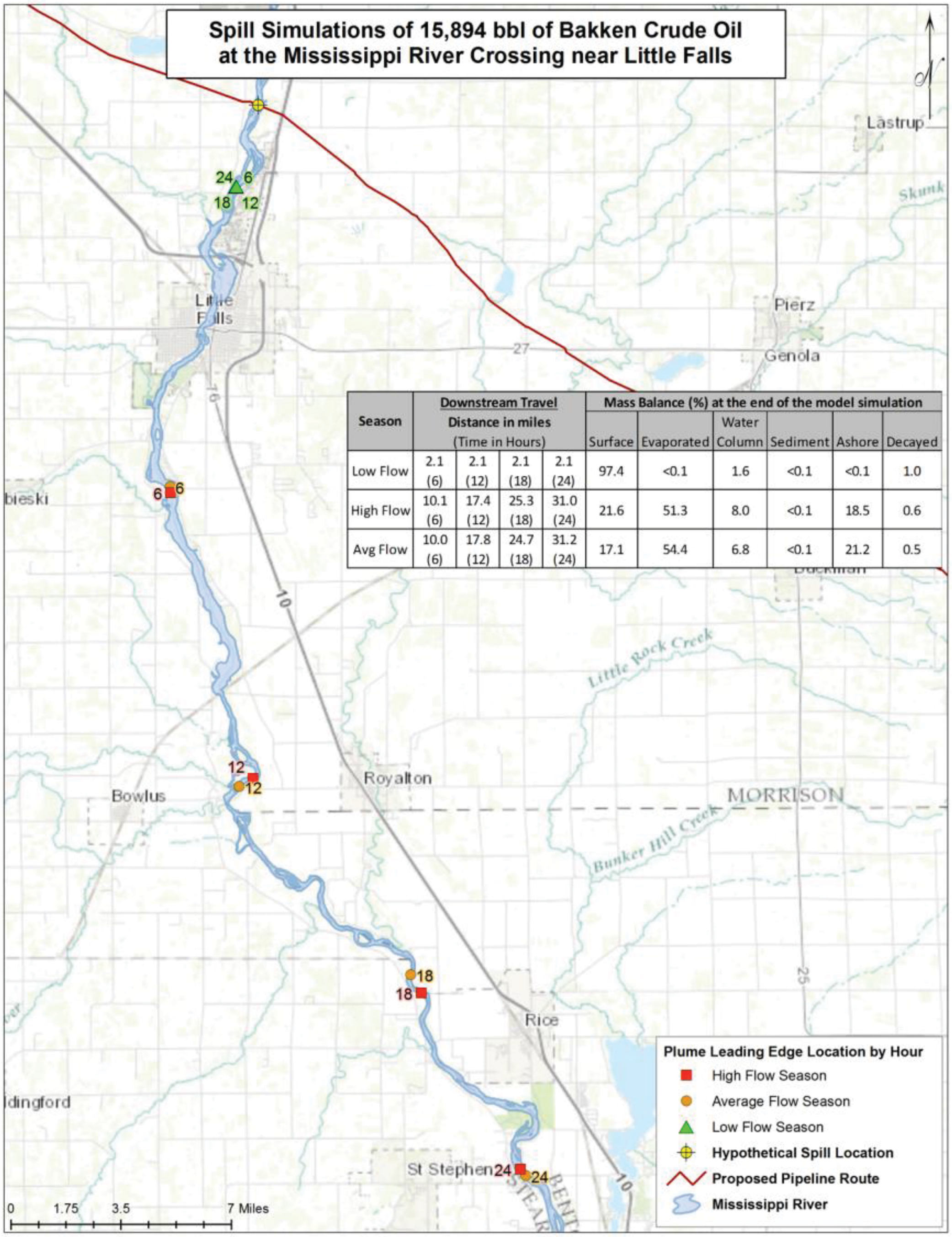

Season	Downstream Travel Distance in miles (Time in Hours)				Mass Balance (%) at the end of the model simulation					
					Surface	Evaporated	Water Column	Sediment	Ashore	Decayed
Low Flow	2.1 (6)	2.1 (12)	2.1 (18)	2.1 (24)	97.4	<0.1	1.6	<0.1	<0.1	1.0
High Flow	10.1 (6)	17.4 (12)	25.3 (18)	31.0 (24)	21.6	51.3	8.0	<0.1	18.5	0.6
Avg Flow	10.0 (6)	17.8 (12)	24.7 (18)	31.2 (24)	17.1	54.4	6.8	<0.1	21.2	0.5

Figure 6-80 Predicted Downstream Transport of Bakken Crude Oil at the Mississippi River at Little Falls Release Location

During high and average river flow conditions, the relatively calm waters upstream and downstream of the Little Falls Dam and Blanchard Dam resulted in large amounts of floating oil, which formed extensive surface slicks over much of the river (Figure 6-85 and Figure 6-92). Surface slicks for the Mississippi River at Little Falls were in general thinner and more extensive than those of the Mississippi River at Palisade. This was the result of more rapid and turbulent river flow at Little Falls. Additionally, for Bakken crude, slicks were thinner than CLB. At the end of the 24-hour simulation, floating oil thicknesses between 0.01 and 1 mm (dark brown sheen and black oil) remained on the water surface. There were some areas of river with floating surface oil less than 0.001 mm thick (representing colorless and silver sheens and rainbow sheens). The presence of extensive surface slicks resulted in significant evaporation, with approximately 50% of the total release ending up in the atmosphere (Table 6-5).

Extensive shoreline oiling was observed for approximately 30 miles (48.3 km) of the river below the release location under high river flow conditions (Figure 6-87) and 29 miles (46.7 km) under average river flow conditions (Figure 6-94). The concentrations of Bakken on the shore were generally 100–500 g/m^2 with nearly equal lengths of shoreline exceeding 500 g/m^2. In general, Bakken resulted in less extensive shoreline oiling than the CLB.

Similar to the CLB scenarios, Bakken crude behaved similarly over water falls. A large portion of the released oil would be entrained into the water column at both Little Falls Dam and Blanchard Dam. This would result in large increases in the THC concentration within the water column and would result in enhancements in the dissolved aromatic concentration (Figure 6-81 and Figure 6-88). Slightly lower amounts of entrained oil are found in the water column and surface oil returns more rapidly downstream of dams in the Bakken release. This is the result of the Bakken crude being less dense than CLB, which results in a larger buoyant force and a more rapid rise in velocity of Bakken oil droplets.

Oil-SPM interactions were observed with the Bakken crude oil as well, which resulted in the possibility of "sinking oil" (Figure 6-87 and Figure 6-94). Approximately 30 miles (48.3 km) of river bottom were predicted to have sediment oiling less than 0.01 g/m^2, with some localized areas experiencing 0.01–0.5 g/m^2. Below Blanchard Dam, after the second waterfall entrained oil and further mixing with SPM, some patchy and localized portions of the river bottom may have sediment concentrations between 1 and 10 g/m^2 with values as high as 10–50 g/m^2 in very small areas. In general, Bakken was more easily entrained into the water column due to its lower viscosity. However, the overall quantity of oil interacting with SPM was lower than the CLB. Less than 0.1% of the release is predicted to be found in the sediments under ice-free conditions. This is over six times lower than the predictions for CLB. Higher sediment oiling is predicted under high river flow rates due to the increased turbulence and higher suspended sediment load within the water column. The lowest sediment concentrations and smallest areas with sediment oil were predicted for low flow conditions (Figure 6-101).

The maximum concentration of dissolved aromatics was greater than 500 ppb in small regions within the spill extent; however, most of the dissolved aromatic concentrations ranged between

25 and 100 ppb (Figure 6-87 and Figure 6-94). The enhanced dissolved aromatic concentrations were due to dissolution of the soluble portion of the Bakken into the water column. While this may be expected to cause higher concentrations (as observed in the Palisade case), it is important to consider that in the Little Falls scenarios, vertical mixing resulted in more uniform concentrations throughout the water column, as opposed to a localized or thin layer with elevated concentrations at the surface for the scenarios at Palisade. Although Bakken has a higher aromatic content than Bakken, concentrations were slightly lower for Bakken than the CLB as entrained droplets rose more quickly through the water column downstream of the dams, where they formed surface slicks and evaporated more completely.

For the low river flow scenario, the hydrocarbon trajectory at the end of the 24-hour simulation extended 1.5 miles (2.4 km) of the hypothetical release point, while the maximal extent of oil was approximately 2.0 miles (3.2 km) (Figure 6-98). The downstream extent is further in this scenario than for those at Palisade due to the higher river velocity, which transported oil more rapidly as it rose through the water column. In addition the water column is deeper at this release point, relative to Palisade. However, the extent was smaller than that of the CLWB, due to the lower density and more rapid rise rate through the water column, before sticking to the underside of the ice. Under low river flow conditions the 100% surface coverage of ice kept the entrained oil in the water column at the ice/water interface (97.4%) (Figure 6-95 and Figure 6-99). Extremely patchy oiling along river banks was observed downstream from the release point, with concentrations on the shoreline less than 1 g/m^2 (Figure 6-101). Extremely small amounts of oil may be found on the sediments, with most concentrations falling less than 0.01 g/m^2.

Large portions of the soluble portion of the Bakken dissolved into the water column and was transported downstream, resulting in elevated dissolved aromatic concentrations within the water column (Figure 6-100). Dissolved aromatic components traveled downstream from the initial spill location with maximum concentrations greater than 5,000 ppb directly under the oil trapped under the ice. Much larger portions of the river are predicted to experience dissolved aromatic concentrations in excess of 5,000 ppb, when compared to average or low flow scenarios.

At the end of the 24-hour simulation, floating oil under the ice had a thickness greater than 1 mm thick (heavy black oil) (Figure 6-99). There was no floating surface oil less than 0.1 mm thick (black oil). Small amounts of sediment oiling did extend dowstream, although the total hydrocarbon concentrations on the sediment were generally less than 0.01 g/m^2 due to the small amount of SPM in the water column.

There was very little decay from any of the three hypothetical releases within the timeframe modeled (Table 6-5).

6.2.2.2.1 Trajectory and Fate Results for High Flow (Spring)

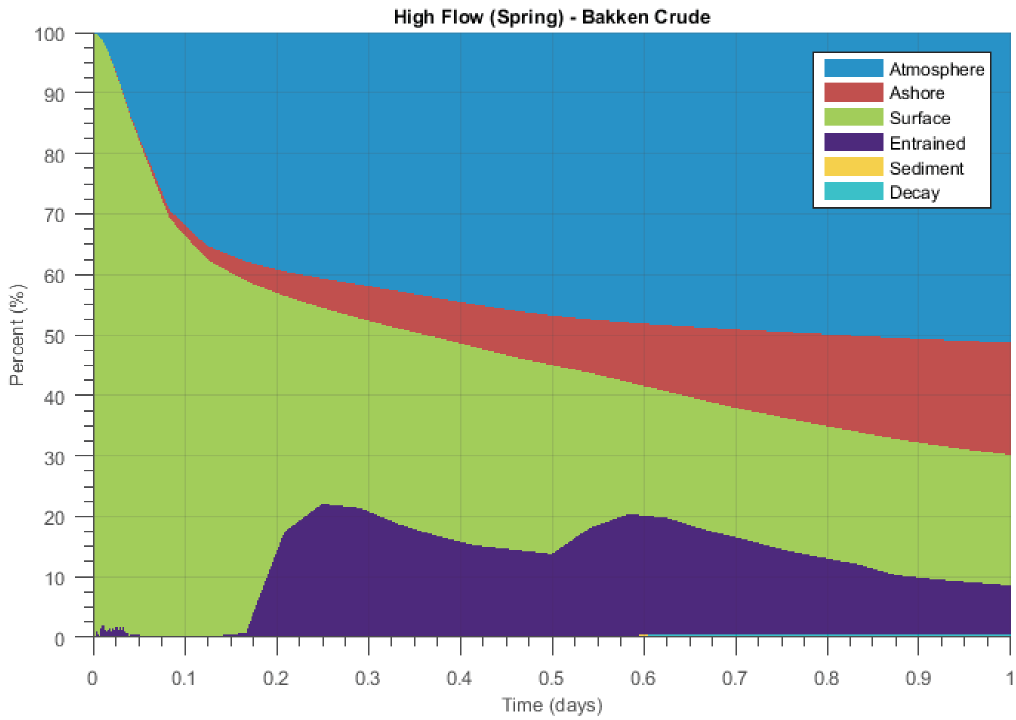

Figure 6-81 Oil Mass Balance Graph for the release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

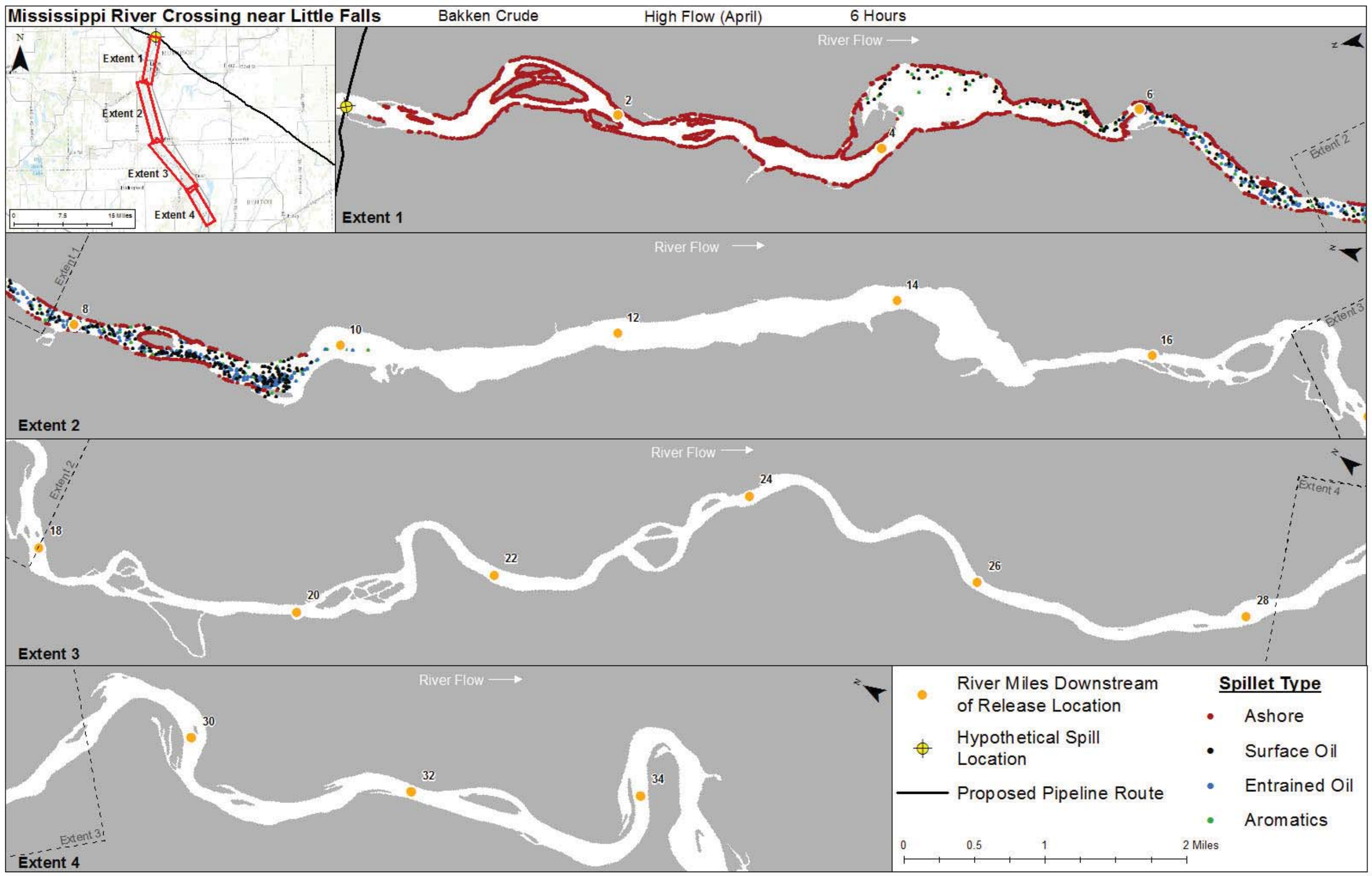

Figure 6-82 Oil Trajectory at 6 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

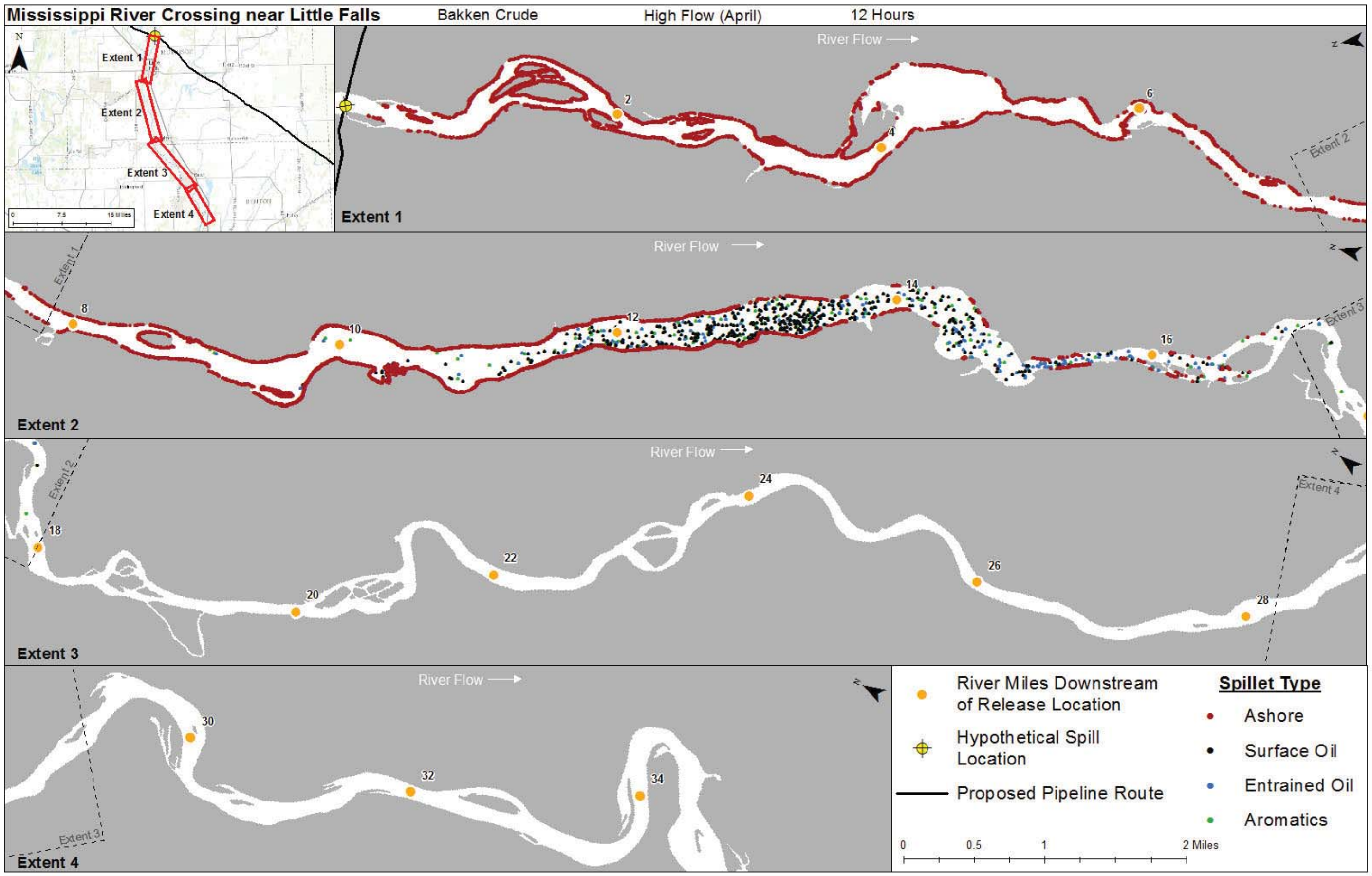

Figure 6-83 Oil Trajectory at 12 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

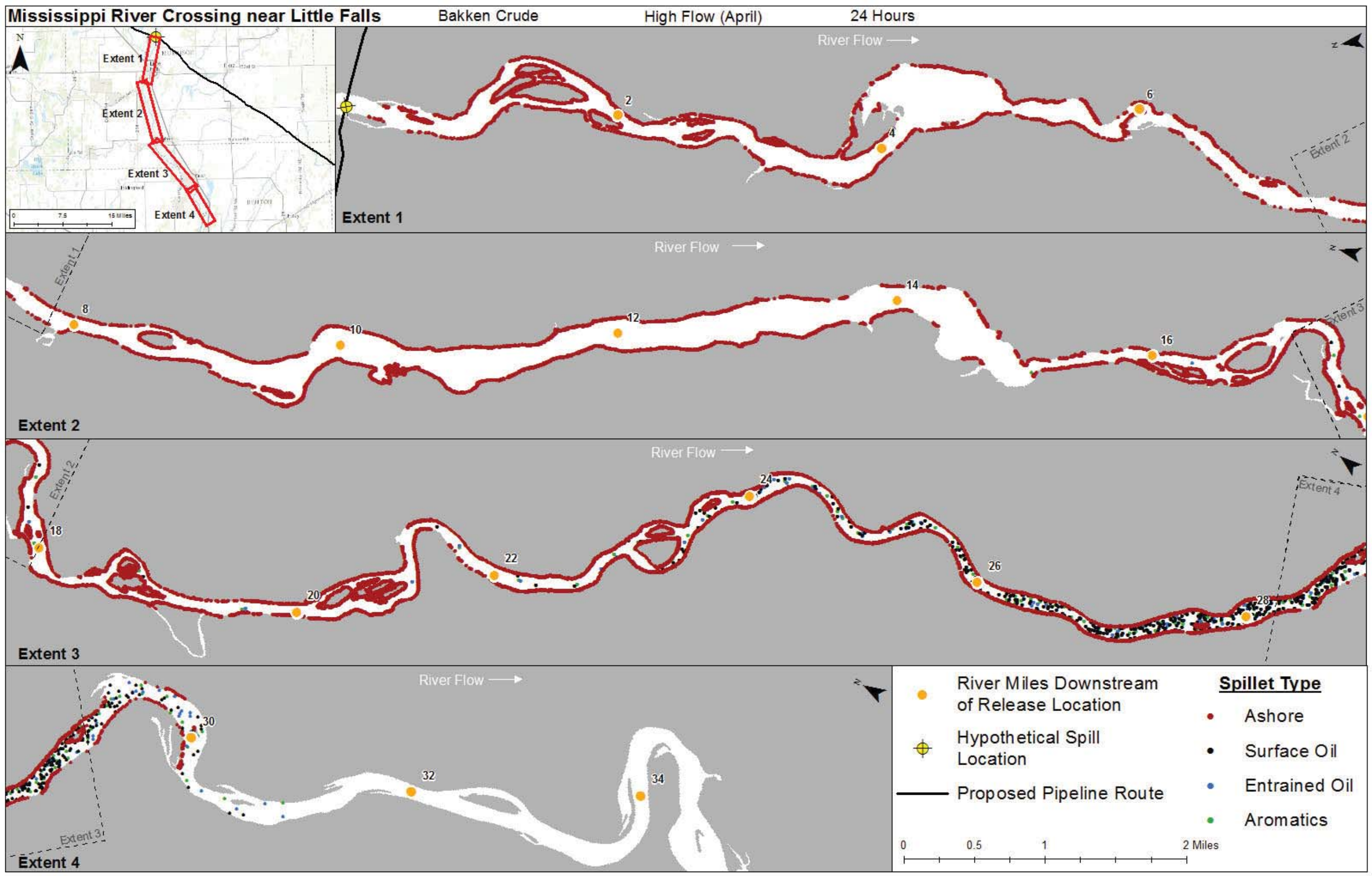

Figure 6-84 Oil Trajectory at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

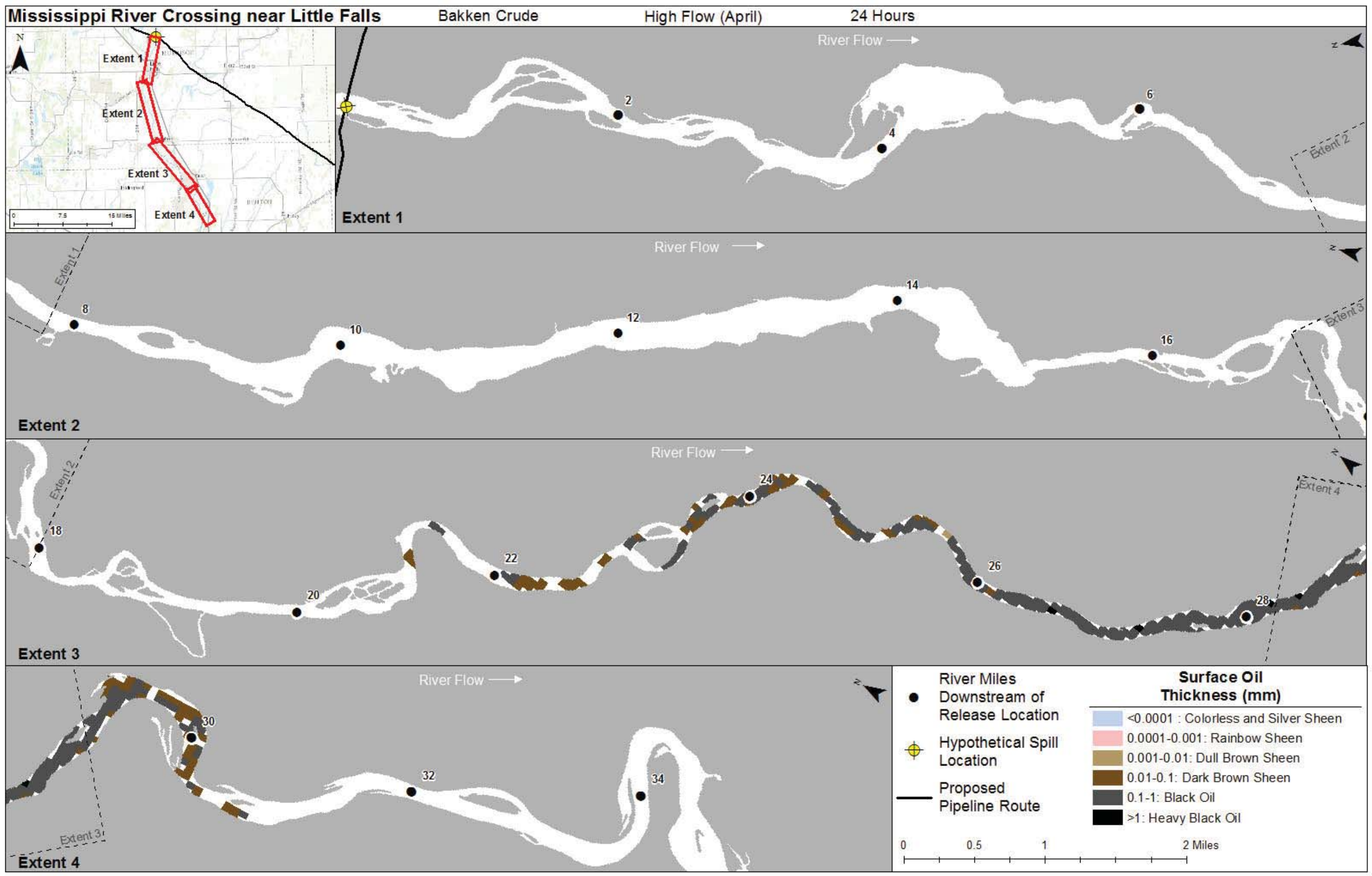

Figure 6-85 Maximum Floating Surface Oil at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location during the High Flow (Spring) Season

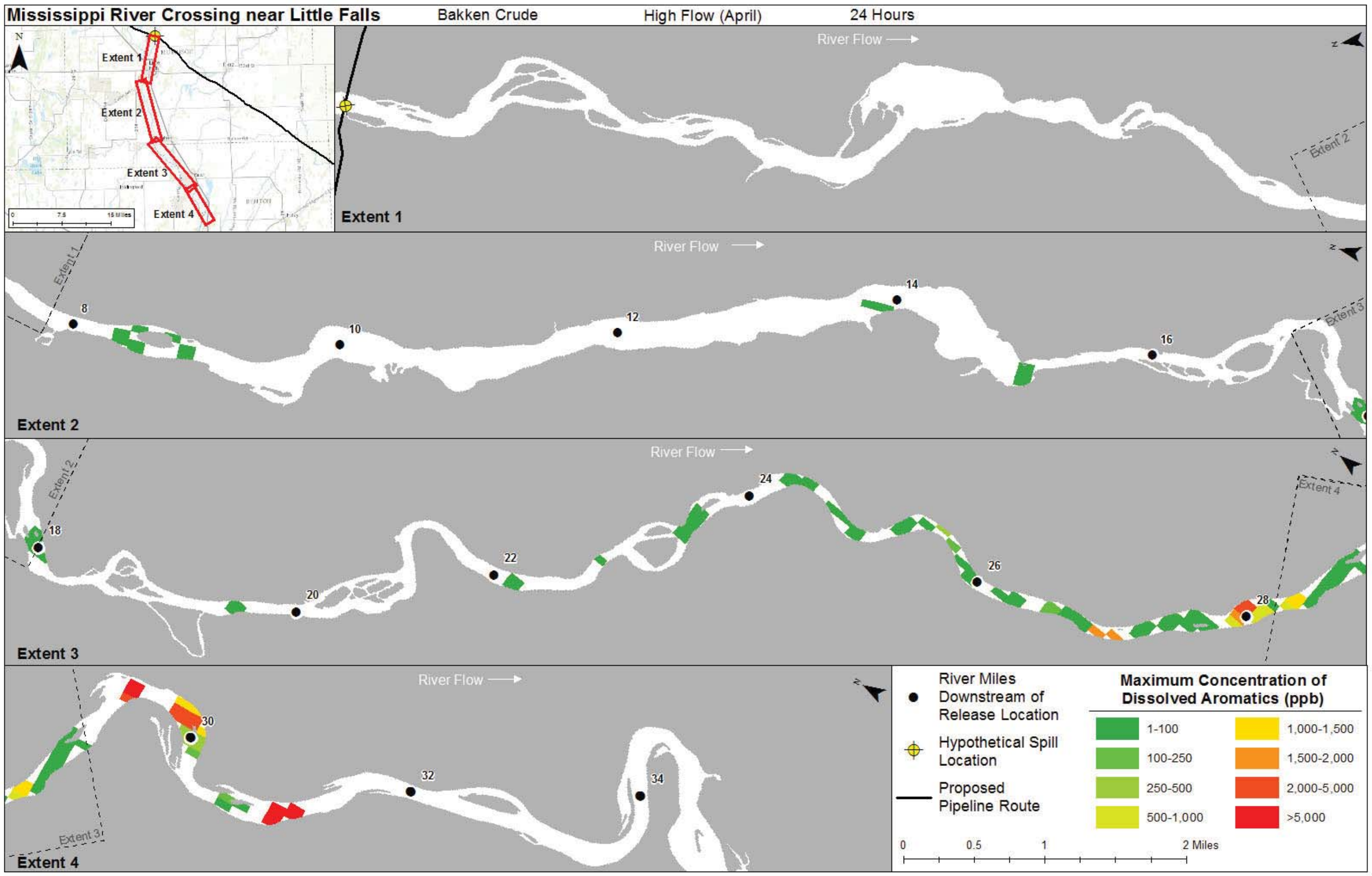

Figure 6-86 Maximum Total Dissolved Aromatic Concentration at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

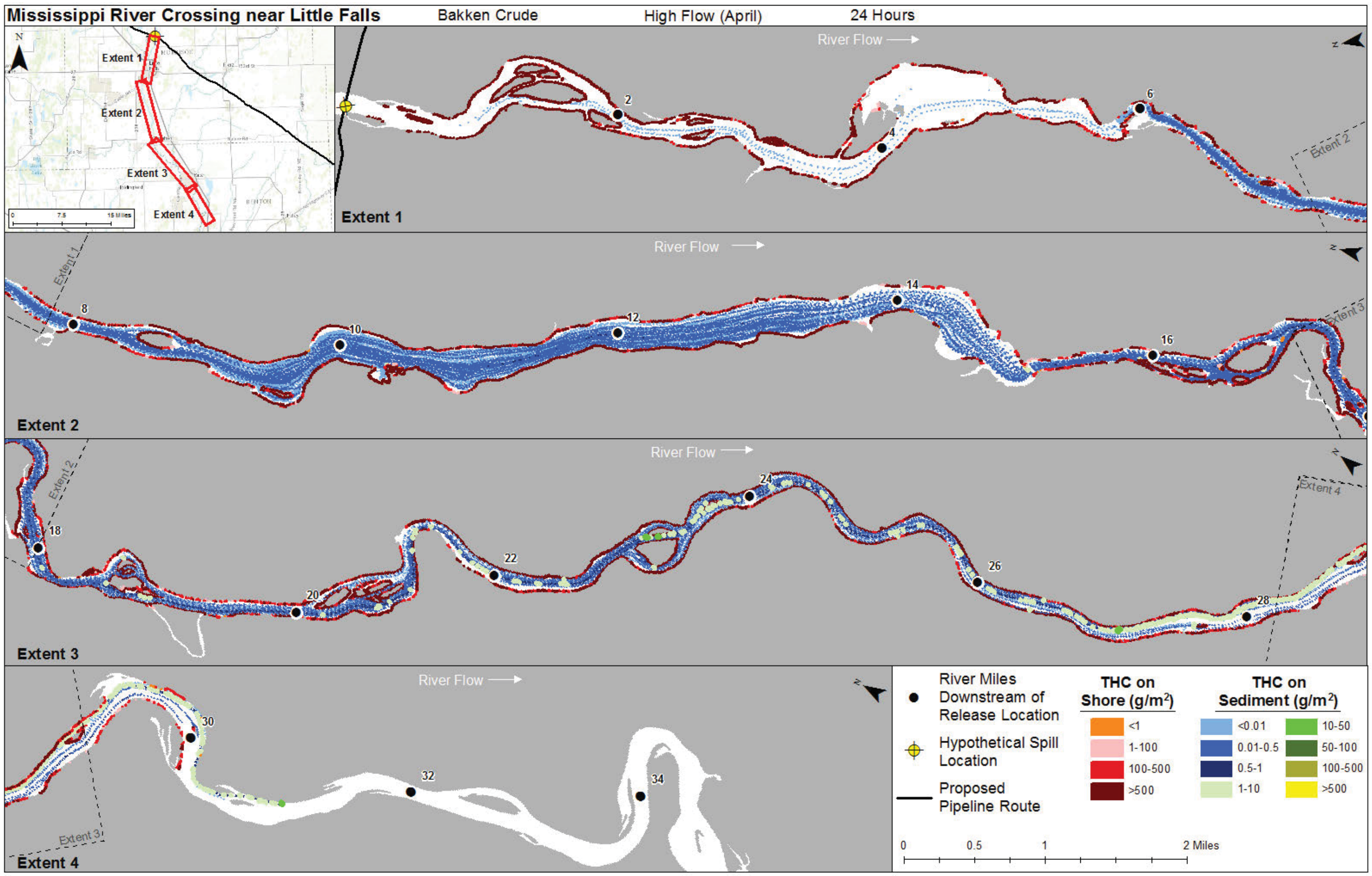

Figure 6-87 Maximum Total Hydrocarbon Mass on the Shore and on Sediments at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the High Flow (Spring) Season

6.2.2.2.2 Trajectory and Fate Results for Average Flow (Summer-Fall)

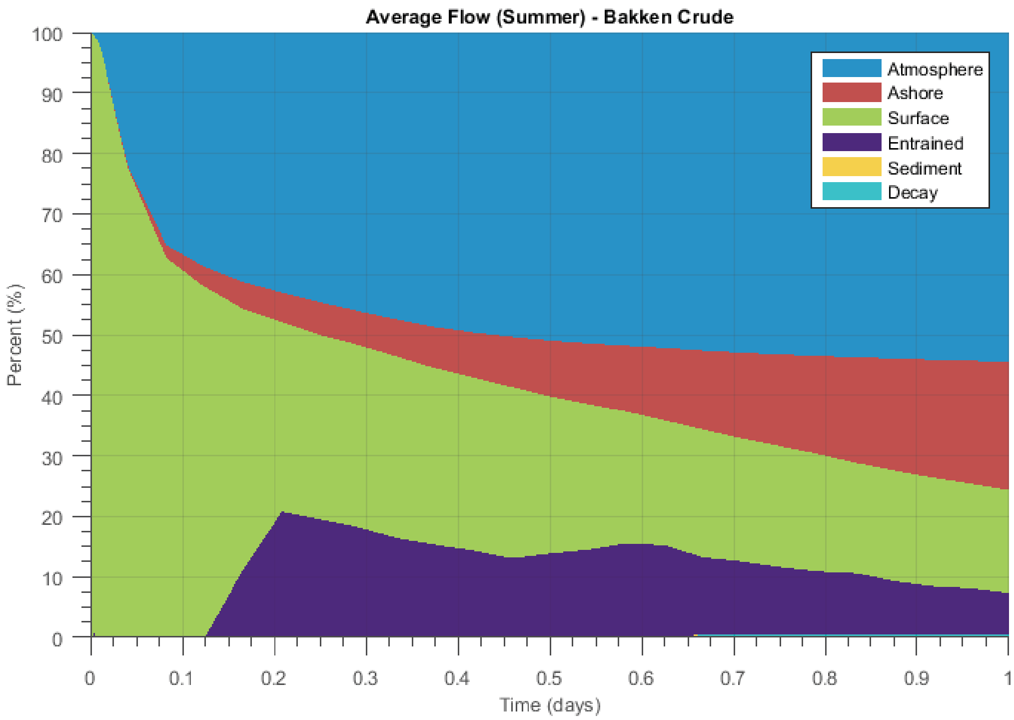

Figure 6-88 Oil Mass Balance Graph for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

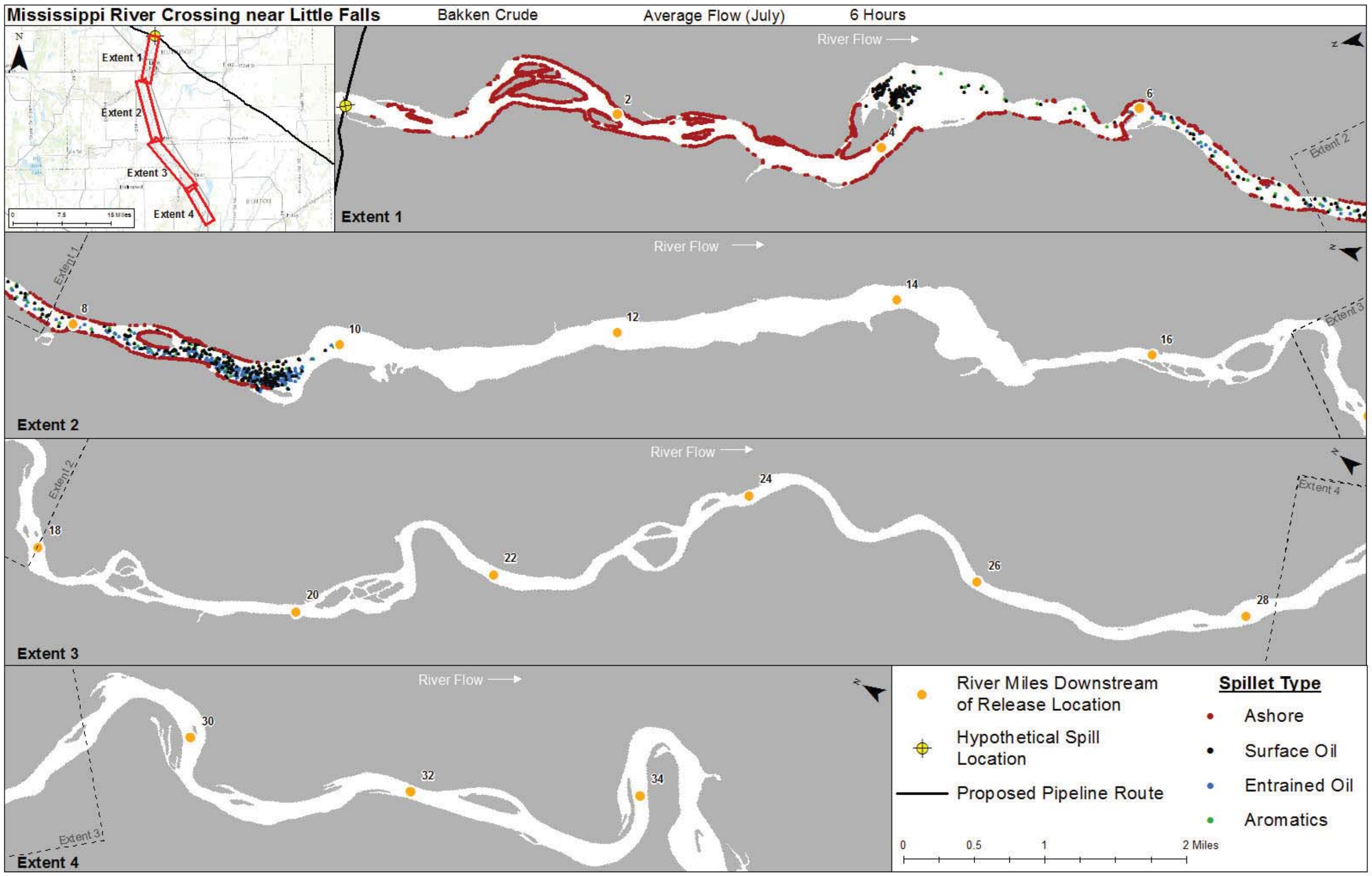

Figure 6-89 Oil Trajectory at 6 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

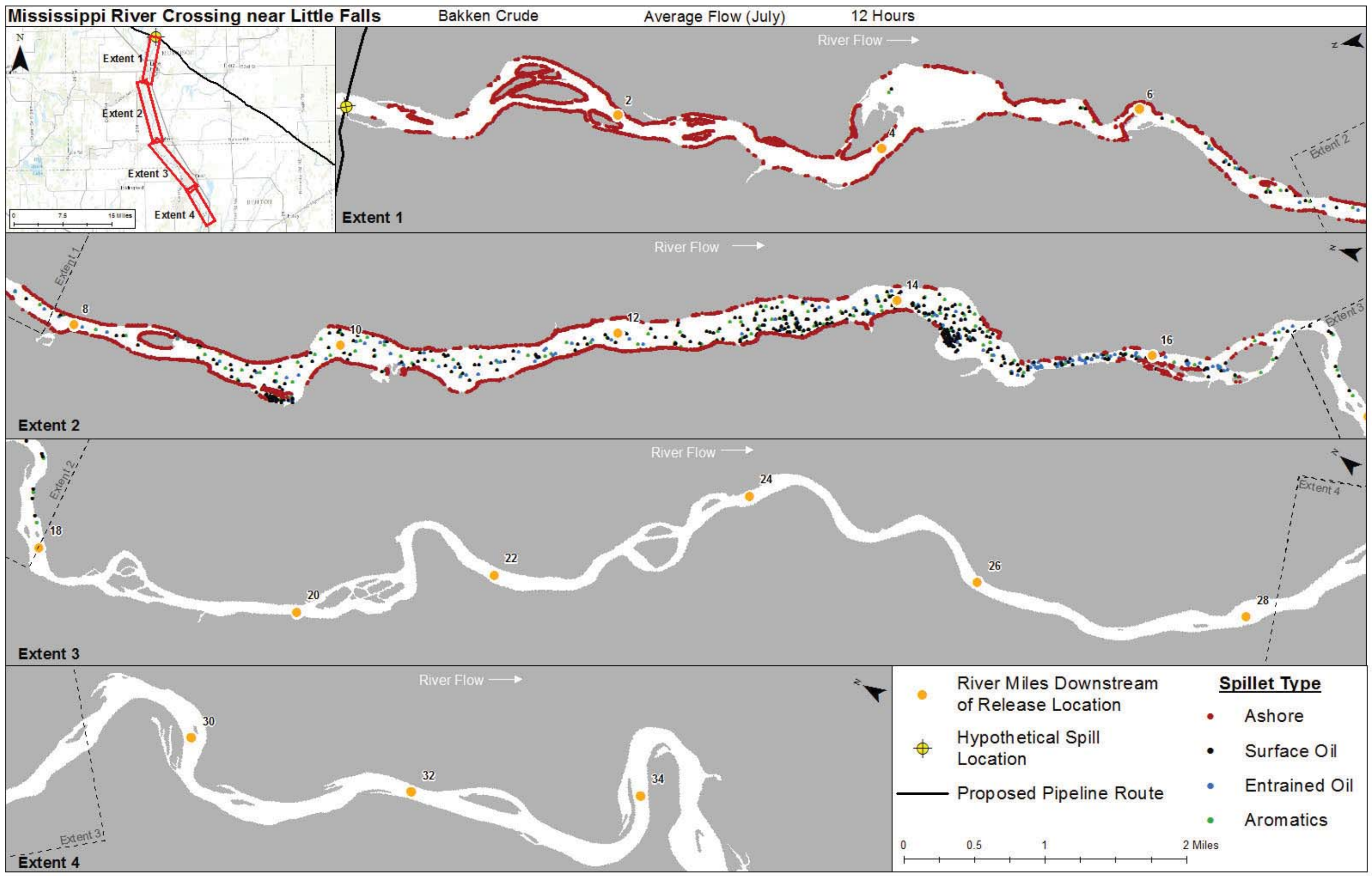

Figure 6-90 Oil Trajectory at 12 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

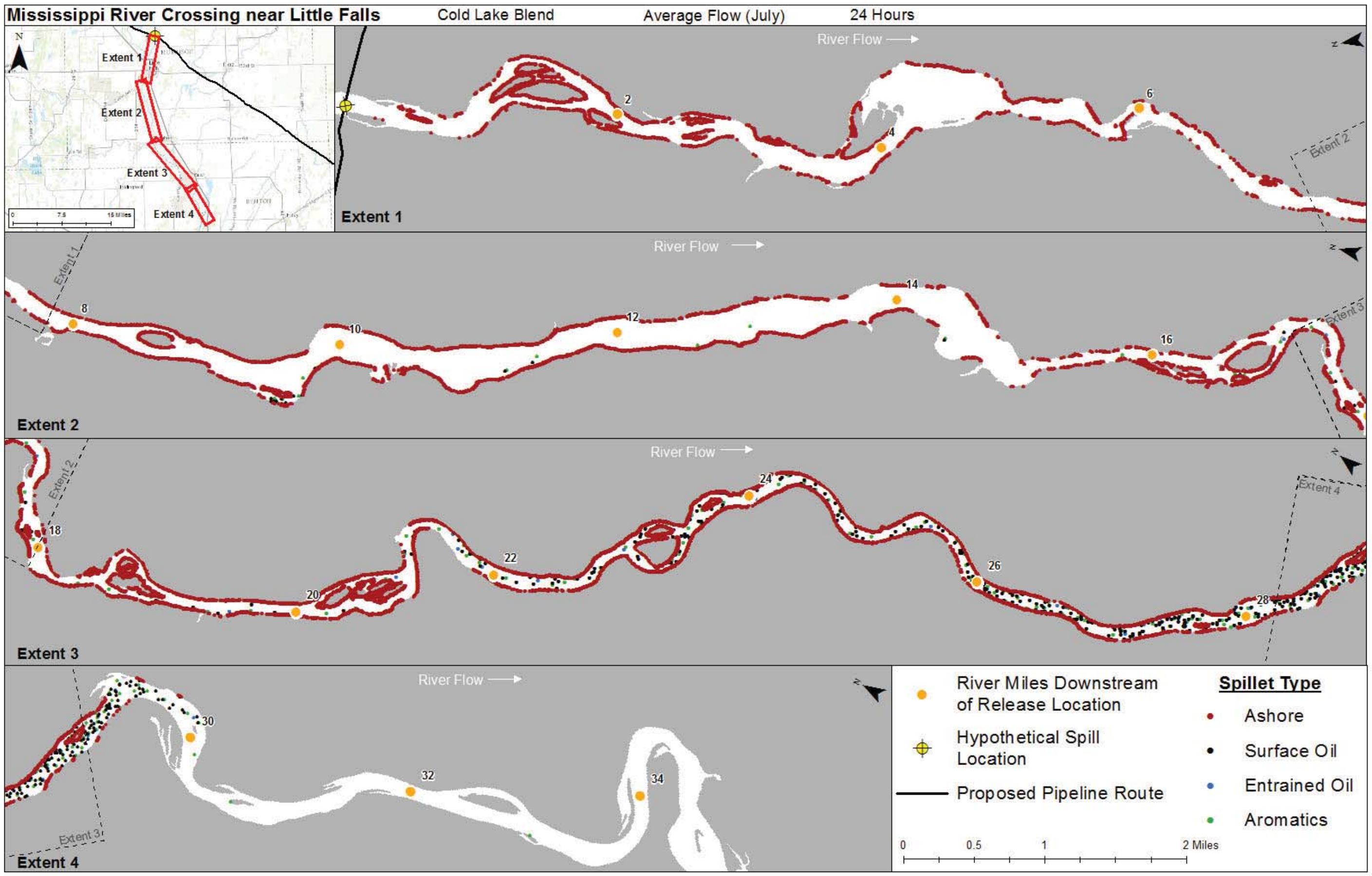

Figure 6-91 Oil trajectory at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

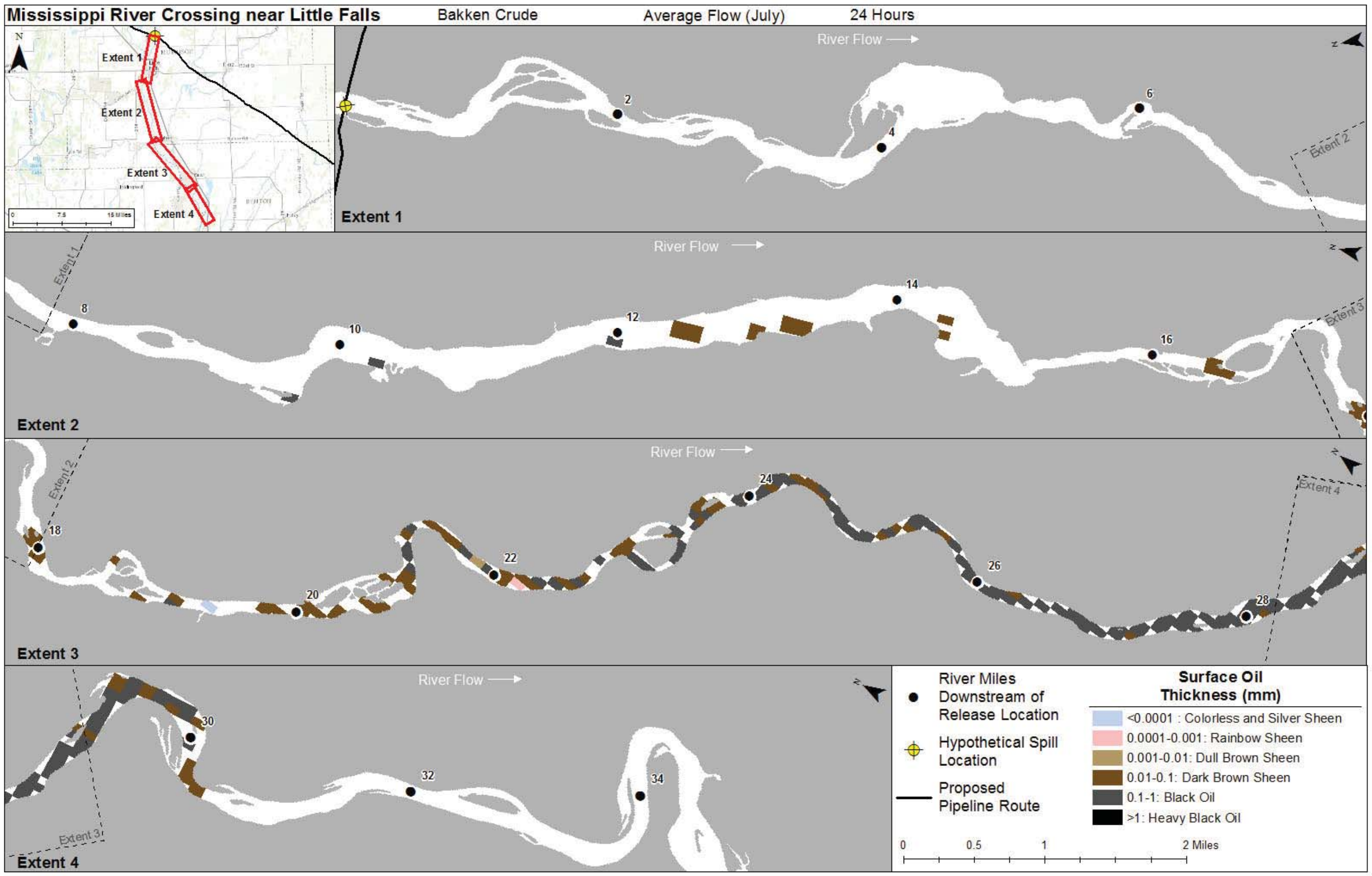

Figure 6-92 Maximum Floating Surface Oil at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

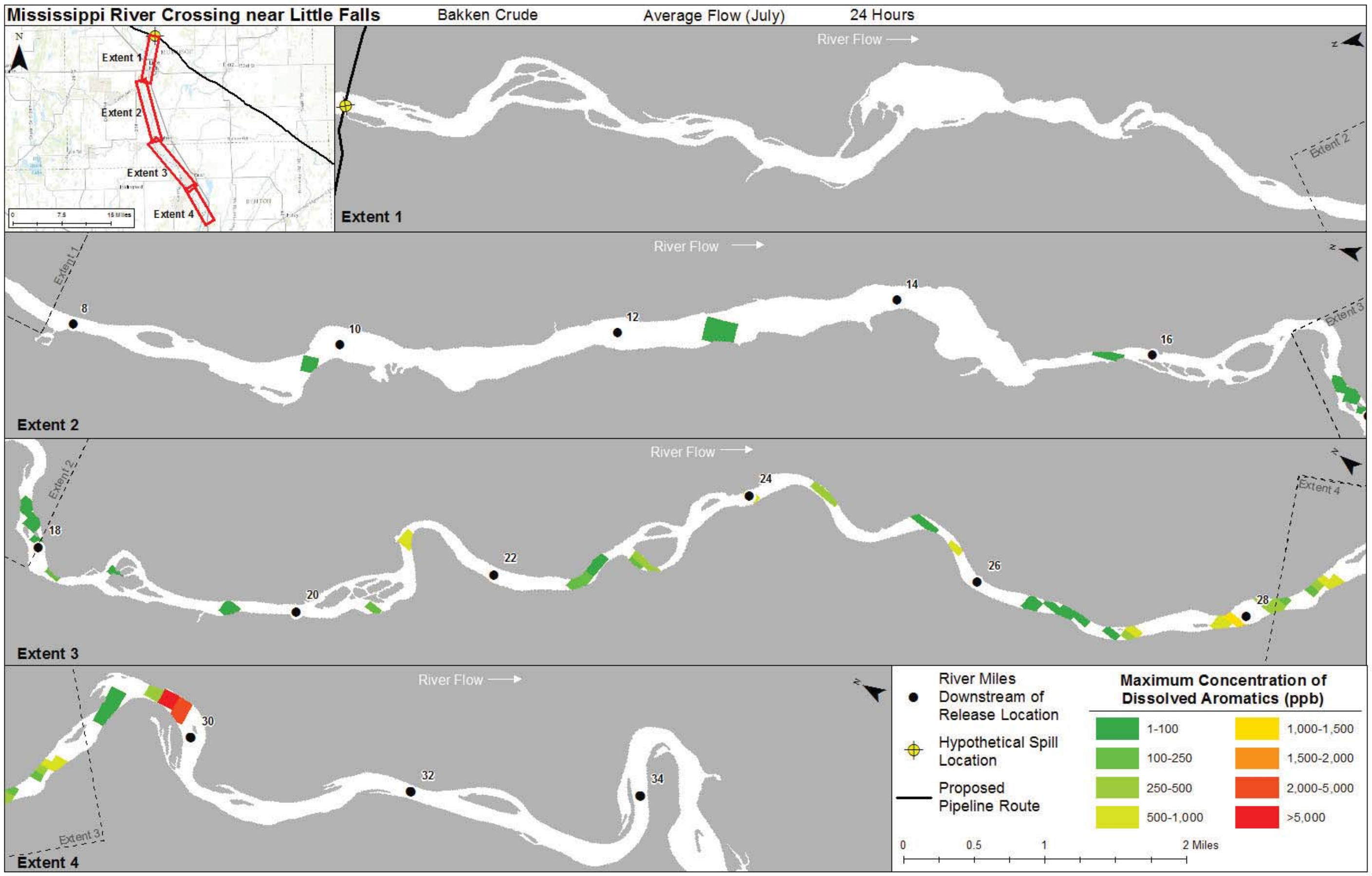

Figure 6-93 Maximum Total Dissolved Aromatic Concentration at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

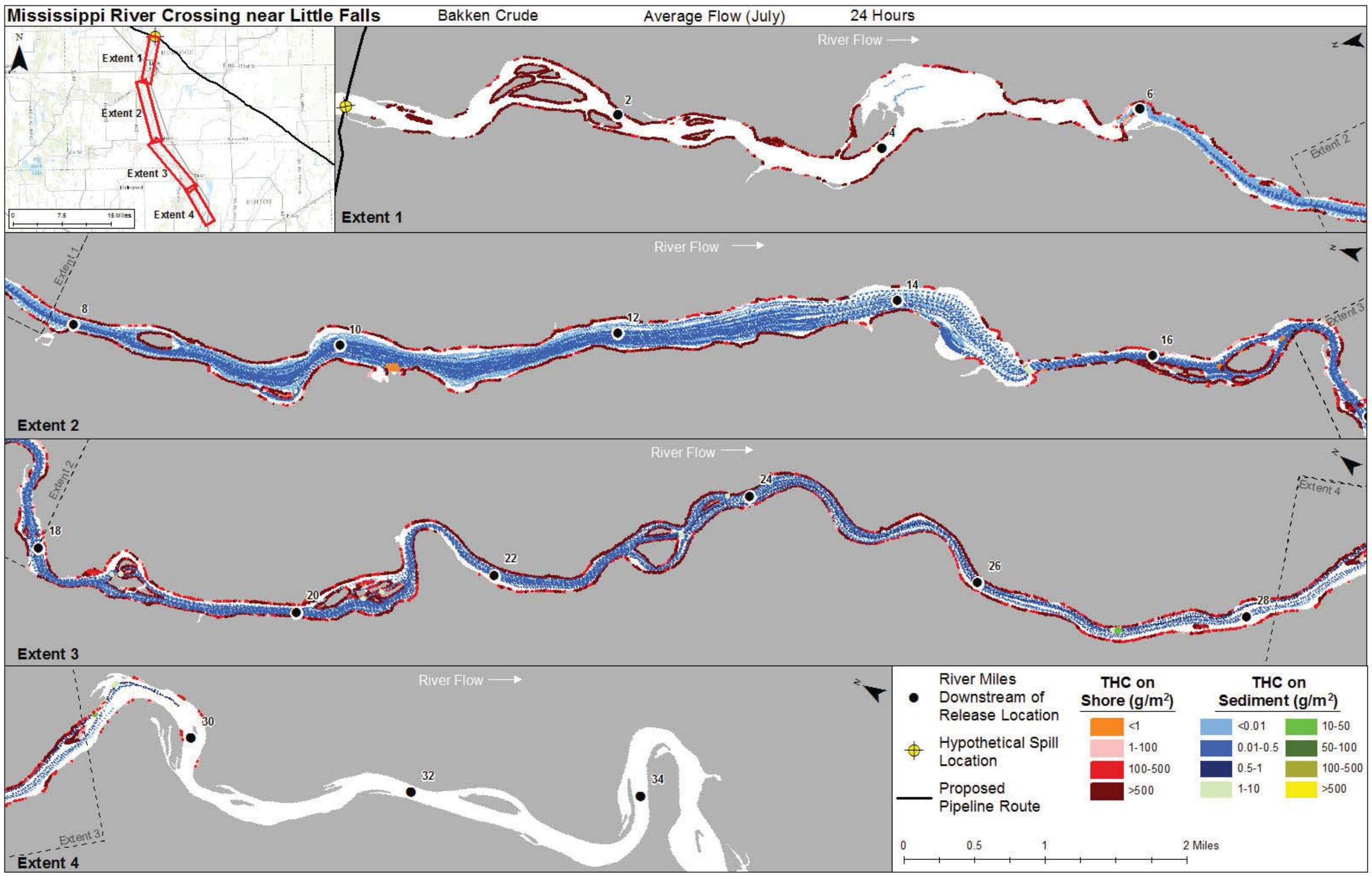

Figure 6-94 Maximum Total Hydrocarbon Mass on the Shore and on Sediments at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Average Flow (Summer-Fall) Season

6.2.2.2.3 Trajectory and Fate Results for Low Flow (Winter)

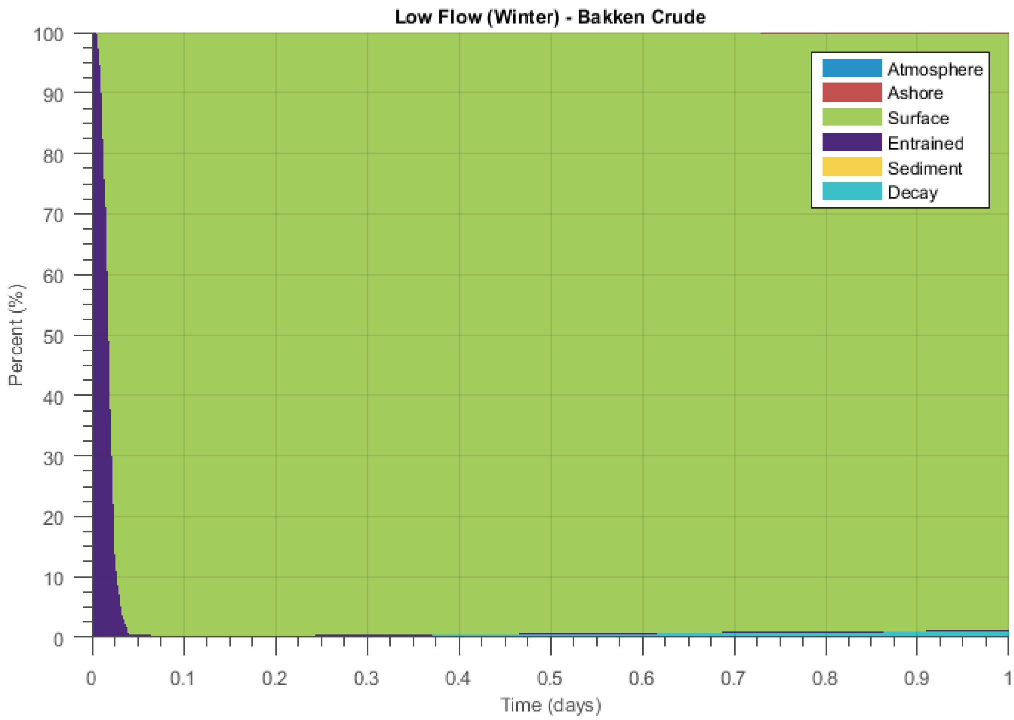

Figure 6-95 Oil Mass Balance Graph for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

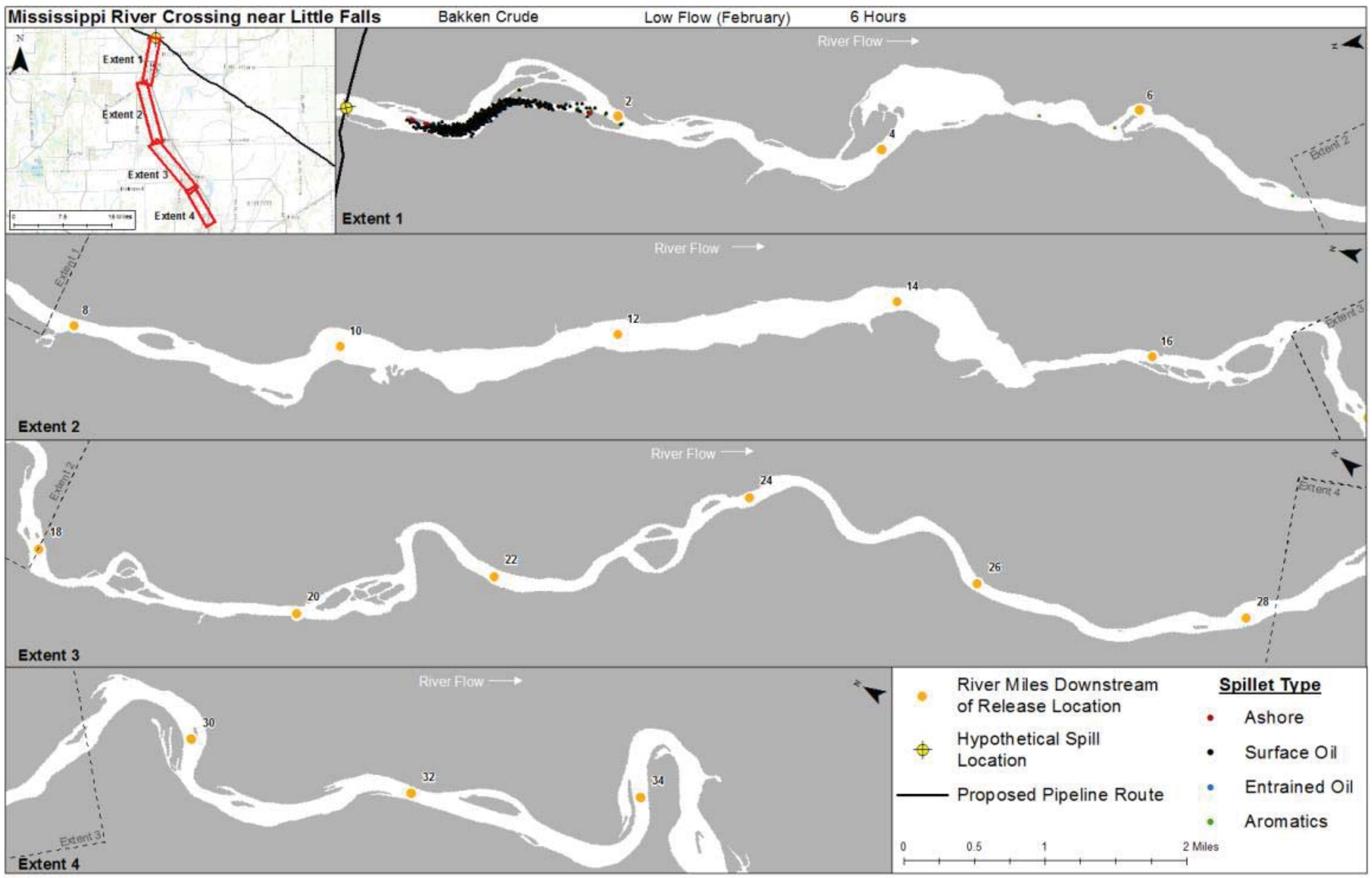

Figure 6-96 Oil Trajectory at 6 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

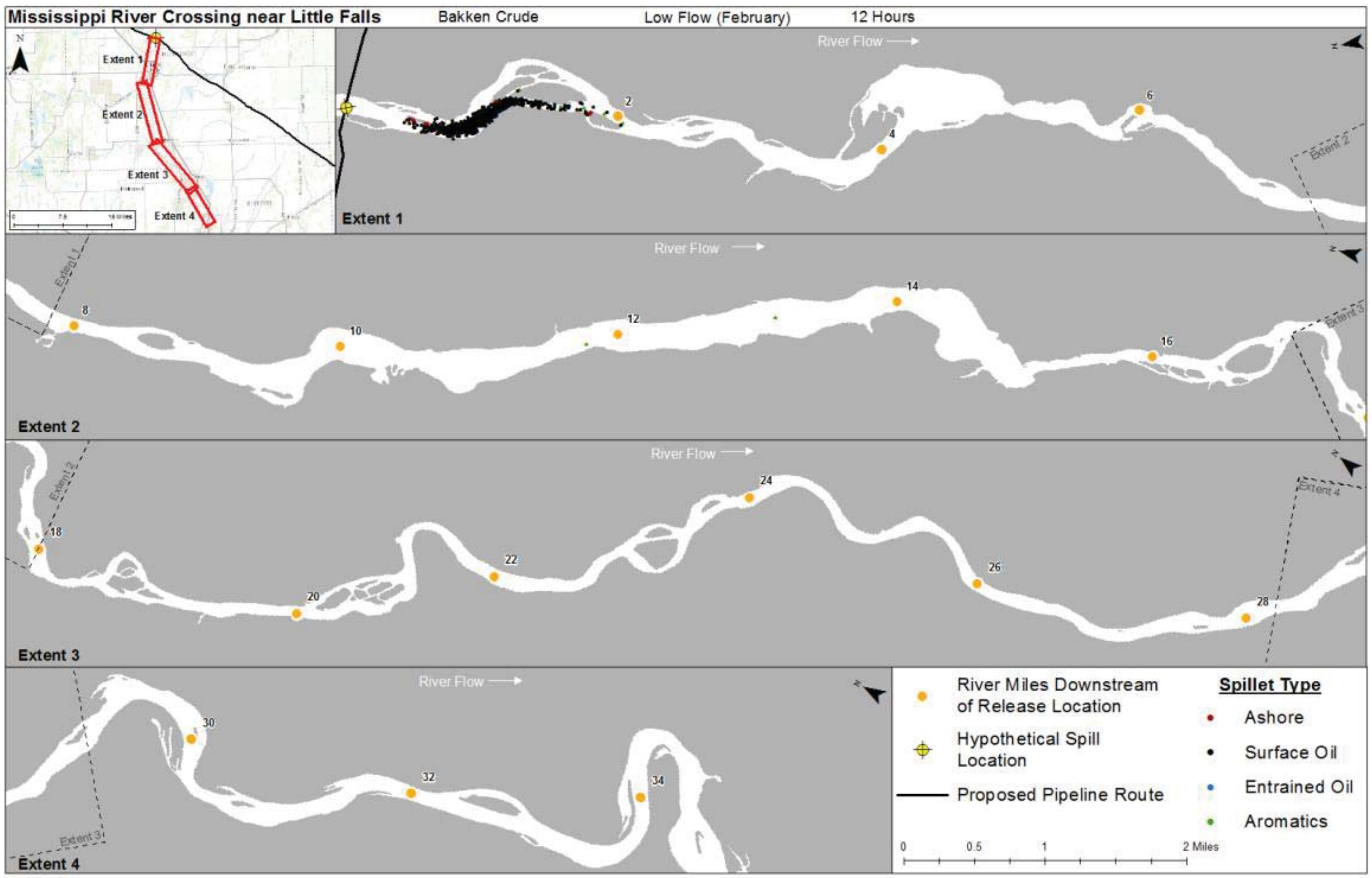

Figure 6-97 Oil Trajectory at 12 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

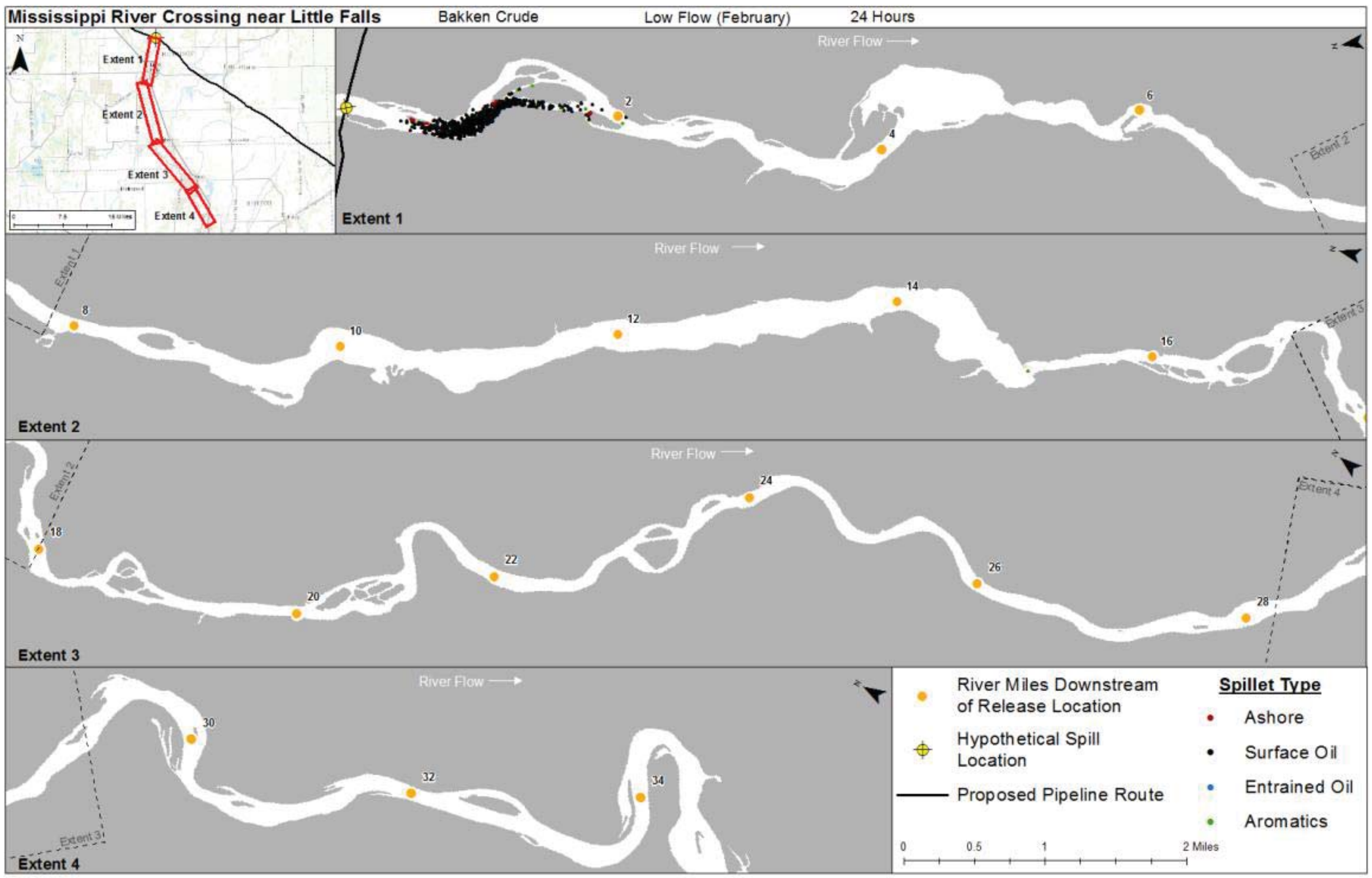

Figure 6-98 Oil Trajectory at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

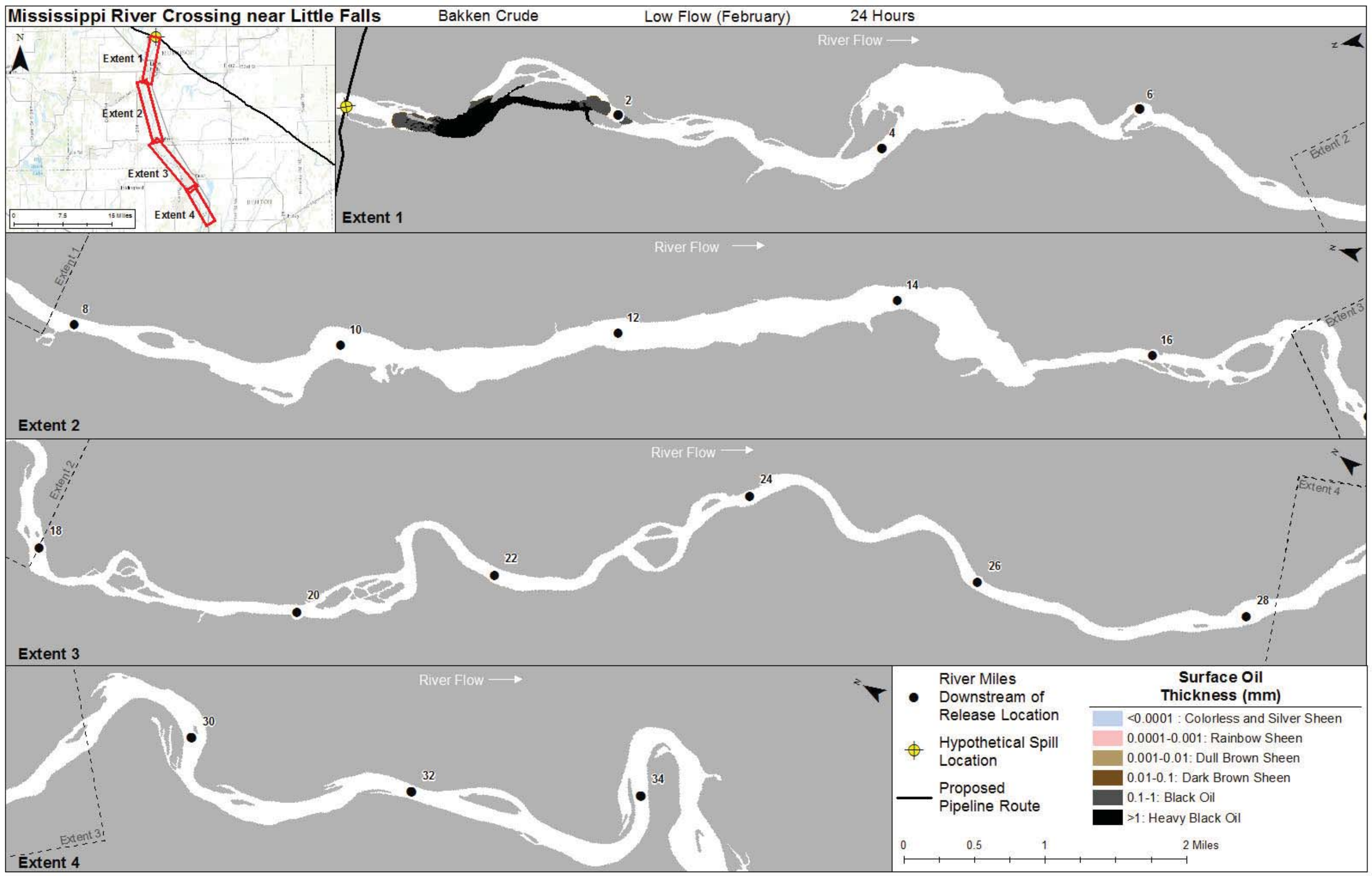

Figure 6-99 Maximum Floating Surface Oil at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

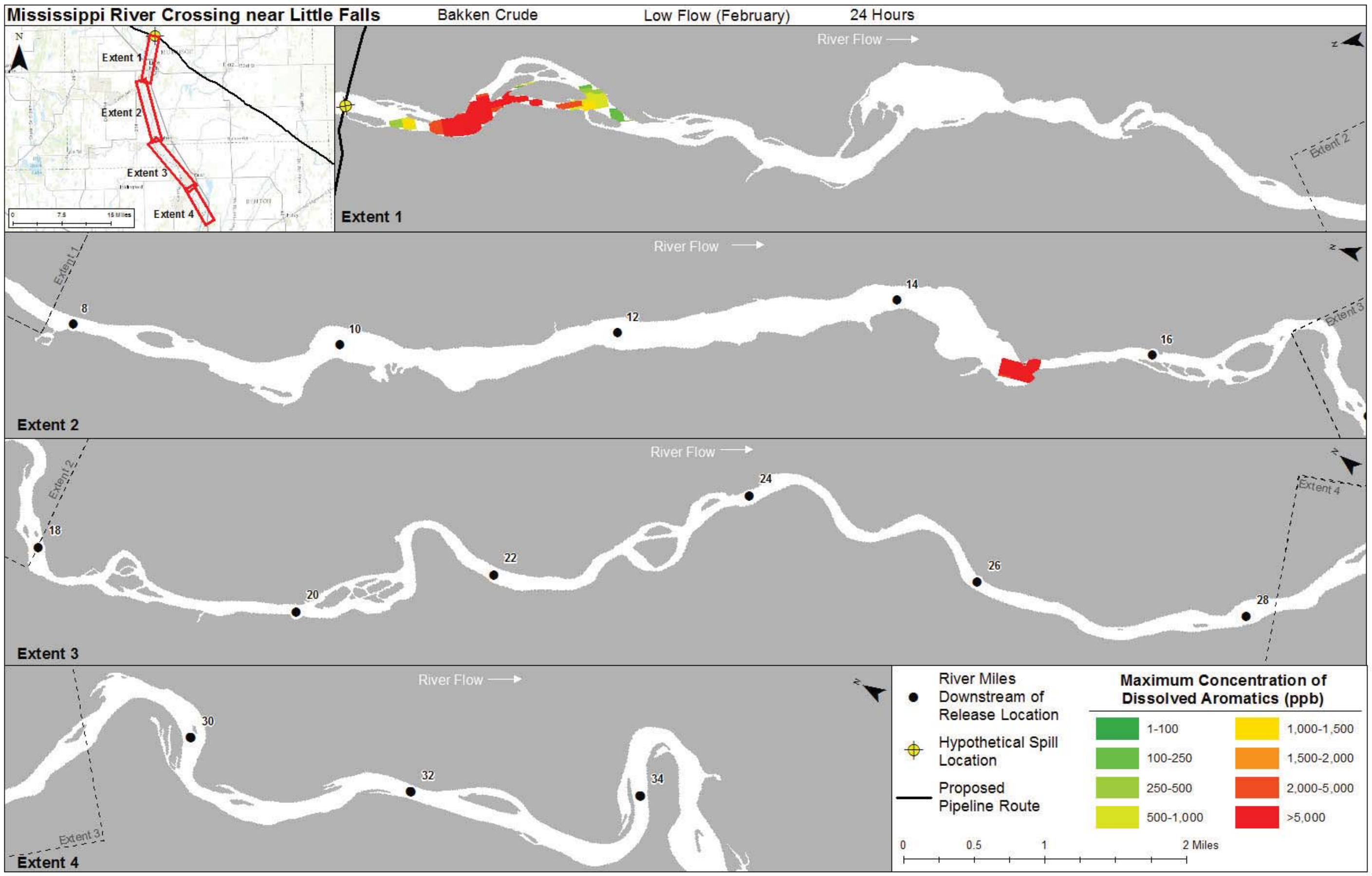

Figure 6-100 Maximum Total Dissolved Aromatic Concentration at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

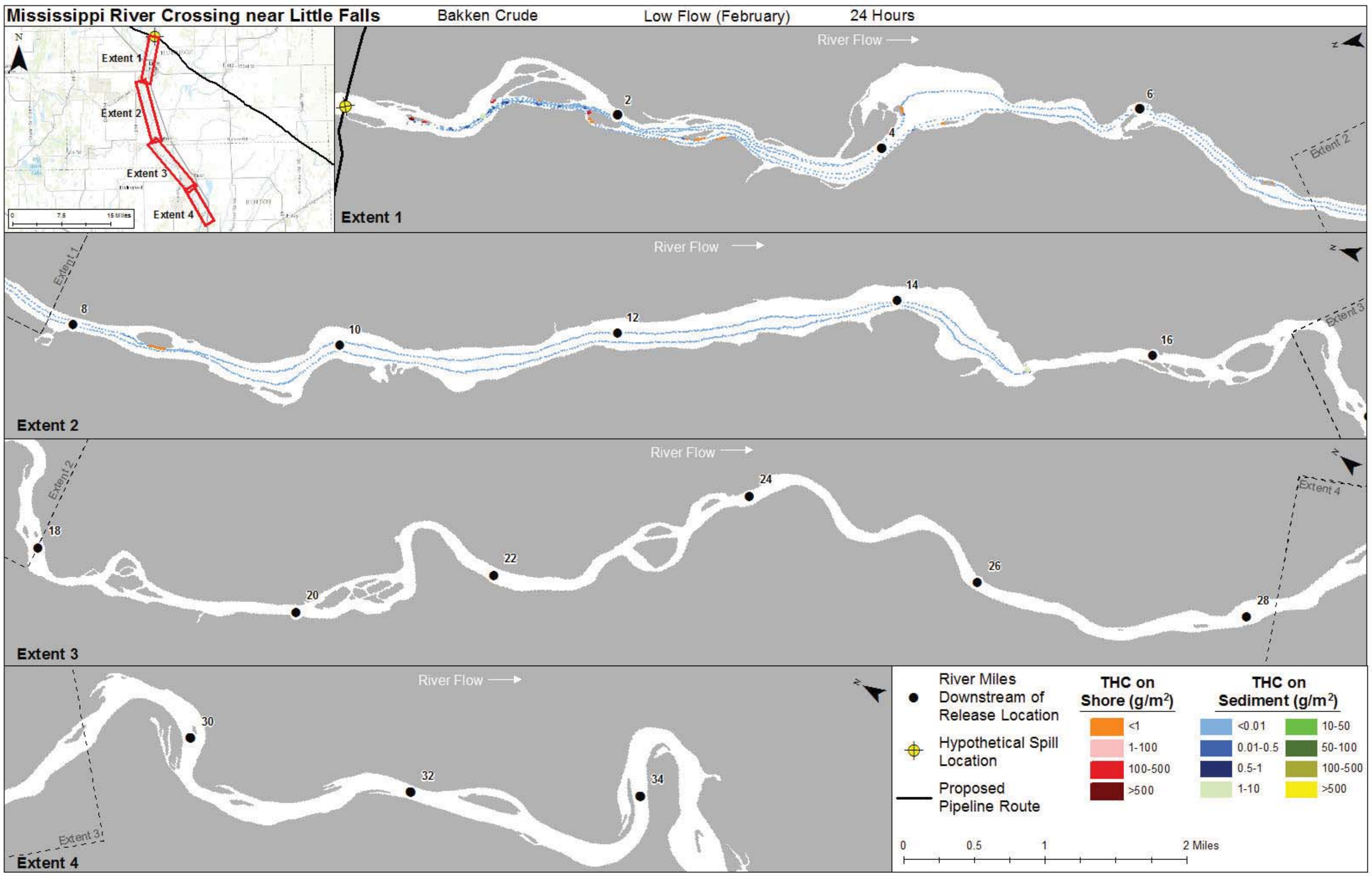

Figure 6-101 Maximum Total Hydrocarbon Mass on the Shore and on Sediments at 24 Hours for the Release of Bakken Crude at the Mississippi River at Little Falls Release Location During the Low Flow (Winter) Season

6.2.3 Summary of SIMAP Trajectory and Fate Results

In general, higher river flow resulted in further potential to oil regions downstream from the release location (Table 6-6). Modeled releases in the quiescent waters of the Mississippi River at Palisade resulted in large surface oil slicks, which resulted in large evaporative losses. Approximately 20% of the CLB and approximately 50% of the Bakken evaporated under high and average river flow conditions. Extensive shoreline oiling was also observed, with thicker shoreline oiling greater than 500 g/m^2 in CLSB scenarios, and 100–500 g/m^2 in Bakken release scenarios. Dissolved aromatic concentrations did exceed 5,000 ppb in both scenarios, due to dissolution of oil into the waters immediately below the surface slick. In general, dissolved aromatic concentrations were relatively patchy and generally lower than 100 ppb for both oil types. A small amount of sediment oiling (generally less than 0.01 g/m^2) was possible for releases at Palisade, with the highest potential under high flow conditions with larger concentrations of SPM within the water column. CLB had a higher potential to make its way to sediments, when compared to Bakken.

Table 6-6 Downstream Distance (miles) Maximum Oil Flow at the End of the Simulations

Location	Oil Type	Season / River Flow		
		Low	Average	High
Mosquito Creek	Bakken Crude	0.8	9.7	10.5
	Cold Lake Blend	0.8	3.5	3.5
Mississippi River at Ball Club (assumed grass shore type)	Bakken Crude	6.5 (6.5)	5.7 (15.9)	6.4 (23.0)
	Cold Lake Blend	1.3 (6.5)	1.3 (8.0)	1.3 (8.1)
Sandy River	Bakken Crude	6.0	9.1	12.2
	Cold Lake Blend	6.0	7.8	8.1
Shell River to Twin Lakes	Bakken Crude	1.5	13.9	21.9
	Cold Lake Blend	0.8	3.7	3.7
Red River	Bakken Crude	16.0	22.8	40.3
	Cold Lake Blend	16.0	19.2	10.5
Mississippi River at Palisade	Bakken Crude	0.6	14.3	17.8
	Cold Lake Blend	2.4	14.0	17.9
Mississippi River at Little Falls	Bakken Crude	2.1	31.2	31.0
	Cold Lake Blend	5.6	29.9	32.3

Modeled releases in the more turbulent waters of the Mississippi River at Little Falls still had large surface oil slicks, which resulted in large evaporative losses. Similar to the Palisades scenarios, under high and average river flow rates, approximately 20% of the CLB and approximately 50% of the Bakken evaporated. Extensive shoreline oiling was also observed, with thicker shoreline oiling greater than 500 g/m^2 in CLSB scenarios, and 100–500 g/m^2 in Bakken release scenarios. Dissolved aromatic concentrations did exceed 5,000 ppb in both scenarios, due to dissolution of oil into the waters immediately below the surface slick. In general, dissolved aromatic concentrations were relatively patchy and generally lower than 100 ppb for both oil types. The presence of the Little Falls Dam and Blanchard Dam resulted in large amounts of oil being entrained into the water column at the waterfalls and sections of rapids. Hydrocarbon concentrations within the water column were typically much higher after the dams, with greater than 25 ppm for THC and 250-500 ppb for dissolved aromatics. In the quiescent waters downstream, the oil resurfaced and once again formed surface slicks.

Due to the large amount of vertical mixing and the presence of suspended sediments, particularly under high flow conditions, there was a substantially higher potential for more extensive sediment oiling at Little Falls. Higher THC concentrations on sediments were predicted for CLB and mass balance results indicate that a larger portion of the total amount released was predicted to settle on the bottom after 24 hours, when compared to the Bakken scenarios. Maximum concentrations of 50 g/m^2 were predicted for Bakken, while some areas exceeded 500 g/m^2 for CLB.

For both oil types, the localized and patchy nature of sediment oiling is difficult to predict. Results are therefore helpful in indicating the potential presence of the amount of oil, rather than the exact location where it may be found, which is dynamic in time. Due to the lower viscosity of Bakken, the entrainment of oil, and ultimate oil-SPM interactions, lower level contamination (i.e., lower THC concentrations) of sediments was predicted to take place over a much larger area, when compared to the CLB. On the other hand, larger amounts of CLB were predicted to settle on the bottom, but over a much smaller areal extent, with localized patches. In all cases, it is important to note that less than 1% of the total amount of released oil (for both CLB and Bakken) was predicted to settle. In each case, the majority of the oil was predicted to oil shorelines and evaporate to the atmosphere.

Under low flow river conditions, with 100% ice coverage, the oil was predicted to rise within the first few miles downstream of the release location. The distance downstream that the oil was transported was mainly controlled by the river velocity and the density of the oils, which controlled its rise rate before reaching the ice at the surface. In general, CLB was predicted to oil slightly more areas of ice, while the Bakken was predicted to be more contained. A large portion of the soluble portion of both oils dissolved into the water column where it was transported downstream. Much larger portions of river were predicted to experience dissolved aromatic concentrations in excess of 5,000 ppb during low flow conditions with complete ice cover, when compared to average or low flow scenarios. Very limited shoreline and sediment oiling occurred in the winter scenarios, when compared to the ice free scenarios.

7.0 ASSESSMENT OF ENVIRONMENTAL EFFECTS OF OIL RELEASES

The assessment of environmental effects of crude oil releases begins with a description of the observed and expected effects of oil on key ecological and human receptors, including how oil behaves (i.e., its fate) in terrestrial, atmospheric and freshwater environments, and how it affects associated biological resources (Section 7.1). Information in this section is informed by a number of case studies with circumstances similar to those that might be encountered in the event of an oil release from a pipeline in Minnesota. This is followed (Section 7.2) by an assessment for each of the seven modeled sites in Minnesota that were determined to be representative of most of the predominant ecological units, major hydrological features, watercourse widths, and watercourse features along the preferred and alternative routes:

- Site 1—Mosquito Creek to Lower Rice Lake (Section 7.2)
- Site 2—Mississippi River at Ball Club (Section 7.3)
- Site 3—Sandy River (Section 7.4)
- Site 4—Shell River to Twin Lakes (Section 7.5)
- Site 5—Red River (Section 7.6)
- Site 6—Mississippi River at Palisade (Section 7.7)
- Site 7—Mississippi River at Little Falls (Section 7.8)

The location of these seven sites and the spatial extent of the assessment of environmental effects are illustrated on Figure 7-1.

The assessment of each site includes a description of the environmental setting at and downstream of the hypothetical release location, and a detailed discussion of the expected environmental effects of an oil release (based on two crude oil types that provide bounding cases for oils that range from light (e.g., Bakken crude oil having low viscosity and density) to heavy (CLB/CLWB)) on the physical, biological and human environments; namely:

- Terrestrial receptors (i.e., soil, groundwater, terrestrial, vegetation)
- Aquatic receptors (i.e., rivers, lakes, sediment, shorelines and riparian areas, wetlands, aquatic plants, benthic invertebrates, fish)
- Semi-aquatic wildlife receptors (i.e., amphibians and reptiles, birds, semi-aquatic mammals)
- Human and socio-economic receptors (i.e., air quality, human receptors, public use of natural resources)

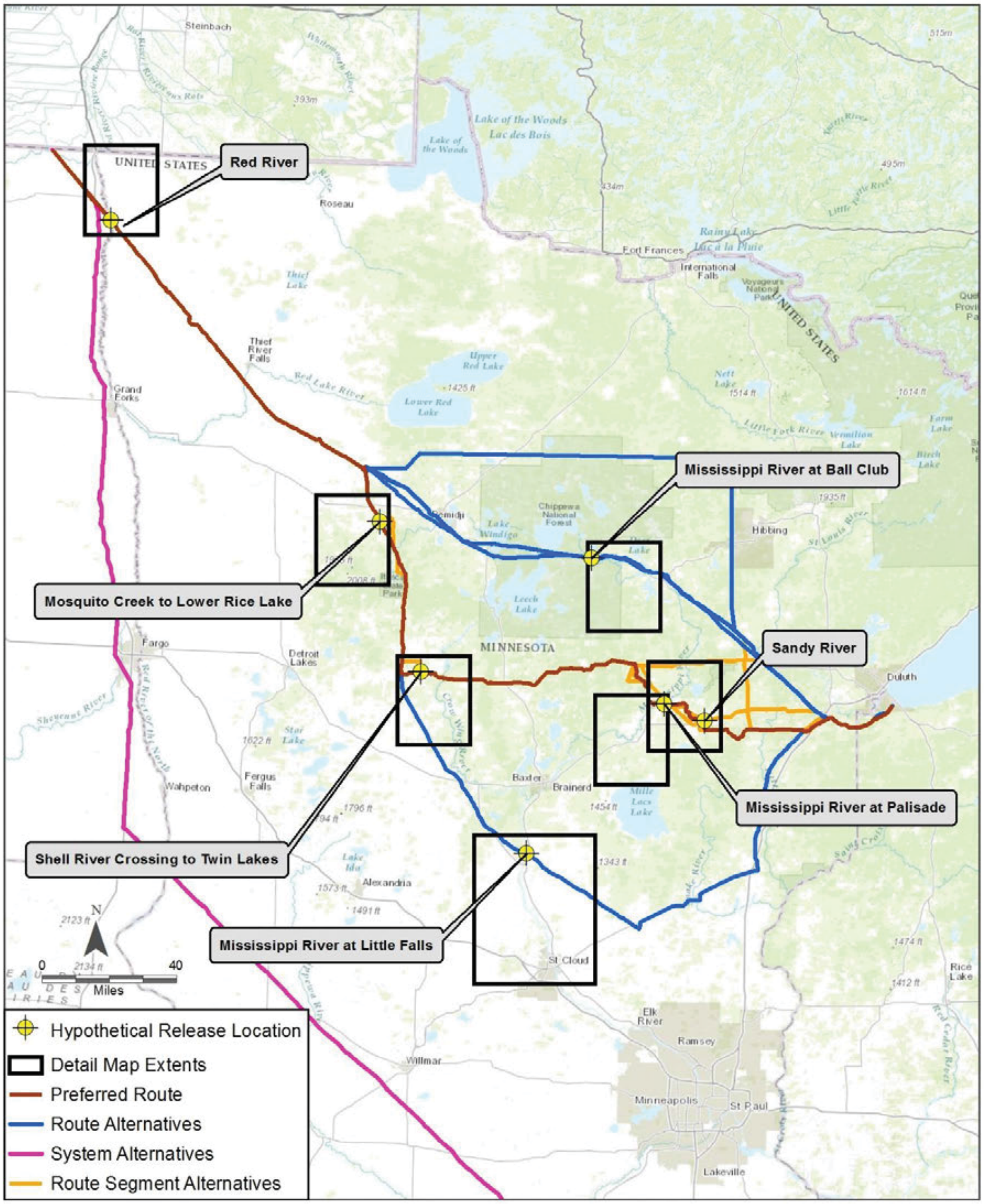

Figure 7-1 Locations of Hypothetical Release Sites and Spatial Extent of the Assessment of Environmental Effects

In addition, the potential overlap of oil releases with federally-designated (i.e., U.S. Department of Transportation [USDOT] PHMSA) HCAs and other sensitive locations not included in the USDOT PHMSA data (defined as AOIs) is included. HCAs include populated areas, unusually sensitive ecological areas, drinking water sources and commercially navigable waterways. Populated areas are broken down as high population areas (i.e., urban areas), and "other populated areas," which consist of smaller towns and villages. Ecologically-sensitive areas include imperiled species and ecological communities, threatened and endangered species, depleted marine mammals, and migratory water bird concentrations (USDOT PHMSA 2016a). The drinking water data consist of public water systems, source water protection areas, and sole source aquifers (USDOT PHMSA 2016b). Sources of these data for the environmental effects assessment are shown in Table 7-1.

Table 7-1 Sources of HCA Data

HCA Type	HCA Subtype	Source
Population Area	Other	USDOT PHMSA, 2011; 2016a; 2016b
	Other	Provided by Enbridge in 2014
	High Population	USDOT PHMSA, 2011; 2016a; 2016b
Environmentally Sensitive Area	N/A	USDOT PHMSA, 2011; 2016a; 2016b
		Provided by Enbridge in 2014
Drinking Water	N/A	USDOT PHMSA, 2011; 2016a; 2016b
		Provided by Enbridge in 2014
Commercially Navigable Waterways	N/A	USDOT PHMSA, 2011; 2016a; 2016b
		Provided by Enbridge in 2014

AOIs depict other sensitive locations where a release could have a detrimental impact. These areas include local Minnesota drinking water management areas, native plant communities, sensitive lake shores, recreational areas, tribal lands, and protected areas of several types (e.g., national forests, military lands, state parks). Data for the AOI analysis were derived from multiple datasets provided on the Minnesota Geospatial Commons website (MN Geospatial Commons 2016), USGS Protected Areas Database of the United States (PAD-US; USGS 2015), and the Minnesota Department of Transpiration (MN DOT 2016; see

Table 7-2 Sources of AOI Data

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Table 7-2 Sources of AOI Data

AOI Type	AOI Subtype	Source
Drinking Water	Surface Water Supply Management Area	MN Geospatial Commons 2016
	Water Supply Management Area	
	Wellhead Protection Areas	
Environmental	Central Region Green Infrastructure	MN Geospatial Commons 2016
	Central Region Regionally Ecological Significant Areas	
	Designated Wildlife Lakes	
	Designated Trout Stream	
	Lakes of Phosphorus Sensitivity Significance	
	Lakes with Fish-based IBI Score	
	Muskie Lakes	
	Migratory Waterfowl Feeding and Resting Areas	
	Native Plant Community	
	Native Plant Community (candidate)	
	Native Prairies	
	Potentially Undisturbed Land (Virgin Sod)	
	Regionally Significant Ecological Areas and Regional Ecological Corridors	
	Sensitive Lake Shore	
	Site of Biodiversity Significance	
	Stream Trout Lakes	
	Trout Lake Designation	
	Trout Stream Special Regulations	
	Wetland Banking Program Easements	
	Wild Rice Lake	
Protected Area	Bureau of Land Management	MN Geospatial Commons 2016; USGS 2015b
	Farm Service Agency Interest of Minnesota	
	Lake of Biological Significance	
	Military Land	
	National Forest	
	Private Conservation Land	
	Scientific and Natural Area Units	
	State Aquatic Management Area (AMA) Acquisitions	
	State Forest	
	State Park	

Table 7-2 Sources of AOI Data

AOI Type	AOI Subtype	Source
	State Wildlife Management Area	
	The Nature Conservancy	
	Wildlife Management Area	
	US NRCS Easement	
	Calcareous Fens	
Recreational	State Recreation Area	MN Geospatial Commons 2016
Tribal Lands	Tribal Lands	MN DOT 2016

An overall summary of the assessment of environmental effects of hypothetical crude oil releases at the seven representative locations is provided in Section 7.9.

7.1 REVIEW OF OBSERVED AND EXPECTED EFFECTS OF OIL RELEASES ON KEY ECOLOGICAL AND HUMAN RECEPTORS

7.1.1 Fate of Oils Released to Freshwater Environments

Crude oils and refined petroleum products are complex mixtures of hydrocarbon compounds derived from naturally occurring geological formations. When released into the environment, various weathering processes work to break down the hydrocarbons into primarily carbon dioxide and water. The rate of these weathering processes depends principally upon the type of oil (i.e., the specific mixture of hydrocarbon compounds present), the characteristics of the receiving environment (e.g., location of the release, season, and weather conditions), and the volume released, among other factors.

Individual crude oils and petroleum products are composed of differing mixtures of hydrocarbon compounds. Each has physical properties (e.g., viscosity, density, solubility) that reflect its chemical composition and affect its fate and transport once released into the environment (NRC 2003). For example, heavy oils (i.e., those with a higher percentage of heavy fractions, or high asphaltene and resin content) tend to be viscous and weather slowly because they do not readily spread into thin oil slicks, and they contain chemical constituents that resist degradation.

The high viscosity of heavy crude oil makes it difficult to pump and transport through a pipeline. Therefore, bitumen is often diluted with other petroleum products such as natural gas condensates. In addition to Bakken Crude, two of the products proposed for transport by the L3RP pipeline are CLB and CLWB. These two diluted bitumen (dilbit) petroleum products have been the subject of substantial review in the past several years.

Two recent high-profile studies of the behavior and fate of dilbits in the environment came to different key conclusions regarding their environmental fates.

The National Academies of Sciences, Engineering and Medicine (NAS 2015) formed a committee to study the relevant properties and characteristics of the transport, fate, and effects of diluted bitumen and commonly transported crude oils when released in the environment from U.S. transmission pipelines (NAS 2015). The committee concluded that:

> "In comparison to other commonly transported crude oils, many of the chemical and physical properties of diluted bitumen, especially those relevant to environmental impacts, are found to differ substantially from those of the other crude oils. The key differences are in the exceptionally high density, viscosity, and adhesion properties of the bitumen component of the diluted bitumen that dictate environmental behavior as the crude oil is subjected to weathering …" (NAS 2015).

The Royal Society of Canada likewise convened an expert panel to review the behavior and environmental effects of crude oil released into aqueous environments. The expert panel concluded that:

> "the dozens of crude oil types transported in Canada exist along a chemical continuum, from light oils to bitumen and heavy fuels, and the unique properties of each of these oil types (their chemical 'fingerprints') determine how readily released oil spreads, sinks, disperses, impacts aquatic organisms, including wildlife, and what proportion ultimately degrades in the environment. Despite the importance of oil type, the Panel concluded that the overall impact of an oil release, including the effectiveness of an oil release response, depends mainly on the environment and conditions (weather, waves, etc.) where the release takes place and the time lost before remedial operations." (Lee et al. 2015).

In this section the characteristics of light, medium, and heavy crude oils proposed for transport by the proposed L3RP pipeline are described. In addition, information is provided on how environmental factors such as season, water levels and physical processes may affect the behavior and fate of different crude oil/petroleum products if released into environments encountered by the proposed pipeline. A key objective of this section is to discuss information that will help reconcile the seemingly divergent conclusions of the two expert panels with regards to transport of dilbit products.

7.1.1.1 **Oil Characteristics**

CLB and CLWB crude oils are diluted bitumens with characteristic properties of density and viscosity falling in the upper range of values allowed by pipeline tariff specifications. General characteristics of CLB include an American Petroleum Institute gravity (API, a measure of how heavy or light a petroleum liquid is compared to water) of 20.7°, a density of 0.93 at 15°C, and a sulfur content ranging between 3.6% and 4.7% (Environment Canada 2016). Similarly, CLWB has typical characteristics that include API gravity of 22.7° and density at 15°C of 0.92 (Horn 2016). Seasonal variation in environmental temperature affects the viscosity of diluted bitumen; therefore, the amount of condensate or other diluent added is adjusted through the year to meet shipping requirements. The bitumen feedstock used in CLB and CLWB remains consistent on a seasonal basis, but the CLWB contains relatively more diluent to maintain the desired viscosity characteristic during the winter months.

Bakken crude is a light sweet crude oil with an API gravity generally between 40° and 43° and a sulfur content less than 0.2 wt.%. A crude oil with less than 1 wt.% total sulfur content is referred to as being low-sulfur or sweet crude oil. A crude oil with more than 1 wt% total sulfur is referred to as being high-sulfur or sour crude oil. As such, Bakken crude oil is similar to many other light sweet crude oils produced and transported in the United States (Auers et al. 2014). The light end concentration of Bakken crude is between 3% and 9%, with 5% being the typical concentration (NDPC 2016). As a point of reference, the Energy Information Administration categorizes crude oil that has API gravity between 35° and 50° and less than 0.3 wt% sulfur as being light sweet. Bakken falls in the middle of those ranges for both properties (Auers et al. 2014).

BTEX compounds generally represent a small fraction in each of the oil products. Diluted bitumens appear to contain around 1% BTEX by weight (Zhou et al. 2015), varying principally in accordance with the properties and quantity of diluent added. Light crude oils tend to contain rather more BTEX (2 to 3% by weight, Zhou et al. 2015). Light crude oils and Bakken crude oil in particular would be expected to contain a larger fraction of both aliphatic and aromatic low boiling point hydrocarbons, and relatively less of the high boiling point and recalcitrant fractions such as resins and asphaltenes, than diluted bitumens.

The crude oil types discussed here (i.e., Bakken and diluted bitumen) represent products that exist on opposite ends of the spectrum of crude oil types commonly encountered in North America. This fact was recognized by Lee et al. (2015), but was obscured by the methodology employed by NAS (2015). The terms of reference established for the NAS committee led them to focus their evaluation of "commonly transported" crude oil types. As a result of this direction, the analysis carried out by NAS (2015) focused on the properties of Scotia Light (actually an ultralight crude or gas condensate produced in Nova Scotia, Canada, not likely to be transported by U.S. pipelines, and having API gravity 53.2°), and West Texas Intermediate (actually a light crude oil, API gravity 34.4 to 40.8), to the exclusion of the many medium and conventional heavy crude oils that allowed Lee et al. (2015) to identify diluted bitumens as belonging within a "continuum" of crude oil types.

The physical and chemical characteristics of released oils have a direct effect on their behavior and fate. Seasonal considerations and physical processes that affect the fate of released oils are also discussed in the sections below.

7.1.1.2 Seasonal Considerations for the Fate of Released Oil

The season in which a release occurs (and related freshwater levels during each season) can influence release behavior, fate, effects, and clean-up response actions. Seasonal variations in potential release behavior are addressed in this section.

Spring—Midsummer: For this analysis, the spring to midsummer is defined as the period when mid-continent streams and rivers exhibit seasonal high flow due to snow melt and drainage of temporarily stored groundwater. Water levels in ponds, lakes, and reservoirs are also seasonally high. Temperatures may range from cool to warm. The land is mostly snow-free, and biological productivity of land and water bodies is high.

Releases to land would directly affect soils and vegetation, although spreading of the released material is likely to be impeded by the vegetation. Releases to wetlands may float and spread if there is a free-water surface (as in a fen, marsh, or pond) or be absorbed if there is an abundance of vegetation or other organic matter (as in a bog). Currents, winds, and gravitational thinning forces would promote the spreading of releases that reach water bodies.

Weather, especially rapid warming periods and heavy rainfall, may cause rapid melting of snow on land and ice in rivers at this time of the year. These conditions can result in major flood flows that breach levees along larger rivers, erode river banks, and alter channels. If oil is released to a flooded area, oil could be distributed over a large area to adjacent terrestrial, wetland, and aquatic habitats that normally would not be exposed.

Late Summer—Fall: This period of the year extends from August until freeze-up of water bodies. Water levels in mid-continent streams, rivers, reservoirs, ponds, and lakes tend to be lower at this time of year than in the spring - midsummer period. Precipitation tends to be lower during the late summer and fall than in the spring - midsummer period, although strong storm events can still generate occasional flood flow periods. Oil released into water bodies will tend to remain within banks and strand along shorelines, limiting the potential for oiling of adjacent riparian, wetland, and terrestrial habitats.

Winter: Winter is the period when mid-continent water bodies are likely to be ice-covered and the land surface is likely to be frozen or covered with snow. Due to generally cold conditions, stream and river discharge may approach seasonally low levels, although periods of thaw may result in fluctuating flows. Oil released to the land generally would be slowed, although not necessarily stopped, by the snow cover. Releases reaching streams, rivers, and lakes could potentially be prevented from entering the water by snow and ice covering the water body. However, releases that penetrate ice might be more difficult to detect, contain, and clean-up.

Freeze-up and Breakup in Aquatic Environments: Freeze-up is the transitional time in the fall when streams, rivers, lakes and other water bodies begin to freeze. Breakup or spring melt is the transitional period when ice thins and breaks up, and river flows increase to freshet or flood stage. Major floods may cause bank erosion and potentially pipeline failure, with the oil entering the river and likely being widely dispersed and difficult to contain or clean-up.

An oil release that results in oil reaching water bodies during either freeze-up or breakup may be difficult to contain, remove, and clean-up. The ice may not be strong enough to support people or equipment. In rivers, the oil may be transported several miles under the ice or in broken ice before it can be contained. Once the ice is strong enough to support people and equipment, it may be more difficult to detect the oil under the ice, and implement measures to affect rapid containment/clean-up at or near the release site.

7.1.1.3 Physical Factors Affecting the Behavior and Fate of Released Oil

The primary and shorter-term processes that affect the fate of released oil are spreading, evaporation, dispersion, dissolution, and emulsification (Payne et al. 1987; Boehm 1987; Boehm et al. 1987; Overstreet and Galt 1995). These processes contribute to the overall process of oil weathering (the physical and chemical change of released oil). Weathering dominates during the first few days to weeks of a release. A number of longer-term processes also occur, including photo-degradation, biodegradation, auto-oxidation, and sedimentation. These longer-term processes are more important in the later stages of weathering and usually determine the ultimate fate of the released oil not recovered by the clean-up program.

The chemical and physical composition of oil changes with weathering. Because of evaporation and dissolution, the effects of weathering are generally rapid (one to a few days) for hydrocarbons with lower molecular weights (e.g., gasoline, aviation gas, and diesel). Degradation of the higher weight fractions (e.g., medium and higher molecular weight components of crude oil, and bitumens in CLB and CLWB) is slower and occurs primarily through microbial degradation and chemical oxidation.

The weathering or fate of released oil depends on the oil properties and on environmental conditions, both of which can change over time.

Spreading: Spreading, either by gravity (e.g., unconfined oil on the ocean or a large lake) or by advection (e.g., oil being carried away from a release location by river flow), reduces the bulk quantity of oil present in the vicinity of the release, but increases the spatial area over which adverse effects could occur. Thus, oil in flowing systems (e.g., rivers and creeks) rather than confined systems (e.g., wetlands, ponds, and lakes) would be less concentrated in any given location, but could cause environmental effects, albeit reduced in intensity, over a larger area.

Spreading and thinning of released oil also increases the surface area of the slick, enhancing surface-dependent fate processes such as evaporation, biodegradation, photo-degradation (see below), and dissolution. Previous inland oil releases indicate, though, that the degree of spreading of oil from the release source may be constrained by natural conditions in the vicinity of the release site. For example, released oil will tend to adhere to riparian bank, lake shores, and wetlands with which oil contact is made. On land, oil spreading is limited; but it may occur immediately once the oil reaches a water surface, and will continue to spread out into a thin film unless constrained through interactions with riparian banks, wetlands, shorelines, man-made structure, or response actions. Small amounts of crude oil can spread on water into a very thin layer ("sheen"). Sheening represents an impairment of water quality that can determine the degree of oil recovery that is required (NAS 2015).

Light crude oils such as Bakken crude are anticipated to spread more quickly due to their low viscosity relative to heavier oils such as CLB and CLWB. The spreading of oil on water may be one of the most important processes during the first hours of a release, provided the oil pour point (the temperature at which it becomes a semi-solid and loses its flow characteristics) is lower than the ambient temperature (Lee et al. 2015).

Oil Particle Aggregate Dynamics: The fate of released oil may be significantly affected by the presence of mineral or organic particulate matter in terrestrial and aquatic environments. The manner in which oil interacts with particles and its eventual transport and fate depend on the physical properties of the oil and the particles, as well as environmental conditions, including the geomorphic setting, weather, currents, and vertical mixing of the water column (Lee et al. 2011; Lee 2002).

Crude oil contacting soil will adsorb or adhere to soil particles—usually binding most strongly to particles in organic soils and less strongly to particles in sandy soils. In aquatic environments, such as rivers, floodplains, wetlands, lakes, and associated shorelines, suspended particles affect the fate and transport of released oil (Muschenheim and Lee 2002; Owens and Lee 2003; Khelifa et al. 2005a, 2005b, and 2005c; Sun and Zheng 2009; Gong et al. 2014).

Combinations of oil and particles have various names, including clay-oil flocculation (Bragg and Yang 1995), oil-mineral aggregates, and oil-suspended sediment-aggregates (Khelifa et al. 2002) depending on the type of particle involved in the interaction. The term oil particle aggregate (OPA) is a generic term that includes a wide range of particles containing both mineral sediment and organic matter in association with oil that may be retained in suspension and (or) settled out (Fitzpatrick et al. 2015). Formation of OPAs happens naturally when oil and suspended particles mix in turbulent water (Lee 2002; Muschenheim and Lee 2002; Owens and Lee 2003; Khelifa et al. 2005a; Sun and Zheng 2009; Gong et al. 2014). Major factors affecting the formation of OPA are (1) the quantity, viscosity and chemical composition of the oil; (2) the quantity, type, and surface properties of the particles; (3) the magnitude and variability in physical energy of the aquatic environment; (4) the temperature; (5) oil-water interfacial tension; and (6) (while not applicable in northern Minnesota) the salinity of the water (Lee 2002; Khelifa et al. 2002; Payne et al. 2003).

The first step to forming OPAs in the water lies with the initial breakup of a slick of oil into oil droplets. Once released into a water body with turbulence created by waves or currents, floating oil can break up into droplets and reach a stable droplet size distribution (DSD) relatively quickly, perhaps in minutes to tens of minutes (Zhao et al. 2014a). Smaller droplets are generated when the oil-water interfacial tension is small and/or the oil viscosity is small. However, oil viscosity can increase by orders of magnitude among different types and temperatures of oils. Oil viscosity substantially increases as the temperature lowers to near oil's pour point. Further, the viscosity of a heavy crude oil or dilbit product such as CLB or CLWB is higher than that of light crude such as BAK oil (Fitzpatrick et al. 2015).

Evaporation: Evaporation is the primary mechanism for loss of low-molecular-weight constituents and light oil products. As lighter components evaporate, remaining petroleum hydrocarbons become denser and more viscous. Oil evaporation can be considerably slowed down by the formation of a "crust" or "skin" on top of the oil. This happens primarily on land where the oil layer is not agitated by water movement (Fingas 2015a). The rate of evaporation is very rapid immediately after oil release and then slows considerably (Fingas 2012). About 80% of evaporation occurs in the first few days after a release (Fingas 2015a).

Oil undergoing evaporation loses its more volatile and readily degraded components, leaving behind those components that weather more slowly. Hydrocarbons that volatilize into the atmosphere are broken down by sunlight into smaller compounds. This process, referred to as "photo-degradation," occurs rapidly in air; the rate of photo-degradation decreases as molecular weight increases.

While evaporation tends to reduce acute toxicity and result in overall mass reduction, the residual components may exhibit chronic, sublethal toxicity properties. Examples of sublethal effects observed in aquatic biota include external and internal lesions, developmental abnormalities in early-life stages, and behavioral changes in feeding and breeding. Delayed effects are also a possibility with measurable effects arising later in life or in subsequent generations (Dupuis and Ucan-Marin 2015).

Much of the light components of Bakken crude and the condensate diluent of CLB and CLWB will volatilize within the first few days of an oil release. Losses through volatilization likely are more pronounced in Bakken crude relative to CLB and CLWB.

Dispersion: Dispersion refers to the entrainment of oil droplets in the water column. The extent of oil dispersion depends on the interfacial tension between oil and water, oil viscosity, and the mixing energy that may be driven by wind and currents (Zhao et al. 2014b). The interfacial tension between the oil and water does not vary widely among oil types. The range is typically less than twofold. The mixing energy varies across environments, and over space and time in a particular environment (e.g., rivers passing over dams, and windy versus calm weather on lakes) (NAS 2015).

The DSD of oil dispersed in water plays an important role in the behavior of oil in the aquatic environment. Larger droplets are more buoyant than smaller droplets and thus rise more readily to the water surface, regardless of whether they were released underwater, or on the water surface and entrained into the water column by turbulence. The DSD affects not only the transport but the fate and toxicity of released oil. Increasing the proportion of small droplets increases the surface area per unit mass of oil, increasing the dissolution of hydrocarbons in the water column (Reddy et al. 2012) and their potential for bioaccumulation via transport across biological membranes (NAS 2015).

It is anticipated that Bakken crude will disperse more readily than CLB or CLWB products, if released into a water body.

Dissolution: Dissolution involves the more water-soluble components of a crude oil dissolving in the water column. Dissolution is not the primary process controlling the fate of oil in the environment. More commonly, oil floats, strands on shorelines/riparian banks, or volatilizes. The range of oils (i.e., Bakken crude through to CLB and CLWB) that would be transported by the proposed pipeline is lighter than water.

Some crude oil components are water-soluble and, to the extent that dissolution does occur, it is one of the primary processes affecting the toxic effects of a release to aquatic organisms, especially in confined water bodies. The potential for dissolution decreases with increasing hydrocarbon molecular weight and decreasing water temperature. Aromatic compounds are generally more water-soluble than aliphatic compounds having the same number of carbon atoms. The BTEX compounds are among the more water soluble hydrocarbon compounds and are of particular relevance to short-term or acute toxicity to aquatic life.

Emulsification: Emulsification is the incorporation of water in oil as a colloidal suspension. During emulsification, small drops of water become surrounded by oil. External energy from wave or strong current action is needed to naturally emulsify oil. In general, heavier oils emulsify more readily than lighter oils, although recent reports suggest that diluted bitumens do not readily emulsify. The oil could remain in a slick, which could contain as much as 70% water by weight, and could have a viscosity of a hundred to a thousand times greater than the original oil. Water-in-oil emulsions often are referred to as “mousse.” Emulsification is more common in large water bodies (e.g., large lakes, major rivers, and the ocean) where waves and/or currents mix the surface waters, than in smaller water bodies where this mixing energy is usually much less. The high viscosity results in a semi-solid or gel, which contributes to the persistence of the emulsified oil and makes clean-up more difficult.

Benthic Deposition/Sinking: A recent National Academies of Science, Engineering and Medicine report (NAS 2015) states that diluted bitumen products such as CLB and CLWB (dilbits), if released to a waterbody, can sink and accumulate on the underlying bed leading to difficult cleanup. Specifically, NAS (2015) states that immediately after a release, exposure to the environment begins to change released diluted bitumen through various weathering processes. The net effect is a reversion toward properties of the initial bitumen. An important factor is the amount of time necessary for the oil to weather into an adhesive, dense, viscous material. For any crude oil release, lighter, volatile compounds begin to evaporate promptly. In the case of diluted bitumen, a dense, viscous material with a strong tendency to adhere to surfaces begins to form as a residue, creating particular challenges in those cases where the residue reaches water bodies and submerges or sinks to the bottom of a water body. The density of the residual oil does not need to reach or exceed the density of the surrounding water for this to occur, since the crude oil may combine with particles present in the water column to submerge, and then remain in suspension or sink (NAS 2015).

In essence, NAS (2015) posits that the diluent in dilbits will immediately undergo weathering leaving leftover bitumen to sink due to its inherent high density or accommodation of suspended sediments/particulates.

In comparison, a recent Royal Society of Canada study (Lee et al. 2015) indicates that a driving factor in whether or not dilbits sink is the amount of loss of the diluent following release of the product to a water body. Specifically, the density of many crude oils, including diluted bitumen products, is less than that of both fresh water (~1 g/cm^3) and sea water (~1.03 g/cm^3). Therefore, these oils will float when released onto or into water. However, bitumen by definition has a density greater than 1 g/cm^3 and, if diluent evaporates from dilbit during a release, the residual bitumen will become more dense and may become submerged or sink. Even so, oil droplets of density ~1.0 can be neutrally buoyant and remain suspended in the water column, especially if present in turbulent water such as in a rapidly flowing river or high wave energy system (Lee et al. 2015).

While the amount of diluent lost to weathering following release is critical to whether or not dilbits sink, the degree of evaporation and dissolution of diluent is poorly understood. The Royal Society of Canada report (Lee et al. 2015) further indicates that there is debate about whether 100% of the diluent component of bitumen blends can be lost by natural evaporation (Fingas 2015b) or whether the residual bitumen/heavy oil will retain some of the diluent components as intimately blended constituents, conferring novel properties on the partially weathered oil (Winter and Haddad 2014). This is particularly important for predicting if weathered dilbit will float or sink in water. The observation of evaporative mass losses of less than 20% after rigorous weathering at environmentally-relevant temperatures for dilbits nominally containing greater than or equal to 30% diluent, suggests that a substantial proportion of diluent remains intimately associated with bitumen (Lee et al. 2015).

Photo-Degradation: Photochemical processes result from exposure of released oil to sunlight, leading to cleavage and formation of covalent bonds. Oxygen is typically incorporated into the products and thus the term photo-oxidation is commonly used (NAS 2015). These oxidized products include both carbon dioxide and other oxygenated compounds (Aeppli et al. 2012). Typically, aromatic hydrocarbons are transformed more rapidly than alkanes (Garrett et al. 1998), thereby increasing the relative abundance of resins and asphaltenes in the residual oil (Aeppli et al. 2012; Prince et al. 2003). In one set of laboratory experiments, the photo-oxidation of crude oil in fresh water under direct ultraviolet irradiation showed oxidation of 5% of the branched alkanes, 9% of the linear alkanes, and 37% of the aromatic hydrocarbons (D'auria et al. 2009; NAS 2015).

Photo-degradation of oil increases with greater solar intensity. It can be a significant factor controlling the disappearance of a slick, especially of lighter constituents, but it would be less important during cloudy days and in winter months.

Due to the relative increase in spreading and relatively higher fractions of lighter aromatic petroleum components relative to asphaltene components, Bakken crude is likely subject to increased photo-oxidation relative to CLB and CLWB.

Biodegradation: Biodegradation is the breakdown of compounds by native or introduced microorganisms. Biodegradation of oil by native microorganisms, in the hours to days following an oil release, would likely not be a significant process controlling the fate of oil in water bodies previously unexposed to oil. Although oil-degrading microbial populations are ubiquitous at low densities, a sufficiently large population must become established before biodegradation can proceed at any appreciable rate. Biodegradation is typically a long-term (weeks to years) process that reduces both the toxicity and volume of released oil.

Biodegradation can occur either aerobically or anaerobically, with aerobic processes typically occurring more rapidly and extensively. Biodegradation is accelerated in the presence of abundant oxygen and nutrients (Boufadel et al. 2010) at moderate temperature, salinity (where applicable), and reasonable oil-water interfacial surface area (Geng et al. 2014). At this time, there are no quantitative field studies on the biodegradation of releases of diluted bitumen such as CLB and CLWB, but saturates and aromatics are expected to biodegrade within weeks to years (NAS 2015).

7.1.1.4 Summary of Factors Influencing the Fate and Behavior of Released Oils

The environmental fate of released oil and oil products is controlled by many factors. Major factors affecting environmental fate include the release volume, release rate, oil temperature, terrain, receiving environment, time of year, and weather. For example, Bakken crude oil, a light, sweet crude oil, would weather differently than dilbit oils such as CLB and CLWB, in that the light ends of Bakken and the condensate diluent of CLB and CLWB would evaporate faster and dissolve to a greater degree in water than the heavier ends of Bakken and the bitumen component of CLB and CLWB.

The characteristics of the receiving environment, such as the type of land cover, soil porosity, land surface topography and gradient, type of freshwater body, particulate load in the water, presence of ice and/or snow cover on water or land, and flowing water current velocity, would affect how the release behaves. In ice-covered waters, many of the same weathering processes occur as in open water. However, ice changes the rates and relative importance of these processes (Payne et al. 1991).

The time of year when a release occurs has a major effect on the fate of crude oil. The time of year controls climatic factors such as the temperature of the air, water, or soil; depth of snow cover; presence of ice; and the depth of the active (soil frost) layer. During winter, colder air temperatures can modify the viscosity of oil so that it would spread less and potentially solidify. Temperature also affects the rate of evaporation of the volatile fraction of hydrocarbons. Frozen ground would limit the depth of penetration of any release. Weather could also affect the ability to detect, contain, or clean-up a release.

The physical and chemical processes discussed herein, which govern the fate of released oils, will drive exposure and manifest effects to ecological, land cover, and human receptors. For example, lighter oils such as Bakken tend to more readily evaporate and dissolve relative to dilbits, resulting in potential effects to biological communities residing in the water surface, column, and atmosphere, as well as result in potential inhalation exposure for human receptors. Comparatively, heavier oils such as dilbits tend to adhere to encountered riparian banks and lakeshores, resulting in marked exposure to biological communities residing there. Importantly, the specifics of any given incident will drive the fate and effects of released crude and refined petroleum products.

7.1.2 Land Cover Receptors

7.1.2.1 Air/Atmosphere

Section 109(b) of the Clean Air Act (CAA) requires that the USEPA establish National Ambient Air Quality Standards (NAAQS) "requisite to protect" public health and public welfare (40 CFR Part 50). The CAA identifies two class types of NAAQS: primary standards and secondary standards. Primary standards are limits set to protect the public health of the most sensitive populations, such as asthmatics, children and the elderly. Secondary standards are limits set to protect public welfare such as protection against visibility impairment or damage to vegetation, wildlife and structures. The CAA requires the USEPA to periodically review and, if new data indicate, update the NAAQS.

The USEPA has promulgated NAAQS for six criteria pollutants: ozone, particulate matter (PM), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and lead. Particulate matter (PM) is a term for particles in the air, such as dust, soot, smoke, and liquid droplets. Standards for PM are categorized on the size of the PM based on the aerodynamic diameter of the particle. The term PM_{10} represents particulate matter with an aerodynamic diameter less than 10 µm and $PM_{2.5}$ is PM with a diameter less than 2.5 µm.

In Minnesota, the MN PCA monitors and regulates air pollution. MN PCA is required to develop regulations, referred to as the State Implementation Plan (SIP) to outline how the areas under their jurisdiction will attain and maintain ambient air concentration levels in compliance with the NAAQS. Within their SIP, MN PCA has developed state air quality regulations under Section 7009.0800 of the Minnesota Administrative Rules. In general, the state standards mirror the USEPA

NAAQS. The primary difference is that the state has also developed ambient air quality standards for hydrogen sulfide (H_2S). In a proposed amendment to the state air quality rules published on February 29, 2016, the state has stated its intention to align their criteria pollutant standards with the current USEPA NAAQS, while retaining the H_2S standard. Long term ambient air monitoring has demonstrated that Minnesota attains compliance with all USEPA NAAQS within the counties traversed by this Project and throughout the state with the exception of a localized area in the Minneapolis-St. Paul area that is classified as nonattainment for the lead NAAQS.

The MN PCA has also worked with the Minnesota Department of Health (MN DH) to assess the health risk from air pollution beyond the NAAQS. While attainment of the NAAQS is a good overall indicator of air quality, the NAAQS do not address potential issues associated with individual chemicals or chemical species. The MN DH and MN PCA have identified a list of chemicals referred to as air toxics that cause or may cause cancer or other serious health effects or adverse environmental and ecological effects. Health Risk Values, Health-Based Values, and Risk Assessment Advice have been established as benchmarks to aid the agencies in air permitting and environmental review decisions and to prioritize air toxic emission reduction programs across the state. Chemicals for which ambient air values have been developed include BTEX and naphthalene. These are chemicals commonly found in crude oil. The standards that have been developed by MN DH represent acute (one-hour average), subchronic (13-week average), and chronic (annual average) exposures. The chronic standards define levels of increased risk to human health over the long term, or lifetime, of exposures to a specific chemical, whereas an acute standard addresses the short-term risks associated with a transient event such as an oil spill.

Crude oil is a complex mixture of organic compounds. The organic compounds, also referred to as hydrocarbons, are molecules primarily made up of carbon and hydrogen atoms. These molecules may also contain small amounts of elemental sulfur, nitrogen, and oxygen. Some metals and other trace compounds such as hydrogen sulfide also may be found in the mixture.

The number and arrangement of the carbon atoms in each compound define the physical properties of the compounds such as whether they are normally found as gases, liquids or solids and the density of the compound. Compounds with less than five carbon atoms such as methane (one carbon) and ethane (two carbons) are generally found in their gaseous form at standard conditions (also referred to as normal conditions) of temperature and pressure (e.g., conditions found near ground level in the atmosphere). Slightly larger compounds with about 5 to 10 carbon atoms (e.g., octane, which has 8 carbons) found in gasoline are liquids at standard conditions. In this range, the shorter chained compounds will readily evaporate (or volatilize) if exposed to air and are; therefore, referred to as volatile organic compounds (VOCs). Other compounds in this range are the BTEX compounds, which are generally considered toxic chemicals with Health-Based rules established by MN DH.

Organic compounds with about 11 to 20 carbon atoms can be very complex. Within this range, there is a group of compounds (including naphthalene) that are liquid or solid at standard conditions, but which will evaporate or sublimate over time. These compounds are referred to as semi-volatile organic compounds and include fuel oil and a family of chemicals referred to as PAHs. The largest hydrocarbon compounds, having 20 carbon atoms or more, can be found in products such as lube oils or asphalt. These are generally thick, viscous liquids or waxy solids under standard conditions.

Crude oil is a complex mixture of all of these classes of hydrocarbons. Depending on the geographic area or geological formation from which crude oil is recovered, the relative composition of volatile and non-volatile compounds may vary considerably. Industry classifies crude oil into three general categories (light, medium and heavy) based on a measure of density (API gravity) which reflects the chemical composition of the oil. In transitioning from light to heavy oils, the percentage of volatile organic compounds typically decreases, and the fraction of non-volatile compounds increases. Bitumen is a very heavy type of crude oil that contains very little volatile hydrocarbon. However, depending upon the type of diluent used to manufacture diluted bitumen (dilbit), the volatile content of diluted bitumen may be relatively high (i.e., similar to that of a light oil) or very low.

The physical characteristic used by the petroleum industry to classify crude oil is the specific gravity or density of the mixture. For crude oils, the density of the material is reported as a dimensionless number referred to as API gravity. API gravity has an inverse relationship with density, therefore the less dense the oil, the higher the API gravity is of the mixture. A light crude oil is a material with an API gravity greater than 31.1° (Speight 2014; Lee et al. 2015). Medium crude oils have an API gravity between 31.1° and 22.3° (Speight 2014; Lee et al. 2015). Heavy crude oils have an API gravity less than 22.3° (Speight 2014; Lee et al. 2015). For comparison, a chemical with a density equal to that of water would have an API gravity of 10°.

A crude oil with a high API gravity will generally have a high concentration of VOCs and low viscosity. Viscosity is the property that defines how easily a liquid will flow and spread out. A low viscosity liquid, such as gasoline, has low internal friction and will easily spread out into a thin film as a result of gravity. A highly viscous material like asphalt or bitumen will not readily spread. The viscosity of a material changes with temperature, with an increase in temperature resulting in a decrease in the viscosity of the material.

The high viscosity of bitumen makes it difficult to pump and transport through a pipeline. Therefore, bitumen is either heated or diluted with another petroleum product such as natural gas liquids (condensate) or synthetic oil in order to lower its viscosity. Bitumen may be diluted by 10 to 40% with a diluent in order to meet standards for pipeline transportation.

In addition to being described as a function of density and viscosity, crude oils can also be classified as being either "sweet" or "sour". A crude oil with less than 1 wt% sulfur content is referred to as being low-sulfur or sweet crude oil. A crude oil with more than 1 wt% sulfur is referred to as being high-sulfur or sour crude oil. Typically crude oils range from less than 0.1–5 wt% sulfur. The sulfur content is important relative to the potential perceived odor from the material and the possible emission of H_2S, a toxic gas, from an oil release.

Of the six USEPA criteria air pollutants, the pollutant most theoretically likely to be affected by a crude oil release (although not contained in the crude oil) would be ozone. Ground-level ozone is produced on hot, sunny days by a chemical reaction between VOCs and oxides of nitrogen (NOx). Volatile organic carbon compounds are released by many activities, including the use of paints and solvents. NOx emissions are released from motor vehicles, power plants, and other activities that require fuel combustion. Levels of ozone are dependent on the amount of VOCs and NOx in the air, as well as weather conditions including sunlight, temperature, and wind speed and direction. Based on the need for specific meteorological conditions and the time delay for ozone to form in the atmosphere, the more immediate concern of the local community would be the short term exposure to VOCs (including benzene), H_2S or other specific chemicals, in addition to any odors associated with the volatilization of the crude oil following a release. To better define how oil releases have affected the local air quality, a review of historical data and laboratory studies was performed.

7.1.2.1.1 Observed Effects

The following section summarizes a review of some historic oil releases and their environmental effects on local air quality (only) following the release. This section also reviews some laboratory studies that have been completed to better define environmental effects on air quality from oil releases.

> ***Exxon Valdez Release, Alaska**: A study performed by Hanna and Drivas (1993) evaluated the VOC emissions from the Exxon Valdez Oil Release. The purpose of the study was to "reconstruct the time and space variation of air concentrations from the Exxon Valdez oil spill on March 24, 1989 in Prince William Sound, Alaska." The author stated that as much as 25% of the oil may have evaporated during the first two weeks following the release and all of the VOC or BTEX compounds evaporated within a few hours. The study concluded:*
>
> 1. *Benzene, toluene, and n-hexane evaporated completely within about 12 hours of the spill, and the evaporation was primarily diffusion-limited.*
> 2. *The less volatile compounds (e.g., n-pentadecane) evaporated at a much slower, more constant rate over the first two weeks, and their evaporation was controlled primarily by mass-transfer to the air.*

The first conclusion indicates that the evaporation rate of the more volatile components was limited by the ability of the volatile compounds to travel within the layer of oil floating on the water and come into contact with the air, where they evaporated immediately. The second conclusion indicates that the evaporation of the less volatile components of the oil was limited by temperature, airflow, and the physical properties of the compounds, such as vapor pressure.

The mass-transfer process would require more time to complete than the diffusion-limited process.

Environment Canada: *Experimentation was conducted by the Emergencies Science Division of Environment Canada on crude oil evaporation (Fingas 1999). The purpose of the study was to understand the evaporation process during an oil release and to develop an oil release behavior model. Through a series of studies the author determined that up to 75% by volume of light crude oils were lost to evaporation in the first few days following a release. The value reported was 40% for a medium crude oil and 5% for a heavy crude oil. In this study, the author concluded that:*

1. *Evaporation rate of several oils with increasing wind speed shows that, unlike water, the evaporation rate does not change significantly except for the initial step over 0-level wind*
2. *Increasing area does not significantly change oil evaporation rate*
3. *Decreasing thickness does not increase oil evaporation rate*
4. *Volume or mass of oil evaporating correlates with the evaporation rate*
5. *Evaporation of pure hydrocarbons with and without wind (turbulence) shows that compounds larger than nonane and decane are not boundary-layer regulated*

The author also stated, "The fact that oil evaporation is not strictly boundary-layer regulated implies a simplistic evaporation equation will suffice to describe the process. A simple equation of the form, evaporation = constant x logarithm of time, is sufficient to describe evaporation. The following processes do not require consideration: wind velocity, turbulence level, area, thickness, and scale size. The factors found to be important to evaporation are time and temperature." Therefore, Fingas's conclusion mirrors the finding of Hanna and Drivas, that evaporation of the larger compounds in the crude oil matrix is constant based on the temperature and controlled by mass-transfer processes.

OSSA II Pipeline, Bolivia: *On January 30, 2000, a fracture developed on the OSSA II pipeline over the Rio Desaguardo in Bolivia releasing 29,000 barrels of mixed crude oil and condensate into the river during a high flow event. At the time of the release, the pipeline was carrying a heavy crude oil diluted with kerosene-range petroleum product. Studies (Henshaw et al. 2001; Douglas et al. 2002) evaluated the weathering of the crude oil over the months following the spill. Samples of raw crude oil were compared to samples of stranded oil collected along the river banks following the release.*

Douglas concluded that the light hydrocarbons (3 to 18 carbons), which includes the BTEX compounds, were almost completely removed by evaporation. The *results indicated that as much as 45% of the released oil may have evaporated. However, there are no reported data on air quality for this event.*

Wabamun Lake Train Derailment, Alberta, Canada: *On August 3, 2005, a CN freight train derailed near the Village of Whitewood Sands in Alberta, Canada. Approximately 4,500 barrels of Bunker C fuel oil were released. The Bunker C fuel oil was being delivered to be utilized as asphalt stock. The Bunker C contained no BTEX and was primarily composed of non-volatile, long-chained organic compounds. A sample of the Bunker C fuel oil was collected three days after the derailment from a pool near the ruptured rail cars. A fingerprint analysis of the pooled oil indicated that the oil was identical to samples of the Bunker C fuel oil produced by the refinery from which the material originated (Hollebone et al. 2011). The lack of physical change to the oil over the three days indicates that there was minimal loss of oil constituents to evaporation.*

Trans Mountain Pipeline, Burnaby, British Columbia: *In July 2007, a backhoe accidentally struck the Trans Mountain Pipeline in Burnaby, British Columbia. A total of 1,500 barrels of Albian Heavy Synthetic crude oil blend, a type of partially upgraded heavy crude oil known as a dilsynbit, was sprayed into the air and covered surrounding streets and buildings (Trans Mountain Pipeline ULC 2014). Air quality monitoring began immediately following the incident. VOC levels declined rapidly during the clean-up efforts (Eykelbosh 2014). The residents that were evacuated in response to the spill reported various symptoms including headache, nausea, dizziness, upper respiratory tract irritation and eye irritation. No long term effects study has been completed.*

Immediately following the spill, approximately 225 people were evacuated by the fire department. More than half of the people were able to return to their homes that evening. A total of 101 people representing 42 families spent the night of the release in other accommodations away from their homes (Trans Mountain 2015).

Marshall, Michigan: *On July 26, 2010, Enbridge reported a 30-inch pipeline had ruptured near Marshall, Michigan. The break resulted in the release of an estimated 20,000 barrels of a crude oil mixture of which approximately 8,200 barrels reached Talmadge Creek and the Kalamazoo River (Enbridge 2013a). The pipeline was transporting Western Canadian Select and CLB crude oils. These crude oils are classified as heavy crude oils (diluted bitumens). To allow the heavy crude oil to flow through the pipeline a diluent was added to the crude oil at a concentration of about 30%.*

A review of the USEPA certified air quality ozone monitoring data collected by Michigan Department of Environmental Quality (MI DEQ) (USEPA 2016) for *southern Michigan on the day of the release and through the remainder of 2010 indicates that there were no violations of the ozone NAAQS.*

Beginning on July 26, 2010 and continuing through 2012, the USEPA and Enbridge through their contractors routinely monitored the air quality throughout the project area. Initial testing was performed for VOCs, H_2S, CO, and benzene. Numerous methodologies were employed to monitor for emissions. Human health screening levels were developed and decision trees were created by the Agency for Toxic Substances and Disease Registry (ATSDR), the Calhoun County Public Health Department, and Michigan Department of Community Health (MI DCH) to determine if evacuation orders would be required (MI DCH 2014a). An initial screening level was developed by MI DCH for acute (short-term) exposure to benzene and was set at a level of greater than 200 parts per billion (ppb)at which evacuation would be recommended, if confirmed by a second test (MI DCH 2014a). Longer term, chronic screening levels were developed by MI DCH to determine when homes could be re-occupied and were set at a level of 6 ppb benzene. The 6 ppb level cited by MI DCH is a level derived by the ATSDR as an intermediate-duration inhalation Minimal Risk Level for inhalation exposures to benzene.

For comparison, in the state of Minnesota, the MN DH and MN PCA health based guidance for benzene sets an acute (short-term) exposure level of 1,000 micrograms per cubic meter, which is roughly equivalent to 320 ppb (MN DH 2016). The MN DH guidance sets a benchmark of 1.3 to 4.5 micrograms per cubic meter for longer term (chronic) exposures, which is equivalent to a range of 0.4 to 1.5 ppb (MN DH 2016)).

MI DCH prepared a report (MI DCH 2014a) assessing the extent of air contamination as monitored throughout the project period. MI DCH divided the data for 2010 into three time frame groupings:

- *Initial Response Period from July 26 through July 28, 2010*
- *Voluntary Evacuation Period from July 29 to August 17, 2010*
- *Post Evacuation Period from August 18 to December 31, 2010*

The data were primarily collected in four locations, which are identified as: 1) the Voluntary Evacuation Area (along Talmadge Creek from the release site to the confluence with the Kalamazoo River, 2) Squaw Creek Subdivision (west of the confluence of Tallmadge Creek and the Kalamazoo River about 2.5 miles downstream from the release), 3) the town of Ceresco (about 6 miles downstream from the release), and 4) Baker Estates Subdivision in Battle Creek (about 13.5 miles downstream from the release). Additional samples were also collected in the area referred to as the Oil Release Site, but no homes were located in this area.

Initial Response Period (July 26 through July 28, 2010)

During the Initial Response Period (the first three days following the release), air sampling was begun the day of the release using hand-held meters and Draeger tubes. More extensive monitoring began on the day following the release when more sophisticated monitoring was performed, which included the use of mobile field gas chromatograph monitors and the collection of Summa canister and Tedlar bag samples, which were sent to a laboratory of chemical analysis.

For VOCs, a screening level of 1,000 ppb of total VOCs was utilized by MI DCH to indicate if further chemical specific monitoring (such as benzene) might be appropriate. About half of the measured concentrations exceeded 1,000 ppb in the evacuation area, Squaw Creek Subdivision, and in Ceresco. However, VOCs were not detected in air at Baker Estates. (MI DCH 2014a). The results of the VOC monitoring during the Initial Response Period are shown in Table 7-3.

Table 7-3 Total VOC Concentrations in ppb during the Initial Response Period

Area	Number of Measurements	Screening Level (ppb)	Range of Detections (ppb)
Voluntary Evacuation Area	98	1,000	ND to 120,000
Squaw Creek Subdivision	30	1,000	ND to 71,600
Ceresco Area	8	1,000	ND to 6,000
Baker Estates Neighborhood	2	1,000	ND
NOTE: ND = Not Detected			
Source: MI DCH 2014a (Tables B-1 and B-2)			

A screening level of 60 ppb benzene was utilized by MI DCH to indicate if use of the mobile field gas chromatograph monitor was appropriate. The screening samples were collected primarily using an UltraRAE real-time monitor. Benzene was detected in concentrations up to 6,250 ppb. Exceedances of the screening level were detected in the Voluntary Evacuation Area and the Ceresco Area. The mobile field gas chromatograph was used and analyzed four samples in the Voluntary Evacuation Area during this timeframe with detections from 1.2 to 27.3 ppb recorded and no exceedances of the 60 ppb benzene screening level indicated (MI DCH 2014a). The results of the benzene monitoring during the Initial Response Period are shown in Table 7-4.

Table 7-4 Benzene Concentrations in ppb during the Initial Response Period

Area	Screening Level (ppb)	Number of UltraRAE Monitor Readings	Number of UltraRAE Monitor Readings Above Screening Level	Range of UltraRAE Detections (ppb)	Number of Field GC Monitor Readings	Number of Field GC Monitor Readings Above Screening Level	Range of Field GC Detections (ppb)
Voluntary Evacuation Area	*60*	*13*	*8*	*ND to 6,250*	*4*	*0*	*1.2 to 27.3*
Squaw Creek Subdivision	*60*	*4*	*0*	*ND*	*0*	*NA*	*NA*
Ceresco Area	*60*	*4*	*2*	*ND to 500*	*0*	*NA*	*NA*
Baker Estates Neighborhood	*60*	*1*	*0*	*ND*	*0*	*NA*	*NA*
NOTE: *NA = Not Available; ND = Not Detected*							
Source: MI DCH 2014a (Tables B-6)							

Hydrogen sulfide monitoring was also performed at these locations during these periods. A screening level of 70 ppb H_2S was established for this response. Of the four sampled areas, the screening level was only exceeded in the Voluntary Evacuation Area. During the initial response period one of four samples taken in the Voluntary Evacuation Area exceeded the screening level. (MI DCH 2014a). The results of the H_2S monitoring during the Initial Response Period are shown in Table 7-5.

Table 7-5 Hydrogen Sulfide Concentrations during the Initial Response Period

Area	Screening Level (ppb)	Number of Measurements	Number of Measurements Above Screening Level
Voluntary Evacuation Area	*70*	*4*	*1*
Squaw Creek Subdivision	*70*	*14*	*0*
Ceresco Area	*70*	*0*	*0*
Baker Estates	*70*	*0*	*0*

Table 7-5 Hydrogen Sulfide Concentrations during the Initial Response Period

Area	Screening Level (ppb)	Number of Measurements	Number of Measurements Above Screening Level
Neighborhood			
Source: MI DCH 2014a (Tables B-3 and B-4)			

Voluntary Evacuation Period (July 29 to August 17, 2010)

During the voluntary evacuation period 98 of 3,925 VOC measurements at all four locations indicated concentrations greater than 1,000 ppb screening level (MI DCH 2014a). The results of the VOC monitoring during the Voluntary Evacuation Period are shown in Table 7-6.

Table 7-6 Total VOC Concentrations in ppb during the Voluntary Evacuation Period

Area	Number of Measurements	Number of Measurements Above Screening Level	Screening Level (ppb)	Range of Detections (ppb)
Voluntary Evacuation Area	2,244	84	1,000	ND to 568,000
Squaw Creek Subdivision	658	8	1,000	ND to 2,600
Ceresco Area	467	2	1,000	ND to 3,000
Baker Estates Neighborhood	556	3	1,000	ND to 266,000
NOTE: ND = Not Detected				
Source: MI DCH 2014a (Tables B-1 and B-2)				

During the voluntary evacuation period, 64 of 2,591 samples collected using an UltraRAE real-time monitor indicated exceedances of the 60 ppb benzene screening level, with detections up to 2,200 ppb. The mobile field gas chromatograph analyzed 36 samples in the four areas during this timeframe with detections up to 17.6 ppb recorded and no exceedances of the 60 ppb benzene screening level indicated (MI DCH 2014a). The results of the benzene monitoring during the Voluntary Evacuation Period are shown in Table 7-7.

Table 7-7 Benzene Concentrations in ppb during the Voluntary Evacuation Period

Area	Screening Level (ppb)	Number of UltraRAE Monitor Readings	Number of UltraRAE Monitor Readings Above Screening Level	Range of UltraRAE Detections (ppb)	Number of Field GC Monitor Readings	Number of Field GC Monitor Readings Above Screening Level	Range of Field GC Detections (ppb)
Voluntary Evacuation Area	*60*	*1,619*	*62*	*ND to 2,200*	*24*	*0*	*ND to 17.6*
Squaw Creek Subdivision	*60*	*437*	*0*	*ND to 50*	*7*	*0*	*ND to 2.2*
Ceresco Area	*60*	*271*	*1*	*ND to 200*	*2*	*0*	*ND to 0.2*
Baker Estates Neighborhood	*60*	*264*	*1*	*ND to 250*	*3*	*0*	*ND*
NOTE: ND = Not Detected							
Source: MI DCH 2014a (Tables B-6)							

During the voluntary evacuation period seven of 3,175 samples exceeded the 70 ppb screening level for H_2S. All of the exceedances occurred in the Voluntary Evacuation Area (MI DCH 2014a). The results of the H_2S monitoring during the Voluntary Evacuation Period are shown in Table 7-8.

Table 7-8 Hydrogen Sulfide Concentrations during the Voluntary Evacuation Period

Area	Screening Level (ppb)	Number of Measurements	Number of Measurements Above Screening Level	Range of Detections (ppb)
Voluntary Evacuation Area	*70*	*1,747*	*7*	*ND to 112*
Squaw Creek Subdivision	*70*	*507*	*0*	*ND*
Ceresco Area	*70*	*412*	*0*	*ND*
Baker Estates Neighborhood	*70*	*509*	*0*	*ND*
NOTE:				

Table 7-8 Hydrogen Sulfide Concentrations during the Voluntary Evacuation Period

NA = Not Available; ND = Not Detected
Source: MI DCH 2014a (Tables B-3 and B-4)

Post Evacuation Period (August 18 to December 31, 2010)

In the Post-Evacuation Period 25 of 11,252 VOC measurements exceeded the 1,000 ppb screening level. Higher readings during these periods were attributed to oil recovery activities along Talmadge Creek and at Ceresco dam. (MI DCH 2014a). The results of the VOC monitoring during the Post Evacuation Period are shown in Table 7-9.

Table 7-9 Total VOC Concentrations in ppb during the Post Evacuation Period

Area	***Number of Measurements***	***Number of Measurements Above Screening Level***	***Screening Level (ppb)***	***Range of Detections (ppb)***
Voluntary Evacuation Area	*4,281*	*18*	*1,000*	*ND to 9,000*
Squaw Creek Subdivision	*1,059*	*1*	*1,000*	*ND to 1,200*
Ceresco Area	*5,149*	*5*	*1,000*	*ND to 2,800*
Baker Estates Neighborhood	*767*	*1*	*1,000*	*ND to 1,200*
NOTE: *ND = Not Detected*				
Source: MI DCH 2014a (Tables B-1 and B-2)				

A screening level of 6 ppb benzene was utilized by MI DCH in the Post Evacuation Period to indicate if long term chronic exposures may have resulted from the release. During the post evacuation period 27 of 7,377 samples collected using an UltraRAE real-time monitor indicated exceedances of the 6 ppb benzene screening level, with detections up to 9,450 ppb. The mobile field gas chromatograph was not used during this period (MI DCH 2014a). The results of the benzene monitoring during the Voluntary Evacuation Period are shown in Table 7-10.

Table 7-10 Benzene Concentrations in ppb during the Post Evacuation Period

Area	*Screening Level (ppb)*	*Number of UltraRAE Monitor Readings*	*Number of UltraRAE Monitor Readings Above Screening Level*	*Range of UltraRAE Detections (ppb)*
Voluntary Evacuation Area	*6*	*3,095*	*17*	*ND to 9,450*
Squaw Creek Subdivision	*6*	*274*	*0*	*ND*
Ceresco Area	*6*	*3,704*	*10*	*ND to 4,500*
Baker Estates Neighborhood	*6*	*304*	*0*	*ND*
NOTE: *ND = Not Detected*				
Source: MI DCH 2014a (Tables B-6)				

During the post evacuation no detections were identified for H_2S in a total of 9,977 samples recorded. (MI DCH 2014a). The results of the H_2S monitoring during the Post Evacuation Period are shown in Table 7-11.

Table 7-11 Hydrogen Sulfide Concentrations during the Post Evacuation Period

Area	*Screening Level (ppb)*	*Number of Measurements*	*Number of Measurements Above Screening Level*	*Range of Detections (ppb)*
Voluntary Evacuation Area	*70*	*3,270*	*0*	*ND*
Squaw Creek Subdivision	*70*	*921*	*0*	*ND*
Ceresco Area	*70*	*5,071*	*0*	*ND*
Baker Estates Neighborhood	*70*	*715*	*0*	*ND*
NOTE: *ND = Not Detected*				
Source: MI DCH 2014a (Tables B-3 and B-4)				

Throughout 2011, no detectable concentrations were recorded associated with the pipeline release in a total of 3,146 VOC samples taken. No detections of *benzene were monitored in a total of 2,593 UltraRAE samples and no detections of H_2S were identified in 2,968 H_2S samples (MI DCH 2014a).*

***Rainbow Pipeline, Alberta, Canada:** On April 29, 2011, Plains Midstream Canada ULC (ERCB 2013) reported a pipeline failure which released 28,300 barrels of light sweet crude oil from their Rainbow Pipeline in Alberta. There were no residences within 12 km (7.5 miles) of the release point. A school located in Little Buffalo, 12 km from the release, was evacuated and closed voluntarily on April 29 as a precautionary measure. The school remained closed on the following Monday, May 3. Air monitoring was performed from May 3 to May 14 at the school. The monitoring indicated no evidence of substantive risk from airborne contaminants. Three additional sites were also monitored. No exceedances of ambient air quality standards were measured.*

***Silvertip Pipeline, Laurel, Montana:** On July 1, 2011, the ExxonMobil Silvertip Pipeline carrying medium sour crude oil ruptured, releasing 1,500 barrels into the Yellowstone River in Laurel, Montana (USDOT 2012). The typical concentration of VOCs in this crude oil is 142 milligrams per kilogram (mg/kg) of benzene, 1,060 mg/kg of toluene, and 2,530 mg/kg of xylenes. Samples of weathered crude oil collected four days after the release indicated that the BTEX compounds were no longer detectable (USEPA 2011). However, there is no information available regarding VOC concentrations in air.*

***Mid Valley Pipeline, Mooringsport, Louisiana:** On October 13, 2014, the Sunoco Logistics Mid Valley Pipeline ruptured near Mooringsport, Louisiana releasing 4,500 barrels of light sweet crude oil. Two residences adjacent to the spill were voluntarily evacuated. Air monitoring around the perimeters of the homes showed no detectable VOC concentrations in the air six days after the release, so the residents were allowed to return home on October 19 (USEPA 2014a).*

***Yellowstone River, Glendive, Montana:** On January 17, 2015, Bridger pipeline released 715 barrels of Bakken light crude oil into the Yellowstone River five miles upstream of Glendive, Montana (MT DEQ 2015a). For the seven consecutive days after the release, ambient air quality sampling indicated no elevated levels of hydrocarbon components in the city of Glendive (USEPA 2015a).*

***Marshall, Michigan, and Red Deer, Alberta:** Laboratory experiments were performed by Zhou et al. (2015) to evaluate the behavior of a conventional light crude oil release (Red Deer Alberta 2012) versus a diluted heavy crude oil (diluted bitumen) release (Marshall, Michigan 2010). The study shows that diluted bitumen products have lower BTEX contents than conventional light and medium crudes, which contain 2 to 4 vol % BTEX. The study states that the volatile fraction of the* *conventional light crude oil was 30 weight percent versus 13.3 weight percent for the dilbit.*

The study also evaluated the rate of evaporative loss of the volatile fraction of both the dilbit and the conventional light crude oil based on the laboratory experiment. The majority (75 to 85%) of the loss occurred within the first six hours of the test. Further continued loss occurred over the following two to seven days.

The Red Deer release resulted in strong odors that lasted for several hours. At Marshall the odor persisted for a longer period, but that may have been due to the larger size of the release and the longer duration of the actual release. The author did suggest that a secondary consideration may have been the slower release of the volatile compounds from the dilbit (Zhou et al 2015).

***USEPA and U.S. Coast Guard – Bakken Crude**: The USEPA shipped 1,675 gallons of Bakken light crude oil to Eddystone, Pennsylvania for a pilot test, which was supported by the US Coast Guard. The study goals were stated to be (USEPA 2015b):*

1. *Evaluate benzene and other VOC emissions from a discharge of Bakken oil to gain more information to support Health and Safety decisions for responders and the public*
2. *Evaluate physical properties of Bakken oil, including weathering progresses, to better predict the fate on the surface water*
3. *Evaluate recoverability of fresh and weathered Bakken oil using standard methods*

On February 11, 2015, 660 gallons of crude oil shipment was discharged into a 100 ft by 65 ft outdoor test tank filled with water. The maximum ambient temperature during the study was 34°F. The oil was allowed to sit in the tank for 24 hours while air emission information was collected. The oil was then allowed to weather an additional week. Sampling of the oil indicated that within 24 hours all of the benzene evaporated from the oil sheen. Within six hours of the initial release, all VOC readings of the ambient air above the tank were below 5 ppm. USEPA estimated that 27% of the oil was lost to evaporation within the first 24 hours. After one week, 40% of the crude oil had been lost, with the majority of the loss being assumed to be evaporation.

7.1.2.1.2 Expected Effects of Released Oils

Key findings related to the potential effects of crude oil releases to air are presented below.

Table 7-12 and Table 7-13 provide a summary of the expected environmental effects of oil releases to air. Table 7-12 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-13 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

- Crude oil is a complex mixture of petroleum hydrocarbons. These hydrocarbons may contain only a few carbon atoms or contain 20 or more carbon atoms in long-chained, complex hydrocarbon molecules. In general, shorter and less complex hydrocarbons are more volatile, which means they evaporate more readily than longer chained hydrocarbons. These shorter chained compounds are referred to as VOCs.
- The release of VOCs, such as benzene, primarily occurs within the first 24 hours of an oil release.
- Since the rate at which the volatile organic compounds, such as benzene, evaporate from an oil release does not vary greatly, the actual concentrations observed in the surrounding community will be most affected by initial concentrations of benzene in the crude oil, the actual mass of oil released, the size of the area impacted by the release due to movement of the oil plume, and weather conditions, such as winds and atmospheric stability that will impact dissipation of the evaporated chemicals.
- The evaporative loss of longer chain petroleum hydrocarbons is controlled by weather conditions, such as wind and temperature and the depth of the pooled oil.
- The areas most affected by releases from a crude oil incident to the atmosphere are in the near vicinity of the oil release site or near areas of extensive recovery operations.

Table 7-12 Environmental Effects: Air Exposures

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil chemistry—volatile compounds and BTEX	Light crude oils contain 35 to 40 wt% volatile organic compounds (less than C10) (Crude Monitor 2016). The C2 to C4 organics are 3 to 9 wt% (NDPC 2016). The total BETX concentration of light crude is 2 to 4 Vol % (Zhou et al. 2015)	Medium crude oils contain 25 to 30 wt % volatile organic compounds (less than C10) (Crude Monitor 2016). The C2 to C4 organics are less than light crude oils. The total BTEX concentration of medium crude is 1 to 3 Vol % (Zhou et al. 2015)	Heavy crude oils contain 15 to 20 wt % volatile organic compounds (less than C10) (Crude Monitor 2016). The C2 to C4 organics are minimal. The total BTEX concentration of heavy crude is 0.5 to 1.5 Vol % (Zhou et al. 2015).	Diluted bitumens may contain variable amounts of BTEX, depending upon the characteristics and amount of the diluent used. For all of the crude oil types the benzene concentration represents 10 to 15 % of the total BTEX concentration (Crude Monitor 2016).
Oil chemistry—sulfur concentration	Light sweet crude oil contains less than 0.5 wt% Sulfur. Light sour crude oil contains 0.5 to 1.5 wt% Sulfur (Zhou et al. 2015). Bakken Crude oil contains less than 0.2 wt% Sulfur and less than 1 ppm H2S. (NDPC 2016)	Medium conventional crude oil contains 1.5 to 2.5 wt % Sulfur (Zhou et al. 2015).	Heavy conventional crude oil contains 3 to 5 wt % Sulfur (Zhou et al. 2015).	The sulfur content of diluted bitumens are similar to conventional heavy crude oil, but contains a relatively low level of H2S (Zhou et al. 2015).

Table 7-13 Environmental Effects: Air

Environment Characteristic	Low	Medium	High	Other Comments
Topographical change (terrain)	An oil release in a relatively flat area will result in pooling. The release of BTEX compounds is diffusion limited, so deeper pooling will slow the release of BTEX compounds, but also results in the compounds being released in a very localized area (Hanna and Drivas 1993).	As topography provides a means to move the oil release, the pooling of the crude oil will lessen. An increase in surface area does not significantly increase the oil evaporation rate (Fingas 1999), but the released compounds will be spread over a wider area.	See medium terrain effects.	
Flow velocity of the water body	An oil release into a slow moving water body, such as a lake, will result in a slower spread of the oil with a smaller area being directly affected relative to bodies of water with higher currents. Organic compounds evaporated from the release will be concentrated in a localized area.	An increase in the velocity of the affected water body will result in increased spreading of the crude oil. An increase in the surface area of the oil sheen does not significantly increase the oil evaporation rate (Fingas 1999), but the released compounds will be spread over a wider area.	See medium velocity effects. Higher velocity stream flows may also result in additional mixing, which would bring soluble constituents such as benzene into the water column, delaying the release of the benzene to the atmosphere.	The spread of petroleum released on water, including a waterbody with a slow to no current will generally be faster than the spread of a petroleum release on land.
Temperature	Low temperatures will mostly slow the volatilization rate of the heavier organic compounds (Fingas 1999). The light ends (C_2 to C_4 organics) will flash off readily as they are gases at lower temperatures and BTEX compounds will evaporate in the first 24 hours (USEPA study 2015, Zhou et al. 2015).	Heavier organic compounds will volatilize faster (Fingas 1999) in warmer temperatures, but the loss of light ends and BTEX are constrained by diffusion through the oil matrix, more than the increase in temperature (Hanna and Drivas 1993).	See medium temperature effects. High temperatures could lead to localized increases in ground-level ozone concentrations, but monitoring data has not shown any apparent increase based on case studies. (see Marshall case study).	

Table 7-13 Environmental Effects: Air

Environment Characteristic	Low	Medium	High	Other Comments
Distance to receptors	The potential effects to humans due to atmospheric concentrations of organic compounds are greatest near the release site and in areas of oil recovery activities. Voluntary evacuation orders were made for homes within 500 meters of Talmadge Creek (Marshall Case Study) and adjacent to the release in Louisiana (Mooringsport Case Study). The evacuation orders were lifted within one to three weeks of the release.	Odors and VOC concentrations were monitored two to six miles from the release site in the Squaw Creek subdivision and the village of Ceresco along the Kalamazoo River, but benzene alert levels were not exceeded (see Marshall Case Study). A school was voluntarily evacuated 7.5 miles from a release site, but real time air monitoring determined there was no substantive risk (Rainbow Pipeline Case Study).	VOCs were first detected at the Baker Estates subdivision in Battle Creek 3 days following the oil release. The subdivision is located ~15 miles from the original release location. No alert levels were exceeded (Marshall Case Study). Air monitoring performed in Glendive, Montana (5 miles upstream of a release) did not detect any VOC or benzene in the air for the 7 days following the release. (See Yellowstone River Case Study).	
Wind speed	Calm wind conditions will retard the evaporation of heavier volatile organic compounds (Fingas 1999). The evaporation rate of the more volatile organic compounds, such as benzene are unaffected by the wind conditions, so calm conditions and stable atmospheric conditions can result in the organic compounds being retained within the vicinity of the release site and can result in elevated concentrations.	A small increase in wind will allow mixing and increase the evaporation rate of the heavier organic compounds. Beyond the initial increase in wind from calm conditions to light, the volatilization rate of the organics is temperature related (Fingas 1999, Hanna and Drivas 1993). An increase in wind speed and instability will also increase the dissipation of volatile organic compounds, such as benzene and reduce ambient concentrations.	Heavy winds do not increase the volatilization rate of the heavier organic compounds from the crude oil matrix (Fingas 1999). Heavy winds will dissipate the volatile organic compound emissions, such as benzene, reducing ambient atmospheric concentrations.	

7.1.2.2 Groundwater

7.1.2.2.1 Description

Groundwater is water below the earth's surface that occurs in a porous or fractured geologic medium. The term groundwater is generally reserved for subsurface water that occurs beneath the water table and represents fully saturated geologic media (Freeze and Cherry 1979). However, the near surface partially saturated zone—referred to as the vadose zone—can be hydraulically connected to the underlying saturated zone and, as such, can play an important role in the discussion of potential groundwater effects from oil releases.

Groundwater is important as a water resource because of its significance as a source for domestic, agricultural, and industrial water supply, and its connection (source of recharge and discharge) to surface water bodies and natural surface water features (e.g., wetlands, fens, bogs, and marshes).

An oil pipeline release could potentially affect groundwater if the oil infiltrated into the soil and water soluble constituents in the oil partitioned into groundwater. If a sufficient volume of oil is released and the hydraulic pressure is sufficient to create a downward driving force, the oil in the pore space may infiltrate and reach the water table. Once in contact with the saturated zone, the vertical migration of the oil continues until buoyancy and increasing water content impede vertical migration. Water soluble compounds in the oil in contact with groundwater may form a dissolved-phase groundwater plume. If insufficient volumes and pressures of oil are present, the partially saturated vadose zone above the water table may hold oil in place and the released oil may never reach the water table. However, water soluble compounds may still dissolve into infiltrating pore water and may migrate to the water table. In general, sands and gravels allow for faster vertical migration of oil than less permeable soils composed of silts and clays.

Groundwater containing dissolved hydrocarbons may form an elongated plume in the direction of groundwater flow. Groundwater moves slowly, generally more slowly than water in rivers or streams. Groundwater flow rate is governed by the hydraulic gradient, and by the permeability of the medium and the effective porosity of the medium containing the groundwater (Freeze and Cherry 1979). In addition, natural attenuation processes such as retardation, biodegradation, and volatilization will limit the distance that dissolved phase constituents may migrate from the source of the oil release.

7.1.2.2.2 Observed Effects

Studies of crude oil and petroleum-related constituent releases provide a basis for evaluating the potential effects of crude oil releases on groundwater. A literature review was conducted to identify information on releases to groundwater. Following are the results of the review.

Most components of oils are relatively insoluble (Wang et al. 2003). However, oil in contact with groundwater will result in some dissolution of the soluble components. Generally, aqueous-phase solubility decreases with increasing molecular mass (and size) of the hydrocarbon molecule (Rivett 2014). The relatively low molecular weight monocyclic-aromatic components of crude oil (BTEX) are some of the more water soluble hydrocarbon components of crude oil. Crude oil also contains PAHs, composed of between two and six fused benzene rings, often with alkyl side chains of one or more carbon units in length (i.e., alkylated PAHs). PAHs have moderate (e.g., naphthalene with two rings) to very low (e.g., 5- or 6-ring PAH molecules with alkyl side chains) solubility in water. The PAHs are considered to be toxic, and those PAHs having four or more benzene rings can also be carcinogenic. Therefore, the presence of PAHs can be a source of concern, even at low concentrations. Additionally, crude oil also contains heavy fractions that include waxes, asphaltenes, and nonpolar compounds, which are functionally insoluble in water, and may have limited bioavailability.

For those constituents that are relatively water soluble, the effective dissolved phase concentration is controlled by the concentration of the constituent in the oil and its solubility in water. It has been found that the maximum dissolved concentration of a constituent of oil in contact with groundwater is proportional to the mole fraction of the constituent in the oil (this is referred to as Raoult's Law), and as a result the individual constituents do not achieve the dissolved concentration in groundwater that might be expected based upon the solubility of the pure substance in water. Individual compounds are often more soluble in oil than in water, thus they tend to remain in the oil (O'Reilly et al. 2001). Additionally, because the most soluble components constitute a relatively small percentage of the overall mass of the oil, the effective soluble concentrations are relatively low. A study that compared the calculated dissolved-phase concentrations of 69 crude oils found that benzene was the only aromatic or PAH compound tested that is capable of exceeding groundwater protection values for drinking water (O'Reilly et al. 2001). Despite the relatively limited solubility of petroleum related constituents in groundwater, BTEX, and to a lesser degree PAH, dissolution remains one of the potential concerns of an oil release on groundwater.

MN PCA (2005) states that "[v]arious natural processes control the movement of a petroleum plume and act to limit the risk exposure. These processes include dispersion, sorption to soil particles, dilution, volatilization, natural biodegradation and natural chemical degradation. Of these processes, natural biodegradation through metabolism by naturally occurring microorganisms is the primary mechanism responsible for petroleum mass reduction. For most petroleum releases, natural biodegradation will reduce toxic chemical compounds to non-toxic metabolic byproducts". Numerous multi-site studies conducted since the 1990s have presented results that indicate dissolved-phase hydrocarbon plumes (primarily BTEX) stabilize at relatively short distances from the source area (Newell et al. 1990; Rice et al. 1995; Mace et al. 1997; Groundwater Services Incorporated 1997; Newell and Connor 1998; Ruiz-Aguilar et al. 2003; Kamath et al. 2012; Connor et al. 2015). Each of these studies indicated that dissolved-phase hydrocarbon plumes are unlikely to be greater than a few hundred feet in length. Newell and Connor (1998) presented a summary of four multi-site studies that evaluated the length of dissolved-phase BTEX plumes. Based upon the combined results of 604 sites, the median plume length was reported to be 132 ft, and 90% of the plumes were less than 319 ft in length. Similarly, Connor et al (2015) presented a summary of 10 previous multi-site investigations in which plume length was evaluated for a total of 1,320 benzene plumes. Connor et al (2015) reported a median benzene plume-length of 140 ft and a 90th percentile of 345 ft at 772 sites delineated to 10 µg/L.

Of particular relevance is a study of 217 groundwater contaminated sites in Iowa that has similar surficial geology to that of the majority of the proposed pipeline routes, characterized by Quaternary glacial deposits (Ruiz-Aguilar et al. 2003). That study indicated mean plume lengths of 193 ft and 185 ft for dissolved benzene and toluene, respectively.

Studies of historical oil releases in Minnesota provide additional insight into the potential effects of oil releases on groundwater. The following provides a focus on a few cases with particular relevance to the conditions anticipated to be associated with the proposed pipeline.

> ***Bemidji, Minnesota****: Extensive studies of a release of crude oil near Bemidji, Minnesota, provided an in-depth understanding of the behavior of crude oil in a subsurface setting with similar geology and climate to sections of the proposed Project. The release has become known as the USGS Bemidji Crude Oil Research Site and is one of the most extensive research centers for land-based hydrocarbon releases. Researchers and regulatory agency personnel have agreed to limit remediation activities and to leave the remaining oil in place to study the effects of long-term natural attenuation processes. Research at Bemidji has involved extensive investigations of multiphase flow and transport, volatilization, dissolution, geochemical interactions, microbial populations, and biodegradation with the goal of providing an improved understanding of the natural processes limiting the extent of hydrocarbon contamination.*
>
> *On August 20, 1979, approximately 10 miles northwest of Bemidji, Minnesota, the land surface and shallow subsurface were contaminated when a crude-oil pipeline burst, releasing approximately 10,700 barrels of light crude oil (specific gravity 0.837 at 23°C; Baedecker et al. 2011) onto a glacial outwash deposit (Essaid et al. 2011). The site is located in the Bagley outwash plain near Bemidji, Minnesota. The surficial aquifer is approximately 60 ft thick and consists of sand and gravel outwash overlying till. Thin, discontinuous silt layers are inter-bedded with sand near the water table (Franzi 1988). The release occurred in the recharge area of a local flow system that discharges to a small closed lake approximately 1,000 ft hydraulically down gradient (Dillard et al. 1997). The burst section of pipeline was buried 5 to 10 ft below land surface, next to a railroad ROW, and approximately 15 ft above the water table. Locally, groundwater flows to the northeast with a mean groundwater flow velocity of approximately 300 ft per year (Bennett et al. 1993). Neither man-made hydraulic stresses (e.g., pumping wells and irrigation) nor other anthropogenic sources of the compounds of interest were present at the site at the time of the release.*

Clean-up efforts undertaken immediately following the release were able to recover approximately 75% of the released oil, and the remaining 25% is estimated to have infiltrated into the sand-gravel outwash aquifer forming three separate subsurface oil bodies (Essaid et al. 2011). Additional remediation activities during 1999 – 2004 removed a further 30,000 gallons of crude oil using a pump and skim remediation method (Enbridge 2008 in Essaid et al. 2011), but researchers requested that remediation be suspended to avoid interfering with ongoing research. Researchers and regulatory agency personnel have agreed to leave the remaining oil in place to study the effects of long-term natural attenuation processes.

Some crude oil infiltrated through the unsaturated zone to the water table near the rupture site and formed what is referred to as "the North pool." The separate-phase oil in the North pool was present within the sediment pore space from the land surface down through the unsaturated zone, and to 3 to 6 ft below the water table. Oil infiltrated through the unsaturated zone to form approximately a 5-ft thick zone containing separate phase oil at and below the water table. Some of the oil flowed over the surface toward a small wetland forming another oil-infiltration area (south oil pool). Oil saturations in the sediments (the volume fraction of pore space filled with oil) range from 10 to 20% in the unsaturated zone, to 30 to 70% near the water table (Dillard et al. 1997).

Spatial differences in the physical properties and degradation of the oil over time have caused alteration of the originally uniform source. The oil is selectively losing soluble and volatile compounds through dissolution and vaporization. Annual oil-mass loss rates of the crude oil source at different locations range from 0 to 1.25%, and total accumulated losses from the original oil mass are as much as 11% (Landon and Hult 1991). Dissolution of the free-phase oil into the groundwater has resulted in the formation of a plume of aliphatic, aromatic, and alicyclic (both aliphatic and cyclic) hydrocarbons. Infiltrated crude oil moved as a separate fluid phase approximately 100 ft in the direction of groundwater flow, while the plume of dissolved hydrocarbons in the groundwater extended up to 450 ft down-gradient from the leading edge of the source (600 ft in total; Cozzarelli et al. 2001). Most of the petroleum derivatives, including both aromatic and aliphatic compounds, migrating as solutes are actively being degraded by biologically mediated processes to carbon dioxide, water, and methane (Baedecker and Cozzarelli 1991).

An additional concern at the Bemidji site is the potential mobilization of naturally occurring heavy metals or trace elements such as arsenic. As a result of the geochemical and biochemical reactions occurring during the breakdown of hydrocarbons within the plume, studies have reported arsenic concentrations within the groundwater plume of 230 μg/L compared to less than 5 μg/L in *groundwater outside the plume (Cozzarelli et al. 2015). The arsenic was found to decrease down-gradient of the plume by re-attaching to the overburden solids through adsorption or co-precipitation with iron hydroxides, leading researchers to conclude that the breakdown of hydrocarbons alters the geochemistry of the area causing the release of arsenic from the overburden materials. Long-term monitoring of arsenic mobilization, as well as other naturally occurring heavy metals, is now occurring at the site.*

The Bemidji site is in a remote area with sparse population. Therefore, the potential for harmful effects to groundwater used for water supply is low. Because of the large area over which the oil infiltrated the Bemidji aquifer, about 40% of the oil is trapped in the unsaturated zone, and a considerable volume of oil is in hydrodynamic equilibrium at the water table. Both the dissolved-phase plume and crude oil in the subsurface source have evolved over time as hydrocarbon compounds have degraded and dissolved at different rates (Landon 1993). Model results have also shown that compounds with high effective solubility (i.e., benzene) and/or rapid biodegradation rates (i.e., toluene) were more depleted in the oil body than heavier compounds (Essaid et al. 2003). The existing subsurface oil body remains source of hydrocarbon components that dissolve into and can be transported with groundwater. Nevertheless, the dissolved-phase plume at Bemidji site has stabilized at 450 ft long, predominantly due to biodegradation and spatial variability of site's hydraulic properties (Franzi 1988, Baehr and Hult 1991).

***Cass Lake, Minnesota**: An additional case study is available from a site near Cass Lake, Minnesota where a leak at a crude-oil pipeline pumping station resulted in subsurface infiltration of an estimated 1,150 barrels of crude oil to the water table, and development of a corresponding plume of dissolved constituents in groundwater. Unlike the Bemidji release, which occurred in a single incident more than 35 years ago, the Cass Lake release occurred as an ongoing leak over an unknown period of time, but may date back to when the pumping station began operations in 1971, ending after it was discovered in early 2002.*

The Cass Lake site is located approximately 25 miles from the USGS Bemidji, Minnesota, research site. The glacial outwash aquifer beneath the Cass Lake site constitutes part of the Bagley outwash plain. The aquifer consists primarily of moderately well sorted fine to medium grained sand and silt with some interbedded gravel. Grey calcareous clay-rich till underlies the aquifer approximately 25 to 45 ft below the land surface. The groundwater in the glacial outwash has a high horizontal hydraulic conductivity compared to the groundwater in the till (Drennan et al. 2010; Lohman 1972). Depth to the water table generally varies with topography and is roughly 25 to 30 ft below land surface (Wenck Associates 2006 in Drennan et al. 2010). Previous work indicated *that groundwater movement in the area is generally from northwest to southeast at a velocity of approximately 85 ft per year (Drennan et al. 2010).*

A dissolved plume of benzene was estimated to extend approximately 500 ft to the southeast from the source. The dissolved plume is approximately 130 feet across and extends 6 to 10 ft vertically, with the location of maximum concentration becoming deeper with distance.

A monitoring program was established to define the extent of the contamination for the site and to verify human or ecological exposure. The remedial investigation included a review of all wells within a one mile radius of the site. The review concluded that no wells exist within 0.5 mile of the site in the direction the groundwater flows, 0.5 miles being greater than 5 times the estimated extent of the plume. Therefore, no humans have been exposed to any site contamination. Monitoring wells remain in place to detect if any contamination is moving toward any water wells. The monitoring also shows that the contamination is not entering a surface water body. The nearest potential surface water is Spike Lake, 0.5 mile away, well beyond the limits of contamination.

The USGS began a research project at the site in 2007 (Drennan et al. 2010). The research is focused on the natural attenuation and biodegradation of petroleum constituents in groundwater. As part of the USGS research, additional monitoring wells were installed specifically to monitor the natural attenuation of the dissolved groundwater plume in the down gradient direction. In 2010, the USGS published "U.S. Geological Survey Scientific Investigations Report 2010-5085: Fate and Transport of Petroleum Hydrocarbons in the Subsurface near Cass Lake, Minnesota," which details the results of the 2007 research project (Drennan et al. 2010).

The small area of the Cass Lake site leak presumably resulted in oil in hydrostatic equilibrium at the water table and with a minor amount of oil in the unsaturated zone. The progression of biodegradation of oil proceeds in a quasi-sequential manner with easily degradable compounds being lost first, but more resistant classes of compounds begin degrading before complete loss of less-resistant compounds. Data for the Cass Lake site oil samples show near complete depletion of the n-alkane fraction, placing the oil in the category of "heavily degraded" (Drennan et al. 2010). The alkyl-cyclohexanes are only partially degraded, indicating that the oil has not yet reached the category of "severely degraded." As oil degradation proceeds through higher levels of severity, the soluble fraction decreases to the point where very little dissolution of compounds into the groundwater occurs. Once the oil reaches this degradation state, at an unknown time in the future, the groundwater plume is not expected to pose a risk for further expansion. In the long term, a residual fraction of heavily degraded oil

> *consisting mainly of an unresolvable complex mixture of compounds will remain in the aquifer.*
>
> *The highly degraded state of the Cass Lake oil represents one of the important findings of the study. Although the start date of the Cass Lake leak is unknown, the highly degraded nature of the Cass Lake oil suggests the leak was active for decades. The Bemidji release is known to have occurred on August 19, 1979. After more than 30 years, the released oil in some locations is less degraded than the Cass Lake samples. Three possible aspects of the Cass Lake release that may contribute to the highly degraded state of the Cass Lake oil are: (1) the leak was active for many years, (2) high recharge rates stimulate degradation, and (3) the leak occurred slowly. The geochemical and microbial data show the redox conditions are similar to the Bemidji plume, which is decades old. Thus, the Cass Lake oil leak may have been present since the pumping station first began operations in 1971.*

7.1.2.2.3 Expected Effects of Released Oils

The potential effects of crude oil releases on groundwater include infiltration of residual oil into the vadose and saturated zones. The infiltrated oil may serve as a source of dissolved-phase volatile organic compounds in groundwater which in addition may alter the geochemical character of groundwater facilitating the increased dissolution of metals and other trace elements. The potential for releases to adversely affect groundwater quality depends upon multiple factors, including hydraulic gradient, soil type, geology, seasonal conditions, oil type, and the water solubility of constituents in the oil.

When crude oil is released to the ground, it needs to displace an equivalent volume of the resident fluids (air and/or water) from the soil. To infiltrate and enter a pore space it must overcome both the capillary pressure and the hydrostatic pressure needed to displace water (referred to as pore entry pressure). The ability of the oil to enter the pores is largely a function of the pressure of the release, properties of the geologic media, and density and viscosity of the oil (ITRC 2009). If a sufficient volume of oil is present overlying a porous media, it begins to enter the unsaturated pore spaces by moving downward under the force of gravity. This can be accompanied by lateral spreading due to geologic heterogeneity. Such liquids must have a sufficiently low viscosity to move through the local surface soils and overburden to reach the groundwater.

The percentage of oil held in pore space by the formation is referred to as "residual saturation." Oil at residual saturation is functionally immobile. It is in a state where additional movement is not anticipated because the forces of gravity are balanced by the capillary pressure. The oil distribution following gravity drainage from pores is characterized by an irregular, heterogeneous distribution of disconnected ganglia. Because a small amount of oil is retained in the pore space, the ability of the crude oil to reach the groundwater is a function of the vertical distance that the oil must travel. The residual oil in the pore space may come in contact with infiltrating water and become a source of a dissolved-phase contaminant plume.

In the case of crude oil, which is less dense than water, downward migration continues through materials that are partially saturated with water until it reaches the water table. This impedes its migration deeper due to both increasing water content and associated buoyancy forces arising from the oil-water density contrast. Near the water table crude oil and water coexist in pore space as a smear zone and the vertical equilibrium distribution is determined by capillary pressure. The magnitude of lateral spread of oil near the water table is determined principally by the subsurface geology, size of the release, as well as the properties of the crude oil (e.g., density and viscosity) (Rivett 2014).

The mobility of oil in the unsaturated zone depends primarily on several factors: (1) its saturation in the pore space relative to the other fluids, (2) the pressure (matric potential) that drives the flow of oil (driving head); (3) the vertical permeability of the unsaturated soils; and (4) the physical properties of the oil (largely viscosity and density).

The horizontal flow velocity in groundwater is a function of fluid physical properties (e.g. viscosity), the groundwater pressure gradient, and hydraulic properties of the porous media (Freeze and Cherry 1979). The equation for flow velocity (Darcy's law) may be written as follows:

$$v = k\, \mathbf{d}P / \mathbf{u}\, \mathbf{d}x$$

Where:

- v = fluid flow velocity
- k = intrinsic permeability of the media
- **d**P = the applied pressure difference
- **d**x = the thickness of the porous media
- **u** = viscosity

Factors that modify the behavior of crude oil releases with respect to groundwater contamination include soil type, hydraulic pressure, and crude oil properties, especially the amount and solubility of BTEX compounds. More permeable soils, such as sand and gravel, will allow for relatively faster infiltration and lateral migration of crude oil than less permeable soils, such as silt and clay. Coarse-grained soils would more readily admit or absorb released oil and, therefore, would be more prone to the development of persistent hydrocarbon plumes or free product. Increased hydraulic pressure results in increased gradients and faster flow velocity. Crude oils with low viscosity would also be more readily absorbed by soils and have greater potential to reach the water table.

Because both water and oil move slowly in the pores between soil grains, the distance between the ground surface and the water table (i.e., the depth to the water table) will also affect whether the oil reaches the water table, and the time it takes to get there. Thick unsaturated zones (greater depths to the water table) may act as a "sponge" to hold crude oil in place, more so than thin unsaturated zones with less pore volume storage. In situations where a small amount of oil is released, the soils are less permeable, or where the water table is very deep, oil may remain in the unsaturated zone and never reach the water table. At some time following termination of the release, the oil will reach a hydrostatic equilibrium and be functionally immobile (ITRC 2009). At that point dissolution and volatilization cause gradual depletion of lighter crude oil constituents, which may be accelerated by local dissolved-phase plume biodegradation (Rivett 2014). The degradation of the oil body may be relatively slow. As described in the Bemidji and Cass Lake releases, more than 30 years following the releases, oil and groundwater plumes remain in the subsurface (Essaid et al. 2011; Drennan et al. 2010).

Dissolved hydrocarbons may enter the groundwater through preferential dissolution of the soluble constituents. Light oils also typically contain higher levels of the more water soluble hydrocarbons, such as BTEX, and this also would tend to increase the potential for the development of groundwater contamination. Benzene is the primary constituent of crude oil that is capable of exceeding drinking water standards in groundwater (O'Reilly et al. 2001). Dissolved hydrocarbon plumes may move laterally; however, the lateral distance traveled is relatively short, generally less than a few hundred feet, and balanced by natural attenuation processes that reduce the concentration in groundwater over time. Natural attenuation will transform most toxic constituents of petroleum releases into non-toxic metabolic byproducts, typically carbon dioxide and water (MN PCA 2005). Numerous multi-site studies conducted since the 1990s have presented results that indicate dissolved-phase hydrocarbon plumes stabilize at relatively short distances from the source area and are unlikely to be greater than a few hundred feet in length (Newell and Connor 1998; Connor et al. 2015). The groundwater plumes resulting from the Bemidji and Cass Lake releases are reported to have traveled a maximum distance of approximately 450 ft and 500 ft, respectively.

Oil releases that affect the groundwater may also change the groundwater geochemistry as the hydrocarbons undergo biodegradation. The microbial degradation of hydrocarbons consumes oxygen and affects the reduction-oxidation (redox) state of other substances, such as sulfate, iron, and manganese present in the subsurface environment. Such redox reactions can transform iron and manganese from solid to soluble phases, and, in the process, release other trace elements that were previously bound by or co-precipitated in the solid phase. Arsenic concentrations within the hydrocarbon plume at the Bemidji site have been reported to be significantly higher than background concentrations and exceed drinking water standard, as the chemical reactions within the plume have caused arsenic to mobilize and leach out of the overburden solid phase (Cozzarelli et al. 2016). Arsenic is naturally present in soils and sediments, but is not usually a health concern unless it is mobilized by a chemical reaction and dissolves into groundwater. Arsenic released in the hydrocarbon plume is expected to reattach to aquifer sediments down-gradient from the plume, limiting the extent of the arsenic contamination in the groundwater to the approximate extent of the dissolved phase plume (Cozzarelli et al. 2016).

Key findings related to the potential effects of crude oil releases to groundwater are presented below.

- A crude oil release could potentially affect groundwater if the oil infiltrated into the soil and water soluble constituents in the oil partitioned into groundwater.
- Specific environmental conditions must be met to allow for the soluble components to reach the groundwater. The ability of a crude oil or the soluble components of crude oil to reach the groundwater is influenced by the depth to groundwater, geologic material permeability, and recharge.
- The ability of a crude oil to migrate vertically through a soil column is also influenced by the crude oil properties and release characteristics: hydraulic pressure, crude oil viscosity, crude oil density, and time.
- Dissolved hydrocarbons may enter the groundwater through preferential dissolution of the soluble constituents with benzene being the primary constituent of crude oil that is capable of exceeding drinking water standards in groundwater.
- Dissolved hydrocarbon plumes may move laterally in the direction of groundwater flow; however, the lateral distance traveled is relatively limited (generally less than a few hundred feet) and balanced by natural attenuation processes that reduce the concentration in groundwater over time and with travel distance in the aquifer.
- Crude oil releases that affect the groundwater also have the potential to change the groundwater geochemistry as the hydrocarbons undergo biodegradation. Redox reactions can transform iron and manganese from solid to soluble phases, and, in the process, release other trace elements, such as arsenic, that were previously bound by or co-precipitated in the solid phase. However, such trace elements are also likely to be removed from the dissolved phase and return to the solid phase once the groundwater emerges from the influence of the dissolved hydrocarbon plume.

Studies show that groundwater plumes of hydrocarbon compounds can persist for many years following a release of crude oil. Residual crude oil has the potential to serve as a source of dissolved phase contaminants in groundwater at concentrations above drinking water standards. However, the effects are generally restricted to low molecular weight hydrocarbons such as the BTEX compounds, and are limited to a relatively small area proximal to the release.

Table 7-14 and Table 7-15 provide a summary of the expected environmental effects of oil releases to groundwater. Table 7-14 considers the effects of specific oil characteristics or oil type on the expected type and scope of environmental effects. Table 7-15 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-14 Environmental Receptor: Groundwater

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil chemistry—soluble constituents	Light crude oils often contain relatively higher levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, depending on the oil type, but can be high (>10,000 mg/kg) in Bakken oils.	Medium crude oils often contain moderate levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, but can exceed 10,000 mg/kg.	Levels of BTEX and other relatively water soluble constituents are variable: generally low in heavy conventional oils, but variable in diluted bitumens depending upon the nature of the diluent. Levels of TPAH are variable, but typically depleted in napthalene and less than 10,000 mg/kg.	Regardless of the specific ratio of soluble constituents in the oil chemistry, benzene is the primary constituent that is typically capable of exceeding drinking water standards in groundwater (O'Reilly et al. 2001). The length of dissolved constituent plumes in exceedance of drinking water standards are generally less than a few hundred feet from the release location.
Oil properties—viscosity	Light crudes exhibit lower viscosity (1 to 5 mPa•s; NAS 2015). As a result of the lower viscosity, light oils are capable of infiltrating into soils at a relatively faster rate than higher viscosity oils.	Medium crudes have an intermediate viscosity (8 to 112 mPa•s; NAS 2015).	Heavy crudes (820 to 475,000 mPa•s) and diluted bitumens (270 to 50,000 mPa•s) weather to high viscosity (NAS 2015). The viscosity of fresh diluted bitumen is reduced by the addition of diluent, to conform to pipeline specifications.	The ability of oil to be transmitted through permeable media is inversely proportional to its viscosity. Viscosity is a function of oil chemistry. Diluted bitumens tend to display a more rapid increase in viscosity due to weathering than conventional heavy crude oils as a result of the rapid initial evaporation of some of the diluent. Viscosity also affects the residual saturation (amount of oil held within the formation). Residual saturation increases with viscosity. Recovery of released oil is facilitated if the oil is less dense and, as a result, exhibits a lower residual saturation.

Table 7-14 Environmental Receptor: Groundwater

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—density	Light crude oils typically have a low relatively specific gravity (0.78–0.88 g/mL, (Dupuis and Ucan-Marin 2015). The ability of the oil to enter the pores of a geologic medium is affected by density (ITRC 2009). Less dense fluids would be anticipated to infiltrate at a lower rate (all other factors being equal). In addition less dense fluids that migrate to the water table may spread more and penetrate the water table less due to the buoyancy effect caused by the density difference between water and oil.	Medium crude oils typically have an intermediate specific gravity compared to light and heavy crudes (Dupuis and Ucan-Marin 2015).	Heavy conventional crude oils can have density ranging of 0.88 to 1.00 g/mL, while fresh diluted bitumen will have a density less than 0.94 g/mL, increasing towards a density of 1.00 g/mL or slightly higher when fully weathered (Dupuis and Ucan-Marin 2015).	Density is directly proportional to the ability of the oil to move through a permeable material. An oil release with a relatively low density will travel faster in the subsurface than a relatively denser fluid. In addition the buoyancy will influence the distribution of oil at the soil water interface with less dense oils accumulating closer to the top of the water table and extending further into the capillary zone. Density and viscosity are correlated, so low density oils also tend to have low viscosity, whereas oils having higher density tend to have higher viscosity. High density slightly increases the ability of crude oil to flow within the overburden, but not to the extent that the higher viscosity is limiting the potential for movement.

Table 7-15 Environmental Receptor: Groundwater

Environmental Characteristic	Low	Medium	High	Other Comments
Soil permeability	Less permeable soils, such as silt and clay, will allow for relatively slower migration of crude oil than more permeable soils.	Medium-grained soil (fine sand to coarse sand) will allow for moderate oil infiltration	More permeable soils, such as sand and gravel, will allow for relatively faster migration of crude oil than less permeable soils.	Coarse-grained soils would more readily admit spilled oil, and, therefore, would be more prone to the development of persistent hydrocarbon plumes or free product. It is also noted that shallow bedrock exhibits a unique environment where permeability may be relatively low but isolated fractures may allow crude oil to be transported relatively quickly through preferential flow pathways.
Depth to groundwater	Thin unsaturated zones with less pore volume storage are more susceptible to oil migrating to the water table and potentially impacting groundwater resources.	Moderate unsaturated zones are relatively less susceptible than thin unsaturated zones.	Thick unsaturated zones are less susceptible to oil migrating to the water table. In situations where a small amount of oil is released or the water table is very deep, oil may remain in the unsaturated zone and never reach the water table.	Because both water and oil move slowly in the pores between soil grains, the distance between the ground surface and the water table (i.e., the depth to the water table) will affect whether the oil reaches the water table, and the time it takes to get there. Unsaturated zones may act as a “sponge” that hold crude oil in place. In situations where a small amount of oil is released or the water table is very deep, oil may remain in the unsaturated zone and never reach the water table.

Table 7-15 Environmental Receptor: Groundwater

Environmental Characteristic	Low	Medium	High	Other Comments
Weather conditions—temperature	Light oils remain fluid at lower temperatures and retain the potential to spread rapidly during the winter. In summer, light crude oils would also flow readily, having a greater potential to infiltrate more quickly than more viscous heavier oils.	Medium oils are slightly more viscous than light oils, and would also tend to flow readily under winter conditions. Medium crude oils would tend to flow readily under summer conditions.	Heavy oils become much more viscous at low temperatures, and as they weather. Heavy oils and diluted bitumens would have more resistance to flow than would be the case for light or medium crude oils. During the summer, diluted bitumens would flow readily.	Temperature affects both the behavior of oil in the environment, and the rate of natural attenuation processes such as volatilization and biodegradation. Key physical properties of oil such as viscosity may be sensitive to temperature. In addition, temperature plays an important role in biodegradation of hydrocarbons by affecting the physiology and diversity of the microbial community. Winter conditions such as frozen ground may greatly reduce the surficial permeability of soils inhibiting the vertical migration to groundwater.
Organic carbon content	Geologic media with low organic carbon content (e.g., clean sands and gravels) may be more prone to larger dissolved phase plumes because the constituents are not retarded by the adsorption/desorption processes.	NA	Soils containing abundant organic carbon (e.g., near surface soils and peats) may retard the transport of petroleum constituents in the subsurface.	Organic carbon can retard transport of dissolved petroleum hydrocarbon constituents reducing the potential overall distribution of these constituents in groundwater.

Table 7-15 Environmental Receptor: Groundwater

Environmental Characteristic	Low	Medium	High	Other Comments
Geochemistry	A relatively low quantity of electron acceptors such as oxygen, nitrate, iron or sulfate may limit the biodegradation processes. A low concentration of metals will limit the potential mobilization of metals in groundwater.	Moderate geochemistry is relatively less amenable to biodegradation and less susceptible to mobilization of metals than zones with an abundance of electron receptors and available metals.	An abundance of electron receptors within the dissolved plume may promote biodegradation processes. A high concentration of heavy metals and trace elements, such as arsenic, may support the potential mobilization of these constituents in groundwater.	The natural geochemistry of groundwater may influence both the natural attenuation processes and the potential dissolution of metals. Many indigenous microorganisms in groundwater and soil are capable of degrading hydrocarbon contaminants; however, this process may be rate limited by the presence of electron acceptors. The infiltrated oil may alter the geochemical character of groundwater, facilitating the increased dissolution of potentially toxic heavy metals and other trace elements such as arsenic.
Local recharge—rainfall	Low recharge will retard or delay the infiltration of soluble oil constituents towards the groundwater table, and into the groundwater.	N/A	High recharge will accelerate the infiltration of soluble oil constituents towards the groundwater table, and into groundwater.	Periods of high rainfall and high water levels could increase dissolution of soluble components of crude oil and facilitate transport to groundwater, while also reducing the time available for oil spill response activities to prevent environmental effects on groundwater quality.

Table 7-15 Environmental Receptor: Groundwater

Environmental Characteristic	Low	Medium	High	Other Comments
Release properties—driving head	The ability of an oil to penetrate a permeable geologic media is partially a function of the driving head (matric potential) exerted by the oil. A relatively small driving head would result in a low infiltration rate, all other factors being equal.	N/A	The ability of an oil to penetrate a permeable geologic media is partially a function of the driving head (matric potential) exerted by the oil. A relatively large driving head would result in a high infiltration rate, all other factors being equal.	Fluid flow velocity in a permeable media is governed by Darcy's law which relates velocity to intrinsic permeability, porosity, and applied pressure. The fluid velocity is directly proportional to the applied pressure.
Release properties—time	The volume of oil able to penetrate the subsurface is related to the rate of infiltration and time. A short time to spill response would be expected to result in a relatively smaller volume of oil in the subsurface, and lower potential for effects on groundwater.	N/A	A long time to spill response would be expected to result in a relatively larger volume of oil in the subsurface, and greater potential for effects on groundwater.	The volume of oil able to migrate vertically through a soil column is influenced by the oil infiltration rate and time. The oil volume able to penetrate the subsurface is directly proportional to the time the oil remains in contact with the geologic media. A quick and effective response to an oil release will minimize the potential for adverse effects on groundwater.

7.1.2.3 Lakes

7.1.2.3.1 Description

Lakes are defined as permanent standing water bodies surrounded by land. The water is typically fresh, although occasionally (usually in arid areas) it can be brackish or saline. Lakes may transition to wetland areas such as bogs, marshes, fens or swamps, but are differentiated by having predominantly open water, not occupied by vegetation. Such wetland areas are often peripheral or adjacent to lakes. Lakes may also transition into slowly moving river areas and can be differentiated on the basis of whether factors dominating flow are hydraulic (i.e., rivers) or wind and thermal circulation (i.e., lakes). Lakes are included in the effects assessment of land cover receptors due to their importance to aquatic and terrestrial life. They provide habitat for fish, amphibians, plants, benthic invertebrates, insects, birds, and mammals.

The effects assessment for lakes focuses on physical and chemical effects (i.e., habitat and water quality) of released, and excludes direct effects of oil on aquatic biota (e.g., aquatic plants, fish, wildlife) or sediment quality, which are considered elsewhere. Crude oil that enters a lake will generally float on the water surface. However, oil can also enter the water column as dissolved hydrocarbons or as liquid hydrocarbon in forms that range from small droplets suspended in the water column, to larger globules or other forms of oil that may re-surface, remain suspended in the water column, or sink to the bottom (Hollebone et al. 2011). Relevant petroleum exposure monitoring parameters in water include benzene, toluene, ethyl benzene and xylene (BTEX, low molecular weight and relatively volatile and water-soluble fractions that weather and biodegrade quickly), polycyclic aromatic hydrocarbons (PAHs, more persistent substances composed of two or more fused benzene rings, which are more often implicated in chronic environmental effects of hydrocarbons) and aliphatic hydrocarbons (hydrocarbon molecules that are composed of more linear, although often branched, chains of carbon atoms). More general monitoring parameters include "total" or "extractable" petroleum hydrocarbon (TPH/EPH).

7.1.2.3.2 Observed Effects

There is potential for oil released accidentally from a pipeline to reach a lake proximal to, and downgradient from, the pipeline corridor. However, releases directly to a lake appear to be rare, given that pipeline routes typically avoid lakes. A more common scenario is for oil to enter a stream or river, and then move downstream to a lake. This is supported by the literature on oil releases. Discussions of four case studies with circumstances similar to those that might be encountered in the event of an oil release from a pipeline in Minnesota are presented below.

> ***Wabamun Lake, Alberta:*** *On August 3, 2005, a train belonging to Canadian National railways derailed, releasing approximately 4,500 barrels of Heavy Fuel Oil 7013 (a Bunker C type fuel oil with a high viscosity and an initial density of about 0.99 at lake temperature) and 553 barrels of pole treating oil (Transportation Safety Board of Canada 2007). About 20% of the released heavy fuel oil*

(950 barrels) traveled overland and entered Wabamun Lake. No appreciable volume of pole treating oil entered the lake (Hollebone et al. 2011).

In the lake, the oil floated and spread rapidly over the lake surface. After a few days, strong winds and wave action dispersed the oil toward the northern, eastern, and southern shorelines, where it became entrained in macrophyte beds (Thormann and Bayley 2008; Anderson 2006). The windy conditions also resulted in mixing of the oil in the water column, with PAH and BTEX concentrations initially higher in boomed areas than Canadian water quality guidelines for protection of aquatic life, but lower than the guidelines in open water areas outside the boomed areas (Anderson 2006). While traveling overland, the oil mixed with soil and organic matter, and in the lake, OPAs formed quickly, including small tar balls, larger balls called "tar logs," submerged sheets, and large lumps. The composition of the aggregates was not static, and tar balls sometimes reformed into oil slicks (Fingas et al. 2006; Hollebone et al. 2011). The aggregates showed a variety of behaviors, including submergence, neutral buoyancy, and resurfacing (Fingas et al. 2006), with extensive tar mat formation in some nearshore areas. Behavior of oil in the lake (rapid formation of tar balls, sinking, slow degradation due to high proportions of high molecular weight components such as resins) and toxicity and persistence due to high PAH levels but low BTEX levels, was related to characteristics of the heavy fuel oil. Within four months of the release, concentrations of BTEX and PAHs were below detection in lake water (Birtwell 2008; Anderson 2006).

High initial density and viscosity, and a lack of lower molecular weight components in the heavy fuel oil distinguish this released oil from the types of crude oil and diluted bitumen products expected to be transported in the proposed pipeline.

***Marshall, Michigan:** On June 25 and 26, 2010, the Line 6B pipeline owned and operated by Enbridge ruptured, releasing approximately 20,000 barrels of heavy crude oil (NTSB 2012a). Of the released oil, approximately 8,200 barrels entered Talmadge Creek, a tributary to the Kalamazoo River, near Marshall, Michigan (NTSB 2012a). The released oil was a combination of Western Canadian Select and CLB diluted bitumens. The release occurred on the floodplain of Talmadge Creek, where wetlands are abundant (USFWS et al. 2015a). Some of the released oil traveled down Talmadge Creek to the Kalamazoo River.*

The Kalamazoo River is a meandering, low gradient river with diverse channel and floodplain features, extensive floodplain forests and wetlands, off-channel water bodies, and impoundments (Dollhopf et al. 2014). Upon entering the water, the density of the crude oil was less than that of water, and it floated, forming an oil slick that flowed downstream. The Kalamazoo River was in flood at the time of *the release, and oil was carried as far as Morrow Lake, an impoundment in the river, 36.5 miles downstream. Oil was deposited on river shoreline, riparian, and depositional areas, and also along the shores at the delta of Morrow Lake (USFWS et al. 2015a).*

High river flows entrained some of the oil into the water column (resulting in submerged oil). Dam spillways may also have caused emulsification of some of the oil, and driven further oil into the water column. Over time, weathering of the lighter components and interaction of the submerged oil with suspended or shoreline/bottom sediments resulted in some of the oil sinking to the river bed in slow-moving or depositional areas of the river, particularly the upper end of Morrow Lake, a lake-like impoundment in the river. Formation of OPAs was likely promoted by the flood conditions at the time of the release, which increased turbulence and suspended sediment loads in the river, and by the turbulent mixing of water and oil (Fitzpatrick et al. 2015). The oil that reached Morrow Lake had been pre-conditioned by river transport (weathering, formation of OPAs) prior to reaching the lake.

Surface water was sampled from July 2010 through April 2012 and measured for oil-related and non-oil related chemicals. Only a very few of these measured chemicals were detected above health-protective screening levels and most of the chemicals detected at these levels were PAHs (MI DCH 2014b). It was not expected that people would be exposed to levels of these chemicals that would cause long-term health concerns.

Oil was deposited on sediments in the delta of Morrow Lake, and subsequently removed during clean-up activities.

***Red Deer River, Alberta:** On June 7, 2012, approximately 2,900 barrels of light crude oil was released from a ruptured pipeline owned and operated by Plains Midstream Canada ULC, into Jackson Creek, a tributary of the Red Deer River, about 1.9 miles north of Sundre, Alberta. Floodwaters 10 times higher than the typical June flows eroded the stream bed and banks, and exposed the pipeline under the river, which then ruptured (Alberta Energy Regulator 2014). Oil travelled at least 25 miles downstream to Gleniffer Lake reservoir, where booms contained the floating oil. Dissolved hydrocarbons in river water were detected up to 5 miles further downstream during the first week post-release (Alberta Environment and Sustainable Resource Development [ESRD] 2012a).*

Hydrocarbon (BTEX, PAH, and alkanes) concentrations in water were monitored twice a day in the first week post-release, then once a day to July 12, 2012 (Alberta ERSD 2012b). Lighter weight hydrocarbons (BTEX) evaporated quickly, but some dissolved in the river water and, in the early days post-release, were *detected up to 30 miles downstream of the release location. One day post-release, benzene and toluene were detected in Gleniffer Lake, with toluene (peak of 0.0314 mg/L near the booms) above the Canadian water quality guideline for aquatic life (0.002 mg/L). BTEX and PAHs attributable to the release were detected up to nine days post-release. PAH concentrations also decreased over time and were below Canadian water quality guidelines for protection of aquatic life on all dates, except for benz(a)anthracene at three times the guideline four days post- release at several locations in Gleniffer Lake.*

The main concerns for Gleniffer Lake and downstream areas were for drinking water quality, but monitoring indicated no detectable hydrocarbons in drinking water intakes (Alberta ERSD 2012b). Reports of habitat studies in Gleniffer Lake were not found. The lack of studies is likely due to concerns about lake habitat being reduced because of the low volume of the release in proportion to the volume of river (large dilution) and the high amount of weathering, related to both distance (25 miles) and type of oil released (light crude oil) upstream of Gleniffer Lake. No reports were found of oil sinking in the river or Gleniffer Lake.

***Unamed Lake, Alberta:** On June 22, 2013, a break in Line 37, the Line 37 pipeline owned and operated by Enbridge Pipelines Inc., resulted in release of 1,300 barrels of synthetic light crude oil onto the pipeline ROW. The oil traveled overland to a fen, then reached a small, unnamed lake. Physical barriers were deployed to limit spreading of the oil. As part of the subsequent site assessment and remediation process, total of 137 sediment samples were collected from 64 locations between July and August, 2014. In sediment, the highest petroleum hydrocarbon concentrations were found along the northwest shoreline of the lake. Targeted sediment excavation occurred in the northwestern portion of the lake where the highest hydrocarbon concentrations were observed close to shore (Hemmings et al. 2015).*

***Mayflower, Arkansas:** On March 29, 2013, a breach in the 20-in. Pegasus Pipeline operated by the ExxonMobil Pipeline Company released crude oil into a residential neighborhood in Mayflower, Arkansas (Arcadis 2014). The crude oil was identified to be Wabasca heavy crude oil (a type of diluted bitumen originating from Alberta, Canada). An emergency response action was implemented to mitigate the release, resulting in the recovery of a substantial amount of the crude oil. From the residential area, some of the oil entered a drainage way leading to a shallow drainage swale along North Main Street. From there the oil flowed east under Highway 365 and Interstate 40 (I-40) into a marsh known as Dawson Cove (Figure 1-1). Dawson Cove is separated from Lake Conway by Highway 89, with water conveyed between the cove and lake by two culverts beneath the highway (Arcadis 2014).*

> *Sediment samples (including both surface and subsurface samples) were collected at 53 locations within the drainage ways, Dawson Cove, and Lake Conway. Background sediment samples were collected from six distant locations in Lake Conway upstream of the generalized flow path from Dawson Cove to the Lake Conway dam and six locations in shallow ditches upstream of the primary drainage path from the residential area to Dawson Cove. A total of 125 sediment samples were collected at 34 locations in Dawson Cove. Based on the screening results, hydrocarbon concentrations in 118 of 125 sediment samples were found to be at levels that did not require further evaluation (Arcadis 2014). Seven samples had xylenes and/or isopropylbenzene above the ESV; a refined risk evaluation, indicated that at the reported concentrations, no adverse effects were anticipated for aquatic life in Dawson Cove sediment (Arcadis 2014). A total of 18 sediment samples were collected at 6 locations in Lake Conway. Based on the screening results, sediments in Lake Conway did not warrant further evaluation (Arcadis 2014).*

7.1.2.3.3 Expected Effects of Released Oils

The expected effects of crude oil released into a lake are changes in water quality and effects on physical habitat quality. The further effects of these changes on sediment quality and biological components of the aquatic environment (such as fish and wildlife) are discussed elsewhere. Most crude oils float on water (i.e., they have an initial density that is less than the density of fresh water). This applies to light crude oils such as Bakken oils, as well as to heavy crude oils such as diluted bitumens, which are generally limited to a maximum density of 0.94 when shipped by pipeline. While raw bitumen may have a density that is greater than 1.0, raw bitumen would be far too viscous to pump through a pipeline. It has been suggested (NAS 2015) that diluted bitumen could weather rapidly after being released, so that changes in its properties could result in sinking. However, Lee et al. (2015) concluded that "the observation of evaporative mass losses of less than 20% after rigorous weathering at environmentally-relevant temperatures for dilbits nominally comprising greater than or equal to 30% diluent suggests that a substantial proportion of diluent remains intimately associated with bitumen". Therefore, diluted bitumen is unlikely to weather naturally to a density greater than that of fresh water within a timeframe that is relevant to oil spill emergency response operations.

A release of fresh diluted bitumen is expected to result in effects similar to those for other heavy crude oils. Diluted bitumen does not completely separate into diluent and bitumen components when released (Taylor et al. 2014; Zhou et al. 2015; Fingas 2015a). Diluted bitumen floats on water and can be stranded on shorelines. Released oil can pick up soil and organic matter from land or water, and then form OPAs, which can sink if sufficient amounts of particulate matter are incorporated in the oil particulate aggregates. A high proportion of diluent (e.g., condensate) will evaporate quickly and some will be dissolved in the water column. The residual oil components (PAHs, heavier alkanes, etc.) will degrade more slowly.

Crude oil released into a lake environment will generally spread as a slick or sheen, depending upon the ambient temperature and viscosity of the oil. Light crude oils might spread out to form very thin slicks or sheens, whereas heavy crude oils will form thicker slicks, with associated sheens. Depending upon the volume of crude oil released, the size of the water body, and weather conditions, the oil could spread out to cover the whole surface of the lake. Alternatively, strong winds might herd the released oil to the downwind side of the lake. There, the oil might be driven onto shore, and wave action might entrain some of the released oil into the water column as droplets of various sizes.

When oil comes into contact with sediment, interactions between the oil and the sediment can result in the formation of aggregates that have a density greater than that of water. Two main types of interaction occur: small droplets of oil suspended in the water can become coated with adhering fine sediment particles to form OPAs. Light crude oils with low viscosity are more readily entrained into water as small droplets than heavy crude oils. Therefore, light crude oils may be more prone to formation of OPAs than heavy crude oils. Alternatively, larger droplets, globules, or masses of oil can acquire silt, sand or gravel-sized particles as a result of interactions along shore. The resulting aggregate can also have density greater than that of the water and sink. Diluted bitumens and other heavy oils appear to be more prone to this second type of interaction with sediment particles. Importantly, however, any type of oil can sink as a result of interaction with particles that are denser than water.

The expected effects of released crude oil on water quality are often of short duration (i.e., days rather than weeks or months) because the more water soluble components of crude oil tend to evaporate within the first 24 hours of release. When dissolved in the water column, these compounds also tend to undergo biodegradation quickly (Lee et al. 2015). However, effects on physical habitat (from oil stranded on shorelines or incorporated into sediment) can last for much longer, and potentially for years if not remediated.

Table 7-16 and Table 7-17 provide a summary of the expected environmental effects of oil releases to lakes. Table 7-16 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-17 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-16 Effects of Oil on Lakes by Oil Characteristic

LAND COVER RECEPTOR: Lakes				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
Density	Light crude oils have API gravity of >31.1°.	Medium crude oils have API gravity of 22.3-31.1°.	Heavy crude oils have API gravity <22.3°, with diluted bitumens generally falling in the range of API gravity between 16 and 23°.	Oils of API gravity >10° will float on fresh water at 15 °C. Therefore, the fresh oils are all expected to float on water.
Viscosity	Light crude oils have viscosity generally in the range of 5 to 50 cP. Low viscosity oils are more likely be become entrained into the water column as small droplets, where mixing energy is high (e.g., windward shorelines).	Medium crude oils have viscosity generally in the range of 100 to 350 cP.	Heavy crude oils have viscosity generally in the range of 350 to 500 cP, although this rises rapidly with weathering. With higher viscosity, heavy crude oils are more resistant to becoming entrained into the water column as small droplets, although larger globules of oil may temporarily become submerged and re-surface.	Viscosity decreases with temperature, and increases with weathering.
Volatility	Contains a large fraction of volatile low molecular weight hydrocarbons; most prone to weathering by volatilization.	Intermediate in volatility and tendency to weather through volatilization between light and heavy crude oil.	The fraction of volatile low molecular weight hydrocarbons depends upon the oil type. Conventional heavy crude oils may have relatively low volatiles content. However, diluted bitumens contain diluent, which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large volatile component. CLWB is an example of a diluted bitumen with a relatively large component of condensate and a volatile content similar to that of many light crude oils.	High volatility is generally correlated with low density, and low viscosity in crude oils.
Solubility in Water	Contains a large fraction of soluble low molecular weight	Intermediate in proportions of soluble low molecular weight hydrocarbons	The fraction of soluble low molecular weight hydrocarbons depends upon the oil type. Conventional heavy crude oils	Undiluted bitumen is virtually insoluble, but diluent added to bitumen contains a high

Table 7-16 Effects of Oil on Lakes by Oil Characteristic

LAND COVER RECEPTOR: Lakes				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
	hydrocarbons, and therefore can release relatively water soluble constituents to lake water, particularly if mixing energy is high and small oil droplets become entrained into the water column.	between light and heavy crude oil.	may have relatively low solubility. However, diluted bitumens (e.g., 2010 Marshall release) contain diluent, which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large component of relatively water-soluble aromatic compounds.	fraction of soluble low molecular weight hydrocarbons.
Adhesion	Low adhesion to surfaces, and tending to weather quickly when deposited as a thin layer on exposed surfaces.	Intermediate adhesion to surfaces between light and heavy crude oil.	High adhesion to surfaces, and weathering more slowly due to greater asphaltene content than lighter crude oils.	Oil may adhere to surfaces such as substrates, debris, flora, and fauna. Heavier oils tend to be more adhesive, and to be deposited as a thicker and more persistent layer, than lighter crude oils.
Emulsification	Unlikely to occur (content of asphaltenes in light crude oil is low).	Unlikely to occur (content of asphaltenes in medium crude oil is low).	Asphaltenes are present in heavy crude oils. Conventional heavy crude oils tend to form emulsions readily. However, diluted bitumens appear to have low potential to form emulsions.	Emulsification is less likely to occur in fresh water than in salt water, even for releases of heavier oils, because there generally is not enough mixing energy to create stable emulsions.

Table 7-17 Effects of Oil on Lakes by Environmental Characteristic

LAND COVER RECEPTOR: Lakes				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Wind speed and direction	Low velocity winds may result in limited spreading or containment of oil.	Moderate velocity winds can have some ability to transport oil across lakes or to contain the oil to an area of a lake, depending on the location of the release and direction of the wind.	High velocity winds can transport oil across lakes or contain the oil to an area of a lake, depending on the location of the release and direction of the wind. High winds may also cause entrainment of oil, particularly low-viscosity oil, into the water column.	Heavy fuel oil released in Wabamun Lake in 2005 was spread by strong winds to the north, east and west shores (Anderson 2006).
Wave action	Low wave action may result in little or no dispersion of oil in water.	Moderate wave action can result in some dispersion of oil in water, particularly low-viscosity oils.	High wave action can result in substantial dispersion of oil in water, with low-viscosity oils more susceptible than high viscosity oils.	Dispersion of crude oil as small droplets into the water column can promote dissolution of more water soluble hydrocarbon constituents (promoting acute toxicity to aquatic life). It can also facilitate interactions with suspended mineral particles in the water column, leading to OPA formation and potential sinking of the aggregate.
Ice cover	Without ice cover, crude oil will spread over the water surface as a result of gravity (facilitated by low viscosity and surface tension) or wind action.	Patchy or partial ice cover will have a limited effect on oil movement on the water surface, but low temperatures will limit spreading due to increased viscosity of the oil.	Full ice cover and low temperatures will limit the ability of oil to penetrate into the water column. Snow pack on ice may also absorb and limit the spread of oil, facilitating its recovery. Oil released under the ice, or entering a lake with river flow, may spread under the ice and be difficult to track.	Ice cover will slow the spread of released oil due to the higher and surface tension induced by cold temperatures. Volatility and biodegradation rates are also reduced at low temperatures.

Table 7-17 Effects of Oil on Lakes by Environmental Characteristic

LAND COVER RECEPTOR: Lakes				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Biodegradation	Low rates of biodegradation can result in slower weathering and increased persistence of oil. Biodegradation rates are typically low when oxygen is limiting or absent. Some hydrocarbons, particularly resins and asphaltenes, are resistant to biodegradation. These substances tend to be more abundant in heavy oils than in light oils.	Moderate rates of biodegradation can increase the rate of oil weathering. Aerobic biodegradation can deplete local dissolved oxygen concentrations.	High rates of biodegradation can result in rapid weathering of oil. Aerobic biodegradation can deplete local dissolved oxygen concentrations. Light crude oils generally biodegrade more rapidly and more completely than heavier oils.	Rates of biodegradation depend on composition of the oil, temperature, dissolved oxygen concentration, and nutrient availability (Lee et al. 2015).
Temperature	At low temperatures, oil viscosity, density, and surface tension increase, and volatility of low molecular weight hydrocarbons decreases. Biodegradation rates are also low.	At moderate temperatures, oil viscosity, density, and surface tension decrease and volatility of low molecular weight hydrocarbons increases, leading to greater potential for spreading of oil. Biodegradation rates increase with increasing temperature.	At high temperatures, oil viscosity, density and surface tension are at a reduced, increasing the potential for spreading and dispersion of crude oil. Low molecular weight hydrocarbons are more volatile at high ambient temperature. Biodegradation rates are highest at high temperatures in freshwater. Some hydrocarbons, such as low molecular weight aromatic hydrocarbons, are more soluble at high temperatures (Lee et al. 2015).	Lake temperature is affected primarily by season.
Dissolved	Low oxygen	Most lakes have moderate	High oxygen environments (saturated)	Oxygen is typically not a

Table 7-17 Effects of Oil on Lakes by Environmental Characteristic

LAND COVER RECEPTOR: Lakes				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
oxygen	environments typically occur in deep zones of stratified lakes, in sediment pore water, or in winter under ice cover. Low oxygen availability limits aerobic biodegradation of oil. Anaerobic degradation of oil can occur but rates are slower than for aerobic processes.	oxygen levels (not fully saturated), especially in sub-surface waters. Oxygen levels are typically greatest near the surface due to wave action and diffusion of oxygen into the water. The rate of phytoplankton growth and degradation influences oxygen levels in the water column. Microbial degradation of crude oil could deplete the oxygen concentration in lake water.	typically occur in near-surface water, or during spring and fall overturn in dimictic lakes. The presence of phytoplankton can result in super-saturation of oxygen in daylight hours, with low oxygen concentrations occurring at night due to dark respiration.	limiting factor to biodegradation except in deep or strongly stratified aquatic environments, and there, only in the unlikely event that oil sinks into the anaerobic environment (Lee et al. 2015). However, almost any sediment can have limiting oxygen conditions, and oil in sediments can be expected to degrade slowly.
Nutrient supply	Oligotrophic lakes contain naturally low levels of nitrogen, phosphorus, and organic carbon. Low nutrient availability can limit the capacity for biodegradation (Lee et al. 2015).	Mesotrophic lakes contain moderate levels of nitrogen, phosphorus, and organic carbon that can support oil biodegradation in a lake (Lee et al. 2015).	Eutrophic lakes provide elevated levels of nitrogen, phosphorus, and organic carbon (either naturally or through human activities), which can support a high capacity for oil biodegradation in a lake (Lee et al. 2015).	Nutrient availability varies seasonally and from lake to lake. Nutrient levels are typically highest in spring and fall, at the time of overturn. Nutrients are sometimes added to oiled environments in order to stimulate microbial degradation of oil (Lee et al. 2015).

Table 7-17 Effects of Oil on Lakes by Environmental Characteristic

LAND COVER RECEPTOR: Lakes				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Suspended Solids	Low levels of suspended solids, typical in open water areas of lakes, provide a low potential for oil to interact with particles and form aggregates.	Moderate levels of suspended solids may occur in near shore areas of lakes, where sediments can be suspended from the bottom, transported from shore by overland flows, or introduced at stream inflows (e.g., during spring freshet and rain events). There is some potential for oil to interact with particles and form aggregates. These aggregates may be neutrally buoyant and enter the water column or become denser than water and sink to the bottom (Lee et al. 2015).	High concentrations of suspended solids may occur in near shore areas of lakes, where sediments can be suspended from the bottom, transported from shore by overland flows, or at stream inflows (e.g., during spring freshet and rain events). There is high potential for oil to interact with particles and form aggregates. These aggregates may be neutrally buoyant and enter the water column becoming denser than water and sink to the bottom (Lee et al. 2015).	Formation of OPAs is limited in fresh waters (i.e., at low levels of salinity). In addition, high levels of both turbulent mixing energy and suspended sediment are required in order for oil-particle interaction to be an important process in the fate of released crude oil. Hospital et al. (2016) concluded that these conditions are rarely met in the lower Fraser River and Salish Sea, and therefore they are also unlikely to be present in most inland lakes.

7.1.2.4 Rivers

7.1.2.4.1 Description

Rivers and streams can be defined as permanent flowing fresh-water bodies surrounded by land, and distinguished loosely on the basis of size (width, depth, flow volumes) and location or stream order within a watershed. They can be differentiated from permanent standing waterbodies such as lakes and ponds on the basis of whether flow is dominated by hydraulic factors (i.e., flow as in rivers and streams) or other factors such as wind or thermal circulation (i.e., water circulation as in lakes). Rivers are included in the present effects assessment of land cover receptors due to their prominence in the proposed ROW routes, their importance to aquatic and terrestrial life, and the role that they can play in transporting released crude oil away from an accidental release point. Rivers provide habitat for fish, amphibians, plants, benthic invertebrates, insects, birds, and mammals, and provide valued recreational, aesthetic, cultural, and economic values for humans.

The effects assessment for rivers focuses on observed and expected physical and chemical effects of released oil on rivers and streams. Effects of accidental crude oil releases on aquatic biota (e.g., benthic invertebrates, fish, and aquatic plants) are discussed separately. Crude oil released in rivers generally floats, interacting with shorelines as it moves downstream. Depending upon the crude oil type, a considerable amount of the released oil may escape to the atmosphere as VOCs. However, crude oil can also enter the water column as the dissolved water-soluble fraction of oil, dispersed as fine droplets, or mixed with soil or sediment as OPAs. Depending upon its interactions with suspended sediments and shoreline, crude oil may also be deposited to bed sediments in depositional areas (such effects are discussed elsewhere).

7.1.2.4.2 Observed Effects

There is potential for oil released accidentally from a pipeline to reach a stream or river, either at a pipeline crossing location, or after overland flow away from the pipeline right of way. In either case, released crude oil that reaches a watercourse can be transported downstream with the flowing water. To better understand the potential effects of oil releases on riverine resources, observed effects are compiled from four case studies where oil was accidentally released into river environments.

> ***Asher Creek, Missouri (1979)****: In August 1979, a pipeline burst, releasing approximately 9,500 barrels of unspecified domestic crude oil into Asher Creek, in southwest Missouri, during low flow conditions (Crunkilton and Duchrow 1990). A responsible party has not been identified for this incident. The creek originates in springs upstream from the release location. Information about hydrocarbon concentrations in water was not provided, but dissolved oxygen, pH, and conductivity levels in water were not changed by the release. The first site downstream from the release point was described as being "completely inundated with oil". Additional study sites were located downstream of six surface skimming siphon dams which were placed across the stream to retain floating oil*

after the release occurred (Crunkilton and Duchrow 1990). These dams were reported to contain most of the released oil. However, upstream of the dams, oil penetrated riffle substrates and coated the stream bed. Oil that entered riffle substrates due to mixing was visible for over a year (Crunkilton and Duchrow 1990). Low water volumes in these headwaters, particularly during summer at the time of the release, provided limited dilution of the oil. The first scouring floods occurred in February, six months after the release, and helped to dissipate the oil. Oil was observed as a sheen on the water surface after disturbing the substrate up to 453 days after the release at Site 2 (above the siphon dams), and up to 336 days after the release at Site 3 (below the siphon dams), but no oil was observed at other sites during the 532 day study (Crunkilton and Duchrow 1990).

***Pine River, British Columbia**: On August 1, 2000, a pipeline owned by Pembina Pipeline Corporation ruptured and released approximately 6,200 barrels of sour light crude oil, of which approximately 2,800 barrels entered the Pine River in British Columbia (BC MOE 2000a). The Pine River is fast flowing, and oil was dispersed up to 50 miles downstream. The fast flowing water allowed rapid dispersion of acutely toxic fractions of the oil into the river water. Oil was stranded and settled in depositional areas along the banks, in back eddies, and in other slow-flowing areas, as well as on organic debris and logjams (AMEC 2001 in Lee et al. 2015). Heavy rainfall later in August and September mobilized stranded oil and oil-contaminated debris and sediments; high water levels scoured some of the more heavily oiled depositional areas. Oil was recovered from the river over a period of two months, with about 91% of the released oil recovered (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015). Most of the oil that remained unaccounted for was considered likely to be located in river sediments, or trapped in woody debris dams in the river. Some of the emergency response activities (e.g., removal of log jams and woody debris, altering of back channels, bank armoring, and presence of heavy machinery in the river) also resulted in habitat damage (Summers 2004 in Bustard and Miles 2011).*

The Pine River is an important source of drinking water for the town of Chetwynd, British Columbia, and as a result of the release, the town closed its water intake and used alternate water sources. Effects on water quality included visual and olfactory evidence of oil contaminants over a 50-mile section of river. After three weeks, hydrocarbons were still detectable chemically in water but had decreased rapidly to below British Columbia water quality guidelines due to evaporation, degradation, and natural dispersion (Lee et al. 2015). Sheen was largely restricted to back eddies and other calm areas along shorelines. The rapid decline in hydrocarbon concentrations in river water was attributed to the characteristics of the light crude oil released (rapid evaporation, dissolution, degradation, and natural dispersion).

***Marshall, Michigan**: On June 25 and 26, 2010, the Line 6B pipeline owned by Enbridge ruptured and released approximately 20,000 barrels of heavy crude oil, of which approximately 8,000 barrels entered Talmadge Creek, a tributary to the Kalamazoo River, near Marshall, Michigan (NTSB 2012a, Enbridge 2013a). The released oil was a combination of Western Canadian Select (23%) and CLB diluted bitumen (77%) (Enbridge 2013a). The release occurred on the floodplain of Talmadge Creek, where wetlands are abundant (USFWS et al. 2015a). The Kalamazoo River is a meandering, low-gradient river with diverse channel and floodplain features, extensive floodplain forests and wetlands, off-channel water bodies, and impoundments (Dollhopf et al. 2014). Oil was transported downstream in the Kalamazoo River, which was in flood at the time of the release, to Morrow Lake (an impoundment in the river 36.5 miles downstream). Oil was deposited on river shoreline, riparian, and depositional areas and along the shores at the delta of Morrow Lake (USFWS et al. 2015a), affecting approximately 40 miles of river (80 miles of shoreline and adjacent lands) (Dollhopf and Durno 2011). There was subsequent associated disturbance from oil removal efforts (removal of riparian vegetation and sediment, access road construction; Dollhopf and Durno 2011). Channel margins, backwaters, side channels, oxbows, and impoundments provided depositional areas for the oil.*

Major factors affecting OPA formation include the quantity and viscosity of the oil, oil-water interfacial tension, and chemical composition of the oil; the quantity and type suspended sediment particles; the magnitude and variability in physical energy of the aquatic environment; temperature and salinity (Fitzpatrick et al. 2015). The first step to forming OPAs lies with the initial breakup of a slick of oil into oil droplets. Once spilled into a water body with turbulence created by waves or currents, floating oil can break up into droplets. In the absence of a surfactant, smaller droplets are generated the viscosity of the oil are low. Oil viscosity can vary by orders of magnitude among different types of oil, and at different temperatures. The viscosity of a heavy crude oil or bitumen is at least 1,000 times that of light crude such as a product from the Alaska North Slope or Bakken Formation (Fitzpatrick et al. 2015). The size of the oil droplet is a very important factor in the transport and fate of the oil and its interaction with particles. Because large droplets have higher buoyancy than smaller droplets, they tend to float to the water surface, whereas smaller droplets could be driven more easily in the water column as a result of mixing energy (Fitzpatrick et al. 2015). Small droplets would only need to interact with a few, small suspended sediment particles in order to achieve neutral or negative buoyancy relative to water. Larger droplets would require considerably more interaction with suspended sediments to reach a sinking density, or could potentially split into "floating" and "sinking" portions. Particle size, amount, and type are important to the formation of OPAs. Clay-sized mineral particles are effective at forming OPAs. However, most natural waters have a range of particle sizes, which may vary with the *amount of mixing resulting from waves or currents. Particles may be smaller than the oil droplet and form a coating, or they may similar in size to the aggregate (Fitzpatrick et al. 2015). However, the practical implication of the foregoing discussion is that classical OPA formation may be insufficient to explain the behavior of crude oil that was released to the Kalamazoo River. Zhou et al. (2015) reported the results of wave tank tests that showed conventional light crude oil forming small droplets that interacted with natural river sediments at realistic concentrations to form OPAs and sink, whereas a more viscous diluted bitumen remained floating on the surface of the tank, without forming entrained droplets, and without interacting with suspended sediments or sinking.*

Some features of the Kalamazoo River likely enhanced the formation, re-suspension, and deposition of OPAs. The Enbridge Line 6B pipeline release happened during a flood on the Kalamazoo River. On the basis of later measurements of suspended sediment it was inferred that the river had relatively low suspended sediment concentrations at the time of the spill (less than 100 mg/L; Fitzpatrick et al. 2015) with suspended particle sizes mainly in the silt-sized range. Water temperatures were warm. Floodwater increased turbulence in river flows, and mixing from flows over two dams may also have played a role, although OPAs and submerged oil accumulated in the first 3 miles (5 km) of river length, between the spill source and the first dam (Fitzpatrick et al. 2015). However, the importance of oil welling upwards through overburden materials from the buried pipeline to the surface, and subsequent overland flow between the failure location and Talmadge Creek has not been widely discussed. The accumulation of soil particles by liquid heavy fuel oil was considered to be an important process in the sinking behavior of that oil following the Wabamun Lake oil spill (Hollebone et al. 2011). It is possible that interactions between bulk diluted bitumen and soil particles up to sand grain size may account for some of the observed deposition of diluted bitumen to sediments in the Kalamazoo River.

Surface water samples were collected between July 2010 and April 2012 from the Kalamazoo River and Morrow Lake (MI DCH 2014b). Parent and alkylated PAHs were analyzed at various depths within the water column (USFWS et al. 2015a). Surface water analyses were conducted to evaluate potential effects on human health and on exposure of fish embryos to oil constituents. The July and August 2010 laboratory results showed that most chemical constituents were below water criteria for both the USEPA and the MI DEQ. The regulatory agencies agreed additional sampling was unnecessary.

***Red Deer River, Alberta**: On June 7, 2012, about 1.9 miles north of Sundre, Alberta, floodwaters 10 times higher than typical June flows eroded the stream bed and banks, exposing the Plains Midstream Canada ULC pipeline, which then ruptured (Alberta Energy Regulator 2014). Approximately 2,900 barrels of light crude oil* *were released into Jackson Creek, a tributary of the Red Deer River. Oil travelled at least 25 miles downstream to Gleniffer Lake reservoir, where booms contained the floating oil. Dissolved hydrocarbons were detected in river water up to 5 miles farther downstream (Alberta ESRD 2012a). Because of the high water levels at the time of the release, the majority of oil stranded in backwater areas, under trees and debris, and in highly braided river margins, and also mixed with silt and sediments well above the normal high water mark for the river (Teichreb 2014).*

The main concerns were for drinking water quality, but monitoring indicated only low levels of hydrocarbons (below Health Canada guidelines for drinking water quality) at intakes along the river downstream of the Gleniffer Lake reservoir (Alberta ESRD 2012a, b). No studies were found of effects on habitat in the river. It is likely that concerns about habitat were reduced because of the small volume of released oil in proportion to the large volume of river water at flood stage (large dilution), and the type of oil released (light crude oil, which weathers quickly) (Alberta ESRD 2012a).

7.1.2.4.3 Expected Effects of Released Oils

The main effects of oil released into a watercourse are changes in water quality and changes in physical habitat. Effects vary, depending on characteristics and volume of the released oil, duration of release (instantaneous versus protracted duration), and environmental conditions within the receiving waters (current velocity, volume of river/stream channel, morphology of channel—i.e., straight versus serpentine, presence of backwaters, oxbows). Relevant oil characteristics that will directly affect the fate and effects of released oil include (but are not limited to) density, viscosity, volatility, solubility, surface tension, adhesion, and emulsification, which affect behavior of oil on water and the weathering of oil.

A release of diluted bitumen is expected to result in environmental effects similar to those observed for other heavy crude oils. Diluted bitumen does not separate into diluent and bitumen components when released (Taylor et al. 2014; Zhou et al. 2015; Fingas 2015a). Diluted bitumen floats on water and can be stranded on shorelines. If the oil first travels over land, it can pick up soil and organic matter and form OPAs in water, which can sink. OPA can form in water as well, the degree of OPA formation depending on concentrations of suspended particulates in the water column and the amount of water column turbulence. Some of the diluent (e.g., condensate) present in diluted bitumen may evaporate quickly, but diluents also contain a wide range of individual hydrocarbon compounds, and the rapid initial weathering phase of diluted bitumen samples is typically followed by a slower secondary phase.

The effects of released oil on water quality are often transient (days) because the acutely toxic components (low molecular weight hydrocarbons like BTEX, some PAHs, and some alkanes) tend to weather (evaporate) quickly, or when dissolved in the water column, degrade quickly. Higher molecular weight PAHs are less likely to be acutely toxic to aquatic life but break down slowly (over months or years), so they persist and can result in chronic effects on aquatic biota. Effects on physical habitat (from oil stranded on shorelines and sediment) can result in habitat smothering and may last for much longer, especially where appropriate remedial actions are not taken. Soluble constituents in the deposited oil can dissolve into the water column over time resulting in ongoing toxicity to aquatic organisms. Effects of hydrocarbon contaminants on river sediments are discussed elsewhere.

Environmental characteristics affecting the behavior and fate of crude oil in watercourses include water flow, channel geometry, hyporheic flow (i.e., beneath and alongside a stream bed where there is mixing of surface waters and shallow groundwater), biodegradation, temperature, dissolved oxygen, nutrient supply, suspended sediment, and sunlight exposure. In rivers and streams, oil is predominantly transported by surface currents. River flow volume and velocity are determined by watershed size, runoff and other water inputs, river slope, and channel characteristics. Physical characteristics may range from small headwater streams with little dilution potential and boulder substrates with little depositional habitat, to higher order streams and rivers with broad floodplains, complex channel morphology and habitat, and abundant depositional areas. Water channels can be simple (e.g., artificially channelized areas) or complex, with meanders, braided areas, backwaters, shoals, and structures such as bridge supports, dams, and jetties, which will result in complex patterns of oil transport and deposition. The oil initially moves on the surface with the current. Evaporation and other weathering processes remove low molecular weight hydrocarbon fractions. Water turbulence can disperse oils that have low viscosity as fine droplets in the water column, where soluble fractions can dissolve in the water. In areas of lower turbulence (slower flows), oil droplets can coalesce and float to the surface again.

Oil can become stranded on shoreline areas, shoals, and shallow, slow-flowing areas when water levels recede. Stranded oil can be re-mobilized and flushed downstream when flows and water levels later increase. If there is a naturally high sediment load in the river (e.g., during a freshet), or if oil travels over land and picks up soil particles, OPAs can form, leading to oil deposition to sediment in slow-flowing areas.

Seasonal weather conditions also have an effect. Releases that occur during the spring freshet or high rainfall events will be rapidly transported downstream. High water levels could result in oil being deposited to riparian habitat, becoming stranded as water levels drop. Releases into ice-covered rivers during winter may be isolated initially, but travel downstream under the ice such that locating and recovering the released oil is challenging. Any residual oil that is not recovered, or oil that has been sequestered beneath the ice, may be remobilized when the ice melts and flow increases.

The effects of crude oil releases on surface water quality typically last only a short time after the release. Crude oil typically undergoes rapid initial mass loss due to weathering. Stranding along shorelines also results in removal of released oil from the water surface. Most hydrocarbons are only sparingly soluble to insoluble in water, so effects on water quality are generally short lived. Remedial activities may help speed up recovery of a water body through collection of oil.

Effects on river from oil stranded on shorelines or deposited to sediment can last for much longer, and long-term or persistent contamination of these physical habitat components can result in chronic low-level release of potentially toxic constituents of the crude oil (e.g., PAHs) back to the water column.

Table 7-18 and Table 7-19 provide a summary of the expected environmental effects of oil releases to rivers. Table 7-18 considers the effects of specific oil characteristics or oil type on the expected type and scope of environmental effects. Table 7-19 considers the effects of environmental factors on the expected types and scope of environmental effects.

Table 7-18 Effects of Crude Oil on Rivers by Oil Characteristic

LAND COVER RECEPTOR: Rivers				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
Density	Low density oils, float on water.	Intermediate in density between light and heavy oils; will float on water.	High density oils; pipeline tariffs require density to be less than 0.94. Fresh diluted bitumen will float on water.	The density of crude oil or diluted bitumen increases with evaporation of lighter components.
Viscosity	Low viscosity oils, have a high tendency to spread and disperse, both on the surface of the water, and potentially as fine droplets in the water column where mixing energy is sufficient.	Intermediate in viscosity, spreading and dispersal characteristics between light and heavy oils.	Heavy crude oils tend to be viscous. Fresh diluted bitumens have viscosity that is regulated through the addition of a diluent.	Viscosity of crude oil decreases with rising temperature, and increases as a function of weathering after release. Diluted bitumens may undergo more rapid initial weathering than conventional crude oils if the diluent is volatile (e.g., condensate). Diluted bitumens contain more diluent in winter than in summer in order to compensate for temperature effects.
Volatility	Light crude oils typically contain a large fraction of volatile (low molecular weight) hydrocarbons. These are prone to weathering by volatilization and dissolution.	Intermediate in volatility and tendency to weather through volatilization between light and heavy oils.	The fraction of volatile low molecular weight hydrocarbons depends on the oil type. Conventional heavy crude oils may have relatively low volatile content. However, diluted bitumens contain diluent, which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large volatile component. CLWB is an example of diluted bitumen with a relatively large component of condensate and a volatile content similar to that of many light crude oils.	Evaporation of volatile components increases with temperature. As volatilization occurs, the density of the residual oil will increase. Diluted bitumen may undergo a rapid initial loss of volatiles, followed by a secondary phase of slow weathering. In contrast, light and medium conventional crude oils that contain more mid-range hydrocarbon compounds have a more gradual weathering behavior.

Table 7-18 Effects of Crude Oil on Rivers by Oil Characteristic

LAND COVER RECEPTOR: Rivers				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
Solubility	Light crude oils typically contain a large fraction of relatively water soluble (low molecular weight) hydrocarbons.	Intermediate in proportions of soluble low molecular weight hydrocarbons between light and heavy oils.	The fraction of relatively water soluble low molecular weight hydrocarbons depends on the oil type. Conventional heavy crude oils may have relatively low solubility. However, diluted bitumens contain diluent which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large component of relatively water-soluble compounds. CLWB is an example of diluted bitumen with a relatively large component of condensate, with BTEX content similar to that of many light crude oils.	Undiluted bitumen has a very low water soluble fraction, but diluent added to bitumen contains a high fraction of soluble LMW hydrocarbons. Dissolution of the lighter fraction can increase oil density.
Adhesion	Relatively low adhesion to surfaces.	Intermediate adhesion to surfaces between light and heavy crude oil.	High adhesion to surfaces.	Oil may adhere to surfaces such as substrates, debris, flora, and fauna.
Emulsification	Unlikely to occur (content of asphaltenes in light crude oil is low).	May occur, depending upon crude oil chemistry.	Asphaltenes are present in conventional heavy crude oils, and these can have a high potential to emulsify. However, diluted bitumens, which contain very large amounts of asphaltenes, appear to have low potential to form emulsions.	Emulsification is less likely to occur in fresh water than marine, even for releases of heavier oils, because there is often not enough consistent and protracted mixing energy to create stable emulsions.

Table 7-19 Effects of Crude Oil on Rivers by Environmental Characteristic

LAND COVER RECEPTOR: Rivers				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Water Flow	Rivers in low flow condition can have exposed substrate (e.g., sandbars) or debris upon which released oil can adhere. Oil will be transported downstream at a low speed, with little dilution. Turbulence levels in the stream are also typically at low levels. Floating oil will likely remain floating, but OPAs can sink to the bottom in slow moving water.	Rivers in moderate flow conditions typically have downstream transport velocities and turbulence levels that are intermediate between low and high flow condition. In-stream features such as sandbars will typically be submerged, but the river remains within its normal banks.	Rivers in high flow conditions typically have the highest downstream transport velocities and turbulence levels within the main river channel. At high flow, the river level may exceed that of the normal banks, with flow extending laterally into riparian or floodplain areas. In these areas, there may be areas of low flow and high potential to trap floating and submerged crude oil.	High river flow conditions can result in the entrainment and virtual "disappearance" of light crude oils as they are dispersed over a large area. On the other hand, the Kalamazoo River oil spill resulted in extensive oiling of floodplain areas, as well as submergence and sinking of the heavy crude oil with subsequent accumulation in areas of quiet water such as the Morrow Lake impoundment.
Turbulence	Crude oil is likely to remain floating on the surface of rivers that have low turbulence levels, regardless of the viscosity of the oil.	Under moderately turbulent flow conditions, light crude oils may become entrained into the water as small droplets, which may then interact with suspended sediment (leading to sinking behavior). Entrainment of oil as small droplets will also promote dissolution of relatively water soluble fractions of the crude oil.	Under highly turbulent flow conditions, both light and heavy crude oils may become entrained into the water. However, the droplet size profile of heavy crude oils will tend to remain skewed towards larger droplet sizes, due to its higher viscosity and surface tension.	Turbulence can be induced in river flows as a result of slope, irregular substrate type, overall water flow, and in-stream features such as natural waterfalls or man-made weirs and dams.

Table 7-19 Effects of Crude Oil on Rivers by Environmental Characteristic

LAND COVER RECEPTOR: Rivers				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Suspended Sediment	Low concentrations of suspended sediment and turbidity typically occur in clear, small streams; in slow moving depositional areas; during low flow periods; or in streams where water inputs are dominated by groundwater. Any of these waterbodies can also experience high sediment loads during freshet flows. There is low potential for oil to interact with particles to form aggregates.	Moderate concentrations of suspended sediment and turbidity typically occur in mid-sized streams; during moderate flow periods; and in streams where inputs include some overland flow. There is some potential for oil to interact with particles and form aggregates. The aggregates may be neutrally buoyant and enter the water column, or sink.	High concentrations of suspended sediment and turbidity typically occur in low gradient rivers and large streams; in fast moving active erosional areas; in streams where there is substantial input from overland flow; and during times of high flow (e.g., spring freshet or high rainfall events). There is high potential for oil to interact with particles and form aggregates that may be neutrally buoyant or sink (Lee et al. 2015).	Geological characteristics, soil types, and land use in the surrounding watershed play large roles in determining the baseline and maximum suspended sediment concentrations in streams and rivers. The baseline may be low (i.e., clear-flowing water), moderate or high (i.e., water that is routinely muddy in appearance), but regardless of the baseline levels, suspended sediment concentrations typically peak during spring freshet and in response to high rainfall events.
Temperature	At low environmental temperatures, oil density, viscosity and surface tension are higher, and volatility of low molecular weight hydrocarbons is lower. Biodegradation rates are also limited.	At moderate temperatures, properties of density, viscosity, surface tension, volatility and biodegradation are at intermediate values.	At high environmental temperatures, oil density, viscosity and surface tension are lower, and volatility of low molecular weight hydrocarbons is higher. Biodegradation rates also tend to be higher, provided oxygen and nutrient availability are not limiting.	River temperature is affected by seasonal changes in ambient temperature, by the temperature and amount of inflowing groundwater, tributary streams and overland flow. Unshaded streams and rivers are more exposed to daily temperature fluctuations than shaded watercourses.

Table 7-19 Effects of Crude Oil on Rivers by Environmental Characteristic

LAND COVER RECEPTOR: Rivers				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Ice Cover	In winter, the ground may be snow covered, but rivers may remain open. Without ice cover, the behavior of crude oil in rivers is generally similar to its behavior in other seasons.	Moderate ice cover and low temperatures may limit the spread of crude oil in rivers, but will also pose challenges to oil spill response and recovery operations.	When there is high ice cover on a river, released oil may pool on the surface of the ice, providing an opportunity to recover the oil or limit its spread. If crude oil is released into a river below the ice, it can move under the ice surface, accumulating in hollows under the ice, and in areas of low water flow near the river margins.	Ice cover implies cold temperatures and low river flow rates, which will slow the spread of released oil due to effects on viscosity. Crude oil released beneath ice cover has limited exposure to the atmosphere, and this will force more of the low molecular weight hydrocarbon to dissolve in water than would otherwise be the case. In combination with low river flow rates, this may result in higher potential for toxicity to fish. Ice cover may impede recovery operations, leading to a secondary episode of crude oil movement in the watercourse during the spring melt period.

Table 7-19 Effects of Crude Oil on Rivers by Environmental Characteristic

LAND COVER RECEPTOR: Rivers				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Dissolved oxygen	Low oxygen environments (e.g., <5 mg/L) may occur in deep, slow moving depositional areas of rivers, or in underlying sediment pore water. Low oxygen availability limits biological communities, as well as limiting aerobic biodegradation of oil. Anaerobic degradation of oil can occur, but rates are much slower than for aerobic processes.	Many rivers are typically under-saturated with dissolved oxygen, particularly during warm periods. However, oxygen concentrations are usually adequate to support a wide variety of aquatic life, and would not be limiting to biodegradation of crude oil.	High oxygen environments (saturated to super-saturated) occur in higher gradient streams where water turbulence results in greater entrainment of oxygen. Super-saturation can also occur as a result of photosynthetic activity in streams and rivers, particularly during daylight hours in the summer. High oxygen environments can facilitate higher rates of aerobic biodegradation.	Oxygen is typically not usually a limiting factor to biodegradation of crude oil in rivers, except in deep, slow moving areas or in sediment pore-water. Biological communities are typically adapted to the prevailing oxygen regime, although still susceptible to events that deplete oxygen.
Nutrient supply (nitrogen, phosphorus, organic carbon)	Nutrient supply can be low in small streams, and can limit the capacity for microbial biodegradation of hydrocarbon residues.	Moderate nutrient availability is typical of mid-sized streams.	High nutrient availability often occurs in rivers and larger streams (as a result of both natural and anthropogenic inputs), and may support a higher capacity for microbial degradation of hydrocarbon residues.	The river continuum concept (Vanotte et al. 1980) proposes that rivers are in a constant but predictable state of development, from headwater reaches to their mouths. This has implications for biological communities, as well as abiotic factors such as nutrient supply. Nutrient levels in rivers also vary as a result of surrounding land use (sources of nutrients) and season.

Table 7-19 Effects of Crude Oil on Rivers by Environmental Characteristic

LAND COVER RECEPTOR: Rivers				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Sunlight exposure	The light environment of rivers varies in relation to a range of factors including the degree of shading (greatest in small watercourses that are overhung by trees), as well as internal factors such as the levels of suspended sediment and dissolved organic carbon in the water.	N/A	Larger watercourses may be partially shaded along their banks, but are unshaded at mid-stream. However, larger watercourses are also more likely to have higher levels of suspended sediment in the water, which may limit light transmission through the water column.	Photo-oxidation is a natural remediation process that helps to break down hydrocarbon residues into less persistent and generally less toxic compounds.
Hyporheic Flow	Stream and river beds dominated by fine-grained materials (silts and clays) have low levels of permeability to flow, and will resist entry of crude oil into the hyporheic zone.	Stream and river beds dominated by sand or sand and gravel will potentially admit hyporheic flow, but may also act as a filter bed, limiting entry of crude oil constituents to soluble components that are readily degraded by microbial processes.	Stream and river beds dominated by gravel, cobbles and boulders will readily admit hyporheic flow, and crude oil droplets may also be entrained into the hyporheic environment.	Oil entering the hyporheic zone can become trapped in the sediment by adsorption to particles and can contaminate interstitial sediment pore water. This can have implications for biota ranging from benthic invertebrates to developing fish eggs and embryos that become exposed to residual or persistent crude oil residues.

7.1.2.5 Sediment

7.1.2.5.1 Description

Sediment is defined as the weathered minerals and organic detritus that form bottom substrates in aquatic environments. Suspended sediment is not discussed here; it is included as a water quality parameter in the effects assessment for lakes and rivers. Sediment can be a repository for contaminants, including petroleum hydrocarbons. Therefore, it is included in the effects assessment of land cover receptors due to its importance to aquatic life (fish, amphibians, plants, invertebrates), birds, and mammals that depend upon it.

The dominant substrate type usually reflects the hydrological regime. The largest materials (cobbles and boulders) are typically moved only by extreme high flow events. As a result, the stable substrate in erosional environments is typically composed of cobble, boulder, and gravel which, due to their large size, have substantial pore spaces between them.

In erosional environments (moderate to high flow river systems), sediments are transported by water movement. Fine sediments (generally composed of silt, clay, fine sand and smaller organic detritus) can be suspended in the water column, while coarse sediments (coarse sand, gravel, cobble, boulder and bedrock) remain on the bottom. In depositional environments (lakes, slow flowing or deep sections of streams and rivers), fine sediments drop out of suspension and form deposits on the bottom. Substrate in depositional environments is composed primarily of fine sediments and organic matter, with small pore spaces between particles. In rivers, deposition and erosional processes can occur alternately according to flow conditions. In lakes, depositional processes are dominant, although erosional processes may prevail along exposed shorelines.

The effects assessment for sediment focuses on physical and chemical effects of released oil on sediment quality in lakes and watercourses, and excludes direct effects of oil on aquatic biota (benthic invertebrates, fish, and aquatic plants), which are discussed elsewhere. Oil released in lakes and watercourses typically remains floating on the surface, but can become stranded on the shoreline and sediment as a result of currents and wind-driven movement, or can sink when OPAs form. The oily sediment may accumulate in depositional (low flow or quiet) areas.

In water, the low molecular weight fractions of oil weather quickly, leaving behind more persistent higher molecular weight hydrocarbons, including PAHs and weathered products (e.g., tar balls, OPAs). Deposited oil can be remobilized during times of high flow or high turbulence, resulting in additional exposure of aquatic biota to the contaminants.

7.1.2.5.2 Observed Effects

There is potential for oil released accidentally from a pipeline to reach one of the many lakes and watercourses in Minnesota, where some of the oil may end up on or in the sediments. Observed effects of released oil on sediment are compiled from four case studies described below, where oil was observed to interact with freshwater sediment. These include the 2010

Marshall, Michigan release, 2005 Wabamun Lake, Alberta release, 2000 Pine River, British Columbia release, and 1979 Asher Creek, Missouri release. The case studies described below are for a variety of river and lake receptors, and oil types. Potential effects of differences in the receiving environment and oil type on the behavior and weathering patterns of released oil, and on resulting potential environmental effects are discussed.

> ***Marshall, Michigan**: On June 25 and 26, 2010 a rupture in Enbridge's Line 6B pipeline released approximately 20,000 barrels of heavy crude oil, of which approximately 8,000 barrels entered Talmadge Creek, a tributary to the Kalamazoo River, near Marshall, Michigan (NTSB 2012a, Enbridge 2013b). The released oil was a combination of Western Canadian Select (23%) and CLB diluted bitumen (77%) (Enbridge 2013a). The release occurred on the floodplain of Talmadge Creek, where wetlands are present (USFWS et al. 2015a). The Kalamazoo River is a meandering, low gradient river with diverse channel and floodplain features, extensive floodplain forests and wetlands, off-channel water bodies, and impoundments (Dollhopf et al. 2014). Oil was transported downstream in the Kalamazoo River, which was in flood state at the time of the release, to Morrow Lake (an impoundment in the river 36.5 miles downstream).*
>
> *Oil was deposited on river shoreline, riparian, and depositional areas (backwaters, side channels, oxbows) and along the shores at the delta of Morrow Lake (USFWS et al. 2015a), affecting approximately 40 miles of river (80 miles of shoreline and adjacent lands) (Dollhopf and Durno 2011). There was associated disturbance from oil removal efforts such as the removal of riparian vegetation and sediment and access road construction (Dollhopf and Durno 2011). Some of the oil mixed with soil and organic matter while moving overland and, after entering the river, with suspended sediment in the water column, resulting in the formation of OPAs that submerged in some locations, especially in depositional areas. These aggregates periodically released oil globules and sheen as late as 2014 (Fitzpatrick et al. 2015). Formation of OPAs was likely promoted by the flood conditions. Based on measurements of suspended sediment at the Marshall stream gage after the release, it can be inferred that the river had relatively low suspended sediment concentrations at the time of the release, but that the floodwaters likely increased the turbulence and the presence of suspended particulate matter (Fitzpatrick et al. 2015). In addition, the high organic matter content of sediments (20% or more) resulting from the extensive floodplain wetlands along the Kalamazoo River could have contributed to OPA formation (Fitzpatrick et al. 2015). Some of the submerged oil settled in areas that became anaerobic, which would reduce the rate of biodegradation.*
>
> *About 90% of the oil entering the river was recovered in the first year. This included floating oil, stranded oil in the floodplains of Talmadge Creek and the Kalamazoo River, and submerged oil (Fitzpatrick et al. 2015). The oil weathered,*

increasing the density of the weathered diluted bitumen. In 2011, additional activities to dislodge and disperse submerged oil resulted in a small amount of additional recovery. Submerged OPAs continued to release oil from sediments in the Kalamazoo River and impoundment areas during 2011 to 2014, with surface sheens observed in impounded sections of the river (Fitzpatrick et al. 2015).

Sediment chemistry was studied in 2011, 2012, and 2013 in depositional areas of the river and in Morrow Lake (Enbridge 2014). Levels of PAHs and other oil related compounds were compared to MI DEQ sediment quality values, including threshold effect concentrations (TEC) and probable effect concentrations (PEC) adopted from USEPA standards (MacDonald et al. 2000; USEPA 2003). Numerous samples from the affected areas and also from upstream and reference areas had concentrations of individual and total parent PAHs higher than the TECs; a few samples from the affected area had concentrations higher than the PECs (Enbridge 2014). Concentrations and exceedances of screening levels decreased between 2012 and 2013 (Enbridge 2014).

Sediment toxicity was tested at the same locations as sediment chemistry during 2012 and 2013, using standard laboratory tests with the amphipod (Hyalella azteca) and larval midge (Chironomus tentans). The extent and number of samples showing toxicity decreased from 2012 to 2013 and indicated overall that toxicity was absent from most parts of the river studied (Enbridge 2014). In both years, many samples showed no toxicity, and some samples showed low levels of both toxicity (e.g., 91% survival in Hyalella and 82% survival for Chironomus) and reduced growth. Effects were similar in affected and reference areas of the river, suggesting that the effects on toxicity and growth were associated with factors other than the oil release (Enbridge 2014). Many samples from affected areas of the Kalamazoo River (i.e., the Morrow Lake headpond) contained naturally high levels of total organic carbon, which were expected to reduce bioavailability of the PAHs, many of which bind to organic carbon.

The 2013 study was a sediment quality triad study of depositional areas, bringing together information about contaminant concentrations in sediment, sediment toxicity, and benthic invertebrate communities. Using a weight-of-evidence approach with multiple lines of evidence to evaluate the ecological significance of the residual hydrocarbons in sediment, it was concluded that by 2013, spill-related hydrocarbons in sediment of the Kalamazoo River were not having adverse effects on the aquatic ecosystem (Enbridge 2014). Other findings were that one line of evidence taken alone (e.g., sediment chemistry compared to guidelines) was not enough to identify the effects on the environment, and that many factors other than, or in addition to, the oil release were affecting the aquatic environment.

***Wabamun Lake, Alberta**: On August 3, 2005, a derailed train released approximately 4,500 barrels of Heavy Fuel Oil 7013 (a Bunker C type fuel oil with a high viscosity and an initial density of about 0.99 at lake temperature) and 550 barrels of pole treating oil. About 20% of the released heavy fuel oil (950 barrels) traveled overland and entered Wabamun Lake; no appreciable volume of pole treating oil entered the lake (Hollebone et al. 2011). In the lake, the oil floated and spread rapidly over the lake surface. After a few days, strong winds and wave action dispersed the oil toward the north, east, and south shorelines, where it became entrained in the beds of emergent vegetation (Anderson 2006, Birtwell 2008).*

While traveling overland, the oil mixed with soil and organic matter, and in the lake, OPAs formed quickly, including small tar balls, larger tar "logs", submerged sheets, and large lumps (Fingas et al. 2006; Hollebone et al. 2011). The aggregates showed a variety of behaviors, including submergence, neutral buoyancy, and resurfacing (Fingas et al. 2006), with extensive tar-mat formation in some nearshore areas. The behaviors of this oil in the lake, including rapid formation of tar balls, sinking, slow weathering and degradation due to high proportions of high molecular weight components such as resins, and its toxicity and persistence, were related to characteristics of the heavy fuel oil that would not be directly comparable to most conventional crude oils or diluted bitumen.

Surface sediment (approximately the top 1 to 2 in.) from open water areas was sampled on two dates in August 2005 and analyzed for particle size, total organic carbon, BTEX, PAHs, metals, and other parameters (Anderson 2006). Results were compared with pre-release data from 2002, which had documented some existing PAH concentrations above Canadian sediment quality guidelines due to natural and anthropogenic sources, including exposed coal seams, industrial activity, fossil fuel burning, and leaching from creosote-treated structures. Sediment samples collected from open water areas in 2005 did not indicate the presence of PAHs related to the release, and PAH levels were similar to or lower than those measured in 2002 (Anderson 2006).

Laboratory toxicity tests using the amphipod Hyalella azteca and larval midge <u>Chironomus tentans</u> showed significant toxicity for sediments collected near the release site, but test results were difficult to interpret because test conditions were not the same for all site and control samples (e.g., samples with high sand content had higher mortality, possibly due to sandier habitats not being the preferred by the organisms, or because of the naturally low organic content and food supply in sand) (Lee et al. 2015). Growth of both species and also the aquatic worm <u>Lumbriculus variegatus</u> in both high- and low-sand sediments was significantly lower than in control sediments. In <u>L. variegatu</u>s, PAH concentration was correlated with toxicity (Lee et al. 2015).

Using microcosms in the laboratory, biodegradation of oil was tested using sediment collected from Lake Wabumun, to which was added either Bunker C oil recovered from the lake or a reference light oil (Alberta Sweet Mix Blend). Tests were run at 22°C for four weeks and at 4°C for eight weeks (Foght 2006; Wang et al. 2011). Microbes in the sediment were able to degrade a substantially greater proportion of the reference oil than the Bunker C oil, which was attributed to the low proportion of low molecular hydrocarbons and the high proportion of components that do not readily biodegrade (including high molecular weight components such as resins) in the Bunker C oil.

Pine River, British Columbia*: On August 1, 2000, a pipeline belonging to Pembina Pipeline Corporation ruptured and released approximately 6,200 bbl of sour light crude oil, of which approximately 2,800 bbl entered the Pine River in British Columbia (BC MOE 2000a). The Pine River has a moderate gradient and is swift and clear-flowing. Crude oil was dispersed up to 50 miles downstream (Lee et al. 2015). The fast flowing water allowed rapid dispersion of acutely toxic fractions of the oil into the river water.*

Oil was stranded and settled in depositional areas along the banks, in back eddies and other slow-flowing areas, and on organic debris and logjams (AMEC 2001 in Lee et al. 2015). Heavy rainfall later in August and September mobilized stranded oil, oil-contaminated debris, and sediments downstream, and high water levels scoured some of the more heavily oiled depositional areas. Over a two month period, about 91% of the released oil was recovered or accounted for. It was estimated that the equivalent of approximately 563 bbl was lost to evaporation. A further 523 bbl was unaccounted for and assumed to have been dissolved, adsorbed in soils, deposited to sediments, and/or trapped in backwaters, eddies and logjams (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015).

Some of the emergency response activities (e.g., removal of logjams and woody debris, altering of backchannels, bank armoring, and presence of heavy machinery in the river) also resulted in habitat damage (Summers 2004 in Bustard and Miles 2011). Of note, prior to the August 2000 release, a small release of diesel fuel (151 barrels) and gasoline (187 barrels) from a tanker truck had occurred in August 1994 in the same area of the Pine River (Goldberg 2011).

Following the release in August 2000, petroleum hydrocarbons were detected chemically and seen and smelled in river water up to 50 miles downstream of the release, with sheen visible in back eddies and other calm areas along shorelines. Hydrocarbons accumulated in sediments and on organic debris (e.g., branches, leaves, and algae) that had accumulated along the shoreline, in front of logjams, and attached to sweeper logs in these calm areas (Lee et al. 2015).

Concentrations in water decreased rapidly to below British Columbia water quality guidelines due to evaporation, dissolving in water, and natural dispersion, occurrences characteristic of light crude oil (Lee et al. 2015). Analysis of semi-permeable membrane devices deployed in the Pine River indicated that two years after the release, hydrocarbons were present in water, implying that hydrocarbons from the release were leaching out of sediment into the water column (De Pennart et al. 2004), although additional sources (e.g., PAHs from coal deposits) in the watershed were also acknowledged. Observations of oil on sediment were made five years after the rupture, although the location and extent were not described (Goldberg 2006 in Bustard and Miles 2011).

Asher Creek, Missouri*: In August 1979, a pipeline burst, releasing approximately 9,500 barrels of an unspecified type of crude oil into Asher Creek, in southwest Missouri, during low flow conditions (Crunkilton and Duchrow 1990). A responsible party has not been identified for this incident. Dissolved oxygen, pH, and conductivity levels in water were not changed by the release (no information about hydrocarbons in water was published).*

Oil that entered substrates in riffle areas due to mixing was observed for over a year post-release (Crunkilton and Duchrow 1990). The creek originates in springs 0.4 mile upstream of the release. Low water volumes in these headwaters, particularly during summer, provided limited dilution of the oil, increasing the residence time of soluble oil components in sediment (Crunkilton and Duchrow 1990). Areas downstream from surface skimming siphon dams were less severely affected and recovered more rapidly than areas where the substrate became covered with oil (Crunkilton and Duchrow 1990).

7.1.2.5.3 Expected Effects of Released Oils

The main effects of oil deposited on substrates of lakes or watercourses are changes in sediment quality and changes in physical habitat associated with weathered oil. The effects on sediment quality typically persist for months or longer because the heavier molecular weight compounds (many PAHs, resins, and asphaltenes) are slow to weather and degrade; these compounds tend to have chronic, rather than acute toxicity to aquatic biota. Effects on physical habitat (from oil stranded on shorelines and sediment (e.g., as tar balls or OPAs) can also persist, and constituents in the deposited oil can dissolve into the water column over time, resulting in ongoing toxicity to aquatic organisms.

The effects on sediment vary, depending on characteristics of both the oil and environmental conditions at the time of the release. Relevant oil characteristics include density, volatility, solubility, and adhesion, which affect behavior of oil in the aquatic system and weathering of the oil. Environmental characteristics that affect behavior and fate of the oil include water flow, hyporheic flow, dissolved oxygen, and sediment grain size.

If there is a naturally high sediment load in a river (e.g., during a freshet) or if the oil travels over land and picks up soil and organic matter before entering the water, OPAs can form. These aggregates can reach densities that are heavier than water and sink to the bottom in slower flowing areas of rivers. Temperature can affect the rate of sinking, as lower temperatures result in greater viscosity and density, and slower rates of volatilization and biodegradation (Lee et al. 2015), which can favor sinking.

In rivers and streams, there are both erosional (fast flowing) and depositional (slow flowing) areas. Oil tends to accumulate and persist in the depositional areas (inside bends of meanders, backwaters, shoals, pools). Changes in water levels and current velocity can re-suspend the oil, making it available in the water column. In erosional habitats, flushing and fast weathering processes result in faster depletion of the oil compared to the slower rates in depositional habitats, which can be exacerbated if the oil enters anoxic layers of fine sediment. Lake substrates often are predominantly fine sediments, and oil can settle or be stranded on shorelines, shallow areas, and, if the oil combines with particles, in deeper areas.

Organic carbon and pore water presence affect the bioavailability of contaminants in sediment (Enbridge 2014). Organic carbons such as humic and fulvic acids can bind contaminants and render them less bioavailable. Sediment pore water, which is the water present between the particles, can act as a pathway for exposure to dissolved contaminants for aquatic biota.

A release of diluted bitumen is expected to result in effects similar to those for other heavy crude oils. Diluted bitumen does not separate into diluent and bitumen components when released (Taylor et al. 2014; Zhou et al. 2015; Fingas 2015a). It floats on water and can be stranded on shorelines. If the oil first travels over land, it can pick up soil and organic matter, then form OPAs, which can sink, A high proportion of diluent (e.g., condensate) will evaporate quickly and some will be dissolved in the water column and degrade relatively quickly. The residual oil components (PAHs, heavier alkanes, etc.) will degrade more slowly.

Environmental standards for petroleum hydrocarbon residues in sediment are limited. Di Toro et al. (2000), Di Toro and McGrath (2000), and USEPA (2003) developed the equilibrium partitioning sediment benchmark approach that is used to assess the potential toxicity of PAHs, either as individual substances or as mixtures. The same approach has also been applied to the toxicity of fresh and weathered crude oils (Di Toro et al. 2007) and refined oil products (McGrath et al. 2005). This approach, however, demands detailed understanding of the hydrocarbon chemistry.

Empirical approaches are also helpful. Routine analytical laboratory detection limits for total petroleum hydrocarbon (TPH) in sediment typically range from about 2.5 to 15 ppm (or mg/kg). Assuming that crude oil is deposited to the surface of the sediment and mixed into a thin surface layer (less than .25 in.) of sediment that has a high water content, then the mass of oil that is deposited to sediment can roughly converted to a concentration basis in the surface sediment layer. These concentrations can then be related to likely environmental effect levels, based on a variety of studies that examined relationships between TPH concentrations in sediment and benthic community response (Nance 1991; Rozas et al. 2000; Pettigrove and Hoffmann 2005; Anson et al. 2008).

- Crude oil deposition of less than 0.1 g/m^2 sediment would result in a surface sediment TPH concentration less than 10 ppm, and would be scarcely detectable in routine chemical analysis, and unlikely to have an ecological consequence.
- Crude oil deposition of less than 1 g/m^2 sediment would result in a surface sediment TPH concentration less than 100 ppm, and would be unlikely to result in detectable biological effects.
- Crude oil deposition of less than 5 g/m^2 sediment would result in a surface sediment TPH concentration less than 500 ppm, which could result in adverse effects to a limited number of sensitive species, but could also increase overall benthic community productivity due to an enrichment effect.
- Crude oil deposition of less than 20 g/m^2 sediment would result in a surface sediment TPH concentration less than 2,000 ppm, which would be expected to cause reduced benthic community diversity, biomass and productivity.
- Crude oil deposition of greater than 20 g/m^2 sediment would be expected to cause progressively more serious reductions in benthic community diversity, biomass and productivity.

Table 7-20 provides a summary of how oil characteristics may affect the expected type and scope of environmental effects of crude oil releases on sediment. Table 7-21 considers relationships between environmental characteristics these environmental effects.

Table 7-20 Effects of Oil on Sediment by Oil Characteristic

LAND COVER RECEPTOR: Sediment				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
Density	Low density crude oils; will float on water. Floating can keep light crude oil away from sediment, but this may change with mixing or changes in density. In the 2000 Pine River, British Columbia release, the light crude oil was well dispersed in river water.	Intermediate in density between light and heavy crude oil; will float on water. Floating can keep medium crude oil away from sediment, but this may change with mixing or changes in density.	Pipeline tariffs require density of diluted bitumen to be less than 0.94. Fresh heavy crude oil and diluted bitumen will float, but may sink with prolonged weathering, or formation of OPAs.	The density of crude oil or diluted bitumen increases with weathering. Density is correlated with viscosity, so that light oils tend to have low viscosity.
Viscosity	Low viscosity oils are readily dispersed in water by turbulence or waves. Dispersal as fine droplets can promote formation of OPAs if other conditions (e.g., suspended sediment concentration, salinity) are favorable.	Intermediate in viscosity between light and heavy crude oils. However, medium crude oils tend to remain within the "low viscosity" range.	Heavy crude oils and diluted bitumens tend to have higher viscosity, although they must still meet requirements for transport by pipeline. With increasing viscosity, and particularly when weathered, diluted bitumens may float on water but resist entrainment as fine droplets except under extremely turbulent conditions.	Crude oil viscosity increases with weathering.
Solubility	Light crude oils typically contain a large fraction of relatively water soluble low molecular weight hydrocarbons. Dissolved hydrocarbons can become adsorbed onto organic matter or suspended sediments and eventually become deposited to sediment.	Intermediate in proportions of soluble low molecular weight hydrocarbons.	The fraction of soluble low molecular weight hydrocarbons depends upon the oil type. Conventional heavy crude oils may have relatively few water soluble components. However, diluted bitumens contain diluent which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large component of relatively water-soluble hydrocarbons.	Undiluted bitumen is a naturally highly weathered material, containing few water-soluble components. However, diluent added to bitumen may contain a large amount of relatively water soluble hydrocarbons.
Adhesion	Light crude oils have low adhesion, and form thin layers	Intermediate properties between light and heavy	Heavy conventional crude oils and diluted bitumen have high adhesion,	

Table 7-20 Effects of Oil on Sediment by Oil Characteristic

LAND COVER RECEPTOR: Sediment				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Comments**
	that may weather quickly when the contact solid surfaces.	crude oils.	and can be difficult to remove after they contact solid surfaces.	

Table 7-21 Effects of Oil on Sediment by Environmental Characteristic

LAND COVER RECEPTOR: Sediment				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Sediment grain size	Fine-grained sediments (clay, silt) may resist penetration by oil, particularly when water-saturated. However, if suspended in the water column, fine grained sediments may interact with oil droplets to form OPAs, which may be deposited to sediment in slow-moving areas of water.	Medium-grained sediments (fine to coarse sand) may resist entry of OPAs, particularly if water saturated.	Oil and OPAs can enter pore spaces between coarse-grained sediments (e.g., gravel, cobble), and can become trapped and persist. On the other hand, these sediment types are often found in areas where water currents or wave action are energetic, which can also help to flush and disperse crude oil residues.	Crude oil interactions with sediment are complex. However, long-term deposition of crude oil to sediment is most likely to occur in conjunction with OPA formation, with deposition occurring in areas of slow-moving water and soft/fine-grained sediment.
Water Flow	In slow flowing or still water, crude oil will likely remain floating at the surface. Interactions between crude oil and sediment will be dominated by interactions with shorelines, which are often coarse-grained or armored.	Rivers with moderate flows can transport oil downstream. Mixing can cause dispersion or submersion of crude oil, particularly if it has low viscosity. Crude oil that submerges is likely to re-surface. Interactions between dispersed oil droplets and suspended sediment depend upon the concentration of suspended sediment, and salinity.	Fast flowing waters are typically turbulent, increasing the likelihood of crude oil dispersion as fine droplets. These waters may or may not contain high levels of suspended sediment.	Suspended sediment levels in streams typically increase during periods of high water flow. However, not all fast-flowing streams have high levels of suspended sediment. Higher levels of salinity increase the potential for OPA formation.

Table 7-21 Effects of Oil on Sediment by Environmental Characteristic

LAND COVER RECEPTOR: Sediment				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Suspended Sediment	Low levels of suspended sediment (e.g., <10 ppm) limit the potential for oil-particle interactions and deposition of crude oil to sediment.	Medium levels of suspended sediment (e.g., 10 to 100 ppm) are also likely to limit the potential for oil-particle interactions, particularly where salinity is low.	Oil particle interactions are most likely to occur where suspended sediment levels are high (e.g., >100 ppm).	True oil-particle interactions require a combination of suspended sediment, as well as sufficient turbulence to disperse crude oil as fine droplets in the water column. Salinity also promotes these interactions.
Dissolved oxygen	Low oxygen environments may occur in lakes or deep, slow-moving depositional areas of rivers. Low oxygen availability limits aerobic biodegradation of oil. Anaerobic degradation of oil can occur, but rates are slower than for aerobic processes.		High oxygen environments (saturated or super-saturated) can occur in high gradient streams where water turbulence results in greater entrainment of oxygen. These high oxygen environments can facilitate aerobic biodegradation of crude oil that may be trapped in interstitial spaces of gravel and cobble.	Oxygen is typically a not limiting factor to biodegradation in rivers, except in deep, slow moving areas or in sediment pore water. Oxygen becomes a limiting factor to biodegradation in areas of depositional sediment. Crude oil deposited in anoxic sediment may persist indefinitely.

Table 7-21 Effects of Oil on Sediment by Environmental Characteristic

LAND COVER RECEPTOR: Sediment				
Environment Characteristic	**Low**	**Medium**	**High**	**Comments**
Hyporheic Flow (water exchange between the river and bed sediment)	Rivers are generally areas of groundwater inflow. In these areas, natural groundwater flow into the river will prevent crude oil residues from entering the hyporheic zone.	Irregular river bed surfaces can create local pressure gradients so that fine-scale interactions driven by hydrostatic pressure may draw water into the river bed, trapping small droplets of oil in the bed sediments.	In steep terrain, hyporheic flow systems may occur on river reach scales, with water entering the river bed near the start of riffles, and exiting in riffle tail pools. In arid environments, rivers may feed water into the regional groundwater flow system on an even larger scale, so that entrained oil droplets would be transported into the river bed on a larger scale.	Oil entering the hyporheic zone can become trapped in the sediment by adsorption to particles or can contaminate interstitial water. These areas are often important for benthic community production, or as spawning or juvenile rearing habitat for fish. Hyporheic flow is more likely in areas of coarse-grained sediment than fine-grained sediment. Continual flushing of the hyporheic system or periodic spate events will typically restore habitat quality.

7.1.2.6 Shoreline and Riparian Bank

7.1.2.6.1 Receptor Description

Shoreline and riparian areas are lands adjacent to lakes, ponds, streams, and rivers where soils and vegetation are strongly influenced by the presence of water and exposure stresses such as waves, flood flows, elevated water tables, scour, erosion, and sediment movement (Boak and Turner 2005). As a result, these areas frequently support a diverse set of environmental processes and associated plant communities adapted to disturbance regimes over varying spatial and temporal scales (Keddy 1982; Keddy 1983; Wilson and Keddy 1986; Gregory et al. 1991; Strayer and Findlay 2010).

Shoreline and riparian areas may have various substrate types (e.g., organic material, sand, silt, clay, gravel, cobble, rip-rap, and cement). Shoreline slopes may range from gentle inclines to steep or undercut, depending upon the prevailing hydraulic regime and landscape they occur in. Plant communities range from types characteristic of exposed beaches, rocky shorelines, and unconsolidated shorelines, to densely vegetated emergent and marsh wetlands, and forested riparian lands. Such communities contain plant species that are adapted to the various combinations of physical gradients and exposure that occur at a particular location (Keddy 1982; Keddy 1983; Wilson and Keddy 1986; Shipley et al. 1991). Communities change over time as physical conditions and competitive interactions are modified by climactic patterns and variations in disturbance stresses (Keddy and Reznicek 1986; Gaudet and Keddy 1995; Boak and Turner 2005; Strayer and Findlay 2010).

Shoreline and riparian areas provide a variety of functions that are valuable to humans. Examples of such ecosystem services include support of fish, wildlife, and non-game species; water quality buffering; flood flow dissipation; erosion protection; and aesthetic quality. Shoreline and riparian areas are often destinations for people seeking to enjoy activities such as fishing, swimming, and boating. Shoreline habitats are at risk from oil releases because of the high likelihood of being directly oiled by floating slicks, or by deposition of oiled debris, tarballs, or other oil aggregates.

Shorelines vary from place to place, based on landform, exposure, and plant community development, making classification a complex undertaking. Most classification systems are based either on the physical characteristics of the shore or on some combination of physical characteristics and vegetation (Reid and Holland 1997). In general, freshwater shoreline types can be placed into the following categories (Owens et al. 1993; NOAA and API 1994):[9]

1. Sand—sandy shorelines are areas where most particles are between 0.003 and 0.079 in. (0.075 to 2 mm) in diameter. Such shorelines may consist of one size of sand or a mixture of different sand sizes with elements of clay, silt, gravel and cobble. Often sandy shorelines

[9] Particle sizes are converted to Imperial measure based metric standards from ISO)publication 14688-1:2002, Identification and Classification of Soil.

have varying amounts of woody and other debris. Plants tolerant of disturbance may grow in areas of stable sand with adequate organic material, moisture, and nutrients.

2. Mixed Sand and Gravel—these shorelines are composed of varying amounts of sand and gravel with particle sizes ranging from 0.00079 to 2.5 in. (0.02 mm to 63.0 mm). Varying amounts of wood and other organic debris may be present. Plant communities tend to be minimal on mixed sand and gravel shorelines due to high levels of disturbance and poor water holding capacity. However some hardy plants may grow in relatively sheltered locations.
3. Gravel/Cobble—gravel shores are dominated by material with particle sizes ranging from 0.079 to 7.9 in. (2 to 200 mm). Scattered larger sized boulders, patches of sand, woody and other debris may also be present. Plant communities tend to be minimal on gravel shorelines due to high levels of disturbance and poor water holding capacity. Some hardy plants may grow in relatively sheltered locations.
4. Bedrock—bedrock shores are composed of impermeable rocky substrate that may be intact or contain cracks, fissures, and crevices. Such shores can range from vertical walls to nearly flat shelves. In most cases bedrock shorelines have limited associated biological communities and human uses, although cliff structures can provide nesting and foraging areas for birds, and some plants may grow where pits and cracks provide rooting opportunities and sufficient moisture.
5. Vegetated banks—vegetated banks are non-wetland areas occurring on mineral or organic soils at and just above the ordinary high water level. Vegetation generally consists of species found in adjacent upland communities, although specialist species such as alders, willows, and cottonwood trees may predominate. Field crops, grassland, or lawns may be present in developed areas. Many animal species use these areas for foraging, nesting, and hiding. Some animals such as swallows and muskrats may also create nests by burrowing into banks.
6. Mud/Sediment—med/sediment shorelines are composed primarily of silt and clay particles (<0.00079 in. or <0.02 mm). They may be intermixed with areas of sand and gravel and generally occur in areas of low exposure. Woody and other debris may be present. Often these areas are high in organic content and support diverse communities of plants and invertebrates.
7. Wetlands—in some locations, the shorelines of lakes, ponds, rivers, and streams are not clearly defined and the aquatic system may transition into a wetland. Depending upon the associated hydrology and plant community type, wetlands may be described as bog, marsh, fen or swamp subtypes.
8. Manmade Structures—manmade structures include shore protection surfacing such as seawalls, bulkheads, riprap revetments and groins, breakwaters and jetties, which may be constructed of rock, concrete, wood, and/or corrugated metal or plastic. Manmade structures usually have specific human use, but may have limited associated value as biological habitat.

The following summary of observed and expected effects of released oil to shoreline and riparian areas considers the non-wetland areas described above. Wetlands are addressed separately in Section 7.1.2.7.

7.1.2.6.2 Observed Effects of Oil along Shoreline and Riparian Areas

Although there are few published reports, data available from field experiments and a small number of freshwater case studies provide a basis for describing what happens to shoreline and riparian areas following a crude oil release, and for categorizing the relative sensitivity of different shoreline types. The overall pattern in these published records is that the key determinants of oil effects to shoreline and riparian areas include the type and quantity of oil released, the type of water body affected, the shoreline type and complexity, and the vegetation community type present (Gundlach and Hayes 1978; Baca et al. 1985; Owens et al. 1987; NOAA and API 1994; Hossler et al. 2007; Michel et al. 2008).

Oil type can influence the fate of released oil because crude oils and petroleum products are composed of differing mixtures of hydrocarbon compounds. Each substance has physical properties (e.g., viscosity, adhesion, density, solubility) that reflect its chemical composition and affect its fate and transport once released into the environment (NRC 2003). Light, low viscosity oils are generally retained on shorelines only as thin layers of oil, which will also weather quite rapidly (Curl and O'Donnell 1977; Davis et al. 2004). In contrast, heavy oils tend to be viscous adhesive, so they tend to be retained on shorelines as thicker layers of oil. Heavy oils exposed to sunlight and wave action weather to form tar balls and other deposits that can be difficult to remove from shoreline rocks and sediments (Atlas 1975; Overstreet and Gault 1995; USEPA 1999; Ansell et al. 2001). Heavy oils also contain larger amounts of substances such as resins and asphaltenes, which weather slowly and render them more persistent than light oils.

The Grapevine Creek oil release in Kern County, California and the Chalk Point oil release into the Patuxent River, Maryland demonstrate the differences between oil type and persistence. The Grapevine Creek release consisted of approximately 6,200 barrels of San Joaquin valley light crude entering a small stream. Sampling data indicated that within two days of the release a majority of the oil had dissipated and over 90% of its toxic compounds were gone (Mancini et al. 1995). In contrast, the Chalk Point oil release consisted of 3,333 barrels of No. 6 heavy fuel oil that ran into Swanson Creek and the Patuxent River. In this case, sampling indicated that within the first five days of the release 39% of the oil had dissipated and the residue remained substantially toxic (NOAA et al. 2002).

The type of waterbody also influences the effects of released oil on shorelines and banks by affecting oil concentration, retention time, flushing rate, and the potential for emulsification and weathering (Baca et al. 1985; NOAA and API 1994; Overstreet and Gault 1995; Owens 2003). In general standing water bodies such as lakes and ponds will have lower physical removal, dilution and flushing rates, and slower weathering of crude oil than moving water such as rivers and streams (Baca et al. 1985; NOAA and API 1994; Overstreet and Gault 1995). In rivers and streams, higher mixing rates may also increase contact between oil and suspended sediments, promoting enhanced biodegradation rates through oil-mineral aggregate formation (Lee 2002; Owens and Lee 2003).

Differences in effect related to the water body type are illustrated by the Marathon oil release into Newton Lake, Illinois, and the tank ship MOBILOIL release into the Columbia River. The Marathon release occurred on April 27, 1985, releasing approximately 10,775 barrels of Southern Louisiana crude oil into the north end of Newton Lake in Jasper County, Illinois. The oil moved slowly along the lake surface allowing retention of most of the oil within about a mile of the release site, although a period of high winds dispersed a small amount past the booms and several miles further south(Sauer et al. 1995; Neff et al. 1995). Shoreline oiling occurred primarily in areas near the release, where wind pushed oil toward the lake edges. In locations farther away from the release site, winds and water currents retained oil on the water surface (Sauer et al. 1995; Neff et al. 1995). In contrast, the MOBILOIL incident released over 3,900 barrels of heavy fuel oil into the Columbia River near St. Helens, Oregon on March 19, 1984. High river flows rapidly carried the oil downstream as surface and subsurface material. After 24 hours, material was detected over 50 miles downriver (Kennedy and Baca 1984). After 48 hours the oil reached 70 miles downstream and entered the convergence zone with the Pacific Ocean. Shoreline oiling above the convergence zone was related to fluctuations in river water level and much of the deposited material was rewashed into the river during subsequent high water events (Kennedy and Baca 1984).

Substrate type (e.g., grain size, mobility, organic content), substrate motility, slope and exposure, and type of vegetation can influence the effects of released oil on shoreline and riparian areas (Gundlach and Hayes 1978; Little and Scales 1987; Humphrey et al. 1993; NOAA and API 1994; Rayburn 2001; Peterson et al. 2002; Short et al. 2004; Owens et al. 2008). The degree of oil penetration into the shoreline substrate depends in large part on the permeability of the substrate (Etkin et al. 2007). There is an interaction between crude oil viscosity and average substrate pore size that determines oil retention capacity. Shoreline substrates that are water-saturated or can maintain water saturation during periods of low water level (e.g., clays, silts, and muds) are resistant to penetration by crude oil. Shoreline substrates that drain down and are porous may be penetrated by crude oil; however, light crude oils with low viscosity may be poorly retained by coarse open substrates such as gravels and cobbles, whereas heavy crude oils with higher viscosity may penetrate and be retained within such substrates. Retention of crude oil in shoreline substrates can increase the complexity and intrusiveness of the clean-up (Li and Boufadel 2010).

Sub-surface or sequestered crude oil may become physically protected from disturbance, oxygenation, and photolysis, only partially weather, and retain some degree of contamination for years (Peterson et al. 2003). Fine sands and muddy sediments have the lowest permeability of unconsolidated types and also tend to be water saturated, so oil penetration is very limited. On the other end of the scale, gravel and cobble substrates are highly permeable. Consolidated shoreline materials such as bedrock, and some manmade materials such as concrete or sheet pile, tend to be impermeable except where cracks, fissures, and other similar features occur.

The importance of shoreline exposure and slope is their effect on wave frequency, magnitude, and action (Owens et al. 1987; Little and Scales 1987; Little et al. 1993; Owens and Lee 2003; Short et al. 2004; Etkin et al. 2007). In lakes, shorelines that are exposed to prevailing summer winds (lee shores) tend to be washed by waves, while windward shorelines are generally calmer. Steep shoreline areas are usually subject to abrupt wave run-up and breaking, and even reflection in places, which enhances natural clean-up of the shoreline. Flat shoreline areas, on the other hand, promote dissipation of wave energy farther offshore, which lets oil remain longer in the shoreline zone.

In rivers, the situation is more three-dimensional but the basic concepts still pertain. As Owens (2003) pointed out, "[g]enerally, the waters of a river move in one direction (downstream) but locally within a channel there are back eddies, whirlpools, and other dynamic hydraulic features that alter the simple unidirectional flow pattern". Once oil enters this dynamic environment, the rate of movement is primarily a function of river flow. It thus tends to be deposited along shorelines in quieter waters where velocity and turbulence decrease at a given river stage rather than along shorelines more exposed to strong currents (Kennedy and Baca 1984; Baca et al. 1985; Owens 2003).

Where dense vegetation exists at the land-water interface and released oil approaches from the water, the vegetation can provide a barrier and protect shoreline resources from contact with substantial amounts of oil. One example of this was reported following the 1988 Shell Oil release in Martinez, California. In this release, nearly 9,405 barrels of San Joaquin Valley crude oil was released into Peyton Slough and Shell Marsh. Researchers found that, in shoreline areas with vegetation, a majority of the oil was absorbed by the vegetation and did not reach soil to the landward side (Fraser et al. 1989). Similarly, shoreline oiling data from the November 2000 M/T Westchester oil release into the Mississippi River showed that along vegetated shorelines oiling occurred usually as a narrow band along the outer fringe, with little penetration into the vegetation and minimal contact with the shoreline substrates (Michel et al. 2002, 2003).

In cases where the oil reaches the shoreline from land or where waterborne oil penetrates the vegetation, shoreline plants can increase the shoreline's oil-holding capacity and oil residence time, thereby resulting in a greater duration of oiling effects than in similar un-vegetated shorelines (Gundlach and Hayes 1978; Baca et al. 1983; NOAA et al. 2002; Peterson et al. 2003; Michel and Rutherford 2013). The trapping capacity of vegetation is illustrated by the May 1983 oil release near Wilmington, North Carolina that released approximately 119 barrels of waste heavy fuel oil into the Cape Fear River (NOAA 1997). The oil affected approximately 30 miles of high-marsh type shoreline dominated by species of *Spartina, Scirpus,* and *Juncus.* Studies five months after the release found that the vegetation trapped oil along the shoreline from which it continued to seep at low tide (Baca et al. 1983). A study of the September 1969 oil release into Buzzard's Bay near West Falmouth, Massachusetts reported that oil residues persisted in the marsh vegetation along the shoreline, but not elsewhere in the release zone (Peacock et al. 2005).

The time of year of a release can influence the resulting effects to shoreline and riparian areas by determining sensitivity of affected resources and the ease of detection and clean-up. Oil released when plants are beginning to grow or reproducing result in greater damage than when plants are dormant. Oil releases in winter and under ice, however, can make detection and clean-up difficult, prolonging the period of oiling (Telford and Quam 1979; Owens et al. 2005).

7.1.2.6.3 Expected Effects of Oils on Shoreline and Riparian Areas

The expected effects of oils in shoreline and riparian areas mirror the observed effects reported in published literature. The magnitude of effects depends on three principal dimensions, namely oil type, shoreline type, and degree of exposure to physical processes

The review of case studies above indicates that in general, the lighter the oil, the more impervious the substrate, and the more exposed the site, the less will be the effect. Thus, a light oil released in a shoreline area consisting of bedrock or concrete with high exposure can be expected to have relatively minor shoreline effects, while a heavy oil released into sheltered shoreline areas with diverse wetland vegetation can be expected to have more severe effects. Assuming a release of an equivalent amount of the same type of oil, the relative sensitivity of different shoreline habitats to the oil can be generally ranked from low to high as shown below (adapted from NOAA and API 1994; Jensen et al. 1998; Peterson et al. 2003; Etkin et al. 2007):

1. Exposed rock cliffs, seawalls, and other exposed, impermeable vertical shorelines
2. Exposed bedrock shelfs, shoals, and ledges, concrete slopes, and other impermeable, non-vertical shorelines
3. Moderately exposed fine-grained sand beaches, eroding sediment scarps and banks, and other semi-permeable, shorelines
4. Moderately exposed coarse-grained sand beaches, sandy bars, sloping sand banks, and other moderately permeable shorelines
5. Moderately exposed mixed sand and gravel beaches, bars, sloping banks and other moderately to highly permeable shorelines
6. Moderately exposed gravel beaches, bars, and sloping banks; rip-rap, and other highly permeable shorelines
7. Moderately exposed soft mud and mixed mud/sand flats and other flat, semi-exposed, semi-permeable shorelines
8. Sheltered, moderately sloping rock, mud, or clay banks; rip-rap or rock rubble, vegetated bluffs and other impermeable shorelines
9. Sheltered sand/mud flats, vegetated low banks and other flat, semi-Permeable shorelines
10. Sheltered organic flats supporting marsh, swamp, and other diverse wetland shorelines

Effects of released crude oil on riparian areas are consistent with effects of released oil on wetlands, soils and terrestrial vegetation communities, as discussed elsewhere. Riparian areas are transitional between water and land, and subject to seasonal cycles of inundation and drainage that depend strongly upon site-specific conditions of hydrology, soil type and vegetation community present.

7.1.2.6.4 Summary of Oil Release Effects on Shoreline and Riparian Areas

Table 7-22 and Table 7-23 provide a summary of the expected environmental effects of oil releases to shorelines. Table 7-22 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-23 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-22 Effects of Oil on Shoreline and Riparian Areas by Oil Characteristic

Oil Characteristics	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—adhesion	Light crudes have low adhesion properties that require less intensive remediation efforts to remove oil from shoreline and riparian areas	Medium crudes have moderate adhesion properties that require more intensive remediation than light crudes, but less intensive than heavy crudes, to remove oil from shoreline and riparian areas.	Heavy crudes have high relative adhesion rates that require intensive remediation efforts to remove oil from shoreline and riparian areas. Diluted bitumens initially have similar adhesion properties, but through weathering become more adhesive than weathered conventional heavy crudes.	The adhesive properties of oils change with weathering as the more soluble and less viscous constituents evaporate to the environment. Adhesion is also related to the viscosity and persistence of oil and is specific to the particular type of crude oil.
Oil properties—viscosity	Light crudes have a low relative viscosity and are more readily disperses in aquatic environments than medium and heavy crude oils. Thus, they have a greater potential to affect larger extents of shoreline and riparian areas.	Medium crudes have a moderate relative viscosity and tendency to disperse in aquatic environments. Thus, they have a moderate potential to affect shoreline and riparian areas.	Heavy crudes have a high relative viscosity and lower tendency to disperse in aquatic environments. Diluted bitumens when fresh have lower viscosity than heavy conventional crudes; however, the viscosity of diluted bitumen increases rapidly with weathering. Heavy crudes and diluted bitumens have a lower potential to affect larger extents of shorelines and riparian areas as the released oil tends to remain aggregated, but oil is also likely to be deposited more thickly than for lighter crudes.	Viscosity of crude oils increases with weathering as low molecular weight components that act as solvents evaporate rapidly.

Table 7-22 Effects of Oil on Shoreline and Riparian Areas by Oil Characteristic

Oil Characteristics	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—persistence	Light crudes tend to be deposited more lightly, and have a lower persistence in the environment due to their more volatile constituents (i.e., low molecular weight hydrocarbons) and smaller proportions of persistent components (e.g., resins and asphaltenes). Therefore, light crude oils tend not to be persistent, and affected shoreline and riparian habitats are likely to recover quickly.	Medium crudes have a moderate relative persistence in the environment due to their mixture of volatile and non-volatile constituents. Therefore, there is a moderate potential duration of effects to shorelines and riparian areas from released hydrocarbons.	Heavy crudes and diluted bitumens are likely to be deposited more thickly, and contain larger proportions of resins and asphaltenes than lighter crude oils. Heavy crudes are therefore more persistent in the environment. Shoreline and riparian areas affected by heavy crude oils will take longer to recover than similar areas affected by lighter crude oils.	Persistence in the environment is assessed here without taking into account oil spill response, including clean-up and removal of released hydrocarbons. Oil spill response activities would enhance natural recovery, reducing although not eliminating differences related to crude oil type.

Table 7-23 Effects of Oil on Shoreline and Riparian Areas by Environmental Characteristic

Environmental Characteristics	Low	Medium	High	Other Comments
Ice cover	Ice-free conditions permit contact between released oil and shoreline/riparian areas. Recovery of hydrocarbons from open-water environments is simpler and more effective, reducing potential for crude oil contact with shorelines.	A release to the aquatic environment during spring break up creates challenging conditions for recovery efforts. Hydrocarbons are likely to contact shoreline and riparian areas. High water levels would promote entry of released oil into flooded areas and riparian zones.	A release to the aquatic environment under ice cover creates challenging conditions for recovery efforts. However, ice cover may limit crude oil contact with shorelines, and prevent contact with riparian areas. Hydrocarbons released onto ice covered aquatic environments or frozen shorelines are more easily recovered and tend to have less substantial effects to shorelines and riparian habitats.	A release under winter ice may be followed by a "secondary release" as oil that was trapped under the ice is mobilized with spring breakup and rising water levels.
Shoreline slope	Steep shorelines are usually subject to abrupt wave run-up and breaking, and even reflection in places, which enhances natural clean-up of the shoreline.	Moderate slope shorelines have intermediate risks of oil retention.	Flat or gentle slope areas promote dissipation of wave energy further offshore, letting oil remain longer in the shoreline zone. In sheltered habitats, slope is a less important factor with regard to oil effects, except that biological communities have more area to develop, and may represent more important units of habitat, where the slopes are gentle.	Shoreline slope is a factor that would be more important in large lakes than in many other freshwater habitats.

Table 7-23 Effects of Oil on Shoreline and Riparian Areas by Environmental Characteristic

Environmental Characteristics	Low	Medium	High	Other Comments
Shoreline exposure	Low energy shorelines and are sheltered from wave energy, except during unusual or infrequent events. Weathering and flushing rates are low and oil can remain adhering to the shoreline for extended periods of time. Sheltered areas also tend to have conditions conducive to development of relatively diverse biological communities making them more sensitive than locations that have greater exposure.	Medium energy shorelines have intermediate characteristics with respect to oil deposition, weathering, flushing, and retention.	High energy shorelines are regularly exposed to large waves or strong currents. The effects of oil on exposed habitats are reduced because: 1) offshore-directed currents generated by waves reflecting off hard surfaces push the oil away from the shore; 2) wave and/or current-generated forces mix and rework shoreline materials that are typically coarse-grained, removing stranded oil; and 3) organisms adapted to living in high energy settings are accustomed to short-term perturbations in the environment.	
Shoreline composition	Impermeable shorelines largely impermeable to oil except when it is able to enter crevices or fractures in rock surfaces. Impermeable shorelines tend to retain less oil, for shorter periods of time, than permeable shoreline types.	Moderate permeability shorelines have intermediate risks of oil penetration, burial, and retention.	Highly permeable shorelines tend to retain more oil and may sequester crude oil in relatively fresh form for longer periods of time. If the substrate pores are large and inter-connected, the substrate will be more permeable and allow deeper penetration and even lateral movement through capillary action.	Water saturation of shoreline substrates can prevent ingress of crude oil.

Table 7-23 Effects of Oil on Shoreline and Riparian Areas by Environmental Characteristic

Environmental Characteristics	Low	Medium	High	Other Comments
Riparian area	Watercourses occupying incised channels with narrow riparian areas present smaller surface area and lower habitat value to be harmed by retained or entrapped crude oil residues.	Watercourses having moderate riparian zones present intermediate surface area and habitat values to be harmed by retained or entrapped crude oil residues.	Watercourses having broad floodplain areas may represent important and rich habitat units, where effects may be more extensive and damaging to biodiversity than in less extensive floodplain areas.	

7.1.2.7 Wetlands

7.1.2.7.1 Description

Wetlands are areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a vegetation community that is typically adapted for life in saturated soil conditions. Three key diagnostic environmental characteristics are therefore used to define wetlands (Environmental Laboratory 1987):

- Soils are present and are classified as hydric, possessing characteristics that are associated with reducing or anaerobic soil conditions
- Area is flooded, either permanently or periodically, with shallow water; or the soil is water-saturated to the surface at some time during the growing season of the prevalent vegetation
- Prevalent vegetation consists of macrophytes that are typically adapted to areas subject to flooding, and that have the ability to thrive in anaerobic soil conditions

Wetlands develop through the recurrent or prolonged presence of water at or near the soil surface, which greatly influences associated soil development and the types of plant and animal communities living in the soil and on its surface (Heimlich et al. 1998). Wetlands provide a variety of ecosystem services of benefit to humans, including the following functions and values that have been identified as important to the people of Minnesota (MN DNR 1997):

Table 7-24 Identified Functions and Values

Wetland Functions	Wetland Values[1]
1. <u>Hydrologic Flux and Storage</u>: includes ground water recharge and discharge; stream discharge and recharge; water storage, and evapotranspiration export. 2. <u>Biological Productivity</u>**:** includes primary productivity; secondary productivity; carbon storage; and carbon fixation. 3. <u>Biogeochemical Cycling and Storage</u>**:** wetlands can be a nutrient source or sink, an area for oxidation and reduction chemical transformations; an area for dentrification; and reservoirs for sediment and organic matter. 4. <u>Decomposition</u>**:** involves carbon release; mineralization; detritus output for aquatic organisms; and release of chemical compounds. 5. <u>Community Wildlife Habitat</u>**:** providing habitat for algae, bacteria, fungi, insects, invertebrates, wetland plants, fish, shellfish, amphibians, reptiles, shorebirds, waterfowl, and other wildlife. Wetlands are often critical habitat for rare and unique species enhance the diversity and resilience of plant and animal communities.	• Water supply and low flow augmentation [A] • Flood water retention [A,B] • Water quality protection [A,B,C] • Sediment control [A,C] • Wastewater treatment [B,C] • Nutrient removal [B,C] • Shoreline anchoring and erosion control [A,B,C] • Education and research [A,B,C,D,E] • Historical and archeological resources [B,E] • Open space [A,B,E] • Aesthetics [A,E] • Recreation [A,E] • Hunting and trapping [B,E] • Plant and animal refuges [E] • Threatened and endangered species habitat [E] • Crop (e.g., hay) and pasture [A,B] • Timber production [A,B] • Peat production [B,C,D] • Shrub crops (e.g., cranberry) [A,B] • Wild rice gathering/production [A,B] • Food production/aquaculture (fish, game) [B,E] • Medical product production (streptomycin) [D,E]

Table 7-24 Identified Functions and Values

Wetland Functions	Wetland Values[1]
NOTE: [1] Bracketed letters indicate influencing wetland functions identified in the first column.	
SOURCE: adapted from MN DNR 1977	

Wetlands generally include bogs, fens, marshes, swamps, and similar areas, and may be bordered by areas that are either wetter (e.g., open water or lake habitats where vegetation is no longer a dominant feature of the environment) or drier (e.g., transitional and upland areas where the water table is rarely at the ground surface, flooding is infrequent, and soils are not hydric).

Minnesota contains seven types of native wetland communities that provide the functions and values listed above to the benefit of individuals, communities, the state's citizens, and the overall integrity of land and water systems. Summary descriptions of these seven wetland communities are presented below. The focus in this section is primarily on plant community type and site hydrology.

7.1.2.7.1.1 Bogs

Bogs are nutrient-poor late-successional communities characterized by the prevalence of sphagnum mosses and ericaceous shrubs (heath family). Bogs have a raised water table relative to the surrounding landscape, and the bog water is classically isolated from deeper groundwaters because of the peat accumulation. Most water and nutrients are derived from rainfall, and bog waters are acidic (Bay 1968; Boelter and Verry 1977).

There are two general bog community types in central and northern Minnesota: forest bog and open bog (Aaseng et al. 1993; MN DNR 1997). Both types have a nearly continuous mat of moss dominated by *Sphagnum* species (especially *Sphagnum fuscum* and *Sphagnum angustifolium*), and an impoverished vascular plant flora. The ground layer is dominated by low ericaceous shrubs (e.g., Labrador tea, leatherleaf, swamp laurel, or bog-rosemary), sedges (*Carex* spp.), or cotton grasses (*Eriophorum* spp.). The forest bog community also has a tree layer dominated by black spruce.

Bogs are very sensitive to changes in hydrology and surface and peat water chemistry. Alterations to these parameters can result in shifts in species composition and associated reductions in community quality (Wilcox 1986; MA DFW 2007; Karofeld et al 2008).

Phytoplankton communities of bog pools are typically species-poor, tending to be dominated by filamentous green algae, acidophilous diatoms, and desmids (USEPA 2002a, 2002b). Algal diversity tends to be greatest in open-water areas and in systems connected to other lakes or streams (Wehr and Sheath 2003).

7.1.2.7.1.2 Fens

Fens include community types that occur on wet mineral or peat soils with seasonally standing or flowing water at the ground surface (Aaseng et al. 1993; MN DNR 1997). Fens are further divided into three sub-types according to water chemistry and associated plant community (poor fen, rich fen, calcareous seepage fen). Generally, they occur on sites too wet for significant invasion by woody species, or on sites that burn frequently. Fens share the general characteristic of a closed canopy of mid-height graminoids (grasses or grass-like plants). Dominant species include grasses (e.g., bluejoint (*Calamagrostis canadensis*, prairie cordgrass (*Spartina pectinata*), sedges (e.g., wiregrass sedge (*Carex lasiocarpa*), lake-bank sedge (*Carex lacustris*), tussock sedge (*Carex stricta*), and rushes (e.g., *Scirpus cespitosa*). Fens may have associated algal communities generally dominated by green algae, cyanobacteria, and alkaliphilous diatoms (USEPA 2002a, 2002b; Rober et al. 2013).

7.1.2.7.1.3 Marshes

Marshes are shallow-basin wetlands that develop in standing water typically in mineral soils or in relatively inorganic sediments associated with lakes, ponds, and streams (Aaseng et al. 1993; MN DNR 1997). Marsh vegetation is composed of tall, erect, rooted graminoids such as cattail (*Typha latifolia* and *T. angustifolia*), common reed grass (*Phragmites australis*), bulrush (*Scirpus* spp.), rush (*Juncus* spp.), spike-rush (*Eleocharis* spp.), and some sedges (*Cyperus* spp.). Common herbs associated with marshes include broad-leaved arrowhead (*Sagittaria latifolia*), swamp milkweed (*Asclepias incarnata*), willow-herb (*Epilobium* spp.), bulb-bearing water-hemlock (*Cicuta bulbifera*), and knotweed (*Polygonum spp.)*. Obligate aquatic plants (including *Potamogeton*, *Elodea*, *Ceratophyllum* and *Myriophyllum*) often are present in the standing water of marshes. Algal communities are also important components of marsh wetland ecosystems, contributing significantly to ecosystem primary production and nutrient retention, which improves water quality (Wehr and Sheath 2003; Rober et al. 2013). Wild rice, a commercially and culturally important species grows in some emergent marshes, and in shallow bays of lakes, generally in water less than about three feet deep, in areas with slow current, over a mucky or silty sediment, with little competition from other plants (Moyle 1944; Tucker et al. 2011).

7.1.2.7.1.4 Swamps

Shrub swamps are minerotrophic, tall-shrub communities occurring on mucks and shallow peat soils dominated either by alders (alder swamps) or willows (willow swamps) (Aaseng et al. 1993; MN DNR 1997). The major shrub species in these communities are usually alders (*Alnus* spp.), willows (*Salix* spp., and red-osier dogwood (*Cornus stolonifera*). Common understory species in the community include tussock sedges (*Carex* spp.), cattail (*Typha latifolia*), blue-joint (*Calamagrostis canadensis*), northern marsh fern (*Thelypteris palustris*), jewel-weed (*Impatiens capensis*), and mosses (e.g., *Sphagnum squarrosum*). Shrub swamps are typically non-stagnant wetlands with high levels of dissolved oxygen and soil nitrogen. Soils range from poorly drained to well drained, with most sites remaining saturated throughout the growing season.

Conifer swamps tend to develop on sites with wet mineral or poorly drained organic soils. There is often standing or barely moving water within the community (Aaseng et al. 1993; MN DNR 1997). The tree canopy is dominated by black spruces, tamaracks, or white cedars. The density of the shrub, herb, and moss layers varies greatly, depending on the density of the tree canopy, soil nutrients, and the level of the water table. Due to anaerobic conditions associated with a high water table and organic soils, trees growing in conifer swamps are shallowly rooted. The understory of the community commonly contains combinations of speckled alder, winterberry, red-osier dogwood, willow species, and mountain fly honeysuckle. On less acidic sites, groundcover includes blue-joint, cattail and jewel-weed, while more acidic sites are characterized by a continuous hummocky mat of sphagnum mosses with bog birch, leatherleaf, other ericaceous species, cinnamon fern (*Osmunda cinnamomea*), and various sedges.

Hardwood swamp forests are minerotrophic wetland communities that occur on muck and shallow peat substrates on wet sites in depressions on level to hummocky glacial lake plains, fine- and medium-textured glacial tills, and broad flat outwash plains (Aaseng et al. 1993; MN DNR 1997). Standing water, usually a result of groundwater seepage, is usually present in spring and drained by late summer. Hardwood swamps have tree canopies dominated by broad-leaved deciduous species, including black ash, paper birch, yellow birch, red maple, American elm, slippery elm, green ash, quaking aspen, or, rarely, balsam poplar. Understory vegetation may include alders, ferns, a variety of herbs, sedges and mosses. Areas of standing water will also contain populations of floating and submerged algae.

7.1.2.7.1.5 Other Related Habitat Types

Wetlands are often associated with streams, rivers and lakes, and intergrade with other recognized habitat types around these features.

Floodplain forest is a bottomland, deciduous or deciduous-conifer forest community occupying riparian areas subject to periodic over-the-bank flooding and cycles of erosion and deposition (Aaseng et al. 1993; MN DNR 1997). Floodplain forests are generally dominated by silver maple, cottonwood, black willow, American elm, green ash, and bur oak. Due to frequent flood disturbance, the understory of floodplain forest is often relatively open, with few tree seedlings and saplings. Shrubs may be a significant component, particularly where canopy gaps occur. Woody vines, including wild grape (*Vitis riparia*), poison ivy (*Rhus radicans*), and Virginia creeper (*Parthenocissus quinquefolia*), are often present in light gaps and along open channels. The herbaceous layer generally has low diversity, and contains only short-lived species or species otherwise tolerant of frequent disturbance, such as wild-rye (*Elymus virginicus*), cleavers (*Galium aparine*), sedges (*Carex* spp.) and nettles (Urticaceae).

Vernal pools are small isolated pocket wetlands that occur in depressions located within forested settings. These depressions, typically in mineral soil with an underlying impermeable clay layer, collect water in the spring from runoff and precipitation then dry out later in the year as water inputs decline below evaporation and infiltration rates (Batzer et al. 2004; Brooks 2004; Leibowitz and Brooks 2007; Palik et al. 2007; Thomas et al. 2010). Vernal pools may occur in all forested community types but are most common in wet forest types with poorly-drained mineral soils and least common in dryer forests with generally sandier, more well drained soils (Leibowitz and Brooks 2007; Thomas et al 2010). Plants that grow in vernal pools are often tolerant of flooding, soil saturation, and drought.

7.1.2.7.2 Observed Effects of Oil on Wetlands

The effects of oil on the plants, soils, and water comprising wetlands have been evaluated in laboratory and field experiments, experimental oil releases, and case studies of accidental oil releases. These data sources span marine, freshwater, terrestrial, arctic, and temperate environments; upland and wetland vegetation; and controlled and uncontrolled settings. Most of the experimental spills and accidental oil release case studies include clean-up and remediation efforts. The body of published studies provides a framework for projecting the effects likely to result from releases of oil into different types of wetlands.

Oil affects wetlands by damaging one or more of their primary components: vegetation, soil, and water. Oil can affect wetland communities directly by blocking metabolic processes and indirectly through changing a plant's internal chemistry or by altering soil characteristics and/or water chemistry. The damage can vary considerably based on several factors. Effects vary based on the time of year, the amount of water flow through the community, water chemistry, abundance of oil, type of oil, and type of release (Michel and Rutherford 2013). The toxicity of an oil depends largely upon its content of aromatic compounds (hydrocarbons containing benzene rings), oxygenated aromatic derivatives, and aliphatic compounds (hydrocarbons without benzene rings). Lighter oils, though more acutely toxic than heavy oils, also undergo more rapid weathering leading to a reduction in toxicity. Heavy oils, while potentially having lesser acute toxicity, also weather more slowly, often resulting in longer persistence in the environment.

When released into water, oil spreads over a wide area forming a slick and immediately begins to undergo a variety of physical, chemical, and biological changes including evaporation of high volatile fractions, dissolution of water-soluble fractions, photochemical oxidation, emulsification, microbial degradation, and sedimentation. These processes are affected by temperature, wind speed, and water chemistry and may vary across different types of wetland habitats. Releases into wetlands will tend to be more confined, and the associated effects more concentrated than in open waters of large bodies of water (Shales et al. 1989). Smaller freshwater wetland environments can also be more sheltered from the effects of wind than larger lakes, resulting in lower rates of physical weathering. The effects of crude oil released to lakes are discussed in Section 7.1.2.3.

Oil that directly contacts plants can impede photosynthesis and gas exchange processes by blocking sunlight, clogging stomata, and raising internal temperature (Baker 1970; Emerson 1983; Michel and Rutherford 2013; Pezeshki et al. 2000). When these conditions are of sufficient extent and duration, the loss of metabolic processes result in a decline in vitality, and eventually, if not reversed, death. While light hydrocarbons such as gasoline, diesel fuel, gas condensates and light crude oils can "burn" green plant tissues, resulting in tissue death and in some cases death of the whole plant, heavier crude oils may coat the plant tissues and cause death by smothering.

Changes to wetland soil or sediment characteristics that can be caused by crude oils include alterations to soil chemistry affecting nutrient availability, decreased water content due to increased repellency, and associated changes to vegetation and soil organisms (De Jong 1980; Emerson 1983; Hemmings et al. 2015). Oil flow into the soil or sediment can cause plant mortality by killing root tissues, restricting the availability of nutrients, and/or preventing regrowth from rhizomes (Corn and Copeland 2010). Because crude oil deposited in wetlands alters the microbial process, there can be a subsequent change in soil or sediment biochemistry (Nyman 1999; Mendelssohn et al. 2012). The presence of crude oil typically causes a decrease in microbial diversity and an increase in abundance of those microbes that can more readily use the carbon source available in the oil. This change in the microbial community can ultimately modify nitrogen cycling dynamics within the wetland, affecting plant growth and associated processes (Plice 1948; Ellis and Adams 1961; Greer et al. 2003).

Following a release of 30,000 barrels of crude oil into a Louisiana cypress swamp, researchers observed plant growth in affected and in unaffected control areas (Baca et al. 1985). According to the researchers:

> Comparisons of control and affected sites one year following the release showed that areas with high shading by cypress, sweetgum, and tupelo had little or no understory and very few effects were seen on the dominant woody vegetation. In addition, perennials (e.g., *Pontederia cordata*) were returning in all sunlit areas. However, floating vascular vegetation suffered significant impacts. Areas of water in the swamp once completely covered by water hyacinth (*Eichhornia crassipes*, an introduced pest) and associated nonvascular plants were devoid of any vegetation.

Following the 1972 release of approximately 160 barrels of diesel fuel into a wet meadow near Mount Baker, Washington, studies were made of the initial effects of the oil on the vegetation and of community recovery over nine years (Belsky 1982). The studies concluded that:

> Both the amount and the type of the oil in the Mt. Baker oil release were responsible for the initial impact which reduced vegetative cover from nearly 100% to less than 1% and all species except *Phyllodoce empetriformis, Carex lenticularis,* and *Rhacomitrium sudeticum* had died. The added burden of a large volume of oil (160 barrels) flowing through a small area increased the damage. The snow cover, steep terrain, and snowmelt water, on the other hand, reduced the impact of the diesel oil on the meadows. In the Mt. Baker release, oil flowed over frozen and saturated soils and contacted dormant vegetation. Most of the diesel oil flowed down the steep slope and out of the area instead of pooling for

> later absorption. In the summer a large volume of snowmelt water flushed much of the oil out of the area. Recovery of the habitat began with seed germination of *Carex nigricans* within one year, followed by seedlings of other common subalpine species two to four years later. Nine years after the perturbation 5 to 20% of the ground was covered with vegetation and the original disturbance could no longer be discerned by a casual observer.

After approximately 24 barrels of fuel oil released into a freshwater marsh along the Mill River near Northampton, Massachusetts researchers followed the growth of vegetation over four years (Burk 1977). The vegetation bad been studied the year prior to the release and, less intensively, three years previously. Following the study, researchers reported that:

> Total plant cover, total number or species, mean number of species per quadrat and the Shannon-Wiener function progressively reduced in both high and mid-marsh zones for two years after the release. Eighteen of the species found before the release were not found the following season. Perennial species generally were less affected than annual species immediately following the oil release. Some species (e.g., *Dulichium arundinaceum and Eleocharis palustris)* declined in abundance the second season following the release. Marked changes in relative abundance of the dominant species of high and mid marsh zones occurred from year to year, with *Onoclea sensibilis* more prominent in high marsh at the end of the study period than prior to the release and *Pontederia cordata* and *Nuphar variegatum* more prominent in different segments of mid-marsh. The vegetation of the high marsh and mid-marsh zones had substantially recovered by the third and fourth years. The low marsh vegetation was apparently unaffected immediately following the oil release but in succeeding years the species diversity declined and luxuriant growth of *Elodea nuttalii, Potomogeton crispus,* and *Potomogeton epihydrus* occurred.

Hutchinson and Freedman (1978) studied the effects of experimental releases of crude oil into a boreal conifer swamp using spray and point discharges. Following the study, they reported that:

> Spray releases of fresh unweathered crude oil at an intensity of 2 gallons per square yard had a general herbicidal effect, causing the death of any green tissue coming in direct contact with the oil. Death of lichens and mosses was rapid and complete. For some higher plants, a lag period (up to 4 years for some individuals of *Picea mariana*) occurred between the time of the release and the time of death. For others, death occurred during the first winter with marked effects on cover values in the spring. These effects resulted in large decreases in total plant cover and frequency at release sites. However, within a few weeks, and in subsequent years, some species developed regrowth shoots. Other species survived as underground rhizomes for a number of years prior to their reappearance above ground (i.e., *Equisetum scirpoides*). Limited seedling

> establishment by vascular plants was first observed in the fourth growing season after the release, when some sporeling establishment was also noted for several bryophyte species. No *Picea mariana* regeneration occurred in the release plots in six post-release growing seasons. Crude oil releases made in winter were found to be less damaging than equivalent summer releases in their short term biological effects and on rates of recovery and species affected. Initial observations indicate that a summer diesel oil release shows roughly equivalent toxicity to a summer crude oil release of the same intensity. Comparisons between an intensive release (53 barrels) made at one location and dispersed spray releases indicate that the former are less damaging per unit of oil, with the scale of adverse effects being related more to the area of contamination.

Racine (1994) studied the same sites 10 years later, and reported that:

> Low volume spray releases that uniformly covered the ground caused initial damage to vegetation, but after 20 years recovery of the understory vegetation was almost complete, with dramatic recovery and expansion of fruticose lichens. High volume point releases created small areas of surface oil saturation with dead vegetation and little sign of recovery, but spread out mostly below ground with little or no apparent effect on the shallowly rooted vegetation even after 15–20 years. Because winter point releases created a much greater area of surface oil, their effects were more damaging. After 15 years on the saturated surface oiled areas, only *Eriophorum vaginatum* tussocks survive and grow. At both sites with surface oil, black spruce mortality was high, with no evidence of long term recovery and with continuing chronic effects after 15 years.

Leck and Simpson (1992) studied the effects of crude oil contaminated soil on plant growth recruitment from the seed bank from two tidal freshwater wetlands along the Delaware River in New Jersey. The authors observed that:

> Oil treatment of marsh soils significantly reduced survival of *Acnida cannabina* and *Bidens laevis,* the dominant species, as well as number of species per sample and height of *B. laevis.* Total perennial seedlings, present in low numbers, also showed significant reduction with treatment. However, during the course of the study, *Peltandra virginica* recruitment and survival were not reduced by soil oil treatments and recruitment of *Sagittaria latifolia* appeared enhanced.
>
> The effect of oil on recruitment from the seed bank depends on: (a) the extent to which it covers the wetland soil thereby acting as a physical barrier to water and oxygen, (b) the extent to which it penetrates and remains in the soil thereby either coating the seeds or being toxic to them, and (c) blocking the ability of germinated seeds to reach above the soil surface.

> Oil releases can have significant short-term effects on seedling establishment and growth that may translate into long-term effects on composition. If a release were to eliminate recruitment and reproduction of annual species, we feel that species with persistent seed banks and ability to germinate throughout the growing season, such *as A. cannabina* and *B. laevis,* or perennials with widespread and summer dispersal, such as *Typha* spp. or *P. arundinacea,* could colonize gaps as they occur. Others such *as P. virginica* and *S. latifolia* with more tolerant seed/seedling characteristics may reinvade more quickly than annuals.

Lin and Mendlssohn (1996) studied the effect of south Louisiana crude oil on the dominant vegetation, *Spartina alterniflora, Spartina patens and Sagittaria lancifolia,* of three types of coastal wetlands, salt, brackish and freshwater marshes, respectively. In a greenhouse, the crude oil was applied to natural marsh sods at rates of 0, 0.88, 1.77, 3.53 and 5.30 gallons/square yard. After measuring plant growth for a year, the researchers concluded that:

> The present study clearly demonstrates that South Louisiana crude oil, when applied to the soil, significantly impairs the two *Spartina* species, while not adversely impacting *S. lancifolia.* The sensitivity is based on the effect of oil on photosynthetic rate, live and dead biomass, plant-stem density, and plant regrowth in the year following oil application. The differential oil sensitivity was partially related to differences in soil organic matter among the marsh-types. The soil organic matter played a key role in accelerating penetration and sorption of oil into the soil. The soil organic matter content, therefore, is a primary factor controlling the effects of oil releases in marshes, as initially hypothesized. Oil releases in marshes of high organic matter content may require particular concern. The plant responses observed were also related to differences in the plant sensitivities to oil.

7.1.2.7.3 Expected Effects of Oil on Wetland Community Types

The summaries below provide a general description of the type of effects that may be expected from an oil release in a given wetland type, absent clean-up, based on the wetland hydrology, soil/sediment type, plant community type. However, each oil release is different with effects that vary depending on the quantity and type of oil released, the characteristics of the affected area, the time of year and the climate/weather conditions prevailing at the time of the release.

7.1.2.7.3.1 Bog

Bogs are susceptible to oil damage due to the predominance of low stature plants with high surface area to mass ratios and shallow roots (Aaseng et al. 1993; MN DNR 1997). Plants of this type would be readily exposed to released oil. Due to the generally low topographic gradient, spongy substrate and slow-moving water, oil released into a bog would likely pool. While this would result in smothering and death of most plants it came into direct contact with, it would also limit the area affected. Subsequently, and following clean-up, vegetation in and around the release would likely be affected by altered water chemistry and nutrient availability, as well as by residual effects of low hydrocarbon concentrations. Light oil released into a bog would likely have more severe short-term effects (due to its lower viscosity and greater tendency to spread horizontally) but less severe long-term effects than heavy oil, which would spread less, but be more persistent if not physically removed. Some plant mortality may be expected along with longer term stress and growth reductions until residual hydrocarbons in the peat and water weathered sufficiently to abate toxic stress. Medium weight oils are expected to exhibit intermediate effects consisting of some smothering and moderate toxicity damage. Changes in water chemistry from the persistence of oil or oil fractions in the bog could potentially encourage the growth of plants such as cattail and reed grass that prefer less acidic conditions and/or are tolerant of persisting hydrocarbon compounds (Werner et al. 1985; King and Coley 1985; Shales et al. 1989; Crowe et al. 2002).

7.1.2.7.3.2 Fen

The wet meadow/fen wetland types are highly susceptible to damage from released oil. Oil released to a fen (where groundwater is expected to be discharging, and the soil surface is water saturated) would spread across the surface of the wetland, contacting ground-level vegetation. Some oil would also likely be incorporated into the soil surface (Hemmings et al. 2015). For heavy oils, the combination of smothering, toxicity, and changes in water chemistry would likely result in plant mortality along with persistent inhibition of regrowth as long as un-weathered oil remains (McCown and Deneke 1972; Leck and Simpson 1992; Hemmings et al. 2015). Woody shrubs would be less likely to be affected.

7.1.2.7.3.3 Marsh

Marshes appear moderately susceptible to damage from released oil, with floating plants in proximity to the release point being more susceptible to damage than larger emergent plants with a small portion of their mass at or below the water and/or away from the oil flow path. Oiling of only the stems of emergent plants often results in limited mortality. If only the aboveground vegetation is oiled, regrowth is likely during the next growing season (Baca et al. 1985; Fraser et al 1989; Mancini et al. 1995; Michel et al. 2002, 2003).

Releases of light refined or crude oils which spread rapidly and have higher acute toxicity can result in high mortality of marsh vegetation. Effects would be more persistent in cases where oil penetrates into marsh soils (Mancini et al. 1995; Davis et al. 2004). Persistence increases with deeper penetration, soils high in organic matter, and sites that are sheltered from natural removal processes (Peterson et al. 2003; Etkin et al. 2007). Heavy oils that coat the entire plant, and particularly the leaves, have the greatest potential for widespread damage. Plants with leaves at or near the water level will be most affected by smothering, while taller plants may suffer dieback, reduced growth, or remain unharmed.

For marshes associated with lakes, less damage would be expected for releases into water or along the outside marsh fringe where natural removal processes from wind and wave exposure are more effective. In this case, plants in shallower water closer to the shore might remain protected and experience little or no damage (Fraser et al. 1989; Michel et al 2002, 2003).

Conversely, a release from shore is likely to result in the greatest exposure to crude oil residues (and correspondingly more severe effects) in the near-shore zone (Gundlach and Hayes 1978; Baca et al. 1983; NOAA et al. 2002; Peterson et al. 2003; Michel and Rutherford 2013).

7.1.2.7.3.4 Swamp

Swamps appear to be moderately susceptible to damage from crude oil exposure. In general, the predominant vegetation is woody and moderately tolerant of crude oil exposure due to the presence of bark which is protective of living tissues beneath. The slow water flow in swamps means that oil released into these systems tends to remain stagnant, limiting the area affected but prolonging contact and potentially exacerbating toxicity in the affected area (Baca et al. 1985; Shales et al. 1989). Shallow rooting structures make plants growing in these areas more susceptible to damage and long-term effects from changes in soil communities and chemistry. A release of light crude oil would likely result in death of ground cover, with less damage to shrubs and herbaceous vegetation in areas of higher relief. In the case of a release of heavy oil, mortality of herbaceous plants and smaller woody plants from smothering and toxicity would be expected, and if not remediated, potential damage to trees and larger shrubs from changes to soil and water quality and the uptake of hydrocarbons through roots and bark (Atlas 1975; Curl and O'Donnell 1977; Davis et al. 2004). Lost productivity and reduced reproduction from plants that do not die is likely (Currier 1951; Dallyn 1953; Baker 1970; Emerson 1983).

The general effects of oil released to a conifer swamp would be similar to, but somewhat more pronounced than the effects of a spill on a hardwood swamp. Black spruce appears particularly sensitive to the presence of crude oil in the root zone (Hutchinson and Freedman 1978; Racine 1994). Therefore, greater potential for tree mortality, growth suppression, and inhibition of regrowth are likely for all types of crude oils although there may be a time-lag between the initial release and mortality of larger trees. Some effects to germination and vegetative reproduction may also occur in the area of the release where seeds, tubers, and rhizomes are damaged (Burk 1977; Leck and Simpson 1992; Adam and Duncan 2002). Where oil persists in the community, regrowth is likely to be suppressed for an extended period until the oil substantially weathers and toxicity abated.

Shrub swamps appear to be moderately susceptible to damage from an oil release. While alders, willows, and dogwoods have an ability to reproduce vegetatively, their prevalent lenticels and shallow rooting habit in this community make them susceptive to intake of toxins and root damage from direct contact and dissolved hydrocarbon compounds. Short-term contact with light oils would likely result in mortality of most herbaceous plants and smaller shrubs. Larger shrubs and those on hummocks may survive but suffer reduced growth (Burk 1977; Belsky 1982; Mancini et al. 1995). Medium and heavy oils would likely cause the mortality of most plants in and around the release. Lighter oils would likely cause some mortality of herbaceous plants and small shrubs and reduced growth rates of the larger shrubs but likely not cause complete mortality except perhaps at the point of release (Atlas 1975; Curl and O'Donnell 1977; Davis et al. 2004). Some effects to germination and vegetative reproduction may also occur in the area of the release where seeds, tubers, and rhizomes are damaged (Burk 1977; Leck and Simpson 1992; Adam and Duncan 2002).

7.1.2.7.3.5 Other Related Habitat Types

Floodplain forest wetlands appear moderately susceptible to damage from oil releases. In general, these communities are composed of larger woody vegetation that is protected by bark, limited herbaceous plants, and common natural disturbances such as flood events that can accelerate flushing, dissipation, and weathering (Currier 1951; Dallyn 1953; Baker 1970; Emerson 1983; Baca et al. 1985). The most severe effects would be from extensive releases of heavy oil. In this scenario, hydrocarbons could coat herbaceous and small woody vegetation to the point of severe stress or mortality, become incorporated into the soil, or settle in ponding areas where it could persist, causing changes to soil and water quality until the oil had substantially weathered and substantively abated in toxicity (Atlas 1975; Curl and O'Donnell 1977; Davis et al. 2004). Less severe effects would be expected for smaller releases or releases of light crude oil where the material may coat or stain vegetation, but rapidly weather. In these cases initial plant mortality may still occur, but soil incorporation or persistent changes to water quality are less likely, although residual effects may occur from portions of the light oil that do not volatilize. Some effects to germination and vegetative reproduction may also occur in the area of the release where seeds, tubers, and rhizomes are damaged (Burk 1977; Leck and Simpson 1992; Adam and Duncan 2002).

A vernal pool could present as a shallow depression in the landscape that could trap released oil during the summer, fall and winter seasons, or as a shallow standing water body in the spring. Oil released into a vernal pool in the spring would be trapped in a relatively small amount of water resulting in minimal dilution and high toxicity to aquatic life (typically insects, crustaceans, mollusks, and amphibians, but not fish), and potentially waterfowl. Crude oil residues would likely become incorporated into the soils when the pool dried up. During dry periods, released oils would collect within the pool depression without any dilution. Light petroleum oils would weather more rapidly than heavier ones but in both instances some fractions of the oil would likely be incorporated into the soil being remobilized when the pool flooded again. Regardless of timing, petroleum oils released into a vernal pool would be expected to cause mortality of herbaceous species and algae as well as shrubs and smaller trees as a consequence of capture and concentration within the pool. Some larger trees and shrubs around the edge of the pool may survive but experience decreased growth and reproduction for several years (Burk 1977; Belsky 1982; Mancini et al. 1995). Growth from seeds, tubers, and rhizomes trapped under residual heavy oil would also likely be inhibited both from oil-related chemicals and the smothering cover (Burk 1977; Leck and Simpson 1992; Adam and Duncan 2002).

7.1.2.7.4 Summary

Table 7-25 and Table 7-26 provide a description of the general relative environmental effects of different types of oil and wetland characteristics. Table 7-25 addresses the relative effects of specific oil characteristics or oil type on wetlands, and Table 7-26 addresses the relative influence of different environmental characteristics on wetlands exposed to oil releases.

Table 7-25 Land Cover Receptor: Wetlands

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Viscosity	Low viscosity oils are more readily absorbed into plant tissues, causing acute damage. Low viscosity oils also have less tendency to adhere to plants and to persist in water and sediment resulting in relatively lower long-term chronic damage.	Intermediate effects based on specific oil constituents.	Greater tendency to adhere to plants causing smothering and greater tendency to sink and persist in water and sediment causing long-term chronic toxicity damage.	Low viscosity oils may spread over larger areas than higher viscosity oils which form thicker but less spatially extensive slicks. Viscosity is also correlated with adhesion and pour point temperature of crude oils.
Proportion of VOCs	Light crude oils generally contain relatively more VOCs, and may have greater acute toxicity to plants as a result.	Intermediate acute toxicity.	Lower acute toxicity due to crude oil chemical properties, but this may be offset by higher viscosity and greater tendency to adhere as a thicker coating on plant tissues.	Some diluted bitumens (e.g., winter blends that contain a large amount of condensate as diluent) may have similar VOC content to light crude oils.
Persistence	Light crude oils tend to have low persistence due to a predominance of chemical constituents that will readily weather, and low concentrations of relatively persistent constituents such as resins and asphaltenes	Intermediate persistence properties.	Heavy crude oils contain relatively more resins and asphaltenes than light crude oils, and these constituents tend to be persistent (i.e., are resistant to microbial and other weathering processes) in the environment.	Heavy crude oils also tend to have high viscosity, and would tend to be deposited more heavily, but over a smaller area, than lighter crude oils.

Table 7-26 Land Cover Receptor: Wetlands

Environment Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Plant type—annual, perennial, shrub, tree	Annual and perennial herbs are most sensitive to oil exposure, and particularly sensitive to light crude oils; shrubs and trees are less sensitive. Light crude oil would be less persistent than heavier crude oils, so long-term or chronic effects on wetland vegetation are less likely.	Effects of medium crude oil are likely to be intermediate between the effects of light and heavy crude oils.	Heavy crude oil is expected to be more adhesive, coating more thickly, but affecting a smaller overall area than lighter crude oils. Heavy crude oil is also likely to persist at higher concentrations in wetland soils and sediments, leading to higher potential for long-term or chronic effects on vegetation.	At low levels of exposure, oiling may kill only the green tissues of plants, with regeneration occurring in the same growing season. At higher levels of exposure, annual and perennial plants and shrubs may be killed outright, and trees may die over the course of several growing seasons.
Wetland type—bog, fen, marsh, swamp	Bogs and fens tend to lack a free water surface, and released oil will follow preferential flow paths according to site-specific topography. This can limit the spatial extent of effects, while facilitating recovery of pooled oil. Marshes and swamps typically have a free water surface that will promote the spreading of released oil, leading to effects over larger areas, and making recovery of released oil more difficult.			
Season	A crude oil release in spring (plant emergence/early growth period) would tend to result in greater mortality of small plants, new plants, and annuals, particularly if growing tips and leaves were contacted by fresh crude oil. A release later in the growing season would have less severe effects on plants where the oil was not in contact with leafy tissues. Effects to wetlands during the winter may be low, if oil can be recovered before spring thaw.			
Ground surface diversity	Hummocky or mounded conditions within a community may allow species growing in locally higher elevations to avoid direct contact with the oil. This would be particularly true in locations where much of the oil presence is transitory (e.g. bogs, fens, swamps and floodplains). Habitat such as vernal ponds formed in depressions where oil would collect are at greatest risk of damage from direct contact and chronic effects from absorption and soil contamination.			
Soil organic content	Soils with low organic content may tend to retain oil constituents for shorter time periods thus resulting in less long-term damage to resident plants. Oil may be more persistent in hydric soils and soils with higher organic matter (where oxygen may would also be limiting) leading to more chronic effects on wetland vegetation. Heavy oils would also tend to be more persistent than lighter oils.			
Wetland hydrology	Wetland habitats with moving water (e.g., marsh and swamp habitats that are marginal to rivers or lakes) allow greater flushing and weathering of released crude oil, while at the same time enhancing the spreading of oil in the environment. Stagnant or ponded areas provide little flushing and less weathering. These habitats would be at greater risk of damage from released crude oil.			

Table 7-26 Land Cover Receptor: Wetlands

Environment Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Water chemistry	Slightly alkaline habitats with high nutrient availability provide better conditions for microbial degradation of released crude oil, particularly for light crude oils that weather and undergo biodegradation more readily than heavy crude oils. More acidic, nutrient-poor habitats would be expected to exhibit slower rates of biodegradation.	Medium crude oils would be expected to exhibit biodegradation rates, and response to water chemistry conditions, intermediate between light and heavy crude oils.	Heavy crude oils tend to be recalcitrant due to their greater resin and asphaltene content. Water chemistry may have little effect on biodegradation rates for heavy crude oils.	Bogs tend to be acidic, with low nutrient availability. Marshes and swamps tend to have greater nutrient availability, but released oil may be deposited to anaerobic areas where biodegradation would be slow. Fens are minerotrophic, and groundwater seepage would tend to prevent oil from penetrating to anaerobic areas. Biodegradation potential in relation to water chemistry and wetland type is expected to improve in the order Bog < Marsh = Swamp < Fen.

7.1.2.8 Soils

7.1.2.8.1 Description

According to the Natural Resource Conservation Service (Soil Survey Staff 2003), soil is a natural material composed of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: (1) horizons or layers that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter; or (2) the ability to support rooted plants in a natural environment."

Soils are open systems that interact with the lithosphere, hydrosphere, atmosphere, biosphere, and society to perform vital ecosystem functions. Major soil functions include (Cornell University 2010):

1. Soil is a medium for plant growth or bio-materials production whereby this medium combines with the other soil functions to anchor roots, and allow for the transport of water and nutrients to the root/soil interface
2. Soil is a habitat for soil organisms, making up more than half of all life on the planet. The micro-organisms are mainly responsible for most of the bio-chemical transformations in the soil medium; whereas, the macro-organisms primarily affect physical soil transformations
3. Soil acts as a biochemical or nutrient reactor which absorbs, releases (i.e., desorbs), and transforms inorganic and biochemical compounds such as essential plant nutrients, pesticides, minerals, heavy metals, and numerous other compounds
4. Soil acts as a hydrologic buffer which stores (i.e., water holding capacity) and regulates the flow (i.e., drainage) of water in the landscape, allowing for the transport of various inorganic and biochemical compounds within and through the soil medium
5. Soil is a foundation for the physical support of structures including everything from plants to skyscrapers

There are numerous types of surface soils, the distribution and characteristics of which are broadly controlled by parent material, topography, climate, biota, and time. Although they are variable, soils typically include a common matrix of mineral and organic particles, water, and gases. This soil matrix directly supports an ecosystem that is commonly made up of microbes, invertebrates, and plants. These organisms in turn, provide a supporting foundation for an even larger ecosystem that includes animals and humans.

Soil microorganisms are an integral part of the soil and include bacteria, fungi, algae, protozoa and nematodes. As a community or assemblage, these organisms are responsible for cycling nutrients such as nitrogen, phosphorous, potassium, calcium, magnesium, iron, and sulfur, through the decomposition of organic matter, which includes oil.

The abundance and diversity of soil organisms depends on the nature of the soil and the associated plant community. A key element regulating these characteristics is the availability of active organic matter that can readily be used by microbes and invertebrates as a source of energy. In addition, oxygen, nutrients, moisture content, temperature and other climatic factors also play important roles in soil organism community structure and abundance. Root growth is a significant contributor to soil ecosystem development. Of particular importance in microbial ecology is the zone of the soil-root interface known as the rhizosphere. The rhizosphere receives photosynthetic carbon compounds secreted from plant roots. These root secreted compounds, including organic, amino and fatty acids, carbohydrates, vitamins, nucleotides, phenolic compounds, polysaccharides, and proteins, are metabolized by surrounding microorganisms. In turn, the microorganisms mediate biochemical reactions that make nutrients available to plants. Nutrients are also made available as microbes die and decay during the cycle of immobilization and mineralization, which is strongly influenced by the carbon to nitrogen ratio. Where conditions are favorable, soil sustains a high abundance and diversity of microorganisms and invertebrates that occupy a broad and complex range of niches.

7.1.2.8.2 Observed Effects

The following case studies, primarily from temperate North American environments, provide examples of the effects that documented oil releases have had on the soil and soil organisms. In most cases, pipeline releases on land are remediated by scraping or excavating the land surface until desired clean-up targets are achieved. Additional details of some of the releases used as case studies for soils and microorganisms can be found in Stantec et al. (2012) and Enbridge (2015). Each of these releases and how they affected soil resources are described in the paragraphs below.

> ***Unknown Operator, Nipisi and Rainbow Releases, Alberta:*** *During 1970–1972, three oil releases occurred in north central Alberta, Canada near Lesser Slave Lake (Wang et al. 1998). These three releases, located at Nipisi, Rainbow and Old Peace Rivers, occurred within about two miles of one another. Little information is readily available about the Rainbow and Old Peace River releases, but the Nipisi release site has been extensively studied. The Nipisi release was one of the largest releases in Canadian history and involved over 60,000 barrels of crude oil that affected over 25 acres of predominantly bog/fen habitat. A variety of clean-up techniques, including burning, tilling, and fertilizer addition, were applied at the Nipisi site, after which it was left for research to evaluate the effectiveness of these techniques and characterize the weathering of the released oil (Wang et al. 1998).*
>
> *Twenty-five years after the releases, researchers returned to the area to assess the oiling conditions and recovery status. Substrate samples were collected from the 3 release locations: 22 samples from the Nipisi site; 9 from the Rainbow pipeline release; and 3 from the Old Peace River site. Most of the samples consisted of 100% organic materials, sphagnum peat, or a similar peat, and a few of the samples included a mineral component. Samples were grouped based on depth of collection. Surface samples were collected from the upper approximately 1.5 inches. One group of subsurface samples was collected primarily between 4*

and 16 inches below ground surface (bgs), and the second group of subsurface samples came from a depth of 16 to below 31 inches (Wang et al. 1998).

Based upon TPH levels, the surface samples were still highly contaminated (20,000–256,000 ppm) with oil, although the oil was highly weathered/degraded. The subsurface samples collected between depths of 4 to 16 inches also were still highly contaminated (10,000–165,000 ppm), but the oil was only lightly to moderately weathered/degraded. The deeper (34 to 39 inches) subsurface samples were only lightly contaminated (less than 673 ppm) with oil. The analysis indicated that the oil released on the surface had started to weather almost immediately through evaporation, but subsequent weathering through biodegradation and other weathering processes were occurring at a much slower rate. Biodegradation rates were projected to be slow because of the acidic condition of the peat, the anaerobic conditions created by the saturated ground and the relatively cool temperatures. Degradation of the subsurface oil was expected to continue and to be aided by rainfall, which would increase ground saturation and bring the oil to the surface where more aerobic conditions exist and more nutrients are available to aid in biodegradation. The researchers' determination was that the site was recovering, but that this recovery was happening slowly and would continue to happen slowly (Wang et al. 1998) on a scale of decades.

***Unknown Operator, Moose Jaw, Saskatchewan**: In January 1974, a pipeline containing crude oil broke within an active agricultural field just north of Moose Jaw, Saskatchewan. The pipe was buried 3.3 ft below the soil surface, and the asphalt-base oil (23 API gravity, 0.92 grams per centimeter cubed [g/cm^3] density) flowed underneath the frozen topsoil. The release was first detected in a ditch approximately 2,789 ft from the pipeline and later in a small pool approximately 82 ft south of the line. There was also some surface pooling closer to the release, but the majority of the oil was present as a thin lens, a fraction of an inch thick, just below the frost line at 3.3 ft in depth. Because the oil was contained, trenches were dug around the release perimeter, and an estimated 10,000 barrels of the 15,725 barrels of oil were recovered. Further remediation of the affected soil was not conducted, and in the spring of 1974 crops were planted. Fertilizer was applied to enhance the rate of oil weathering, but this was limited to the maximum rate tolerated by the crops. Monitoring of the remaining oil showed that from 1974 to 1978, there was a noticeable decrease in oil content, particularly in the 1977 fallow year when higher levels of fertilizer could be applied (De Jong 1980). The surface soil from 0 to 11.8 inches showed the greatest hydrocarbon reductions. Results of the site study provide further support for the role of microbial-mediated degradation in reducing the concentration of oil in soils, and in the recovery of the environment. According to De Jong (1980), addition of fertilizer helped compensate for the increased demand for nitrogen* *made by the microorganisms, which were most active in the surface soil where there was more oxygen.*

Enbridge Line 6, Bemidji, Minnesota: *In 1979, a pipeline released approximately 10,700 barrels of light crude oil in a naturally vegetated area. The oil sprayed over an area of approximately 1.6 acres and collected in topographic depressions before infiltrating the soil and migrating to the groundwater. Although there were immediate effects from the oil on the terrestrial habitat, subsequent burning of the oil sprayed area had a much greater effect on this habitat. The area has remained relatively barren for most of the last 30 years because the soil became water repellent due to the oil contamination and possibly from the burning (Nieber 2013). Using the Water Drop Penetration Time test (Dekker 2009) to assess water repellency of the soil, researchers found that the soil within the oil spray zone ranged from slightly repellent to extremely water repellent. Where the soil was extremely water repellent, the water drops tended to evaporate from the surface before they could be absorbed into the soil. Outside the oil spray zone, the soil was water "wettable." Repellency within the oil spray zone extended to a depth of approximately 16 inches in some locations. A soil erosion survey conducted in this area found that much of the surface soil had eroded from the higher topographic points leaving them very stony. The sand eroded from these higher points was deposited in adjacent topographic depressions (Nieber 2013).*

Line 3 Glenavon, Saskatchewan: On April 15, 2007, an Enbridge Line 3 underground pipeline ruptured near Glenavon, Saskatchewan and released approximately 6,200 barrels of heavy crude oil into a slough (wetland) located in an agricultural area (SLR Consulting 2008a; Transportation Safety Board Canada 2008a). Soil located around the edges of the slough was also exposed to oil. Release response and clean-up efforts included:

- *Repair of the pipe*
- *Recovery of oil from surface water within the affected slough*
- *Deployment of booms*
- *Construction of berms to contain the oil within the immediate area of the affected slough*
- *Removal of oiled vegetation around the perimeter of the affected slough*
- *Removal of water from the affected slough that had hydrocarbon concentrations above applicable criteria, including those established in the Canadian Council of Ministers of the Environment (CCME) Freshwater Aquatic Life Criteria (1999, updated 2007) and/or Saskatchewan Environment*
- *Removal of contaminated sediment and soil*

Recovery of approximately 240,925 gallons (912 m^3) of the released oil was completed by April 22, 2007 (Transportation Safety Board Canada 2008a). Water and crude oil were removed from the affected slough with skimmers and *vacuum trucks. Irrigation sump lines were then used to move the collected water to an on-site above ground storage tank (AST) for temporary storage. Backhoes were used to remove contaminated sediment from the slough and to cut and remove oiled vegetation. Soil from around the edges of the slough also was removed. Contaminated vegetation, sediment and soil were transported to an off-site location for disposal (SLR Consulting 2008a).*

As part of the initial Environmental Site Assessment following the release, soil samples were collected in association with four components of the response and clean-up efforts: site stratigraphy boreholes; pipeline trench repair; irrigation sump lines; and remediation of the affected slough. The collected soil samples were analyzed for BTEX, petroleum hydrocarbon fractions F1 to F4 (PHC F1-F4 {F1: C6 to C10, F2: >C10 to C16, F3: >C16 to C34, F4: C34+}), total metals, and Polycyclic Aromatic Hydrocarbons (PAHs). For soil samples not associated with the affected slough, analyses indicated that contaminant concentrations generally were below Saskatchewan Environment and CCME remedial criteria (Tier 1 Agricultural Criteria for fine grained soil; Saskatchewan Ministry of Environment 2006) with the exception of two sites associated with the irrigation sump lines. Additional excavation was conducted at these two sites, and subsequent sampling indicated that the criteria were met. Concentrations of metals for all these samples either were below CCME agricultural criteria or were consistent with background conditions (SLR Consulting 2008a). Subsequent sampling along the pipeline trench identified some locations where PAH concentrations were above remedial criteria. These areas were further excavated and, as a result, all post remediation soil samples were below CCME remedial criteria (SLR Consulting 2008b).

For the affected slough, estimates were that any remaining crude oil effects after the initial remediation efforts likely were limited to the sediment and possibly the upper 1 ft of underlying native clay soil. Additional remediation efforts were undertaken to remove sediment and native clay soil under the affected slough that had hydrocarbon concentrations exceeding applicable remedial criteria (SLR Consulting 2008b). Following additional remedial actions PAH concentrations were below CCME criteria and BTEX and F1-F4 concentrations from the base of excavation were generally non-detectable. Metals concentrations also were generally below CCME criteria and/or were consistent with conditions in nearby sloughs.

Line 37 Fort McMurray, Alberta: *On June 22, 2013, approximately 1,300 barrels of premium synthetic crude oil were released from an Enbridge Line 37 pipeline located approximately 24.9 miles southeast of Fort McMurray, Alberta, Canada (Hemmings et al. 2015). The contaminants of concern were petroleum hydrocarbon fractions (PHC) F1 to F4, BTEX, and PAH. The oil rose to the surface in* *the saturated soils and flowed overland along the pipeline ROW to a fen and eventually reached the shores of an unnamed lake. The ROW had maintained grassy vegetation, and the fen was dominated by shrubby vegetation. The release site underwent integrated remediation (see below) that was completed in October 2013. Initial remediation efforts involved targeted excavation (soil and sediment), oil skimming of surface water, treatment of surface water and groundwater, soil flushing (fen), and installation of physical barriers (hard and soft booms). Excavation within the ROW included removing affected soil at the release site and soil beyond the release point that showed visual contamination. Depth of excavation ranged from approximately 1 to 2.5 ft below grade. Approximately 7,275 tons of contaminated soil was removed from the ROW. Remediation efforts removed a majority of the released oil (approximately 93%), and natural attenuation monitoring was employed to track the weathering and effects of the remaining product (Hemmings et al. 2015).*

Soils within the ROW are generally mineral soils with a minor organic component. In the fen, peat at the surface is underlain by mineral soils of various textures (silt, clay and sand). Soil samples were collected from the ROW, the fen, and the area surrounding the unnamed lake. These samples were analyzed for BTEX, PHC F1-F4, and PAHs. Concentrations of BTEX and PHC F1-F4 were higher than acceptable Alberta Environment and Sustainable Resources, Albert Tier 1 Soil and Groundwater Remediation Guidelines in many of the samples. Following initial remediation efforts (excavation), residual oil was still detected within the soils of the ROW and fen (Hemmings et al. 2015).

A biotreatability study determined that hydrocarbon degrader bacterial populations were present in the soil in sufficient numbers to allow biodegradation to occur in the presence of oxygen or under anoxic conditions. Further study of these bacterial populations indicated that they would be capable of degrading short-chain, but less able to degrade long-chain hydrocarbons. Eco-toxicological tests were then conducted to determine if residual hydrocarbons posed a risk to ecological receptors. These tests included survival and reproduction of Collembola and avoidance-response in earthworms. Tests also were conducted to assess emergence and growth of plants. Petroleum hydrocarbons did not affect adult Collembola survival or reproduction in the ROW soils, but there was significant reduction in both survival and reproduction in the fen soils (Hemmings et al. 2015). A laboratory ecotoxicity test with earthworms was conducted and the results showed earthworms avoided the petroleum hydrocarbon contaminated ROW and fen soils and showed preferential selection for the uncontaminated reference soils. This avoidance was attributed in part to the petroleum hydrocarbons and to the low soil pH (Hemmings et al. 2015). Site-specific target levels for both PCH F2 and PCH F3 that would be protective of terrestrial ecological receptors were calculated for ROW soils and fen soils. Soil

> *petroleum hydrocarbon concentrations were generally lower than the target levels, although up to 15% of the samples from the fen had petroleum hydrocarbon concentrations that exceeded the target levels. Overall conditions at the site were considered to be "improving" one year after the release, but specific statements regarding recovery status of soils were not made and monitoring at the site was still on-going (Hemmings et al. 2015).*

To understand how soil micro-organisms are affected by oil releases and how oil can be biodegraded by soil micro-organisms, several experimental release sites have been evaluated. The results of such studies are summarized below.

In 1976, at the Caribou-Poker Creek experimental release site in Alaska, for each experimental release, about 2,000 gallons of Prudhoe Bay crude oil was released on a plot 11 by 55 yards in size. Research showed that total fungal biomass decreased and heterotrophic bacterial biomass increased in the first growing season, a trend that appeared to persist for at least a decade (Garron 2007). Lindstrom et al. (1999) found no significant differences in the total bacterial numbers between uncontaminated and hydrocarbon-affected soils, but the population diversity (evenness and/or richness) was diminished in hydrocarbon-affected soils. The hydrocarbon-affected soils did have higher numbers of more oil-tolerant species when compared to uncontaminated soils.

In a study carried out from 1970 to 1971 at Tununuk Point, located on the southern tip of Richards Island, Northern Territory, Canada, light gravity sweet crude oil was applied to plots ranging in size, topography and vegetative cover in spring, summer, and winter. Oil application rates included 0.00 cm (control), 0.25 cm, 0.40 cm, 0.50 cm, 0.75 cm and 1.5 cm in thickness to simulate releases ranging up to 1,950 barrels per acre. Gossen and Parkinson (1972) found that after approximately one year, bacterial numbers and respiration rates in oil treated samples increased, relative to untreated samples.

Sexstone and Atlas (1977) also observed increases in populations of hydrocarbon-degrading soil microbes at an experimental site at Point Barrow, Alaska. Prudhoe crude oil was applied through a perforated plate to provide even coverage at concentrations of 5 L/m^2 and 12 L/m^2, simulating moderate and heavy oil releases. During the first summer following the experimental release, microbial response was limited to the surface soil (top 0.8 in. [2 cm]), but in the following year this extended to greater depths depending on the drainage characteristics of the soil. Researchers anticipated that increased numbers of heterotrophic microbes, including oil utilizers, would persist for at least a decade after the release. Sexstone et al. (1978) also found that oil released onto tundra soils infiltrated the soil, and microbes in the saturated areas showed decreased abundance. However, around the perimeter of these saturated areas, microbial numbers were higher than those found in the reference locations. At the same experimental site, Linkins et al. (1978) found evidence indicating that the organisms were actively modifying the oil and using it to support their metabolism.

Based on these data and observations, it appears that oil releases can have a large effect on both the physical and chemical characteristics of soil. With the change in conditions, certain microbial species are negatively affected, but studies also show that the microbial community is diverse and as a whole is generally able to adapt to the presence of oil and take advantage of petroleum hydrocarbons as an energy source.

7.1.2.8.3 Expected Effects of Released Oils

Soil effects resulting from a release of crude oil from a pipeline would occur as oil is dispersed into the soil vertically and horizontally through interstitial (pore) spaces. For small releases, the oil would likely be contained within the pipeline installation trench, where soil bulk densities tend to be lower. For larger and higher rate releases, oil is expected to migrate through the soil in all directions including laterally and vertically down to the groundwater table. Because oil is less dense than water, oil migrating to the water table tends to form a floating pool, although some constituents are soluble in water and would dissolve, if present (see Section 1.3.2). In addition to lateral and downward dispersal, the oil could also mound within the pipeline trench as a result of hydraulic pressure, potentially surfacing and spreading laterally across the soil surface based on topography. Once on the surface, oil would pool in low lying areas and infiltrate into the soil subsurface, migrating laterally and vertically to the groundwater table. The degree of lateral surface migration would depend on the volume of oil that reached the surface, as well as slope, ground cover, type of oil (viscosity considerations), and temperature.

Environmental effects on soil as a result of oiling are measured by the presence and concentration of oil components such as the F1-F4 fractions, the monoaromatic BTEX compounds, PAHs, and some metals (e.g., nickel and vanadium). Oil presence may modify important soil characteristics, including but not limited to nutrient availability, porosity and water repellency, and in changes to vegetation and soil invertebrate communities. The presence of oil in soil can significantly affect plant growth (De Jong 1980), and petroleum hydrocarbons can affect survival, reproduction, and presence of soil organisms (Hemmings et al. 2015).

Soil quality standards have been developed for petroleum hydrocarbon contaminants in soil, so that after remediation, the capacity of the soil to support plants and invertebrate communities, as well as various human uses (e.g., residential, agricultural or industrial land use) should be restored. At the same time, further natural recovery can occur within a reasonable timeframe. Typically, highly contaminated soil is mechanically removed and hauled to suitable landfill, composting, or recycling facilities. Excavation and hauling will typically cease at a point when the remaining contaminated soil meets standards or guidelines typically established by federal or state agencies, or at a point when continued excavation is deemed to cause more environmental harm than good. The less contaminated soil areas would then be subject to continued monitoring during a natural attenuation process until remediation objectives can be met and the site clean-up procedures can be closed.

Like any contaminant, the potential effects resulting from the introduction of crude oil into the soil matrix depends on contaminant concentration, type of oil released, the soil receiving environment and environmental conditions such as temperature, precipitation and snow cover. When applied as a fine spray over a large area (i.e., at low concentrations), the soil may be able to absorb the oil without deleterious changes to its physical structure. The oil droplets readily adhere to the existing organic matter and have a negligible effect on the moisture content, or porosity.

Where large volumes of oil are rapidly released onto or under the ground, the oil can fill the pore spaces between soil particles. Once the soil becomes saturated with oil, both air and water are displaced. Within these highly saturated soil zones, microbial activity can be greatly impaired both by the direct toxicity of the oil and by the altered physical and chemical condition of the soil. In contrast, a suitable environment for microbes can exist around the periphery of this saturated zone, where water and air are still present with the soil. Although this peripheral zone may be suitable for the survival and growth of microbes, the abundance and diversity of organisms may be different from pre-release conditions.

Table 7-27 and Table 7-28 provide a summary of the expected environmental effects of oil releases to soils. Table 7-27 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-28 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-27 Land Cover Receptor: Soil

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Viscosity	Low viscosity allows for greater soil infiltration and migration potential.	Medium viscosity allows for an intermediate infiltration and migration potential when compared with Light and Heavy Crude.	High viscosity and density allows for less soil infiltration and migration potential.	The viscosity of fresh diluted bitumen is lowered to meet pipeline specifications through the addition of a diluent, which may (e.g., condensate) or may not (e.g., synthetic crude oil) be volatile.
Oil chemistry—BTEX	Light crude oils often contain high levels of BTEX and other relatively water soluble hydrocarbons leading to a higher potential to cause acute toxicity to plants and soil invertebrate communities.	Medium crude oils often contain moderate levels of BTEX and other relatively water soluble hydrocarbons, leading to a moderate potential to cause acute toxicity.	Heavy crude oils often contain lower levels of BTEX and other relatively water soluble hydrocarbons, leading to a lower potential to cause acute toxicity. However, diluted bitumen products often contain similar concentrations of BTEX compounds to lighter crude oil types, due to the addition of diluent.	
Oil chemistry—TPAH	Bakken Crude has proportionally more naphthalenes and alkyl naphthalenes than Alberta oil sands products (Yang et al. 2011).	Medium weight crude oil has proportionally more naphthalenes and alkyl naphthalenes than Alberta oil sands products (Fingas 2010; Yang et al. 2011).	Diluted bitumens typically have similar to lower concentrations of TPAH than light and medium crude oils, although the distribution of PAHs differs.	Low molecular weight PAHs are usually relatively depleted in bitumen from the Alberta oil sands, due to in situ weathering.
Oil chemistry—resins and asphaltenes	Light crude oils contain little in the resins and asphaltenes fraction relative to medium and heavy crude, making their lighter aliphatic and LMW aromatic components relatively bioavailable and subject to weathering.	Medium crude oils also contain relatively small fractions of resins and asphaltenes, although more than light crude oils. Medium crude oils also have good potential for biodegradation in the environment.	Heavy crude oils, and diluted bitumens in particular, contain large amounts of resins and asphaltenes. While these fractions are generally insoluble in water and of limited toxicity, they are slow to degrade and can act as reservoirs for the slow release of other more toxic hydrocarbon constituents such as LMW and medium weight PAHs.	

Table 7-28 Land Cover Receptor: Soil

Environment Characteristic	Low	Medium	High	Other Comments
Organic carbon content	Organic carbon can bind petroleum hydrocarbon residues, lowering bioavailability. Soil with low organic carbon content (<1% of soil dry weight) will poorly sequester petroleum hydrocarbons in soil, facilitating bioavailability of these released hydrocarbons.	Soil containing a moderate amount of organic carbon (1 to 6% of soil dry weight) can help to sequester released oil.	Soils containing abundant organic carbon (>6% of soil dry weight) may be less bioavailable relative to low and medium organic content soils, due to the competing effect of soil organic carbon on bioavailability.	
Soil grain size	Fine-grained soils (clay, silt) may limit oil infiltration into the subsurface.	Medium-grained soil (fine sand to coarse sand) will allow for moderate oil infiltration.	Coarse-grained sediments (gravel, cobble) will allow for rapid oil infiltration.	
Slope	Flat and low slope areas would limit the surface spreading of oil, facilitating pooling and oil infiltration.	Oil spreading will be enhanced relative to flat land soil surfaces.	Steeply sloped areas would increase surface spreading of oil.	

7.1.3 Biological Receptors

7.1.3.1 Terrestrial Vegetation

7.1.3.1.1 Description

Terrestrial vegetation consists of the communities of plant species found on land. For the purpose of this discussion; the terrestrial vegetation resource category also includes lichens and mosses. There are over 230,000 different terrestrial plants ranging from simple forms such as horsetails, and ferns to gymnosperms (including conifers) and angiosperms (flowering plants). The terrestrial vegetation growing in a particular area and time, with specific groundwater, climatic, topographic, and soil conditions, can be grouped into plant communities. Individual plant species interact with each other through competitive, symbiotic, or mutualistic biological interactions.

Plants can be classified by their growth habit (their general appearance, growth form, or architecture (USDA 2016)). The dominant growth habits are trees, shrubs, and herbaceous plants. Trees are defined as perennial, woody plants with a single stem, normally greater than 13 to 16 ft in height (USDA 2016). Shrubs are perennial, multi-stemmed woody plants that are usually shorter than the typical height identified for trees (USDA 2016). Herbaceous plants can be annual, biennial, or perennial, but do not have significant woody tissue above or at the ground (USDA 2016).

Plant communities provide critical ecosystem functions, including soil stability, nutrient availability, nutrient fixations, water retention and cycling; as well as habitat, forage, and shelter for organisms. Plants are the first level of the food chain. They conduct photosynthesis, a process that converts light energy, water, and carbon dioxide into photosynthates (i.e., sugars, starches, carbohydrates, and proteins) and oxygen (Whiting et al. 2015). Plant roots interact with soil organisms, including mycorrhizal fungi, fungal pathogens, bacteria, and invertebrates. Together plants and the soil organism community compose the soil food web. Soil organisms are key components in the degradation of organic contaminants such as oil.

7.1.3.1.2 Observed Effects

The majority of studies on the effects of oil releases on vegetation focus on wetlands, marshes, and riparian environments. There have been limited studies specifically on the effects of crude oil releases on terrestrial vegetation, and most studies have focused on tundra and artic vegetation in Alaska, Canada, and Greenland. The results of these studies on the effects on vegetation from oil releases can be applied to other northern latitude areas such as Minnesota with similar vegetation communities with respect to oil release effects. Studies on the effects of oil on terrestrial vegetation have looked at both accidental and intentional experimental releases, with varying levels of clean-up. Based on the results of the studies, the most detrimental effect on vegetation is damage to photo-synthesizing plant tissues. Other negative effects include oil permeating the soil and affecting soil microorganisms, root uptake, and soil water availability. Oil sealing the surface soil layer, and affecting soil moisture infiltration can result in loss of vegetation through loss of soil moisture, changes in soil temperature and nutrient availability, and reductions in growth, health, and flower bud/seed development. The extent of oiling of individual species has been demonstrated to affect the degree of plant survival (Racine 1994). When an oil release is small or there is rapid remediation of the oil, many long-term effects can be avoided.

The following discussion summarizes relevant case studies on the effects of various oil types on terrestrial vegetation.

> ***Mackenzie Delta, Northwest Territories, 1970****: Wein and Bliss (1973) reported on an experimental releases conducted in northwestern Canada east of the Mackenzie Delta. The test plots were set up in five plant communities: black spruce-alder-heath; medium shrub-alder-heath; sedge-cotton grass-heath; willow-birch-heath; and sedge. Each of the plant communities are underlain by permafrost. Results of this study are applicable to areas where a release occurs in locations with an impermeable layer, frozen soils, or winter conditions. Plot sizes varied in each plant community to account for vegetation diversity and microtopography, with the black spruce-alder-heath having the largest plot (16.4 ft x 16.4 ft [5 m x 5 m]), the willow-birch-heath having the second largest plot (13.1 ft x 13. 1 ft [4 m x 4 m]), and the remaining vegetation communities having 9.8 ft x 9.8 ft (3 m x 4 m) plots. For each plot, the researchers applied Norman Wells light-gravity-sweet crude oil in either spring, summer, or winter at one of four rates. The four rates applied to the plots included: 1) control rate (0 inch.); 2) a quarter of the highest rate; 3) half of the highest application rate; and 4) the highest rate (typically the rate required to saturate the plot). The highest rate saturated the soil profile (approximately 1,300 barrels/acre for spring/winter and 1,950 barrels/acre for summer). The active layer is the portion of the soil above permafrost that thaws and freezes seasonally. In the summer this layer is deeper, which allowed a larger amount of oil to be absorbed before runoff occurred, consequently requiring a higher rate of application in the summer to saturate the soil profile. In spring and winter, the rates of application (i.e., oil thickness on the plots) were 0 in., 0.10 inch (0.25 cm), 0.20 inch (0.5 cm), and 0.39 inch (1 cm); while in the summer, the rates were 0 inch, 0.16 inch (0.4 cm), 0.30 inch (0.75 cm), and 0.59 inch (1.5 cm). In all plots, the low lying vegetation, including low shrubs, were saturated. Different temperatures of oil (194°F and -4°F) were applied in winter to see if oil would penetrate deeper into the snow cover based on oil temperature, but no statistically significant difference was observed.*
>
> *Initial effects on vegetation for the summer treatments were observed within hours of oil application on deciduous species. The initial observations included a water soaked appearance, dry tissue, and the vegetation turning brown. Effects to evergreen shrub species took several weeks. Signs of survival or regrowth were observed within weeks for some plots and species; however the regrown leaves*

tended to be thinner and larger when they grew back than control plants. In plots where the soil was saturated with oil, the vegetation showed no evidence of recovery during the treatment year. On the winter treatments plots, there was a lack or delay in spring growth compared to untreated areas.

After one growing season, plant recovery, based on ground cover of new growth, was between 20% and 55% depending upon the treatment rate, morphological and physiological differences among species, and the season of the treatment. Most of this new growth was from latent buds of dwarf shrub species and sedges. Lichens and the majority of molds showed no regrowth. The species that showed the greatest recovery were the dwarf shrubs.

The extent of effects to vegetation damage and recovery was a combination of the amount of oil applied, and the seasonality of the treatment. In general, the treatment plots with higher rates of oil application had decreased recovery comparative to the treatment plots with lower rates of oil application. Plots where the oil was applied later in the season, and after the snowfall also had decreased rates of recovery. The amount of oil and the seasonality affected how deep and how much of the oil penetrated into the soil based on the depth of the active layer and the permeability of the soil. Greater applications of oil and the deeper active layer led to the greatest effects on vegetation.

***Norman Wells, Northwest Territories, 1972**: Fresh un-weathered Norman Wells light-gravity-sweet crude oil and Arctic diesel were used in an experimental release by the researchers on a black spruce-dominated boreal forest located south of Norman Wells, Northwest Territories along the bank of the Mackenzie River (Hutchinson and Freedman 1978). The site was observed for five years after the experimental plots were treated. Follow-up studies of the same area were conducted in the early 1980s (Hutchinson 1984).*

One treatment and one control plot (32.8 ft x 32.8 ft [10 m x 10 m plots] subdivided into 25 subplots) were set up in an early succession 30- to 40-year-old post-burn area, while two treatment plots of the same size were set up in an older mature forest community that had not experienced a forest fire in more than 80 years (Hutchinson and Freedman 1978). A summer crude oil release was simulated in both communities with oil application occurring on July 5, 1972. A winter crude-oil release was simulated in the mature forest site only with oil application occurring on March 5, 1973. A simulated summer diesel oil release was conducted only in the post-burn area with oil application occurring on June 25, 1975. For each of the experimental plots, oil was sprayed evenly over the ground surface to simulate an oil release. In addition, in the post-burn area, a single-point crude oil release was simulated by pouring approximately one barrel oil onto a fixed point in the center of a 131 ft x 131 ft (40 m x 40 m) grid.

Observations on the summer crude oil sites, noted that within several days of the release, the mosses turned black, and sedges turned brown and withered. The leaves of deciduous trees developed large brown necrotic patches where they had been sprayed with the oil. Unsprayed foliage initially remained healthy and green (Hutchinson and Freedman 1978). For all sites, there was a reduction in vegetation on treated plots that varied in length and intensity. The summer simulated crude oil release was more damaging to the vegetation than the winter release. The point-release damaged less surface area per unit of oil than when the oil was sprayed on the plots, because most of the oil in the point release was absorbed by the organic matter or percolated into the soil profile. Similar effects to vegetation were observed on the diesel oil release plot as compared to the crude oil plots.

Some species recovered within a few weeks on the winter site plots. Recovery from the summer release progressed more slowly. During the study period, recovery of existing plant species occurred predominantly through re-sprouting from surviving aboveground and below ground perennating structures (e.g., shoots, rhizomes, tubers). Some shrub and perennial vascular species developed regrowth shoots within weeks of the release, but these plants died by the following spring. Successful seed establishment was not observed for at least four years post-release. Based on the cover and frequency data collected during the study, the study authors estimated that it would take a minimum of 20 post-release growing seasons to re-establish total ground cover on the treated plots.

Researchers noted that they expected the composition of the re-established vegetation community would be different from the post-release community due to the differing capacities of species to survive and recover from a release (Hutchinson and Freedman 1978). For example, coniferous tree species recovered more slowly than shrub and ground cover vegetation. Within three to four years from the experimental treatment, mosses started to recolonize the sites. Although many of the black spruce exhibited no serious short-term effects, significant mortalities of the black spruce was observed up to four years after the release, and no regeneration of this species occurred during the six years of monitoring. Similarly, no regeneration of larch was observed and no seedlings were found during the study period.

Ten years after the initiation of this study (1980), total vegetative cover and species diversity were substantially lower compared to the control sites. In some areas, the damage to the vegetation extended past the areas directly affected by the original release. The study suggests this was due to oil spreading underground. In general, plant communities affected by released oil were set back to an early stage of ecological succession (Robson et al. 2004), and both *forest types presented lower total vegetative cover and decreased species composition than neighboring unaffected areas.*

Mount Baker, Washington, 1972*: In the winter of 1972, approximately 164 barrels of No. 2 diesel fuel oil leaked out of storage tanks at the Cascade Field Station near Mount Baker, Washington. The owner of the research station was not identified. The oil inundated two subalpine meadow communities: one heather meadow and one sedge meadow. The recovery of these plant communities was studied over the following nine years (Belsky 1975; Belsky 1982). Within two growing seasons, the released oil reduced vegetative cover from 100% to 1% and killed all, but three plant species: a heather (Phyllodoce empetriformis), a sedge (Carex lenticularis), and a moss (Rhacomitrium sudeticum) (Belsky 1982). By the second growing season after the release, seedlings of Carex nigricans, a species of sedge, appeared in the wetter areas, and seedlings of other subalpine species reappeared over the next four growing seasons. After nine years, 5 to 20% of the area affected by the release was covered by seedlings, and 20% of the heather community and 10–20% of the sedge community was covered with vegetation.*

Belsky (1982) stated that the effect of the release on the meadow communities was reduced by the snow cover, steep terrain and snowmelt. Much of the oil flowed down the steep slope rather than pooling and becoming stranded, and summer snow melt helped flush much of the oil out of the area reducing the potential exposure of emerging vegetation. In addition, the timing of the release may have reduced impacts on these communities. Plants were dormant at the time of the release and the frozen ground likely helped protect underground roots. Although diesel fuel is initially more toxic to plants (Walker et al. 1978, Wein and Bliss 1973), it is comprised of relatively small chain, highly refined hydrocarbons, which tend to weather more rapidly relative to heavier oils with a higher proportion of high molecular weight PHCs. By the time plants began to emerge, the remaining oil was less toxic to the plants than it would have been at the time of the release.

Moose Jaw, Saskatchewan, 1974*: In the winter of 1974, a pipe carrying asphalt-based oil (23 API gravity) broke north of Moose Jaw, Saskatchewan. The responsible party for the release was not identified. Approximately 15,725 barrels of oil were released. Although two-thirds of the oil was recovered from excavated trenches during the emergency response effort, an estimated 39.5 acres (159,850.83 m²) of agricultural land was oiled. Remediation of the affected area was not conducted. Beginning in the spring of 1974, grain crops (barley, oats and wheat) were planted to study their performance as a tool for delineating the contaminated areas. Fertilizer, limited to the maximum rate tolerated by the crops, was applied to enhance the rate of oil degradation. In 1974, the results indicated that oil content over one percent (10,000 mg/kg) was associated with* *zero growth. Crop yields on the contaminated areas improved from 1975 to 1978, but were still lower than for uncontaminated areas. In 1978 total yield of wheat from the contaminated sites ranged from 620–8,010 lbs./ac (695–8,990 kg/ha) as compared to the uncontaminated areas with a total yield of 5,550 ± 1,220 lb./ac (6,230 ± 1,370 kg/ha) (De Jong 1980). Oil content and yield were negatively correlated, but there was considerable variability in the data, which was attributed, in part, to the non-uniform distribution of oil in the root zone.*

***Caribou-Poker Creek, Alaska, 1976**: In a test release at the Caribou-Poker Creeks Research Watershed, approximately 48 barrels of hot Prudhoe Bay heavy crude oil (27.5 API gravity) were applied to two 0.12 acre (500 m^2) plots in an open black spruce forest. The test release was conducted by scientists with the Cold Regions Research and Engineering Laboratory (Garron 2007). One experimental release occurred in the winter (February 1976) and the other in the summer (July 1976). The oil was released through a 16 ft (5 m) wide perforated pipe located at the top of the test plots and allowed to flow downslope (Collins et al. 1994). Oil from the winter release primarily flowed under the snow and over the frozen ground and did not go below the surface until the ground thawed. By 1978, the total area covered by the winter release was approximately 807 ft^2 (75 m^2) and approximately 40% of the release area had surface oil visible (Collins et al 1994). In contrast, the soil from the summer release flowed primarily into the organic layer before spreading downslope. The summer release covered an area of approximately 3,261 ft^2 (303 m^2) and only about 10 % of that area had visible surface oil. After three years, nearly all vegetation had died in areas where oil flowed over the surface, but effects from the release were delayed where the oil was below ground and there was less vegetation mortality in these areas (Collins et al. 1994).*

The releases were conducted in open black spruce (Picea mariana) forests with a shrub understory of resin birch (Betula glandulosa), Labrador tea (Ledum decumbens), blueberry (Vacccinium uliginosum) and willow (Salix sp.). Ground cover was primarily mosses and lichens with scattered cotton grass (Eriophorum vaginatum) tussocks. Most mosses, lichens and shrubs died shortly after the initial release, but the cotton grass persisted. Based on surveys 15 years after the releases, the cotton grass appeared to have thrived following the releases (Collins et al. 1994). The response of the cotton grass was attributed to less competition from other species. The black spruce tree also experienced mortality. Surveys conducted 15 years after the releases, determined that approximately 56% of the black spruce trees on the winter plot were dead and about 38% of the black spruce trees were dead on the summer plot. No black spruce seedlings were observed in either plot, although the remaining trees were bearing cones (Collins et al. 1994). The winter oil release produce more oiled surface area and *thus had more long-term and chronic effects on the plant communities (Collins et al. 1994).*

***Bemidji, Minnesota, 1979**: At this site, a Lakehead Co. pipeline released approximately 10,700 barrels of light, low-sulfur crude oil in August, 1979 (Nieber 2013, Associated Press 2014a). The oil sprayed over approximately 1.6 acres (6,500 m^2) and collected in topographic depressions before infiltrating the soil into the groundwater. Clean-up efforts resulted in the capture and recovery of approximately 80% of the released oil. Following clean-up of the areas with pooled oil, the oil-sprayed vegetation was burned. The area has remained relatively devoid of vegetation for most of the last 30 years due in part to the water repellent nature of the surface soil as a result of the burning. Vegetation (species not identified) now is primarily found in topographic depressions where run-off provides sufficient water to support growth (Nieber 2013). Further inhibiting re-vegetation has been erosion of the exposed de-vegetated soil down to the rocky substrate. For this release, the delayed recovery was predominately the result of clean-up efforts (Nieber 2013).*

***Mesters Vig, Northeast Greenland, 1982**: An experimental study was conducted in northeast Greenland on the effects of North Sea (light sweet) crude and diesel oils on wet marsh, grassland, and three types of dwarf-shrub heath (Holt 1987). Plots of 10.7 ft^2 (1 m^2) were set up in the five plant communities. In August 1982, researchers applied North Sea crude oil and diesel oil to separate plots within each of the five plant communities. To approximate a spray release, 0.06 barrels of oil was applied to each plot at an even coating of approximately 0.4 in. Monitoring of effects was conducted for the following three years after application; however, vegetative damage was evident in the first week after the oils were applied. On the crude oil plots, the leaves lost chlorophyll turning yellow or brown; on the diesel oil plots, the leaves lost chlorophyll or were shed. After three years, the total vegetative cover in each of the five plots treated with crude oil was less than prior to application treatment, with the driest sites that began with the least vegetative cover showing the least amount of recovery. The total plant cover in the sparse dry dwarf-shrub heath decreased from 40% prior to treatment to only 0.6% by the third growing season after the treatment (Holt 1987). In comparison, the total plant cover in the wet graminoid marsh decreased from 126% prior to treatment to 23% post-treatment. In addition to the decrease in cover was a reduction in species diversity. The species diversity in each post-treatment community was less than 50% when compared to the pre-treatment communities (Holt 1987). Based on percent cover after three growing seasons, the shrubs and mosses in the communities treated with crude oil showed the best recovery whereas the graminoids (grass and grass-like plants) and forbs showed very limited recovery.*

The plots treated with diesel oil also showed reductions in total cover with the drier sites experiencing the least amount of recovery. The recovery of vegetation was more limited in the diesel treated plots than the crude oil plots. Regardless of the community, shrubs and forbs showed almost no recovery after 3 growing seasons; graminoids and mosses showed some recovery, but recovery was very limited in the drier communities (Holt 1987). In both treatment groups, the wet or mesic conditions appeared to reduce the effects of the oils, which may have led to better recovery. In these wetter sites, the water may have helped protect the belowground structures (i.e., roots and rhizomes) from the oil. The toxic effects of the diesel oil were more significant and the diesel treated plots showed little or no recovery except for mosses and three species of sedge (Holt 1987).

***Tulita (Fort Norman), Northwest Territories, 1988**: Seburn et al. (1996) experimented with a crude oil release designed to simulate a small-scale subsurface pipeline rupture. The study was conducted at the Studies of the Environmental Effects of Disturbances in the Subarctic project site. The study looked at an experimental subsurface point release of approximately 21 barrels of Norman Wells light-gravity-sweet crude oil on a simulated ROW and a simulated buried pipeline trench. The ROW was cleared of trees and shrubs, but the surface vegetation and organic layer were left intact. For the simulated buried pipeline trench, essentially all of the vegetation (trees, shrubs, low-growing plants, mosses and lichens) was removed as was the surface organic soil layers (Seburn et al. 1996). The simulated pipeline trench was fertilized and seeded with an agronomic seed mix. For the study, oil was pumped into an open ended pipe that was buried about 3.3 ft deep, where it flowed to the surface covering approximately 0.17 acres. Sampling was conducted using 9.8 in x 9.8 inches (25 cm x 25 cm) quadrats located in the cleared ROW and simulated trench. After treatment, sample quadrats were classified as heavy, medium or lightly oiled, based on the amount of visible oil in each quadrat.*

The mean total plant cover in the heavily oil ROW declined from almost 75% prior the release to less than 20% a year after the release. Both the lightly oiled ROW and the unoiled ROW showed no significant changes in mean total plant cover the year after the release, but cover increased significantly in the following two years (Seburn et al. 1996). For the simulated pipeline trench, neither the heavily oiled nor lightly oiled areas showed significant changes in mean total plant cover the year after the release. By two years after the release the mean total plant cover in both the heavily and lightly oiled areas had increased significantly above pre-release levels (Seburn et al. 1996). The simulated pipeline trench had standing and flowing water on the surface that kept the soils saturated and limited how much oil could penetration into the soil, which in turn reduced the effects of the oil on the vegetation community. In addition, the soils within the *simulated pipeline trench lacked the organic soil component present in the ROW soils, which absorbed and retained the oil (Seburn et al. 1996).*

In the heavily oiled ROW, cover of 16 of the total 30 plant taxa changed significantly after the release with some of these taxa completely eliminated from the study quadrants (Seburn et al. 1996). Two of the 16 taxa increased post-release. By the third year post-release, both the agronomic grasses and cotton grasses had increased significantly above pre-release levels. In the lightly oiled ROW and both the lightly and heavily oiled simulated pipeline trench, 6 or fewer taxa changed significantly after the release. A few species appeared to tolerate the oil. Except in the heavily oiled ROW, the cover of mosses increased significantly by the second or third growing season. Researches attributed the increase in mosses to the physiological adaptation where by most of these taxa do not draw water from the soil (Seburn et al. 1996). Other taxa, sedges and cotton grasses, also appeared to experience limited effects from the oil and in many situations experienced significant increases in cover. Because cotton grasses establish new root systems each year, researchers suggested that this adaptation might reduce the effects of oil that penetrates into the soil. The researchers noted that identifying effects from the oil were complicated by the clearing and trenching activities, but they attributed the more persistent changes in vegetation to the oil (Seburn et al. 1996).

***Fort McMurray Alberta, 2013**: In 2013, an Enbridge pipeline running south from Fort McMurray in northern Alberta released approximately 1,300 barrels of premium synthetic crude oil (Hemmings et al. 2015). The release occurred underground, but the oil migrated off the pipeline right-of-way into a neighboring forested area and fen. Contaminants of concern included PHC, BTEX, and PAH. An emergency response and release recovery was initiated immediately, which included remediation of soil, groundwater, and fen material. The remediation removed 93% of the oil. Remedial activities consisted of excavating visibly effected soils, sediments, and vegetation; flushing of the fen; and oil recovery from an adjacent lake. Due to the rapid response combined with natural volatilization and degradation, effects to plants, beyond the effect of the remediation operation itself, were not initially observed. However, during the on-going monitoring program the following year, stressed and dead birches were observed (Hemmings et al. 2015). An ecotoxicological assessment was completed to determine if the remaining hydrocarbons posed a risk to vegetation and other ecological receptors. The assessment used sediment and soils that remained in place after initial remediation efforts. Negative effects to shoot and root lengths for bluejoint reedgrass (Calamagrostis canadensis), and to shoot length for black spruce (Picea mariana) were observed.*

7.1.3.1.3 Expected Effects of Released Oils

The literature review on the effects of oil releases on terrestrial vegetation provides detail on what factors will play a role in determining the severity of effects. The identification of these factors is limited since the majority of the studies were conducted in northern latitudes for similar plant communities. The majority of the releases studied occurred over 30 to 40 years ago, and as such, may not reflect current clean-up methodologies.

In general, direct exposure of plants to the oil types as described in the above case studies results in direct damage to active living tissue or killing of the entire plant. The temporal extent of effects and recovery of vegetation can be a function of oil type, the mechanism of release (spray, point, or subsurface), the seasonal timing of the release, the oiling intensity, and the method of clean-up. Long-term effects to vegetation result from changes in soil moisture and nutrient availability, oil saturation in the soil reaching the roots, and changes in plant communities based on the immediate direct effects.

Holt (1987) and Hutchinson and Freedman (1978) compared the effects of diesel oil to crude oil on vegetation. Other studies evaluated one type of oil typically at various rates of application or different seasonal timing of the release. Holt found greater effects to vegetation from the initial application of diesel oil compared to crude oil. In contrast, Hutchinson and Freedman (1978), observed similar effects to vegetation from diesel oil and crude oil. The effects of a diesel oil release on subalpine meadow communities at Mt. Baker may have been limited because the release occurred during the winter and the oil had an opportunity to weather before plant emergence and because the steep topography and snow melt that helped oil flush oil from the area (Belsky 1975, 1982). None of the studies made any observation or provided any analysis in terms of effects being greater for different types of crude oils (e.g. light, medium, heavy).

The method of a release, the timing of the release (summer vs. winter), the species exposed , and the amount of oil released all combine together as factors that influence how much of the active living plant tissue is directly affected by the oil, how much of the oil penetrates to the roots, and the surface area affected. Spraying the oil on the vegetation to provide an even coating appeared to have the greatest damage to vegetation. For most of the studies, the application of oil in the summer had a greater long-term effect on vegetation recovery. Frozen or saturated soils can minimize the penetration of oils into the soil profile, allowing time for evaporation of the oil, and for spring run-off events to transport it away from the release area. The timing of the release in relation to the life stages (e.g., sprout, seedling, mature) or annual cycles of the individual plants (e.g. seeding, flowering) can affect the sensitivity of the plant, and its correspondent reproductive functions such as flowering and seed production, to released oil. For example, releases that occur before or during flowering, especially for annuals, could result in decreased seed production, and substantially decrease future vegetative cover for those species.

Vegetation communities that were lightly oiled generally experienced less change in cover and composition when compared to heavily oiled communities (Seburn et al. 1996). Effects also varied due to growth form, species morphology and physiology. For ground-level releases, trees may not show noticeable effects from the oil for months to years after the release and only if sufficient amounts of oil penetrate the soil and affected their root system. Once the root systems are affected, it can take many years for the tree component of a community to recover (Collins et al. 1994). Groundcover vegetation such as graminoids, forbs and mosses typically experience significant declines almost immediately after a release, although some species including cotton grasses and some sedge survive and increase in cover within a relatively brief period (Collins et al. 1994; Seburn et al. 1996). Vegetation that better tolerates oil releases and recovers more quickly appears to have adaptations such as annual growth of new root systems that may promote their recovery.

In most of the case studies, over time vegetation was able to recolonize disturbed areas without clean-up efforts, however, post-release vegetation typically had lower percent cover, often with shifts of dominant species and habit. New growth typically developed from root stock or rhizomes of perennial species, existing seedbanks in undisturbed soils, and unaffected vegetation that spread from undisturbed areas into disturbed areas. Recovery was dependent on soil types, vegetation community types, morphological characteristics of individual species, spring runoff, and the infiltration depth of the oil. Even though vegetative cover may recover, oil may remain present in the area. In areas where oil was not removed from the soil, vegetation typically did not recover, or only species that appeared to be oil tolerant revegetated the disturbed areas. The time to recovery is highly variable and is dependent upon both the characteristics of the release and the characteristics of the affected plant community.

7.1.3.1.4 Summary of Inland Oil Release Effects on Terrestrial Vegetation

Table 7-29 and Table 7-30 provide a summary of the expected environmental effects of oil releases to terrestrial vegetation. Table 7-29 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-30 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-29 Biological Receptor: Terrestrial Vegetation

Oil Characteristic	Low	Medium	High	Other Comments
Viscosity	Oil with low viscosity would spread more slowly and have a limited effects area which would limit effects on terrestrial vegetation.	Oil with a medium viscosity would spread at a moderate rate and have a wider effect area compared to low viscosity oil. Medium viscosity oil would have a wider area of effects than a lower viscosity oil.	Oil with a high viscosity would spread at a faster rate and could have a relatively large effects area compared to low and medium viscosity oil.	The spatial extent of oiling from overland flow would be highly dependent on the local topography.
Pour point temperature	At a temperature below pour point, oil flow from a release would be minimal, limiting effects to vegetation near the oil release site.	At a temperature at pour point, oil flow from a release would be increased, effects to vegetation would be near the oil release site and spread further out from there.	At a temperature above pour point, oil flow from a release would be greatly increased, effects to vegetation would be near the oil release site and could spread a much further distance.	
Oil release volume	Lightly oiled sites are often able to recover quickly.	Sites with increased oil volume from a release have greater effects on vegetative tissue.	Sites with high volumes typically have greater effects and increased loss of species, and vegetative cover.	The volume of oil and mechanism of release are the greatest contributing factors affecting the spatial extent of oiling.
Physical and chemical properties of the oil	Lighter refined products such as diesel fuel) while initially more toxic to plants, weathers more rapidly resulting in decreased long-term effects.		Those crude oils that are more persistent take longer to weather, stay in the ecosystem and can result in longer-term effects and recovery such as decreases in plant diversity and abundance.	Selection of remedial methods to remove oil can have a significant effect on recovery.

Table 7-30 Biological Receptor: Terrestrial Vegetation

Environment Characteristic	Low	Medium	High	Other Comments
Seasonality of release	Winter: frozen conditions can limit the penetration of oils into the soil. The amount of aboveground active living tissue in the winter is also decreased, limiting effects from oil that sprays onto vegetation.	Spring/Fall: Oil not volatilized or cleaned up can move during spring melt then seep into the soil.	Summer: In general, summer releases have the greatest effects due to the deeper active soil layer and the increased active living tissue present. Releases that occurred before seeds were produced had greater effects on the next growing season's recovery.	
Soil permeability/ moisture	Soils with low permeability include those with high moisture content, high percentage of clay, or frozen soils. These soils limit the ability of the oil to penetrate and saturate the soil limiting damaging effects on the oil on the roots, nutrient content, and soil microorganisms.	Soils with medium permeability would result in increased toxicity to terrestrial vegetation due to increased saturation of the soil by the released oil. Soil saturation with oil could also go deeper in the soil profile affecting deeper-rooted plant species.	Soils with high permeability would result in increased toxicity to terrestrial vegetation due to increased saturation of the soil by the released oil. This could result in long-term effects such as loss of deep-rooted woody vegetation, and long-term decreases in total vegetative cover and species diversity.	Mosses are sometimes able to recover quickly as they lack roots in the soil and are able to stay above the oil saturated soil.
Plant habit/ type	Herbaceous (including lichen and mosses): Effects depend on timing of the release which impacts seed production. Annual species that are unable to produce seed due to a release are frequently lost from the site. Perennial species are often able to re-sprout from below ground biomass. Lichens are often permanently affected, while mosses varied in their effects.	Shrub/sub-shrub: Surface saturation can affect the actively living tissue; however shrubs are able to recover from below ground biomass (root structure) when oil contaminants stay on the soil surface. When soils are saturated and the oil reaches the roots, effects can be long-term.	Tree: When soils are saturated with oil, long-term effects, including mortality and loss of resilience may occur. Effects to trees often take several years to be observed. Oil releases that stay on the soil surface often do not affect the taller tree species.	
Plant Species	NA	NA	NA	Certain species have been identified for

Table 7-30 Biological Receptor: Terrestrial Vegetation

Environment Characteristic	Low	Medium	High	Other Comments
				reclamation purposes due to their ability to survive and thrive in oiled environments.

7.1.3.2 Benthos

7.1.3.2.1 Description

Benthic macro-invertebrates (or more generally, aquatic invertebrates) are those invertebrates that live on or in the bottom sediments, including a wide variety of arthropods (e.g., aquatic insects, crustaceans, and others), mollusks, annelids, turbellarians, and other phyla. Functionally they are considered to be those invertebrates that live on or in the sediments and are visible to the naked eye or retained on a sieve having a mesh size of about 0.02 inches (0.5 mm, Barbour et al. 1999; Klemm et al. 1990). Sediments also support a wide variety of other, smaller, animal life forms.

Aquatic invertebrates are assessed here because of their ubiquitous importance in the aquatic food web (e.g., as processors of detritus and plant materials, and as prey items for fish), and for their value as bio-indicators and a monitoring tool for assessing the environmental effects of changes in water and sediment conditions (Barbour et al. 1999). Freshwater benthic macro-invertebrates inhabit a variety of substrates, ranging from soft sediments to large rocks, submerged woody debris, aquatic vegetation, and root masses (Klemm et al. 1990).

Because benthic macro-invertebrates are abundant in most waterbodies, relatively easy to sample and identify, tend to stay in a localized area, and have a wide range of feeding strategies and tolerance of environmental conditions, they are a common tool for monitoring health of aquatic ecosystems (Barbour et al. 1999). The use of standard sampling protocols, often based on the USEPA Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers (Barbour et al. 1999), provides a consistent monitoring approach and allows statistical treatment of the data, to reliably identify adverse effects of human activities and trends over time. After identifying and counting the organisms, the data can be evaluated for abundance, diversity, evenness, species composition, dominance, and other community indices that indicate environmental disturbance, relative tolerance of the organisms present, and effects of contaminants on community structure and composition (Pontasch and Brusven 1988).

In watercourses, particular attention is paid to abundance and diversity of some orders of insect larvae in riffle habitat. Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), referred to as EPT taxa, are considered pollution sensitive, and are abundant in conditions preferred by trout and other salmonids (i.e., undisturbed rivers and streams in riffle and run areas, with high oxygen levels, and with low levels of sedimentation, organic contaminants, and nutrient enrichment). While some EPT taxa also inhabit depositional areas of lakes, rivers, and streams, other taxonomic groups (e.g., aquatic worms, midge larvae, mollusks, and crustaceans) that naturally tolerate fine sediment are usually predominant in these areas.

The effects assessment for benthic macro-invertebrates focuses on direct effects of crude oil on invertebrate communities. Oil released to water mainly remains on the surface, but it can also enter the water column (dissolved, dispersed, or as fine droplets) or be stranded on the shore and sediment. Toxicity to aquatic biota varies with the type of oil and manner of exposure, and can be identified through water and sediment monitoring and toxicity testing. Relevant hydrocarbon monitoring parameters are BTEX (which have low molecular weight fractions that weather quickly), PAHs (which have persistent higher molecular weight fractions), and alkanes (aliphatic hydrocarbons, straight chain with varying numbers of carbon atoms). Acute toxicity is generally associated with the lower molecular weight compounds (e.g., BTEX), some PAHs such as naphthalene, and short chain alkanes (NRC 2005).

7.1.3.2.2 Observed Effects

There is potential for crude oil released accidentally from a pipeline to reach one of the many lakes, streams, or rivers in Minnesota. Oil has the potential to affect macro-invertebrates directly through acute or chronic toxicity or smothering of habitat, and indirectly by altering essential habitat characteristics). Immediately following a release, biota can be exposed to acutely toxic hydrocarbon concentrations dissolved in the water (Stalfort 1999; Poulton et al. 1997). The low molecular weight compounds (BTEX, some PAHS, and short chain alkanes) most associated with acute toxicity generally weather and disperse quickly (NRC 2003), so that concentrations in surface water are usually below levels associated with acute effects to benthic macro-invertebrates or fish within days or weeks. Oil deposited in sediment (whether stranded along shorelines, or sunken) contains PAHs that weather and degrade more slowly than the low molecular weight compounds, sometimes over a period of years, and can be associated with chronic toxicity. Indirect effects on macro-invertebrates can occur through effects on other aspects of the habitat (e.g., increase in nutrient release from sediment, increase in algal production, decrease in dissolved oxygen levels during decomposition of the oil, and decrease in decomposition of natural sources of organic matter (Crunkilton and Duchrow 1990). Over time, and as the released oil becomes increasingly weathered, biodegraded and/or dispersed, benthic macro-invertebrate communities recover. Recovery is facilitated by natural dispersal mechanisms of these organisms, such as downstream drift, and upstream movement of aerial life stages prior to egg deposition. Remediation activities can speed up the recovery process, but the habitat-associated disturbance (e.g., removal of riparian and in-water vegetation, substrate disturbance, and flow alteration) can also result in adverse effects on the benthic community.

Observed effects of released oil on benthic macro-invertebrates are compiled from seven case studies where oil was accidentally released in freshwater environments. Only one of the case studies is for a lake, reflecting the paucity of literature available on effects of oil releases in lakes and ponds, as compared to releases into rivers and streams.

> ***Asher Creek, Missouri:*** *In August 1979, a pipeline burst, releasing approximately 9,500 barrels of an unspecified type of domestic crude oil into Asher Creek, in southwest Missouri, during low-flow conditions (Crunkilton and Duchrow 1990). A responsible party has not been identified for this incident. Dissolved oxygen, pH, and conductivity levels in water were not changed by the release (no information about hydrocarbons in water was published), and oil that entered substrates in riffle areas due to mixing was observed for over a year post-release*

(Crunkilton and Duchrow 1990). The creek originates in springs 0.4 miles upstream of the release site. Low water volumes in these headwaters, particularly during summer, provided limited dilution of the oil, increasing the residence time of soluble oil components in sediment (Crunkilton and Duchrow 1990). Areas located downstream from surface skimming siphon dams were less severely affected and recovered more rapidly than areas closer to the release, where the substrate became inundated with oil (Crunkilton and Duchrow 1990).

Recovery of the benthic invertebrate community was studied between 1 and 18 months post-release (Crunkilton and Duchrow 1990), with a focus on riffle-dwelling organisms indicative of good water quality (e.g., Ephemeroptera and Plecoptera). Sampling sites were established 0.4 miles upstream (reference area) and about 1.2, 2.5, and 5.0 miles downstream of the release location. Following an initial reduction in benthic populations to 0.1% of expected density, a decrease in species diversity, and a complete loss of some mayflies and stoneflies, the community began recovering through re-colonization from upstream areas. At nine months post-release, density, diversity, and number of mayfly and stonefly taxa had recovered to levels found in the upstream reference area, but remained below the minimum values established for unpolluted Missouri streams. At 12 months post-release, a drought during August and September resulted in a decline in these metrics. At 18 months post-release, density, diversity, and number of mayfly and stonefly taxa had rebounded and were similar to values reported for unpolluted Missouri streams. Factors slowing recovery time included the additional stress of warm summer temperatures and low flows, the large volume of the release compared to the water volume of the creek at the time of the release, and the limited area upstream for providing organisms for re-colonization (the creek originates from a spring only 0.4 miles upstream of the release site).

Gasconade River, Missouri: *On December 24, 1988, a ruptured pipeline owned by Shell Oil Pipeline Corporation released approximately 20,800 barrels of intermediate sweet crude oil near Vienna, Missouri, into Shoal Creek, a tributary of the Gasconade River. Concentrations of petroleum hydrocarbons in sediment decreased rapidly in erosional areas in the months following the release, but persisted in depositional areas (Poulton et al. 1997).*

Benthic invertebrate communities in riffle and backwater areas of the Gasconade River were sampled after the release, from March 1989 to June 1990 (Poulton et al. 1997). In affected riffle habitats, total number of organisms, taxa richness, number of EPT taxa, and EPT/Chironomidae ratio recovered to levels reported in reference areas in the first summer post-release. In backwater areas, however, benthic diversity and abundance of the macro-invertebrate scrapers and shredders functional feeding groups remained diminished until the end of the *study (18 months post-release). This continued effect was attributed to residual hydrocarbon contamination in backwater slough areas despite the ongoing decline in hydrocarbon levels in sediment over that period. Although high flows and scouring increase recovery in both riffle and backwater habitats, the increased flushing potential of riffle areas likely allowed for increased weathering and flushing of oil residue, which allowed more rapid colonization of benthic invertebrate communities in the riffle habitats compared to backwater areas (Poulton et al. 1997).*

Chariton River, Missouri: *On November 5, 1990, a rupture in an Amoco Oil Pipeline Corporation pipeline released approximately 2,600 barrels of light crude oil into a small tributary that flowed into the Chariton River near Ethel, Missouri. Sediment collected from depositional areas located downstream about six weeks after the release was still found to be toxic to mayflies in laboratory experiments (Poulton et al. 1998; Ort et al. 1995).*

Benthic invertebrate surveys, using artificial substrates consisting of packs of natural leaf litter, were conducted one month and one year post-release (Poulton et al. 1998). One month post-release, there were statistically significant differences between reference and affected sites in abundance and taxon richness of macro-invertebrate collector and shredder functional feeding groups, and in EPT taxon richness. One year later, differences between affected and reference sites were no longer significant for many of the metrics, except for taxon richness and overall abundance, which remained slightly lower in affected areas. The authors stated that effects observed after the release appeared to be associated with oil absorption and substrate coating, creating conditions unsuitable for successful colonization.

Cayuga Inlet, New York: *On November 3, 1997, a Conrail train derailed and released 167 barrels of diesel fuel into a first-order reach of the Cayuga Inlet, which flows into Cayuga Lake near West Danby, New York. Diesel fuel slicks escaped the containment booms and were observed on the surface of Cayuga Lake 9.6 miles downstream of the release site within twenty-four hours (Lytle and Peckarsky 2001).*

Recovery of the benthic invertebrate community was measured four times over a 15 month period at sites 0.4, 3.0 and 7.0 miles downstream of the release, and at corresponding reference sites (Lytle and Peckarsky 2001). Immediately after the release, there were statistically significant differences for taxon richness and predominant taxa at the first two sites downstream, and for density at all three sites. Short-term effects included a 90% reduction in invertebrate density at sites 0.4 and 3.0 miles downstream, and a 50% reduction in taxon richness at the site 0.4 miles downstream. The benthic community at the site 0.4 miles downstream *was dominated in autumn 1997 and spring 1998 by a riffle beetle, of the genus Optioservus, known to tolerate oil pollution. The beetle was replaced in dominance by one highly predominant mayfly species later in 1998. At the other sites, various species of mayflies were predominant. Despite the initial severity of the effect, invertebrate density and taxonomic richness at the site closest to the release recovered within a year, with re-colonization from unaffected areas. However, the authors concluded that 15 months was not long enough for complete recovery of the benthic community at the site located closest to the release, given ongoing over-representation of a single predominant taxon at this site during the study period.*

***Pine River, British Columbia**: On August 1, 2000, a Pembina Pipeline Corporation pipeline ruptured and released approximately 6,200 barrels of sour light crude oil, of which approximately 2,800 barrels entered the Pine River in British Columbia (BC MOE 2000a). The Pine River is a low gradient but fast flowing river, and oil was dispersed up to 50 miles downstream. The fast flowing water allowed rapid dispersion of acutely toxic fractions of the oil into the river water. Oil was stranded and settled in depositional areas along the banks, in back eddies and other slow-flowing areas, and on organic debris and logjams (AMEC 2001 in Lee et al. 2015). Heavy rainfall later in August and September mobilized stranded oil, oil-contaminated debris, and sediments downstream, and high water levels scoured some of the more heavily oiled depositional areas. Oil was recovered from the river over a period of two months, with about 91% of the released oil being either recovered, or accounted for through volatilization (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015). Some of the emergency response activities (e.g., removal of logjams and woody debris, altering of backchannels, bank armoring, and presence of heavy machinery in the river) also resulted in habitat damage (Summers 2004 in Bustard and Miles 2011). Prior to the August 2000 release, a small release of diesel fuel (151 barrels) and gasoline (187 barrels) from a tanker truck had occurred in August 1994 in this area of the Pine River (Goldberg 2011).*

Petroleum hydrocarbons were detected chemically, and seen and smelled in river water up to 50 miles downstream of the release, with sheen visible in back eddies and other calm areas along shorelines. Hydrocarbons accumulated in sediments and on organic debris (e.g., branches, leaves, and algae) present along the shoreline, in front of logjams, and attached to sweeper logs in these calm areas (AMEC 2001 in Lee et al. 2015). Concentrations in water decreased rapidly to below British Columbia water quality guidelines due to evaporation, dissolving in water, and natural dispersion (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015), all of which are characteristic of light crude oil. Oil was observed to persist in some bottom substrates five years after the release (Goldberg 2006 in Bustard and Miles 2011). Analysis of semi-permeable *membrane devices deployed in the Pine River indicated that two years after the release, hydrocarbons were present in water, implying that hydrocarbons from the release were leaching out of sediment into the water column (De Pennart et al. 2004), although additional sources (e.g., road runoff, PAHs from coal deposits in the watershed) were also acknowledged.*

Immediately after the release in August, total abundance of benthic macro-invertebrates declined and there were changes in community composition apparent for at least 75 miles downstream of the release (De Pennart et al. 2004). By August of 2001, relative abundance of benthic invertebrates had recovered in much of the river (De Pennart et al. 2004; Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015). Concerns were expressed about decreased food supply for fish, especially young fish during the August–November 2000 period, which was identified as a critical period leading up to overwintering (Birtwell 2008).

***Wabamun Lake, Alberta**: On August 3, 2005, a Canadian National Railway Company train derailed and released approximately 4,500 barrels of Heavy Fuel Oil 7013 (a Bunker C type fuel oil with a high viscosity and an initial density of about 0.99 at lake temperature) and 550 barrels of pole treating oil. About 20% of the released heavy fuel oil (950 barrels) travelled overland and entered Wabamun Lake. No appreciable volume of pole treating oil entered the lake (Hollebone et al. 2011). While travelling overland, the oil mixed with soil and organic matter; and in the lake, OPAs formed quickly, including small tar balls, larger tar "logs", submerged sheets, and large lumps (Fingas et al. 2006; Hollebone et al. 2011). The aggregates showed a variety of behaviors, including submergence, neutral buoyancy, and resurfacing (Fingas et al. 2006), with extensive tar-mat formation in some nearshore areas. In the lake, the oil floated and spread rapidly over the water surface. After a few days, strong winds and wave action dispersed the oil toward the north, east, and south shorelines, where it became entrained in macrophyte beds (Anderson 2006). Behavior of oil in the lake—rapid formation of tar balls, sinking, slow degradation due to high proportions of high molecular weight components such as resins, and its toxicity and persistence (due to high PAH levels but low BTEX levels—were related to characteristics of the heavy fuel oil, which would not be comparable to crude oils and diluted bitumen, given the high density of the fuel oil. Within four months of the release, concentrations of BTEX and PAHs were below detection in lake water (Birtwell 2008).*

Laboratory tests showed statistically significant toxicity to the benthic invertebrates <u>Chironomus tentans</u> and <u>Hyalella azteca</u> for sediments collected near the release site in the weeks following the release. Test results were challenging to interpret because test conditions were not the same for all site *and control samples. Samples with high sand content had higher mortality, possibly due to sandier habitats not being preferred by the organisms, or because of the naturally low organic content and food supply in sand (Lee et al. 2015). However, growth of both species and also the aquatic worm Lumbriculus variegatus in both high- and low-sand sediments was significantly less than in control sediments. For L. variegatus, PAH concentration in sediment was correlated with toxicity (Lee et al. 2015).*

Marshall Michigan: *On June 25 and 26, 2010, Enbridge Line 6B pipeline ruptured and released approximately 20,000 barrels of heavy crude oil, of which approximately 8,200 barrels entered Talmadge Creek, a tributary to the Kalamazoo River, near Marshall, Michigan (NTSB 2012a; Enbridge 2013b). The released oil was a combination of Western Canadian Select (23%) and CLB (77%) diluted bitumens (Enbridge 2013a). The release occurred on the floodplain of Talmadge Creek, where wetlands are abundant (USFWS et al. 2015a). The Kalamazoo River is a meandering, low gradient river with diverse channel and floodplain features, extensive floodplain forests and wetlands, off-channel water bodies, and impoundments (Dollhopf et al. 2014). Oil was transported downstream in the Kalamazoo River, which was in flood at the time of the release, as far as Morrow Lake (an impoundment in the river 36.5 miles downstream).*

Oil was deposited on river shoreline, riparian, and depositional areas (backwaters, side channels, oxbows) of the Kalamazoo River, and in deltaic sediments of Morrow Lake (USFWS et al. 2015a), affecting approximately 40 miles of river (80 miles of shoreline and adjacent lands) (Dollhopf and Durno 2011). There was associated disturbance from remediation efforts such as removal of riparian vegetation and sediment and access road construction (Dollhopf and Durno 2011). Some of the oil mixed with soil and organic matter while moving overland, and with suspended sediment in the water column after entering the river, resulting in formation of OPAs that submerged in some locations, especially depositional areas. These aggregates periodically released oil globules and sheen as late as 2014 (Fitzpatrick et al. 2015). Formation of OPAs was likely promoted by the flood conditions. Based on measurements of suspended sediment at the Marshall stream gage after the release, it can be inferred that the river had relatively low suspended sediment concentrations at the time of the release, but that the floodwaters likely increased the turbulence and the presence of suspended particulate matter (Fitzpatrick et al. 2015). In addition, the high organic matter content of the suspended and bottom sediments (20% or more) due to the abundant wetlands along the Kalamazoo River contributed to OPA formation (Fitzpatrick et al. 2015). Some of the submerged oil settled in areas that became anaerobic, which would reduce the rate of biodegradation.

About 90% of the oil entering the river was recovered in the first year. This included floating oil, stranded oil in the floodplains of Talmadge Creek and the Kalamazoo River, and submerged oil (Fitzpatrick et al. 2015). Much of the diluent portion volatilized, which resulted in increased density of the residual weathered diluted bitumen. In 2011, additional activities to dislodge and disperse submerged oil resulted in a small amount of additional recovery. Submerged OPAs continued to release oil from sediments in the Kalamazoo River and impoundment areas between 2011 and 2014, with surface sheens observed in impounded sections of the river (Fitzpatrick et al. 2015).

Standardized surveys and other studies indicated that benthic invertebrate communities in some sections of Talmadge Creek and the Kalamazoo River were adversely affected following the release (USFWS et al. 2015a). Some of the observed effects were attributed to effects of the oiling and some to the effects of the clean-up activities. Effects attributed to clean-up activities included bank destabilization resulting from vegetation removal and the potential for resulting bank erosion associated with heavy boat traffic (Winter and Haddad 2014). In addition, heavy boat traffic associated with the clean-up was identified as the caused for crushed mussel shell observed in the oil-impacted areas (Winter and Haddad 2014).

To examine impacts and subsequent recovery, the MI DEQ conducted standard macroinvertebrate surveys in September 2010 with additional surveys in 2011, 2012, 2013, and 2014. The Michigan Procedure 51 methods (similar to USEPA Rapid Bioassessment protocols) were used, and communities were ranked as excellent, acceptable, or poor on the basis on nine community metrics. Following the 2010 survey MI DEQ found that both abundance and diversity of macroinvertebrates were impacted due to the spill and associated clean-up activities (Walterhouse 2011). Post-2010 survey data showed improvement in both the Kalamazoo River sites and Talmadge Creek with most sites returning to near baseline conditions by 2012 (Matousek 2013; Walterhouse 2012).

Benthic macro-invertebrate communities in depositional habitat were assessed at several sites in the Kalamazoo River and in reference sites in 2012 and 2013. The 2013 results were used as part of a sediment quality triad study (along with sediment chemistry and sediment toxicity data) to evaluate effects of the release in areas known to accumulate oil (Enbridge 2014). There was high variability in community metrics among the sites, with similar trends for taxon richness, diversity, and relative abundance of <u>Chironomidae</u> (midge larvae) and <u>Tubificidae</u> (oligochaete worms) at reference and affected sites; but density (organisms per m^2) was lower at the affected sites, possibly partly attributable to higher sand content in reference site substrates compared to affected sites.

> *Sediment toxicity was tested in 2012 and 2013 (same depositional habitat locations as sediment chemistry) using standard laboratory tests with two species of benthic invertebrates (the amphipod Hyalella azteca and larval midge Chironomus tentans). The extent and number of samples showing toxicity decreased between 2012 and 2013 and indicated overall that toxicity was absent from most parts of the river studied (Enbridge 2014). In both years, many samples from affected areas showed no toxicity and the remainder showed low levels of toxicity (e.g., 91% survival in Hyalella and 82% survival for Chironomus) and growth reduction. However, the levels of toxicity were similar in affected and reference areas of the river, indicating a background level of sediment toxicity unrelated to the oil release (Enbridge 2014). Many samples from affected areas of the Kalamazoo River contained elevated levels of organic carbon, which were expected to reduce bioavailability of the PAHs, many of which bind to organic carbon.*
>
> *The 2013 study was a sediment quality triad study, bringing together information about contaminant concentrations in sediment, sediment toxicity, and benthic invertebrate communities in depositional area. Using a weight-of-evidence approach to evaluate the ecological significance of the residual hydrocarbons in sediment, the conclusion was that release-related hydrocarbons in sediment of the Kalamazoo River were not having adverse effects on the aquatic ecosystem three years post-release (Enbridge 2014).*

7.1.3.2.3 Expected Effects of Released Oils

The main effects of released oil on benthic macro-invertebrates are physical smothering of benthic habitats by oil, immediate toxicity from hydrocarbon fractions such as BTEX, and longer-term toxicity from persistent hydrocarbon fractions such as PAHs or physical contact with residual oil droplets in sediment. In addition, there may be habitat damage associated with subsequent remediation. Effects persist longer in depositional areas (pools, backwaters, or deltaic sediments where rivers deposit suspended and bedload sediments), than in erosional areas (riffles and runs of rivers and streams), where oil tends to be in transit or rapidly flushed downstream. Standard laboratory toxicity tests with oiled sediments can be used to assess acute and chronic toxicity to invertebrate species. Field assessments of benthic macro-invertebrate community structure show effects in terms of abundance and diversity of benthic organisms, and can be used to assess the health and recovery of the community. Benthic invertebrate communities recover through re-colonization of affected areas, mainly by downstream drift but also by upstream migration, movement from within the substrate, and eggs laid in the water (Williams and Hynes 1976). Case studies conducted post-release typically indicate substantial recovery for benthic invertebrate communities in rivers and streams within one year, and full recovery within two or three years. Delayed recovery may be expected in depositional areas where oil deposition is heavy, if such oil is left in place.

The effects of oil releases on benthic macroinvertebrates vary depending on characteristics of the released oil and environmental conditions at the time of the release. Relevant oil characteristics related to potential for toxicity include solubility and BTEX concentration, total PAH concentrations, resin and asphaltene concentrations, and density and viscosity. These are discussed in Table 7-31. Environmental characteristics that influence the extent of effects on benthic invertebrates include organic carbon content and particle size of the sediment, water flows, and hyporheic flow, as discussed in Table 7-32. The toxicity of oil to benthic macroinvertebrates depends mainly on the extent of exposure to oil. In general, light oils, high in low molecular weight narcotic compounds such as BTEX, are more acutely lethal than medium and heavy oils. Heavy fuel oils with high proportions of three- to five-ringed alkylated PAHs have greater chronic toxicity than light oils, generally due to their high alkylated PAH levels (Lee et al. 2015). The low molecular weight BTEX and some PAHs weather and degrade more quickly than the higher molecular weight or higher alkylated PAHs, which can persist for long periods in anoxic sediments.

Table 7-31 Effects of Oil on Benthic Macroinvertebrates by Oil Characteristic

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Solubility	Contains a large fraction of soluble low molecular weight hydrocarbons like BTEX, leading to a higher potential for acute toxicity, particularly in the water column.	Intermediate in proportions of soluble low molecular weight hydrocarbons (e.g., BTEX) between light and heavy crude oil. There is a moderate potential for dissolved hydrocarbons to enter sediment pore water and for acute toxicity.	The fraction of soluble low molecular weight hydrocarbons depends on the oil type. Conventional heavy crude oils may have relatively low solubility. However, diluted bitumens contain diluent, which may (e.g., condensate) or may not (e.g., synthetic crude oil) contain a large component of relatively water-soluble aromatic compounds (e.g., BTEX). CLWB is an example of diluted bitumen with a relatively large component of condensate, with BTEX content similar to that of many light crude oils.	Soluble fractions (BTEX and low molecular weight PAHs can result in acute toxicity to organisms in the water column. However, oil that reaches substrates inhabited by benthic macro-invertebrates will have undergone some weathering, leading to lower levels of soluble hydrocarbons.
Concentration of total PAH	Among the light crude oils, Alberta sweet mixed blend crude oil has higher total PAH and proportionally more naphthalene and alkylated naphthalenes than heavier crude oils and bitumen (Yang et al. 2011).	Among the medium crude oils, Alaska north slope crude oil has higher TPAH, and proportionally more naphthalene and alkylated naphthalenes than heavier crude oils and bitumen (Fingas 2010; Zhou et al. 2015).	Diluted bitumens typically have concentrations of total PAH that are similar to or lower than many light, medium, and heavy conventional crude oils, although the PAH "fingerprint" varies (Zhou et al. 2015, Fingas 2010). There is no current evidence to suggest diluted bitumens are more toxic than conventional light or medium crude oils (Zhou et al. 2015). Diluted bitumens tend to have relatively more of the C3 and C4 alkylated PAHs, which may be more toxic and persistent, but these PAHs are less soluble in water and therefore less bioavailable. Heavy fuel oils often contain very high concentrations of PAHs.	Many PAHs are have very low aqueous solubility and accumulate in sediment, where benthic macro-invertebrates can be exposed. They do not degrade quickly and can result in chronic toxicity to aquatic biota. Total PAH levels vary from oil to oil, even within a weight class, but as a general rule, most crude oils contain approximately 1% total PAH by weight.
Concentration of resins and	Light crude oils contain very little resin and asphaltene. The light	Medium crude oils also contain little resin and asphaltene, although	Resins and asphaltenes comprise the "heavy" end of crude oils, and diluted bitumens are proportionally richer in these	Resins and asphaltenes are generally insoluble in water and thus not biologically

Table 7-31 Effects of Oil on Benthic Macroinvertebrates by Oil Characteristic

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
asphaltenes	oils weather quickly, resulting in less extensive and shorter-term effects on habitat of benthic macro-invertebrates.	more than light crude oils. Medium crude oils also have good potential for weathering and biodegradation in the environment.	components than light or medium crude oils. Their tendency to adhere to substrates and resist biodegradation results in potential to affect habitat of benthic macro-invertebrates in both depositional and erosional habitats.	available and nontoxic. They can adhere to surfaces and are slow to degrade (Lee et al. 2015), so can act as reservoirs for slow release of other more toxic hydrocarbon constituents such as PAHs.
Density and viscosity	Light crude oils have relatively low density and viscosity. Therefore, although they float and quickly re-surface when submerged, their low viscosity allows formation of small droplets under turbulent flow conditions. Such droplets readily interact with suspended sediments to form OPAs that may have a net density greater than that of the water.	Medium crude oils have intermediate density and viscosity. Therefore, while they readily float on water, they are somewhat more resistant to dispersion into flowing water as fine droplets than light crude oils.	Heavy crude oils have relatively high density (diluted bitumens are typically engineered to have a fresh density of 0.94 or less, similar to conventional heavy crude oil types). Diluted bitumens generally have lower viscosity than heavy conventional crude oils; however, density of diluted bitumen containing a volatile diluent will increase more rapidly than density of a conventional crude oil. The higher density of heavy crude oils suggests a greater tendency to sink; however, the higher viscosity of these oils reduces the likelihood that fine droplets will form in the water column and, therefore, reduces the likelihood of OPA formation.	Density and viscosity of any oil will increase as a result of weathering post-release. Any crude oil can be deposited to sediment, under the right conditions. Wave tank testing of light (Alberta Mixed Sweet Blend) and Cold Lake diluted bitumen crude oil types with natural river sediment showed that the light oil readily formed OPAs and sank, whereas the diluted bitumen remained floating (Zhou et al. 2015).

Table 7-32 Effects of Oil on Benthic Macroinvertebrates by Oil Characteristic

Environment Characteristic	Low	Medium	High	Other Comments
Sediment organic carbon content	Oligotrophic (nutrient-poor) lakes and watercourses tend to have low organic carbon content. Sediments with low organic carbon content may be more prone to toxic effects to benthic macro-invertebrate communities than those with higher organic carbon content, as the organic matter provides binding sites for PAHs and other hydrocarbons.	Freshwater environments, including many watercourses, typically contain moderate amounts of organic carbon, which can bind some of the hydrocarbon fractions, reducing toxicity to aquatic biota.	Sediments containing abundant organic carbon (e.g., eutrophic or nutrient rich lakes and depositional areas of watercourses) may be less prone to exhibiting toxic effects on benthic macro-invertebrates. The high organic carbon content in sediments of the Kalamazoo River was cited as a factor in the low observed toxicity of sediments following the 2010 Marshall release of diluted bitumen (Enbridge 2014).	Oil residues as well as specific classes of compounds such as PAHs can bind to naturally occurring organic matter, limiting hydrocarbon bioavailability and toxicity. Sediment and water flow characteristics are frequently correlated. Flowing water tends to have coarse-grained sediment with less organic matter. Slow-moving or standing water tends to have fine grained sediment, with more organic matter.
Sediment grain size	Fine grained sediments (silt and clay) occur in depositional areas, where oil tends to accumulate. Fine-grained sediments may resist entry of OPAs, although physical mixing may introduce oil into the sediments, where it may persist due to low oxygen levels and lack of water flow. These processes can result in greater or more prolonged effects on benthic macro-invertebrates.	Medium-grained sediments (fine to coarse sand) occur in moderate flow environments, pools in rivers and streams, and some lakes. There is some potential for oil to accumulate in these areas, and the sandy sediment may resist entry of OPAs. The higher load-bearing capacity of these sediments may facilitate recovery of oil without downward mixing and persistence, resulting in less prolonged effects on benthic macro-invertebrates.	Coarse-grained substrates (gravel, cobble) are typical of relatively high flow systems (riffle and run habitat of rivers and streams), where oil does not tend to accumulate. However, oil and OPAs can enter the voids in the substrate, and may persist when flushing flows are limited (Klemm et al. 1990), resulting in prolonged effects on resident benthic macro-invertebrates.	Oil persistence in sediment depends upon oxygen availability (to promote biodegradation) and irrigating water flows (to promote weathering and toxicity reduction through removal of more soluble/bioavailable constituents). Spring freshet is a major seasonal factor that can flush river sediments, leading to a rapid restoration of damaged habitat.

Table 7-32 Effects of Oil on Benthic Macroinvertebrates by Oil Characteristic

Environment Characteristic	Low	Medium	High	Other Comments
Water flow characteristics	OPAs are most likely to be deposited in areas of slow-moving or still water. The slower natural biodegradation in depositional areas results in longer term habitat and toxicity effects on benthic macro-invertebrates, and longer time to community recovery.	OPAs may be locally deposited in areas of flowing water, but then re-mobilized under higher flow conditions and re-deposited elsewhere. Benthic communities in these areas recover more quickly due to faster removal of oil and faster recolonization from surrounding aquatic areas.	OPAs are not likely to be deposited in areas of turbulent flowing water. Lower oil deposition results in fewer and shorter term effects to benthic communities.	Sediment and water flow characteristics are frequently correlated (flowing water tends to have coarser-grained sediment, with less organic carbon, and standing water tends to have finer-grained sediment, with more sediment organic carbon).
Hyporheic (subsurface) flow systems	In streams that receive strong groundwater inflows, the net water flow away from the sediment will tend to prevent oil residues from entering the sediment and the hyporheic flow system, reducing potential effects on the benthic macro-invertebrate community.	Many streams have variable interactions with groundwater, both spatially and seasonally. Water may enter and exit from the hyporheic flow system at scales ranging from less than 1 m to 100 m or more. This can result in varying influences on oil effects to benthic macro-invertebrates.	In arid environments or during dry seasons, streams may regularly "lose" water to the hyporheic and groundwater systems. Under these conditions, dissolved hydrocarbons and very fine oil droplets may be entrained into the river bed or groundwater flow systems, and be resistant to degradation in low-oxygen environments, resulting in more prolonged effects of the oil on benthic macro-invertebrates.	The persistence of crude oil residues in hyporheic flow systems is likely to be low due to fresh water inflow, which will supply oxygen, and provide a flushing flow of clean water to remove relatively water soluble/bioavailable hydrocarbons, helping to reduce toxicity effects associated with the oil.

7.1.3.3 Fish

7.1.3.3.1 Description

Freshwater fish spend some or all of their life cycle stages in streams, rivers, ponds or lakes. As a group they have important ecological and economic functions. The trophic levels freshwater fish occupy range from herbivores to top predators, and the feeding ecology of individual fish may change as they grow from juvenile to adult life stages. Fish are an important food source for mammals such as river otter (*Lontra canadensis*) and American mink (*Neovison vison*), and for birds and waterfowl such as great blue heron (*Ardea herodias*) and common merganser (*Mergus merganser*), and raptors such as osprey (*Pandion haliaetus*) and bald eagle (*Haliaeetus leucocephalus*). Freshwater recreational fishing is a multi-billion dollar industry in North America. Traditional fisheries have been and remain an important food source for Aboriginal people, and in some locations are the basis for commercial fisheries.

Freshwater fish are often used as indicators of the health of a waterbody (Karr 1981), and fish surveys are used to determine both adverse effects and recovery from disturbance (Klemm 1993; Simon 1999). The advantages of fish for bio-monitoring are:

- Life span of fish, compared to benthic invertebrates, allows for longer term monitoring of effects
- Fish occupy multiple positions in the aquatic food web. An assemblage of fish usually includes omnivores, herbivores, insectivores, planktivores, and piscivores, allowing for monitoring across multiple trophic levels
- Fish are relatively easy to collect and identify, and depending upon the nature of the scientific analyses required, can be released unharmed
- Life history traits and environmental requirements of many fish species are relatively well known
- Many fish are important recreational and commercial species (Barbour et al. 1999; Klemm 1993)
- Fish can be one of the more sensitive indicators of water quality (Klemm 1993)

Federal and state agencies may collect fish community data as a measure of waterbody health, providing a robust record of waterbody status over time. Many states follow standard protocols for fish collection, often based on the USEPA Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers (Barbour et al. 1999). Collected fish are typically identified and counted and the data may be evaluated for a variety of metrics including abundance, diversity, species composition and dominance, and indicator species.

7.1.3.3.2 Observed Effects

Oil has the potential to affect fish directly through acute or chronic toxicity and indirectly by altering essential habitat (Enbridge 2015). Some components of oil (generally low molecular weight and aromatic compounds) may be acutely toxic when dissolved in water. Other components (e.g., higher molecular weight compounds such as parent and alkylated PAHs) may cause chronic toxicity when dissolved in water (Lee et al. 2015). Oil stranded on shorelines or deposited to sediments can release hydrocarbon compounds for weeks or months after an accidental release. Contact between floating oil and shorelines will result in oiling of sediments at the water line. In addition, given the right conditions of turbulence and suspended sediment, almost any type of crude oil can become associated with sediment particles (i.e., as OPAs) leading to the deposition of some of the released oil to sediment, where flow conditions transition from moving to still water. The physical presence of oil on or in the substrates of water bodies may disrupt habitat use by fish. Clean-up activities may also disrupt habitat through removal of oiled substrates and riparian vegetation, or physical damage such as boat groundings, propeller wash, or fording of streams by wheeled vehicles.

Observed effects of released oil on fish were compiled from several case studies where oil was released in freshwater environments.

> ***Red Deer River, Alberta:*** *On June 7, 2012, approximately 3,000 barrels of light crude oil were released from a ruptured pipeline owned by Plains Midstream Canada ULC about 1.9 miles north of Sundre, Alberta and entered Jackson Creek, a tributary of the Red Deer River. Floodwaters 10 times higher than typical June flows eroded the stream bed and banks and exposed the pipeline under the river, which then ruptured (Alberta Energy Regulator 2014). Oil traveled at least 25 miles downstream to Gleniffer Lake reservoir, where booms contained the free oil product. Dissolved hydrocarbons in river water were detected up to 5 miles farther downstream (Alberta ESRD 2012a). Low molecular weight aromatic hydrocarbons (BTEX) and some PAHs were detected in the river and lake up to 30 miles downstream of the release location in the early days post-release (Alberta ERSD 2012a). Because of the high water levels at the time of the release, the majority of stranded oil occurred well above the high water mark for the river, in back water areas, trapped under trees and debris, in highly braided river margins, and mixed with silt and sediments (Teichreb 2014). Long-term monitoring showed that PAH concentrations in edible fish tissue were below human consumption guidelines (Teichreb 2014).*

> ***Marshall, Michigan:*** *On June 25 and 26, 2010, the Line 6B pipeline owned by Enbridge ruptured and released approximately 20,000 barrels of heavy crude oil, of which 8,000 barrels entered Talmadge Creek, a tributary to the Kalamazoo River, near Marshall, Michigan (NTSB 2012a). The released oil was a combination of Western Canadian Select (23%) and CLB (77%) diluted bitumens (Enbridge 2013a). The release occurred on the floodplain of Talmadge Creek, where wetlands are abundant (USFWS et al. 2015a). The Kalamazoo River is a meandering, low gradient river with diverse channel and floodplain features, extensive floodplain forests and wetlands, off-channel water bodies, and impoundments (Dollhopf et al. 2014). Oil was transported downstream in the Kalamazoo River, which was in flood state at the time of the release, to Morrow Lake (an impoundment in the river 36.5 miles downstream).*

Oil was deposited on river shoreline, riparian, and depositional areas (backwaters, side channels, oxbows) and along the shores of Morrow Lake (USFWS et al. 2015a), affecting 80 miles of shoreline and adjacent lands. There was associated disturbance from oil removal efforts (removal of riparian vegetation and sediment, access road construction; Dollhopf and Durno 2011). Some of the oil mixed with soil and organic matter while moving overland and also with suspended sediment in the water column, resulting in formation of OPAs that submerged in some locations, especially in depositional areas, and periodically released oil globules and sheen as late as 2014 (Fitzpatrick et al. 2015). Formation of OPAs was likely promoted by the flood conditions. Based on measurements of suspended sediment at the Marshall stream gage after the release, it can be inferred that the river had relatively low suspended sediment concentrations at the time of the release, but that the floodwaters likely increased the turbulence and the presence of suspended particulate matter (Fitzpatrick et al. 2015). In addition, the high organic matter content of the suspended and bottom sediments (20 percent or more) due to the abundant wetlands along the Kalamazoo River contributed to OPA formation (Fitzpatrick et al. 2015).

About 90% of the oil released into the river was recovered in the first year. This included floating oil, stranded oil in the floodplains of Talmadge Creek and the Kalamazoo River, and submerged oil (Fitzpatrick et al. 2015). In 2011, additional activities to dislodge and disperse submerged oil resulted in a small amount of additional recovery. Submerged oil-particle aggregates continued to release oil from sediments in the Kalamazoo River and impoundment areas during 2011–2014, with surface sheens observed in impounded sections of the river (Fitzpatrick et al. 2015).

During fish and wildlife response operations conducted by the MI DNR in 2010 for some sections of Talmadge Creek and the Kalamazoo River, 42 dead fish were found, which was considered a negligible number for this time period (USFWS et al. 2015a). Abundance and diversity of fish in Talmadge Creek decreased in 2010 post-release, but had recovered during subsequent surveys. Results of surveys conducted in 2011, 2012, and 2013 suggested there were changes in species composition, perhaps related to changes in habitat following clean-up (unpublished data provided to the Trustees for review for the Draft Damage Assessment and Restoration Plan [DARP], final results pending). Preliminary results for the Kalamazoo River were less definitive than for Talmadge Creek, with some reductions in smallmouth bass (Micropterus dolomieu) in 2010, but with variable results across all sites and years (USFWS et al. 2015a).

Sublethal effects on exposed fish (condition, tissue histopathology, immunotoxicity, induction of CYP1A, and a necropsy-based assessment of *health) were evaluated by the USGS during an August 2010 fish health assessment two months post-release (Papoulias et al. 2014). There were statistically significant differences for fish captured in affected areas of the Kalamazoo River compared to reference areas, indicating that fish in affected reaches up to 27 miles downstream of the release exhibited effects consistent with crude oil exposure. Follow-up studies on this topic were not completed.*

Following the release, MI DCH put cautionary fish consumption advisories in place. Their analysis of fish collected in 2010 and 2011 determined that PAH concentrations in fish tissue were below levels that would necessitate fisher closure. However, consumption guidelines remained in place due to levels of mercury and polychlorinated biphenyls (PCBs) found in the fish tissue that were not related to the crude oil release (MI DCH 2014b).

***Wabamun Lake, Alberta:** On August 3, 2005, a Canadian National Railway Company train derailed and released approximately 4,500 barrels of Heavy Fuel Oil 7013 (a Bunker C type fuel oil with a high viscosity and an initial density of about 0.99 at lake temperature) and 550 barrels of pole treating oil. About 20% of the released heavy fuel oil (940 barrels) travelled overland and entered Wabamun Lake; no appreciable volume of pole treating oil entered the lake (Hollebone et al. 2011). In the lake, the oil floated and spread rapidly over the surface; after a few days, strong winds and wave action dispersed the oil toward the north, east, and south shorelines, where it became entrained in macrophyte beds (Anderson 2006). While traveling overland, the oil mixed with soil and organic matter, and in the lake, aggregates, including tar balls, larger tar "logs," submerged sheets, large lumps, tar balls that sometimes reformed into oil slicks, and a "slurry" composed of finely divided organic matter and small oil droplets, formed quickly (Fingas et al. 2006, Hollebone et al. 2011). The aggregates showed a variety of behaviors, including submergence, neutral buoyancy, and resurfacing (Fingas et al. 2006), with extensive tar mat formation in some nearshore areas. Sinking oil settled in near-shore vegetated habitats where six out of eight native fish species in Wabanum Lake spawn including lake whitefish (<u>Coregonus clupeaformis</u>) and northern pike (<u>Esox lucius</u>) (Hodson 2008; DeBruyn et al. 2007). Behavior of oil in the lake (sinking, rapid formation of tar balls, slow degradation due to high proportions of high molecular weight components such as resins) and its toxicity and persistence (due to high PAH levels but low BTEX levels) were related to characteristics of the heavy fuel oil that would not be comparable to crude oils and diluted bitumen. Ultimately, clean-up activities recovered more than 95% of the oil.*

About 100 dead fish were observed in macrophyte beds following the release, including species of minnows and adult northern pike, lake whitefish, and burbot (<u>Lota lota</u>) (Birtwell 2008). Although these mortalities were attributed to natural *causes, and the Alberta Sustainable Resource Development ministry concluded the release had left no short term adverse effects on fish (Transportation Safety Board of Canada 2007), Birtwell (2008) argued that the 100 fish died as a result of the release, although toxicological tests to support this assertion were not conducted.*

The shoreline macrophyte beds where oil accumulated are considered important habitat for several species of fish, particularly juvenile stages (Birtwell 2008). Direct fish mortality also occurred when vegetation was removed during clean-up activities. Fish habitat was disturbed or destroyed as a direct result of oiling in the macrophyte beds and also during clean-up activities (related to trampling, low-pressure flushing, vacuuming, and dragging over substrates).

In situ studies were conducted to evaluate potential effects of oil on spawning shoals of lake whitefish and northern pike. In November 2005, four months post-release, whitefish embryos were held in egg containers installed on affected and reference area shoals; survival and prevalence of deformities typical of oil exposure were measured (Debruyn et al. 2007). In general, fish from Wabamun Lake showed high baseline rates of deformities in both reference and affected areas, reflecting historical exposure to elevated concentrations of PAHs, related to public boating on the lake and presence of coal mines and coal fired power plants in the vicinity. However, at the conclusion of the study in April 2006, hatched survivors at the affected shoals had higher rates of severe skeletal deformities (statistically significant) compared to those from the reference area. PAH concentrations measured in passive membrane samplers adjacent to the egg containers were correlated with the rates of moderate to severe deformities (Debruyn et al. 2007). Similar exposure experiments with northern pike larvae resulted in few deformities, none of which could be attributed to PAH exposure, suggesting lower uptake of or sensitivity to PAHs in this species (DeBruyen et al. 2009).

Concerns over human consumption of fish containing hydrocarbons triggered fish tissue sampling and PAH analysis for one year post-release (Sandhu et al. 2008). Although PAH levels in tissue were elevated initially, it was suggested that these concentrations posed little or no risk of adverse effects to people consuming fish six months post-release (Sandhu et al. 2008). Ten years later, the Alberta Department of Fish and Wildlife reported that walleye (<u>Sander vitreus</u>) introduced into Wabamun Lake had become increasingly successful and that there were healthy populations of pike and perch in the lake (Hudson 2015).

Pine River, British Columbia: *On August 1, 2000, a Pembina Pipeline Corporation pipeline ruptured and released approximately 6,200 barrels of sour light crude oil, of which approximately 2,800 barrels entered the Pine River in British Columbia*

(BC MOE 2000a). The Pine River is a low gradient river, but fast flowing, and oil was dispersed up to 50 miles downstream. The fast flowing water allowed rapid dispersion of acutely toxic fractions of the oil. Oil was stranded and settled in depositional areas along the banks, in back eddies and other slow-flowing areas, and on organic debris and logjams (AMEC 2001 in Lee et al. 2015). Heavy rainfall later in August and September mobilized stranded oil, oil-contaminated debris, and sediments downstream; and high water levels scoured some of the more heavily oiled depositional areas. About 91% of the oil was recovered from the river or accounted for through volatilization over about two months (Alpine Environmental and EBA Engineering 2001 in Lee et al 2015). Some of the emergency response activities (e.g., removal of logjams and woody debris, altering of backchannels, bank armoring, and presence of heavy machinery in the river) also resulted in habitat damage (Summers 2004 in Bustard and Miles 2011). In August 1994, a small release of diesel fuel (151 barrels) and gasoline (187 barrels) had occurred in this area of the Pine River (Goldberg 2011).

Petroleum hydrocarbons were detected chemically, and seen and smelled in river water up to 50 miles downstream of the release, with sheen visible in back eddies and other calm areas along shorelines. Hydrocarbons accumulated in sediments and on organic debris (e.g., branches, leaves, and algae) present along the shoreline, in front of logjams, and attached to sweeper logs) in these calm areas (AMEC 2001 in Lee et al. 2015). Hydrocarbon concentrations in water decreased rapidly to below British Columbia water quality guidelines due to evaporation, dissolving in water, and natural dispersion (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015), all of which are characteristic of light crude oil. Oil was observed to persist in some bottom substrates five years after the release (Goldberg 2006, as cited in Bustard and Miles 2011). Analysis of semi-permeable membrane devices deployed in the Pine River indicated that two years after the release, hydrocarbons were present in water, implying that hydrocarbons from the release were leaching out of sediment into the water column (DePennart et al. 2004), although additional sources (e.g., road runoff, PAHs from coal deposits in the watershed) were also acknowledged.

Although not measured directly, the initial release of crude oil into the Pine River was estimated to have resulted in hydrocarbon concentrations (water-soluble fraction likely greater than 3 mg/L) high enough to kill fish within hours of the release (Birtwell 2003 in Lee et al. 2015). Over the first five days post-release, 1,637 dead fish, mostly larger, more visible individuals, were found up to 30 miles downstream (Baccante 2000 in Birtwell 2008). Most were bottom-feeding species, consisting of 64% mountain whitefish (Prosopium williamsoni), 16% slimy sculpins (Cottus cognatus), and 5% burbot. The remainder were surface feeders, consisting of bull trout (Salvelinus confluentus), rainbow trout (Oncorhynchus mykiss), and Arctic grayling (Thymallus arcticus) (Baccante 2000 in Birtwell 2008).

Accurate direct counts of fish mortalities were difficult to make, given the challenges accessing areas of the river before fish decayed or were consumed by scavengers (Hodson et al. 2011). As a result, mortality was estimated using previous estimates of fish density and assumptions of mortality ranges. The mortality estimates ranged from 15,000 to 20,100 fish over a 19 mile section of river, and from 25,000 to 250,000 over a 30 mile stretch (Goldberg 2011). Eleven days after the release, British Columbia Ministry of Environment, Lands and Parks staff biologists reported fish returning to even the most affected areas of the river from adjacent tributaries (BC MOE 2000b).

Snorkel surveys conducted prior to the release (1993, before a small release of gasoline and diesel fuel in 1994) and post-release (2000, 2005, 2006, and 2007) were used to evaluate oil effects on sport fish abundance, species richness, and recovery of the community (Goldberg 2011). Survey results from 2000 demonstrated recruitment was occurring in the first two months post-release, but with lower fish abundance than in 1993 and with suckers absent. For sections of the river surveyed in 2005, 2006, and 2007, sport fish species composition and abundance appeared to have recovered to 1993 levels. Goldberg (2011) noted that with data available for only one survey pre-release, it was not possible to evaluate the inter-annual range of abundance but concluded: "results appear encouraging in that they are, at a minimum, similar to those observed in 1993, suggesting that the fisheries resources are exhibiting on-going recovery since the 2000 pipeline rupture and 1994 spill."

There were insufficient studies to establish the nature and extent of sublethal effects on reproduction and recruitment of fish. The concentrations of PAH compounds in fish stomach contents and bile confirmed PAH exposure via the food chain (Alpine Environmental and EBA Engineering 2001 in Lee et al. 2015). Concerns were also expressed about decreased benthic macroinvertebrate abundance, which provide food, especially for young fish during the first autumn post-release, which is a critical period leading up to overwintering (Birtwell 2008).

Cayuga Inlet, New York: *On November 3, 1997, a train derailed and released 167 barrels of diesel fuel into a first order reach of the Cayuga Inlet, which flows into Cayuga Lake, near West Danby, New York. Diesel fuel slicks escaped the containment booms and were observed within 24 hours on the surface of Cayuga Lake, 9.6 miles downstream (Lytle and Peckarsky 2001). One day post-release, a fish kill of rainbow trout (Oncorhyncus mykiss), white sucker (Catostomus commersoni), blacknose dace (Rhinichthys atratulus) and darters (Etheostoma spp.) was reported, estimated at 92% of total fish abundance in the inlet (Krueger in Lytle and Pekarsky 2001). Cayuga Inlet provides spawning habitat for rainbow trout (spring spawners) and brown trout (Salmo trutta) and salmon (Salmo salar), fall spawners that were beginning their autumn run when the* *release occurred. No information about effects on spawning salmonids was provided.*

Asher Creek, Missouri: *In August 1979, a pipeline burst, releasing approximately 9,500 barrels of an unspecified type of crude oil into Asher Creek, in southwest Missouri, during low flow conditions (Crunkilton and Duchrow 1990). Dissolved oxygen, pH, and conductivity levels in water were not changed by the release (no information about hydrocarbons in water was published) and oil that entered substrates in riffle areas due to mixing was observed for over a year post-release (Crunkilton and Duchrow 1990). The creek originates in springs 0.4 miles upstream of the release site; low water volumes in these headwaters, particularly during summer, provided limited dilution of the oil, which would have increased the residence time of soluble oil components in sediment (Crunkilton and Duchrow 1990). Areas located downstream from surface skimming siphon dams were less severely affected and recovered more rapidly than areas closer to the release, where the substrate became inundated with oil (Crunkilton and Duchrow 1990). Following the release, an estimated 42,000 fish were found dead along a 5 mile section of the creek (Crunkilton and Duchrow 1990).*

7.1.3.3.3 Expected Effects of Released Oils

The effects of released oil on fish depend on characteristics of the oil and environmental conditions at the time of the release. Oil characteristics that may determine the acute effects of oil on fish include tendency to disperse in water, and concentrations of relatively water soluble components in the crude oil, particularly BTEX and low molecular weight PAHs. Chronic effects of crude oil in streams, rivers and lakes would depend more upon residual levels of total PAH (TPAH) in sediment and interstitial waters. Environmental characteristics include water flows, fish species sensitivity, and geomorphic factors that could lead to crude oil deposition in sediment. Effects associated with each characteristic are described in Table 7-33 and Table 7-34.

The potential for oil releases to harm fishery resources is well established, and documented in the case studies. Effects may be acute (e.g., fish kills) or chronic, leading to reduced population density and species richness, and associated potential effects on fish consumption due to increased PAH concentrations in tissue. Habitat disturbance during cleanup activities are another source of stress to fish populations.

Table 7-33 Effects of Oil on Fish by Oil Characteristic

BIOLOGICAL RECEPTOR: Fish and Fish Habitat				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Other Comments**
Viscosity	Low viscosity oils are readily dispersed as small droplets in the water column, when water is turbulent. Partitioning of hydrocarbons from small droplets into water as dissolved hydrocarbon is rapid, leading to high potential for acute toxicity to fish.	The viscosity of medium crude oils is relatively low, so these oils are also readily entrained into the water column, facilitating the dissolution of relatively water soluble components of the crude oil.	Heavy crude oils tend to have high viscosity, making them difficult to entrain into the water column, except under very strong mixing conditions (e.g., waterfalls and rapids). The viscosity of diluted bitumen is initially depressed by the added diluent, but as this weathers away, the viscosity of the weathered crude oil increases rapidly.	The viscosity of any crude oil will increase at low temperature. Viscosity also increases as crude oils weather.
Buoyancy	Light crude oils have low density, and are highly buoyant. Oil droplets entrained into the water column will therefore tend to re-surface rapidly, rejoining a surface slick, when water turbulence decreases.	Medium crude oils have intermediate density, and will typically not weather to a density equal to or greater than 1.0.	Heavy crude oils also have relatively high density. The density of fresh diluted bitumen is required by pipeline tariffs to be less than 0.94, but will increase with weathering after being released to the environment. Diluted bitumens float on water when fresh, and are likely to adhere to shorelines long before they would weather sufficiently to become neutrally buoyant in water (i.e., reach a density of 1.0). Some refined heavy oils (e.g., heavy fuel oils) may have initial density values very close to 1.0.	Density of crude oils will increase at low temperature, and also increases with weathering. Any type of crude oil may also interact with sediment particles (ranging in size from clays to gravels) resulting in an oil-mineral aggregate that has a density greater than 1.0. This can lead to crude oil becoming deposited to sediment.

Table 7-33 Effects of Oil on Fish by Oil Characteristic

BIOLOGICAL RECEPTOR: Fish and Fish Habitat				
Oil Characteristic	**Light Crude Oil**	**Medium Crude Oil**	**Heavy Crude Oil**	**Other Comments**
Chemistry	Low molecular weight aromatic hydrocarbon compounds (e.g., BTEX and some PAHs such as naphthalene) are usually the biggest contributors to acute toxicity. These compounds are often abundant in light crude oils. Light crude oils typically contain only small amounts of highly insoluble hydrocarbon components such as resins and asphaltenes.	Medium crude oils often contain moderate levels of BTEX and other relatively water soluble hydrocarbons, leading to a moderate potential to cause acute toxicity. Synthetic crude oils originating from the oil sands of Alberta may contain only small amounts of BTEX, as well as being depleted in resins and asphaltenes as a result of processing before shipment.	Heavy crude oils and bitumens are often highly weathered, containing only small amounts of BTEX, while containing larger amounts of polar compounds (resins) and asphaltenes. However, depending upon the nature and amount of the diluent added, diluted bitumens may contain levels of BTEX that are similar to light crude oils.	Acute toxicity of crude oils generally reflects the amount of low molecular weight hydrocarbons present (e.g., BTEX). Chronic toxicity reflects the amount of TPAH present. Most crude oils contain approximately 1% TPAH. Some refined oils such as heavy fuel oils contain larger amounts of TPAH (5-6% by weight).
Persistence	Light crude oils generally weather and biodegrade rapidly, and have low persistence in the environment, except when they become deposited in anaerobic environments.	Medium crude oils also weather and biodegrade quite readily.	Heavy crude oils can be resistant to weathering. Bitumen from the Alberta oil sands represents a type of crude oil that has undergone extensive natural weathering *in situ,* before it was extracted. Therefore, diluted bitumens tend to resist further weathering and biodegradation once the diluent component has been removed. This residual crude oil can therefore become a chronic low-level source of PAHs to the aquatic environment.	Any type of crude oil can be persistent if it is deposited in an environment where oxygen is not available. However, heavy crude oils and diluted bitumens contain more resins and asphaltenes than light and medium crude oils, and as a consequence, heavy crude oils tend to biodegrade more slowly, and have higher potential to become a persistent source of chronic, low-level hydrocarbon release to the aquatic environment.

Table 7-34 Effects of Oil on Fish by Environmental Characteristic

BIOLOGICAL RECEPTOR: Fish and Fish Habitat				
Environment Characteristic	**Low**	**Medium**	**High**	**Other Comments**
Water flow characteristics (turbulence)	Crude oils will float on still water, resulting in most of the low molecular weight hydrocarbons being lost to the atmosphere, rather than becoming dissolved in the water. Conditions leading to acute toxicity to fish are unlikely to occur.	Moderately flowing water may result in the entrainment of crude oils that have low viscosity (i.e., light and medium crude oils) into the water as small droplets. This creates conditions where low molecular weight hydrocarbons can more readily dissolve into the water column, potentially leading to acute toxicity to fish. More viscous oils may resist the process of entrainment, and remain floating on the surface of the water.	Highly turbulent flow conditions, such as rapids or waterfalls, will result in the entrainment of more viscous crude oils into the water column, creating conditions where these oil types are more likely to result in acute toxicity to fish.	Within a particular watercourse, flow rates and turbulence levels vary seasonally and in response to storm events. The highest seasonal flow rates in most systems occur during spring freshet.
Volume of water flow	Low water flow rates provide little dilution potential for hydrocarbons that dissolve into the water. Therefore, episodes of acute toxicity are more likely to occur in small streams, or during seasonal periods of low water flow rate (e.g., late summer and winter).		Large rivers have high water flow rates, which will reduce the potential for episodes of acute toxicity in the event of a crude oil release. High water flow rates also occur during the spring freshet.	Information from the case studies indicates that large-scale fish kills are more likely to be observed in streams and smaller rivers than in lakes and large rivers.

Table 7-34 Effects of Oil on Fish by Environmental Characteristic

BIOLOGICAL RECEPTOR: Fish and Fish Habitat				
Environment Characteristic	**Low**	**Medium**	**High**	**Other Comments**
Fish species and life-stage sensitivity	All else being equal, large-bodied fish are typically less sensitive to acute hydrocarbon exposures than small bodied fish. In addition, warm-water fish species are less sensitive than cold-water fish species.		Highly sensitive species are typically represented by small-bodied or juvenile fish. Cold-water fish species such as salmonids (trout and whitefish) are typically more sensitive than warm-water fish species (cyprinids, catfishes and sunfishes). Egg and embryo life stages are typically more sensitive than juvenile and adult life stages.	Toxicity assessment in risk assessment is typically based upon "sensitive" receptor species and life stages, on the assumption that if these receptors are protected, then all other similar receptors will also be protected.

The extent of fish mortality after a release is influenced by the type of oil (e.g., light crude oils will become dispersed and entrained into the water column as small droplets more readily than heavy crude oils, and may contain higher concentrations of low molecular weight hydrocarbons such as BTEX), the size of the receiving water body (a proxy for how much and how quickly dissolved hydrocarbons will become diluted or dispersed to non-lethal concentrations), and the presence of additional environmental stressors that could modify toxicity (Lee et al. 2015).

Fish can be exposed to acutely toxic hydrocarbon concentrations immediately following a release due to exposure to low molecular weight hydrocarbons. These fractions weather (through volatilization and biodegradation) and become diluted over 24 to 48 hours, so fish kills are often short-term and localized, unless there is an ongoing source of oil entering a system that provides little dilution. The low molecular weight hydrocarbons responsible for most of the acutely lethal effects are BTEX, low molecular weight PAHs like naphthalene, and short-chain alkanes (NRC 2005), which produce a narcotic effect on fish.

Bioaccumulation of PAHs in fish tissue can also lead to phototoxicity, which occurs when certain PAH compounds bioaccumulated in the tissues of receptor organisms are exposed to sufficient ultraviolet (UV) light to stimulate the formation of free radicals (Sellin Jeffries et al. 2013). The free radicals so formed can rapidly result in cell and tissue death, leading to the death of the organism. This is most likely to occur near the water surface, because UV light is attenuated with increasing depth in the water column by dissolved organic matter and suspended sediments. It is also more likely to occur during the summer months because day length and light intensity are greater, and light is not reflected or blocked by snow and ice, and in organisms such as juvenile fish that are small, weakly pigmented, and occur close to the water surface during daytime hours.

There are also sublethal effects on fish related to exposure to PAHs (including alkylated PAHs), avoidance of oiled areas, changes in feeding behaviour, developmental effects of PAH exposure on fish eggs and embryos, and delayed effects of such developmental effects such as reduced cardiac fitness in fish that survive embryonic exposure to crude oil (Lee et al. 2015, Incardona et al. 2015). Sublethal effects can include immune dysfunction (e.g., reduced macrophage activities), increased incidence of liver lesions (e.g., P450 [CYP1A] enzymes activity [specific hydrocarbon receptor]; Hudson et al. 2008), and other histopathological endpoints (Higgins 2002). Sublethal effects may also include behavioral endpoints such as impaired swimming in early life stages (Lee et al. 2015). The alkylated PAHs comprise 80 to 95% of total PAHs in crude and refined oils (Wang et al. 2003). They are less soluble in water, and take longer to dissolve in water, than the low molecular weight compounds. Oil stranded on or in sediments will continue to release alkylated PAHs to the water over weeks or months, resulting in ongoing exposure of fish to elevated PAH concentrations. However, within two weeks post-release, hydrocarbon concentrations in the water usually decrease to levels below which chronic effects to fish or other aquatic life would be expected (Stantec et al. 2012, Enbridge 2015).

Most species of fish can metabolize and excrete hydrocarbons, so these compounds do not bioaccumulate in the food web. Fish can rapidly take up water soluble low molecular weight hydrocarbons and release (depurate) them from their bodies when the source is removed (Hodson 2008). However, sensitivity to oil varies considerably among species of fish, related to differences in physiology, eating habits, biology, reproductive, and habitat preferences.

Although there are general trends in the relationship between concentrations of toxic compounds in various types of oils and their toxicity to fish, considerable variability has been identified in laboratory tests and field observations (Lee et al. 2015). For example, acute toxicity tends to be greatest for light crude oils (due to the high proportion of low molecular weight hydrocarbons they contain). Chronic toxicity tends to be greater for some heavy oils (particularly heavy fuel oils due to the high proportions of alkylated PAHs they contain). However, many exceptions have been noted and no definitive relationship between toxicity and concentrations of toxic compounds has been identified (Lee et al. 2015). Other factors that influence toxicity include the proportions of other high molecular weight compounds (e.g., waxes, resins, asphaltenes) that may help to determine physical characteristics of the oil (e.g., density, viscosity) that affect the physical behavior of the oil, as well as the bioavailability of the various classes of hydrocarbon compounds within the bulk oil.

Diluted bitumens contain both diluent (which may weather and disperse quickly) and bitumen (which is low in low molecular weight compounds and tends to persist in the aquatic environment). Chronic toxicity of bitumen is expected to be similar to that of conventional crude oils, given similarity in content of high molecular weight alkylated PAHs (Lee et al. 2015).

Exposure to oil stranded in sediments and related effects on abundance of benthic macroinvertebrate prey can lead to chronic and sublethal effects on fish, including effects on reproduction, growth and survival, which result in overall reduced fish production in areas affected by the release (reviewed in Dupuis and Ucan-Marin 2015 and Lee et al. 2015).

Table 7-33 and Table 7-34 provide a summary of the expected environmental effects of oil releases to fish. Table 7-33 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-34 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

7.1.3.4 Aquatic Plants

7.1.3.4.1 Description

Fassett (1957) defined aquatic plants as those that may, under normal conditions, germinate and grow with at least their base in the water, and that are large enough to be seen with the naked eye. For practical purposes, this definition provides a focus on aquatic vascular plants, and excludes unicellular algae. Filamentous algae can form large submerged or floating mats, and some macroalgae (e.g., the stoneworts, *Chara* and *Nitella*) common in hard water systems have the appearance and form of aquatic plants, but do not produce flowers, floating, or emergent leaves. Mosses, non-vascular plants that are often found in wet places (although not necessarily submerged), will be considered to be part of wetland ecosystems (e.g., bogs), and addressed elsewhere.

Aquatic plants provide many important ecosystem services.

- Energy Flow—aquatic plants are primary producers in the aquatic food chain, converting chemical nutrients in the water and soil into plant matter (Carpenter and Lodge 1986; Dodson et al. 2000).
- Food for Waterfowl and Fish—many submerged plants produce seeds and tubers that are eaten by waterfowl and other wildlife species. Insect larvae, snails, and crustaceans also thrive in plant beds, and these in turn serve as important foods for many wildlife and fish species (Valley et al 2004; MN DNR 2010a).
- Food and Medicinal Properties for Humans—many aquatic plants have been used traditionally for food and medicinal properties by humans. Wild rice (*Zizania aquatic*) is a grass, native to North America, which is an important traditional food to native Americans, and has become commercially important as well.
- Spawning Areas and Shelter for Fish—many fish species spawn in areas where aquatic plants grow or in marshy and flooded areas in early spring. During other times of the year, aquatic plants provide rearing habitat for juvenile fish, and cover for fish of all ages (Valley et al 2004; MN DNR 2010a).
- Improve Water Clarity and Quality—aquatic plants may help to maintain water clarity, and reduce erosion, by trapping suspended sediments and limiting the re-suspension of bottom sediments and some can absorb and break down polluting chemicals (Wolverton et al. 1975).
- Aesthetic Value—many aquatic plants such as reeds, cattails, water lilies, arrowhead, and pickerelweed have flowers or leaves that can be visually appealing in aquatic landscapes (MN DNR 2016a).
- Economic Value—as a natural and in some cases managed component of many water bodies, aquatic plants support the economic value of all aquatic related activities, including but not limited to camping, wildlife observation, hunting and fishing (MN DNR 2016a).

Freshwater aquatic plants are generally limited to shallow water or wetland habitats of lake and river systems.

7.1.3.4.1.1 Non-Vascular Plants

Algae have no true roots, stems or leaves and range in size from tiny, one-celled organisms to large, multi-celled plant-like organisms. Stoneworts (e.g., *Nitella* spp. and *Chara* spp.) are examples of algae that look much like vascular plants and may grow in similar conditions. Other algae bearing less resemblance to vascular plants are also common. Mats of filamentous algae (e.g. *Spirogyra* spp. and *Cladophora* spp.) may cover the bottom in dense blankets, form "clouds", or rise to the surface under certain conditions. Planktonic algae (phytoplankton), which consist of free-floating microscopic plants, grow throughout the well-lit surface waters of lakes, ponds, and rivers.

Aquatic moss beds occur primarily in the riverine system and in permanently flooded and intermittently exposed parts of some lacustrine systems. Mosses (e.g., *Sphagnum* spp.) are also a major structural component of true bog ecosystems. Aquatic mosses are less common than algae or vascular plants but can often dominate vegetation in lakes (Sand-Jensen et al. 1999). The dominant types found in Minnesota include genera such as *Fontinalis, Amblystegium, Fissidens*, and *Drepanocladus* (Moyle 1937).

7.1.3.4.1.2 Vascular Plants

Aquatic plants may occur at any depth within the photic zone, although light attenuation in most natural water bodies is such that the productivity of the aquatic plant community is greatest in shallow water. Most aquatic plants are angiosperms, meaning that they produce flowers that must be pollinated, which requires that they be able to produce flowers at or above the water surface. Aquatic plants that are rooted in sediments may have both submerged and floating leaves, and the form of such leaves may differ. Being supported by water, aquatic plants are often delicate or fragile, and they often occur in sheltered areas where there is little water movement. In flowing water environments, their form may be streamlined or flattened in response to water movement (Wetzel 1975). Typical submerged genera include pondweeds (*Potamogeton* spp.), tape grass (*Vallisneria americana)*, water milfoil (*Myriophyllum* spp.), waterweed (*Elodea canadensis*), pipeworts (*Eriocaulon* spp.), and quillworts (*Isoetes* spp.). Common floating-leaved taxa include water lilies (*Nymphaea, Nuphar*), and water shield (*Brasenia schreberi*). Dimorphic species with distinctive submerged, floating or emergent leaves include lotus (*Nelumbo lutea*), duck potato (*Sagittaria* spp.) and floating-leaf pondweed (*Potamogeton natans*).

Not all vascular plants in aquatic bed communities are necessarily rooted. Aquatic plant species that may form free-floating masses include coontail (*Ceratophyllum demersum*), bladderworts (*Utricularia* spp.), and ivy-leaved duckweed (*Lemna trisulca*). Some non-rooted plants float and are found in areas with little or no current. Examples include duckweeds (*Lemna* spp.) and watermeal (*Wolffia columbiana*).

Emergent vascular plants are those that are rooted in sediment below the water level (sometimes at considerable depth), and which project leaves into the air above the water. Examples include cattails (*Typha* spp.), rushes (e.g., *Juncus* spp.), grasses and reeds (including but not limited to wild rice, *Zizania aquatica* and reed grass, *Phragmites* sp.), sedges (e.g., *Carex* spp., *Scirpus* spp.) and others.

7.1.3.4.2 Observed Effects of Oil on Aquatic Plants

Published reports specific to the effects of released oil on freshwater aquatic plants that can grow in temperate environments absent associated spill response activities are few in number. However, the general effects of oil directly on plants and indirectly through their growing media have been reported from various sources including laboratory and field experiments, experimental oil spills, and case studies of accidental oil spills (although such studies include the associated effects of response activities). Available data sources include observed effects of oil releases in marine, freshwater, terrestrial, arctic, and temperate environments, upland and wetland vegetation, and controlled and uncontrolled settings. This body of published studies provides a framework for inferring the likely effects to aquatic plants that may result from spills of oil into different aquatic systems.

Oil that directly contacts aquatic plants in large quantity can impede photosynthesis and gas exchange processes by blocking sunlight, clogging stomata, and raising internal temperature (Baker 1970; Emerson 1983; Michel and Rutherford 2013; Pezeshki et al. 2000). In addition, toxic compounds in the oil may burn sensitive plant tissues. When these conditions are of sufficient extent and duration, the direct toxicity or indirect loss of metabolic processes may cause death of the tissues (e.g., leaves) and potentially death of the whole plant. Such “burning” effects are more marked with light oils (or gasoline) than with heavier oils while “smothering” effects are more prominent with spills of heavy oils which are thicker and relatively more persistent in the environment.

Oil which contacts plants but does not kill by smothering can cause damage through biophysical and biochemical means (Currier 1951; Dallyn 1953; Baker 1970; Emerson 1983; Shales et al. 1989; Pezeshki et al. 1998). When oil adheres to and spreads over the plant surface, toxic compounds from the oil may enter the plant through stomata, by damaging and passing through the cuticle, or by entering plant roots through the soil. The rate and extent of penetration is affected by the number of stomata, resistance of the plant cuticle or root epidermis, and the viscosity of the oil. Plants with few stomata and thicker cuticles tend to be more resistant to oil penetration. Once in the plant, petroleum compounds move through intercellular spaces then through cell walls and plasma membranes, reducing transpiration, photosynthesis, movement of materials from leaves to other tissues, and altering respiration (Currier 1951; Dallyn 1953; Baker 1970; Emerson 1983). Internal physical damage can result when cell membranes are damaged by penetration of hydrocarbon molecules, leading to leakage of cell contents (Baker 1970; Shales et al. 1989). Biochemical effects may result from inhibition of enzyme reactions by toxic components of the oil, especially PAHs and water soluble components of the oil such as the BTEX compounds which can affect submerged tissues (Baker 1970; Shales et al. 1989).

Aquatic plants may also be affected by oil indirectly through water and sediments. In addition, the presence of degradable organic matter in the oil can lead to an increase in oxygen demand which, if there is no additional aeration, may lead to oxygen depletion and anoxic conditions associated metabolic stress on aquatic organisms including plants (Shales et al. 1989; Kennedy et al. 1992; Summers et al. 2000; Edema et al. 2008; Edema 2012).

Potential damage to aquatic plants resulting from the incorporation of oil into sediment depends on the oil type and concentration. In general, light hydrocarbons have high acute toxicity to plants but, because of their rapid evaporation and/or dissolution, generally do not reach submerged sediments in concentrations which yield acute effects. Heavier hydrocarbon fractions have less acute toxicity to plants but can submerge and affect sediments due to their greater persistence in releasing toxic compounds (Shales et al. 1989; Overstreet and Galt 1995). Low concentrations of oil incorporated into soil and sediments have also, in some limited cases, been shown to stimulate growth of individual plant species perhaps by acting as a nutrient source or stimulator of nitrogen fixing organisms (Baker 1970; Snow and Rosenberg 1975a, 1975b; Burk 1977; Lin and Mendelssohn 1996; Mollard et al. 2012).

The type of waterbody can also affect the extent and duration of oil release effects to aquatic plants as a consequence of variations in dilution factors, flushing (or lack thereof), residence time, and aquatic plant community composition. Ponds and small lakes with standing water for example will have longer residence times, lower dilution factors, less physical disturbance, and greater magnitude and duration of impacts than large lakes or rivers characterized by large water volumes, wave action, and/or flushing (Baca et al. 1983, 1985).

Through its effects on individual plants, oil can alter plant communities by selectively killing or suppressing some plant species, allowing more tolerant species to colonize affected areas and become more abundant. Oil can also alter seed production, germination, and growth rates leading to further changes in plant community composition over time as a consequence of modified reproduction abilities (McCown and Deneke 1972; Burk 1977; Leck and Simpson 1992; Nicolotti and Egli 1998; Pezeshki et al. 1998; Pezeshki et al. 2000; Adam and Duncan 2002).

Currier and Peoples (1954) completed a laboratory study regarding the toxicity of hydrocarbons (n-hexane, hexene-1, cyclohexane, cyclohexene, and benzene) on various plants including the aquatic species elodea (*Anacharis canadensis)*. With respect to the elodea, saturated solutions of all the hydrocarbons except hexane killed quickly, at least within one hour. The hexane treated shoots showed no significant injury after 20 hours of exposure to the solution. Stepwise following trials led the researchers to conclude that: "On a per cent saturation basis, the increasing toxicity series is hexane, hexene, cyclohexane, cyclohexene, benzene. However, on a concentration basis the order is just the reverse."

Snow and Rosenberg (1975a, 1975b) studied the effects of experimental oil releases on the physical, chemica1, and biotic parameters of two sub-arctic lakes. Following the studies, they observed that:

> [T]he effects of crude oil on such lakes occur in three phases. The first is a period of acute toxicity which is of short duration (~ 2 days) and overlaps with a physically deleterious phase extending to several weeks. These effects may then

> be replaced by a chronic eutrophication, i.e., acceleration in rate of nutrient supply. The relative lengths and severity of each phase will be dependent upon such factors as volume of oil, type of oil, and climate.
>
> With respect to plant growth, periphytic filamentous blue-green algae were observed to have increased following the experimental oil spill, possibly in response to the addition of crude oil to the system as a nutrient source or stimulator of nitrogen-fixing organisms.

Hellebust et al. (1975) studied an experimental release of Norman Wells crude oil into Hanna lake near Norman Wells, NWT, Canada in order to evaluate the effects of crude oil on phytoplankton, periphyton, and attached macrophytes in terms of population composition, seasonal succession, and biomass. According to the researchers:

> The presence of crude oil had no significant effects on the total phytoplankton population, nor the seasonal succession of 20 common individual species except that some growth stimulation occurred in two blue-green algae, *Oscillatoria angustissima* and *O. tenuis.* Growth inhibition of the green alga *Ankistrodesmus braunii* was most noticeable at light intensities above and below those optimal for rapid growth. These findings show that the effects of an accidental oil spill on phytoplankton may be most serious if it occurs early or late in the growth season when temperature and light conditions are suboptimal for growth.
>
> In contrast to these minor effects of crude oil on phytoplankton abundance and species composition, algae growing on periphyton traps (i.e. species which normally grow on suspended particles or on the lake bottom) were strongly inhibited by the presence of oil. A probable reason for the inhibition of periphyton growth is that these algae, in contrast to the phytoplankton, were trapped on a solid substratum that also trapped oil components. The phytoplankton cells, which are free floating or swimming, were only exposed to dissolved oil components, which did not appear to be present in sufficient concentrations, possibly due to evaporation from the surface and microbial degradation, to cause significant adverse effects.
>
> Surface contact by crude oil of sedge, horsetail, and moss populations proved to be very damaging in terms of chlorophyll loss and extensive killing of the affected shoots. However, plant parts below the water level appeared to survive well, and this allowed considerable recovery of the plants by the next growing season.

Snow and Scott (1975) studied the effect and fate of Pembina and Norman Wells and crude oils respectively on Lakes 4C and 8 near Norman Wells, NWT, Canada. The researchers partitioned the lakes using plastic sheeting then introduced the crude oil to the center of one partition in each lake at a concentration of approximately 600 L/ha. With respect to aquatic plants, Snow and Scott found:

> The development of blue-green algae on experimental substrates in the areas of the lakes treated with crude oil was most striking. Coccoid blue-green algae were mixed with a dense mat of several morphologically different kinds of filamentous algae. Achlorophyllous filaments interwoven with the algae suggested that heterotrophic fungal filaments were present, although no fruiting bodies were observed. Blue-green algae were present in the control samples, though far less abundant. It is important to note that the samplers were at no time actually in contact with the oil in either lake; therefore, whatever the nature of the growth stimulant, it was present in the water itself. These data indicate that the presence of crude oil in a lake has a potentially eutrophying effect. The only dissolved nutrient measured which showed any significant change in the water of the oil spill section of each lake when compared to levels in the control areas following the spills was total dissolved nitrogen (TDN). … An increase in TDN in the oil spill sections of the lakes could occur through two main processes: firstly, by the dissolving of nitrogen contained in the oil itself, either by physical solution or via the intermediary of microorganisms, phytoplankton, or fungi; and secondly, from increased nitrogen fixation by indigenous oil stimulated lake biota.

Burk (1977) completed a four year study of vegetation following the release of approximately 1,000 gallons of fuel oil into a freshwater marsh within the Arcadia Wildlife Sanctuary near Northhampton, Massachusetts. At the end of the study, Burk reported that:

> Total plant cover, total number of species, mean number of species per quadrat and the Shannon-Wiener function progressively reduced in both high and mid-marsh zones for two years after the spillage. Eighteen of the species found before the spill were not found the following season. Perennial species generally were less affected than annual species immediately following the oil spill. Some species (e.g. *Dulichium arundinaceum* and *Eleocharis palustris*), declined in abundance the second season following the spill. Marked changes in relative abundance of the dominant species of high and mid marsh zones occurred from year to year, with *Onoclea sensibilis* more prominent in high marsh at the end of the study period than prior to the spill and *Pontederia cordata* and *Nuphar variegatum* more prominent in different segments of mid-marsh. The vegetation of the high marsh and mid-marsh zones had substantially recovered by the third and fourth years. The low marsh vegetation was apparently unaffected immediately following the oil spillage but in succeeding years the species diversity declined and luxuriant growth of *Elodea nuttallii*, *Potamogeton crispus* and *P. epihydrus* occurred.

Bott and Rogenmuser (1978) studied the effects of No. 2 fuel oil, Nigerian crude oil, and used crankcase oil to attached algal communities from Oldman's Creek, a tributary to the Delaware River in Glouster County, New Jersey. Communities were exposed to water extracts of the oils for five weeks during the summer and five weeks during the fall. After the treatments, the researchers reported that:

> In both experiments, No. 2 fuel oil extract reduced biomass visibly, which was confirmed by lower chlorophyll a concentrations than those of the control. Species changes also occurred; bluegreen algae became dominant and diatoms became less important in community composition. Exposure to used crankcase oil extract also depressed biomass but microscopic observations and pigment ratios indicated that changes in dominant algal types were less dramatic than those with No. 2 fuel oil exposure. Communities exposed to Nigerian crude extracts possessed biomass comparable to the control.

Kauss et al. (1973) completed a two-year field and laboratory study of the toxicity of crude oil (mixed sour blend and seven western Canadian crude oils) to phytoplankton. The site chosen for field experiments was a small, oligotrophic pond located about 500 ft from the eastern shore of Lake Huron, near Douglas Point, Ontario. At the end of the study, the researchers observed:

> Field experiments have shown that a varying response can be expected from freshwater phytoplankton exposed to crude oil pollution. The response varies from inhibition to stimulation of growth. This is probably due to the interaction of biological and physical variables. Examples of biological variables are: composition of the algal community, the relative susceptibility of individual species and the availability of oil-degrading organisms. Physical factors would include the nutrient status of the water body, conditions of wind, temperature, insolation, etc.
>
> Experiments with *Chlorella* and *Chlamydomonas* have shown that a large part of the toxicity of aqueous crude oil extracts is due to compounds which are rapidly lost by volatilization. These compounds result in decreased growth and bicarbonate uptake of algal cells. These results suggest that the major toxicity of oil spills would be of short duration (considering only the effects of water soluble components).
>
> Marked stimulation of *Chlorella* growth in some oil extracts occurred after loss of toxic compounds. This may represent bacterial contamination of the oil extracts or an actual ability to utilize certain hydrocarbons. Literature evidence suggests the latter. It is noteworthy that the extract which most stimulated growth was outboard motor oil, composed mainly of paraffinic hydrocarbons. It is unlikely that the response of *Chlorella* and *Chlamydomonas* to water soluble components of oils is representative of all freshwater algae. Indeed, *Chlorella* may well be an oil tolerant species.

Ren et al. (1994) investigated the photoinduced toxicity of crude oil constituents (fluoranthene, pyrene, and naphthalene) to duckweed (*Lemna gibba*) in a laboratory setting. The researchers found that fluoranthene and pyrene had a linear rate of growth inhibition with a threshold of impact at 0.5 µg/ml and a 50% of inhibition growth at 16 µg/ml. Conversely, naphthalene appeared essentially nontoxic to the duckweed, perhaps as a consequence of its greater volatility. The researchers then tested whether light intensity would modify the toxicity results and found that ultraviolet light enhanced the harmful effects of the chemicals. Based on these findings, they reported that:

> It is apparent that light will significantly increase they phytotoxicity of fluoranthene, pyrene, and naphthalene. Toxicity was increased both when the plants and the chemicals were incubated together and when the chemicals were pretreated with light then incubated with plant tissue. The only region of the solar spectrum that effectively enhanced toxicity was the UV. The order of toxic strength of the PAHs was correlated with the rate of photomodification of the chemicals thought it is suggested that the chemicals have photosensitization activity in the intact form as well.

McGlynn and Livingson (1997) studied the distribution of PAHs between aquatic plants and sediments using water hyssop (*Bacopa caroliniana)* and threadleaf arrowhead (*Sagittaria stagnorum*). The researchers found that:

> The effects of sediment PAHs (greater than 10 ppm) on growth were significant for both species. New growth of *B. caroliniana* was inversely associated with sediment PAH concentrations. The biomass, old growth, and new growth of *S. stagnorum* were also inversely related to sediment PAH concentration.
>
> PAHs are assimilated by the root systems of aquatic macrophytes and that the assimilation exhibits saturation effects and the presence of PAHs in the shoots of these plants is the result of root to shoot transport. Rooted rosette monocots assimilated significantly fewer PAHs from the sediments than did rooted vittate dicots. These differences might be attributed to the lignified structure of the dicot root system, and it might be inferred that this lignification leads to a reduction of either PAH binding sites or PAH entry channels. The lake data also indicate that nonrooted plants behave quite differently from rooted plants in that their PAH loads do not seem to correlate with sediment PAH concentrations.
>
> Aquatic plants grow well at sediment PAH concentrations over 1,000 times as concentrated as the sediment PAH concentrations at which aquatic fauna exhibit toxicological effects. At low sediment PAH concentrations, aquatic plants commonly achieve PAH tissue concentrations that exceed the sediment PAH concentrations. At high sediment PAH concentrations; however, aquatic plants cease to bioaccumulate sediment PAHs.

Marwood et al. (2001) studied the effects of coal tar creosote-derived PAHs on the growth of duckweed (*Lemna gibba*) and water milfoil (*Myriophyllum spicatum*) by measuring photosynthetic activity. The researchers reported that:

> The PAHs caused a 50% growth reduction in duckweed and milfoil at concentrations of 7.2 mg/L and 2.6 mg/L respectively. The results of this study using the PAM fluorescence technique support previous studies of PAH effects on electron transport. The different responses of the various chlorophyll-*a* fluorescence parameters, when taken together, support a mechanism of PAH toxicity in which photosynthetic efficiency was impaired as a result of general damage to essential cellular components, possibly from reactive oxygen species. Based on the loss of leaf chlorophyll in plants exposed to low PAH concentrations, destruction of chlorophyll pigments is apparently an important mechanism of PAH toxicity in plants and may precede damage to the proteins of the photosynthetic apparatus.

Akapo et al. (2011) studied the morphological and anatomical effects of Forcados Mix Nigerian crude oil at concentrations ranging from 10 to 100 ppm on water lettuce (*Pistia stratiotes*). Following the study, the researchers made several observations:

> The growth of water lettuce (*Pistia stratiotes*) is retrogressively affected by crude oil, and the effect is dependent on the concentration of crude oil in environment. All physical growth parameters measured (such as number of leaves, root length, leaf area, and number of sprouts) declined during growth in the presence of crude oil. The decline was shown to be concentration dependent. The THC accumulated in the roots was greater than in the leaves for all treatment and the roots of plants exposed to various concentration of crude oil were observed to shrink and detach. Shrinking was also concentration dependent. The rate of accumulation of lead and manganese and the total hydrocarbon content (THC) was seen to be greater at low concentrations and the rate decreased as concentration increased.

Lopes and Piedade (2014) performed an experimental study on the survival and response of water hyacinth (*Eichhornia crassipes*) when exposed to Urucu light Brazilian crude oil. The study applied six different oil doses ranging from 0 to 150 mL/L and five exposure times ranging from 1 to 20 days. Results of the study showed an inverse relationship between increasing concentrations of oil and exposure times, plant survival, and the number and sizes of leaves. The factors also interacted such that the effect of both together was larger than each individually. Anatomical modifications and alterations in cell organization were also observed in plants exposed to high concentrations. The researchers concluded that:

> Dose and time of exposure are two of the most important factors controlling the effects of Urucu petroleum hydrocarbons on *E. crassipes*. While relatively low

> doses of oil may cause a reduction in the number of leaves and plant biomass, high doses can even cause death of the plants. The lower dose of Urucu oil tested, 3 mL/L, did not cause significant alteration in morphology and biomass of the plants. Moderate oil doses, 12.5 and 25 mL/L, caused an increase in dead biomass and a decrease in the ratio of live/dead biomass and number of leaves. When exposed to high doses, 75 and 150 mL/L, the decline in biomass and increase in plant mortality were intensified.

7.1.3.4.3 Expected Effects of Oil on Aquatic Plants

The effects of crude oil releases on aquatic plants depend upon the type of habitat into which the oil is introduced, as well as the type of oil and quantity released. In some cases (e.g., submerged weed beds), contact between released oil and aquatic plants may be avoided altogether. However, when contact does occur, aquatic plant response to oiling depends on the amount of the plant that is oiled, the resistance of the particular plant or plant tissue to petroleum compounds, the type of oil, and the duration of contact. Contact between crude oil and unprotected green tissues can be assumed to result in tissue (e.g., leaf) death, and potentially death of the whole plant. Plant stems may be protected by waxy cuticles, bark, or multiple layers of leafy material so that contact between oil and the plant stem may not result in serious harm to the plant.

Where aquatic plants are affected by oil, some general longer-term patterns resulting in community-level effects may also be expected:

- A reduction in aquatic plant growth while exposed to oil constituents (Burk 1977; Lin and Mendelssohn 1996; McGlynn and Livingston 1997; Marwood et al. 2001; Akapo et al. 2011; Mollard et al. 2012; Lopes and Piedade 2014)
- An increase in algal biomass and shifts in community composition (Snow and Rosenberg 1975a, 1975b; Hellebust et al. 1975; Snow and Scott 1975; Bott and Rogenmuser 1978; Kauss et al. 1973)
- A reduction in the relative abundance of floating plants, and increase in abundance of submerged aquatic plants such as *Elodea, Potomogeton,* and *Ceratophyllum* (Burk 1977)
- A reduction in the relative abundance of annual plants (Burk 1977; Leck and Simpson 1992)
- A decrease in overall community diversity, with a shift in dominance to more oil-tolerant species (Snow and Rosenberg 1975a, 1975b; Hellebust et al. 1975; Snow and Scott 1975; Burk 1977; Bott and Rogenmuser 1978; Kauss et al. 1973; Lin and Mendelssohn 1996; Marwood et al. 2001)

Light refined oils with high amounts of water-soluble fractions can cause acute mortality to aquatic plants, but these oils are likely to disperse and weather rapidly so that the effects may be short-lived (NOAA and API 1994). A spill of light crude oil or refined products would be expected to result in the death of most floating plants that come into direct contact with the material. Rooted floating-leaved plants would likely suffer growth reductions and dieback for one or two growing seasons but not outright mortality (Hellebust et al. 1975; Burk 1977; Lin and Mendelssohn 1996). Algal species, aquatic mosses, and submerged plants in the vicinity of a surface oil slick, but not in physical contact with the oil on the water surface, might suffer minimal damage from dissolved chemical constituents of the oil (Hellebust et al. 1975; McGlynn and Livingson 1997).

Heavier oils tend to coat vegetation, although the vegetation may survive if the roots are not affected (Hellebust et al. 1975; Burk 1977; Baca et al. 1985; Lin and Mendelssohn 1996). These oils can persist for longer periods and may sink under certain conditions (e.g., due to formation of OPAs). Light oils may be more prone to formation of true OPAs, due to their lower viscosity and greater tendency to form small droplets entrained in the water column under turbulent flow conditions. However, this process also enhances microbial degradation of crude oil, and light crude oils tend to be less persistent than heavy crude oils. Oil that becomes incorporated into bottom sediments might affect plant roots (NOAA and API 1994).

Algal species, aquatic mosses, and submerged plants would likely suffer little or no damage unless the oil became submerged or sank. Some algae (e.g., cyanobacteria) may experience growth increases, likely in response to alteration in the availability of key plant nutrients.

Submerged aquatic plants contacted by submerged or sinking oil could experience reductions in growth. Should the oil be extensive and/or persist for an extended period, the plants could die and the oil could impede growth of new vegetation from the sediment. Where plants are damaged but not killed, regrowth in a growing season or two is likely for perennial plants while annual plants may require longer to recover, depending upon the timing of the spill with respect to seed set, as well as seed dispersal mechanisms and the extent of representation in the existing seed bank (Baker 1971; Burk 1977; Shales et al. 1989; Pezeshki et al. 1998).

Annual plants (e.g., wild rice) may be more severely affected, likely as a consequence of oil effects to seeds, seedlings, and/or reproductive organs that disproportionately affect species that rely on seeds for yearly growth (Baker 1971; McCown and Deneke 1972; Burk 1977; Shales et al 1989; Leck and Simpson 1992; Adam and Duncan 2002).

Perennial aquatic plants appear to be at least somewhat tolerant of dissolved oil constituents (Baker 1971; Burk 1977; Kauss et al. 1973; Baca et al. 1985). Therefore, some species of perennial rooted and floating plants, may experience some growth reduction but not death where toxic water soluable factions (WSFs) are in moderate to high concentrations, or in low concentrations for extended periods of time, as could be the case where there is submerged heavy oil (Snow and Rosenberg 1975a, 1975b; Hellebust et al. 1975; Snow and Scott 1975; Bott and Rogenmuser 1978; Kauss et al. 1973). There would likely be a short-term loss of productivity from diminished photosynthetic activity and growth (Carr et al. 1997). Short term reproduction is likely to be curtailed somewhat from spills during the growing season where there are energy losses and damages to reproductive structures.

Table 7-35 and Table 7-36 provide a summary of the expected environmental effects of oil releases to aquatic plants. Table 7-35 considers the effects of specific oil characteristics or oil type on the expected type and scope of environmental effects. Table 7-36 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-35 Biological Receptor: Aquatic Plants

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Comments
Density	Light crude oils have low density, and generally float on the water surface, where they can contact floating and emergent aquatic plants, or plants in shallow water along shorelines, while weathering rapidly. Even weathered light crude oil residues will normally float on fresh water. However, the WSF of oil may enter the water column.	Medium crude oils have intermediate density, and will float on the water surface, where contact with floating and emergent aquatic plants is likely. Medium crude oils will weather more slowly than light crude oils. These oils generally have a lower WSF than light crude oils.	Heavy crude oils generally have density values lower than that of fresh water, and will float if spilled. However, as they weather, their density may increase over time so that they eventually exceed the density of fresh water. Such oils would typically have high viscosity, and will not readily become entrained into the water column as fine droplets. Heavy crudes have the lowest WSF, so little dissolution is anticipated. However, these oils can form OPAs if the oil travels over soils or is discharged into waters with high suspended sediment loads and is well-mixed. OPAs which exceed a specific density of 1 may sink.	Fresh diluted bitumens have a density that should not exceed 0.94, although density will increase and may slightly exceed the density of fresh water given sufficient exposure to the elements, or formation of OPAs. With weathering, the viscosity of diluted bitumen increases rapidly, so that it becomes increasingly resistant to the formation of small droplets in turbulent water.
Viscosity	Light crude oils have low viscosity and may readily become entrained into the water column as small droplets by breaking waves. Low viscosity oils are more readily absorbed into plant tissues, causing acute damage. However they also have a lesser tendency to adhere to plants, and are less likely to persist in water and sediment resulting in relatively lower long-term chronic damage to associated plant communities.	Intermediate environmental behavior and effects based on specific oil constituents.	Greater tendency to adhere to plants causing smothering. Higher potential to sink and be persistent in sediment causing long-term chronic toxicity damage to associated plant communities.	Diluted bitumens that contain volatile diluents (e.g., gas condensate) can have similar concentrations of low molecular weight hydrocarbons to light crude oils.
Proportion of low molecular weight VOCs	Light crude oils usually contain a larger proportion of VOCs than heavier crude oils. The VOCs (which include mono-aromatic hydrocarbons such as the BTEX compounds) are potentially damaging to plant tissues on direct contact.	Intermediate acute toxicity depending upon relative proportion of BTEX and other low molecular weight hydrocarbons.	Heavy crude oils of natural origin may contain relatively low concentrations of BTEX and other low molecular weight hydrocarbons.	Diluted bitumens that contain volatile diluents (e.g., gas condensate) can have similar concentrations of low molecular weight hydrocarbons to light crude oils.

Table 7-36 Biological Receptor: Aquatic Plants

Environmental Characteristic	Low	Medium	High	Comments
Plant growth form	Submerged forms avoid direct contact with floating crude oil on the water surface. Submerged plants may suffer some indirect damage from water column contact with WSFs.	Free-floating plants would be killed if contacted by released oil. However, these plants also disperse readily, and can reproduce quickly by vegetative means. Floating-leaved rooted plants may suffer damage to leaves from direct contact with oil at the water surface, but may avoid damage to roots and rhizomes, allowing re-growth from root systems.	Leaves of emergent plants are typically protected from contact with released crude oil, and the limited contact of oil with stems at water level may not result in plant death. Many emergent plants also have energy storage tissues in the roots, and can survive damage to above-water tissues.	Wild rice is an annual emergent plant (a type of grass). It is possible that an oil spill that occurred as shoots were emerging from the water could result in tissue or plant death. Otherwise, if a release of crude oil occurred earlier or later in the growing season, wild rice plants might not be seriously affected. Plants having thick cuticles and/or few stomata would be less sensitive to released crude oil than plants with thin cuticles and/or many stomata.
Water depth	Shallow water provides less scope for dilution of water soluble fractions of crude oil, however, plants are not particularly sensitive to the water soluble fraction. However, a large proportion of plants in shallow water may be free-floating or have floating leaves, making them more susceptible to crude oil exposure on the surface.		Deep water provides greater dilution of WSFs. Plants located in deep water are more likely to have mainly submerged growth form, which would have low exposure to crude oil on the surface.	
Water currents	Stagnant or ponded areas provide little flushing and dispersal of released crude oil or water soluble components of the oil. This may result in greater oil thickness on the water surface, and longer duration of exposure for both floating and submerged aquatic plants.		Habitats with moving water (rivers) or water circulation (large lakes) provide greater flushing and dispersal of crude oil. Although larger areas of habitat may be affected, oil slicks may be thinner, and exposure may be of shorter duration.	During the Marshall, Michigan release of heavy crude oil to the Kalamazoo River in 2010, deposition of crude oil to sediments occurred mainly in areas of still water.
Plant lifespan	Annual plants that generally rely on seed production tend to be more sensitive to the presence of oil. If seed is not set, then these plants may not be able to grow in the following season (e.g., wild rice).		Perennial plants are more resistant to damage than annual plants. Even when vegetative tissues are damaged, perennial plants can re-grow from the root system, often within the same growing season.	Many aquatic plants have several means of reproduction, including seed production, root spreading and production of new shoots from rootstock, and vegetative reproduction from plant fragments that drift into new and potentially favorable habitats.
Plant age	Young plants may be susceptible to damage because they generally have more sensitive tissues, and have fewer energy stores.	Annual plants exposed to crude oil prior to seed set may still be sensitive, if the oil exposure prevents or inhibits seed set.	Mature rooted perennial plants would be less susceptible to damage because their roots would have low exposure to released oil, and are the site of energy storage from which the plant could re-grow. Annual plants post seed set would have low sensitivity as these plants would be senescent, and dying in any case.	

7.1.3.5 Amphibians and Reptiles

7.1.3.5.1 Description

Amphibians and reptiles are considered together as a group in this study because both classes of vertebrates are ectothermic (i.e., cold-blooded) species. In Minnesota, amphibians include frogs, toads, salamanders, and newts; and reptiles include snakes, lizards, and turtles. Effects of releases from oil pipelines are typically greatest in aquatic and riparian environments (NAS 2016); given that lizards and snakes are primarily terrestrial species with little or no association with aquatic environments, this assessment focuses on amphibians and turtles.

There are three key differences between reptiles and amphibians that have implications for potential effects of hydrocarbon releases. First, amphibians have porous skin that generally requires that they inhabit areas near water or damp environments; their porous skin may also facilitate dermal absorption of contaminants, an important exposure route. Reptiles have scaly, keratinous skin or shell (i.e., turtles) that is not porous and enables them to live in arid or hypersaline environments. Second, amphibians lay eggs that do not have a thick protective membrane or shell. Their eggs are laid in aquatic environments where they may absorb dissolved contaminants. Many amphibians are also external breeders meaning sperm is expelled into the aquatic environment and swim to eggs (Vitt and Caldwell 2013). In contrast, reptilian eggs have a leathery or shell membrane, and are laid in burrows where they are less predisposed to direct contaminant exposure. Some snakes do lay live young (viviparous) in cold climates (Vitt and Caldwell 2013). Finally, amphibians hatch from their eggs as tadpoles that are entirely aquatic with rudimentary gills used for respiration underwater. These juvenile amphibians undergo metamorphosis to become adults that are semi-aquatic organisms. On the other hand, juvenile reptiles hatch as small versions of their adult counterparts and are fully independent and capable of inhabiting aquatic or terrestrial environments.

As ectothermic individuals, amphibians and reptiles undergo a winter dormancy period when temperatures drop below approximately 41 to 45°F (Obbard and Brooks 1981; Tattersall and Ultsch 2008). Most aquatic reptiles and amphibians overwinter by burying themselves in mud and sediment of shallow lakes and wetlands. However, even in northern temperate regions some amphibians (e.g., ranid frogs) remain active in underwater environments where they are dependent on respiratory gas exchanges with the aquatic environment (Tattersall and Ultsch 2008).

As a group, amphibians and reptiles are omnivorous with some species' having a diet consisting primarily of invertebrates, and some species that are more predatory/carnivorous, while others subsist to a greater degree on vegetation. Juvenile reptiles typically feed on smaller prey (plant or animal) of the same trophic order as their adult counterparts; however juvenile amphibians (e.g., tadpoles) are more herbivorous and subsist on algae in early development (Kupferberg 1997).

Amphibians and aquatic reptiles typically respond to stressors through avoidance escape behavior seeking shelter in aquatic vegetation and benthos (Licht 1986). This avoidance may result in fewer amphibians and reptiles observed being affected by hydrocarbon releases. Unlike fish that will float to the surface when dead because of their air bladder, amphibians and reptiles will likely sink to the bottom and go undetected. Frogs are also prey for many species of fish, mammals, birds, other amphibians and reptiles, which could result in rapid scavenging of amphibians in some environments post-release.

There are no federally-listed amphibian or reptile species known to occur in Minnesota (USFWS 2016). However, under Minnesota's Endangered Species Statute (MN DNR 2013) there are 2 species listed as "endangered," 4 as "threatened," and 10 as "special concern." Of the semi-aquatic amphibian and turtles considered in this receptor group, Minnesota Endangered Species include:

- Northern cricket frog (*Acris blanchardi*) Endangered
- Blanding's turtle (*Emydoidea blandingii* Threatened
- Wood turtle (*Glyptemis insculpta)* Threatened
- Spotted salamander (*Ambystoma maculatum*) Special Concern
- Great Plains toad (*Anaxyrus cognatus*) Special Concern
- Four-toed salamander (*Hemidactylium scutatum*) Special Concern
- Mudpuppy (*Necturus maculosus*) Special Concern

7.1.3.5.2 Observed Effects

A review of several hydrocarbon releases from pipelines, and one resulting from a rail car accident, provided an overview of observed effects of releases on amphibians and reptiles in similar aquatic environments (e.g., river, lakes and wetlands) to those encountered in Minnesota. This review is not exhaustive, but provides a range of observed effects on amphibians and reptiles under different environmental conditions. While some of the case studies involve releases of light or medium crude oils, the effects are taken in context of the differences in properties of the oil types and provide some contrast of the potential effects among different oil types.

> ***Exxon Bayway****: On January 2, 1990, an Exxon underwater pipeline released approximately 13,500 barrels of No 2 heating oil into the Arthur Kill waterway at the mouth of Morse Creek between New Jersey and Staten Island, New York (NOAA 1992). Initial response efforts focused on containment of the release as well as removal of the larger masses of oil. Concentrations of floating oil and mousse in the open water, primarily between Howland Hook and Fresh Kills, were collected by self-propelled skimmers. Oil concentrated and stranded above the berm on the beaches from Cedar Point to Rossville. Environmentally sensitive areas were protected with boom and skimmers that collected the larger masses of free-floating oil. By February 20, 1990, monitoring crews reported nine terrapin turtles captured and released among other affected wildlife (NOAA 1992).*

***Lakehead**: On March 3, 1991, a Lakehead Pipeline Company, Inc. owned pipeline ruptured and released over 40,000 barrels of crude oil (NOAA 1992) approximately 2 miles north of Grand Rapids. Some of the oil flowed onto the 18 in. thick ice sheets on the Prairie River. Oil formed into 8-inch deep pools on top of the ice and was also present under the ice. Vacuum trucks were used by clean-up personnel to remove the oil from the ice surface. Workers used squeegees to push the oil along the ice to a removal location. Booms were used on the river by cutting a slot through the ice cover with chainsaws. Ice that had been permeated with oil was chopped into blocks small enough to be carried away to a separate part of the river. Clean-up personnel sprayed the ice blocks with hot water to wash out the oil, which was then recovered with skimmers. Blocks that were only slightly contaminated were moved to lined holding tanks and broken up. The crushed ice was then allowed to melt to recover residual oil. There were no reports of amphibians or reptiles injured during the post-release clean-up and monitoring, though the area would have been inhabited by several species. Overall effects to fish and wildlife were reported as minimal by the MN DNR (Telegraph Herald 1991), likely due to ice-covered conditions at the time of the release.*

***OSSA II:** On January 30, 2000, an estimated 29,000 barrels of mixed heavy crude oil and diluent (density of approximately 0.8 g/mL) were released from the OSSA II pipeline, operated by Transredes S.A., at the Rio Desaguadero river crossing in Bolivia as the river was rising to peak flood conditions (Lee et al. 2001, 2002; Owens and Henshaw 2002). Due to the very high river flow and water velocity conditions, and perhaps also due to the low viscosity of the oil, which would allow it to become dispersed into the water as fine droplets, oil was found up to 230 miles downstream from the release location. For the most part, the surface oil was deposited in strips, generally 3 to 6 ft wide and up to 0.5 to 1 inch thick. Many sections of river bank had a horizontal line of oil, "a bathtub ring" where the oil was deposited and stranded indicating the water level at the time (Owens and Henshaw 2002). The response effort included more than 3,600 people that recovered the oil within three months. Wasson et al. (2000 in Owens and Henshaw 2002) reported on the wildlife effects of the release and indicated that no wildlife fatalities other than a small number of birds were observed during the extensive post-release monitoring and clean-up.*

***Tinicum:** On February 5, 2000, a Sunoco pipeline cracked in Tinicum, Pennsylvania, releasing approximately 4,575 barrels of crude oil (USFWS 2009). The pipeline rupture was located at the eastern end of the John Heinz National Wildlife Refuge and flowed onto an ice-covered freshwater impoundment (Saba and Spotila 2003). It took approximately one month for clean-up crews to recover the oil, and before that was achieved, by February 17, the ice on the impoundment started to melt in some areas exposing aquatic species to the oil. Turtles started emerging and becoming coated in oil remaining on site before recovery had been completed. Tri-state bird rehabilitation center was contracted to recover, clean and rehabilitate oiled turtles. In total, there were 19 oiled turtles captured at the site. All captured turtles were cleaned, and* *monitored for one month during which time only one turtle died from apparent crude oil inhalation (Saba and Spotila 2003). The remaining 18 turtles were used in a study, along with a control group of turtles not exposed to oil to assess effects of oil exposure on survival and behavior. No effects of oil exposure were noted and the 18 turtles released survived (Saba and Spotila 2003). In total there are 19 species of reptiles and amphibians that use the John Heinz National Wildlife Refuge, but only the 19 individuals of four species of turtles were reportedly affected by the release.*

Pine River: *On August 1, 2000, a pipeline operated by Pembina Pipelines failed and released approximately 6,200 barrels of light crude oil, of which an estimated 2,800 barrels entered the Pine River 70 miles upstream of Chetwynd, British Columbia. An estimated 300 to 710 barrels remained unaccounted for following the clean-up and remediation (BC MOE 2000a). Most of the unaccounted for oil was considered to be likely entrained in sediment or debris within the river. Response measures included placing two containment systems: one approximately 14 miles downstream and a second approximately 19 miles downstream (BC MOE 2000c). The river was flowing at a low stage at the time of the release (approximately 5,680 ft^3/s measured at a station 100 miles downstream, compared to flow rates above 31,880 ft^3/s during late spring and early summer). The Pine River has a gradient of approximately 0.225% in the first 25 miles downstream from the release location, decreasing to 0.1% farther downstream. There were reports from government staff and contracted clean-up crews of oiled wildlife (all birds), but no oiled amphibians or reptiles were reported (BC MOE 2000b).*

Wabamun Lake*: On August 3, 2005, a Canadian National freight train derailed near the Village of Whitewood Sands, Alberta, releasing approximately 4,500 barrels of Bunker C fuel oil (Heavy Fuel Oil 7102; Hollebone et al. 2011) and 550 barrels of pole treating oil. An estimated 950 barrels of the Bunker C oil entered Wabamun Lake and formed a thick black slick approximately 0.5 in. thick (Wernick et al. 2009).*

While traveling overland, the oil mixed with soil and organic matter, and in the lake, OPAs formed quickly, including small tar balls, larger tar "logs", submerged sheets, and large lumps (Fingas et al. 2006; Hollebone et al. 2011). The oil-sediment complexes exhibited a variety of behaviors including submergence, neutral buoyancy, and resurfacing (Fingas et al. 2006).

No dispersions of oil in water were observed in the lake, and no mousse formation was reported in the three years following the release (Hollebone et al. 2011). Overall, the water in the open water area of the lake was reported not to be contaminated with released hydrocarbons or associated metals (Anderson 2006). This is consistent with the very low concentration of relatively water-soluble components (such as BTEX) in the released oil, and the relatively low water solubility of this heavy oil. Similarly, sediments beneath the open water portions of Wabamun Lake were reported not to have been *contaminated with petroleum hydrocarbons and were considered to be of similar quality to concentrations measured in 2002 or shortly before the release (Anderson 2006).*

Clean-up activities included cutting of the vegetation and vacuum removal of submerged tar balls entrained in the reed bed detritus (Wernick et al. 2009). A two year study was conducted to assess regrowth. The study found that exposure to the oil, which was released in the late growing season, did not cause large-scale changes to these emergent plant communities (Wernick et al. 2009). Physical factors such as clean-up activities and vegetation management appeared to be responsible for reduced regrowth observed at some locations (Wernick et al. 2009; Thormann and Bayley 2008). Despite an intensive wildlife monitoring program, and a wildlife recovery center set up immediately after the release, there were no reports of amphibians or reptiles injured by the oil (TSBC 2007).The area would have been inhabited by several species of amphibians and reptiles.

***Glenavon**: On April 15, 2007, a release occurred on the Enbridge Line 3 pipeline approximately 1 mile downstream of the Glenavon pump station near Glenavon, Saskatchewan. The rupture released approximately 6,200 barrels of heavy crude oil and affected approximately 5 acres of a wetland on farmland (TSBC 2008a; SLR Consulting 2008a). Within two days of the release, approximately half of the crude oil had been recovered (Canada.com 2007a). In April 2007, surface water samples from the affected wetland exceeded applicable guidelines for hydrocarbons and total metal concentrations and background, and exceeded concentrations from nearby reference wetlands (SLR Consulting 2008a). As remediation actions, the affected surface water (approximately 1.8 million gallons) was collected and disposed in approved wastewater facilities (SLR Consulting 2008a). These activities were complete in early May 2007, and surface water samples conducted in August had concentrations below guidelines (SLR Consulting 2008a). The site was monitored for one week for exposure of wildlife to oil, and wetlands within 0.6 miles (1 km) were surveyed for any wildlife that may have been oiled initially and moved away from the release site. The only reported injured wildlife were birds (SLR Consulting 2008a); there were no reports of injured or dead amphibians or reptiles, though amphibians would have inhabited the wetland.*

***Marshall**: On July 25, 2010, Enbridge's Line 6B pipeline experienced a release in a wetland near Marshall, Michigan. Approximately 20,000 barrels of heavy crude oil containing diluted bitumen were released over a period of about 17 hours. The pipeline contained two different batches of crude oil at the time of the release. It is estimated that the released oil consisted of approximately 77% CLWB diluted bitumen and 23% Western Canadian Select, also diluted bitumen (NTSB 2012a). Of this, approximately 8,200 barrels reached Talmadge Creek and the Kalamazoo River (Enbridge 2013a). Talmadge Creek was flowing with higher than normal flow due to recent heavy rains. The crude oil flowed down Talmadge Creek to the confluence with the Kalamazoo River, and then into the Kalamazoo River. Due to the elevated water level, the crude oil affected* *floodplain areas on both sides of Talmadge Creek. The river was also high at the time of the release and had overflowed its banks in many areas. As a result, oil entered the floodplain areas. As water levels in the river receded, much of the crude oil flowed with the flooding water back within the banks of the Kalamazoo River, although crude oil also became stranded in hydrologically isolated areas such as depressions, cavities, burrows, and other traps within the riparian zone (Enbridge 2013a). These conditions resulted in oil being stranded in areas that would be suitable habitat for amphibians and reptiles. As a result, 106 reptiles were found dead or subsequently died during rehabilitation, and approximately 3,931 turtles and 73 amphibians were captured, treated and released (USFWS et al. 2015a). Many (over 600) of the oiled and captured turtles were recaptured at least once, which suggests that the oiling effects were relatively benign (Lee et al. 2015). The primary species affected were common map turtles (77%), snapping turtles (11%), painted turtles (6%), and eastern spiny softshell turtles (3%). Other species included common musk, Blanding's, eastern box, and spotted turtles (USFWS et al 2015 a).*

***Rainbow Pipeline, Alberta, Canada**: On April 28, 2011, approximately 28,300 barrels of sweet crude oil were released from a Plains Midstream Canada pipeline into a muskeg/stagnant water area near the community of Little Buffalo in the Peace River region of Alberta. The release occurred on a hillside, and the oil flowed a half mile down the pipeline ROW and pooled in a low-lying area containing abandoned beaver ponds. The release encompassed an area of approximately 20 acres (ERCB 2013). During response activities, perimeter fencing and wildlife deterrents (including eagle kites and bear-scare canyons) were used to prevent wildlife from entering the release site (ERCB 2013). However, over the course of the following 18 months (i.e., by November, 2012) 12 amphibians (11 frogs and one toad) were found deceased (ERCB 2013). No cause-of-mortality analysis was conducted for the deceased wildlife, but it is presumed that oiling was the likely cause.*

***2011 Yellowstone River**: On July 1, 2011, flood conditions in the Yellowstone River resulted in a release from the ExxonMobil Silvertip Pipeline near Laurel, Montana. Riverbed erosion had exposed the 12 inch pipeline beneath the crossing, and debris caught on the washed-out pipeline caused excessive stress, resulting in a clean break. The failure was detected at the pipeline control center and the line was shut down within 10 minutes (USDOT 2012). Approximately 1,500 barrels of medium sour crude oil were released into the Yellowstone River (USDOT 2012). High flood flows carried the oil downstream and prevented it from settling on the river bottom. Crude oil affected primarily shorelines and banks immediately downstream of the release site (MT DEQ 2015b). A pocket of emulsified oil was found approximately 72 miles downstream, but the majority of the release effects were observed within 20 miles of the release location (USEPA 2011). Search efforts found two toads that were captured and cleaned and two additional oiled toads and one garter snake were observed, but not captured (USEPA 2011).*

***Red Deer River**: On June 7, 2012 a Plains Midstream Canada ULC (Plains) pipeline released, as a result of high water levels in the river, approximately 2,900 barrels of light crude oil into the Red Deer River downstream of Sundre, Alberta (AER 2014). The migration of visible oil was stopped by booms placed at Gleniffer Lake, but dissolved hydrocarbons continued to move downstream. This resulted in potential toxic and oiling effects upstream of the booms, and toxic effects downstream of the booms in Gleniffer Lake (Teichreb 2014). Officials with Alberta Environment indicated that effects to wildlife were minimal (Derworiz 2012). During the post-release clean-up, there were no reports of amphibians or reptiles injured and monitoring, though the area would have been inhabited by several species of amphibians and reptiles.*

***Line 37**: On June 22, 2013, unusually heavy rains resulted in ground movement that compromised the integrity of the Enbridge Line 37 pipeline, approximately 1 mile north of the terminal in Cheecham, Alberta. The resulting failure released approximately 1,300 barrels of synthetic light crude oil underground with some oil seeping to the surface where it flowed overland entering a wetland and unnamed lake (Enbridge 2013c). Initial clean-up and remediation recovered 93% of the crude oil with the remaining oil found in soils and a fen. During the post-release clean-up and monitoring, there were no reports of amphibians or reptiles injured (Focus Wildlife Canada 2013), though the area would have been inhabited by several species of amphibians, and, possibly, reptiles.*

***Mid Valley**: On October 13, 2014, an oil release from a Sunoco Logistics Partners pipeline occurred near Mooringsport, Louisiana. Approximately 4,500 barrels of sweet crude oil were released into the Miller branch of the Tete Bayou, which feeds into Caddo Lake. Although containment booms prevented the oil from entering Caddo Lake, approximately 10 miles of the creek were affected by the release. Initial media reports were that approximately 66 animals, including 30 fish, crayfish and 10 reptiles died as a result of the release (Welborn 2014a). Later media reports about one month following the release were that 486 dead animals were collected and 47 cleaned and released (Welborn 2014b). Most of the animals were crawfish and amphibians, but species and specific numbers were not provided (Welborn 2014b).*

***2015 Yellowstone River**: On January 17, 2015, a pipeline owned by Bridger Pipeline Co. released approximately 715 barrels of Bakken crude oil (estimates ranged from 300 to 1,200 barrels) into the Yellowstone River approximately 5 miles upstream of Glendive, Montana (MT DEQ 2015b). The breach in the pipeline occurred where the pipeline crossed under the river. Winter conditions resulted in extensive ice cover, but aerial patrols discovered oil as far as 25 miles downstream of Glendive, (The Guardian 2015). Booms were deployed on the ice to collect oil from the surface but winter conditions combined with thawing resulted in unsafe working conditions and only a limited amount of oil could be recovered from the river (approximately 60 barrels) (MT DEQ 2015a). There were no reports of oiled wildlife (including amphibians or reptiles) or dead fish (Stuart 2015). The Montana Departments of Natural Resources and Conservation; and Fish,*

> *Wildlife and Parks expressed concern that the most significant source of damage to the riverine system was the physical damage caused by response crews and equipment during clean-up operations.*

7.1.3.5.3 Expected Effects of Released Oils

Compared to birds and semi-aquatic mammals, effects of oil and PAHs on amphibians and reptiles is less well understood, particularly for inland freshwater species (Albers 2003; Malcolm and Shore 2003; Lee et al. 2015). Reported injuries to amphibians and reptiles from hydrocarbon releases suggest that semi-aquatic amphibians and reptiles are regularly affected species, though most likely go undetected. The extent of injuries varies and fatal injuries were more common in amphibians than in reptiles. Amphibians are generally smaller organisms than birds, mammals or even reptiles, and their propensity to seek shelter in sediment or aquatic vegetation when disturbed may result in fewer affected individuals being detected following a hydrocarbon release. Furthermore, smaller organisms are often not detected because of scavenging by predators. There are no reports of studies assessing detection or scavenging rates for amphibians. However, bird scavenging rates tend to be higher for smaller species and detection rates of individuals present lower than that of larger species (Ponce et al. 2010), and this likely would apply to other species groups as well.

There are few published studies about effects of crude oil, particularly diluted or synthetic bitumen and heavy crude oils, or hydrocarbons on amphibians and reptiles. Like other vertebrate species (i.e., mammals and birds), effects can be classified into direct physical effects, direct toxicological effects, and indirect effects. The observed effects of hydrocarbons on amphibians or reptiles are variable and likely due to differences in search effort, release environment, species present, and time of year. Generalizations about effects on amphibians and reptiles are challenging to draw based on limited research for this species group. In some case studies, reported injuries were primarily fatalities (e.g., Mid-valley release) and consisted mostly of amphibians, while in other case studies injuries were generally minor with most captured individuals treated and released (e.g., Marshall and Tinicum releases). The Mid-Valley release where most reported injuries were fatalities, consisted of light crude, whereas the Marshall release, where thousands of individuals were captured and rehabilitated, was heavy crude. The mode of action causing fatalities is challenging to determine without conducting necropsies, and the difference between the two releases could be due to difference in toxicity of the oil components or differences in the physical properties. The magnitude of effect is also difficult to interpret when estimates of population size are not available against which to compare injury rates. Based on two case studies where turtles were oiled and monitored (Marshall and Tinicum releases), the population viability of turtles is not affected by oil releases in freshwater environments.

7.1.3.5.3.1 Direct Physical Effects on Amphibians and Reptiles

Direct physical effects generally involve adhesion (i.e., oiling) of exposed individuals. For amphibians, oiling would occur primarily in the adult stage when individuals are more terrestrial and frequent the water surface and shorelines; eggs and tadpoles are generally submerged and would not be as readily oiled. Because reptiles transition between aquatic and terrestrial environments at all life stages, oiling could affect juveniles to the same extent as adults. However, reports of injured or oiled amphibians and reptiles in case studies did not identify the age of individuals.

Saba and Spotila (2003) found that oiled adult turtles had no difference in survival or home range size than non-oiled individuals. This is consistent with reports of approximately 3,900 turtles being captured, cleaned and released following the Marshall release into the Kalamazoo River, as many individuals (n = 622) were recaptured up to five times (USFWS et al. 2015a). This recapture rate suggests that the physical effects of oiling from diluted bitumen are relatively benign (Lee et al. 2015). During the clean-up of the Marshall release 73 oiled amphibians were also captured, treated and released. Given the smaller size of amphibians and their propensity to seek shelter underwater, it is possible that oiling of frogs, toads and other amphibians would lead to individuals not being detected or recovered following a release. Oiling of amphibians and reptiles would also be limited to the active period of spring, summer and early fall as hibernating individuals buried in sediment would not be exposed to oil, as was the case in the release at the John Heinz National Wildlife Refuge where three weeks passed before ice melted and emerging turtles came in contact with the exposed oil at the water surface (Saba and Spotila 2003). One exception might be ranid frogs that are partially active underwater during the winter period. These individuals may be exposed to oil under ice of shallow lakes and rivers, if the release occurred in the winter. Oiling of reptile eggs, particularly turtles, may occur if oil permeates sandy beaches where turtles are known to dig nests to bury their eggs for incubation. Oiling of eggs may create barriers to respiration and cause the embryos to die, though distinguishing physical effects from toxic effects on eggs is difficult (Rowe and Mitchelmore 2009).

7.1.3.5.3.2 Direct Toxicological Effects on Amphibians and Reptiles

The response of amphibians and reptiles to hydrocarbon exposure has not been well studied (Albers 2003; Malcolm and Shore 2003; Lee et al. 2015). Reptiles are likely to be exposed primarily through consumption of contaminated food, direct ingestion of oil and/or inhalation of volatile hydrocarbons. These same exposure pathways would apply to amphibians that would also have higher exposure than reptiles through dermal absorption. The soft skin of amphibians would make them more susceptible to dermal exposure of dissolved hydrocarbons in the aquatic environment (Stabenau et al. 2006). Amphibian embryos have been described as slightly less sensitive to fuel oils and crude oils as fish embryos, and mortality in amphibians is most common in late-stage developing tadpoles (Albers 2003).

Studies on the effect of hydrocarbons on turtles from the John Heinz National Wildlife Refuge demonstrated that there was no difference in post-release survival, home range, or water temperature preference among exposed and non-exposed turtles (Saba and Spotila 2003). Subsequent studies reported that female snapping or painted turtles exposed to crude oil did not have lower fertility, or clutch size, but there was a measured effect on embryonic development, though the source of the hydrocarbons is questionable because of historic site contamination (Bell 2005; Bell et al. 2006).

Studies examining the effect of petroleum hydrocarbons on hatching and growth of frog eggs found that while hatching success did not decrease in one study (Mahaney 1994), which may be attributed to the protective jelly coat of eggs, Marquis et al. (2006) noted that effects on hatching and the protective jelly coat is species-specific and not applicable to all species. Mahaney (1994) also reported that tadpole growth was also affected increasingly with higher concentrations of dissolved oil, although his study used crankcase oil, which contained a similar proportion of aromatic hydrocarbons as heavy crudes and diluted bitumens (~20%). Similarly, results from a study examining hatching success and embryo deformity rates of turtle eggs exposed to oil depended on the specific population from which individuals originated (Van Meter et al. 2006). Hydrocarbon releases into the aquatic environment that result in lower concentrations of dissolved hydrocarbons, and in PAHs, would likely result in reduced effects on egg survival and tadpole growth. Diluted bitumens have lower quantities of BTEX, USEPA priority PAHs, and total alkylated PAHs than do conventional crude oils, and have been shown to have lower or equal toxicity in zebrafish studies (NRC 2003; Zhou et al. 2015). This suggests that toxicity of diluted bitumens would have equal or lower toxicity to amphibians and reptiles adults and eggs. Moreover, evidence suggests that even light crude oil tested in experimental studies resulted in no biological effects on diamondback terrapin or snapping turtle egg survival or other biological endpoints of hatchlings after 13 months (Rowe and Mitchelmore 2009).

7.1.3.5.3.3 Indirect Effects of Oil Release on Amphibians and Reptiles

Indirect effects occur over longer term and are the result of loss of habitat, increased predation risk, or change in food abundance or availability. Loss of vegetation, and effects to local populations of algae, invertebrates or fish could have long-term effects on the survival and reproduction, and, therefore, on population abundance of amphibians and reptiles. The remedial actions taken in response to hydrocarbon concentrations exceeding guidelines from the Glenavon release likely resulted in effects to amphibian habitat, particularly where remediation activities occurred during the breeding season of species like the northern leopard frog. Wetland drainage is considered a high concern activity for this species (Environment Canada 2013). Vegetation removal and clean-up of the Wabamun release likely affected habitat for several amphibian species both as eggs, juveniles and adults, though this effect would have likely lasted only until vegetation regrowth occurred in the wetland areas the following year.

Mahaney (1994) reported that hydrocarbons from crankcase oil had a negative effect on algal growth rates. The hydrocarbon composition of crankcase oil (20% aromatic, 80% aliphatic) reported in this study is similar to heavy crude oils and diluted bitumens (Dupuis and Ucan-Marin 2015; Zhou et al. 2015), and the expected effects might be similar. However, water quality monitoring following the Wabamun Lake release indicated that water and sediment quality parameters measured in the open water portion of the lake did not indicate any contamination by hydrocarbons, and therefore algal populations were likely not affected by this release.

Table 7-37 Biological Receptor: Amphibians and Reptiles

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—buoyancy	Light crude oils typically have a low relatively density (0.78-0.88 g/mL, Dupuis and Ucan-Marin 2015) and are buoyant in freshwater aquatic environments.	Medium crude oils typically have an intermediate density compared to light and heavy crudes, and are buoyant in freshwater aquatic environments (Dupuis and Ucan-Marin 2015).	Heavy conventional crude oils can have density ranging of 0.88 to 1.00 g/mL, while diluted bitumen will have density less than 0.94 g/mL (Dupuis and Ucan-Marin 2015).	Density of crude oils will increase over time with weathering. It has been suggested (NAS 2016) that diluted bitumen will rapidly weather to a state where its density will exceed the density of fresh water. However, this conclusion is based on data from a high-temperature rotary evaporation procedure, which both accelerates weathering and drives it to an endpoint that may not be reached in a relevant period of time under more realistic environmental conditions. Lee et al. (2015) concluded that "evaporative mass losses of <20% after rigorous weathering at environmentally-relevant temperatures for dilbits nominally comprising ≥30% diluent suggests that a substantial proportion of diluent remains intimately associated with bitumen". This will mitigate against sinking behavior of diluted bitumen in fresh water. These details are further discussed in Section 7.1.2. Recovery or released oil is facilitated if the oil floats on the surface of the water. More rapid recovery of oil will result in a reduced duration of potential exposure, and will avoid contact with submerged amphibians and reptiles.
Oil properties—viscosity	Light crudes will spread rapidly on water because of their low viscosity (1 to 5 mPa•s, NAS 2016).	Medium crudes have an intermediate viscosity (8 to 112 mPa•s, NAS 2016).	Heavy crudes (820 to 475,000 mPa•s) and diluted bitumens (270 to 50,000 mPa•s) weather to high viscosity (NAS 2016). Of note, the viscosity of fresh bitumen is reduced by the addition of diluent (referred to as diluted bitumen), to conform to pipeline specifications.	Viscosity is a function of oil chemistry. Diluted bitumens tend to display a more rapid increase in viscosity due to weathering than conventional heavy crude oils as a result of the rapid initial evaporation of some of the diluent. Oil having low viscosity will rapidly spread across the water surface forming a thin and relatively uniform slick that may result in a larger area where amphibians and reptiles may be exposed to released oil. More viscous oils will spread more slowly and may exhibit thicker but patchier slicks with associated sheens. This would allow for some areas to serve as refuges for amphibians and reptiles in an aquatic system.

Table 7-37 Biological Receptor: Amphibians and Reptiles

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—adhesion	Light crudes have low adhesion and viscosity (NAS 2016) and lower quantities of oil will adhere to amphibians and reptiles exposed to released oil.	Medium crudes have an intermediate adhesion and viscosity (NAS 2016). Lower quantities of medium crude will adhere to amphibians and reptiles exposed to released oil.	Heavy crudes and diluted bitumens are highly adhesive and more viscous than light and medium crude oils. When fresh, diluted bitumens have relatively low viscosity, and would penetrate feathers. However, weathered heavy crudes may tend to adhere to amphibians and reptiles.	Properties of adhesion and viscosity may change the way that crude oil interacts with wildlife through adhering to the exterior of individuals. Light oils form thin layers on surfaces and would be more easily cleaned or removed from the skin or surface of amphibians and reptiles than heavier oils.
Oil chemistry—toxic constituents	Light crude oils often contain high levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, depending on the oil type, but can be high (>10,000 mg/kg) in Bakken oils.	Medium crude oils often contain moderate levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, but can exceed 10,000 mg/kg.	Levels of BTEX and other relatively water soluble constituents are variable: generally low in heavy conventional oils, but variable in diluted bitumens depending upon the nature of the diluent. Levels of TPAH are variable, but typically depleted in napthalenes and less than 10,000 mg/kg.	Diluted bitumens do not contain higher concentrations of either BTEX or TPAH than many conventional crude oils (Lee et al. 2015). Diluted bitumens contain the same suite of PAHs as conventional crude oils, but at different relative concentrations due to the highly weathered nature of the bitumen component, and the modifying effect of the diluent. These details are further discussed in section 7.1.2. Compared to endothermic vertebrates (i.e., birds and mammals), acute effects on amphibian and reptiles are more likely to occur through chemical toxicity of oil than physical effects of oiling. Lower proportions of toxic constituents would result in reduced potential effects on amphibians and reptiles.

Table 7-37 Biological Receptor: Amphibians and Reptiles

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—persistence	Light crude oils typically contain only small proportions of higher molecular weight components, such as resins and asphaltenes. Light crude oils generally biodegrade readily.	Medium crude oils contain variable proportions of resins and asphaltenes. Asphaltenes would be removed from synthetic medium crudes during processing of bitumen.	Heavy conventional crude oils and diluted bitumens typically contain higher proportions of resins and asphaltenes, which tend to resist biodegradation.	In general, heavy conventional crude oils and diluted bitumens would be expected to biodegrade less rapidly than light or medium crude oils. However, any oil can be persistent if deposited in an environment where there is little or no available oxygen. Increased persistence in the environment would result in a similar increase in potential exposure duration by amphibians and reptiles.

Table 7-38 Biological Receptor: Amphibians and Reptiles

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Habitat type	Light crude oil will spread rapidly due to its low viscosity, potentially resulting in effects over a larger area in lakes and wide rivers.	Medium crude oil has low viscosity, although viscosity increases at lower temperatures, and will behave similarly to light crude oils.	Heavy crude oils have high viscosity. Diluted bitumens also have high viscosity (although reduced while fresh due to the effect of the diluent), potentially resulting in effects over a smaller area in lakes and wide rivers, due to the oil's resistance to spreading in these habitats.	Low viscosity oils will spread more rapidly, and to thinner slicks, than high-viscosity oils. As a result, low viscosity oils have a higher potential to affect a larger area of habitat, particularly open-water habitats such as lakes and wide rivers, than higher viscosity oils. At the same time, higher viscosity oils will tend to form thicker slicks than low viscosity oils. This could result in a smaller area of higher impact to habitat suitability for amphibians and reptiles compared from heavy oils compared to light oils.
Season	Light oils remain fluid at low temperature and retain the potential to spread rapidly during the winter. Light oils may penetrate cracks in ice or close to shore, allowing the oil to get beneath the ice and spread downstream. In summer, light crude oils would also flow readily and spread rapidly, having the potential to contact larger numbers of amphibians and reptiles than heavier, more viscous oils.	Medium oils are slightly more viscous than light oils, and would also tend to flow readily under winter conditions. Medium crude oils would tend to flow readily and spread rapidly under summer conditions	Heavy oils become much more viscous at low temperatures, and as they weather. Heavy oils and diluted bitumens would have more resistance to flowing or penetrating cracks in ice to reach the water surface than would be the case for light or medium crude oils. During the summer, diluted bitumens would flow readily and spread rapidly while fresh. Weathering in the first 24 to 48 hours would result in increasing viscosity and density, limiting further spreading of the oil on the water surface.	Season affects both the behavior of oil in the environment, and the types and abundance of amphibians and reptiles that could be exposed. Most amphibians and reptiles become dormant during the winter and would only be exposed to oil during the open water period when they are active. This would limit the potential for direct exposure during the winter period, though indirect effects to food and habitat may still occur from a winter release.

Table 7-38 Biological Receptor: Amphibians and Reptiles

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Weather conditions—rainfall and water levels	Periods of high rainfall and high water levels could transport released crude oil into riparian areas, in addition to potentially increasing downstream transport distances. This would affect all crude oil types. If crude oil is transported into riparian areas, then this could increase the potential for more terrestrial species (toads and snakes) to be exposed, as well as have potential effects to nests of reptiles that burrow into riparian substrates to build their nests (e.g., turtles).			
Weather conditions—temperature	Temperature would have limited implications for effects oil on amphibians and reptiles due to their ectothermic nature (e.g., cold-blooded), which prevents these species from becoming hypothermic. Temperature would have effects on the behavior of oil in the environment (see oil characteristics table above).			
Slope	Lakes have negligible slope, and therefore the short-term distribution of crude oil on the water surface may be determined primarily by wind. Streams and rivers have slope, which determines the downstream water flow velocity, as well as influencing the turbulence of that flow. Slope therefore helps to determine the downstream transport distance for spilled oil before emergency response can be effectively applied. This can affect the types of habitat that the spilled oil could affect, as well as the numbers and types of amphibians and reptiles.			

7.1.3.6 Birds

7.1.3.6.1 Description

There are hundreds of species of birds in North America, many of which are aquatic or semi-aquatic, using wetlands, lakes, rivers, or streams as components of their habitats. The dependence of birds on aquatic habitat ranges from facultative (e.g., use of aerial habitat over water by swallows when foraging for emerging aquatic invertebrates) to obligate (e.g., use of aquatic and shoreline habitat by divers and some ducks for foraging, rearing young, and constructing nests along shorelines or on floating vegetation). This receptor group—Birds—focuses primarily on waterbirds (e.g., gulls, terns, loons), waterfowl (e.g., ducks, geese, swans), and shorebirds (e.g., sandpipers, plovers, herons, cranes) that are often intimately associated with aquatic environments, as these are the most vulnerable to releases of hydrocarbons (Albers 2003). However, members of other bird groups, such as raptors and songbirds, are also considered in this environmental effects assessment.

Birds have dietary preferences that range from piscivory (fish-eating species such as osprey, loons, mergansers) and insectivory (insect-eating species such as swallows, lesser scaup and spotted sandpiper) to omnivory (species that consume a variety of foods such as mallard) and herbivory (species that consume primarily vegetation such as Canada goose). Nesting habits of aquatic birds range from stick nests in trees located close to water (e.g., eagles, osprey, and herons), and ground-nesting species that may build nests in adjacent uplands or close to shorelines (e.g., spotted sandpiper, and lesser scaup), to species that build nests on floating vegetation as a predator avoidance mechanism, such as the horned grebe.

Unlike many other vertebrate receptors, aquatic bird species in the northern temperate zone are nearly all seasonal migrant species which leave their summer (and often breeding) habitat in the fall for wintering areas farther south, where they can find open-water habitat. Timing of migration varies among species, and is usually a function of migratory distance. Long-distance migrants depart earlier and arrive later, with more predictable migration timing, whereas short-distance migrants will arrive as soon as aquatic environments begin to open in the spring and depart only when lakes and rivers freeze in the fall. However, some aquatic birds (e.g., Canada goose) will opportunistically remain in freezing conditions if there is reliable open water and a source of food available.

There is only one federally-listed bird in this receptor group (the piping plover, *Charadrius melodus*, Endangered, USFWS 2016) that is likely to occur in the study area (i.e., Minnesota). In addition, there are several receptor group species listed under Minnesota's Endangered Species Statutes (MN DNR 2013). These include:

- Horned grebe (*Podiceps auritus*) — Endangered
- King rail (*Rallus elegans*) — Endangered
- Wilson's phalarope (*Phalaropus tricolor*) — Threatened
- Common tern (*Sterna hirundo*) — Threatened
- Yellow rail (*Coturnicops noveboracensis*) — Special concern

- Trumpeter swan (*Cygnus buccinator)* Special concern
- Common gallinule (*Gallinula galeata*) Special concern
- Franklin's gull (*Leucophaeus pipixcan*) Special concern
- Marbled godwit (*Limosa fedoa*) Special concern
- Louisiana waterthrush (*Parkesia motacilla*) Special concern
- American white pelican (*Pelecanus erythrorhynchos*) Special concern
- Forster's tern (*Sterna forsteri*) Special concern

7.1.3.6.2 Observed Effects

A review of hydrocarbon releases from pipelines, as well as one example each for a rail car release and a release from a storage tank, provide an overview of observed effects of oil releases on birds in aquatic environments (e.g., river, lakes and wetlands) similar to those that could be encountered in Minnesota. This review is not exhaustive, but provides a range of observed effects of a variety of oil types on birds, under different environmental conditions. The case studies will provide an empirical basis from which the likely effects of oil releases on aquatic birds can be predicted, with consideration of the modifying effects of oil type, and environmental factors.

> ***Ashland Petroleum**: On January 2, 1988, a 40 year old storage tank collapsed at the Ashland Oil Facility in West Elizabeth, Pennsylvania. The tank collapse released approximately 90,500 barrels of diesel fuel, of which 23,800 barrels flowed into the Monongahela River 27 miles south of Pittsburgh, Pennsylvania. As the release moved downstream, water supplies were contaminated, resulting in the disruption of water services to riverside cities in Pennsylvania, Ohio, and West Virginia. As of January 7, 1988, only 1,900 barrels of product had been recovered (NOAA 1992). The effort to recover the oil was hindered by dams and locks along the Ohio River, ice cover, emulsification of the oil, and dispersion of the oil into the water. The Pennsylvania Game Commission assisted by volunteers set up bird cleaning programs and monitored for oiled wildlife, though efforts were hampered by weather conditions and by partial ice cover that resulted in rescue workers not being able to access areas where birds were concentrated. Waterbird and waterfowl mortality estimates ranged from 2,000 to 4,000 birds, including ducks, loons, cormorants and geese among others (Miklaucic and Saseen 1989). The high mortality was likely due to the response limitations arising from environmental conditions which prevented crews from deterring birds from oiled sites and rescuing birds that had remained in open water areas of the river (Miklaucic and Saseen 1989).*

> ***Exxon Bayway**: On January 2, 1990, an underwater pipeline released approximately 13,500 barrels of No. 2 heating oil into the Arthur Kill waterway at the mouth of Morse Creek between New Jersey and Staten Island, New York (NOAA 1992). Initial response efforts focused on containment of the release and removal of the larger masses of oil. Concentrations of floating oil and mousse in the open water, primarily between Howland Hook and Fresh Kills, were collected by self-propelled skimmers. Oil concentrated and stranded above the berm on the beaches from Cedar Point to Rossville, as well as in other natural areas. Factors resulting in the dispersal of oil beyond the berm were not*

reported, though it could have been due to tidal and wave action. Environmentally sensitive areas were protected with boom and skimmers that collected the larger masses of free-floating oil. Even though the incident occurred in January, the environment was a coastal marsh system that allows many species of aquatic birds to overwinter as a result of the open water maintained by tidal action and salt water. A total of 841 birds were reported oiled, with 691 fatalities. The most common groups were waterfowl and gulls (45% of the oiled birds each) (NOAA 1992; French McCay and Rowe 2004).

***Lakehead**: On March 3, 1991, a Lakehead Pipeline Company, Inc. owned pipeline ruptured and released over 40,000 barrels of crude oil (NOAA 1992) approximately two miles north of Grand Rapids, Minnesota. Some of the oil spread onto the 18-inch thick ice sheets on the Prairie River. Oil formed into 8 inch deep pools on top of the ice in the middle of the river and was also present under the ice. Vacuum trucks were used by clean-up personnel to remove the oil from the surface of the ice. Workers used squeegees to push the oil along the ice to a removal location. Booms were used on the river by cutting a slot through the ice cover with chainsaws. Ice that had been permeated with oil was chopped into blocks small enough to be carried away to a separate part of the river. Clean-up personnel sprayed the ice blocks with hot water to wash out the oil, which was then recovered with skimmers. Blocks that were only slightly contaminated were moved to lined holding tanks and broken up. The crushed ice was then allowed to melt to recover residual oil. There were no specific reports of oiled birds, or of the death of any birds; effects to fish and wildlife were reported as minimal by the MN DNR (Telegraph Herald 1991), likely due to ice-covered conditions at the time of the release.*

***OSSA II**: On January 30, 2000, an estimated 29,000 barrels of mixed heavy crude oil and diluent (combined density of approximately 0.8 g/mL) were released from the Transredes S.A operated OSSA II pipeline at the Rio Desaguadero river crossing in Bolivia as the river was rising to peak flood conditions (Lee et al. 2001, 2002; Owens and Henshaw 2002). Due to the very high river flow and water velocity conditions, and perhaps also due to the low viscosity of the oil which would allow it to become dispersed into the water as fine droplets, oil was found up to 230 miles downstream from the release location. For the most part, the surface oil was deposited onto river banks in strips, generally 3 to 6 ft wide and up to 0.5 to 1 inch thick. Many sections of river bank had a horizontal line of oil (a bathtub ring) where the oil was stranded, indicating the water level at the time (Owens and Henshaw 2002). The response effort included more than 3,600 people who recovered the oil within three months. Wasson et al. (2000; in Owens and Henshaw 2002) reported that few birds (in the order of tens; species not reported) were initially oiled by the release; observers did not detect additional birds in the weeks and months following the release, despite the high numbers of birds in the area.*

***Pine River**: On August 1, 2000, a Pembina Pipeline Corp. pipeline failure released approximately 6,200 barrels of light crude oil, of which an estimated 2,800 barrels entered* *the Pine River 70 miles upstream of Chetwynd, British Columbia (BC MOE 2000a). An estimated 300 to 710 barrels remained unaccounted for following the clean-up and remediation (Goldberg 2011). Most of the oil unaccounted for was considered likely to be entrained in sediment or debris in the river channel. Response measures included placing two containment systems, one approximately 14 miles downstream and a second approximately 19 miles downstream (BC MOE 2000c). The river was flowing at a low stage at the time of the release (approximately 5,680 ft^3/s measured at a station 100 miles downstream compared to flow rates above 31,880 ft^3/s during late spring and early summer) (Bustard and Miles 2011). The Pine River has a gradient of approximately 0.225% in the first 25 miles downstream from the release location, decreasing to 0.1% farther downstream (Bustard and Miles 2011).*

A golden eagle and a hooded merganser were reportedly affected by the release. The eagle recovered, but the merganser was euthanized. No other birds were found by government staff or clean-up crews (BC MOE 2000b).

***Wabamun Lake**: On August 3, 2005, a Canadian National freight train derailed near the Village of Whitewood Sands, Alberta, releasing approximately 4,500 barrels of Bunker C fuel oil (Heavy Fuel Oil 7102; Hollebone et al. 2011) and 550 barrels of pole treating oil. An estimated 950 barrels of the Bunker C oil entered Wabamun Lake where it formed a thick black slick approximately 0.5 in. thick (Wernick et al. 2009). The heavy Bunker C product formed several types of aggregates including tar balls, larger tar "logs", submerged sheets, large lumps, tar balls that sometimes reformed into oil slicks, and a "slurry" composed of finely divided organic matter and small oil droplets (Fingas et al. 2006; Hollebone et al. 2011). The oil exhibited a variety of behaviors including submergence, neutral buoyancy, and resurfacing as a result of contacting and taking up foreign matter (such as mineral particles and organic debris) on its path to the lake (Fingas et al. 2006). No dispersion of oil in water was observed in the lake, and no mousse formation was reported in the three years following the release (Hollebone et al. 2011). Overall, the water in the open water area of the lake was reported to be not contaminated with released hydrocarbons or associated metals (Anderson 2006). This is consistent with the very low concentration of relatively water-soluble components (such as BTEX) in the released oil, and the relatively low water solubility of this heavy oil. Similarly, sediments beneath the open water portions of Wabamun Lake were reported not to have been contaminated with petroleum hydrocarbons and were considered to be of similar quality to concentrations measured in 2002 or shortly before the release (Anderson 2006).*

Clean-up activities included cutting of the vegetation and vacuum removal of submerged tar balls entrained in the reed bed detritus (Wernick et al. 2009). A two-year study was conducted to assess regrowth. The study found that exposure to the oil, which was released late in the growing season, did not cause large-scale changes to these emergent plant communities (Wernick et al. 2009). Physical factors such as clean-up activities and vegetation management appeared to be responsible for reduced *regrowth of vegetation observed at some locations (Wernick et al. 2009; Thormann and Bayley 2008).*

Wabamun Lake is one of nine lakes in Alberta found to support western grebe colonies in 2006 (Kemper et al. 2008). The Alberta population is estimated at between 10,000 and 11,000 birds, representing approximately 10% of the North American population. The Wabamun Lake colony contains between 100 and 500 nests and is considered to be regionally important (Kemper et al. 2008). During 2001–2005, western grebes at Wabamun Lake nested in one main colony (Rich's Point), and the lowest reported number of nests was 243 in 2005. The release occurred after completion of nesting that year, killing an estimated 333 western grebes (about 69% of the adult population). A wildlife recovery center was set up immediately after the release. More than 530 oiled birds were recovered within five days after the release. Of those, 156 were either dead when recovered, or euthanized thereafter (TSBC 2007). The following summer, the resurfacing of submerged oil resulted in the oiling of additional waterfowl, though specific estimates were not provided (TSBC 2007).

In 2006, western grebes returned to nest at Rich's Point, and in addition, formed a second colony at the Ascot Beach reed bed. Together, the two sites contained 456 nests in 2006 and over 1,000 nesting adults (Kemper et al. 2008; Wollis and Stratmoen 2010). Populations at Wabamun lake followed similar trends pre- and post-release to those of the regional population (Wollis and Stratmoen 2010; AESRD and ACA 2013), suggesting that the release did not cause substantial long-term changes at this location.

***Glenavon**: On April 15, 2007, a release occurred on the Enbridge Line 3 pipeline approximately 1 mile downstream of the Glenavon pump station near Glenavon, Saskatchewan. The rupture released approximately 6,200 barrels of heavy crude oil and affected approximately five acres of a wetland on farmland (TSBC 2008a; SLR Consulting 2008a). Within two days of the release, approximately half of the crude oil had been recovered (Canada.com 2007a). The site was monitored for one week for exposure of wildlife to oil, and wetlands within 0.6 miles (1 km) were surveyed for any wildlife that may have been oiled initially and moved from the release site. Of the five birds affected (four Canada geese and one savannah sparrow), two Canada geese were euthanized, one Canada goose (which was able to fly) eluded capture and disappeared from the area, and one Canada goose and savannah sparrow were captured and transported to the Small Animal Clinic at the Western College of Veterinary Medicine. The Canada goose was successfully cleaned and considered for release, though the final action was unknown. The savannah sparrow died during clean-up (SLR Consulting 2008a). Response activities included the use of wildlife deterrents and fencing around the perimeter of the slough. The small number of birds oiled by the release was attributed to the release occurring at night when semi-aquatic birds are less likely to be active (SLR Consulting 2008a), and to mobilizing of a rapid response to avoid further exposure of birds.*

***Marshall**: On July 25, 2010, Enbridge's Line 6B pipeline experienced a release in a wetland near Marshall, Michigan. Approximately 20,000 barrels of heavy crude oil containing diluted bitumen were released over a period of about 17 hours. The pipeline contained two different batches of crude oil at the time of the release (NTSB 2012a). It is estimated that the released oil consisted of approximately 77% CLWB diluted bitumen and 23% Western Canadian Select, as well as diluted bitumen (Enbridge 2013a). Of this, approximately 8,000 barrels reached Talmadge Creek and the Kalamazoo River (Enbridge 2013a). During clean-up and monitoring, 52 birds were either found dead or died during attempted rehabilitation (USFWS et al. 2015a). In addition, 144 oiled birds were captured, successfully rehabilitated and released. There were approximately 140 additional birds observed oiled, but never captured. The primary species were Canada goose (75%), mallard (9%), and great blue heron (5%) (USFWS et al. 2015a). Of the birds rehabilitated and released, 127 were banded including 109 Canada geese. Between 2010 and 2015, 39 of those bands were recovered from hunters (unpublished banding data), indicating that birds survived post-release and were able to complete migration and dispersal.*

***Rainbow**: On April 28, 2011, a pipeline owned by Plains Midstream Canada released approximately 28,300 barrels of sweet crude oil into a muskeg/stagnant water area near the community of Little Buffalo in the Peace River region of Alberta. The release occurred on a hillside, and the oil flowed a half mile down the pipeline ROW and pooled in a low-lying area containing abandoned beaver ponds. The release encompassed an area of approximately 20 acres (ERCB 2013). As part of the response, wildlife mitigation measures, which included fencing and various deterrents, were implemented (ERCB 2013). Despite these measures 79 birds were reported to have died by November 2012, with most of the deaths occurring shortly after the release (i.e. within a few months). Bird species included in the reported fatalities were a mixture of approximately one-third waterfowl and two-thirds shorebirds and passerines; the particular species affected were not reported (ERCB 2013).*

***2011 Yellowstone River**: On July 1, 2011, flood conditions in the Yellowstone River resulted in a release from the ExxonMobil Silvertip Pipeline carrying medium sour crude oil near Laurel, Montana. Riverbed erosion exposed the 12-in. pipeline beneath the crossing, and debris caught on the washed-out pipeline causing stress, resulting in a clean break (i.e., a full bore rupture). The failure was detected at the pipeline control center and the line was shut down within 10 minutes (USDOT 2012). Approximately 1,500 barrels of crude oil was released into the Yellowstone River (USDOT 2012). The affected reach of the Yellowstone River has an average gradient of 0.17%. Crude oil affected primarily shorelines and banks immediately downstream of the release site (MT DEQ 2015b). According to the USEPA (2011), at least 19 oiled animals were confirmed to have been visibly oiled, including one bald eagle. Ten wildlife fatalities were reported, though no information on species or fate was provided (USEPA 2011).*

***Red Deer River**: On June 7, 2012 a Plains Midstream Canada ULC (Plains) pipeline released approximately 2,900 barrels of light crude oil into the Red Deer River downstream of Sundre, Alberta as a result of high water levels in the river that exposed the pipeline and caused structural damage (AER 2014). The migration of surface oil was stopped by booms placed at Gleniffer Lake, but dissolved hydrocarbons continued to move downstream. This resulted in potential for both toxicological and physical effects upstream of the booms, but limited potential for physical effects downstream (Teichreb 2014). As a result of the release, one Canada goose and one American crow were oiled; the animals were brought to the Medicine River Wildlife Centre where they were cleaned and treated (Derworiz 2012). Officials with Alberta Environment indicated that impacts to wildlife were minimal (Derworiz 2012).*

***Line 37**: On June 22, 2013, unusually heavy rains caused ground movement that compromised the integrity of the Enbridge Line 37 pipeline approximately 1 mile north of the terminal in Cheecham, Alberta. The resulting failure released approximately 1,300 barrels of synthetic light crude oil underground with some oil seeping to the surface where it flowed overland entering a wetland and unnamed lake (Enbridge 2013c). Initial clean-up and remediation recovered 93% of the crude oil with the remaining oil found in soils and the fen. Effects on semi-aquatic birds included two blue-winged teal found dead as a result of the release. A third teal was observed to be oiled, but may have been oiled post-mortem after predation by a fox (Focus Wildlife Canada 2013). The small number of reported oiled birds was potentially due to the low density of waterfowl and other aquatic birds in the area, but may also have been influenced by the short time required to implement spill response and mitigation measures.*

***Mid Valley**: On October 13, 2014, a Sunoco pipeline release occurred near Mooringsport, Louisiana, resulting in approximately 4,500 barrels of sweet crude oil entering the Miller branch of the Tete Bayou, which feeds into Caddo Lake. Although containment booms prevented the oil from entering Caddo Lake, approximately 10 miles of the creek were affected. Media reported that 486 dead animals were collected and 47 were cleaned and released (Wellborn 2014a). Most of the animals were crawfish and amphibians, but numbers and species were not provided. One wood duck was reportedly oiled, cleaned and released (Welborn 2014b), but this area would likely have been inhabited by shorebirds, wading birds, waterfowl, and other marsh birds.*

***Yellowstone River**: On January 17, 2015, a Bridger Pipeline LLC pipeline released approximately 715 barrels of Bakken crude oil (estimates ranged from 300 to 1,200 barrels) into the Yellowstone River approximately 5 miles upstream of Glendive, Montana (MT DEQ 2015b). The pipeline breach occurred where the pipeline crossed under the river. Winter conditions resulted in extensive ice cover, but aerial patrols discovered oil as far as 25 miles downstream of Glendive (The Guardian 2015). Booms were deployed on the ice and in areas of open water downstream to collect oil from the surface (Hirji 2015) but winter conditions combined with thawing resulted in unsafe working conditions and*

> *only a limited amount of oil (approximately 60 barrels, MT DEQ 2015a) was recovered from the river. There were no reports of oiled wildlife (including birds) or dead fish (Stuart 2015). The Montana Departments of Natural Resources and Conservation and Fish, Wildlife and Parks expressed concern that the most important source of damage to the riverine system was the physical damage caused by response crews and equipment during clean-up operations.*

7.1.3.6.3 Expected Effects of Released Oils

The case studies in the foregoing section provide the opportunity to highlight key differences between oil releases to inland waters to those in marine environments.

The first consideration is the environment in which the releases occur. For marine releases, oil can spread and be transported by wind and currents with the potential to affect a very large area. In contrast, inland releases are almost always constrained. Releases to wetlands and small lakes (e.g., the Line 37 release) provide natural traps limiting the spread of oil and preventing damage to downstream habitats. Even releases to rivers are constrained to the river channel. River banks provide substrates where oil can strand and be retained, thereby limiting downstream migration and facilitating emergency response measures.

Secondly, the effects of an inland oil release, while potentially having severe local effects to birds, are likely to have only minor regional or population level effects unless they occur in sites where a high proportion of a species' population congregates. This is due to the redundancy provided by unaffected habitat upstream, downstream, or in unaffected nearby watersheds. As a result, only a small portion of a regional population may be exposed to oil after an inland oil release. Exceptions could occur if releases affect areas where birds are concentrated in an isolated area of open water during winter conditions (e.g., the Ashland release) or where there are breeding concentrations of birds (e.g., the Wabamun Lake release). Locations of importance to regional or continental populations of birds, such as Western Hemisphere Shorebird Reserve Network Sites or Important Bird Areas, are generally well known and potential effects of releases predicted. Thus, except in unusual circumstances, the environmental effects of oil releases on birds in inland habitats tend to be limited to small numbers of individuals than for marine oil releases. Large releases of crude oil to the marine environment have the potential to affect large numbers of individuals and species (as was the case for the Exxon Valdez oil release; Weins et al. 2013).

Hydrocarbon releases can harm birds through physical effects, acute and chronic toxicological effects, and through changes in habitat (Albers 2003; Malcolm and Shore 2003). The environmental effects of an oil release on aquatic and semi-aquatic birds will therefore depend upon the amount of oil released, the environment that the oil is released into, and the numbers and types of aquatic and semi-aquatic birds that are exposed to the oil. Secondarily, oil spill response measures will help to limit the spread of released oil and, in doing so, will reduce the potential exposure of birds. In addition, capture and rehabilitation of oiled birds may help to reduce mortality.

Detecting dead birds following a hydrocarbon release in the aquatic environment is challenging, and is known to under-represent the true number of fatalities associated with a hydrocarbon release. For example, Byrd et al. (2009) estimated that only 14.6% of carcasses along coastal (marine) beaches remained after 24 hours due to scavenging. Moreover, searchers averaged a 40% detection rate of carcasses known to be present after a single pass, and a cumulative increase to 70% detection following a second pass. Comparable statistics for inland water bodies are not available.

The following sections provide further insight into the role of oil type and environmental factors on the environmental effects of released oil on aquatic and semi-aquatic birds.

7.1.3.6.3.1 Direct Physical Effects of Oil on Birds

The most easily observed and reported effect of a hydrocarbon release on birds is physical oiling of plumage. Feathers provide aquatic birds with buoyancy and insulation. Oiling impairs both of these properties, and the added weight may affect a bird's ability to fly, affecting foraging, migration, and predator avoidance. Also, oiling often results in death from hypothermia or drowning of birds that are obligate users of aquatic habitat (Vermeer and Vermeer 1975; Jenssen 1994), particularly in cold-water environments. Smaller birds are likely to succumb to physical oiling at a faster rate than larger birds, as the surface area of smaller organisms is larger in proportion to their body mass. Body size effects would also result in greater impairment of small birds, which would require proportionally greater effort to fly with partial oiling. Lower ambient temperature will amplify the physiological effects of reduced insulation in organisms. As noted above, heat loss will also be much greater for a bird immersed in cold water than for a bird immersed in air at the same temperature (Knopper et al. 2016). A higher rate of heat loss will lead to faster onset of hypothermia and potentially death in oiled birds. A partially oiled bird might be susceptible to hypothermia if exposed to cold air or water, while the same bird might survive partial oiling if exposed to moderate or warm temperatures (Knopper et al. 2016). However, for birds such as gulls, shorebirds, and waders that have sufficient behavioral plasticity to avoid immersion in cold water when oiled, long-term survival and an ability to self-clean and recover from light to moderate oiling has been reported (Camphuysen 2011).

The effect of oil type on oiling of birds has not been directly studied, but evidence from marine studies would suggest that any oil type can be harmful. The NRDAM/CME (French et al. 1996) bases the assessment of harm to marine birds on slick thickness, with predictions of bird mortality on a threshold slick thickness of 10 µm. As heavier crude oils have higher adhesion than lighter crude oils (NAS 2016), it would be more difficult for individuals to remove heavier crude oil from feathers through preening, and could also result in greater ingestion of hydrocarbons by birds than for lighter crude oils. While it is reasonable to conclude that light oils could spread to very thin sheens (less likely to be harmful to aquatic birds) than more viscous heavy oils, it is also reasonable to conclude that a release of light oil could spread to affect a larger area and therefore affect more birds than a similar sized release of heavy oil. The exact outcome of exposure of birds to oil will depend on climate and other influences on both oil dispersion and the distribution of birds, as well as oil type.

7.1.3.6.3.2 Direct Toxicological Effects of Oil on Birds

Acute toxic effects are less common in birds and other terrestrial vertebrates that can escape from a region where oil has been released into the environment. Acute and chronic effects on birds of hydrocarbon exposure through ingestion or inhalation pathways are generally considered less serious than the physical effects of external oiling (Albers 2003). Acute toxicity of ingested hydrocarbons or inhaled hydrocarbon vapor in birds is generally the result of liver failure, narcosis and other biochemical responses (Albers 2003, 2006). Low molecular weight hydrocarbons can result in acute effects shortly after an oil release when they are in sufficiently high concentrations at the site of release (and in the ingested oil), prior to being diluted in the environment or evaporating into the atmosphere (weathering).

Direct toxicological effects on birds of hydrocarbons released to the environment are generally less significant for adult birds than physical effects described previously. Studies, generally with ducks, have shown that naturally weathered Exxon Valdez crude oil presented little potential for toxicity to wildlife species from oral ingestion (Stubblefield et al. 1995a, b). In the short term, birds are most likely to ingest hydrocarbons directly as a result of preening oiled feathers with their bills, but also through ingestion of food and incidental ingestion of sediment (Albers 2003). Ingestion of oil is seldom directly lethal, but it can cause many debilitating sublethal effects that promote death from other causes, including starvation, disease, and predation (Albers 2003, 2006). Effects include gastrointestinal irritation, pneumonia, dehydration, red blood cell damage, impaired osmoregulation, immune system suppression, hormonal imbalance, inhibited reproduction, retarded growth, and abnormal parental behavior (Albers 2003, 2006). Therefore, birds that survive external oiling without succumbing to hypothermia may be at secondary risk of death due to ingesting a quantity and mixture of hydrocarbon compounds, which can then result in multiple additional effects. Birds that survive external oil exposure may subsequently be indirectly exposed to hydrocarbons (of which the polycyclic aromatic hydrocarbons or PAHs are of greatest concern) through contaminated food, and incidental ingestion of contaminated sediment, soil or water.

During the breeding season, birds carrying hydrocarbons on their feathers are also at risk of transferring oil to their eggs. Studies examining the effect of eggshell oiling found that small quantities of oil can cause embryonic death. Effects were more pronounced for light crude oils, as they contain higher proportions of BTEX and 2-ring PAHs (Hoffman 1990), which are capable of penetrating through the eggshell and egg membrane. This is consistent with results of a study by Szaro et al. (1980) showing that weathered oils were slightly less toxic to mallard eggs than fresh oils. However, toxicity was dose-dependent through the range of 1 and 50 µL of oil per egg (Szaro et al. 1980).

7.1.3.6.3.3 Indirect Effects of Oil on Birds

Indirect effects of hydrocarbon releases to birds occur through effects to habitat or food quality or availability (Wiens et al. 2013). Because aquatic birds inhabiting inland freshwater environments are typically only present during the open-water season, their habitat requirements are seasonal during the migration and breeding period. The magnitude of effects on breeding habitat of semi-aquatic bird species depends on their nesting behavior. Species such as gulls or terns that nest in colonies on islands, or in habitat that may be limiting (e.g., grebes nesting in reed beds) may have fewer options when seeking alternative nesting locations following a disturbance than species with greater plasticity in habitat requirements (e.g., spotted sandpiper). Where oil becomes entrained in riparian or wetland vegetation, remediation activities that include vegetation clearing could affect nesting or roosting habitat of aquatic and semi-aquatic birds (see Wabamun Lake case study).

Foraging habitat loss depends on a species foraging behavior and the fate of released hydrocarbons in the environment. Hydrocarbons collecting along shorelines and riparian bank areas would primarily affect shorebirds. Oil entrained in emergent or submerged vegetation in wetlands, deadwater areas of rivers, and shallow portions of lakes would affect waterfowl, waterbirds and wading birds (e.g., herons). However, as birds are capable of dispersing to unaffected areas to forage, effects of hydrocarbon releases would be limited to the aquatic system in which the release occurred. At a regional level, population effects would not likely be observed (Albers 2003). Indirect effects could also result from changes in food quality or abundance. Effects of hydrocarbon releases on aquatic invertebrates or fish could temporarily reduce prey availability or quality for birds.

7.1.3.6.4 Summary of Inland Oil Release Effects on Birds

Table 7-39 and Table 7-40 provide a summary of the expected environmental effects of oil releases to aquatic and semi-aquatic birds in inland environments. Table 7-39 considers the effects of specific oil characteristics or oil type on the expected types and scope of environmental effects. Table 7-40 considers the effects of environmental characteristics on the expected types and scope of environmental effects.

Table 7-39 Biological Receptor: Semi-aquatic Birds

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—buoyancy	Light crude oils typically have a low relatively density (0.78-0.88 g/mL, Dupuis and Ucan-Marin 2015) and are buoyant in freshwater aquatic environments.	Medium crude oils typically have an intermediate density compared to light and heavy crudes, and are buoyant in freshwater aquatic environments (Dupuis and Ucan-Marin 2015).	Heavy conventional crude oils can have density ranging of 0.88 to 1.00 g/mL, while diluted bitumen will have density less than 0.94 g/mL (Dupuis and Ucan-Marin 2015).	While raw bitumen has a higher density than water, diluted bitumen is less dense and limited evaporative mass loss at environmentally-relevant temperatures suggests that weathered dilbit will remain afloat as it will retain sufficient diluent to maintain a lower density ((Lee et al. 2015; see also Section 7.1.2). Recovery of released oil is facilitated if the oil floats on the surface of the water.
Oil properties—viscosity	Light crudes will spread rapidly on water because of their low viscosity (1 to 5 mPa•s, NAS 2016).	Medium crudes have an intermediate viscosity (8 to 112 mPa•s, NAS 2016).	Heavy crudes (820 to 475,000 mPa•s) and diluted bitumens (270 to 50,000 mPa•s) weather to high viscosity (NAS 2016).	Viscosity is a function of oil chemistry. Diluted bitumens tend to display a more rapid increase in viscosity due to weathering than conventional heavy crude oils as a result of the rapid initial evaporation of some of the diluent. Oil having low viscosity will rapidly spread across the water surface forming a thin and relatively uniform slick. More viscous oils will spread more slowly and may exhibit thicker but patchier slicks with associated sheens.
Oil properties—adhesion	Light crudes have low adhesion and viscosity (NAS 2016) and can be expected to penetrate the feather layer to contact skin.	Medium crudes have an intermediate adhesion and viscosity (NAS 2016). Medium crude oils also readily penetrate the feather layer to contact skin.	Heavy crudes, particularly diluted bitumens, are highly adhesive and more viscous than light and medium crude oils. Fresh diluted bitumens have relatively low viscosity, and would penetrate feathers. However, weathered heavy crudes may tend to stick to the surface of feathers without penetrating to contact the skin.	Properties of adhesion and viscosity may change the way that crude oil interacts with feathers. Light oils may more readily penetrate feathers and destroy insulation; heavy oils, particularly when weathered, may tend to adhere in a thick layer to the feather surface without immediately penetrating to the skin surface. This results in more difficult cleaning and removal of oils from feathers, greater added weight and extended duration of physical effects.
Oil chemistry—	Light crude oils	Medium crude oils	Levels of BTEX and other relatively	Diluted bitumens do not contain higher

Table 7-39 Biological Receptor: Semi-aquatic Birds

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
toxic constituents	often contain high levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, depending on the oil type, but can be high (>10,000 mg/kg) in Bakken oils.	often contain moderate levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, but can exceed 10,000 mg/kg.	water soluble constituents are variable: generally low in heavy conventional oils, but variable in diluted bitumens depending upon the nature of the diluent. Levels of TPAH are variable, but typically depleted in napthalenes and less than 10,000 mg/kg.	concentrations of either BTEX or TPAH than many conventional crude oils (Dupuis and Unca-Marin 2015; Lee et al. 2015). The characteristics of diluted bitumen are further discussed in Section 7.1.2. Acute effects on bird populations are generally caused by physical oiling, not related to the BTEX content of the oil. Chronic effects on birds of released crude oil, if any, are likely due to dietary TPAH exposure. Diluted bitumens contain the same suite of PAHs as conventional crude oils, but at different relative concentrations due to the highly weathered nature of the bitumen component, and the modifying effect of the diluent.
Oil properties—persistence	Light crude oils typically contain only small proportions of higher molecular weight components, such as resins and asphaltenes. Light crude oils generally biodegrade readily.	Medium crude oils contain variable proportions of resins and asphaltenes. Asphaltenes would be removed from synthetic medium crudes during processing of bitumen.	Heavy conventional crude oils and diluted bitumens typically contain higher proportions of resins and asphaltenes, which tend to resist biodegradation.	In general, heavy conventional crude oils and diluted bitumens would be expected to biodegrade less rapidly than light or medium crude oils. However, any oil can be persistent if deposited in an environment where there is little or no available oxygen.

Table 7-40 Biological Receptor: Semi-Aquatic Birds

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Habitat type	Light crude oil will spread rapidly due to its low viscosity, potentially resulting in effects over a larger area in lakes and wide rivers.	Medium crude oil has low viscosity, although viscosity increases at lower temperatures, and will behave similarly to light crude oils.	Heavy crude oils have high viscosity. Diluted bitumens also have high viscosity (although reduced while fresh due to the effect of the diluent), potentially resulting in effects over a smaller area in lakes and wide rivers, due to the oil's resistance to spreading in these habitats.	Low viscosity oils will spread more rapidly, and to thinner slicks, than high-viscosity oils. As a result, low viscosity oils have a higher potential to affect a larger area of habitat, particularly open-water habitats such as lakes and wide rivers, than higher viscosity oils. At the same time, higher viscosity oils will tend to form thicker slicks than low viscosity oils. This could lead to a contrast of "more habitat and birds oiled less heavily" (lighter oils) as compared to less habitat and fewer birds oiled more heavily (heavier oils) for a spill of the same magnitude.
Season	Light oils remain fluid at low temperature and retain the potential to spread rapidly during the winter. Light oils may penetrate cracks in ice or close to shore, allowing the oil to get beneath the ice and spread downstream. In summer, light crude oils would also flow readily and spread rapidly, having the potential to contact larger numbers of birds than heavier, more viscous oils.	Medium oils are slightly more viscous than light oils, and would also tend to flow readily under winter conditions. Medium crude oils would tend to flow readily and spread rapidly under summer conditions.	Heavy oils become much more viscous at low temperatures and as they weather. Heavy oils and diluted bitumens would have more resistance to flowing or penetrating cracks in ice to reach the water surface than would be the case for light or medium crude oils. During the summer, diluted	Season affects both the behavior of oil in the environment, and the types and abundance of birds that could be exposed to spilled oil. Most aquatic birds migrate south during the winter, unless reliable open water conditions (e.g., fast-moving water where ice does not form) create access to a reliable food supply. Most northern hemisphere birds breed during the summer months, and for some species this implies colonial nesting habits. Birds may also congregate in

Table 7-40 Biological Receptor: Semi-Aquatic Birds

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
			bitumens would flow readily and spread rapidly while fresh. Weathering in the first 24 to 48 hours would result in increasing viscosity and density, limiting further spreading of the oil on the water surface.	feeding or staging areas during seasonal migration events.
Weather conditions—rainfall and water levels	Periods of high rainfall and high water levels could transport spilled crude oil into riparian areas, in addition to potentially increasing downstream transport distances. This would affect all crude oil types. If crude oil is transported into riparian areas, then different species of birds (e.g., shorebirds and ground-feeding birds) could be exposed to the oil and its effects either through direct contact with oil, or though food chain effects as PAHs and oily residues are ingested with food and associated soil.			
Weather conditions—temperature	The survival of oiled birds could be affected by ambient temperatures, regardless of season. The primary cause of mortality in oiled birds is hypothermia caused by the loss of insulation value of oiled feathers. Birds that are in contact with cold water experience far greater thermal stress than birds that are in contact with air. Oiled birds may move onto land to reduce thermal stress. Such birds might survive for longer periods of time (providing an opportunity for capture and rehabilitation) during periods of warm weather, as compared to periods of cold weather.			
Slope	Lakes have negligible slope, and therefore the short-term distribution of crude oil on the water surface may be determined primarily by wind. Streams and rivers have slope, which determines the downstream water flow velocity, as well as influencing the turbulence of that flow. Slope therefore helps to determine the downstream transport distance for spilled oil before emergency response can be effectively applied. This can affect the types of habitat that the spilled oil could affect, as well as the numbers and types of birds.			

7.1.3.7 Semi-Aquatic Mammals

7.1.3.7.1 Description

Most North American mammals are terrestrial in nature. However, some species have evolved to use aquatic environments as facultative or obligate habitat (Vaughan et al. 2000). Species inhabiting aquatic environments are more likely to be exposed to and be affected by oil in the event of a release because oil disperses more readily in aquatic environments, and because contact with cold water results in a much higher level of thermal stress on oiled animals than exposure to air (McEwan et al. 1974; Knopper et al. 2016). Semi-aquatic species also tend to seek refuge in their aquatic environment rather than disperse over land. For example, beavers, muskrats and otters will seek refuge in lodges when threatened by predators. Therefore, semi-aquatic mammals were selected as a receptor group to focus upon for this effects assessment. The semi-aquatic mammal species found in Minnesota include terrestrial species such as moose and raccoon, but this assessment will focus particularly upon species that have a primary association with the aquatic environment such as muskrat, beaver, American mink, river otter, and the water shrew.

Among semi-aquatic mammals, moose are the least dependent on aquatic environments. Their association is based on the preferential foraging for vegetation in lakes and wetlands during the open-water season (Franzmann 1981), which would limit oil exposure to periods when hypothermia would be less severe than during the winter period. Moose are large-bodied, and would be less prone to hypothermia due to oiling of the fur than smaller mammals. The raccoon is less dependent on aquatic environments, but is associated with riparian areas, foraging on aquatic invertebrates and fish during the open-water season (Lotze and Anderson 1979). Both moose and raccoon would be expected to have the behavioral plasticity to select habitat where thermal stress would be reduced if they were to be oiled, and in addition would be able to continue to feed even when denied access to an oiled watercourse. These species are considered to have low (i.e., moose) or moderate (i.e., raccoon) sensitivity to crude oil exposure.

Other semi-aquatic herbivores in this receptor group include beaver and muskrat. These species inhabit aquatic environments year-round and overwinter in lodges located on lakes, rivers, or wetlands (Jenkins and Busher 1979; Willner et al. 1980). Both species eat a mixture of aquatic and terrestrial vegetation. American mink, North American river otter, and northern water shrews are also semi-aquatic species that forage year-round in aquatic environments, raising their young in dens along shorelines or in abandoned beaver lodges. These are primarily carnivorous species that generally eat a mixture of fish and invertebrates (Larivière 1999; Larivière and Walton 1998; Beneski and Stinson 1987). These species would have little or no opportunity to select environments where contact with water could be avoided if they were to become oiled, and similarly little behavioral plasticity to continue feeding if forced away from the aquatic environment. These species are considered to have high sensitivity to crude oil exposure.

Among semi-aquatic mammals, only the moose (Special Concern) is listed under either the federal *Species at Risk Act* or under Minnesota's Endangered Species Statutes (MN DNR 2013; USFWS 2016).

7.1.3.7.2 Observed Effects

A number of hydrocarbon oil releases from pipelines, as well as rail car and storage tank examples, provide an overview of observed effects of oil releases on mammals in aquatic environments (e.g., river, lakes and wetlands) similar to those that could be encountered in Minnesota. This review is not exhaustive, but provides a range of observed effects of a variety of oil types on semi-aquatic mammals, under different environmental conditions. The case studies provide an empirical basis from which the likely effects of oil releases on semi-aquatic mammals can be predicted, with consideration of the modifying effects of oil type, and environmental factors.

> ***Ashland Petroleum****: On January 2, 1988, a 40 year old storage tank collapsed at the Ashland Oil Facility in West Elizabeth, Pennsylvania. The tank collapse released approximately 90,500 barrels of diesel fuel, of which 23,800 barrels flowed into the Monongahela River 27 miles south of Pittsburgh, Pennsylvania. As the release moved downstream, water supplies were contaminated, resulting in the disruption of water services to riverside cities in Pennsylvania, Ohio, and West Virginia. As of January 7, only 1,900 barrels of product had been recovered (NOAA 1992). The effort to recover the oil was hindered by dams and locks along the Ohio River, ice cover, emulsification of the oil, and dispersion of the oil into the water. The Pennsylvania Game Commission assisted by volunteers set up bird cleaning programs and monitored for oiled wildlife, though efforts were hampered by weather conditions and partial ice cover that resulted in rescue workers not accessing areas where wildlife might concentrate. While bird fatalities were reported as a result of the release, there were no semi-aquatic mammals reportedly affected (Miklaucic and Saseen 1989), though there would have likely been muskrat, beaver, mink, and river otter inhabiting the aquatic environment.*

> ***Exxon Bayway****: On January 2, 1990, an underwater pipeline released approximately 13,500 barrels of No. 2 heating oil into the Arthur Kill waterway at the mouth of Morse Creek between New Jersey and Staten Island, New York (NOAA 1992). Initial response efforts focused on containment of the release and removal of the larger masses of oil. Concentrations of floating oil and mousse in the open water, primarily between Howland Hook and Fresh Kills, were collected by self-propelled skimmers. Oil concentrated and stranded above the berm on the beaches from Cedar Point to Rossville as well as in other natural areas. Factors resulting in the dispersal of oil beyond the berm were not reported, though it could have been due to tidal and wave action. Environmentally sensitive areas were protected with boom and skimmers that collected the larger masses of free-floating oil. Through February 20, 1990, monitoring crews reported 29 dead muskrats among other affected wildlife (NOAA 1992).*

***Lakehead**: On March 3, 1991, a Lakehead Pipeline Company, Inc. owned pipeline ruptured and released over 40,000 barrels of crude oil (NOAA 1992) approximately two miles north of Grand Rapids. Some of the oil spread onto the 18 in. thick ice sheets on the Prairie River. Oil formed into 8 inch deep pools on top of the ice in the middle of the river and was also present under the ice. Vacuum trucks were used by clean-up personnel to remove the oil from the surface of the ice. Workers used squeegees to push the oil along the ice to a removal location. Booms were used on the river by cutting a slot through the ice cover with chainsaws. Ice that had been permeated with oil was chopped into blocks small enough to be carried away to a separate part of the river. Clean-up personnel sprayed the ice blocks with hot water to wash out the oil, which was then recovered with skimmers. Blocks that were only slightly contaminated were moved to lined holding tanks and broken up. The crushed ice was then allowed to melt to recover residual oil. There were no reports of semi-aquatic mammals affected by the oil release; effects to fish and wildlife were reported as minimal by the MN DNR (Telegraph Herald 1991), likely due to ice-covered conditions at the time of the release.*

***OSSA II**: On January 30, 2000, an estimated 29,000 barrels of mixed heavy crude oil and diluent (combined density of approximately 0.8 g/mL) were released from the Transredes S.A operated OSSA II pipeline at the Rio Desaguadero river crossing in Bolivia as the river was rising to peak flood conditions (Lee et al. 2001, 2002; Owens and Henshaw 2002). Due to the very high river flow and water velocity conditions, and perhaps also due to the low viscosity of the oil which would allow it to become dispersed into the water as fine droplets, oil was found up to 230 miles downstream from the release location. For the most part, the surface oil was deposited in strips, generally 3 to 6 ft wide and up to 0.5 to 1 inch thick. Many sections of river bank had a horizontal line of oil (a bathtub ring) where the oil was stranded, indicating the water level at the time (Owens and Henshaw 2002). The response effort included more than 3,600 people who recovered the oil within three months. Wasson et al. (2000; in Owens and Henshaw 2002) reported on the wildlife effects of the release and indicated that no wildlife fatalities other than a small number of birds were observed during the extensive post-release monitoring.*

***Pine River**: On August 1, 2000, a Pembina Pipeline Corp. pipeline failure released approximately 6,200 barrels of light crude oil, of which an estimated 2,800 barrels entered the Pine River 70 miles upstream of Chetwynd, British Columbia (BC MOE 2000a). An estimated 300 to 710 barrels remained unaccounted for following the clean-up and remediation (Goldberg 2011). Most of the oil unaccounted for was considered likely to be entrained in sediment or debris in the river channel. Response measures included placing two containment systems, one approximately 14 miles downstream and a second approximately 19 miles downstream (BC MOE 2000c). The river was flowing at a low stage at the time of the release (approximately 5,680 ft^3/s measured at a station 100 miles downstream compared to flow rates above 31,880 ft^3/s during late spring and early summer) (Bustard and Miles 2011). The Pine River has a gradient of approximately 0.225% in the first 25 miles downstream from the release location, decreasing to 0.1% farther* *downstream (Bustard and Miles 2011). There were incidental reports of beaver, otter, and mink being affected, though no injured or oiled mammals were detected or captured during the wildlife monitoring program (BC MOE 2000b).*

***Wabamun Lake**: On August 3, 2005, a Canadian National freight train derailed near the Village of Whitewood Sands, Alberta, releasing approximately 4,500 barrels of Bunker C fuel oil (Heavy Fuel Oil 7102; Hollebone et al. 2011) and 550 barrels of pole treating oil. An estimated 950 barrels of the Bunker C oil entered Wabamun Lake where it formed a thick black slick approximately 0.5 inch thick (Wernick et al. 2009). The heavy Bunker C product formed several types of aggregates including tar balls, larger tar "logs", submerged sheets, large lumps, tar balls that sometimes reformed into oil slicks, and a "slurry" composed of finely divided organic matter and small oil droplets (Fingas et al. 2006; Hollebone et al. 2011). The oil exhibited a variety of behaviors including submergence, neutral buoyancy, and resurfacing as a result of contacting and taking up foreign matter (such as mineral particles and organic debris) on its path to the lake (Fingas et al. 2006). No dispersions of oil in water were observed in the lake, and no mousse formation was reported in the three years following the release (Hollebone et al. 2011). Overall, the water in the open water area of the lake was reported to be not contaminated with released hydrocarbons or associated metals (Anderson 2006). This is consistent with the very low concentration of relatively water-soluble components (such as BTEX) in the released oil, and the relatively low water solubility of this heavy oil. Similarly, sediments beneath the open water portions of Wabamun Lake were reported not to have been contaminated with petroleum hydrocarbons and were considered to be of similar quality to concentrations measured in 2002 or shortly before the release (Anderson 2006).*

Clean-up activities included cutting of the vegetation and vacuum removal of submerged tar balls entrained in the reed bed detritus (Wernick et al. 2009). A two-year study was conducted to assess regrowth. The study found that exposure to the oil, which was released late in the growing season, did not cause large-scale changes to these emergent plant communities (Wernick et al. 2009). Physical factors such as clean-up activities and vegetation management appeared to be responsible for reduced regrowth observed at some locations (Wernick et al. 2009; Thormann and Bayley 2008).

Despite an intensive wildlife monitoring program, and a wildlife recovery center set up immediately after the release, there were no reports of semi-aquatic mammals injured by the oil, although there was considerable mortality of waterfowl (TSBC 2007). It is likely that beavers, muskrat, mink, and possibly river otters inhabit this system.

***Glenavon**: On April 15, 2007, a release occurred on the Enbridge Line 3 pipeline approximately 1 mile downstream of the Glenavon pump station near Glenavon, Saskatchewan. The rupture released approximately 6,200 barrels of heavy crude oil and affected approximately five acres of a wetland on farmland (TSBC 2008a; SLR Consulting*

2008a). Within two days of the release, approximately half of the crude oil had been recovered (Canada.com 2007a). The site was monitored for one week for exposure of wildlife to oil, and wetlands within 0.6 miles (1 km) were surveyed for any wildlife that may have been oiled initially and moved from the release site. Wildlife monitoring did not detect mammals affected by the release (SLR Consulting 2008a), though it is likely that this system provided habitat for muskrats and possibly mink. The small number of wildlife (five birds) oiled by the release was attributed to the fact that the release occurred at night, and the rapid mobilization of a response to remove oil and reduce exposure of wildlife.

***Marshall**: On July 25, 2010, Enbridge's Line 6B pipeline experienced a release in a wetland near Marshall, Michigan. Approximately 20,000 barrels of heavy crude oil containing diluted bitumen were released over a period of about 17 hours. The pipeline contained two different batches of crude oil at the time of the release (NTSB 2012 a). It is estimated that the released oil consisted of approximately 77% CLWB diluted bitumen and 23% Western Canadian Select, also diluted bitumen (Enbridge 2013a). Of this, approximately 8,000 barrels reached Talmadge Creek and the Kalamazoo River (Enbridge 2013a). Wildlife monitoring programs reported that 40 mammals were either found dead or subsequently died during rehabilitation (USFWS et al. 2015a). In addition, 23 oiled mammals were captured, successfully rehabilitated, and released. An unknown number of mammals are assumed to have been oiled but never found or captured. The primary species reported affected were muskrat (45%), raccoon (13%), and beaver (13%) (USFWS et al. 2015a).*

***Rainbow**: On April 28, 2011, a pipeline owned by Plains Midstream Canada released approximately 28,000 barrels of sweet crude oil into a muskeg/stagnant water area near the community of Little Buffalo in the Peace River region of Alberta. The release occurred on a hillside, and the oil flowed a half mile down the pipeline ROW and pooled in a low-lying area containing abandoned beaver ponds. The release encompassed an area of approximately 20 acres (ERCB 2013). As part of the response, wildlife mitigation measures, which included fencing and various deterrents, were implemented (ERCB 2013). Despite spill-response wildlife-mitigation measures, wildlife mortality included 11 beavers and several small rodents (ERCB 2013) during response activities up through November 2012. No cause-of-mortality analysis was conducted for the deceased wildlife, but it is presumed that oiling was the likely cause.*

***2011 Yellowstone River**: On July 1, 2011, flood conditions in the Yellowstone River resulted in a release from the ExxonMobil Silvertip Pipeline carrying medium sour crude oil near Laurel, Montana. Riverbed erosion exposed the 12-inch pipeline beneath the crossing, and debris caught on the washed-out pipeline causing stress, resulting in a clean break. The failure was detected at the pipeline control center and the line was shut down within 10 minutes (USDOT 2012). Approximately 1,500 barrels of crude oil was released into the Yellowstone River (USDOT 2012). The affected reach of the Yellowstone River has an* *average gradient of 0.17%. Crude oil affected primarily shorelines and banks immediately downstream of the release site (MT DEQ 2015b). According to the USEPA (2011), no oiling of semi-aquatic mammals was reported, though muskrats, mink, river otters, and possibly beavers likely inhabited the area.*

***Red Deer River**: On June 7, 2012 a Plains Midstream Canada ULC (Plains) pipeline released approximately 2,900 barrels of light crude oil into the Red Deer River downstream of Sundre, Alberta as a result of high water levels in the river that exposed the pipeline and caused structural damage (AER 2014). The migration of surface oil was stopped by booms placed at Gleniffer Lake, but dissolved hydrocarbons continued to move downstream. This resulted in potential for both toxicological and physical effects upstream of the booms, but limited potential for physical effects downstream (Teichreb 2014). Two beavers were reported among the affected wildlife (Derworiz 2012). Officials with Alberta Environment indicated that effects to wildlife were minimal (Derworiz 2012).*

***Line 37**: On June 22, 2013, unusually heavy rains caused ground movement that compromised the integrity of the Enbridge Line 37 pipeline approximately 1 mile north of the terminal in Cheecham, Alberta. The resulting failure released approximately 1,300 barrels of synthetic light crude oil underground with some oil seeping to the surface where it flowed overland entering a wetland and unnamed lake (Enbridge 2013c). Initial clean-up and remediation recovered 93% of the crude oil with the remaining oil found in soils and the fen. No affected semi-aquatic mammals were detected (Focus Wildlife Canada 2013), though it is likely that muskrat and mink inhabited the wetland.*

***Mid Valley**: On October 13, 2014, a Sunoco pipeline release occurred near Mooringsport, Louisiana, resulting in approximately 4,500 barrels of sweet crude oil entering the Miller branch of the Tete Bayou, which feeds into Caddo Lake. Although containment booms prevented the oil from entering Caddo Lake, approximately 10 miles of the creek were affected. Media reported that 486 dead animals were collected and 47 were cleaned and released (Welborn 2014a). Most of the animals were crawfish and amphibians, but numbers and species were not provided. No semi-aquatic mammals were reportedly affected (Welborn 2014b), though this area would likely be inhabited by nutria, muskrat, river otter, beaver, and mink.*

***Yellowstone River**: On January 17, 2015, a Bridger Pipeline LLC pipeline released approximately 715 barrels of Bakken crude oil (estimates ranged from 300 to 1,200 barrels) into the Yellowstone River approximately 5 miles upstream of Glendive, Montana (MT DEQ 2015b). The pipeline breach occurred where the pipeline crossed under the river. Winter conditions resulted in extensive ice cover, but aerial patrols discovered oil as far as 25 miles downstream of Glendive (The Guardian 2015). Booms were deployed on the ice and in areas of open water downstream to collect oil from the surface (Hirji 2015) but winter conditions combined with thawing resulted in unsafe working conditions and only a limited amount of oil (approximately 60 barrels, MT DEQ 2015a) was recovered* *from the river. There were no reports of oiled wildlife (including mammals) or dead fish (Stuart 2015). The Montana Departments of Natural Resources and Conservation and Fish, Wildlife and Parks expressed concern that the most significant source of damage to the riverine system was the physical damage caused by response crews and equipment during clean-up operations (MT DEQ 2015a.*

7.1.3.7.3 Expected Effects of Released Oils

The case studies presented in the foregoing section highlight some of the key factors of oil releases in aquatic environments on semi-aquatic mammals.

As previously indicated, semi-aquatic mammals are expected to be more vulnerable than terrestrial mammals since they rely on aquatic system for all or a portion of their life cycle, and releases into aquatic environments may result in oil dispersing or being transported further from the release site. Unlike waterbirds that often flock and congregate in large numbers (e.g., ducks, geese, gulls) which can be susceptible to a release, semi-aquatic mammals are typically territorial species that are more evenly distributed and have lower densities spread across suitable habitat in the landscape. Consequently for semi-aquatic mammals, the potential effects of an oil spill on regional populations are expected to be relatively low. However, there are also exceptions to low density mammal populations. Muskrats are occasionally found in high densities in wetland systems, making local populations more vulnerable to releases.

The effects of hydrocarbon releases on semi-aquatic mammals can be difficult to quantify directly because of challenges associated with detecting dead and injured individuals post-release. Bowyer et al. (2003) indicated that searching shorelines was not a reliable method of locating dead river otters following a release. This is likely a function of many semi-aquatic mammals (i.e., beavers, mink, muskrat, and otter) seeking refuge in lodges or burrows out of sight when distressed, which prevents detection. Greer et al. (2005) reported that 70 muskrats were recovered during monitoring programs following a crude oil release, but their assessment indicated that this represented less than 20% of the likely affected muskrats based on population estimates within the affected area. However, this is not likely to be the case for a large mammal such as the moose, which is more easily observed than aquatic mammals. The case studies do not provide any records of oiled or dead moose (or other ungulates) following an oil release, and it is concluded that these animals are not highly exposed to crude oil release, or highly sensitive to oiling in the event of such exposure.

Effects to semi-aquatic mammals, like other species of wildlife, are typically described in terms of three types of effects: direct physical effects, direct toxicological effects, and indirect effects through changes to habitat (e.g., land cover and food availability) (Albers 2003; Malcolm and Shore 2003; Lee et al. 2015). These three types of effects on semi-aquatic mammals are discussed below.

7.1.3.7.3.1 Direct Physical Effects on Semi-aquatic Mammals

The most frequently reported direct physical effect of a hydrocarbon release is the adhesion of oil to the fur of semi-aquatic mammals and the subsequent loss of insulation and buoyancy. This is generally considered the most adverse of effects to this receptor group (Albers 2003). Mammals rely on fur for thermal regulation, and aquatic mammals have fur that is adapted to repel water and maintain insulation under water. Loss of water repellency as a result of contact with oil and associated hypothermia can greatly reduce the survival of semi-aquatic mammals and rapidly result in death (McEwan et al. 1974; Kooyman et al. 1977; Wolfe and Esher 1981; Lipscomb et al. 1994).

Several factors affect the severity of the effects of oiling of fur. Lower ambient temperature will amplify the physiological effects of reduced insulation, because of the increased heat loss with increased temperature gradients between organisms and the ambient temperature (i.e., colder air or water temperatures). Smaller organisms (e.g., shrews) are likely to succumb to physical oiling at a faster rate than larger organisms (e.g., moose) because the surface area to volume ratio of smaller organisms is larger resulting in a greater rate of heat loss per volume, reducing body temperatures faster in smaller organisms. Exposure of an oiled animal to water also results in much greater thermal stress than exposure of the same animal to ambient air (McEwan et al. 1974; Knopper et al. 2016).

At higher temperatures, in addition to a reduced heat gradient, oil tends to weather at a faster rate, shortening the duration of insulation loss reducing the potential for adverse effects (Hurst and Oritsland 1982). However, the severity of effect also depends on the type of crude oil released. Hurst and Oritsland (1982) studied the effect of oiling on the insulation of polar bear fur using different oil types and found that thermal conductivity increased with increasing viscosity of the oils, likely due to prolonged matting of the fur by heavier oils. Weathered diluted bitumens have both high density and viscosity, and are more adhesive than other crude oils (NAS 2016). This would reduce the likelihood of unassisted wildlife survival and recovery from oiling for diluted bitumens, relative to that for lighter crude oils.

7.1.3.7.3.2 Direct Toxicological Effects on Semi-aquatic Mammals

Acute toxicity of hydrocarbons is generally the result of narcosis from exposure to certain components of oil, namely some alkanes, mono-aromatics (BTEX) and PAHs (2-ringed naphthalenes) (Dupuis and Ucan-Marin 2015). Exposure to sufficient quantities of these low molecular weight hydrocarbons typically results in acute narcotic effects shortly after an oil release. This effect is more pronounced at the site of release prior to vapors being diluted in the environment or evaporating from the water surface into the atmosphere. In semi-aquatic mammals, the more important exposure routes are direct ingestion of oil or contaminated food, and inhalation. While dermal absorption may occur, exposure is reduced by the fur of semi-aquatic furbearers, particularly for heavier oil types that would have lower potential to penetrate the fur and contact the animal's skin. Semi-aquatic mammals may ingest oil following physical oiling of their fur by grooming and cleaning themselves to remove the contaminants (McEwan et al. 1974).

The contamination of water surfaces by oil may increase the inhalation exposure to toxic components for semi-aquatic mammals that are swimming on the surface (Peterson 2001; Frost et al. 1994). Inhalation of vapors was suggested as a probable cause of interstitial pulmonary emphysema following necropsies of dead sea-otters, after the Exxon Valdez spill (Lipscomb et al. 1994). This could be of similar concern for species such as beaver, river otter, and muskrats which also spend the majority of their life cycle in water. However, the ultimate cause of death of recovered wildlife following a release is challenging as few animals are necropsied and results reported. Baker et al. (1981) reported on the death of otters near the Sullom Voe oil terminal, in the Shetland Islands, United Kingdom, following a release of Bunker C fuel oil on December 31, 1978. Heavy fuel oil (bunker C) would contain much less volatile material than most crude oils, so narcosis as a result of inhalation is unlikely to cause death; however, the heavy fuel oil would also contain much higher levels of PAHs than most crude oils (Dupuis and Ucan-Marin 2015). At least 13 otters died following the Sullom Voe release, although others presumably also died but were not detected (Baker at al. 1981). Five animals, with external oiling ranging from minor on the rump and tail, to heavy coating the entire body, were sent for post-mortem examination. The cause of death for each of the animals examined was determined to be a hemorrhagic gastro-enteropathy, presumably caused by ingestion of oil as a result of grooming. However, hypothermia was also considered to be a potential contributor to the death of these animals (Baker et al. 1981). Two dead sheep, which had been eating oil contaminated seaweed, were also examined and showed oesophageal and gastric ulceration (Baker et al. 1981).

Sublethal effects of oil exposure in mammals also occur. Schwartz et al. (2004a, 2004b) determined that exposure of mink to bunker C fuel oil, at low concentrations (500 ppm in diet) for extended periods of time, would result in immune system, systemic, and hematological responses with potential consequences for survival and reproduction in individuals. These effects may not be observed in field monitoring programs or during wildlife rehabilitation programs following a release. Similar results were also observed in studies by Mohr et al. (2008, 2010). Note, however, that bunker C oil contains different proportions of toxic hydrocarbons (e.g., less BTEX, but more PAHs; Dupuis and Ucan-Marin 2015) than diluted bitumens and conventional crude oils.

7.1.3.7.3.3 Indirect Effects of Oil Release on Semi-aquatic Mammals

Oil releases may have indirect effects on semi-aquatic mammals through effects to habitat or changes in food quality or availability. Habitat loss is more easily quantified than effects to individuals, because suitable habitat characteristics of mammals are generally well known, and effects are more easily quantified.

Indirect effects on individuals may also occur as a result of rehabilitating efforts alone. Ben-David et al. (2002) examined the survival rate of captured and rehabilitated otters exposed to oiling compared to wild otters. They found that survival was lower for captured and released otters, but the effect of oiling was not a factor because the survival rates of captured, oiled, and rehabilitated otters were similar to those captured and released without oiling (i.e., capture controls), indicating that the toxicological effect of oiling was not significant. Otters are known to suffer from capture myopathy (Hartup et al. 1999), which would have implications for indirect effects of rehabilitation following oiling of this species, and potentially other wildlife species.

Bowyer et al. (2003) noted that following the Exxon Valdez spill, river otters had larger home ranges, lower body mass, and a less varied diet than individuals in control sites. Density of otters did not differ between sites, suggesting no population level effects occurred. However, it does suggest that otters may require larger areas to obtain sufficient food sources in areas affected by oil. Loss or degradation of habitat may lead to dispersal of individuals in search of suitable habitat, which can reduce survival through competition between immigrants and local residents, particularly in territorial species (Crawford et al. 2015).

Wolfe and Esher (1981) found that rice rat swimming behavior was affected when oil was added to swim tanks (both south Texan and empire crudes) compared to controls, and individuals avoided swimming in oiled water. The higher adhesion rate of weathered diluted bitumens and heavy crudes (NAS 2016) also requires more intensive remediation efforts that could result in more severe changes to habitat quality, though effects are typically of short to medium duration (e.g., one to two years) as was observed from the Glenavon, Rainbow, and Wabamun releases described above.

Table 7-41 and Table 7-42 provide a summary of the expected environmental effects of oil releases to semi-aquatic mammals in inland environments. Table 7-41 considers the effects of specific oil characteristics on the expected types and scope of environmental effects. Table 7-42 considers the effects of environmental factors characteristics on the expected types and scope of effects.

Table 7-41 Biological Receptor: Semi-Aquatic Mammals

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—buoyancy	Light crude oils typically have a relatively low density (0.78-0.88 g/mL, Dupuis and Ucan-Marin 2015) and are buoyant in freshwater aquatic environments.	Medium crude oils typically have an intermediate density compared to light and heavy crudes, and are buoyant in freshwater aquatic environments (Dupuis and Ucan-Marin 2015).	Heavy conventional crude oils can have density ranging of 0.88 to 1.00 g/mL, while fresh diluted bitumen will have density less than 0.94 g/mL (Dupuis and Ucan-Marin 2015).	While raw bitumen has a higher density than water, diluted bitumen is less dense and limited evaporative mass loss at environmentally-relevant temperatures suggests that weathered dilbit will remain afloat as it will retain sufficient diluent to maintain a lower density ((Lee et al. 2015; see also Section 7.1.2). Recovery of released oil is facilitated if the oil floats on the surface of the water. A more rapid recovery of oil will reduce the potential exposure duration to semi-aquatic mammals. Buoyancy of oil will also prevent contact with semi-aquatic mammals swimming submerged or foraging in the benthic environment.
Oil properties—viscosity	Light crudes will spread rapidly on water because of their low viscosity (1 to 5 mPa•s, NAS 2016).	Medium crudes have an intermediate viscosity (8 to 112 mPa•s, NAS 2016).	Heavy crudes (820 to 475,000 mPa•s) and diluted bitumens (270 to 50,000 mPa•s) weather to high viscosity (NAS 2016).	Viscosity is a function of oil chemistry. Diluted bitumens tend to display a more rapid increase in viscosity due to weathering of low molecular weight hydrocarbons associated primarily with the diluent than conventional heavy crude oils. Oil having low viscosity will rapidly spread across the water surface forming a thin and relatively uniform slick. More viscous oils will spread more slowly and may exhibit thicker but patchier slicks with associated sheens. Higher viscosity oils will have lower dispersion and generally result in smaller spatial areas where semi-aquatic mammals may come in contact with the oil. Oil viscosity also influences adhesion, which is relevant to physical oiling (see Oil Properties – adhesion below)

Table 7-41 Biological Receptor: Semi-Aquatic Mammals

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—adhesion	Light crudes have low adhesion and viscosity (NAS 2016) and can be expected to penetrate the fur to contact skin.	Medium crudes have an intermediate adhesion and viscosity (NAS 2016). Medium crude oils also readily penetrate fur to contact skin.	Heavy crudes and particularly diluted bitumens are highly adhesive and more viscous than light and medium crude oils. Fresh diluted bitumens have relatively low viscosity, and would penetrate fur. However, weathered heavy crudes may tend to stick to the surface of fur without penetrating to contact the skin.	Properties of adhesion and viscosity may change the way that crude oil interacts with fur. Light oils may more readily penetrate fur and reduce insulation; heavy oils, particularly when weathered, may tend to adhere in a thick layer to the hair without immediately penetrating to the skin surface. This results in more difficult cleaning and removal of oils from fur and extended duration of physical effects, though less potential for dermal exposure to toxic hydrocarbon components there is increased potential for ingestion (see toxicity of chemical components discussion below).
Oil properties—toxicity of chemical constituents	Light crude oils often contain high levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, depending on the oil type, but can be high (>10,000 mg/kg) in Bakken oils.	Medium crude oils often contain moderate levels of BTEX and other relatively water soluble hydrocarbons. Levels of TPAH are variable, but can exceed 10,000 mg/kg.	Levels of BTEX and other relatively water soluble constituents are variable: generally low in heavy conventional oils, but variable in diluted bitumens depending upon the nature of the diluent. Levels of TPAH are variable, but typically depleted in napthalenes and less than 10,000 mg/kg.	Acute effects on mammals are generally caused by physical oiling, not related to the BTEX content of the oil. Chronic effects on mammals of released crude oil, if any, are likely due to dietary TPAH exposure. Diluted bitumens do not contain higher concentrations of either BTEX or TPAH than many conventional crude oils (Lee et al. 2015). Diluted bitumens contain the same suite of PAHs as conventional crude oils, but at different relative concentrations due to the highly weathered nature of the bitumen component, and the modifying effect of the diluent. Additional details on the characteristics of diluted bitumen are provided in Section 7.1.2.

Table 7-41 Biological Receptor: Semi-Aquatic Mammals

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil properties—persistence	Light crude oils typically contain only small proportions of higher molecular weight components, such as resins and asphaltenes. Light crude oils generally biodegrade readily.	Medium crude oils contain variable proportions of resins and asphaltenes. Asphaltenes would be removed from synthetic medium crudes during processing of bitumen.	Heavy conventional crude oils and diluted bitumens typically contain higher proportions of resins and asphaltenes, which tend to resist biodegradation.	In general, heavy conventional crude oils and diluted bitumens would be expected to biodegrade less rapidly than light or medium crude oils. However, any oil can be persistent if deposited in an environment where there is little or no available oxygen. Persistence in the environment will directly influence the potential exposure duration of semi-aquatic mammals to oil.

Table 7-42 Biological Receptor: Semi-aquatic Mammals

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Habitat type	Light crude oil will spread rapidly due to its low viscosity, potentially resulting in effects over a larger area in lakes and wide rivers.	Medium crude oil has low viscosity, although viscosity increases at lower temperatures, and will behave similarly to light crude oils.	Heavy crude oils have high viscosity. Diluted bitumens also have high viscosity (although reduced while fresh due to the effect of the diluent), potentially resulting in effects over a smaller area in lakes and wide rivers, due to the oil's resistance to spreading in these habitats.	Low viscosity oils will spread more rapidly, and to thinner slicks, than high-viscosity oils. As a result, low viscosity oils have a higher potential to affect a larger area of habitat, particularly open-water habitats such as lakes and wide rivers, than higher viscosity oils. At the same time, higher viscosity oils will tend to form thicker slicks than low viscosity oils. This could lead to a contrast of "more mammals oiled less heavily" with lighter oils, as compared to fewer mammals oiled more heavily with heavier oils.
Season	Light oils remain fluid at low temperature and retain the potential to spread rapidly during the winter. Light oils may penetrate cracks in ice or close to shore, allowing the oil to get beneath the ice and spread downstream. In summer, light crude oils would also flow readily and spread rapidly, having the potential to contact larger numbers of mammals than heavier, more viscous oils.	Medium oils are slightly more viscous than light oils, and would also tend to flow readily under winter conditions. Medium crude oils would tend to flow readily and spread rapidly under summer conditions.	Heavy oils become much more viscous at low temperatures, and as they weather. Heavy oils and diluted bitumens would have more resistance to flowing or penetrating cracks in ice to reach the water surface than would be the case for light or medium crude oils. During the summer, diluted bitumens would flow readily and spread rapidly while fresh. Weathering in the first 24 to 48 hours would result in increasing viscosity and density, limiting further spreading of the oil on the water surface.	Season affects both the behavior of oil in the environment, and the distribution and behavior of mammals that could be exposed to released oil. Some mammals do not use aquatic environments during the winter (e.g., moose and raccoon), while others become isolated within an aquatic system (e.g., beaver and muskrat) and would be more vulnerable to a release into an aquatic system. During the open water season, mammals have the ability to disperse from waterbodies and seek new habitat.
Weather	Periods of high rainfall and high water levels could transport released crude oil into riparian areas, in addition to potentially increasing			

Environmental Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
conditions—rainfall and water levels	downstream transport distances. This would affect all crude oil types. If crude oil is transported into riparian areas, then mammals that use terrestrial areas more (e.g., raccoons, moose) could be exposed to the oil and its effects either through direct contact with oil, or though food chain effects as PAHs and oily residues are ingested with food and associated soil.			
Weather conditions—temperature	The survival of oiled mammals could be affected by ambient temperatures, regardless of season. Mammals that are in contact with cold water experience far greater thermal stress than mammals that are in contact with air; especially for more aquatic mammal species (e.g., muskrat, beaver, otter). Some oiled mammals may avoid entering the water to reduce thermal stress. Those individuals might survive for longer periods of time during periods of warm weather as compared to periods of cold weather, providing greater opportunity for capture and rehabilitation.			
Slope	Lakes have negligible slope, and therefore the short-term distribution of crude oil on the water surface may be determined primarily by wind. Streams and rivers have slope, which determines the downstream water flow velocity, as well as influencing the turbulence of that flow. Slope therefore helps to determine the downstream transport distance for spilled oil before emergency response can be effectively applied. This can affect the types of habitat that the spilled oil could affect, as well as the numbers and types of birds.			

7.1.4 Human Receptors

7.1.4.1 Human Health

7.1.4.1.1 Description

Human health relates to the physical health and well-being of people living or using lands near the Project, and is intrinsically important to the public. Many factors may influence a community's sense of well-being, including concepts such as trust and risk perception. However, in the context of an oil release, public health concerns are focused on the potential environmental effects to health that could arise from exposure to contaminants. People want to understand how their health may be affected by oil-related contaminants in the air they breathe, the water they drink, and the food they eat.

The typical health effects associated with short-term (acute) inhalation of volatiles from crude oil (including petroleum hydrocarbons and hydrogen sulfide) are headaches, dizziness, nausea, vomiting, cough, respiratory distress, and chest pain. Short-term skin contact with oil may result in dermatitis (Solomon and Janssen 2010). The literature suggests that these acute health effects observed in residents and clean-up workers do not persist over the long-term (Eykelbosh 2014). However, relatively little has been published regarding the long-term effects of exposure to an oil release. The International Agency for Research on Cancer (IARC 1989) has determined there is "limited evidence of carcinogenicity" of crude oil in experimental animals and "inadequate evidence of carcinogenicity" of crude oil in humans.

Crude oils are complex mixtures of thousands of PHC, and many non-petroleum compounds. To understand how crude oil may affect human health, it is necessary to assess the crude oil in terms of the various constituents, or chemicals of potential concern (COPC) that characterize its potential fate, transport, and toxicity in the environment. The primary groupings considered relevant to the assessment of human health are low molecular weight aromatics (BTEX), aliphatic and aromatic PHC fractions, PAHs, and other volatiles (including other types of organic compounds containing sulfur and nitrogen).

Higher molecular weight aliphatic and aromatic hydrocarbons (greater than C_{16}), including higher molecular weight PAHs, exhibit very low to negligible vapor pressure and are typically considered non-volatile. These non-volatile compounds are not expected in to be present in ambient air at substantive concentrations following an oil release, but they may persist in soil or sediment, affecting the biological tissue concentrations of food sources (e.g., fish). Conversely, other COPC such as BTEX and lower molecular weight hydrocarbons are highly volatile and may be relatively water soluble. While these lower molecular weight compounds are expected to be present in air and water in the short term, they are unlikely to persist as residues in sediment or biological tissues in the longer term.

7.1.4.1.2 Observed Effects

The following section summarizes a review of some historical oil releases and reported health effects. For some spills, no health effects were reported, but regulatory agencies imposed restrictions (e.g., evacuations, closure of potable water intakes, fishery closures) as a precaution to prevent exposures above levels that could be associated with health effects. These instances of regulatory restrictions are also considered relevant to the assessment of human health.

> ***Pine River, British Columbia**: On August 1, 2000, a failure of the Pembina Petroleum pipeline resulted in the release of approximately 6,200 barrels (985 m^3) of light crude oil. Approximately half of the released oil was estimated to have reached the Pine River (Goldberg 2011), which was experiencing low flows at the time of the release (5,700 ft^3/s at time of release versus 32,000 ft^3/s in late spring/early summer) (Bustard and Miles 2011). Of the oil that reached the Pine River, approximately 2,830 barrels (450 m^3) was later recovered (BC MOE 2000a). Following the release, the Pine River was closed to angling and area residents were advised not to use water directly from the river (BC MOE 2000b). The water intake for the water treatment plant in the Town of Chetwynd, located 68 miles (110 km) downstream of release was temporarily closed, and the use of many groundwater wells near the river was discontinued (BC MOE 2000a). The District of Chetwynd was able to resume use of the Pine River for their water supply three years later (Brown 2003).*

> ***Cass Lake, Minnesota**: In May 2001, during the installation of shallow groundwater monitoring wells at the Enbridge Energy Limited Partnerships South Cass Lake Pump Station in Cass Lake, Minnesota, crude oil contamination was detected in the subsurface. The site is located within the reservation environment of the Leech Lake Band of Ojibwe, and 12 residential homes and businesses, were identified within 0.6 miles of the of the site. There were concerns that the crude oil would affect domestic water-supply wells and result in human health risks. Initial groundwater samples collected in 2001 showed a maximum benzene concentration of 6,500 µg/L close to the source (Wenck Associates 2006), and a maximum benzene concentration 1,300 µg/L offsite. A contaminant plume of greater than 10 µg/L of benzene extends approximately 500 ft down-gradient from the crude oil source, 130 ft across, and vertically 6 to 10 ft (Drennan et al. 2010). Since drinking water wells were not located within 0.5 miles down-gradient of site, they were not affected by the crude oil (Natural Resources Engineering Company 2004).*

> ***Burnaby, British Columbia**: In July 2007, a backhoe ruptured the Trans Mountain pipeline in Burnaby, British Columbia. Heavy crude oil (diluted bitumen) sprayed 40 to 50 ft into the air for approximately 25 minutes, covering the surrounding area (TSBC 2008b). Several people were reportedly covered with oil, including emergency workers, two firefighters, and two members of the public (TSBC 2008b). Subsequent assessment classified 8 residential properties as heavily oiled, 15 as moderately oiled, and 21 as lightly oiled (TSBC 2008b). Approximately 250 people voluntarily left their homes (TSBS 2008b, Trans*

Mountain 2015). More than half of the people returned later that night and another 100 people returned the following day (Trans Mountain 2015). Residents from the most heavily oiled properties were housed in longer-term accommodations (Trans Mountain 2015). Air quality monitoring was initiated immediately after the release. Very high volatile organic compound levels were detected during the early stages of the incident, but declined rapidly as clean-up progressed (Eykelbosh 2014). Affected residents reported a number of health effects, including headaches (15%), respiratory tract irritation (8%), nausea (6%), dizziness (3%), and eye irritation (3%) (Eykelbosh 2014).

***Salt Lake City, Utah**: On June 12, 2010, approximately 800 barrels of medium crude oil were released from a Chevron crude oil transfer pipeline, spilling into Red Butte Creek in Salt Lake City, Utah. The creek flows through residential and commercial properties, affecting an estimated 600 homes and 1,800 residents (Utah Department of Health 2011).*

Environmental monitoring included both water and air sampling. Air monitoring for specific compounds (benzene, toluene, ethylbenzene, xylenes) was initiated on June 13, 2010. The highest benzene concentration in indoor air at a residential property was 1.9 µg/m^3 *(0.60 ppb), while outdoor air sampling indicated a maximum benzene concentration of 1.7 µg/m*^{3} *(0.53 ppb) (Utah Department of Health 2011). The maximum benzene concentration in water samples from Red Butte Creek was 27.6 µg/L (Utah Department of Health 2011).*

A public health assessment was completed to address community health concerns related to the crude oil contaminants, specifically focusing on water and air. The public health assessment concluded that measured concentrations of crude oil components in water did not represent a health hazard to the community from ingestion or dermal absorption and that measured concentrations of volatile components in air did not have the potential to harm human health through inhalation (Utah Department of Health 2011). However, because air sampling did not begin until one day after the release, the health risk from inhalation of vapors during the minutes and hours following the release could not be determined.

In November 2010, a survey was sent to over 600 residences in the community and over 131 responses were received (Utah Department of Health 2011). Of those that responded, 23% indicated the creek ran through their backyard, and 73% said they had smelled an unusual odor in the early days of the release (Utah Department of Health 2011). Respondents answered questions about the symptoms they had experienced at the onset of the release and at the time of the survey. From the data, the most common reported symptoms were nausea, headache, irritated eyes, and anxiety (Utah Department of Health 2011). The number of people experiencing symptoms decreased from June 2010 when the release occurred through November 2010 when the public health assessment survey was distributed (Utah Department of Health 2011). There was no control group identified for the study.

***Marshall, Michigan**: On July 25, 2010, approximately 20,000 barrels of heavy crude oil containing diluted bitumen were released over a period of approximately 17 hours from Enbridge's Line 6B pipeline near Marshall, Michigan (NTSB 2012a). At the time of the release, the pipeline contained two different batches of crude oil estimated to consist of approximately 77% CLWB diluted bitumen and 23% Western Canadian Select, also a diluted bitumen (Enbridge 2013a). Of this, approximately 8,000 barrels reached Talmadge Creek and the Kalamazoo River (Enbridge 2013a). These two watercourses were between 25-year and 50-year flood levels at the time of the release (MI DCH 2014b). The oil was transported approximately 37 miles downstream of the release (MI DCH 2013). Approximately 41,500 people were estimated to live within 1 mile of the affected area (MI DHC 2015).*

Air monitoring and sampling activities were initiated in the area of the release on July 26, 2010, and quickly expanded to include other nearby populated areas. Approximately 24 hours after the pipeline burst, benzene concentrations of 9,600 µg/m^3 (3 ppm) were recorded close to the initial release location, at the confluence of the Talmadge and Kalamazoo Rivers (MI DCH 2015). Residents in this area had already relocated due to the odors from the released oil (MDCH 2015). The highest concentrations of benzene reported were approximately 31,900 µg/m^3 (10 ppm), observed approximately two days after the release at a location where no one was living (MI DCH 2015). Lower levels of benzene were measured at the same location or nearby on the same day, and in the days after, indicating that these air concentrations were not sustained (MI DCH 2015).

At the time of the release, the MI DCH (2014b) issued a precautionary advisory against swimming and fishing, and local health departments banned recreational use of the affected river reaches. Surface water samples (collected during July 2010–April 2012) and fish tissue samples (collected in 2010 and 2011) were submitted for analysis of crude oil constituents, particularly PAHs and certain metals, as well as other contaminants not related to crude oil (e.g., mercury and PCBs) to evaluate if the oil release, or the resulting clean-up activities, caused changes to contaminant levels in the fish (MI DCH 2014b). Oil-related and non-oil-related chemicals were measured in the surface water. Only a few chemicals (mostly PAHs) were detected above health-protective screening levels, and these exceedances occurred in only a small percentage of the surface water samples. Nickel and vanadium were not detected in fish filets, but some PAHs were detected in some filets (MI DCH 2014b). Mercury and PCB levels in fish filets were similar to those observed prior to the release (MI DCH 2014b). In June 2012, most of the river was re-opened for recreational use, and the fish consumption advisory in relation to the release was lifted.

Although there was no evidence to suggest that the oil release had contaminated groundwater resources, a precautionary bottled water advisory was issued on July 29, 2010 to allow time for well water samples to be collected and analyzed (MI DCH 2013). Approximately 168 private wells were selected for sampling based on proximity to the *release (i.e., within 200 feet of the high-water level mark from the July 2010 flood event) (MI DCH 2013). Water samples from the wells were analyzed for both crude-oil related chemicals and other chemicals. No oil-related organics above their screening levels were detected in the potable water samples (MI DCH 2013).*

Sediment samples collected from the Kalamazoo River and Morrow Lake in the spring of 2011 from areas exhibiting moderate to heavy amounts of submerged oil had detectable concentrations of VOCs, PAHs, TPHs, and metals (i.e., molybdenum, nickel, and vanadium) (MI DCH 2012).

In response to concerns about acute health effects associated with the release, MI DCH collected data from health care providers and the state surveillance system, conducted a door-to-door health survey, and reviewed Poison Control Center hotline reports. Headache, nausea, and respiratory symptoms were the predominant symptoms reported by exposed individuals (MI DCH 2010).

Subsequently, a number of public health assessments were completed in relation to the release. The first addressed concerns related to submerged oil located in the sediment. The study concluded that contact with sediment containing submerged oil, tar patties, or oil sheens could cause temporary health effects such as skin irritation, which would not persist in the absence of continued exposure (MI DCH 2012). The study further concluded that repeated skin contact and accidentally eating a small amount of sediments containing submerged oil would not result in long-lasting health effects or in a higher than normal risk of cancer (MI DCH 2012).

A separate public health assessment was completed to assess potential health effects associated with drinking water from wells located along stretches of Talmadge Creek and the Kalamazoo River. Two oil-related inorganic chemicals (nickel and iron) were found in private drinking water wells, but were at concentrations that would not be expected to produce health effects. The nickel and iron were likely naturally occurring metals (MI DCH 2013). No oil-related organic chemicals were found in the samples of potable well water. Arsenic and lead, two metals not present in crude oil, were present at levels that may harm people's health (MI DCH 2013). MI DCH (2013) concluded that arsenic is a naturally occurring metal in the area and lead could be naturally occurring or be present in people's plumbing.

A third public health assessment addressed health concerns related to exposures to chemicals in surface water and fish. In its assessment, MI DCH (2014b) concluded that chemical levels found in surface water are not expected to cause long-term harm to people's health but, similar to conclusions reached for sediment, people may have temporary health effects, such as skin irritation, from contact with the oil sheen or tar globules in the water. Further, the MI DCH (2014b) concluded that oil-related chemical levels found in fish from the Kalamazoo River and Morrow Lake will not harm people's *health. However, MI DCH (2014b) did issue fish consumption guidelines because of levels of two chemicals not related to the oil release (mercury and PCBs) found in the filets.*

The most recent public health assessment addressed concerns related to inhalation of volatile chemicals (MI DCH 2015). The study reviewed the air monitoring and sampling efforts completed during July 2010 through 2012. The study concluded that people experienced short-term effects associated with inhaling oil-related volatiles (headaches, nausea, respiratory discomfort and eye irritation), but that these health effects diminished or stopped once people were no longer breathing the oil-related chemicals (MI DCH 2015). Some people may have experienced anxiety, regardless of exposure (MI DCH 2015). The study further concluded the people did not breathe oil-related chemicals long enough, or at high enough levels, to cause long-term health effects (MI DCH 2015).

***Laurel, Montana**: On July 1, 2011, a break of the ExxonMobil pipeline near Laurel, Montana released an estimated 1,500 barrels of medium crude oil into the Yellowstone River, which was at the peak of a 30-year flood event at the time of the release (MT DEQ 2015c). High flows transported the oil up to 72 miles downstream, although the majority of the effects were observed within 20 miles of the release location (USEPA 2011).*

A number of public drinking water systems obtain water from the Yellowstone River, downstream of the release location. Operators of these systems were notified of the release. Monitoring and testing of the water supply systems for more than 100 contaminants did not identify any exceedances of drinking water standards. In May 2013, the MT DEQ determined that no additional sampling of the downstream public drinking water systems was necessary after tests showed contamination was below human health screening levels (MT DEQ 2013).

Several monitoring wells were installed in areas where crude oil was considered most likely to affect groundwater. Samples were obtained from these wells, as well as from over 300 private wells (MT DEQ 2015b). Crude oil-related petroleum hydrocarbons were not detected in the samples (MT DEQ 2015b). In September 2013, MT DEQ determined that petroleum hydrocarbons from the discharge were not present in groundwater and did not pose an unacceptable risk to public health (MT DEQ 2015b).

A fish consumption advisory was issued after the release as a precaution until laboratory testing could be completed (Montana Fish, Wildlife, and Parks 2011a). Fillet tissues were tested to reflect potential effects on human health from fish consumption. No petroleum hydrocarbons or oil residues were detected in any of the samples (Montana Fish, Wildlife, and Parks 2011b).

***Sundre, Alberta**: On June 7, 2012 a rupture released approximately 2,900 barrels (463 m^3) of light crude oil from the Plains Midstream pipeline into the Red Deer River downstream of Sundre, Alberta (Alberta Energy Regulator [AER] 2014). The release occurred in a* *populated area at a time of high water levels (i.e., flow in Red Deer River was ten times seasonal flow) and affected landowners and businesses more than 25 miles (40 km) downstream of the release (AER 2014).*

Air monitoring, including a monitor near the release location, was initiated on June 8, 2012 and continued while clean-up activities progressed. No hydrogen sulfide or other air quality issues were detected, and no exceedances of the provincial ambient air quality objectives were reported at any time during clean-up activities (AER 2014).

Water quality monitoring of drinking water samples reported hydrocarbon concentrations below applicable guidelines (Teichreb 2014).

***Mayflower, Arkansas**: On March 29, 2013, a breach released approximately 3,190 barrels of heavy crude oil from the ExxonMobil pipeline into a residential area, resulting in the evacuation of 22 homes (ADEQ 2013a; NAS 2015). Response crews were on site within 30 minutes of detection of the release (ADEQ 2013a). Air quality monitoring in residential areas on the days after the release reported that benzene concentrations were below detection (0.05 ppm) (ADEQ 2013b). VOC concentrations of up to 29 ppm were reported on the day of the release, but had diminished to 0.2 ppm by April 2, 2013 (ADEQ 2013b). Higher levels of both benzene and VOCs were measured in work areas, and workers wore respiratory protection as specified in the health and safety plan (ADEQ 2013b; NAS 2015).*

***Mooringsport, Louisiana**: On October 13, 2014, approximately 4,500 barrels of sweet crude oil were released from the Sunoco Logistics pipeline near Morringsport, Louisiana, affecting approximately ten miles of creek (USEPA 2014b). Although oil entered the Tete Bayou, it was prevented from entering Caddo Lake, which is used for potable water.*

Continuous air monitoring was conducted under supervision of the environmental agencies. Two households temporarily relocated; however, air monitoring results indicated that no hazards were present in populated/residential areas and that detected levels would not pose a health issue to residents (USEPA 2014b; USEPA 2014a).

***Glendive, Montana**: On January 17, 2015, a rupture of the Bridger Pipeline LLC pipeline released approximately 715 barrels (30,000 gallons) of Bakken light crude oil into the Yellowstone River, approximately 5 miles upstream of Glendive, Montana (MT DEQ 2015a). At the time of the release, there was extensive ice cover, restricting recovery efforts. The City of Glendive obtains its water from the Yellowstone River.*

Soon after the release, a malodorous odor was reported to be present in the City of Glendive drinking water. As a result, the Centers for Disease Control and Prevention recommended that residents not ingest municipal water. Analysis of the water later showed elevated concentrations of VOCs, predominantly benzene exceeded the *drinking water standard of 5 ppb (MT DEQ 2015c). Despite these elevated concentrations, additional sampling and analysis of the municipal water resulted in the water supply being declared safe to drink on January 22, 2015 (i.e., one week after the release). During the ice-breakup in the river on March 14, 2015, monitoring equipment installed at the water treatment plant detected higher than normal levels of VOCs. The plant was subsequently shut down and a water conservation request was made to the City of Glendive. The water treatment plant completed the installation of an aeration system to treat VOCs and allow the plant to continue operating during the breakup. The conservation request was lifted on March 16 and no VOC detections have been made since (MT DEQ 2015a).*

Ten groundwater wells were also sampled. The wells were selected based on their shallow depth and close proximity to the break. No VOCs were detected in any of the ten wells (MT DEQ 2015a).

Seven days of continuous ambient air monitoring in the City of Glendive during January 2015, following the release, showed non-detectable concentrations of VOCs, including benzene. As a result, scientists from the National Oceanographic and Atmospheric Administration Emergency Response Division concluded that the levels of contaminants were "…well below public health concern thresholds and may in fact be near background levels" (MT DEQ 2015a).

After the release, the Montana Department of Fish, Wildlife, and Parks issued a fish consumption advisory since it was confirmed that fish tissue samples showed detectable levels of PAHs. However, by the time the ice had left the river, the fish tissue samples showed no detectable concentrations in edible muscle tissue and the advisory was lifted (MT DEQ 2015a; Stuart 2015).

***Santa Barbara, California**: On May 19, 2015, a rupture of the Plains All American Pipeline near Santa Barbara, California resulted in the discharge of an estimated 2,400 barrels (101,000 gallons) of heavy crude oil, 480 barrels (20,000 gallons) of which is estimated to have reached the ocean near Refugio Beach (NAS 2015). The heavy crude oil was discharged from a heated transmission pipeline and comprised a blend of oils from four nearby platforms (i.e., it was a conventional heavy crude oil, not a diluted bitumen). As a result, 138 square miles of fishing grounds were closed to harvesting (Hamm 2015). To assess concentrations of oil related contaminants in seafood, the California Office of Environmental Health Hazard Assessment (OEHHA) developed a sampling and analysis plan that focused on concentrations of PAHs in mussels, but also included samples of finfish and invertebrates (OEHHA 2015). Elevated PAH concentrations were observed initially but were below levels of concern within six weeks of the release (OEHHA 2015).*

7.1.4.1.3 Expected Effects of Released Oils

The effects of released oil on human health will vary depending on both the characteristics of the released oil and ambient/meteorological conditions at the time of the release. While a number of oil characteristics may influence the fate and transport, oil chemistry is the strongest influence, affecting both the route of potential exposure and the longevity of exposure (i.e., short term or long term). Environmental characteristics include river flow and proximity of human receptors.

One important finding was that contamination of potable wells, while possible, appears unlikely. Of the case studies examined, surface releases of crude oil did not appear to affect potable wells. The Cass Lake, Minnesota case study considered a subsurface release of crude oil and determined that the groundwater plume was limited 500 ft beyond the oil source. Therefore, effects on groundwater quality (as a potential source of potable water) are unlikely where spill response is prompt and effective, and likely to be localized even where spill response is delayed or not effective.

The environmental effects associated with the type of oil, and characteristics of the environment in which a release occurs, are described in Table 7-43 and Table 7-44 respectively.

Table 7-43 Environmental Effects: Human Health

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil chemistry—volatiles	Light crude oils contain 35 to 40 wt % volatile organic compounds ($\leq C_{10}$) (www.crudemonitor.ca) The higher percentage of volatiles increases the risk of short-term inhalation exposure relative to other oil types.	Medium crude oils contain 25 to 30 wt % volatile organic compounds ($\leq C_{10}$) (www.crudemonitor.ca).	Heavy crude oils contain 15 to 20 wt % volatile organic compounds ($\leq C_{10}$) (www.crudemonitor.ca). Diluted bitumens tend to have a lower proportion of light, volatile compounds than conventional heavy oils (NAS 2015). With the lowest level of volatile compounds, heavy crude oils would be expected to have the lowest risk of inhalation exposures. Although diluted bitumens have a lower proportion of light volatile compounds than other commonly transported crude oils, the level of concern with respect to health risk from inhalation is reportedly the same as other commonly transported crude oils (NAS 2015).	Although the risk of vapor inhalation varies by oil type, health effects associated with short term inhalation exposures have been reported for spills of light, medium and heavy oils, as indicated by the case studies.
Oil chemistry—TEX	The total BETX concentration of light crude oils is 2 to 4 wt % (Zhou et al. 2015). Light oil spills have affected surface drinking water supplies (see case studies for Pine River, BC and Glendive, Montana).	The total BTEX concentration of medium crude is 1 to 3 wt % (Zhou et al. 2015).	BTEX concentration of heavy crude oils, including diluted bitumens, is 0.5 to 1.5 wt % (Zhou et al. 2015).	BTEX are among the most volatile, soluble, and toxic of the crude oil components, with low thresholds for taste and odor in water. Increasing concentrations would be expected to increase potential for inhalation exposures and impacts to drinking water supplies.

Table 7-43 Environmental Effects: Human Health

Oil Characteristic	Light Crude Oil	Medium Crude Oil	Heavy Crude Oil	Other Comments
Oil chemistry—TPAH	Alberta sweet mixed blend crude oil has higher TPAH, and proportionally more naphthalenes and alkyl naphthalenes than oil sands hydrocarbons (Yang et al. 2011). Although PAHs were detected in fish muscle tissues following a light oil release (Glendive, Montana case study), this environmental effect appears to have been influenced by the presence of an ice cover and PAHs were not detected following ice break up.	Alaska north slope crude oil has higher TPAH, and proportionally more naphthalenes and alkyl naphthalenes than oil sands hydrocarbons (Fingas 2010; Yang et al. 2011). PAHs were not detected in fish tissues following a medium crude oil release (Laurel, Montana case study).	Diluted bitumens typically have similar to lower concentrations of TPAH than light and medium crude oils, although the distribution of PAHs differs. PAHs were found in fish tissues following spills of diluted bitumen (Marshall, Michigan case study) and heavy crude oil (Santa Barbara, California case study).	Total PAH levels in diluted bitumen appear to be similar to or lower than levels in light, medium and heavy conventional crude oils (Zhou et al. 2015). PAHs are the crude oil components most commonly found in fish and shellfish, as indicated by the case studies.
Oil chemistry—resins and asphaltenes	Light crude oils contain very little in the resins and asphaltenes fractions, making their lighter aliphatic and aromatic components relatively bioavailable, but also allowing for rapid biodegradation or weathering of these oils, reducing the potential for long-term (chronic) exposures.	Medium crude oils also contain relatively small fractions of resins and asphaltenes, although more than light crude oils. Medium crude oils also have good potential for biodegradation in the environment.	Heavy crude oils, and diluted bitumens in particular, contain large amounts of resins and asphaltenes. While these fractions are generally insoluble in water and thus non-toxic, they are slow to degrade and can act as reservoirs for the slow release of other more toxic hydrocarbon constituents such as PAHs.	Resins and asphaltenes comprise the "heavy" end of crude oils, and diluted bitumens are proportionally richer in these components than light or medium crudes.

Table 7-44 Environmental Effects: Human Health

Environment Characteristic	Low	Medium	High	Other Comments
Distance to human receptors	The potential for inhalation exposures to the general public are greatest near the release site and in areas of oil recovery activities. These exposures may result in residents leaving their homes (e.g., Burnaby, British Columbia, Marshall, Michigan, and Mayflower, Arkansas case studies). Occupants typically return to their homes within a few days to a few weeks. Reported health effects from oil spills in populated areas (such as Burnaby, British Columbia, Salt Lake City, Utah, and Marshall, Michigan case studies) included headaches, eye and respiratory irritation, and nausea.	N/A	Air monitoring performed in Glendive, Montana (five miles upstream of a release) did not detect VOC or benzene in the air at levels that would represent a health concern following the release (Glendive, Montana case study).	Although toxicological effects from short-term chemical exposure are associated with distance of human receptors from released oil, other health effects, such as anxiety and depression, may be more strongly related with an individual's perceived risk regardless of whether the individual was physically exposed (Eykelbosh 2014).
River flow	Rivers with low flow are more likely to experience laminar flow and lower velocities, reducing the opportunities for mixing and the length of watercourse exposed to oil (e.g., Mooringsport, Louisiana case study).	Rivers with moderate flows will transport oil downstream and mixing could cause dispersion or submersion of oil.	Rivers with high flows can transport oil rapidly downstream and laterally onto floodplains (e.g., Marshall, Michigan case study; Laurel, Montana case study; and Red Deer River, Alberta case study).	The further the oil is transported downstream, and the more turbulent the flow conditions, the greater the likelihood of public exposures via inhalation of VOCs and BTEX from oil and direct contact with oiled shorelines and sediment. Long-distance transport would also increase the likelihood for potable water intakes to be reached and potentially affected.

Table 7-44 Environmental Effects: Human Health

Environment Characteristic	Low	Medium	High	Other Comments
Seasonal temperature	Low ambient temperatures may reduce the rate of evaporation of VOCs in spilled crude oil. However, low temperatures may also be accompanied by "inversion" conditions in low-lying areas, reducing the rate of dispersion for vapors in air. Ice cover may restrict the amount of volatilization of the BTEX components of the oil, increasing the presence of these compounds in water (e.g. Glendive, Montana case study).	N/A	High ambient temperatures could theoretically lead to localized increases in volatile concentrations. However, "inversion" conditions are less likely and atmospheric stability is usually lower at warm temperatures, resulting in more rapid dispersion of vapors in air.	Prediction of hydrocarbon vapor concentrations in air is complex, depending upon multiple factors. Spatial heterogeneity is likely to be high. Localized exposure to high concentrations of hydrocarbon vapors in air is possible for any release, however, such exposures would be indicated by strong odors making it likely that individuals would become aware of their exposure and respond accordingly.

7.1.4.2 Land Resource Use

7.1.4.2.1 Description

Releases of oil and the subsequent activities related to clean-up and remediation have the potential to disrupt normal land and resource use activities. The nature and duration of the effects will depend on the setting and the types of land and resource use activities that could be affected. Depending on the setting, an accidental release of oil can result in injury or loss of life, short- or long-term evacuation of people living or working in the area, temporary closures of water treatment facilities and other infrastructure (including roads), and suspension of activities in outdoor parks, and recreational areas and facilities.

Land and resource use activities can also be adversely affected by oil releases as a result of closures, suspensions or other constraints on these activities that remain in place until clean-up and remediation activities have been completed and response authorities have determined that conditions are safe for resumption of land and resource activities. Examples of land and resource uses and associated activities that may be adversely affected by an accidental oil release include agricultural lands, aquaculture resources (including the harvesting of wild rice), recreational or commercial fishing, forestry and other industrial activities, outdoor recreation activities (e.g., boating, swimming, hiking, biking), recreational facilities such as parks and historical or cultural sites, and cultural use of resources (use by indigenous peoples).

7.1.4.2.2 Observed Effects

The following sections provide examples of instances where accidental releases of oil have adversely affected land and resource use activities and describe the nature and extent of those effects.

Accidental releases of oil can lead to loss of life and injuries for people engaged in land and resource use activities in proximity to the release site, particularly in cases where the oil ignites. There are relatively few situations where oil releases lead to loss of life or injury, and most of these involve accidental releases caused by construction or repair activities, typically involving refined products or light oils. For example, in 2010, two people working to repair an Enbridge pipeline at a location near Clearbrook, Minnesota were killed when leaking oil ignited (Bloomberg News 2010). In 2005, a bulldozer operator working near Lufkin, Texas was injured after he accidentally struck a crude oil pipeline operated by Sunoco Pipeline L.P.; the released oil ignited (ProPublica 2005). Near Walnut Creek, California, five workers were killed and another four were injured in 2004 when contractors accidentally struck a Kinder Morgan Energy Pipeline Partners pipeline carrying gasoline (Office of the State Fire Marshall 2004).

Accidental oil releases in populated areas and potential for adverse effects on health and safety can lead to evacuation of nearby residents or workers. The Westridge release in Burnaby British Columbia occurred in 2007 and resulted in approximately 1,500 barrels (240 m^3) of heavy synthetic crude oil being released as a result of damage to a pipeline. This resulted in 50 homes being evacuated for several nights (CBC News 2007) and residents of five houses being evacuated for four months or more until clean-up operations were completed (Raptis 2011). The

2010 Marshall pipe rupture, where 20,082 barrels (3,193 m^3) of crude oil were accidentally released and a substantial portion entered the Kalamazoo River, resulted in six houses being evacuated on the day after the release due to concerns about odor (NTSB 2012b). A voluntary evacuation notice was issued to about 50 homes four days after the release and were not lifted until 18 days after the release occurred (NTSB 2012b). In these cases, the evacuations were issued due to concerns related to public health and safety resulting from direct contact with oil (see Section 6.1.5.1).

Evacuations have also occurred when oil releases have occurred in rural settings. In 2011, the rupture of ExxonMobil's Silvertip Pipeline near Billings, Montana resulted in crude oil entering the Yellowstone River. Due to fears about a possible explosion, 140 residents of the community of Laurel were evacuated for about four hours until fumes had dissipated (O'Connor 2011). The release of crude oil from ExxonMobil's Pegasus Pipeline at a location near Mayflower, Arkansas in 2013 resulted in more than 20 homes being evacuated due to fumes and fire hazard. One year after the release, residents claimed to continue to have adverse health effects from the release (rt.com 2014).

In the case of the 2005 Lake Wabamun release in Alberta, where approximately 4,500 barrels of Bunker C fuel oil (Heavy Fuel Oil 7102) and 550 barrels of Pole Treating Oil were released as a result of a train derailment, local residents were evacuated 30 minutes after the release but were allowed back to their homes later that same day (Lake Wabamun Residents Committee 2007). As a result of the 2002 Cohasset release, 6,000 barrels of crude oil (954 m^3) were released in forested-shrub-scrub wetland in Minnesota. Potentially affected land owners were contacted immediately, and seven residents were evacuated for a period of 24 hours while 11 acres of the affected land were burned to prevent the oil from reaching the Mississippi River (NTSB 2004).

Odors associated with the 2011 Plains Midstream Canada Rainbow pipeline release in northern Alberta (approximately 28,000 barrels of crude oil) were identified as the reason for suspension of classes at the Little Buffalo School on Lubicon Cree First Nation in Cadotte Lake (Henton 2011).

Accidental releases of oil have adversely affected municipal and residential water supplies, including surface water and groundwater. In 2000, 6,200 barrels (986 m^3) of oil entered the Pine River upstream of the Town of Chetwynd, British Columbia and resulted in Chetwynd shutting down its water withdrawals from the river following the release due to concerns about oil contamination of the water supply (BC MOE 2000c). As a consequence, the Town developed an alternate water supply using groundwater (Green 2000).

Only July 29, 2010, 4 days after the Enbridge Line 6B release in Marshall, Michigan, the Calhoun County Health Department issued a precautionary Bottle Water Advisory to allow time for well water sampled to be collected and analyzed for possible contamination from the release (MI DCH 2013). Wells located more than 200 ft from the high water mark of the flood event, which included most of the municipal wells in the area, were not expected to be a risk of contamination. The Bottled Water Advisory remained in effect until November 8, 2010 (MI DCH 2013), 105 days after the release occurred.

Following the Lake Wabamun release, the local health authority advised all residents not to use lake water for drinking purposes but advised that lake water could be used for recreational purposes (CAW/TCA 2006). The ban on use of lake water for drinking was still in place one year after the release but testing at that time determined that lake water no longer represented a threat to human health (Edmonton Journal 2007).

As a result of the Silvertip pipeline release into the Yellowstone River, the City of Billings and the community of Lockwood closed their municipal water intakes as a precautionary measure for a couple of hours after the release (Ritter 2011). Another release on the Yellowstone River in 2015 from the Bridger Pipeline resulted in the community of Glendive, Montana being unable to use water from the river for six days, with residents having to rely on bottled water (Lutey 2015; USEPA 2015a).

Accidental releases of oil have also adversely affected urban infrastructure, other than water and industrial intakes. For example, the 2007 Westridge release in Burnaby caused a section of the Barnett Highway to be closed for several days after the release (CBC News 2007).

Some of the best documented effects of oil releases on land and resource use relate to impacts on recreational resources and activities, notably beach activities and fishing. The nature of effects, such as the closure of recreational facilities (e.g., beaches) and the implementation of advisories related to swimming, boating, and fishing are usually well documented for releases in the United States because such damages are a key element of the NRDA process. Some examples of release effects on recreational resources and activities include:

- In 1996, heavy oil released from a pipeline owned by Chevron Industries into Pearl Harbor, Hawaii resulted in the USS Arizona Memorial and visitors' center being closed due to odors from the release (Kakesako et al. 1996). The visitors center was closed for four days following the release, which also resulted in closure of nearby bicycle/jogging paths for two weeks due to clean-up activities and the closure of Pearl Harbor to vessel traffic and recreational and commercial fishing and boating (Natural Resources Trustees for Pearl Harbor, Oahu, Hawaii 1999).
- The Red Butte Creek oil release resulted in the immediate closure of the creek and nearby parks, portions of which were still closed 40 days after the release (Salt Lake City no date), with clean-up operations being adjusted to accommodate two important holiday events. Red Butte Creek was declared safe for regular use by local residents two years after the release occurred (O'Donoghue 2012).
- As a result of the Marshall release, county health agencies closed 39 miles of the river system to the public for reasons of health and safety. Parts of the river were opened for public use 21 months after the event, and a Fish Consumption Advisory and a swimming advisory were also lifted at that time. Small sections of the river were subsequently closed to recreational activities for short periods of time during the following two years to allow reclamation and restoration activities to be completed (USFWS et al. 2015b).

- As a result of the Lake Wabamun release, parts of the lake were closed to swimming and boating for nearly one year, and a fish and waterfowl consumption advisory for the lake remained in place for another two years (Sherwood Park News 2008).
- Oil from the Westridge release resulted in the closure of Cates Park in North Vancouver (Woodward 2007). Some beaches were closed for 4 months after the release, and 15 kilometers of beaches eventually required remediation (Canada.com 2007b).
- The 2013 release of 600 barrels of diesel fuel (80 m^3) from a pipeline adjacent to Willard Bay, a reservoir connected to the Great Salt Lake, caused closure of some facilities in Willard Bay State Park for a period of four months (O'Donoghue and Cabrero 2013).
- In 2015, crude oil from a break in a pipeline owned by Plains All American Pipeline released into the Pacific Ocean at a location north of Santa Barbara, California (NOAA Office of Restoration 2015) and resulted in the closure of two California State Beaches for a period of up to two months (Panzar 2015).

Accidental releases of oil can adversely affect agricultural land use. In 2013, 20,600 barrels of crude oil (3,227 m^3) leaked from a Tesoro Logistics pipeline in North Dakota in the middle of a farmer's field. The affected landowner indicated that it would likely take two to three years of cleaning up the release before agricultural activities could resume and that there would be negotiations for compensation (FoxNews 2013). Clean-up activities were still underway in 2014 and, at that time, Tesoro Corp estimated that it would be another year before clean-up activities would be complete (Associated Press 2014b).

In the case of the 2008 Mt. Erie pipeline release, about 5,000 barrels (795 m^3) of crude oil affected agricultural and forested lands, and the responsible party eventually purchased 157 acres of agricultural land in the release zone (Arcadis 2011). For the Marshall release, the Michigan Department of Agriculture issued a ban on surface water withdrawals for crop or lawn irrigation, or livestock watering (NTSB 2012b). With the release from the Silvertip Pipeline occurring while the Yellowstone River was in flood, some of the released oil was deposited on cropland and pasture-land along the river (Fox News.com 2011). For the Silvertip pipeline release, farmers were advised not to use water from the river for irrigation or for stock watering (Ritter 2011). More recently, in 2015 a farmer near the Manitoba-Saskatchewan border discovered that 500 barrels (79 m^3) of oil had leaked from a Tundra Oil and Gas pipeline onto his farmland, but there is no information on the extent of damages to his agricultural operations (Dyck 2015).

Accidental releases of oil can affect industrial activities, particularly in situations where released oil enters water bodies that are used as an industrial water source.

The Wabamun release resulted in a thermal power plant having to shut down for about 40 days due to contamination of lake water that was being used to produce steam (TransAlta 2005). Clean-up operations associated with Westridge release resulted in closure of parts of Burrard Inlet for shipping and caused Shell Canada's refinery to cease operating for 11 days (Canada.com 2008).

When over 6,000 barrels of heavy Venezuelan crude oil released from the Athos I tanker entered the Delaware River in 2004, two reactors at the Salem Nuclear Power Plant were closed down for

10 days, and the Port of Philadelphia was shut down for three days (NOAA Office of Response and Restoration 2014; University of Delaware 2004;). Compensation for closing the nuclear power facilities was determined to be $33.1 million (NOAA Office of Response and Restoration 2014).

There are likely many more examples of these effects, but the details are seldom made public because claims for damages are negotiated directly between the responsible and affected parties, and the terms of the settlements are never made public.

While an accidental release of oil may affect land and resource use by Indigenous People (Canada) and Native American tribes (United States), the nature of these effects has not been well documented or reported. Where tribes and First Nations have legally established rights to harvest affected resources, responsible parties may negotiate settlements with affected parties and the terms of the settlement, including the nature and extent of damages, are not usually disclosed to the public. In the case of the Lake Wabamun release, the Paul First Nation initiated lawsuits for damages to lands and resources, as well as the effect to the residents' way of life, and ultimately received a settlement of $10 million (CBC News 2008). Under United States regulations, Indian tribes can be included as Trustees in the NRDA process when natural resources under their jurisdiction are injured (OPA 1990; 33 U.S.C. 2706b). Although tribes face multiple barriers to participation in the NRDA process (Hildreth 2011), there are some examples where tribes have been designated as trustees in an NRDA process. For example, the Nottawaseppi Huron Band of the Potawatomi Tribe (the Huron Tribe) and the Match-E-Be-Nash-She-Wish Band of the Pottawatomi Indians (the Gun Lake Tribe) were trustees involved in the NRDA process for the Marshall release (USFWS 2015b). However, in the case of the NRDA conducted for the Buzzard's Bay Oil release, the Wampanoag Tribe of Gay Head (the Aquinnah) reached a separate settlement with the Responsible Party and was not part of the final agreement (NOAA et al. 2014).

7.1.4.2.3 Expected Effects of Oil Releases

There are four factors that help determine the nature and magnitude of land and resource effects associated with an accidental petroleum release.

- The intensity of land and resource use and the potential for adversely affecting large numbers of people. Releases in densely populated or intensively used areas tend to have larger effects than releases in rural or unpopulated areas. Similarly, releases can potentially affect large numbers of people where they affect water intakes, other public infrastructure, or areas or facilities that are used for recreational or cultural purposes.
- Whether the release can be contained on land or whether the oil is able to enter a waterbody, especially a moving water body. With oil being able to spread more easily on water than on land, accidental releases into water are likely to affect a larger area and potentially affect a greater number and types of land and resource uses. The effects on land and resource use that result when a release enters a creek, river, or lake are likely to be much greater in magnitude than a release restricted to land.
- The season during which the release occurs. Releases during winter months tend to be less severe and easier to manage. Cold weather makes released oil more viscous, so it is less likely to spread and easier to contain. Also, if the surface water and ground is frozen,

released oil is less likely to spread or penetrate below frozen surfaces, so it is easier to contain and recover. However, releases from underwater pipelines in winter may present real challenges to oil collection because oil may pool underneath ice.

- The duration and invasiveness of clean-up and restoration activities. Oils that are more volatile might have a greater short-term effect (combustion leading to risk to life or odor and volatility issues leading to evacuation) but, in the longer term, may be easier to clean-up such that recovery occurs more quickly. Heavy oils, especially if they enter a water body during the summer months, tend to be more difficult to clean-up. As was observed in the case of the Marshall release, the released oil affected at least 39 miles of river bed and shoreline, and it took considerable time and effort for reclamation and restoration activities to be completed.

Table 7-45 summarizes how these factors may affect the duration and magnitude of the effects of an accidental oil release on different types of land and resource uses. In all cases, the extent of the effects will also be highly dependent on the duration of clean-up and remediation activities and the time required before response authorities have determined that land and resource use activities can be safely resumed.

Table 7-45 Summary of Expected Effects of Oil Releases on Land and Resource Uses

Effect	Oil Properties	Setting (Land/Water)	Season of Release
Loss of life and injuries	Lighter oils have greater potential for combustion	Oil releases on or in water may quickly spread and release volatile, explosive compounds, especially for lighter oils during warm seasons	Releases in winter have lower potential for effect
Evacuation	Lighter oils have greater potential for odors that cause evacuation	Oil releases on or in water may quickly spread and release volatile, explosive compounds, especially for lighter oils during warm seasons	Releases in winter have lower potential for effect
Public water supplies and other infrastructure	Lighter oils have potential for short-term effect but heavier oils may have long-term effect	Oil releases on or in water have very high potential for long-term effect	Releases in winter have lower potential for effect
Recreation	Lighter oils have potential for short-term effect but heavier oils may have long-term effect due to clean-up activities	Oil releases on or in water have very high potential to affect a greater area and to have long-term effect associated with clean-up activities	Releases in winter have lower potential for long-term effects and will affect fewer users
Agriculture	Lighter oils have potential for short-term effect but heavier oils may have long-term effect due to clean-up activities	Oil releases on or in water have higher potential to affect a greater area while releases on land may require long-term clean-up.	Releases in winter have lower potential for long-term effects and will affect fewer users

Table 7-45 Summary of Expected Effects of Oil Releases on Land and Resource Uses

Effect	Oil Properties	Setting (Land/Water)	Season of Release
Industrial activities	Lighter oils have potential for short-term effect but heavier oils may have long-term effect	Oil releases on or in water have very high potential to affect a greater number of users	Releases in winter have lower potential for long-term effects and will affect fewer users
Cultural Activities	Lighter oils have potential for short-term effect but heavier oils may have long-term effect due to clean-up activities	Oil releases on or in water have very high potential to affect a greater area and to have long-term effect associated with clean-up activities.	Releases in winter have lower potential for long-term effects and will affect fewer users

7.2 EXPECTED ENVIRONMENTAL EFFECTS OF LARGE RELEASES OF CRUDE OIL NEAR MOSQUITO CREEK

The proposed pipeline is expected to pass approximately 2,000 ft northeast of the head of Mosquito Creek. Mosquito Creek flows into Lower Rice Lake, which is located on tribal lands of the White Earth Reservation, and is a growing area for wild rice. Therefore, the potential for overland flow of crude oil from the release area to Mosquito Creek, and subsequent transport down Mosquito Creek to Lower Rice Lake, was investigated. The hypothetical release location is in a relatively flat forested area that gently slopes toward a homestead and agricultural and grassland habitats. The overland flow path is approximately 0.6 miles long. Agricultural drainage ditches provide a preferential flow path towards Mosquito Creek, and sections of the creek also have been channelized. Thus, Mosquito Creek can be described as a semi-natural watercourse that ranges in width from approximately 3 to 30 ft as it flows approximately 11.75 miles to the south and west before entering Lower Rice Lake. As identified in Chapter 3, Mosquito Creek is part of the Mosquito Creek Wildlife Management Area (WMA) located in the Chippewa Plains Subsection of the Northern Minnesota Drift and Lake Plains Section of the greater Laurentian Mixed Forest Province (MN DNR 2016b; MN DNR 2016c). Land cover is predominantly forest (57%) and is dominated by aspen (MN DNR 2006).

7.2.1 Description of the Freshwater Environment

At its origin, Mosquito Creek is a narrow ditch or swale (Figure 7-2). As it grows to around 30 ft in width, Mosquito Creek flows through marshy grassland and riparian bog (occasionally treed), passing through agricultural land and nature preserves before entering Lower Rice Lake. The average velocity of the Mosquito Creek changes with season, with slowest velocities (e.g., about 0.52 ft per second) expected during low flow periods in the winter, and greater velocities (e.g., about 3 ft per second) during the spring high flow period. Mosquito Creek enters Lower Rice Lake at its north end, about 0.4 miles from the lake outflow, also at the north end. A non-vegetated channel between the inflow and outflow indicates that much of the creek flow is likely to bypass the lake and report directly to the outflow. A water level control structure is located approximately 0.64 miles downstream from the lake outflow. Lower Rice Lake is approximately 0.5 to 1 mile wide and 4.2 miles long.

Recreation, tourism and forestry are the major land uses in the area of Mosquito Creek and Lower Rice Lake (MN DNR 2016b). Although much of the land is agricultural (grassland), it does not appear to be under intensive use. Deer, bear, waterfowl, and migratory species offer hunting and trapping opportunities (MN DNR 2006; MN DNR 2016b). Being part of the Chippewa Plains, Mosquito Creek is known or expected to be home to 83 Species in Greatest Conservation Need (SGCN); these include birds (60 species), fish (4 species), insects (8 species), mammals (6 species), mollusks (2 species), and reptiles (2 species) (MN DNR 2006). Of these, 22 species are afforded federal or state endangered, threatened, or of special concern status (MN DNR 2006; MN DNR 2016d). It is foreseeable that some of these SGCN could utilize aquatic habitats along the Mosquito Creek. The area around Mosquito Creek and Lower Rice Lake is shared by White Earth Reservation, private owners, and DNR Forestry Trust lands and is populated with summer homes and Native American communities (White Earth, Pine Point/Ponsford, Naytahwaush, Elbow Lake, and Rice Lake [IAC 2012]). The Mosquito Creek WMA is complex of forest, agricultural lands and 24 emergent wetlands (MN DNR 2016b). The lower section of Mosquito Creek enters White Earth Reservation, which surrounds Lower Rice Lake (known for wild rice), and is directly downstream of the hypothetical release location.

Several access points downstream from the proposed pipeline crossing location were visited in May, 2016, to provide additional insight into baseline environmental conditions for Mosquito Creek and surrounding environments. Representative site photographs are provided in Figure 7-2 through Figure 7-5. Field observations are summarized in Table 7-46.

Figure 7-2 Mosquito Creek and Habitat Approximately 2 Miles Downstream of the Pipeline Crossing Looking Upstream

Figure 7-3 Mosquito Creek and Habitat Approximately 2 Miles Downstream of the Pipeline Crossing Looking Downstream

Figure 7-4 **Mosquito Creek and Riparian Habitat Approximately 25 Miles Downstream of the Pipeline Crossing to the West of Lower Rice Lake**

Figure 7-5 **Mosquito Creek and Riparian Habitat Approximately 55 Miles Downstream of the Pipeline Crossing to the West of Lower Rice Lake**

Table 7-46 Environmental Characteristics Observed at Selected Access Points on the Mosquito Creek in May, 2016

Access Point	Latitude Longitude	Notes
211th Avenue and Mosquito Creek approximately 2 miles downstream of pipeline crossing	47.4479 -95.3396	Habitat Description: both sides of road are cattle pasture and nearly level. There was no water flowing in the shallow, excavated ditch (Mosquito Creek) at the time of the field visit. An approximately 36-inch CMP culvert is under road here. Dominant vegetation is nonnative, cool season pasture grasses, with scattered small patches and groves of bur oak/aspen trees. Wildlife observed: bobolink, yellowthroat, ruby-throated hummingbird, gray tree frog.
County State Aid Highway 4 and Mosquito Creek approximately 25 miles downstream of pipeline crossing	47.3873 -95.6367	Habitat Description: this segment has a broad floodplain with a mix of shrub swamp, wet/sedge meadow and lesser amounts of wet/aspen stands on slightly higher ground. The stream has good water clarity and abundant wild celery (*Vallisneria americana*). Wildlife observed: barn swallow, yellow warbler, American toad, yellow throat.
Creek 132 Road and Mosquito Creek approximately 50 miles downstream of pipeline crossing	47.35421 -95.76347	Habitat Description: this area has a relatively narrow stream corridor amid irregular, rolling hills (glacial moraine topography). The stream has riffles and pools, as well as a relatively narrow floodplain. The invasive, nonnative reed canary grass is codominant with native plants along stream margins. The dominant vegetation in stream buffer areas is lowland hardwood forest and mesic hardwood (oak) forest with good plant species richness/quality. Wildlife observed: veery, yellow throat, catbird, flycatcher, hairy woodpecker Fish & Wildlife likely to occur in vicinity: creek chub, smallmouth bass (personal communication from angler).

7.2.2 High Consequence Area Assessment for the Mosquito Creek to Lower Rice Lake Scenario

As defined in Section 7.0, HCAs include populated areas, drinking water source areas, ecologically sensitive areas, and commercially navigable waterways. Sensitive AOIs include Minnesota drinking water management areas, native plant communities, sensitive lake shores, recreational areas, tribal lands, and protected areas of several types (e.g., national forests, military lands, state parks).

While environmentally sensitive and populated HCAs are present near the confluence of Mosquito Creek and Lower Rice Lake, modeling demonstrated that neither Bakken crude oil nor CLB floating on the surface would reach these areas under any of the seasonal flow conditions (Figure 7-6). However, AOIs are present along Mosquito Creek (Table 7-47). The locations of the HCAs and AOIs are shown in Figure 7-6.

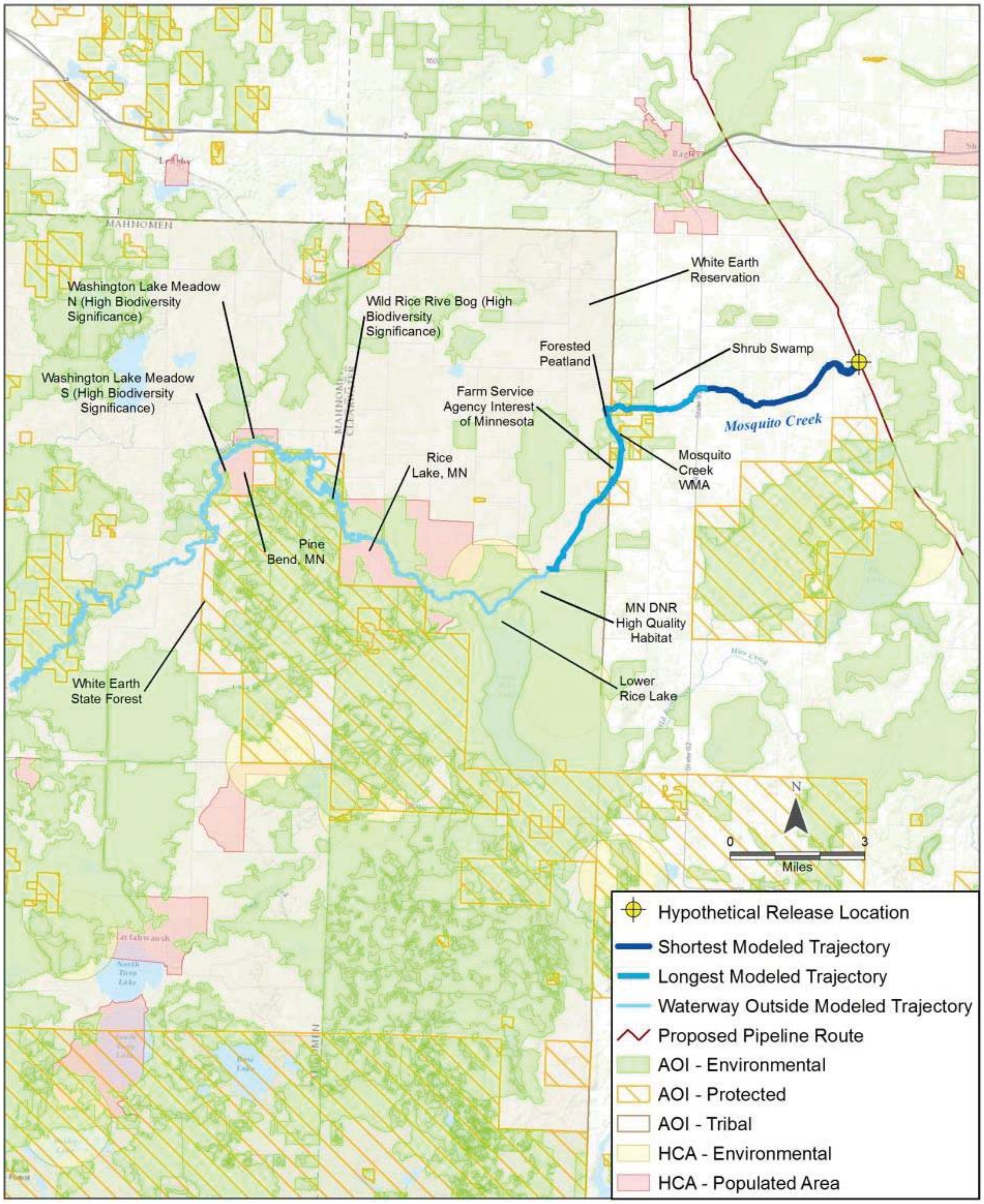


Figure 7-6 HCAs and AOIs Potentially Affected by a Crude Oil Release near Mosquito Creek

Table 7-47 Areas of Interest Potentially Affected by a Release of CLB and Bakken Crude Oil at the Mosquito Creek to Lower Rice Lake Scenario

AOI Type	AOI Subtype	Description / Locations
Environmental	Native Plant Community (Candidate)	Forested Peatland, Shrub Swamp, Tribal Lands
Protected Area	Farm Service Agency Interest of Minnesota	N/A
	Wildlife Management Area	Mosquito Creek WMA
Tribal Lands	N/A	White Earth Reservation
NOTE: Data for the AOI analysis were derived from multiple datasets provided on the Minnesota Geospatial Commons website, USGS Protected Areas Database of the United States and the Minnesota Department of Transportation.		

7.2.3 Selection of Key Ecological and Human Environment Receptors for Mosquito Creek to Lower Rice Lake Scenario

Taking into account the environmental characteristics of Mosquito Creek and Lower Rice Lake, the potential interactions of released crude oil with key ecological and human environment receptors were screened to identify key receptors for the subsequent environmental effects analysis. The rationale and results of this screening step are provided in Table 7-48.

Table 7-48 Key Ecological and Human Environment Receptors for the Mosquito Creek to Lower Rice Lake Scenario

Receptor	Relevance for Inclusion as an Environmental Receptor for the Mosquito Creek to Lower Rice Lake Scenario	Selected (Y/N)
Terrestrial Receptors		
Soils	Low. An assumption made in the fate modeling for this scenario is that released oil in spring and summer-fall conditions would flow approximately 0.6 miles overland before reaching the channel of Mosquito Creek. After reaching the creek, crude oil could be transported downstream following a defined channel. Under winter conditions, the released crude oil is not predicted to reach the creek, but could be retained by snowpack over frozen ground. It is assumed that oil that remained on land would be physically remediated to established standards.	N
Groundwater	Low. In the event of an actual oil release, effects on groundwater quality after cleanup would be localized and/or negligible.	N

Table 7-48 Key Ecological and Human Environment Receptors for the Mosquito Creek to Lower Rice Lake Scenario

Receptor	Relevance for Inclusion as an Environmental Receptor for the Mosquito Creek to Lower Rice Lake Scenario	Selected (Y/N)
Terrestrial Vegetation	Low. An assumption made in the fate modeling for this scenario is that released oil in spring and summer-fall conditions could flow approximately 0.6 miles overland before reaching the channel of Mosquito Creek. After reaching the creek, crude oil could be transported downstream following a defined channel. Under winter conditions the released crude oil is not predicted to reach the creek, but could be retained by snowpack over frozen ground. It is assumed that oil that remained on land would be physically remediated to established standards. Terrestrial vegetation communities along the flow path would be killed or impaired, but this area would be remediated, and vegetative cover would be restored as part of the cleanup process.	N
Aquatic Receptors		
River (Mosquito Creek)	High. An assumption made in the fate modeling for this scenario is that oil released under spring or summer-fall conditions could reach Mosquito Creek via overland flow, with subsequent physical transport downstream.	Y
Lake (Lower Rice Lake)	Medium. An assumption made in the fate modeling for this scenario is that oil released under spring or summer-fall conditions could reach Mosquito Creek via overland flow, with subsequent physical transport downstream towards Lower Rice Lake. While none of the simulations indicated that floating oil would reach the lake within 24 hours, this receptor was included in the assessment due to the importance of the area to Native Americans and local residents.	Y
Sediment	High. An assumption made in the fate modeling for this scenario is that oil released under spring or summer-fall conditions could reach Mosquito Creek via overland flow, with subsequent physical transport downstream. This allows potential interaction and/or deposition of crude oil residues to sediments.	Y
Shoreline and Riparian Areas	High. An assumption made in the fate modeling for this scenario is that oil released under spring or summer-fall conditions could reach Mosquito Creek via overland flow, with subsequent physical transport downstream. This allows potential interaction with shoreline and riparian habitat.	Y
Wetlands	High. An assumption made in the fate modeling for this scenario is that oil released under spring or summer-fall conditions could reach Mosquito Creek via overland flow, with subsequent physical transport downstream. This allows for potential interaction with riparian wetlands, and wetlands associated with Lower Rice Lake.	Y
Aquatic Plants	High. Mosquito Creek supports aquatic plant communities.	Y
Benthic Invertebrates	High. Mosquito Creek and Lower Rice Lake support benthic invertebrate communities.	Y
Fish	High. Mosquito Creek and Lower Rice Lake support fish communities.	Y
Semi-Aquatic Wildlife Receptors		

Table 7-48 Key Ecological and Human Environment Receptors for the Mosquito Creek to Lower Rice Lake Scenario

Receptor	Relevance for Inclusion as an Environmental Receptor for the Mosquito Creek to Lower Rice Lake Scenario	Selected (Y/N)
Amphibians and Reptiles	High. Mosquito Creek and Lower Rice Lake support amphibians and reptiles.	Y
Birds	High. Mosquito Creek and Lower Rice Lake support waterfowl and other birds.	Y
Semi-aquatic Mammals	High. Mosquito Creek and Lower Rice Lake support semi-aquatic mammals.	Y
Human and Socio-Economic Receptors		
Air Quality	High. The Mosquito Creek and Lower Rice Lake area is shared by White Earth Reservation, private land owners, and MN DNR Forestry Trust lands. Effects on air quality have the potential to temporarily disrupt human use and occupancy patterns.	Y
Human Receptors	High. The Mosquito Creek and Lower Rice Lake area is shared by White Earth Reservation, private land owners, and MN DNR Forestry Trust lands. Effects on air quality or the presence of crude oil residues in aquatic and riparian habitat have the potential to temporarily affect human health.	Y
Public Use of Natural Resources	High. The Mosquito Creek and Lower Rice Lake area is shared by White Earth Reservation, private land owners, Mosquito Creek WMA and MN DNR Forestry Trust lands. Effects on air and water quality, or the presence of crude oil residues in the sediment, riparian or wetland habitat, could potentially disrupt public use of natural resources (e.g., wild rice harvest, drinking water supplies, hunting, fishing, recreation).	Y

7.2.4 Modeled Conditions at the Release Location

A description of key modeling assumptions for the environmental effects analysis for the Mosquito Creek to Lower Rice Lake scenario is provided in this section. The OILMAP Land software was used by RPS ASA to simulate hypothetical releases of CLB and Bakken crude oils into Mosquito Creek and the flow of oil over land (Chapter 5.0) for a 24 hour period. A longer time period was not modeled as it was assumed that emergency response measures to prevent further downstream transport of released oil would be in place within the 24 hour period.

While OILMAP Land does provide an indication of the overland and downstream extent of oiling and mass balance of oil within the modeled period, it does not quantify the amounts of oil components dissolved into the water column (Chapter 5.0). The ability of the OILMAP Land model system to accurately predict overland release pathways is in large part controlled by ground cover and the vertical and horizontal resolution of the elevation grid. In this scenario, a 0.6 mile flow path of predominantly grassland/herbaceous land cover (during non-winter months) or snow/ice land cover (during winter months) extended downslope to Mosquito Creek. This is a worst-case assumption for a release of crude oil near the watercourse. In the event of an actual release, emergency response measures to prevent further possible downstream transport of oil would be expected to be in place within several hours of the release.

Based on data obtained from weather stations (Thorhult, MN and the University of Minnesota Itasca Biological Station, MN) near the hypothetical release location, long cold winters with periods of snow cover occur between October (averaging 0.5 inch) and May (averaging 0.4 inch), with maximum average coverage in February (13.7 inches). The retention of light crude oil in snow was assumed to be 20% of the snowpack depth for the Bakken crude oil, and 40% of the snowpack depth for the heavier CLWB. Elevation data used for overland flow modeling were obtained from the MN DNR (MN DNR 2014a) and have 10 ft horizontal resolution and 0.4 inch vertical resolution.

The two crude oil types provide bounding cases for oils that range from light (e.g., Bakken crude oil having low viscosity and density) to heavy (CLB/CLWB, heavy diluted bitumen crude oil types having higher viscosity and density). Seasonal variations in river flow velocity, temperature, wind speed, and snow and ice cover were all considered at the release location. A summary of key variables is provided in Table 7-49.

In the event of an actual release, the downstream extents of CLB and Bakken crude oil may be more similar, and the effects of CLB may extend farther downstream than predicted, with patchy coverage.

Table 7-49 Environmental and Hydrodynamic Conditions for the Three Modeled Periods at the Mosquito Creek Crossing

Season	Month	Air Temperature (°C)	Wind Speed (m/s)	Average River Velocity (m/s)
Low Flow (Winter)	February	-11.50	4.44	0.16
Average Flow (Summer)	July	19.25	3.68	0.21
High Flow (Spring)	April	4.17	4.88	1.03
NOTE: A velocity of 1 m/s is equivalent to 2.25 miles per hour.				

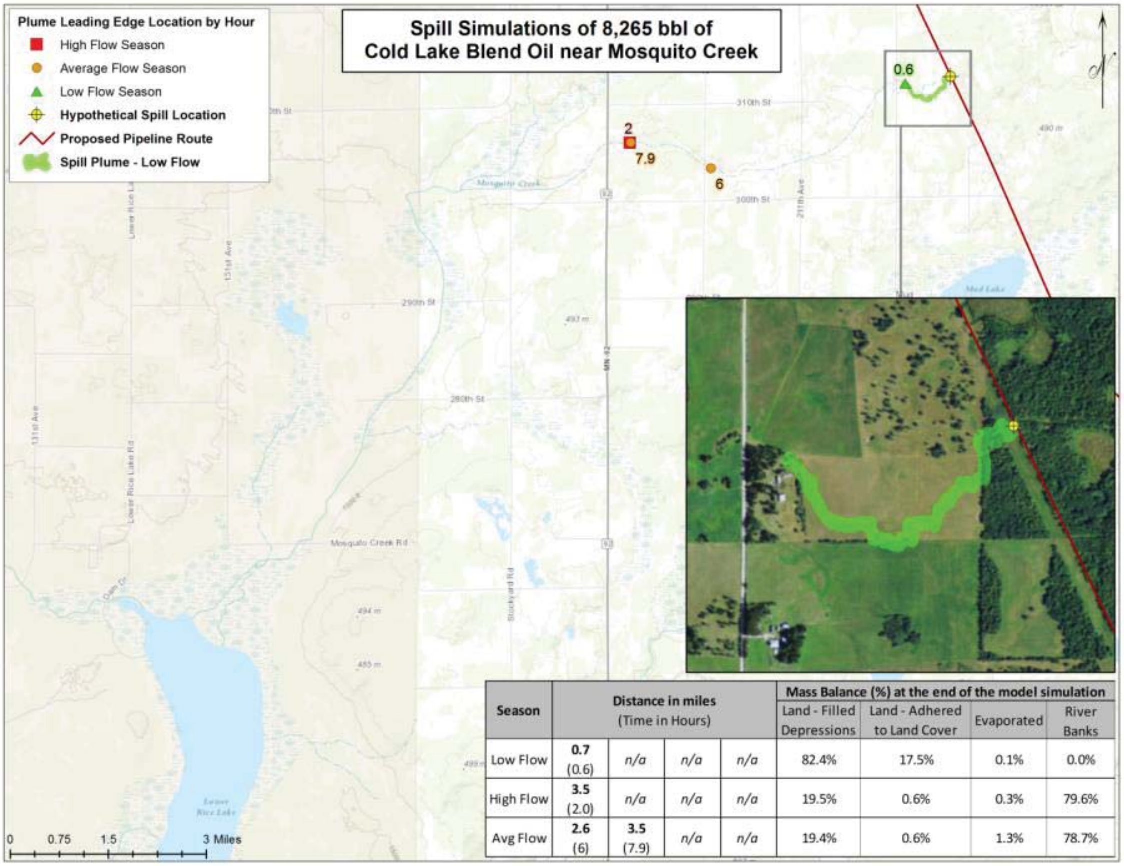
The highest average flow velocity of the Mosquito Creek coincides with the spring freshet (i.e., April-June), a result of rising temperatures and snowmelt. Average flow would typically occur in summer and fall seasons. July, the month with the warmest temperature, was selected to represent the maximum amount of evaporation. The lowest flow rate occurs in winter (i.e., January-March), and was typified by freezing conditions and probable ice cover on water.

The crude oil release volume was calculated as a full bore rupture, with a maximum time to response in the pipeline Control Center of 10 minutes, followed by a 3-minute period to allow for valve closure. Therefore, the release volume represents the volume of oil actively discharged in the period of time required to detect and respond to the event (taking into consideration the pipeline diameter, pipeline shutdown time, pipeline design flow velocity), followed by the volume of oil lost due to drain-down of the elevated segments of pipeline. The maximum 13-minute response time to valve closure is an Enbridge standard for safe operations and leak detection. This includes the combination of identification of the rupture, analysis of the pipeline condition, pipeline shutdown and full valve closure in the affected pipeline section. While 13 minutes is the maximum time for valve closure, this is a conservative assumption, since a response through to valve closure is expected to occur in less than 13 minutes in a full bore rupture leak scenario. Based on these assumptions, the site-specific hypothetical release volume was estimated to be 8,265 bbl of Bakken, CLB, or CLWB crude oil.

7.2.5 Summary of Predicted Downstream Transport of Bakken and Cold Lake Crude Oils

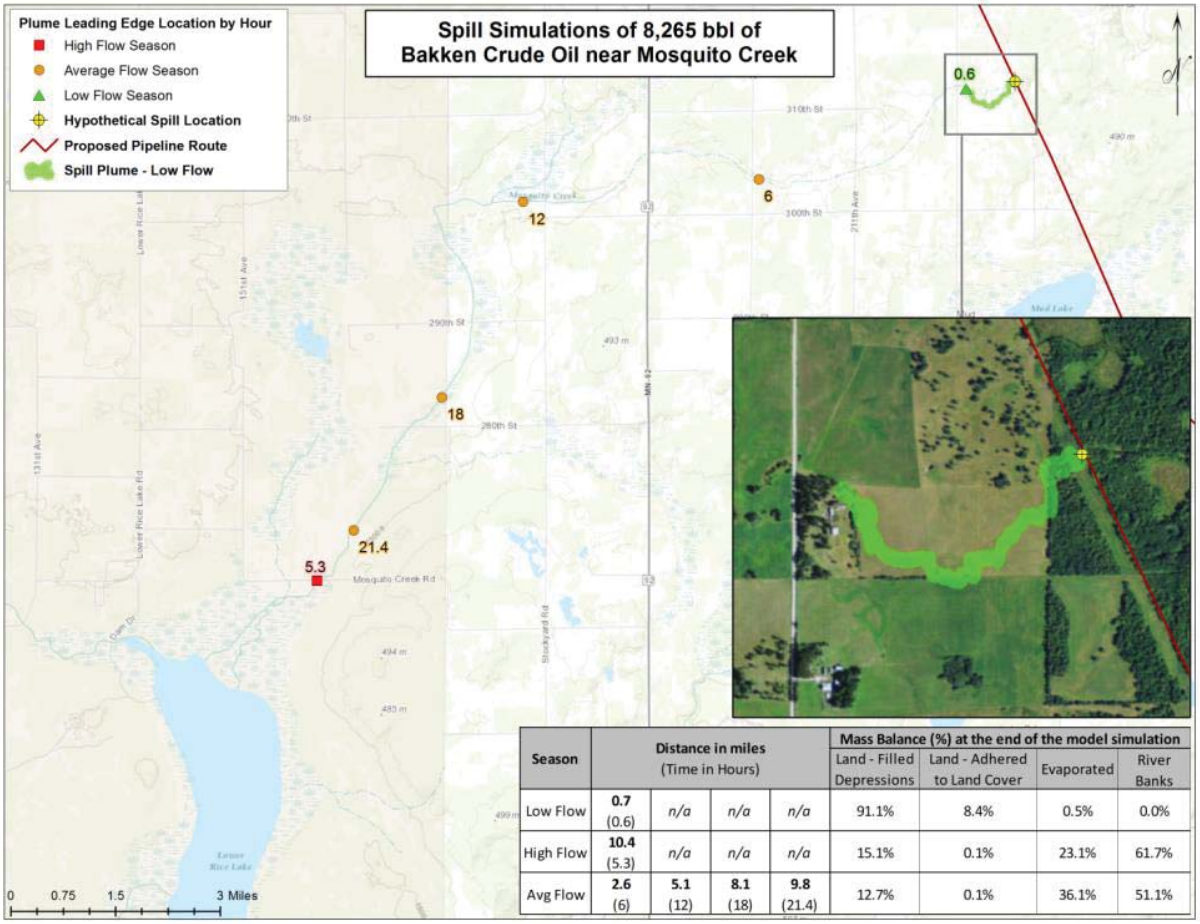
A summary of the predicted downstream trajectories and mass balance for Cold Lake and Bakken crude oils, under the three seasonal scenarios, is provided in Figure 7-7 and Figure 7-8, respectively. These simulations are assumed to provide bounding conditions for a release of heavy or light crude oil types. The fate of most types of crude oil, if released, would lie within the envelope of predictions for the Cold Lake and Bakken crude oil types. The Cold Lake crude oil was assumed to be CLB for the high flow and average flow scenarios, and to be CLWB for the low flow (winter) scenario. As noted in Chapter 5.0, while OILMAP Land does provide an indication of the downstream extent of oiling and mass balance of oil within the modeled period, it does not quantify the amounts of oil components dissolved into the water column.

The maximum simulation duration using OILMAP Land was 24 hours, as it was assumed that emergency response measures to prevent or reduce further downstream transport of released oil would be in place within that length of time. Symbols on the drawings indicate the river seasonal flow condition (high corresponding to spring freshet, average corresponding to summer-fall conditions, and low corresponding to winter flow under ice). Numbers associated with the symbols indicate the predicted location of the leading edge of the released oil in the river after 6, 12, 18 or 24 hours. Numbers other than these (e.g., 7.9) indicate the time in hours of the predicted termination of downstream transport of the released oil due to adhesion or holdup of the oil along the river banks. Tables inserted within the Figures also provide information on the mass balance (i.e., oil remaining on the surface of the river, adhering to river banks, or evaporated to the atmosphere) of the released oil at relevant points in time after the start of the release.



Season	Distance in miles (Time in Hours)				Mass Balance (%) at the end of the model simulation			
					Land - Filled Depressions	Land - Adhered to Land Cover	Evaporated	River Banks
Low Flow	0.7 (0.6)	n/a	n/a	n/a	82.4%	17.5%	0.1%	0.0%
High Flow	3.5 (2.0)	n/a	n/a	n/a	19.5%	0.6%	0.3%	79.6%
Avg Flow	2.6 (6)	3.5 (7.9)	n/a	n/a	19.4%	0.6%	1.3%	78.7%

Figure 7-7 Predicted Downstream Transport of Cold Lake Blend Oil at the Mosquito Creek Crossing Location



Season	Distance in miles (Time in Hours)				Mass Balance (%) at the end of the model simulation			
					Land - Filled Depressions	Land - Adhered to Land Cover	Evaporated	River Banks
Low Flow	**0.7** (0.6)	n/a	n/a	n/a	91.1%	8.4%	0.5%	0.0%
High Flow	**10.4** (5.3)	n/a	n/a	n/a	15.1%	0.1%	23.1%	61.7%
Avg Flow	**2.6** (6)	**5.1** (12)	**8.1** (18)	**9.8** (21.4)	12.7%	0.1%	36.1%	51.1%

Figure 7-8 Predicted Downstream Transport of Bakken Crude Oil at the Mosquito Creek Crossing Location

7.2.5.1 Mosquito Creek to Lower Rice Lake Release During High Flow (Spring) Period

Under the high flow scenario, CLB was predicted to travel approximately 3.5 miles downstream in Mosquito Creek, with downstream transport being terminated 2 hours after the release. This is largely a result of crude oil being held up on land (20.1%) or adhering to shorelines (79.6%). Only a small amount (0.3%) of the CLB was predicted to have evaporated to the atmosphere during that period. In the event of an actual release, emergency response measures to prevent further possible downstream transport of oil would be expected to be in place within several hours of the release.

Bakken crude oil was predicted to be transported approximately 10.4 miles downstream (or approximately 1.4 miles upstream of Lower Rice Lake), with downstream transport being terminated within 5.3 hours of the release. After 5.3 hours, approximately 23.1% of the Bakken crude oil was predicted to have evaporated to the atmosphere, with 15.2% filling depressions on land or adhered to land cover, and the remaining 61.7% predicted to be adhering to shorelines.

The release of Bakken crude oil under high flow conditions was predicted to result in shoreline oiling nearly 3 times farther downstream in Mosquito Creek than the CLB. The difference in the extent of downstream transport was primarily due to differences in shoreline retention. Because of its higher viscosity and adhesiveness, larger amounts of CLB are predicted to strand, as a thicker layer of oil on a given length of shoreline, than for the Bakken oil. Conversely, the same amount of Bakken crude oil would affect a greater length of shoreline, with a lesser thickness of oil. This result is based on the assumption of 100% shoreline oiling coverage (i.e., all shoreline up to that point was oiled to its maximum holding capacity for that oil type) as oil made its way downstream. In the event of an actual release, the downstream extents of CLB and Bakken crude oil may be more similar, and the effects of CLB may extend farther downstream than presented, with patchy coverage or partial oiling of shorelines.

A larger proportion of the Bakken crude oil was predicted to evaporate to the atmosphere than was predicted for CLB. This was due in part to the lighter and more volatile character of the Bakken crude oil. In addition, the greater downstream transport of the Bakken crude oil took more time, and resulted in more water surface area with oil, both of which would allow more of the released oil to evaporate. Volatile components of the CLB would continue to evaporate after becoming stranded on the shoreline, but this process was not included within the OILMAP Land model for stranded oil.

7.2.5.2 Mosquito Creek to Lower Rice Lake Release During Average Flow (Summer-Fall) Period

Under the average river flow condition, CLB crude oil was predicted to travel up to 2.6 and 3.5 miles downstream after 6 and 7.9 hours, respectively, at which time the leading edge of the release is predicted to be 8.3 miles upstream of Lower Rice Lake (Figure 7-7). At that time, approximately 1.3% of the CLB was predicted to have evaporated to the atmosphere, 20.0% filled depressions on land or adhered to land cover, and the remaining 78.7% was predicted to be adhering to shorelines. Emergency response measures to prevent further possible downstream transport of oil would be in place within 24 hours of the release.

Bakken crude oil was predicted to travel approximately 2.6, 5.1, 8.1 and 9.8 miles downstream after 6, 12, 18 and 21.4 hours. Downstream transport was predicted to terminate 21.4 hours after the release. By that time, approximately 36.1% of the Bakken crude oil was predicted to have evaporated to the atmosphere, 12.7% filled depressions on land or adhered to land cover, and the remaining 51.1% was predicted to be retained on shorelines. Slightly more of the released CLB crude oil was predicted to evaporate under the average river flow condition than under the high river flow condition (Figure 7-7). This difference is due largely to the warmer temperatures in the summer-fall season as compared to the spring freshet, and also due to the greater length of time, and greater surface area of water that was predicted to be oiled during the simulation.

When compared to CLB was predicted to be transported farther downstream than Bakken crude oil. This is a result of the lower overland and shoreline oil retention values for the low viscosity Bakken crude oil, when compared to the more viscous and adhesive CLB. Although not modeled here, it is expected that a medium crude oil would exhibit fate and transport properties intermediate between those of the Bakken and CLB crude oil types, with a tendency to behave more like the Bakken crude oil. This is because the viscosity and adhesiveness properties of a medium crude oil would typically be higher but more similar to those of the Bakken crude oil, than to the CLB.

7.2.5.3 Mosquito Creek to Lower Rice Lake Release During Low Flow (Winter) Period

Under the low flow conditions of winter, it was assumed that Mosquito Creek would be frozen over (100% coverage of ice), with a layer of snow on top. Therefore, a release of CLWB from the pipeline onto land could result in a release traveling over the land surface to reach the channel of Mosquito creek, but the oil would likely pool in the dry or frozen stream channel without contacting water.

Under low flow conditions, CLWB was predicted to travel approximately 0.7 miles over the land surface, within 0.6 hours of release. At that time, approximately 82.4% of the CLWB was predicted to be held up by snow or filling depressions in the land surface, with 17.5% adhering to the land cover and only 0.1% predicted to have evaporated. A considerable amount of CLWB was predicted to adhere to the land cover and be retained in depressions along due to the high holding capacity of the snow cover. With Mosquito Creek frozen over, CLWB that reached the creek would be expected to pool in the dry stream channel, or on the surface of the ice. Little evaporation was predicted to occur under winter conditions due to low air temperature which would slow evaporation, and reduced surface area due to the predicted thick retention of CLWB on the overland flow path. Evaporation was also limited by the short (0.6 hour) duration of the simulation.

Under low flow conditions, the Bakken crude oil was predicted to travel approximately 0.7 miles over the land surface, within 0.6 hours of release. At that point, approximately 91.1% of the oil was predicted to be filling depressions in the land surface, 8.4% adhering to the land cover, and only 0.5% was predicted to have evaporated. Considerably more Bakken crude oil was predicted to adhere to land cover during low flow conditions than during high or average river flow conditions, due to the holding capacity of snow cover.

7.2.6 Qualitative EHHRA for the Mosquito Creek to Lower Rice Lake Scenario

In this section the likely environmental effects of a crude oil release at the pipeline crossing location near Mosquito Creek are described. A worst case crude oil release from a main-line pipeline, such as described here, would be an unlikely event (Chapter 4.0). The proposed pipeline would carry a variety of crude oil types, ranging from very light (e.g., Bakken crude oil) to heavy (e.g., diluted bitumens such as CLB). Therefore, the following discussion describes the likely environmental effects of a crude oil release on relevant ecological and human environment receptors (identified in Section 7.2.3), using the predicted geographic extent of effects of released Bakken or CLB crude oil types over the 24 hour simulations as bounding conditions. Effects of season (including temperature, river flow conditions, and receptor presence/absence and sensitivity) were also considered. The rationale supporting the effects analysis, based on case studies describing the effects of crude oil releases on the various ecological and human environment receptors, was provided in Section 7.1 and Table 7-48.

7.2.6.1 Terrestrial Receptors

In spring and summer-fall seasons it is assumed that a release will flow over 0.6 miles of land downslope to Mosquito Creek, with most of the released crude oil entering the creek, rather than remaining on land. Environmental effects on soils and terrestrial vegetation are assumed to be localized to the overland flow path of the released oil. This area is limited in spatial extent, and would be remediated using conventional clean-up techniques. In the winter season it is expected that virtually all of the released crude oil would be retained in snow and fill depressions on land. This type of release would also be physically remediated using conventional clean-up techniques. The environmental effects of a crude oil release on land cover receptors are not considered further for this release scenario.

7.2.6.2 Aquatic Receptors

The aquatic environmental and ecological receptors are most closely associated with Mosquito Creek. These receptors include creek water and sediment quality, shoreline and riparian areas, wetlands, aquatic plants (including wild rice), benthic invertebrates, and fish.

If crude oil was to enter Mosquito Creek during the spring (high flow), it is predicted to travel downstream, interacting with vegetation and seasonal shoreline areas. The distance travelled would depend upon river flow and oil type. Based on OILMAP Land simulations, light oils oil is predicted to travel father downstream than heavy oil. For heavy oil, stranding on shore would be the primary fate, with only small amounts of evaporative weathering of the oil occurring before the oil becomes stranded. For light oil, stranding would remain the primary fate, but considerably more of the released oil could be lost to evaporation.

The effects of crude oil releases on benthic invertebrates and fish depend on the characteristics of the released oil and environmental conditions at the time of the release. Acute toxicity to fish is commonly but not always observed in association with crude oil releases, and is an indicator that, at least briefly, concentrations of dissolved hydrocarbons (particularly mono-aromatic hydrocarbons, some low molecular weight PAHs, and short-chain aliphatic hydrocarbons) are sufficiently high to cause acute toxicity due to narcosis. Light oils have low viscosity relative to heavier oils. Turbulence in flowing water could potentially disperse light oil as small droplets in the water column, increasing the potential for toxic fractions of the light oil to dissolve into the water column. As a result of the flow conditions, and the relatively small volume of flow in Mosquito Creek providing dilution to dissolved hydrocarbons, the potential for acute toxicity to fish and benthic invertebrates could be high, and greater for the light oil than for heavy oil.

As a headwater system, the volume of water flow associated with the spring freshet in Mosquito Creek is not likely to be sufficient to dilute and limit the maximum dissolved hydrocarbon concentration in water. Therefore, it is likely that acute toxicity to fish would occur in Mosquito Creek during spring flows, extending at least as far as the longest modeled trajectory, and potentially farther as dissolved hydrocarbons could continue to be transported downstream even when the surface oil slick has terminated. Toxicity to fish would also be more likely for the light crude oil than for the heavy crude oil due to the higher proportion of low molecular weight (and relatively water soluble) hydrocarbons in the light crude oil. The lower viscosity of the light crude oil, which would enhance the potential for small droplets of oil to become entrained in the water column, would also enhance the rate of hydrocarbon dissolution into water.

There would also be high potential for chronic effects of released crude oil on fish eggs and embryos (i.e., induction of deformities or mortality collectively termed blue sac disease). Many of the fish species present in the Mosquito Creek spawn in the spring and early summer. The eggs and embryos of these species could be exposed to total PAH concentrations in the river water that could be sufficiently high to induce deformities or cause mortality. In addition the potential for phototoxicity, caused by an interaction of UV light with PAHs accumulated in fish tissues, would be greatest for a crude oil release in summer due to high light intensity and long day length. Small fish that are lightly pigmented or transparent (i.e., embryos, larval and juvenile fish) are most susceptible to phototoxicity. In addition the potential for phototoxicity, caused by an interaction of UV light with PAHs accumulated in fish tissues, would be greatest for a crude oil release in summer due to high light intensity and long day length. Small fish that are lightly pigmented or transparent (i.e., embryos, larval and juvenile fish) are most susceptible to phototoxicity. The risk of phototoxicity could be partially mitigated by periods of high concentrations of suspended sediment and dissolved organic carbon present in the water.

Entrainment of small crude oil droplets in the water column also enhances the potential for light crude oils to interact with suspended sediment particles in the water column resulting in the formation of OPAs. Such aggregates may subsequently be preferentially deposited in areas of still or slowly moving water, such as oxbows and backwaters. Formation of true OPAs is less likely to occur with heavy crude oils such as diluted bitumen, as the higher viscosity of the oil precludes the ready formation of fine droplets in the water column (Zhou et al. 2015). However, heavy oils can still contact sediment particles along the shoreline, and some accumulation of both light and heavy oils in depositional areas is likely, although the precise mechanisms of deposition may vary. Neither crude oil type is likely to reach a density greater than that of the water and sink directly to the sediment within the first few days following release. During the high flow spring period, while neither oil is predicted to be on the water surface beyond 10.4 miles downstream of the release location within the first 24 hours of the release, it is possible that oil accumulated in depositional areas could mobilize over time and move farther downstream towards, and potentially into the north end of Lower Rice Lake.

For a hypothetical release under spring freshet conditions, it is likely that most aquatic plants would still be dormant or submerged, and that environmental effects on this receptor type would be minimal. However, where they occur, floating aquatic plants would be expected to be killed if contacted by an oil slick. Submerged aquatic plants ould be less vulnerable, as they would be exposed primarily to dissolved hydrocarbons, and are not considered likely to be among the more sensitive groups of aquatic biota to such exposure. Emergent aquatic plants are generally quite tolerant of moderate exposure to floating oil (such that a portion of the stem could be oiled). However, flooded riparian areas and wetland habitats would also be exposed to the released oil, and if not properly remediated, crude oil residues could kill plants in these areas. This could affect the biological integrity and productivity of the habitat, and potentially lead to erosion and further damage to the habitat.

Wild rice is an emergent aquatic plant of biological and cultural importance and occurs where Mosquito Creek enters Lower Rice Lake. Wild rice provides a food source and nesting cover for many birds, and is also harvested as a food source by people in the area. Based on the 24 hour simulations, the longest modeled trajectory during the high flow period extended 10.4 miles downstream of the releases and 1.4 miles upstream of Lower Rice Lake. This suggests that it is unlikely that released crude oil during this season would result in adverse effects to wild rice in Lower Rice Lake. However, it is possible that oil accumulated in depositional areas could mobilize with time and move farther downstream towards, and into the north end of Lower Rice Lake. This would be similar to the process that led to accumulation of diluted bitumen in the upper end of Morrow Lake following the Marshall, Michigan oil spill in 2010. The mobilization of oil that accumulates in depositional areas would be more likely to occur for the heavy crude oil which weathers more slowly and is more persistent than the light crude oil. Accumulation of crude oil in the sediment at the north end of Lower Rice Lake could be detrimental to the germination and growth of wild rice.

Crude oil released during the summer-fall (average flow) period is predicted to travel downstream, stranding on grassy and marshy banks and losing volatile components of the oil to evaporation. Results for Bakken and Cold Lake crude oil types provide bounding cases for the products likely to be carried in the pipeline. Based on a 24 hour model run, the OILMAP Land simulations indicate that crude oil could be carried between 2.6 and 9.8 miles downstream from the point of release under summer-fall average-flow conditions. For heavy oil and light oil, stranding on creek banks would be the primary fate, with only small amounts of evaporative weathering of the heavy oil and moderate amounts of weathering for lighter oils within the first 24 hour period. The lower water flow in summer-fall could result in less dilution of water soluble components in the creek as compared to spring flow. However, the lower flow rates would be accompanied by lower turbulence in the water column, and a reduced tendency for crude oil to be dispersed as fine droplets in the water column. Periodic drying of the creek headwaters during summer and fall conditions would also limit crude oil transport should a release occur during a dry summer, as well as limiting the interaction between oil and aquatic receptors. As a result, acute lethality caused by narcotic effects on fish and benthic invertebrates are less likely during the summer-fall season than in spring. The potential for blue sac disease to harm or kill developing fish eggs and embryos is also lower, due to the timing which avoids the reproductive period for most fish species. Taking into consideration the lower river flow and turbulence, deposition of crude oil residues to sediment in areas of still water is also less likely than during the spring period. These factors would also limit the potential for downstream movement of submerged crude oil into Lower Rice Lake, and subsequent interaction with aquatic plants and wetland areas.

Under low flow winter conditions, neither of the two bounding crude oil types is predicted to enter Mosquito Creek. As such, a crude oil release in winter would not be expected to seriously affect aquatic receptors.

7.2.6.3 Semi-Aquatic Wildlife Receptors

Habitat of the Mosquito Creek downstream of the hypothetical release location supports amphibians (e.g., salamander, mudpuppy), reptiles (e.g., turtles, snakes), semi-aquatic birds (e.g., ducks, geese) and semi-aquatic mammals (e.g., muskrat, otter). Habitat along Mosquito Creek varies in quality for semi-aquatic wildlife receptors. The creek is generally narrow, with grassy, marshy or boggy banks, and flows through a corridor dominated by bog/marsh, bounded by agricultural lands. Semi-aquatic wildlife receptors (e.g., amphibians, turtles, waterfowl, muskrat, and mink) will certainly be present throughout the length of Mosquito Creek. While individuals may be affected by exposure to released oil in the immediate area of the creek during the spring freshet and the summer-fall average-flow conditions, regional populations of these animals will be robustly supported by the extensive wetland and aquatic habitats in the area. Crude oil from a hypothetical release is not predicted to enter Mosquito Creek in winter, so effects on semi-aquatic wildlife would be minimal in that season. Details on predicted environmental effects for amphibians and reptiles, birds and mammals are provided below.

7.2.6.3.1 Amphibians and Reptiles

Crude oil released to the Mosquito Creek during the spring (high flow) or summer-fall (average flow) seasons is predicted to travel downstream, interacting with vegetation and seasonal shoreline areas in the riparian floodplain. The distance travelled would depend upon river flow and oil type. Based on OILMAP Land simulations, light oils oil is predicted to travel father downstream than heavy oil. For heavy oil, stranding on shore would be the primary fate, with only small amounts of evaporative weathering of the oil occurring within the first 24 hour period. For light oil, stranding would remain the primary fate, but considerably more of the released oil could be lost to evaporation.

Within the oil-exposed habitats along the river that support amphibians (adults, juveniles, and eggs), oiling effects including mortality would be observed. Turtles appear to be relatively tolerant of external crude oil exposure, and although these animals are likely to become oiled, mortality of turtles as a result of this exposure is less likely. Reptiles like lizards and snakes are primarily terrestrial species and are less intimately associated with aquatic environments. As a result, exposure of these animals to released crude oils would be limited. After the Kalamazoo River oil release in 2010 snakes did not appear to be highly exposed to released oil. A release of light crude oil during the spring would likely have a greater effect than in summer due to the greater predicted downstream transport distance and interaction with greater areas of riparian and wetland habitats than later in the year.

Under low flow winter conditions, neither of the two bounding crude oil types is predicted to enter Mosquito Creek. As such, exposure of amphibians and reptiles in winter would not be expected. In addition, amphibians and reptiles undergo a dormancy period when temperatures drop below approximately 41 to 45°F. Therefore, even if crude oil were to reach the creek, it is unlikely that amphibians and reptiles would be materially exposed to or affected by the released oil.

7.2.6.3.2 Birds

Aquatic and semi-aquatic birds are those that use rivers, lakes, wetlands, and riparian areas as components of their habitat, particularly for nesting and feeding. These birds belong to a variety of guilds including but not limited to waterfowl, divers, gulls and terns, raptors, shorebirds, waders, and some songbirds. They have a variety of dietary preferences, including piscivory, insectivory, omnivory and herbivory. If exposed to external oiling, the ability of birds to maintain body temperature may be compromised, leading to death as a result of hypothermia. Even if they survive their initial exposure to crude oil, the exposure may require an increase in metabolic rate to survive. In turn this may compromise other life functions such as reproduction or growth. Birds that survive external oiling may experience toxicological stresses as a result of ingesting crude oil residues while preening or attempting to clean and restore the normal properties and functions of feathers. Birds can also transfer potentially lethal quantities of crude oil residue from their feathers to the external surface of eggs, resulting in death of developing embryos.

Unlike many other vertebrate receptors, aquatic bird species in the northern temperate zone are nearly all seasonal migrant species which leave their summer (and often breeding) habitat in the fall for wintering areas farther south where they can find open-water habitat. However, some birds (e.g., Canada goose) will opportunistically remain in freezing conditions if there is reliable open water and a source of food available. Timely capture and rehabilitation of oiled birds may help to mitigate the environmental effects of a crude oil release. During the spring (high flow) season, many migratory birds would be returning to riverine and lacustrine habitats in Minnesota, or migrating through these areas on their way to breeding habitats farther north. With cold water temperatures prevailing, aquatic and semi-aquatic birds contacted by crude oil are likely to die as a result of hypothermia. Waterfowl and other semi-aquatic birds present in the affected river reach would be most affected. Animals upstream, farther downstream, or occupying other nearby habitats, would likely be less affected as it is assumed that emergency response measures to prevent or reduce further possible downstream transport of oil would be in place within 24 hours of the release.

Environmental effects of a crude oil release in the summer-fall period are likely to be of similar or lesser magnitude. With rising water temperatures, mortality of lightly oiled adult birds due to hypothermia becomes less likely than in the spring. However, in the early summer, environmental effects could include egg mortality due to transfer of oil from the feathers of lightly oiled adult birds in the nest. Chronic adverse effects on the health of birds that survive their initial exposure to crude oil are also possible as a result of ingesting crude oil residues while preening, or while consuming food items. However, as in the spring, effects are expected to be limited to areas of oil exposure and areas of the creek with suitable habitat, which could range from 2.6 to 9.8 miles downstream from the release point.

Under low flow winter conditions, neither of the two bounding crude oil types is predicted to enter Mosquito Creek, and most aquatic or semi-aquatic birds would have migrated away from the area for wintering habitat farther south. As such, exposure of birds to released crude oil in winter would be very limited.

7.2.6.3.3 Semi-aquatic Mammals

While the semi-aquatic mammal species found in Minnesota include terrestrial species such as moose and raccoon, this assessment focuses particularly upon species that have a primary association with the aquatic environment such as muskrat and beaver (herbivores), American mink (*carnivore-piscivore*), and river otter (*piscivore*). These species are at greater risk of exposure to an oil release in water than terrestrial mammals.

Effects to semi-aquatic mammals are typically described in terms of direct physical effects (e.g., hypothermia due to loss of insulation), direct toxicological effects (e.g., gastro-enteropathy caused by ingestion of crude oil residues while grooming oiled fur or ingesting food), and indirect effects caused by changes to habitat (e.g., land cover and food availability). The spatial extent along Mosquito Creek where effects may occur, and the magnitude of effects, is related to the oil type released, season and flow rate. Effects to semi-aquatic mammals relate more to the amount of time spent in the water (and consequent exposure to physical oiling) than to dietary preferences. Timely capture and rehabilitation of oiled mammals may help to mitigate the environmental effects of a crude oil release.

During the spring (high flow) season, with cold water temperatures prevailing, semi-aquatic mammals contacted by crude oil are likely to die as a result of hypothermia. Based on the OILMAP Land simulations, the leading edge of the releases could range from 3.5 to 10.4 miles in extent. Animals upstream, farther downstream where there is no exposure, or occupying other nearby habitats, would likely be unaffected. Therefore, although mortality of some semi-aquatic mammals could be expected, large-scale (i.e., regional) population level effects are unlikely.

Environmental effects of a crude oil release in the summer-fall period are likely to be of similar or lesser magnitude than those associated with a release during a spring freshet. With rising water temperatures, mortality of lightly oiled semi-aquatic mammals due to hypothermia is expected to be less likely than in the spring. Chronic adverse effects on the health of semi-aquatic mammals that survive their initial exposure to crude oil also are possible as a result of ingesting crude oil residues while grooming, or while consuming food items.

In the winter months, muskrat and beaver are likely to reduce their activity levels, although American mink and river otter would remain active. Animals that became oiled in the winter would be likely to rapidly die as a result of hypothermia.

7.2.6.4 Human and Socio-Economic Receptors

Crude oils are complex mixtures of hydrocarbon compounds. Light crude oils typically contain more VOCs than heavier crude oils, although diluted bitumens may contain similar amounts of VOCs to light crude oils, depending upon the type and amount of diluent they contain. Air quality in the vicinity of a crude oil release, and along the downstream corridor, would be affected by the release of VOCs (such as benzene, which is often used as an indicator substance) primarily within the first 24 hours of an oil release. Under spring and summer-fall conditions, most of the released CLB or Bakken crude oil is predicted to reach Mosquito Creek, spreading on land and on the water. In contrast, under winter conditions virtually all of the released crude oil is predicted to be retained in snow or fill depressions on land. Low air temperatures, as well as the relatively thick layer and limited surface area of crude oil retained in the snow pack, are expected to minimize release of volatile components to the atmosphere in winter.

Typical human health effects associated with short-term (acute) inhalation of volatiles from crude oil include headache, dizziness, nausea, vomiting, cough, respiratory distress, and chest pain. Short-term or repeated skin contact with crude oil may result in dermatitis. The case studies (Section 7.1) do not reveal any instances of human fatality as a result of inhalation of crude oil vapor. Similarly, ATSDR (1995) report that there are no known instances of human fatality as a result of inhalation of vapor from fuel oils, which would be comparable to light crude oils.

The potential for VOC inhalation exposures by the public would be greatest near and downwind from the release site and near to Mosquito Creek while the released oil is on the water surface. For the most part, the areas around Mosquito Creek are sparsely populated (i.e., farms and country dwellings). The nearest HCA representing a populated area is located west of Lower Rice Lake, and not within the area identified to be potentially contacted by released oil within 24 hours of a release. One farm is located within approximately 300 ft of the overland flow path between the hypothetical point of release and the head of Mosquito Creek, and a number of other homes are located within a similar distance of Mosquito Creek, upstream of Lower Rice Lake. In the unlikely event of a crude oil release, a human fatality is highly unlikely. Most of the volatile hydrocarbons would be lost within the first 24 hours following a release of crude oil.

Residents in close proximity to the flow path would become aware of a strong hydrocarbon odor that would alert them to the presence of a hazard. It is also expected that emergency response personnel would contact such residents and advise them to evacuate. Actual or potential exposure to crude oil vapor may result in residents leaving, or being advised to leave their homes for a period of time while the emergency response takes place.

No drinking water HCAs were identified along the path of the release. However, a number of homes are located along the trajectory of the overland flow path and adjacent to Mosquito Creek upstream of Lower Rice Lake. It is assumed that residents of these homes rely on groundwater as a drinking water source. In the event of a crude oil release, people would be notified and testing would be completed to confirm the safety of the water supply. Based upon case studies involving crude oil releases elsewhere, this process could take a few days to two weeks, but reports of crude oil releases affecting private wells are rare, making this an unlikely effect.

Relatively little has been published regarding the long-term effects of exposure to an oil release. Health effects observed in residents and clean-up workers in the months following an oil release generally do not persist over the long term (Eykelbosh 2014). The International Agency for Research on Cancer (IARC 1989) has determined there is "limited evidence of carcinogenicity" of crude oil in experimental animals and "inadequate evidence of carcinogenicity" of crude oil in humans. Although toxicological effects from short-term exposure to volatile hydrocarbons are reversible when exposure is reduced, other health effects such as anxiety and depression may occur, and may persist, regardless of whether the individual was physically exposed to hydrocarbons.

Effects of a crude oil release on human receptors would be generally similar for the spring (high flow) and summer-fall (average flow) seasons, except that warmer temperatures and slower river flow velocities in the summer would promote more rapid evaporation of volatile hydrocarbons in a smaller area, whereas higher river flow velocity in the spring freshet period would transport the released oil farther downstream within the first 24 hours, potentially resulting in lesser exposures, but to a larger number of people. The distance of downstream oil transport depends upon river flow rate, oil type and bank type. Based on OILMAP Land simulations of lighter oils are predicted to travel father downstream than heavier oils (Figure 7-7 and Figure 7-8). As a result, a release of the light crude oil may affect a larger number of individuals than a release of the heavy crude oil type. Both Bakken crude oil and Cold Lake diluted bitumen are expected to contain similar overall amounts of volatile hydrocarbons, so differences related to the chemical characteristics of the released oil are likely to be minor.

Recreation, tourism, forestry and agriculture are the major land uses in the area of Mosquito Creek and Lower Rice Lake. Based on the 24 hour simulations and taking release response activities into account, neither heavy nor light crude oil is predicted to move on the water surface beyond 10.4 miles downstream of the releases. However, it is possible that oil accumulated in depositional areas would mobilize with time and move farther downstream,