R.H., Fitzpatrick, F.A., Kimble, J.W., Capone, D.M., Graan, T.P., Zelt, R.B. and Johnson, R. 2014. Response to heavy, non-floating oil spilled in a Great Lakes river environment: a multiple-lines-of-evidence approach for submerged oil assessment and recovery. In International Oil Spill Conference Proceedings (Vol. 2014, No. 1, 434-448). American Petroleum Institute.

Dubansky, B., Whitehead, A., Miller, J.T., Rice, C.D., and Galvez, F. 2013. Multitissue molecular, genomic, and developmental effects of the Deepwater Horizon oil spill on resident Gulf killifish (Fundulus grandis). *Environmental Science & Technology*, 47(10), 5074-5082.

Dubansky, B., Rice, C.D., Barrois, L.F. and Galvez, F. 2017. Biomarkers of Aryl-hydrocarbon Receptor Activity in Gulf Killifish (*Fundulus grandis*) From Northern Gulf of Mexico Marshes Following the Deepwater Horizon Oil Spill. *Archives of Environmental Contamination and Toxicology*, 1-13.

Duesterloh, S., Short, J.W. and Barron, M.G. 2002. Photoenhanced toxicity of weathered Alaska north slope crude oil to the calanoid copepods *Calanus marshallae* and *Metridia okhotensis*. *Environmental Science & Technology*, 36(18), 3953-3959.

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*, 379 p. https://mipetroleumpipelines.com/document/alternatives-analysis-straits-pipeline-final-report

Echeveste, P., Agustí, S., and Dachs, J. 2010. Cell size dependent toxicity thresholds of polycyclic aromatic hydrocarbons to natural and cultured phytoplankton populations. *Environmental Pollution*, 158(1), 299–307.

Echols, B., Smith, A., Gardinali, P.R. and Rand, G.M. 2016. Chronic toxicity of unweathered and weathered Macondo oils to mysid shrimp (*Americamysis bahia*) and inland silversides (*Menidia beryllina*). *Archives of Environmental Contamination and Toxicology*, 71(1), 78-86.

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

El-Sheekh, M.M., El-Naggar, A.H., Osman, M.E. and Haieder, A. 2000. Comparative studies on the green algae Chlorella homosphaera and Chlorella vulgaris with respect to oil pollution in the river Nile. *Water, Air, & Soil Pollution*, 124(1), 187-204.

Esler, D., Bowman, T.D., Dean, T.A., O'Clair, C.E., Jewett, S.C. and McDonald, L.L., 2000. Correlates of harlequin duck densities during winter in Prince William Sound, Alaska. The Condor, 102(4), 920-926.

Estes, J.A. and Duggins, D.O. 1995. Sea otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. *Ecological Monographs*, 65(1), 75-100.

Fitzpatrick, F.A., Boufadel, M.C., Johnson, R., Lee, K.W., Graan, T.P., Bejarano, A.C., Zhu, Z., Waterman, D., Capone, D.M., Hayter, E. and Hamilton, S.K., 2015. Oil-particle interactions and submergence from crude oil spills in marine and freshwater environments: Review of the science and future research needs. *U.S Geological Survey Open-File Report 2015-1076*, 33 p.

Feder, H.M., and Blanchard, A. 1998. The deep benthos of Prince William Sound, Alaska, 16 months after the Exxon Valdez oil spill. *Marine Pollution Bulletin*, 36(2), 118–130.

Federle, T.W., Vestal, J.R., Hater, G.R., and Miller, M.C. 1979. Effects of Prudhoe bay crude oil on primary production and zooplankton in arctic tundra thaw ponds. *Marine Environmental Research*, 2(1), 3–18.

Fefilova, E.B. 2011. The state of a river in Pechora basin after an oil spill: assessment of changes in zooplankton community. *Water Resources*, 38(5), 637-649.

Fingas, M. (ed.) 2016. *Oil Spill Science and Technology, 2nd Edition*. Elsevier, Amsterdam, 1078 p.

Fingas, M. and Fieldhouse, B. 2015. Water-in-oil emulsions: formation and prediction. *Handbook of Oil Spill Science and Technology*, 225-270.

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.

Fleeger, J.W., Carman, K.R., Riggio, M.R., Mendelssohn, I.A., Lin, Q.X., Hou, A., Deis, D.R. and Zengel, S., 2015. Recovery of salt marsh benthic microalgae and meiofauna following the Deepwater Horizon oil spill linked to recovery of *Spartina alterniflora*. *Marine Ecology Progress Series*, 536, 39-54.

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.

French McCay, D.P. 2004. Oil spill impact modelling: development and validation. *Environmental Toxicology and Chemistry*. 23(10): 2441-2456.

Fritelli, 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.

Frouin, H., Pellerin, J., Fournier, M., Pelletier, E., Richard, P., Pichaud, N., Rouleau, C. and Garnerot, F. 2007. Physiological effects of polycyclic aromatic hydrocarbons on soft-shell clam Mya arenaria. *Aquatic Toxicology*, 82(2), 120-134.

Galloway, T.S., and Depledge, M.H. 2001. Immunotoxicity in invertebrates: Measurement and ecotoxicological relevance. *Ecotoxicology*, 10, 5–23.

Garcia, T.I., Shen, Y., Crawford, D., Oleksiak, M.F., Whitehead, A. and Walter, R.B. 2012. RNA-Seq reveals complex genetic response to deepwater horizon oil release in Fundulus grandis. *BMC Genomics*, 13(1), p.474.

Garmestani, A., Allen, C. and Gunderson, L., 2009. Panarchy: discontinuities reveal similarities in the dynamic system structure of ecological and social systems. *Ecology and Society*, 14(1).

Gauthier, P.T., Norwood, W.P., Prepas, E.E. and Pyle, G.G., 2014. Metal–PAH mixtures in the aquatic environment: A review of co-toxic mechanisms leading to more-than-additive outcomes. *Aquatic Toxicology*, 154, 253-269.

Gesteira, J.L.G., and Dauvin, J.-C. 2005. Impact of the Aegean Sea oil spill on the subtidal fine sand macrobenthic community of the Ares-Betanzos Ria (Northwest Spain). *Marine Environmental Research*, 60(3), 289–316.

Gewurtz, S.B., Backus, S.M., Bhavsar, S.P., McGoldrick, D.J., de Solla, S.R. and Murphy, E.W. 2011. Contaminant biomonitoring programs in the Great Lakes region: review of approaches and critical factors. *Environmental Reviews*, 19(NA), 162-184.

Giesy, J.P., Anderson, J.C. and Wiseman, S.B. 2010. Alberta oil sands development. *Proceedings of the National Academy of Sciences*, 107(3), 951-952.

Gilde, K. and Pinckney, J.L. 2012. Sublethal effects of crude oil on the community structure of estuarine phytoplankton. *Estuaries and Coasts*, 35(3), 853-861.

Gin, K.Y.H., Huda, M.K., Lim, W.K. and Tkalich, P., 2001. An oil spill–food chain interaction model for coastal waters. *Marine Pollution Bulletin*, 42(7), 590-597.

Gobas, F.A., Burkhard, L.P., Doucette, W.J., Sappington, K.G., Verbruggen, E.M., Hope, B.K., Bonnell, M.A., Arnot, J.A. and Tarazona, J.V., 2016. Review of existing terrestrial bioaccumulation models and terrestrial bioaccumulation modeling needs for organic chemicals. *Integrated Environmental Assessment and Management*, 12(1), 123-134.

Golet, G.H., Seiser, P.E., McGuire, A.D., Roby, D.D., Fischer, J.B., Kuletz, K.J., Irons, D.B., Dean, T.A., Jewett, S.C. and Newman, S.H. 2002. Long-term direct and indirect effects of the 'Exxon Valdez'oil spill on pigeon guillemots in Prince William Sound, Alaska. *Marine Ecology Progress Series*, 241, 287-304.

González, J., Figueiras, F.G., Aranguren-Gassis, M., Crespo, B.G., Fernández, E., Morán, X.A.G., and Nieto-Cid, M. 2009. Effect of a simulated oil spill on natural assemblages of marine phytoplankton enclosed in microcosms. *Estuarine, Coastal and Shelf Science*, 83(3), 265–276.

Gordon, D. 2012. *Understanding unconventional oil*. Carnegie Endowment for International Peace. http://carnegieendowment.org/2012/05/03/understanding-unconventional-oil-pub-48007

Graziano, M. 2017. The Economic Impact of Crude Oil Transportation in the Great Lakes. Prepared for the Great Lakes Commission

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.

Great Lakes Commission. 2015. Issues and Trends Surrounding the Movement of Crude Oil in the Great Lakes-St. Lawrence River Region. http://www.glc.org/wp-content/uploads/Oil-Transportation-Full-Report-2015.pdf

Green, S.J., Demes, K., Arbeider, M., Palen, W.J., Salomon, A.K., Sisk, T.D., Webster, M. and Ryan, M.E., 2016. Oil sands and the marine environment: Current knowledge and future challenges. *Frontiers in Ecology and the Environment*, 15(2), 74-83

Gros, J., Nabi, D., Wurz, B., Wick, L.Y., Brussard, C.P.D., Huisman, J., van der Meer, J.R., Reddy, C.M., Arey, J.S. 2014. The first day of an oil spill on the open sea: Early hydrocarbon mass transfer fluxes to air and water. *Environmental Science & Technology*, 48, 9400–9411.

Grundy, M.M., Moore, M.N., Howell, S.M. and Ratcliffe, N.A. 1996. Phagocytic reduction and effects on lysosomal membranes by polycyclic aromatic hydrocarbons, in haemocytes of Mytilus edulis. *Aquatic Toxicology*, 34(4), 273-290.

Gutierrez, T., Singleton, D.R., Berry, D., Yang, T., Aitken, M.D. and Teske, A. 2013. Hydrocarbon-degrading bacteria enriched by the Deepwater Horizon oil spill identified by cultivation and DNA-SIP. *The ISME Journal*, 7(11), 2091.

Gutleb, A.C., Appelman, J., Bronkhorst, M., van den Berg, J.H. and Murk, A.J. 2000. Effects of oral exposure to polychlorinated biphenyls (PCBs) on the development and metamorphosis of two amphibian species (Xenopus laevis and Rana temporaria). *Science of the Total Environment*, 262(1), 147-157.

Hailong, L., and M.C. Boufadel. 2010. Long-term persistence of oil from the Exxon Valdez spill in two-layer beaches. *Nature Geoscience*, Vol. 3, February 2010.

Hall, G.J., Frysinger, G.S., Aeppli, C., Carmichael, C.A., Gros, J., Lemkau, K.L., Nelson, R.K., Reddy, C.M. 2013. Oxygenated weathering products of Deepwater Horizon oil come from surprising precursors. *Marine Pollution Bulletin*, 75, 140-149.

Halling-Sørensen, B., Nyholm, N., Kusk, K.O., and Jacobsson, E. 2000. Influence of Nitrogen Status on the Bioconcentration of Hydrophobic Organic Compounds to Selenastrum capricornutum. *Ecotoxicology and Environmental Safety*, 45(1), 33–42.

Haney, J.C., Geiger, H.J., Short, J.W. 2014a. Bird mortality from the Deepwater Horizon oil spill. I. Exposure probability in the offshore Gulf of Mexico. *Mar Ecol Prog Ser*, 513:225–237.

Haney, J.C., Geiger, H.J., Short, J.W. 2014b. Bird mortality from the Deepwater Horizon oil spill. II. Carcass sampling and exposure probability in the coastal Gulf of Mexico. *Mar Ecol Prog Ser*, 513:239–252.

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.

Hannan, M.L., Bamber, S.D., Moody, J.A., Galloway, T.S., and Jones, M.B. 2009. Immune function in the Arctic scallop, Chalamys islandica, following dispersed oil exposure. *Aquatic Toxicology*, 92, 187–94.

Hannan, M.L., Bamber, S D., Galloway, T.S., Moody, A.J., and Jones, M.B. 2010. Effects of the model PAH phenanthrene on immune function and oxidative stress in the haemolymph of the temperate scallop Pecten maximus. *Chemosphere*, 78, 779–84.

Hansen, B.H., Altin, D., Vang, S.-H., Nordtug, T., and Olsen, A.J. 2008. Effects of naphthalene on gene transcription in *Calanus finmarchicus* (Crustacea: Copepoda). *Aquatic Toxicology*, 86(2), 157–165.

Harwell, M.A. and Gentile, J.H. 2006. Ecological significance of residual exposures and effects from the Exxon Valdez oil spill. *Integrated Environmental Assessment and Management*, 2(3), 204-246.

Hayes, T., Haston, K., Tsui, M., Hoang, A., Haeffele, C. and Vonk, A. 2002. Herbicides: feminization of male frogs in the wild. *Nature*, 419(6910), 895-896.

Hayworth, J.S., Clement, T.P., John, G.F. and Yin, F. 2015. Fate of Deepwater Horizon oil in Alabama's beach system: Understanding physical evolution processes based on observational data. *Marine Pollution Bulletin*, 90(1), 95-105.

Head, I.M., Jones, D.M. and Röling, W.F. 2006. Marine microorganisms make a meal of oil. Nature reviews. *Microbiology*, 4(3), p.173.

Headley, J.V. and McMartin, D.W., 2004. A review of the occurrence and fate of naphthenic acids in aquatic environments. *Journal of Environmental Science and Health, Part A*, 39(8), 1989-2010.

Hebert, C.E., Weseloh, D.V., MacMillan, S., Campbell, D. and Nordstrom, W. 2011. Metals and polycyclic aromatic hydrocarbons in colonial waterbird eggs from Lake Athabasca and the Peace–Athabasca Delta, Canada. *Environmental Toxicology and Chemistry*, 30(5), 1178-1183.

Heintz, R.A., Short, J.W. and Rice, S.D. 1999. Sensitivity of fish embryos to weathered crude oil: Part II. Increased mortality of pink salmon (*Oncorhynchus gorbuscha*) embryos incubating downstream from weathered Exxon Valdez crude oil. *Environmental Toxicology and Chemistry*, 18(3), 494-503.

Heintz, R.A., Rice, S.D., Wertheimer, A.C., Bradshaw, R.F., Thrower, F.P., Joyce, J.E., Short, J.W. 2000. Delayed effects on growth and marine survival of pink salmon Oncorhynchus gorbuscha after exposure to crude oil during embryonic development. *Mar Ecol Prog Ser*, 208:205–216

Henkel, J., Sigel, B., and Taylor, C. 2012. Large-scale impacts of the Deepwater Horizon oil spill: can local disturbance affect distant ecosystems through migratory shorebirds? *BioScience*. http://www.bioone.org/doi/abs/10.1525/bio.2012.62.7.10

Hester, M.W. and Mendelssohn, I.A., 2000. Long-term recovery of a Louisiana brackish marsh plant community from oil-spill impact: vegetation response and mitigating effects of marsh surface elevation. *Marine Environmental Research*, 49(3), 233-254.

Hicken, C.E., Linbo, T.L., Baldwin, D.H., Willis, M.L., Myers, M.S., Holland, L., Larsen, M., Stekoll, M.S., Rice, S.D., Collier, T.K. and Scholz, N.L. 2011. Sublethal exposure to crude oil during embryonic development alters cardiac morphology and reduces aerobic capacity in adult fish. *Proceedings of the National Academy of Sciences*, 108(17), 7086-7090.

Ho, K.A.Y., Patton, L., Latimer, J.S., Pruell, R.J., Pelletier, M., McKinney, R. and Jayaraman, S. 1999. The chemistry and toxicity of sediment affected by oil from the North Cape spilled into Rhode Island Sound. *Marine Pollution Bulletin*, 38(4), 314-323.

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.

Holling, C.S., 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4(1), 1-23.

Holling, C.S. and Gunderson, L.H., 2002. Resilience and adaptive cycles. In: *Panarchy: Understanding Transformations in Human and Natural Systems*, 25-62.

Hook, S.E. and Osborn, H.L. 2012. Comparison of toxicity and transcriptomic profiles in a diatom exposed to oil, dispersants, dispersed oil. *Aquatic Toxicology*, 124, 139-151.

Hose, J.E. and Guillette, L.J. 1995. Defining the role of pollutants in the disruption of reproduction in wildlife. *Environmental Health Perspectives*, 103(Suppl 4), p.87.

Hose, J.E., McGurk, M.D., Marty, G.D., Hinton, D.E., Brown, E.D. and Baker, T.T. 1996. Sublethal effects of the (Exxon Valdez) oil spill on herring embryos and larvae: morphological, cytogenetic, and histopathological assessments, 1989 1991. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(10), 2355-2365.

Hu, C., Weisberg, R.H., Liu, Y., Zheng, L., Daly, K.L., English, D.C., Zhao, J. and Vargo, G.A. 2011. Did the northeastern Gulf of Mexico become greener after the Deepwater Horizon oil spill? *Geophysical Research Letters*, 38(9).

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.

Hull, C.L., Hindell, M.A., Gales, R.P., Meggs, R.A., Moyle, D.I. and Brothers, N.P. 1998. The efficacy of translocating little penguins *Eudyptula minor* during an oil spill. *Biological Conservation*, 86(3), 393-400.

Ikenaka, Y., Sakamoto, M., Nagata, T., Takahashi, H., Miyabara, Y., Hanazato, T., Ishizuka, M., Isobe, T., Kim, J.W. and Chang, K.H. 2013. Effects of polycyclic aromatic hydrocarbons (PAHs) on an aquatic ecosystem: acute toxicity and community-level toxic impact tests of benzo [a] pyrene using lake zooplankton community. *The Journal of Toxicological Sciences*, 38(1), 131-136.

Incardona, J.P., Collier, T.K. and Scholz, N.L. 2004. Defects in cardiac function precede morphological abnormalities in fish embryos exposed to polycyclic aromatic hydrocarbons. *Toxicology and Applied Pharmacology*, 196(2), 191-205.

Incardona, J.P., Vines, C.A., Linbo, T.L., Myers, M.S., Sloan, C.A., Anulacion, B.F., Boyd, D., Collier, T.K., Morgan, S., Cherr, G.N. and Scholz, N.L. 2012. Potent phototoxicity of marine bunker oil to translucent herring embryos after prolonged weathering. *PLoS One*, 7(2), e30116.

Incardona, J.P. 2017. Molecular mechanisms of crude oil developmental toxicity in fish. *Archives of Environmental Contamination and Toxicology*, 1-14.

Interlandi, S. J. 2002. Nutrient–toxicant interactions in natural and constructed phytoplankton communities: results of experiments in semi-continuous and batch culture. *Aquatic Toxicology*, 61(1), 35–51.

Irons, D.B., 1996. Size and productivity of Black-legged Kittiwake colonies in Prince William Sound before and after the Exxon Valdez oil spill. *In Proceedings of the Exxon Valdez Oil Spill Symposium, American Fisheries Society Symposium 18*, Bethesda, MD.

Jensen, L.K., Honkanen, J.O., Jæger, I., and Carroll, J. 2012. Bioaccumulation of phenanthrene and benzo[a]pyrene in *Calanus finmarchicus*. *Ecotoxicology and Environmental Safety*, 78, 225–231.

Jensen, M.H., Nielsen, T.G., and Dahllöf, I. 2008. Effects of pyrene on grazing and reproduction of *Calanus finmarchicus* and *Calanus glacialis* from Disko Bay, West Greenland. *Aquatic Toxicology*, 87(2), 99–107.

Jha, M.N., Levy, J. and Gao, Y., 2008. Advances in remote sensing for oil spill disaster management: State-of-the-art sensors technology for oil spill surveillance. *Sensors*, 8(1), 236-255.

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.

Johansson, S., Larsson, U. and Boehm, P. 1980. The Tsesis oil spill impact on the pelagic ecosystem. *Marine Pollution Bulletin*, 11(10), 284-293.

Johnson-Restrepo, B., Olivero-Verbel, J., Lu, S., Guette-Fernández, J., Baldiris-Avila, R., O'Byrne-Hoyos, I., Aldous, K.M., Addink, R. and Kannan, K. 2008. Polycyclic aromatic hydrocarbons and their hydroxylated metabolites in fish bile and sediments from coastal waters of Colombia. *Environmental Pollution,* 151(3), 452-459.

Jung, J.H., Chae, Y.S., Kim, H.N., Kim, M., Yim, U.H., Ha, S.Y., Han, G.M., An, J.G., Kim, E. and Shim, W.J. 2012. Spatial variability of biochemical responses in resident fish after the M/V Hebei Spirit oil spill (Taean, Korea). *Ocean Science Journal*, 47(3), 209-214.

Jung, S.W., Kwon, O.Y., Joo, C.K., Kang, J.-H., Kim, M., Shim, W.J., and Kim, Y.-O. 2012. Stronger impact of dispersant plus crude oil on natural plankton assemblages in short-term marine mesocosms. *Journal of Hazardous Materials*, 217, 338–349.

Khairy, M.A., Weinstein, M.P. and Lohmann, R., 2014. Trophodynamic behavior of hydrophobic organic contaminants in the aquatic food web of a tidal river. *Environmental Science & Technology*, 48(21), 12533-12542.

King, T.L., Robinson, B., Boufadel, M. and Lee, K. 2014. Flume tank studies to elucidate the fate and behavior of diluted bitumen spilled at sea. *Marine Pollution Bulletin*, 83(1), 32-37.

King, Thomas L., Robinson, Brian, McIntyre, Claire, Toole, Patrick, Ryan, Scott, Saleh, Firas, Boufadel, Michel C., and Lee, Kenneth. 2015. Fate of Surface Spills of Cold Lake Blend Diluted Bitumen Treated with Dispersant and Mineral Fines in a Wave Tank. Environmental Engineering Science, 32(3), 250-261.

King, T., Robinson, B., Boufadel, M., Lee, K., Cui, F. and Clyburne, J.A. 2017. An Oil Spill Decision Matrix in Response to Surface Spills of Various Bitumen Blends. *Environmental Science: Processes & Impacts*.

Kocan, R.M., Marty, G.D., Okihiro, M.S., Brown, E.D. and Baker, T.T. 1996. Reproductive success and histopathology of individual Prince William Sound Pacific herring 3 years after the (Exxon Valdez) oil spill. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(10), 2388-2393.

Kocan, R.M., Hose, J.E., Brown, E.D. and Baker, T.T. 1996. Pacific herring (*Clupea pallasi*) embryo sensitivity to Prudhoe Bay petroleum hydrocarbons: laboratory evaluation and in situ exposure at oiled and unoiled sites in Prince William Sound. *Canadian Journal of Fisheries and Aquatic Sciences*, 53(10), 2366-2375.

Kochhann, D., Meyersieck Jardim, M., Valdez Domingos, F.X., and Luis Val, A. 2015. Biochemical and behavioral responses of the Amazonian fish Colossoma macropomum to crude oil: The effect of oil layer on water surface. *Ecotoxicology and Environmental Safety*, 111, 32–41.

Koelmans, A., Van der Heijde, A., Knijff, L., and Aalderink, R. 2001. Integrated Modelling of Eutrophication and Organic Contaminant Fate & Effects in Aquatic Ecosystems. A Review. *Water Research*, 35(15), 3517–3536.

Kong, Q., Zhu, L., and Shen, X. 2010. The toxicity of naphthalene to marine *Chlorella vulgaris* under different nutrient conditions. *Journal of Hazardous Materials*, 178(1), 282–286.

Koslow, M., J. Berrio, P. Glick, J. Hoffman, D. Inkley, A. Kane, M. Murray and K. Reeve. 2014. *Restoring the Great Lakes' Coastal Future - Technical Guidance for the Design and Implementation of ClimateSmart Restoration Projects with Seven Case Studies*. National Wildlife Federation, Reston, VA and National Oceanic and Atmospheric Administration, Silver Spring, MD.

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.

Lanctot, R., Goatcher, B., Scribner, K., Talbot, S., Pierson, B., Esler, D. and Zwiefelhofer, D., 1999. Harlequin Duck recovery from the Exxon Valdez oil spill: A population genetics perspective. *The Auk*, 781-791.

Landrum, P.F. 1988. Toxicokinetics of organic xenobiotics in the amphipod, *Pontoporeia hoyi*: Role of physiological and environmental variables. *Aquatic Toxicology*, 12(3), 245–271.

Landrum, P.F., Lotufo, G.R., Gossiaux, D.C., Gedeon, M.L., and Lee, J.-H. 2003. Bioaccumulation and critical body residue of PAHs in the amphipod, *Diporeia sp*.: Additional evidence to support toxicity additivity for PAH mixtures. *Chemosphere*, 51(6), 481–489.

Lardner, R.W. and G. Zodiatis. 1998. An operational oil spill model in the Levantine Basin (Eastern Mediterranean Sea). *Int. Symp. Mar. Pollut*., 10, 5-9.

Laskowski, S.L. and Voltaggio, T.C., 1988. The Ashland Oil Spill of January 1988-an EPA Perspective. *In Chemical Spills and Emergency Management at Sea*, 421-434. Springer, Dordrecht, The Netherlands.

Lavarías, S., Pollero, R.J., and Heras, H. 2006. Activation of lipid catabolism by the water-soluble fraction of petroleum in the crustacean Macrobrachium borellii. *Aquatic Toxicology*, 77(2), 190–196.

Lee, L.E.J., McDonald, A., Stassen, J. and Lee, K. 2000. Effects of oil-spill bioremediation strategies on the survival, growth and reproductive success of the mystery snail, Viviparus georgianus. In *Environmental Toxicology and Risk Assessment: Science, Policy, and Standardization—Implications for Environmental Decisions: Tenth Volume*. ASTM International.

Lee, R.F., Köster, M. and Paffenhöfer, G.A. 2012. Ingestion and defecation of dispersed oil droplets by pelagic tunicates. *Journal of Plankton Research*, 34(12), 1058-1063.

Lee, K., Boufadel, M., Chen, B., Foght, J., Hodson, P., Swanson, S., and Venosa, A. 2015. The Royal Society of Canada Expert Panel: *The Behaviour and Environmental Impacts of Crude Oil Released into Aqueous Environments*, 461.

Lefcort, H., Hancock, K.A., Maur, K.M. and Rostal, D.C., 1997. The effects of used motor oil, silt, and the water mold Saprolegnia parasitica on the growth and survival of mole salamanders (Genus Ambystoma). *Archives of Environmental Contamination and Toxicology*, 32(4), 383-388.

Le Hénaff, M., Kourafalou, V.H., Paris, C.B., Helgers, J., Aman, Z.M., Hogan, P.J. and Srinivasan, A. 2012. Surface evolution of the Deepwater Horizon oil spill patch: Combined effects of circulation and wind-induced drift. *Environmental Science & Technology*, 46(13), 7267-7273.

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.

Lennuk, Lennart, Jonne Kotta, Kristiina Taits, Karolin Teeveer. 2015. The short-term effects of crude oil on the survival of different size-classes of cladoceran Daphnia magna (Straus, 1820), *Oceanologia*, 57, 1, 71-77.

Lewis, M. and R. Pryor. 2013. Toxicities of oils, dispersants and dispersed oils to algae and aquatic plants: Review and database value to resource sustainability. *Environmental Pollution*, 180: 345-367.

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.

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.

Lotufo, G.R. 1998. Bioaccumulation of sediment-associated fluoranthene in benthic copepods: uptake, elimination and biotransformation. *Aquatic Toxicology*, 44(1), 1–15.

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

Ludsin, S.A. and Hook, T.O., 2013. *Interactive effects of nutrient inputs and climate change on Lake Erie fish community*. Report to International Joint Commission, 24 p.

Ludsin, S.A., K.M. DeVanna, and R.E.H. Smith. 2014. Physical-biological coupling and the challenge of understanding fish recruitment in large lakes. *Canadian Journal of Fisheries and Aquatic Sciences,* 71:775-794.

Luiselli, L. and Akani, G.C. 2003. An indirect assessment of the effects of oil pollution on the diversity and functioning of turtle communities in the Niger Delta, Nigeria. *Animal Biodiversity and Conservation*, 26(1), 57-65.

Lutcavage, M.E., Lutz, P.L., Bossart, G.D. and Hudson, D.M., 1995. Physiologic and clinicopathologic effects of crude oil on loggerhead sea turtles. *Archives of Environmental Contamination and Toxicology*, 28(4), 417-422.

Luquet, P., Cravedi, J.P., Choubert, G., Tulliez, J. and Bories, G. 1983. Long-term ingestion by rainbow trout of saturated hydrocarbons: Effects of n-paraffins, pristane and dodecylcyclohexane on growth, feed intake, lipid digestibility and canthaxanthin deposition. *Aquaculture*, 34(1-2), 15-25.

Luquet, P., Cravedi, J.P., Tulliez, J. and Bories, G. 1984. Growth reduction in trout induced by naphthenic and isoprenoid hydrocarbons (dodecylcyclohexane and pristane). *Ecotoxicology and Environmental Safety*, 8(3), 219-226.

Mackay, D. and Fraser, A. 2000. Bioaccumulation of persistent organic chemicals: mechanisms and models. *Environmental Pollution*, 110(3), 375-391.

Macnaughton, S.J., Swannell, R., Daniel, F. and Bristow, L. 2003. Biodegradation of dispersed Forties crude and Alaskan North Slope oils in microcosms under simulated marine conditions. *Spill Science & Technology Bulletin*, 8(2), 179-186.

Madison, B., Hodson, P., and Langlois, V. 2015. Diluted bitumen causes deformities and molecular responses indicative of oxidative stress in Japanese medaka embryos. *Aquatic Toxicology*, http://www.sciencedirect.com/science/article/pii/S0166445X15001782.

Madison, B.N., Hodson, P.V. and Langlois, P.V. 2017. The effects of Cold Lake Blend diluted bitumen toxicity on the early development of Japanese medaka (Oryzias latipes). *Environmental Pollution*. In press.

Mager, E.M., Esbaugh, A.J., Stieglitz, J.D., Hoenig, R., Bodinier, C., Incardona, J.P., Scholz, N.L., Benetti, D.D. and Grosell, M. 2014. Acute embryonic or juvenile exposure to Deepwater Horizon crude oil impairs the swimming performance of mahi-mahi (Coryphaena hippurus). *Environmental Science & Technology*, 48(12), 7053-7061.

Magnusson, K., Magnusson, M., Östberg, P., Granberg, M., Tiselius, P. 2007. Biomagnification of 14C-PCB 101 and 14C-PBDE 99 in the marine planktonic copepod *Calanus finmarchicus* under different food regimes. *Mar. Environ. Res.* 63, 67–81.

Manzetti, S., 2012. Ecotoxicity of polycyclic aromatic hydrocarbons, aromatic amines, and nitroarenes through molecular properties. *Environmental Chemistry Letters*, 10(4), 349-361.

Marty, G.D., Hoffmann, A., Okihiro, M.S., Hepler, K., and Hanes, D. 2003. Retrospective analysis: bile hydrocarbons and histopathology of demersal rockfish in Prince William Sound, Alaska, after the Exxon Valdez oil spill. *Marine Environmental Research*, 56(5), 569–584.

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

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.

Masnik, M.T., Stauffer, J.R., Hocutt, C.H., and Wilson, J.H. 1976. The effects of an oil spill on the macroinvertebrates and fish in a small southwestern Virginia creek. *Journal of Environmental Science & Health Part A*, 11(4-5), 281-296.

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

Maynard, L., and Wilcox, D.A., 1997. *Coastal wetlands of the Great Lakes—State of the Lakes Ecosystem Conference 1996 background paper: Environment Canada and U.S. Environmental Protection Agency*, EPA 905–R–97–015b, 99 p.

Mazet, J.A., Gardner, I.A., Jessup, D.A. and Lowenstine, L.J., 2001. Effects of petroleum on mink applied as a model for reproductive success in sea otters. *Journal of Wildlife Diseases*, 37(4), 686-692.

McCall, B.D., and Pennings, S.C. 2012. Disturbance and recovery of salt marsh arthropod communities following BP Deepwater Horizon oil spill. *PloS one*, 7(3), e32735.

McCauley, R.N. 1966. The biological effects of oil pollution in a river. *Limnol. Oceanogr*. 11: 475–486.

McDonald, B.G., and Chapman, P.M. 2002. PAH phototoxicity––an ecologically irrelevant phenomenon? *Marine Pollution Bulletin*, 44(12):1321-1326.

McElroy, A., Leitch, K. and Fay, A., 2000. A survey of in vivo benzo [α] pyrene metabolism in small benthic marine invertebrates. *Marine Environmental Research*, 50(1), 33-38.

McGrath, J.A. and Di Toro, D.M. 2009. Validation of the target lipid model for toxicity assessment of residual petroleum constituents: monocyclic and polycyclic aromatic hydrocarbons. *Environmental Toxicology and Chemistry*, 28(6), 1130-1148.

McGurk, M.D. and E.D. Brown. 1996. Egg-larva mortality of Pacific herring in Prince William Sound, Alaska, after the Exxon Valdez oil spill. *Canadian Journal of Fisheries and Aquatic Sciences*, 53: 2343–2354

McKnight, D., et al. 2016. *Spills of Diluted Bitumen from Pipelines: A Comparative Study of Environmental Fate, Effects, and Response*. National Academies Press, Washington, DC. https://www.nap.edu/catalog/21834/spills-of-diluted-bitumen-from-pipelines-a-comparative-study-of

McNutt, M.K., Camilli, R., Crone, T.J., Guthrie, G.D., Hsieh, P.A., Ryerson, T.B., Savas, O. and Shaffer, F., 2012. Review of flow rate estimates of the Deepwater Horizon oil spill. *Proceedings of the National Academy of Sciences*, 109(50):20260-20267.

Mendelssohn, I.A., Andersen, G.L., Baltz, D.M., Caffey, R.H., Carman, K.R., Fleeger, J.W., Joye, S.B., Lin, Q., Maltby, E., Overton, E.B. and Rozas, L.P., 2012. Oil impacts on coastal wetlands: implications for the Mississippi River Delta ecosystem after the Deepwater Horizon oil spill. *BioScience*, 62(6), 562-574.

Mignucci-Giannoni, A.A. 1998. Assessment and rehabilitation of wildlife affected by an oil spill in Puerto Rico. *Environmental Pollution*, 104, 323–333.

Miller, M.C., Alexander, V. and Barsdate, R.J. 1978. The effects of oil spills on phytoplankton in an arctic lake and ponds. *Arctic*, 192-218.

Milton, S., Lutz, P. and Shigenaka, G. 2003. Oil toxicity and impacts on sea turtles. Oil and Sea Turtles: Biology, Planning, and Response. NOAA National Ocean Service. 35-47.

Monnett, C. and Rotterman, L.M., 2000. Survival rates of sea otter pups in Alaska and California. *Marine Mammal Science*, 16(4), 794-810.

Moody, R. M., Cebrian, J., Heck, K. L., and Browman, H. 2013. Interannual recruitment dynamics for resident and transient marsh species: Evidence for a lack of impact by the Macondo oil spill. *PLoS ONE*, 8(3), e58376.

Murawski, S.A., Hogarth, W.T., Peebles, G.M., Barbeiri, L. 2014. Prevalence of external skin lesions and polycyclic aromatic hydrocarbon concentrations in Gulf of Mexico fishes, post-Deepwater Horizon. *Transactions of the American Fisheries Society*, 143(4), 1084-1097.

Murphy, M.L., Heintz, R.A., Short, J.W., Larsen, M.L. and Rice, S.D. 1999. Recovery of pink salmon spawning areas after the Exxon Valdez oil spill. *Transactions of the American Fisheries Society*, 128(5), 909-918.

Muschenheim, D.K. and Lee, K. 2002. Removal of oil from the sea surface through particulate interactions: review and prospectus. *Spill Science & Technology Bulletin*, 8(1), 9-18.

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

Neff, J.M., 1979. *Polycyclic aromatic hydrocarbons in the aquatic environment*. Applied Science Publ. Ltd., London. 262 pp.

Neff, J.M. and Stubblefield, W.A. 1995. Chemical and toxicological evaluation of water quality following the Exxon Valdez oil spill. In *Exxon Valdez oil spill: fate and effects in Alaskan waters*. ASTM International.

Neff, J.M., Ostazeski, S., Gardiner, W. and Stejskal, I. 2000. Effects of weathering on the toxicity of three offshore Australian crude oils and a diesel fuel to marine animals. *Environmental Toxicology and Chemistry*, 19(7), 1809-1821.

Newman, M.C. and W.H. Clements. 2008. *Ecotoxicology: A Comprehensive Treatment*. CRC Press, Boca Raton, Florida, 852 pp.

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.

Nunes, B., Silva, V., Campos, I., Pereira, J.L., Pereira, P., Keizer, J.J., Gonçalves, F. and Abrantes, N. 2017. Off-site impacts of wildfires on aquatic systems—Biomarker responses of the mosquitofish Gambusia holbrooki. *Science of the Total Environment*.

NOAA. 2016. *Automated Data Inquiry for Oil Spills (ADIOS)*. NOAA Office of Response and Restoration. https://response.restoration.noaa.gov/adios

NYOGLECC (New York Ocean and Great Lakes Ecosystem Conservation Council) 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%20Sept2007.pdf

Oliva, A., Arias, A., Quintas, P., and Buzzi, N. 2017. Polycyclic Aromatic Hydrocarbons in Mussels from a South American Estuary. *Archives of Environmental Contamination and Toxicology*. http://link.springer.com/article/10.1007/s00244-017-0392-y.

Østgaard, K., Eide, I. and Jensen, A. 1984. Exposure of phytoplankton to Ekofisk crude oil. *Marine Environmental Research*, 11(3), 183-200.

Page, D.S., Boehm, P.D., Stubblefield, W.A., Parker, K.R., Gilfillan, E.S., Neff, J.M. and Maki, A.W. 2002. Hydrocarbon composition and toxicity of sediments following the Exxon Valdez oil spill in Prince William Sound, Alaska, USA. *Environmental Toxicology and Chemistry*, 21(7), 1438-1450.

Palmqvist, A., Rasmussen, L.J., and Forbes, V.E. 2006. Influence of biotransformation on trophic transfer of the PAH, fluoranthene. *Aquatic Toxicology*, 80(3), 309–319.

Parab, S.R., Pandit, R.A., Kadam, A.N. and Indap, M.M. 2008. *Effect of Bombay high crude oil and its water-soluble fraction on growth and metabolism of diatom Thalassiosira sp*.

Payne, J.R. and Driskell, W.B., 2003, April. The Importance of Distinguishing Dissolved-Versus Oil-Droplet Phases in Assessing the Fate, Transport, and Toxic Effects of Marine Oil Pollution 1. In *International Oil Spill Conference* (Vol. 2003, No. 1, 771-778). American Petroleum Institute.

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.

Pelletier, M.C., Burgess, R.M., Ho, K.T., Kuhn, A., McKinney, R.A. and Ryba, S.A. 1997. Phototoxicity of individual polycyclic aromatic hydrocarbons and petroleum to marine invertebrate larvae and juveniles. *Environmental Toxicology and Chemistry*, 16(10), 2190-2199.

Pennings, S.C., McCall, B.D., and Hooper-Bui, L. 2014. Effects of oil spills on terrestrial arthropods in coastal wetlands. BioScience, 64(9), 789-795.

Perhar, G., and Arhonditsis, G. 2014. Aquatic ecosystem dynamics following petroleum hydrocarbon perturbations: A review of the current state of knowledge. *Journal of Great Lakes Research*. http://www.sciencedirect.com/science/article/pii/S0380133014001397

Pérez, P., Fernández, E., and Beiras, R. 2010. Fuel toxicity on Isochrysis galbana and a coastal phytoplankton assemblage: Growth rate vs. variable fluorescence. *Ecotoxicology and Environmental Safety*, 73(3), 254–261.

Peterson, C.H., Rice, S.D., Short, J.W., Esler, D., Bodkin, J.L., Ballachey, B.E. and Irons, D.B. 2003. Long-term ecosystem response to the Exxon Valdez oil spill. *Science*, 302(5653), 2082-2086.

Peterson, E.K. and Schulte, B.A., 2016. Impacts of pollutants on beavers and otters with implications for ecosystem ramifications. *Journal of Contemporary Water Research & Education*, 157(1), 33-45.

Petersen, G.I. and Kristensen, P. 1998. Bioaccumulation of lipophilic substances in fish early life stages. *Environmental Toxicology and Chemistry*, 17(7), 1385-1395.

Philibert, D.A., Philibert, C.P., Lewis, C. and Tierney, K.B. 2016. Comparison of Diluted Bitumen (Dilbit) and Conventional Crude Oil Toxicity to Developing Zebrafish. *Environmental Science & Technology*, 50(11), 6091-6098.

Piatt, J.F. and Ford, R.G. 1996. How many seabirds were killed by the Exxon Valdez oil spill. *American Fisheries Society Symposium* (Vol. 18, No. 1993, 2-5).

Pilcher, W., Miles, S., Tang, S., Mayer, G. and Whitehead, A. 2014. Genomic and genotoxic responses to controlled weathered-oil exposures confirm and extend field studies on impacts of the Deepwater Horizon oil spill on native killifish. *PloS one*, 9(9), p.e106351.

Potok, A.J., and Quinn, F.H. 1979. A hydraulic transient model for the upper St. Lawrence River for water resources studies. *Water Resources Bulletin*, 15:15381555.

Prahl, F.G., and Carpenter, R. 1979. The role of zooplankton fecal pellets in the sedimentation of polycyclic aromatic hydrocarbons in Dabob Bay, Washington. *Geochimica et Cosmochimica Acta*, 43(12), 1959–1972.

Ramachandran, S.D., Sweezey, M.J., Hodson, P.V., Boudreau, M., Courtenay, S.C., Lee, K., … Dixon, J.A. 2006. Influence of salinity and fish species on PAH uptake from dispersed crude oil. *Marine Pollution Bulletin*, 52(10), 1182–1189.

Ramseur, J.L. 2017. *Oil spills: Background and Governance*. Congressional Research Service Report RL33705, 29 p.

Rao, Y.R. and Schwab, D.J., 2007. Transport and mixing between the coastal and offshore waters in the Great Lakes: a review. *Journal of Great Lakes Research*, 33(1), 202-218.

Rao, Y.R. and Schwab, D.J., 2012. Laurentian Great Lakes, Interaction of Coastal and Offshore Waters. In *Encyclopedia of Lakes and Reservoirs* (pp. 479-485). Springer, Netherlands.

Rebar, A.H., Lipscomb, T.P., Harris, R.K. and Ballachey, B.E. 1995. Clinical and clinical laboratory correlates in sea otters dying unexpectedly in rehabilitation centers following the Exxon Valdez oil spill. *Veterinary Pathology*, 32(4), 346-350.

Redman, A.D., Butler, J.D., Letinski, D.J. and Parkerton, T.F. 2017. Investigating the role of dissolved and droplet oil in aquatic toxicity using dispersed and passive dosing systems. *Environmental Toxicology and Chemistry*, 36(4), 1020-1028.

Ribecco, C., Hardiman, G., Šášik, R., Vittori, S. and Carnevali, O., 2012. Teleost fish (*Solea solea*): a novel model for ecotoxicological assay of contaminated sediments. *Aquatic Toxicology*, 109, 133-142.

Rice, S.D., Thomas, R.E., Carls, M.G., Heintz, R.A., Wertheimer, A.C., Murphy, M.L., Short, J.W. and Moles, A. 2001. Impacts to pink salmon following the Exxon Valdez oil spill: persistence, toxicity, sensitivity, and controversy. *Reviews in Fisheries Science*, 9(3), 165-211.

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.

Roemer, G.W., Gompper, M.E. and Van Valkenburgh, B. 2009. *The ecological role of the mammalian mesocarnivore*. *BioScience*, 59(2), 165-173.

Roth, A.M.F. and Baltz, D.M., 2009. Short-term effects of an oil spill on marsh-edge fishes and decapod crustaceans. *Estuaries and Coasts*, 32(3), 565-572.

Rowe, C.L. and C.L. Mitchelmore. 2009. Lack of biological effects of water accommodated fractions of chemically-and physically-dispersed oil on molecular, physiological, and behavioral traits of juvenile snapping turtles following embryonic exposure. *Science of the Total Environment*, ISSN 0048-9697, Vol 407, Number 20.

Ruggerone, G.T. and Rogers, D.E. 2003. Multi-year effects of high densities of sockeye salmon spawners on juvenile salmon growth and survival: A case study from the Exxon Valdez oil spill. *Fisheries Research*, 63(3), 379-392.

Saba, V.S., and Spotila, J.R. 2003. Survival and behavior of freshwater turtles after rehabilitation from an oil spill. *Environmental Pollution*, 126(2), 213-223.

Salehi, M., Rodriguez, R., Boettcher, A., Powers, S., Geitner, N., Ladner, D.A., Rikard, S. and Whelton, A.J. 2017. Impact of dispersant on early life stages of the water flea Daphnia magna and the eastern oyster Crassostrea virginica. *Journal of Applied Toxicology*.

Sargian, P., Mostajir, B., Chatila, K., Ferreyra, G.A., Pelletier, É. and Demers, S. 2005. Non-synergistic effects of water-soluble crude oil and enhanced ultraviolet-B radiation on a natural plankton assemblage. *Marine Ecology Progress Series*, 294, 63-77.

Schaefer, J., Frazier, N. and Barr, J. 2016. Dynamics of near-coastal fish assemblages following the Deepwater Horizon oil spill in the northern Gulf of Mexico. *Transactions of the American Fisheries Society*, 145(1), 108-119.

Schloesser, D.W., T. A. Edsall, B.A. Manny, S.J. Nichols. 1991. Distribution of *Hexagenia* nymphs and visible oil in sediments of the Upper Great Lakes Connecting Channels, Hydrobiologia, 1991, 219, 1, 345.

Schroeder, B.C., and Dann, S.L., 2003. *The Life of the Lakes: A Guide to the Great Lakes Fishery*. Michigan Sea Grant College Program, 120 p.

Schwab, D.J., J.R. Bennet, and E.W. Lyn. 1984. *'PATHFINDER'—A trajectory prediction system for the Great Lakes, Tech*. Memo. ERL GLERL-53, Great Lakes Environ. Res. Lab., Natl. Oceanic and Atmos. Admin., Ann Arbor, Mich.

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

Selweski, C. 2017. Toxic chemical spill? Wait for our fax. *Bridge Magazine*, October 31, 2017, http://www.bridgemi.com/quality-life/toxic-chemical-spill-wait-our-fax

Shen, H.T., P.D. Yapa, and M.E. Petrosk., 1987. A simulation model for oil slick transport in lakes. *Water Resour. Res.*, 23(10), 1949–1957.

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.

Shen, A., Tang, F., Xu, W. and Shen, X., 2012. Toxicity testing of crude oil and fuel oil using early life stages of the black porgy (*Acanthopagrus schlegelii*). In *Biology and Environment: Proceedings of the Royal Irish Academy*, 35-41.

Sheng, Y., Tang, D. and Pan, G. 2011. Phytoplankton bloom over the Northwest Shelf of Australia after the Montara oil spill in 2009. *Geomatics, Natural Hazards and Risk*, 2(4), 329-347.

Short, J. 2003. Long-term effects of crude oil on developing fish: lessons from the Exxon Valdez oil spill. *Energy Sources*, 25(6), 509-517.

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.

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.

Skei, J., Larsson, P., Rosenberg, R., Jonsson, P., Olsson, M. and Broman, D. 2000. Eutrophication and contaminants in aquatic ecosystems. *AMBIO: A Journal of the Human Environment*, 29(4), 184-194.

Speight, J.G. 2011. History and Terminology of Crude Oil, *in An Introduction to Petroleum Technology, Economics, and Politics*, John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/9781118192528.ch1

Sperduto, M.B., Powers, S.P. and Donlan, M., 2003. Scaling restoration to achieve quantitative enhancement of loon, seaduck, and other seabird populations. *Marine Ecology Progress Series*, 264, 221-232.

Steinman, A.D., Cardinale, B.J., Munns Jr, W.R., Ogdahl, M.E., Allan, J.D., Angadi, T., Bartlett, S., Brauman, K., Byappanahalli, M., Doss, M. and Dupont, D., 2017. Ecosystem services in the Great Lakes. *Journal of Great Lakes Research*, 43(3), 161-168.

Sturdevant, M.V., Wertheimer, A.C. and Lum, J.L. 1996. Diets of juvenile pink and chum salmon in oiled and non-oiled nearshore habitats in Prince William Sound, 1989 and 1990. In *Am. Fish. Soc. Symp*. 18, 578-592.

Suedel, B.C., Boraczek, J.A., Peddicord, R.K., Clifford, P.A. and Dillon, T.M., 1994. Trophic transfer and biomagnification potential of contaminants in aquatic ecosystems. *Reviews of Environmental Contamination and Toxicology*, 136, 21-90.

Sureda, A., Box, A., Tejada, S., Blanco, A., Caixach, J. and Deudero, S. 2011. Biochemical responses of *Mytilus galloprovincialis* as biomarkers of acute environmental pollution caused by the Don Pedro oil spill (Eivissa Island, Spain). *Aquatic Toxicology*, 101(3), 540-549.

Tardif, B., G. Lavoie and Y. Lachance, 2005. Québec Biodiversity Atlas. Threatened or Vulnerable Species. Gouvernement du Québec, Ministère du Développement durable, de l'Environnement et des Parcs, Direction du développement durable, du patrimoine écologique et des parcs, Québec, 60 p.

Truscott, B., Idler, D.R. and Fletcher, G.L. 1992. Alteration of reproductive steroids of male winter flounder (*Pleuronectes americanus*) chronically exposed to low levels of crude oil in sediments. Canadian *Journal of Fisheries and Aquatic Sciences*, 49(10), 2190-2195.

Truter C, J., van Wyk, J.H., Oberholster, P.J., Botha, A.M. and Mokwena, L.M. 2017. An evaluation of the endocrine disruptive potential of crude oil water accommodated fractions and crude oil contaminated surface water to freshwater organisms using in vitro and in vivo approaches. *Environmental Toxicology and Chemistry*.

Tukaj, Z. 1987. The effects of crude and fuel oils on the growth, chlorophyll "a" content and dry matter production of a green alga *Scenedesmus quadricauda* (Turp.) bréb. *Environmental Pollution*, 47(1), 9–24.

United State Energy Information Administration (EIA). *September 2017 Outlook Report*.

USDOT Maritime Administration 2013. *Status of the U.S.-Flag Great Lakes Water Transportation Industry*, 144 p. https://www.marad.dot.gov/wp-content/uploads/pdf/US-Flag_Great_Lakes_Water_Transportation_Industry_Final_Report_2013.pdf

USEPA 2012. *Ecological Risk Assessment Glossary of Terms*. https://ofmpub.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do?details=&glossaryName=Eco%20Risk%20Assessment%20Glossary

Vadeboncoeur, Y., McIntyre, P.B. and Vander Zanden, M.J., 2011. Borders of biodiversity: life at the edge of the world's large lakes. BioScience, 61(7), 526-537.

Varela, M., Bode, A., Lorenzo, J., Álvarez-Ossorio, M.T., Miranda, A., Patrocinio, T., ... Groom, S. 2006. The effect of the "Prestige" oil spill on the plankton of the N–NW Spanish coast. *Marine Pollution Bulletin*, 53(5), 272–286.

Venosa, A.D. and Holder, E.L. 2013. Determining the dispersibility of South Louisiana crude oil by eight oil dispersant products listed on the NCP Product Schedule. *Marine Pollution Bulletin*, 66(1), 73-77.

von Stackelberg, K., Williams, M.A., Clough, J. and Johnson, M.S., 2017. Spatially explicit bioaccumulation modeling in aquatic environments: Results from 2 demonstration sites. *Integrated Environmental Assessment and Management*.

Vosyliene, M.Z. and Kazlauskiene, N. 2005. Toxic Effects of Crude Oil Combined with Oil Cleaner Simple Green on Yolk-sac Larvae and Adult Rainbow Trout Oncorhynchus mykiss (4 pp). *Environmental Science and Pollution Research*, 12(3), 136-139.

Walker, B., Holling, C.S., Carpenter, S. and Kinzig, A. 2004. Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2): article 5.

Wan, Y., Jin, X., Hu, J. and Jin, F., 2007. Trophic dilution of polycyclic aromatic hydrocarbons (PAHs) in a marine food web from Bohai Bay, North China. *Environmental Science & Technology*, 41(9), 3109-3114.

Weisberg, R.H., Zheng, L., Liu, Y., Murawski, S., Hu, C. and Paul, J., 2016. Did Deepwater Horizon hydrocarbons transit to the west Florida continental shelf? *Deep Sea Research Part II: Topical Studies in Oceanography*, 129, 259-272.

Wernersson, A.S. 2003. Predicting petroleum phototoxicity. *Ecotoxicology and Environmental Safety*, 54(3), 355-365.

Whitehead, A., Dubansky, B., Bodinier, C., Garcia, T. I., Miles, S., Pilley, C., ... and Rice, C. D. 2012. Genomic and physiological footprint of the Deepwater Horizon oil spill on resident marsh fishes. *Proceedings of the National Academy of Sciences*, 109(50), 20298-20302.

Wilcox, D.A., and Whillans, T.H., 1999. Techniques for restoration of disturbed coastal wetlands of the Great Lakes. *Wetlands*, 19, 835–857.

Wiens, J.A., Crist, T.O., Day, R.H., Murphy, S.M. and Hayward, G.D., 1996. Effects of the Exxon Valdez oil spill on marine bird communities in Prince William Sound, Alaska. *Ecological Applications*, 6(3), 828-841.

Willette, M. 1996. Impacts of the Exxon Valdez oil spill on the migration, growth, and survival of juvenile pink salmon in Prince William Sound. *Am. Fish. Soc. Symp* (Vol. 18, 533-550).

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.

Yagi, J.M., Neuhauser, E.F., Ripp, J.A., Mauro, D.M. and Madsen, E.L., 2010. Subsurface ecosystem resilience: long-term attenuation of subsurface contaminants supports a dynamic microbial community. *The ISME Journal*, 4(1), p.131.

Yakimov, M.M., Timmis, K.N. and Golyshin, P.N. 2007. Obligate oil-degrading marine bacteria. *Current Opinion in Biotechnology*, 18(3), 257-266.

Yankielun, N.E., Barone, R., Cables, E., Locklear, C. and Wilson, K., 2013. *Great Lakes Oil-in-Ice Demonstration 3 Final Report*. U.S. Coast Guard Research and Development Center, Report No. CG-D-08-13.

Yapa, P.D., Shen, H.T., Wang, D., and Angammana, K. 1992. An Integrated Computer Model for Simulating Oil Spills in the Upper St. Lawrence River. *Journal of Great Lakes Research*, 18(2), 340–351.

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

Yender, R.A. and Mearns, A.J. 2003. Case studies of spills that threaten sea turtles. Oil and Sea Turtles: Biology, Planning, and Response. NOAA, National Ocean Service, Office of Response and Restoration, Seattle, Washington, p. 69-86.

Yergeau, E., Lawrence, J.R., Sanschagrin, S., Roy, J.L., Swerhone, G.D., Korber, D.R. and Greer, C.W. 2013. Aerobic biofilms grown from Athabasca watershed sediments are inhibited by increasing concentrations of bituminous compounds. *Applied and Environmental Microbiology*, 79(23), 7398-7412.

Yu, X., Xu, C., Liu, H., Xing, B., Chen, L. and Zhang, G. 2015. Effects of Crude Oil and Dispersed Crude Oil on the Critical Swimming Speed of Puffer Fish, Takifugu rubripes. *Bulletin of Environmental Contamination and Toxicology*, 94(5), 549-553.

Zhang, Y., Dong, S., Wang, H., Tao, S. and Kiyama, R. 2016. Biological impact of environmental polycyclic aromatic hydrocarbons (ePAHs) as endocrine disruptors. *Environmental Pollution*, 213, 809-824.

Zhang, Y., Wang, C., Huang, L., Chen, R., Chen, Y., and Zuo, Z. 2012. Low-level pyrene exposure causes cardiac toxicity in zebrafish (*Danio rerio*) embryos. *Aquatic Toxicology*, 114, 119–124.

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.