1.0 INTRODUCTION

Stantec Consulting Services Inc. (Stantec), RPS Group PLC (RPS), and Dynamic Risk Assessment Systems, Inc. (Dynamic Risk) (referred to collectively as the Consulting Team) were retained to prepare a risk assessment for potential large releases of oil from the Line 3 Replacement Project (L3RP). The proposed preferred route for the L3RP is provided in Figure 1-1.

1.1 BACKGROUND ON L3RP

Enbridge Energy, Limited Partnership (Enbridge) is proposing the L3RP to replace Enbridge's existing Line 3 pipeline, from the Joliette Valve in Pembina County, North Dakota to Clearbrook, Minnesota, and then on to an existing terminal in Superior, Wisconsin (Figure 1-1).

The L3RP route is approximately 363 miles long, 337 of which are in Minnesota. The remainder of the pipeline is located in North Dakota and a small portion in Wisconsin. Within Minnesota, L3RP would involve the construction and operation of a 36-inch diameter, underground crude oil pipeline. The Project would also include a new pump station and improvements at the existing Clearbrook Terminal, the expansion of three other existing pump stations west of Clearbrook, and the addition of four new pump stations in Minnesota east of Clearbrook.

The replacement pipeline will be co-located with the existing Line 3 and Enbridge's Mainline Corridor from the Minnesota/North Dakota border to Clearbrook. This portion of L3RP would be parallel to and approximately 25 feet (ft) from the existing Line 67 pipeline. For the remaining 246 miles of the L3RP route south and east of Clearbrook, the pipeline would be located in a new right-of-way (ROW), portions of which will parallel other existing third-party pipelines, electric transmission corridors, and transportation corridors.

L3RP would transport a variety of crude oils that range from light to heavier crude oils, including diluted bitumen.

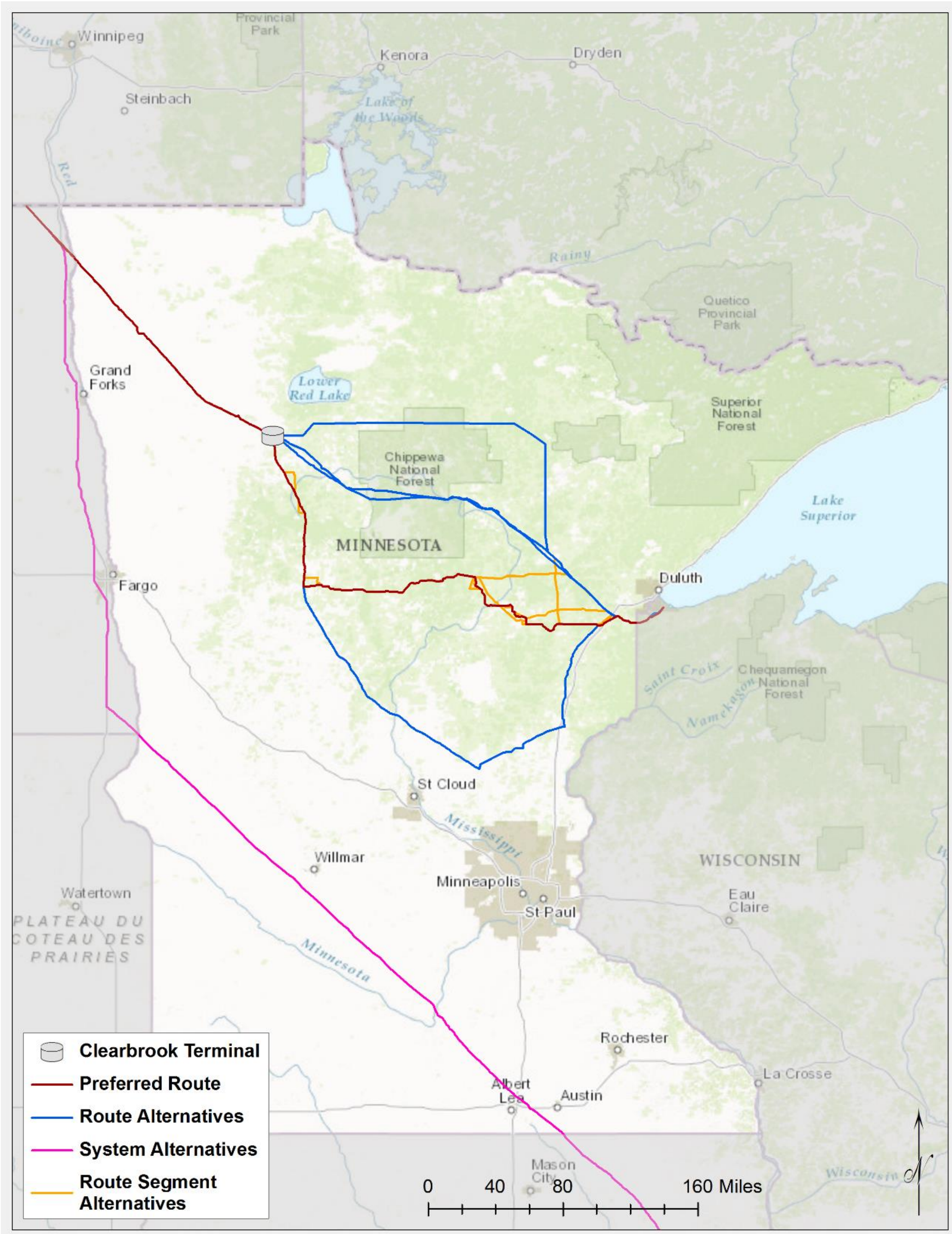

Figure 1-1 Map of the Preferred Route for L3RP, Route Alternatives, Route Segment Alternatives and System Alternatives

1.2 SCOPE OF THE ASSESSMENT

The Final Scoping Decision Document (FSDD) for L3RP (Minnesota DOC-EERA 2016) describes the topics that need to be addressed in the Environmental Impact Statement (EIS) to be prepared by the Minnesota Department of Commerce, Energy Environmental Review and Analysis (DOC-EERA).

In regard to the analysis of large oil releases, the EIS is to include "spill modeling and a summary and application of analysis methods from other projects." The FSDD states that the Applicant (Enbridge) will provide "data on maximum spill volumes, spill frequency, and the types of crude oil to be transported based on the proposed engineering and operations for the pipeline". This information will be applied to all large-volume spill impact analysis methods. An estimated large-volume spill footprint will be established using these data and based on methods used by other current or recent investigations. The methods will consider general geomorphic conditions in Minnesota to develop a general spill footprint. The analysis will also include a review of crude oil release data from the Pipeline and Hazardous Materials Safety Administration (PHMSA) database."

In addition, the FSDD states that "to assess potential impacts associated with an accidental release, the Applicant will provide maximum spill volume estimates based on response times, valve locations, and pipeline volumes at seven representative sites assuming a complete pipeline rupture. Data generated from modeling at representative sites will be used to make broad environmental comparisons among and across routes in areas with similar features." Modeling will include "a set of scenarios that include the following crude oil types: light sweet Bakken crude oil, Cold Lake Blend (CLB), and Cold Lake Winter Blend (CLWB). These crude oils represent the range of oil densities and chemical compositions expected. Additional modeling parameters include seasonal variation to capture water flow volumes (high flow, low flow, and snow/ice covered), and a 24-hour model run with outputs at 6, 12, and 24 hours. The combinations of model inputs will result in more than 40 modeling scenarios from which to analyze potential impacts to resources along route alternatives."

1.3 PURPOSE

The purpose of this document is to provide information on the risk of a large volume release of crude oil from the proposed L3RP. Risk is defined most concisely as the "chance of loss". Accordingly, in the context of the risk associated with the operation of the L3RP pipeline, the term "risk" is used as a joint expression of chance (the annual probability of incurring a rupture in the L3RP pipeline), and loss (the consequences associated with such a rupture).

For an oil release, there are several probabilities that should be considered in a risk assessment:

- Probability that a release will occur (i.e., failure frequency)
- Probability that any released oil will reach an environmentally sensitive area or receptor (modeling helps to understand spatial and temporal behavior of oil releases)

- Probability that environmentally sensitive and vulnerable species will be present or a human use will occur in the area affected by a release during the period in which there is a possibility of exposure to oil (i.e., knowing how an oil release behaves in space and time provides a better understanding of how an environmental component might be exposed to the release and what the environmental effects might be if a spill occurred)

To address the probability of large volume releases of crude oil, as well as the likely consequences associated with large volume releases of crude oil release if it were to occur, a number of factors and aspects are considered in this report, including:

- Probability that a large release of oil will occur, including an assessment of natural and human-caused threats to the pipeline, an assessment of the likelihood of a specific type of threat resulting in a large oil release (i.e., failure frequency), and the corresponding reasonable worst-case volume of oil released
- Modeling hypothetical large releases of several types of crude oil in terrestrial and freshwater environments to understand the fate of potential large oil releases with respect to the likely trajectory from specific release locations and the potential behavior of the oil within the environment, taking into account the geographic and environmental conditions where the modeled release occurs, including seasonal variability in the conditions
- Based on the results of the oil release modeling, assessment of the resources that may be affected and the range of potential effects that may result, should a large release of oil occur in the natural (physical and biological) and human environment[1]
- Potential for the natural and human environment to recover from the effects of a large oil release following the event, including a discussion of factors that can promote or impair recovery and the approximate timing of recovery

Each of these topics is discussed in the corresponding chapters of this report (see Section 1.4 for a discussion of the report structure and content).

Other topics of relevance to understanding the potential for, and management of, accidental releases of crude oil include:

- Understanding how the likelihood of an oil release can be reduced through pipeline design, construction techniques, technical specifications, operational protocols, ongoing monitoring, inspection, and maintenance
- Preparation of emergency response plans, including the incident command structure, internal communications, and ongoing commitments by the project proponent, Enbridge, and government agencies for preparedness of personnel and equipment, training, and regular exercises and drills
- Development of measures to reduce and manage the physical spread of hydrocarbons if a release occurs
- Range of measures that would be employed by Enbridge to clean up and rehabilitate areas affected by an oil release

[1] The natural environment includes the atmospheric environment, ground water and surface water, terrain, soils, freshwater fish, vegetation, wetlands, and wildlife, including rare and endangered species. The human environment includes human uses, social, cultural and economic values, and heritage resources.

These topics will be addressed in other submissions to the DOC-EERA by Enbridge.

1.4 OVERVIEW AND RATIONALE OF APPROACH TO ASSESSING THE LIKELIHOOD AND EFFECTS OF OIL RELEASES

1.4.1 Differences in Assessing the Effects of Routine Activities versus Accidental Releases of Oil

Environmental assessments are generally intended to predict the type and range of effects on the natural and human environment that could occur as a result of the construction, operation and decommissioning of a project. In addition, they typically describe recommended measures to mitigate and reduce effects of the Project, such as the effects of the routine activities during any phase of a project, as well as potential accidents and malfunctions.

However, there are number of key differences in how effects of routine activities differ from accidents and malfunctions (especially oil releases) and how they can be assessed. These include the following:

- While the effects of routine activities will or are likely to occur if the Project is constructed, operated and decommissioned, accidents and malfunctions and associated effects on the environment are, by definition, not common or may not occur at all. The likelihood of a large oil release occurring (i.e., the failure frequency) and the potential outflow volume (e.g., lower volume versus larger volume releases) are therefore important considerations in a risk assessment for an accident or malfunction.
- Effects of routine activities on the natural and human environment can be adverse (e.g., air emissions, loss of habitat) or positive (e.g., economic benefits). In contrast, effects of oil releases are almost always adverse. The significance of these effects to the natural or human environment will therefore depend on existing conditions and the characteristics of the resulting effects.
- While the specific effects of routine activities and infrastructure (e.g., the physical footprint, intakes and outputs to the environment) can often be predicted with a high degree of confidence through the multiple phases of the Project (e.g., construction, operation, decommissioning), the effects of an accidental release of crude oil must be based on a number of assumptions about the release and some form of modeling. Modeling results are specific to the assumptions and inputs used in modeling, including the conditions for the release (e.g., seasonal and weather conditions), the type and volume of crude oil released, the duration of the release, the specific location of the release, and several other factors. Modeling results for the same location can vary greatly, depending on the timing of the release (e.g., seasons, month), temporally-specific conditions such as weather and water flows (which can vary at scales of minutes to hours), release duration (instantaneous versus protracted duration of release), and other associated site conditions.
- Because there are differences in the certainty for routine activities (which will or will likely happen), versus a hypothetical release of crude oil (which may never happen), the resulting effects carry different weights or certainty. Routine activities are often quantified by estimating the physical and temporal overlap with environmentally sensitive components (e.g., distribution patterns of biota, movement patterns of biota, important habitats for fish or

wildlife, human use areas). There is less certainty in the estimates and likely spatial and temporal overlap of potential trajectories and site-specific behaviors of an accidental crude oil release with biological species or human uses. This is especially the case as species presence and human use also may be changing in space and time.
- When quantifying potential effects, the certainty of the value or benefit of mitigation measures for effects associated with routine activities is greater than those of accidents and malfunctions (i.e., a release of crude oil).

Statutes and regulations are in place that account for risks from potential future release incidents; this includes response preparedness and coordination, as well as full restoration of natural resource losses resulting from actual release incidents (i.e., the federal Oil Pollution Act and its implementing natural resource damage regulations at 15 United States Code of Federal Regulations [CFR] part 990).

1.4.2 Approach Used in Assessing Large Releases of Crude Oil

Given these differences in assessment approaches between routine activities and accidental releases, as well as the requirements for the assessment as described in the FSDD, the approach used for assessing the risks of a large release of crude oil from L3RP included several important components to improve an understanding of:

- How a large release of crude oil might occur and the likelihood of such a release (i.e., a threat assessment and failure frequency analysis)
- Likely trajectory and fate (i.e., behavior) of large unmitigated (i.e., no emergency response) releases of several types of crude oil under different environmental and seasonal conditions
- Range of potential effects an unmitigated large release of crude oil may have on the natural and human environment
- Potential and timing for the recovery of the natural and human environments following a large release of crude oil

To predict the potential threats, failure frequencies, and the trajectory and fate of hypothetical releases of crude oil, several representative sites along the preferred route for L3RP were suggested by the Consulting Team for consideration by the DOC-EERA and other state and federal agencies. Based on input from the DOC-EERA and these agencies, sites on some alternative routes were also considered. The approach for engagement of these agencies, the process used to select sites, and the methods used to characterize each hypothetical release location are described in Section 3.1.

The sites selected for the threat and failure frequency assessments, modeling of hypothetical releases, and assessment of effects were deliberately chosen to represent a variety of biophysical conditions, including the type and size of water features (e.g., size of watercourse, size of water body, speed and turbulence of water flow, and water depth), the type and density of vegetation cover, the type and intensity of land use, and human and ecological values. Issues raised through consultation with government agencies, affected stakeholders, the general public and native tribes also influenced the types of sites chosen. As discussed in Section 3.1, DOC-EERA coordinated a collaborative process with state and federal agencies to develop criteria for selection of preferred sites for modeling of hypothetical releases of crude oil and the assessment of effects. The criteria that were developed by this group took into account a range of biophysical conditions, as well as issues raised through consultation and regulatory processes.

For the assessment of large releases of crude oil from L3RP, once the criteria for selection of modeling locations had been determined, the needs of the assessment (as described in DOC-EERA 2015) were considered in developing the general assumptions for the spill modeling with respect to:

- **Type of crude oil:** To account for the differences in the types of crude oil that could be transported by the proposed L3RP, and the behavior of these crude oils within the environment, both a light crude oil (i.e., Bakken Crude) and two mixtures of a single heavy crude oil (i.e., CLB and CLWB) were considered. Note that CLWB was only used in winter time scenarios with low river flow conditions in the receiving water body. CLB was used in the spring high river flow and summer average river flow scenarios, corresponding to the seasonal availabilities of these two products.
- **Volume of oil:** To model a large release of crude oil (DOC-EERA 2015), a full bore rupture (i.e., complete severing of the pipeline) of the pipeline at a modeling site was modeled. In addition, conservative assumptions were used to account for the time for full shutdown of the affected pipeline (i.e., taking into account elapsed time for alarm notification, stopping the pumps, and closure of the shut-off valves). The maximum volume of crude oil hypothetically released at each site included both the initial release volume prior to shutdown (i.e., actively pumping out), as well as hydraulic drain down of the pipeline (i.e., gravity drained oil within the pipeline between the valves), following shutdown at that site.
- **Duration of model run:** To provide a conservative estimate of the trajectory and fate of crude oil, it was assumed that the maximum volume of crude oil released would flow downstream for 24 hours without mitigation (i.e., the initiation of an emergency response and clean up). However, modeling results were captured at 6, 12, 18, and 24 hours to approximate the downstream/down current extent and weathering of crude oil over the 24-hour period. Of note, a response would be initiated in a shorter period; therefore, this is a conservative assumption for these hypothetical release scenarios.
- **Seasonal differences in river flow conditions:** To account for seasonal fluctuations in the characteristics of water features, especially watercourses; high river flow (spring), average river flow (summer), and low river flow (winter) conditions were modeled at each site.
- **Seasonal differences in weather:** To account for differences in the behavior of several types of crude oil under different weather conditions, the corresponding weather information (e.g., temperature, wind speed) for each river flow condition (i.e., season) were identified and used in modeling.

Pinhole leaks were identified as a concern by regulators and the public; pinhole leaks are addressed in a separate report (Stantec and Barr 2016).

Based on the selection criteria for modeling locations (Chapter 3.0), the DOC-EERA, in collaboration with other state and federal agencies and the Consulting Team, chose seven representative sites across western, central, and northern Minnesota for modeling of hypothetical releases of crude oil. The seven sites represent a broad geographic range throughout areas of Minnesota that could be crossed by L3RP. In combination, the seven sites represent a diversity of water features including large rivers down to small streams and ditches, with a range of flows from slow to rapid, varying amounts of turbulence, differences in channel types (e.g., sinuous to straight), and several lakes. They also represent a wide range of vegetation types and land uses, including several different forest types, protected areas, cultivated land, rice lakes, recreational areas, and human settlements.

For each of the seven representative sites that were selected, a threat assessment, failure frequency assessment, modeling of the potential trajectory and fate of large crude oil releases, and an assessment of effects to the biophysical and human environment were completed. Combined with the three flow conditions/seasons and the two types of crude oil (CLB and CLWB are considered one type of crude oil), the modeling completed for the seven representative sites equates to a total of 42 release scenarios (7 sites x 3 flow conditions x 2 types of crude oil).

During the public scoping comment period, questions were raised about the total number of sites to be investigated in these analyses. Some comments/questions implied that more than seven representative sites should have been chosen, with the same analyses completed for each site as those described in this report. Because the seven sites were selected to reflect a broad range of geographic and environmental characteristics, together they provide an understanding of a broad range of potential effects, should there be a large release of crude oil. This is consistent with the FSDD that "data generated from modeling at representative sites will be used to make broad environmental comparisons among and across routes in areas with similar features". Therefore, while modeling a larger number of sites may address site-specific concerns raised by stakeholders, the public, and native tribes, the incremental information gained regarding the potential fate of released crude oil and the associated range of effects would be marginal. The range of potential effects on the biophysical and human environment at these additional sites would not be expected to differ greatly from those assessed for the seven modeled sites.

It is the opinion of the principal authors of this report (as described in the preface) that additional modeling would not add proportionately to a better understanding of hypothetical releases of crude oil, nor would it change the conclusions of the anticipated environmental effects should there be a large release of crude oil. The breadth of water features and biophysical conditions included within the combined footprint of the seven modeling locations and the associated oil release trajectories are large. When this is combined with the seasonal differences and variable behavior of several types of crude oil, a broad range of potential environmental effects has been considered relating to physical and biological attributes of the environment and the socio-economic aspects and cultural values of the human environment (Chapter 7.0). It is the opinion of the principal authors of this report that adding additional modeling locations would not greatly alter the breadth of environmental effects considered, nor would it affect the conclusions that are made in this report.

1.5 USE OF THE OIL RELEASE MODELING INFORMATION

As noted in the FSDD, "information from the modeling is to be used to make broad environmental comparisons along and across routes in areas with similar features" (DOC-EERA 2016). The modeling of oil release trajectories and fate for each of the seven representative sites was intended to assist the DOC-EERA in addressing the environmental consequences of accidental large releases of crude oil as part of their broader assessment of the preferred and alternate routes for L3RP.

The analysis of environmental effects of an accidental large release of crude oil presented in this report (Chapters 5 through 7) is known as a consequence assessment. The intent of the assessment was to investigate the range of potential outcomes (effects) to the natural and human environment if an accidental release of a large volume of crude oil was to occur at any point along the pipeline (including preferred and alternative routes). The assessment involved quantitative modeling at carefully selected sites to predict the likely trajectory and fate and behavior of released oil, as well as assessments of the probable range of environmental effects under a variety of conditions. Through a careful and deliberate selection of representative sites across northern and central Minnesota, a broad spectrum of terrain, land-cover types, watercourses, waterbodies, wetlands, associated freshwater and riparian habitat types, vegetation, environmentally-sensitive areas, and human land uses were considered in the modeling and effects assessment. Therefore, this assessment can be used to consider the range of consequences that may be possible should there be an accidental release of crude oil along the proposed route or the proposed alternative routes for L3RP. Several different summary tables are provided in Chapter 3.0 to assist in the application of information from modeled locations to other locations.

As discussed in detail in Chapters 3 and 5, the consequence assessment for accidental large releases of crude oil involved quantitative modeling and assessment of potential environmental effects for 42 scenarios to demonstrate the anticipated range of outcomes that might occur in different seasons following an accidental large release of crude oil in a number of representative site conditions in central and northern Minnesota. The assessment considered:

- the range of product types (i.e., light and heavy crude oils) that may be shipped on the proposed pipeline
- environmental variability (i.e., 3 time periods including seasonal differences in river flow rate, snow/ice coverage, temperature, wind speed, etc.)
- biogeographic variability (i.e., 7 sites carefully chosen to represent different biotic and environmental factors, including climate, geology, topography, soils, hydrology, and vegetation, as well as human land use)

Results pertaining to the potential trajectory (movement), fate (behavior and weathering), and potential environmental effects of an accidental full bore rupture and resulting release of crude oil are provided for each of the scenarios. Together, these scenarios can be used to bound the range of potential consequences at potential accidental release points in areas with similar features.

While seven specific representative release locations were investigated in this study, the careful and deliberate selection of the 42 representative release scenarios allows this consequence assessment to be used to determine the range of potential effects that may be possible should there be an accidental release at other locations along the preferred or alternate routes for L3RP. An equivalency table has been provided (Table 3-4) to aid users of this report in applying the results of the consequence assessment to other locations. Should an interested party have concerns over a specific watercourse that was not modeled, this table can be used to find an equivalent representative release location. From there, the interested party can consider the range of seasons to bound and/or determine the range of potential consequences for their specific location. As an example, should an individual near Bemidji be concerned about the possible effects of a release into Lake Irving, they can refer to Table 3-4 to find an equivalent site. The Lake Irving location includes a small watercourse (<10 m) that travels a short distance and connects to a lake/pond with recreational use and sensitive ecosystems. Upon comparison, the Shell River representative release location would be a logical substitute. Similarly, if one were to consider another release location that entered a medium watercourse that traveled a longer distance before entering a lake/pond system, they could consider the Sandy River representative release location as an equivalent site.

The term "representative" release location is used, as each site serves as a proxy for other similar sites. Because oil behaves similarly in water bodies and locations with similar geographic and environmental conditions, there is not a need to model multiple watercourses that have similar features. The predicted trajectory, fate, and effects results would essentially be the same or similar. While results would be very similar, there would be small differences in the actual downstream distance traveled and the potential location-specific sensitive receptors or regions of interest, should a release occur at a site that was not modeled. Similarly, should a release occur during a transitional season that was not modeled, the end result may be slightly different given differences in water flows, vegetation condition, etc. However, as the consequence assessment did include a broad range of geographic and environmental variability that are representative of the areas of Minnesota that are crossed by the preferred and alternate routes for L3RP, it is expected that the likely outcomes for sites not modeled would be bounded by the results provided in this report.

1.6 ORGANIZATION OF THE REPORT

This report consists of individual chapters that have been prepared by one or more members of the consultant team, consisting of Stantec, RPS, and Dynamic Risk. Enbridge prepared Chapter 2.0. The lead authors for each chapter of the report are identified in the Preface.

In addition to this Introduction, the report includes the following chapters and topics.

- Chapter 2: Project Description—provides a description of the proposed L3RP.
- Chapter 3: Framing the Site Selection and Modeling Analyses—documents the approach used to frame the modeling analyses for L3RP. This chapter includes a summary of regulatory and agency engagement in developing release modeling scenarios, the identification of important considerations in modeling (e.g., hydrodynamic, seasonal, environmental, geographic, and oil chemistry considerations for modeling of crude oil releases), selection of oil release modeling tools, the development of criteria for selecting modeling locations, and the rationale for selecting specific sites for modeling.
- Chapter 4: Pipeline Failure Probability Analysis—this chapter includes an analysis of the types of threats that could cause failure, as well as a failure frequency analysis for each of the seven specific segments of L3RP associated with the modeling sites. As part of this analysis, a review of releases, as documented in the Hazardous Liquids Incident database of the U.S. Department of Transportation's PHMSA was undertaken.
- Chapter 5: Modeling of Crude Oil Releases—provides a description of the modeling tools used to predict the trajectory and fate of several types of crude oil under different seasonal conditions, including a description of key assumptions and the input data used for modeling.
- Chapter 6: Trajectory and Fate Results for Modeling Locations—this chapter describes the oil release modeling outputs for hypothetical, unmitigated, full bore releases of several types of crude oil and varying environmental conditions at the seven representative modeling locations in western, central, and northern Minnesota.
- Chapter 7: Assessment of Environmental Effects of Crude Oil Releases—the assessment begins with a description of the observed and expected effects of crude oil on key ecological and human receptors, including how crude oil behaves (i.e., its fate) in atmospheric, freshwater and terrestrial environments, followed by an assessment of effects for each of the seven representative sites. The assessment for each site includes a description of the environmental setting, the potential overlap of the modeled oil releases on High Consequence Areas (HCAs) and Areas of Interest (AOIs), and a description of the effects of a large release of crude oil on the natural and human environment.
- Chapter 8: Review of Environmental Recovery Following Releases of Crude Oil—this chapter describes the current state of knowledge of how various components of the natural and human environment are known to recover following a release of crude oil. The review focuses on information most relevant to environmental conditions in Minnesota. It also addresses how emergency response, clean up, and remediation measures can promote or impair recovery.
- Chapter 9: Summary and Conclusions—this chapter provides general conclusions on the risks of large releases of crude, including types of threats, the likelihood of occurrences of these threats for specific segments of the pipeline, the range of potential effects, including the benefits of emergency response, site clean-up and remediation, and environmental recovery of the receiving environment.

2.0 PROJECT DESCRIPTION

2.1 OVERVIEW

2.1.1 Line 3 Replacement Project

The integrity concerns on the existing Line 3 necessitate constructing of the proposed L3RP. Construction will consist of a new pipeline and associated facilities to replace Enbridge's existing Line 3 pipeline, which transports crude oil from the Joliette Valve in Pembina County, North Dakota to Clearbrook, Minnesota; and then on to an existing terminal in Superior, Wisconsin. The proposed L3RP route is approximately 363 miles long, 337 of which are in Minnesota. L3RP includes in Minnesota a new pump station and improvements at the existing Clearbrook Terminal, the expansion of three existing pump stations west of Clearbrook, and the addition of four new pump stations east of Clearbrook.

2.2 PROPONENT

Enbridge is the project proponent of L3RP.

2.3 PIPELINE ROUTES

2.3.1 Line 3 Replacement Project

Approximately 337 miles of new 36 inch diameter, underground crude oil pipeline would be constructed along the proposed L3RP route between the North Dakota/Minnesota and the Minnesota/Wisconsin borders, crossing portions of Kittson, Marshall, Pennington, Red Lake, Polk, Clearwater, Hubbard, Wadena, Cass, Crow Wing, Aitkin, and Carlton Counties.

West of Clearbrook, the L3RP route would generally follow the existing Enbridge Mainline Corridor and would be installed approximately 25 ft from the existing Line 67 pipeline. East of Clearbrook, the L3RP would generally follow other existing third-party pipelines, electric transmission corridors, and transportation corridors.

2.4 PIPELINE FACILITIES AND INFRASTRUCTURE

2.4.1 Line 3 Replacement Project

2.4.1.1 Clearbrook Terminal Modification

As part of L3RP, Enbridge would modify equipment and construct a new pump station at the existing Clearbrook Terminal, located near MP 909.4 of the existing Enbridge Mainline Corridor in Clearwater County, Minnesota.

2.4.1.2 Pump Stations

As described in Table 2-1, Enbridge would install three new pump stations adjacent to existing pump stations west of Clearbrook. The four new pump station sites would be located east of Clearbrook. Mainline valves, metering, monitoring equipment, and associated electrical facilities would also be installed at all facilities. In addition, Enbridge would install new pipeline inspector gauge launcher and receiver traps at the Backus Pump Station.

Table 2-1 L3RP Minnesota Pump Stations

County	Facility	MP	Description
West of Clearbrook			
Kittson	Donaldson	814.5	Expansion of pump capacity to 7,000 HP at existing Donaldson Pump Station
Marshall	Viking	848.2	Expansion of pump capacity to 7,000 HP at existing Viking Pump Station
Red Lake	Plummer	877.0	Expansion of pump capacity to 7,000 HP at existing Plummer Pump Station
Clearbrook			
Clearwater	Clearbrook Terminal	909.4	Installation of terminal connectivity, a new 7,000 HP Clearbrook Pump Station, PIG receiver and launcher traps, and injection from existing tanks 61, 62, 63 and 64
East Of Clearbrook			
Hubbard	Two Inlets	956.6	New 7,000 HP Pump Station
Cass	Backus	1,007.1	New 7,000 HP Pump Station and receiver and launcher traps
Aitkin	Palisade	1,061.7	New 7,000 HP Pump Station
Carlton	Cromwell	1,106.4	New 7,000 HP Pump Station

2.4.1.3 Mainline Valves

A valve is a shutoff mechanism that would be used to isolate a segment of pipeline in the rare event of a leak. At each valve location, Enbridge proposes to install the following equipment: a slab gate valve that would be remotely controlled from the Enbridge Control Center and that could be operated manually as well; digital pressure and temperature monitoring devices that would provide real-time pressure and temperature information to the Control Center; and associated electrical and communications equipment required to control the valve and monitor instrumentation.

2.5 PIPELINE CONSTRUCTION

For when pipeline construction is referenced at later parts of the report, the typical pipeline construction sequence is as follows.

First, appropriate safety measures would be implemented, including notification through the One-Call system to ensure third-party utilities and adjacent pipelines are properly marked. Next, the workspace would be surveyed, staked, and prepared for clearing. The workspace would then be cleared and graded, as necessary, to provide construction access and safe movement of equipment and personnel during construction. Silt fence[2] and other erosion control measures would be installed, and sensitive areas would be marked for avoidance. Pipe, valves, and fittings would be transported to the workspace by truck and placed along the workspace by sideboom tractors (also known as pipelayers) or cranes. After individual pipe sections are strung along the workspace, they would be bent to conform to the contours of the trench and terrain. The pipe segments would be lined up, clamped, welded, the welds inspected and subsequently treated with a protective coating. Trenching may occur before or after the pipe has been welded. Trenching is typically conducted using a backhoe or trenching machine. Where appropriate, topsoil would be segregated according to applicable permit conditions. The prepared pipe would be lowered into the trench and, where applicable, tied into existing facilities. Precautions such as padding the trench with soil would be taken during backfilling to protect the pipe from rock damage. During backfilling, subsoil would be replaced first and then the topsoil would be replaced.

[2] Silt fence: A silt fence is a sediment control device used on construction sites to protect nearby wetlands and waterbodies from stormwater runoff. A typical fence consists of a piece of synthetic fabric (sometimes referred to as geotextile fabric) stretched between a series of stakes where runoff is expected to reach wetlands or waterbodies. The fabric filters remove sediment from the water before it reaches the wetland or waterbody.

Once the pipeline has been welded and inspected and the trench has been backfilled, the pipeline would be hydrostatically tested[3] to ensure its integrity prior to the line being filled with crude oil and placed into service. The construction workspace would then be cleaned up and restoration activities would commence. Restoration would include implementing temporary and permanent stabilization measures such as slope breakers[4], mulching, and seeding.

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[3] Hydrostatic testing: Hydrostatic testing is a process of verifying the integrity of the pipeline before it is placed into service. Hydrostatic testing involves filling the pipeline with water to a designated pressure and holding it for a specified period of time.

[4] Slope breaker: A slope breaker is an erosion control device to reduce stormwater runoff velocity and divert it from the disturbed construction area to more stable ground. A typical slope breaker consists of a ridge or channel constructed diagonally across the ROW on a hill.

3.0 FRAMING THE SITE SELECTION AND MODELING ANALYSIS

3.1 INTRODUCTION

As noted in the Introduction, the approach used for assessing the risks of a large release of crude oil from L3RP involves:

- Analyses of how a large release might occur and the likelihood of such a release
- Prediction of the trajectory and fate (behavior) of a large unmitigated release under different seasonal conditions, environmental settings and with different types of oils
- Assessment of the environmental effects on and recovery by the natural and human environment from hypothetical oil releases

As each of these aspects are strongly determined by the biophysical conditions at the time and location of the release, it is necessary to choose specific locations for these hypothetical releases, and make assumptions regarding the environmental conditions at the time of the release.

The DOC-EERA worked collaboratively with cooperating state and federal agencies and the Consulting Team to frame the selection of sites for hypothetical releases and develop specific assumptions about a release for use in the modeling analyses. The site selection process developed and implemented by this group was also informed by concerns and issues raised by members of the public, local communities, and Native American tribes during the scoping process.

This chapter describes:

- Engagement of state and federal agencies in identifying important considerations for site selection, including feedback from local communities and Native American tribes, and developing criteria for selecting sites for detailed assessment
- Process for identifying an array of potential sites for modeling of large oil releases along preferred and alternate routes, and then selecting a smaller number of representative sites for detailed assessment
- Rationale for the selection of the models used

This chapter concludes with an overview regarding how the modeling results are used in other sections of the report for understanding the potential effects of an accidental release of crude oil on environmental and human resources. The use of information from the threat assessment, failure frequency analysis, and modeling in planning emergency and remediation efforts is also discussed.

3.2 ENGAGEMENT IN FRAMING THE ASSESSMENT APPROACH

The engagement process for framing the assessment for large releases of crude oil involved three sequential approaches:

- Discussions with DOC-EERA to develop an overarching approach for the risk assessment of large releases
- Engagement of other State of Minnesota and federal agencies in refining the approach for assessment of large releases, including the development of criteria for selecting sites, the screening of candidate sites and the selection of sites for detailed assessment; and the selection of modeling tools and conditions for each of the selected sites
- Incorporation of scoping comments received from the public, local communities and Native American tribes in the approach for assessment of large releases of crude oil

3.2.1 Initial Discussions with DOC-EERA and Enbridge

DOC-EERA began investigating oil release modeling methodologies in July 2015, following the Commission's decision directing DOC-EERA to analyze the risk of pipeline ruptures. DOC-EERA met with representatives from Enbridge to discuss the types of approaches that might be used to assess the effects of large releases of crude oil. Technical consultants from Stantec and RPS were asked to provide technical support for these meetings.

Initial discussions focused on approaches for understanding the probability of a large release of crude oil and analyzing the potential effects of a large release of crude oil (e.g., purpose of modeling, types of models that could be used, and approaches for assessing potential effects to and recovery by important components or indicators of the natural and human environment).

Additional information was gathered and discussed that addressed the types of modeling tools, including a presentation on two modeling packages developed by RPS: OILMAP Land and SIMAP[5]. An example of the use of OILMAP Land for the Enbridge Line 3 Pipeline application to the National Energy Board in Canada was reviewed.

3.2.2 Engagement of Additional State of Minnesota and Federal Agencies

From October 2015 to March 2016, DOC-EERA met multiple times with state and federal agencies to discuss the approaches being considered for assessment of hypothetical large release of crude oil from the L3RP with a focus on developing approaches for selecting sites and the detailed analyses and modeling that would be conducted. State participation in the

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[5] OILMAP Land and SIMAP are two separate computational oil spill modeling tools that have been developed by RPS to predict the trajectory, fate, and potential acute effects of released hydrocarbons on land and into water. Both models have been used extensively in the United States and internationally to meet regulatory requirements and other recommendations and guidelines. Computational oil spill models such as OILMAP Land and SIMAP meet these requirements and are used frequently by industry, government, and academia. See also Section 4.2.1.

consultations included representatives from DOC-EERA, the Minnesota Department of Natural Resources (MN DNR), the Minnesota Pollution Control Agency (MN PCA), the Minnesota Department of Agriculture (MN DA), and the technical consultant for the State of Minnesota, Cardno ENTRIX. At the federal level, the United States Army Corps of Engineers (USACE) was involved.

DOC-EERA also arranged for Enbridge, Stantec, RPS, and Dynamic Risk to provide technical presentations and participate in discussions with the attending state and federal agency representatives. These meetings occurred over a series of conference calls, in-person meetings, and workshops.

Key topics discussed during the various presentations included:

- Assessing threats to the pipeline and estimating the site-specific likelihood of an incident (i.e., failure frequency)
- Reviewing and providing guidance on modeling approaches for assessment of large release of crude oils. This included framing the desired information to be provided by modeling, selecting appropriate modeling tools and representative sites, and estimating the trajectory and fate of released hydrocarbons in space and time.
- Assessing the range of effects that might occur to different components of the natural and human environment if a release of crude oil were to occur

The primary focus of the Q4 2015/Q1 2016 meetings was the development of methods for predicting the behavior, eventual fate, and environmental effects of several hypothetical large volume releases of crude oil from L3RP spanning the diversity of the geographic and environmental conditions through areas of Minnesota where the pipeline passes. Other topics discussed included the assessment of pinhole leaks.

This dialogue yielded a number of recommendations regarding:

- Framing the modeling exercise with respect to the types of information to be provided through modeling and the assessment of effects
- Modeling tools to be used for predicting the trajectory and fate of oil releases (OILMAP Land and SIMAP were the models chosen)
- Data required for modeling (e.g., watercourse flows and characteristics, biophysical conditions, land use, and availability of data from state and federal agencies)
- Criteria for selection of specific sites for modeling of accidental releases, identification of a large number of potential sites, and subsequently the identification of the specific representative sites for modeling large release of crude oils (note: the potential locations that were considered, as well as the locations that were selected as representative site involved locations on both the preferred and alternative routes for L3RP)
- Variables to be modeled such as the type of release (full bore rupture), volume of the release at each site, the type of oil released, weather and seasonal conditions, receiving environmental characteristics, and flood stages
- Required documentation of modeling methods and results
- Assessment of environmental effects

In addition to the discussions on scoping, there also were separate meetings on pinhole leaks (addressed in Stantec and Barr 2016), the assessment of threats to the pipeline, and associated failure frequency analyses.

The results of consultation are further discussed in the sections below.

3.3 SELECTION OF MODELING RELEASE SITES

3.3.1 Environmental and Geographic Diversity along Pipeline Route

The preferred and alternative routes for the proposed L3RP pipeline traverse the width of Minnesota, starting in the northwestern part of MN (at the state border between Drayton, North Dakota and Hallock, Minnesota), and extending over 300 miles south-east before reaching the Wisconsin border south of Duluth (Figure 3-1).

The proposed pipeline covers a diversity of landscape and habitat types, including grasslands, agricultural lands, forests, streams, rivers, lakes, and wetlands. There are also regional and seasonal differences in aspects such as temperature, wind speed, river flow conditions, and amounts of rain, snow, and ice. Differences in terrain, land-cover types, habitat types, and land use exist and will influence how released crude oil might be transported over land into water features, as well as how much oil may be retained on different land and shore types.

3.3.2 Framing the Assessment of Hypothetical Large Releases of Crude Oil

During the initial meetings with the DOC-EERA and the state and federal agencies, discussions focused on the overall approach to the assessment of the fate and effects of large release of crude oils, important considerations with respect to natural and human environments, and the types of information that would be provided by oil release modeling.

Conservative choices for modeling purposes perform several functions. First, conservative choices tend to maximize predicted effects and help to improve our understanding of worst case outcomes with respect to oil trajectories, behavior and associated effects. Second, as not all factors can be anticipated, a conservative choice allows the model to bound upper and lower limits, thereby reducing the number of scenarios required, while still maintaining the integrity and likelihood of the model and scenario. Lastly, the modeling of worst case scenarios aids pipeline engineers and emergency response planners to better understand and prepare for a potential worst case scenario.

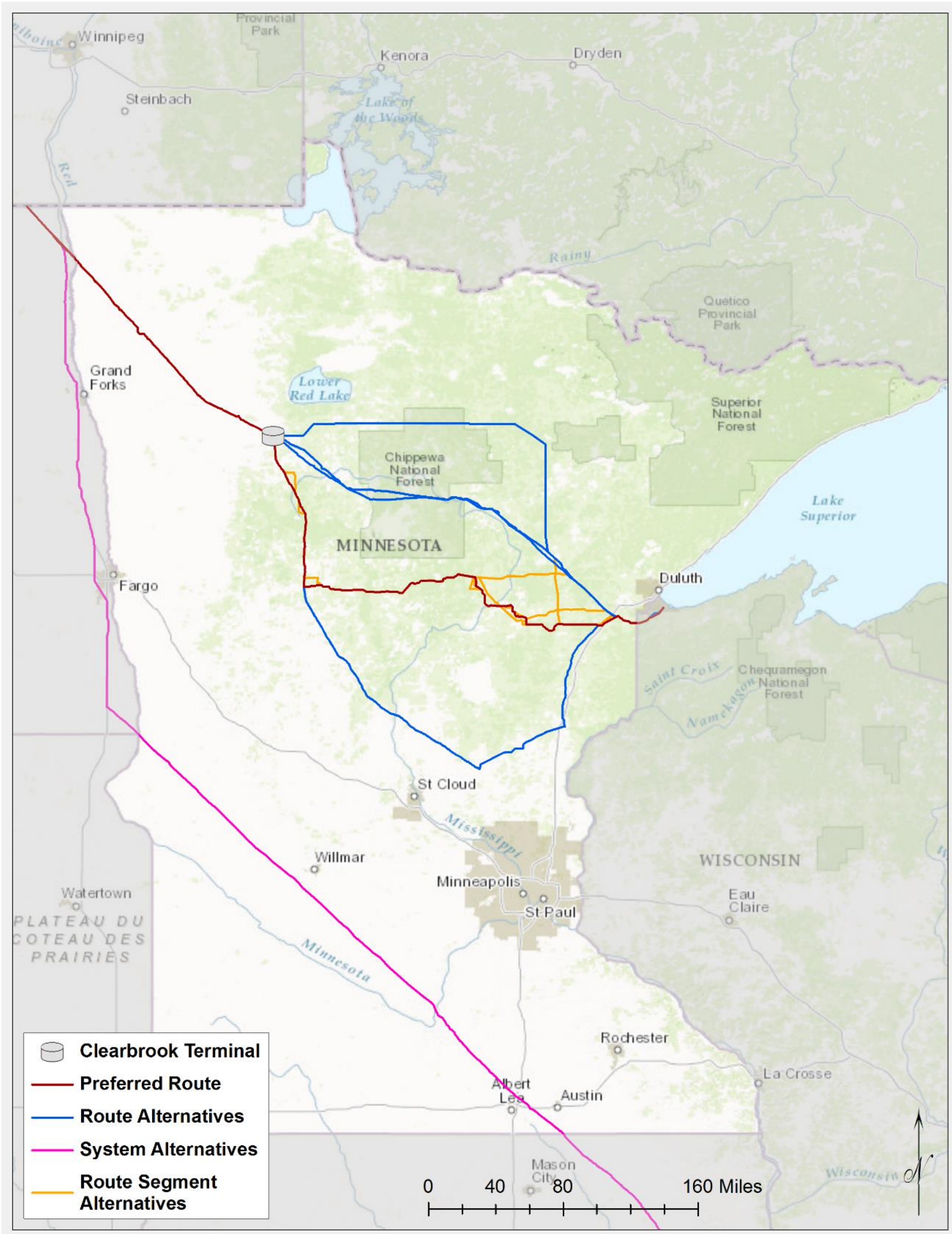

Figure 3-1 Map of the Preferred and Alternate Routes for L3RP

A primary consideration for developing appropriate scenarios for modeling of large releases of crude oil was the understanding that in the event of a full bore rupture incident (where the pipeline is essentially severed across the full diameter of the pipe), crude oil releases to land (as opposed to releases in water) often result in only small areas of land (i.e., a few acres) becoming contaminated by released oil. On land, crude oil will pool and collect in depressions and adhere to vegetation and soil. In contrast, if crude oil was accidentally released into water, crude oil can travel over larger distances due to water movement and the behavior of crude oil in water, thereby potentially exposing a larger area to contact with crude oil. This is not to suggest that effects of a release of crude oil on land would not be consequential, but it does justify the selection of locations for the hypothetical releases of crude oil that would result in oil entering watercourses (rivers or lakes) as being a conservative choice with respect to the fate, transport, and potential effects of released oil.

Given the larger spatial distribution possible from releases of crude oil into water features, unmitigated releases of oil would have greater potential to cause adverse effects to larger numbers and a greater diversity of ecological and human receptors downstream of the hypothetical release location. Therefore, it was decided that the modeling scenarios would focus on release locations where the hypothetical release of oil would either occur directly into a watercourse or would travel overland before reaching a watercourse. This approach was considered to be conservative with respect to the potential trajectory of released oil, the fate of released oil, and the potential effects of accidental oil releases on the natural and human environment.

Early discussions also focused on the type of releases to be considered and the specifics regarding these releases. Given that DOC-EERA wanted to focus on an assessment of potential large releases of crude oil (DOC-EERA 2015), the Consulting Team recommended that a full bore rupture (complete severing of the pipeline) be considered as a worst case scenario. A full bore rupture would result in a large instantaneous release of oil both through the initial release volume prior to shutdown (i.e., active pumping of oil), as well as the hydraulic drain down of the pipeline (i.e., gravity drained oil within the pipeline between the valves). This type of incident would result in more crude oil being released into the environment in a shorter period than partial ruptures or pinhole leaks (see Stantec and Barr 2016 for an assessment of pinhole leaks). While a full bore rupture is unlikely, it is again, a conservative choice used for modeling purposes. Accordingly, the maximum volume that could be released from each of the seven representative sites along the L3RP was calculated (Section 3.4); the specific maximum volume for that location was then used in the modeling of large releases of oil.

As a range of crude oils will be carried by the proposed pipeline, it was decided that several types of crude oil should be considered in the modeling of crude oil releases and the assessment of environmental effects. To reflect differences in the chemical make-up, density and viscosity of the crude oils that could be transported in the L3RP, a light crude oil (Bakken) and two blends of a heavy crude oil (CLB for spring and summer conditions, CLWB for winter conditions) were selected as representative crude oils that bound the anticipated range of products to be shipped in the pipeline. The latter heavy crude oil would be representative of what is commonly referred to as diluted bitumen (i.e., dilbit). These two different types of crude oil were used in modeling and the assessment of environmental effects.

A number of issues and concerns were identified during public input to the regulatory review (e.g., via written submissions, comments during public meetings, and open houses) and through comments from the State of Minnesota and federal agencies. These issues and concerns were used to identify the type and range of conditions that would need to be considered in the assessment of large releases of crude oils. This information was also used to identify potential locations for the modeling of releases, as well as the types of issues and concerns that should be considered in the framing of the assessment of large releases of crude oil. Such modeling considerations included:

- Sites where the downstream movement of a crude oil release could overlap with and potentially affect a range of human uses (e.g., sources of drinking water, wild rice cultivation, agricultural lands, fishing, recreational uses, urban areas), as well as sensitive ecosystems (wetlands, sensitive fish spawning habitat for species such as walleye and trout, sensitive vegetation communities, forested regions, rare and endangered species).
- The need to assess potential effects of crude oil releases into large watercourses such as the Mississippi River. This reflected concerns for effects on environmental and human receptors, as well as concerns for interaction of the crude oil with suspended sediments in the water column and the potential for the oil-mineral aggregates, which may result in "sinking oil".
- The importance of considering differences in the characteristic of water features, including river width, the length of watercourses before entering larger water bodies, and differences in turbulence (e.g., flat calm water, riffles, rapids, and waterfalls) and other water feature characteristics (e.g., sediment loads, presence of emergent vegetation).

3.3.3 Development of Site Selection Criteria for Hypothetical Oil Releases

Information from the discussions with the public and state and federal agencies was used by the DOC-EERA and the Consulting Team in the development of specific criteria to guide the identification of the range of potential locations and the selection of a representative sites for modeling and assessment of hypothetical releases of crude oil.

The selection criteria for the modeling locations addressed engineering and environmental/ socio-economic considerations as follows:

- Be located so that a hypothetical large release of crude oil could potentially enter a watercourse; this included selection of locations where the hypothetical release of crude oil would either occur directly into a watercourse or would travel overland into a watercourse
- Be located where shut-off valves would not overly restrict the volume of crude oil that could potentially be released (i.e., the hydraulic drain down of pipeline would be a substantial contributor to the oil release volume)
- Include sites along both the preferred and alternate routes for L3RP

- Be representative of the geographic and environmental conditions and land uses along the proposed ROW for L3RP to aid in the evaluation of the range of potential effects to the natural and human environment along the pipeline
- Include a range of watercourse types (e.g., size, flow, energy level) and water bodies, including wetlands
- Support evaluation of potential effects to environmentally sensitive resources (e.g., spawning grounds for fish, wild rice lakes, or other sensitive habitats)
- Represent areas of expressed concern by Native American tribes, the general public, and/or state and federal agencies
- Support evaluation of potential effects to traditional use, other human use or infrastructure (e.g., potable water intakes or treatment facilities)

3.3.4 Identification of Potential Sites

A series of meetings was used to identify a number of candidate locations where modeling of crude oil releases might be conducted and, based on these candidate locations, select a suite of representative locations for the detailed analysis and modeling. The meetings involved representatives of the state and federal agencies, and the technical support consultant for the DOC-EERA, as well as Enbridge and their corresponding technical support consultants (Stantec, RPS, and Dynamic Risk).

Each water crossing transected by the preferred and alternative routes was identified and investigated as a potential location for hypothetical release modeling (major water crossings are shown in Figure 3-1). In total, nearly 1,000 watercourses were considered. The preferred route for L3RP transects 274 watercourses, and the alternative routes transect 641 watercourses.

To facilitate timely and effective modeling to inform decision-making, site selection criteria (described above) were then used to identify a number of candidate sites from the large number of watercourse crossings. Regions of interest to regulatory agencies and identified locations from discussions with the public were considered in selecting the candidate sites. Through several meetings with DOC-EERA, state and federal agencies, and the Consulting Team, a total of 27 candidate sites were identified for detailed evaluation as modeling locations. The selection of the candidate sites took into account the geospatial distribution of the sites along the preferred and alternate routes in central and northern Minnesota (Figure 3-2).

To facilitate the selection of the representative sites from the candidate sites, tables were constructed to summarize the attributes of candidate site with respect to:

- Location (within the portion of Minnesota crossed by the preferred and alternate routes for L3RP)
- Geomorphology
- Ecological land classification (see below)
- Location of sensitive resources or habitats in proximity to the preferred and alternate routes
- Watercourse characteristics
- Potential human uses (Table 3-1)

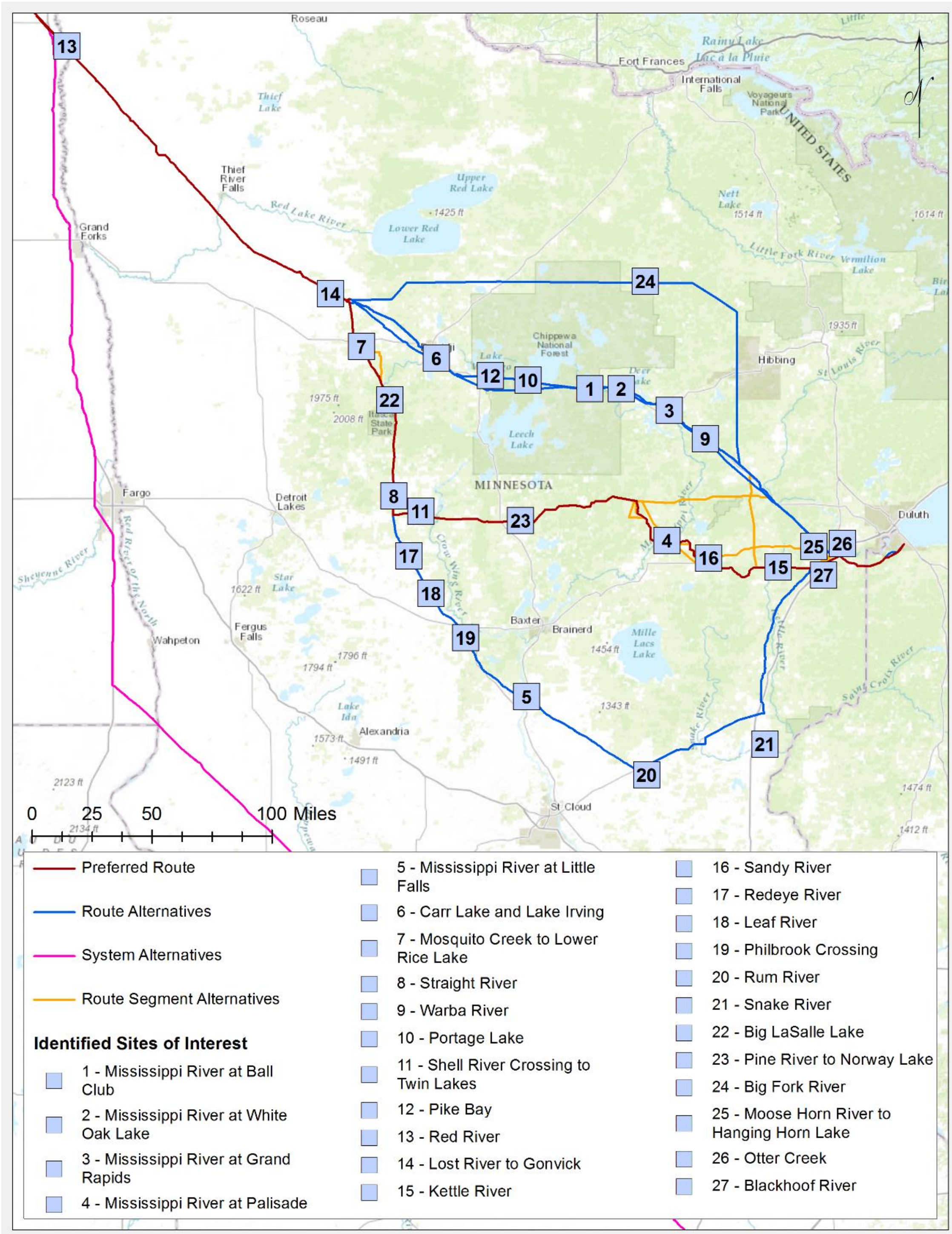

Figure 3-2 Candidate Locations Considered for Modeling along the Preferred and Alternative Routes for L3RP

Table 3-1 Characteristics of Candidate Locations for Modeling along the Preferred and Alternative Routes for L3RP

											MN EcoRegion			River Width			River Length to Nearest Waterbody		Watercourse Characteristics			Identified Uses			
Site Name	Proposed Route	N	W	Nearest Municipality	Description	Rice Lake	Agricultural Land	Forested Region	Urban Area	Mississippi River	Province	Section	Subsection	Small (<10 m)	Med. (10-50 m)	Large (>50 m)	Short (<5 km)	Long (>5 km)	Flat Water	Rapids / Falls	Lake	Recreational	Drinking Water	Populated Area	Sensitive Ecosystem
Big Fork River	Northern Alternative	47.760 810	93.625 157	Big Fork	Water crossing of Big Fork River (~25 m wide). River has many bends and does include sections with rapids passing through dense forest and some State Forest and Parks.			X			Laurentian Mixed Forest Province	N. Minnesota Forest & Ontario Peatlands	Littlefork-Vermillion Uplands		X			X		X		X		~	~
Blackhoof River	Preferred Route	46.603 105	92.553 646	Atkinson	Water crossing of the Blackhoof River (~5 m wide), with a sinuous marshy and scrub channel winding through forest and agricultural land before draining into the Nemadji River.		X	X			Laurentian Mixed Forest Province	Western Superior Uplands	Mille Lacs Uplands	X				X				X	~		X
Carr Lake and Lake Irving	Northern Alternative	47.447 557	94.886 677	Bemidji	Water crossing of (~25 m wide) river connecting Lake Irving and Carr Lake. The waterway is mainly lined by wetland passing beneath Route 2. To the south, Carr Lake contains wild rice, is lined with marshy wetlands and sporadic forest with some houses, and connects to Lake Marquette. To the north, Lake Irving has wild rice, two large marsh areas, residential housing along the banks, and an industrial complex of Bemidji on the north shore, connecting to Lake Bemidji.	X			X		Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains		X		X		X		X	X		X	X
Deer River Crossing to White Oak Lake	Northern Alternative	47.323 131	93.772 166	Zemple	Water crossing through (~10–15 m wide) winding channel leading to White Oak Lake (~4 x 0.6 km) shallow lake and wetland system and Mississippi River. Wildlife is present, as well as the extensive marshes and wetlands lining the perimeter. No residences.	X		X		X	Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains		X		X		X		X	~		X	X
Kettle River	Preferred Route	46.588 802	92.823 334	Cromwell	Water crossing of the Kettle River (~15 m wide) which winds through forested regions with few houses along the banks.			X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	St. Louis Moraines		X		N/A	N/A	X			X			
LaSalle Creek	Preferred Route	47.276 260	95.167 827	Lake Itasca	Water crossing to small creek (~2-5 m wide) running through marsh lands adjacent to forest. Leading to southern edge of Big LaSalle Lake (0.5 x 2 km), which has extensive forest cover along banks and sporadic housing along the shores.			X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains	X			X		X		X	X			
Leaf River	Southern Alternative	46.478 883	94.918 511	Aldrich	Water crossing at Leaf River (~25–35 m wide) meandering through predominantly agricultural land with forested banks.		X	X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash	X			N/A	N/A	X					X	X

Table 3-1 Characteristics of Candidate Locations for Modeling along the Preferred and Alternative Routes for L3RP

											MN EcoRegion			River Width			River Length to Nearest Waterbody		Watercourse Characteristics			Identified Uses			
Site Name	Proposed Route	N	W	Nearest Municipality	Description	Rice Lake	Agricultural Land	Forested Region	Urban Area	Mississippi River	Province	Section	Subsection	Small (<10 m)	Med. (10-50 m)	Large (>50 m)	Short (<5 km)	Long (>5 km)	Flat Water	Rapids / Falls	Lake	Recreational	Drinking Water	Populated Area	Sensitive Ecosystem
													Plains												
Lost River to Gonvick	Preferred Route	47.710 842	95.525 294	Gonvick	Water crossing of Lost River (~5 m wide) with marshy grassland and forest along the banks leading to Gonvick through agricultural land.		X		X		East Broadleaf Forest Province	Minnesota & NE Iowa Morainal	Hardwood Hills	X				X	X					X	
Mississippi River at Ball Club	Northern Alternative	47.323 602	93.959 643	Ball Club	Water crossing through sinuous (~25 m wide) channel of the Mississippi River with oxbows through extensive wetlands leading to White Oak Lake.	X		X		X	Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains		X			X	X		X	X		X	X
Mississippi River at Grand Rapids	Northern Alternative	47.233 729	93.480 856	Grand Rapids	Water crossing at Prairie River (~30–40 m wide) approximately 2 km east of Grand Rapids with several bends leading into Mississippi River (~50 m wide). Mainly forested banks with some residences and sporadic agriculture.				X	X	Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	St. Louis Moraines		X		N/A	N/A		X		X		X	X
Mississippi River at Little Falls	Southern Alternative	46.048 333	94.341 999	Little Falls	Water crossing at Little Falls into Mississippi River (~250 m wide) with forested banks buffering agriculture and urban areas (Little Falls). The damn and falls at Little falls could potentially entrain a large amount of oil if released.		X		X	X	Eastern Broadleaf Forest Province	Minnesota & NE Iowa Morainal	Anoka Sand Plain			X	N/A	N/A		X	X	X		X	X
Mississippi River at Palisade	Preferred Route	46.698 284	93.494 993	Palisade	Water crossing of the Mississippi River (~75 m wide) approximately 1.5 km S of Palisade. Sinuous channel and oxbows, some turbulent stretches of water, and forest and some agriculture lining the banks.		X	X		X	Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Tamarack Lowlands			X	N/A	N/A		X		X	~	~	X
Moose Horn River to Hanging Horn Lake	Northern Alternative	46.668 779	92.608 862	Sawyer	Water crossing of the Moose Horn River (~5 m wide) through marshy wetlands leading to Hanging Horn Lake.	X					Laurentian Mixed Forest Province	Northern Superior Uplands	North Shore Highlands	X			X		X		X	X	X	X	~
Mosquito Creek to Lower Rice Lake	Preferred Route	47.460 399	95.306 555	Bagley	Seasonal water crossing that forms drainage into Mosquito Creek (~1 m wide) with marshy grassland and sporadic forest cutting through agriculture and nature preserves to Lower Rice Lake (~1 x 6.5 km) with a large amount of wild rice.	X	X				Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains	X				X	X		X	X		X	X
Otter Creek	Northern Alternative	46.643 024	92.493 218	Otter Creek	Water crossing of the Otter Creek (~5 m) in a marshy wetland area ultimately draining into Lake Superior.						Laurentian Mixed Forest Province	Western Superior Uplands	Mille Lacs Uplands	X				X	X	X	X	X	X	X	X

Table 3-1 Characteristics of Candidate Locations for Modeling along the Preferred and Alternative Routes for L3RP

Site Name	Proposed Route	N	W	Nearest Municipality	Description	Rice Lake	Agricultural Land	Forested Region	Urban Area	Mississippi River	MN EcoRegion			River Width			River Length to Nearest Waterbody		Watercourse Characteristics			Identified Uses			
											Province	Section	Subsection	Small (<10 m)	Med. (10-50 m)	Large (>50 m)	Short (<5 km)	Long (>5 km)	Flat Water	Rapids / Falls	Lake	Recreational	Drinking Water	Populated Area	Sensitive Ecosystem
Philbrook Crossing	Southern Alternative	46.295 106	94.709 837	Philbrook	Water crossing at Philbrook (~50 m wide) is meandering through agricultural regions with patchy forest along the bank. There are several oxbows and small island.		X				Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash Plains			X		X	X	X	X	X		X	X
Pike Bay	Northern Alternative	47.376 184	94.560 297	Cass Lake	Release location between Route 2 and train tracks, approximately 60 m from Pike Bay (~5.4 x 4.5 km). Extensive forest (Chippewa National Forest) and some marshy wetland along the shores, with a number of houses along the banks.			X	X		Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains	N/A	N/A	N/A	N/A	N/A			X	X		X	X
Pine River to Norway Lake	Preferred Route	46.781 178	94.377 541	Pine River	Water crossing of the Pine River (~20 m wide) with extensive forest along the banks and eventually marshy wetland leading to Norway Lake. The Lake is lined with patchy forest, wetland, and many houses, including Chickamaw Beach and the town of Pine River likely affected in the event of a release.	X		X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash Plains		X			X	X		X	X	~	X	X
Portage Lake	Northern Alternative	47.358 011	94.333 189	Ryan Village	Water crossing of marshy wetland leading 150 m to Portage Lake (~4.5 x 1.5 km) lined extensively with forest and some marshy wetlands. Wild rice is present, with many residences along the NE shore.	X		X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Chippewa Plains	X			X		X		X	X		~	X
Red River	Preferred Route	48.705 332	97.114 837	Drayton and Hallock	Water crossing of Red River, which flows north through a moderately sinuous channel with a width of 40–60 m. The river passes through areas predominantly used for agriculture with patchy forested regions along the banks.		X	~			Prairie Parkland Province	Red River Valley	Red River Prairie			X	N/A	N/A	X			X	X	X	X
Redeye River	Southern Alternative	46.634 343	95.051 682	Sebeka	Water crossing at the Redeye River (~10 m wide) meandering through predominantly agricultural land with some forested banks.		X				Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash Plains	X			N/A	N/A	X		X				~
Rum River	Southern Alternative	45.719 326	93.617 614	Milaka	Water crossing at Rum River (~50 m wide) into meandering channel with partial forested and mainly agricultural banks. Some small islands and a few oxbows.		X				Laurentian Mixed Forest Province	Western Superior Uplands	Mille Lacs Uplands			X	N/A	N/A	X	X		X		X	~
Sandy River	Preferred Route	46.626 342	93.243 089	McGregor	Water crossing of (~10 m wide) Sandy River flowing to the west through a bifurcated channel with one sinuous channel and another straight drainage	X	X	X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Tamarack Lowlands	X	X			X	X		X	X			X

Table 3-1 Characteristics of Candidate Locations for Modeling along the Preferred and Alternative Routes for L3RP

											MN EcoRegion			River Width			River Length to Nearest Waterbody		Watercourse Characteristics			Identified Uses			
Site Name	Proposed Route	N	W	Nearest Municipality	Description	Rice Lake	Agricultural Land	Forested Region	Urban Area	Mississippi River	Province	Section	Subsection	Small (<10 m)	Med. (10-50 m)	Large (>50 m)	Short (<5 km)	Long (>5 km)	Flat Water	Rapids / Falls	Lake	Recreational	Drinking Water	Populated Area	Sensitive Ecosystem
					type ditch. The waterway is lined mainly by marshy grasses and wetland, with some forested regions. The river flows through Steamboat and Davis lake to Flowage Lake and eventually Big Sandy Lake. The region is known to contain fish spawning habitat.																				
Shell River Crossing to Twin Lakes	Preferred Route	46.819 605	95.042 982	Hubbard	Water crossing of the Shell River (~25 m wide) through a straight marshy channel in agricultural land leading to Upper Twin and Lower Twin Lakes. The lakes contain wild rice, have forest along the shores, and many houses lining Lower Twin Lake.	X	X	X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash Plains		X		X		X		X	X			X
Snake River	Southern Alternative	45.848 879	92.903 915	Pine City	Water crossing at Snake River (~75 m wide) flowing through a meandering channel to the east leading to the St. Croix River. Banks extensively forested with some agricultural lands.		X	X			Laurentian Mixed Forest Province	Western Superior Uplands	Mille Lacs Uplands			X	N/A	N/A	X	X		X		X	X
Straight River	Preferred Route	46.882 162	95.143 189	Park Rapids	Water crossing of the Straight River (~10–25 m wide), with a sinuous marshy channel winding through agricultural land with agriculture on either side.		X	X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Pine Moraines & Outwash Plains		X			X	X		X	X	X		X
Warba River	Northern Alternative	47.118 892	93.264 112	Warba	Water crossing of Warba River (~10–15 m wide) is sinuous, traveling through dense forest. This is a tributary to Mississippi River.			X			Laurentian Mixed Forest Province	N. Minnesota Drift & Lake Plains	Tamarack Lowlands		X			X	X			~			X

Shading legend:
Selected for a SIMAP Scenario
Selected for a OILMAP Land Scenario

The objective was to identify a smaller number of representative sites that would reflect most of the major attributes described above.

Minnesota uses an Ecological Classification System (ECS) for ecological mapping and landscape classification (MN DNR 1999). As stated by the MN DNR and the U.S. Forest Service: "Ecological land classifications are used to identify, describe, and map progressively smaller areas of land with increasingly uniform ecological features. The system uses associations of biotic and environmental factors, including climate, geology, topography, soils, hydrology, and vegetation. ECS mapping enables resource managers to consider ecological patterns for areas as large as North America or as small as a single timber stand and identify areas with similar management opportunities or constraints relative to that scale. There are eight levels of ECS units in the United States. Map units for six of these levels occur in Minnesota: Provinces, Sections, Subsections, Land Type Associations, Land Types, and Land Type Phases."

The ECS breaks the state up into 4 ecological Provinces (Figure 3-3), which include a total of 10 ecological Sections (Figure 3-4). Provinces are units of land defined using major climate zones, native vegetation, and biomes such as prairies, deciduous forests, or boreal forests. Sections are units within Provinces that are defined by origin of glacial deposits, regional elevation, distribution of plants, and regional climate.

Portions of the preferred and alternative routes for L3RP pass through each of the four Provinces (Table 3-2). The preferred route includes six Sections, while the alternative routes include eight Sections. Table 3-2 summarizes the locations identified in Table 3-1 by their respective Provinces and Sections.

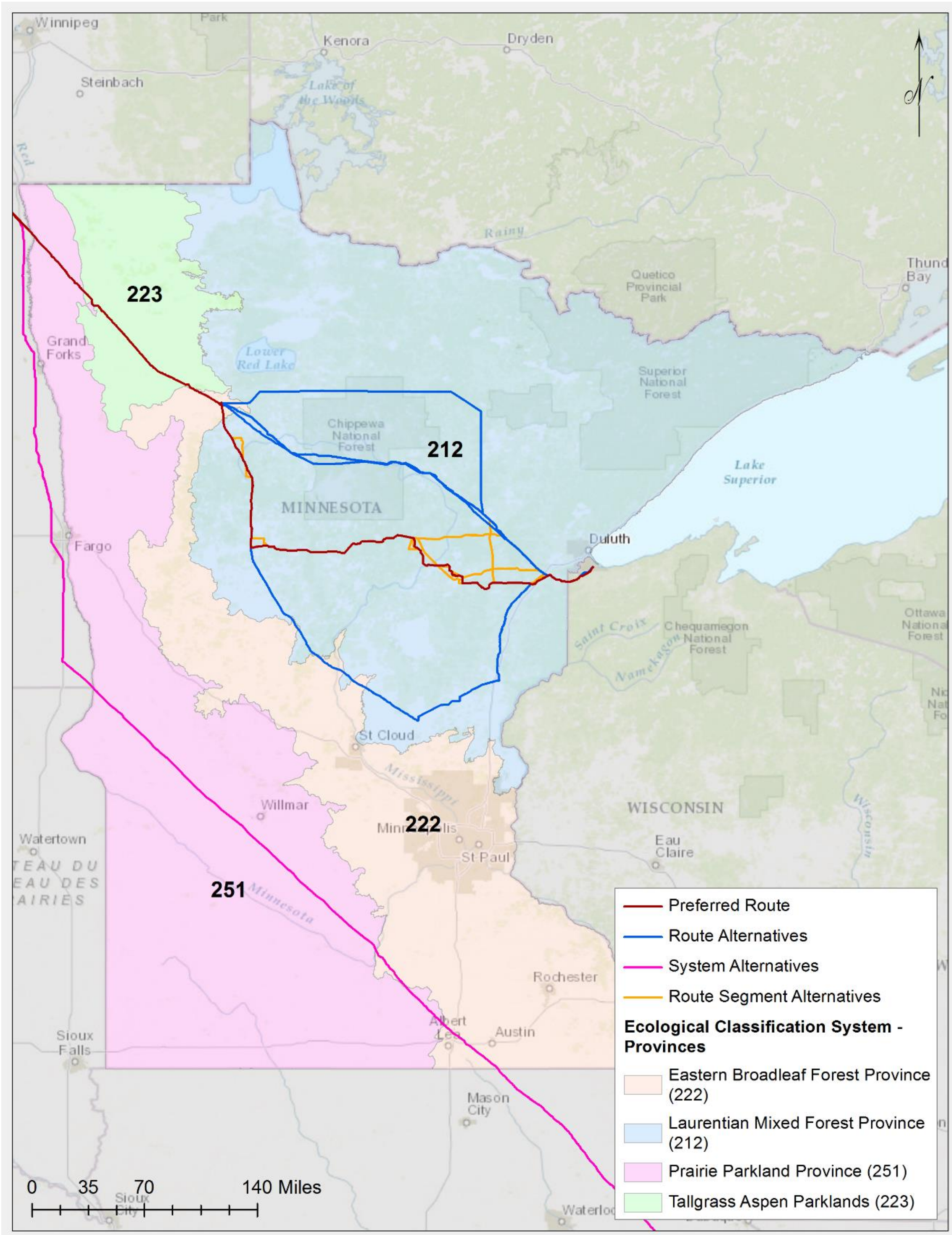

Figure 3-3 Ecological Provinces along the Preferred and Alternative Routes for L3RP

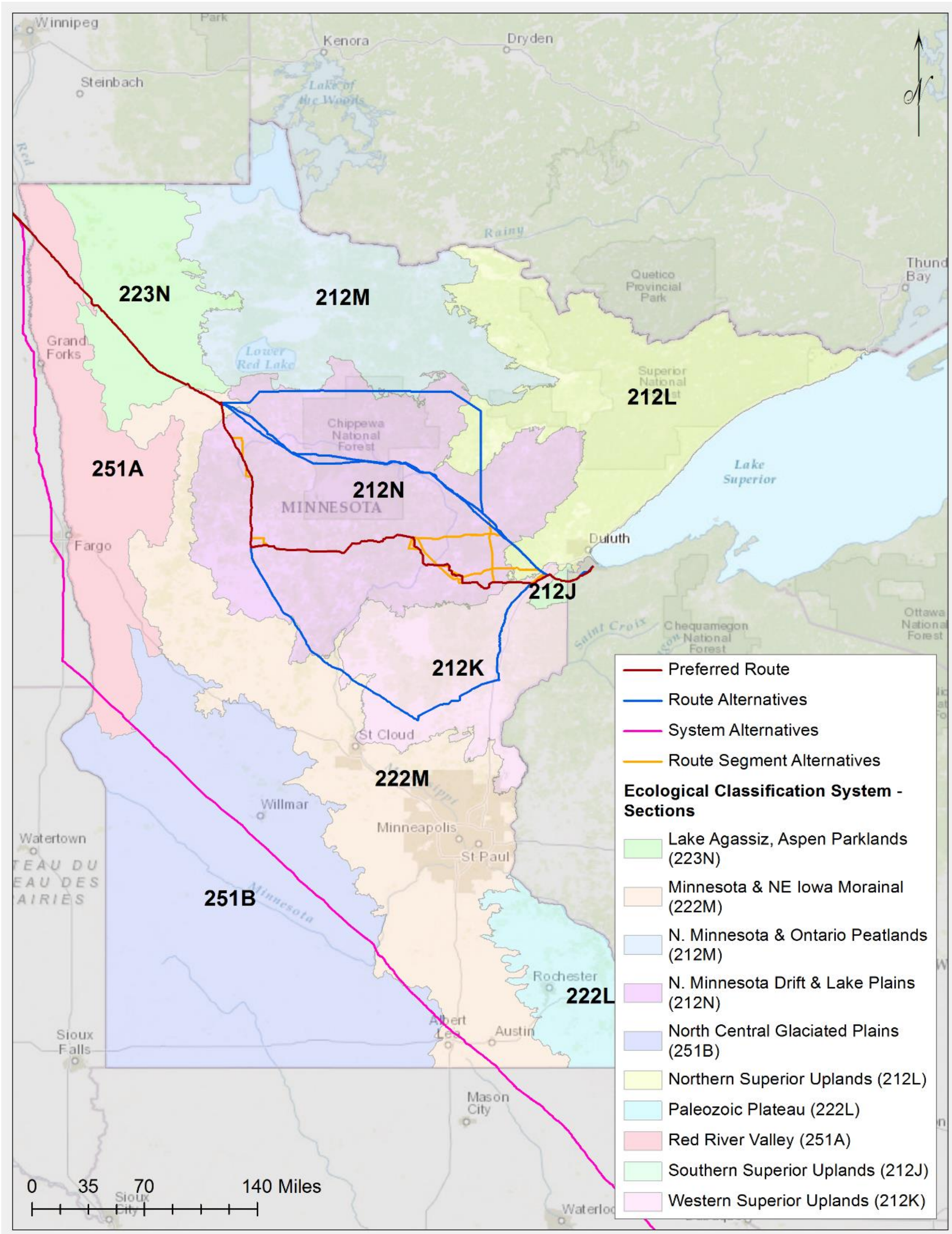

Figure 3-4 Ten Ecological Sections along the Preferred and Alternative Routes for L3RP

Table 3-2 Representation of Ecological Provinces and Sections by the Candidate Locations along the Preferred and Alternate Routes for L3RP

Province	Sections	Locations Considered	Preferred Route	Route Alternative
Prairie Parkland Province	Red River Valley	*Red River	X	X
	North Central Glaciated Plains	---	---	---
Tall Grass Aspen Parklands	Lake Agassiz, Aspen Parklands	---	X	---
East Broadleaf Forest Province	Minnesota and NE Iowa Morainal	Lost River to Gonvick ***Mississippi River at Little Falls**	X	X
	Paleozoic Plateau	---	---	---
Laurentian Mixed Forest Province	Southern Superior Uplands	---	X	---
	Western Superior Uplands	Blackhoof River Otter Creek Rum River Snake River	X	X
	Northern Superior Uplands	Moose Horn River to Hanging Horn Lake	---	X
	No. Minnesota and Ontario Peatlands	Big Fork River	---	X
	No. Minnesota Drift Lake Plains	Carr Lake and Lake Irving Deer River Crossing to White Oak Lake LaSalle Creek Leaf River Kettle River ***Mississippi River at Ball Club** Mississippi River at Grand Rapids ***Mississippi River at Palisade** ***Mosquito Creek to Lower Rice Lake** Philbrook Crossing Pike Bay Pine River to Norway Lake Portage Lake Redeye River ***Sandy River** ***Shell River Crossing to Twin Lakes** Straight River Warba River	X	X

NOTES:
Dark grey cells depict regions along the preferred route
Light grey cells depict regions along the route alternatives
Bolded locations with a (*) depict the representative locations used in the detailed modeling and assessments.

3.3.5 Selected Sites for Modeling and Comparison of Site Characteristics and Equivalency

The DOC-EERA, together with state and federal agencies and the Consulting Team, employed the above criteria and considerations to select a total of 7 representative locations for detailed modeling and assessment from the 27 candidate locations; specifically:

- Site 1—Mosquito Creek to Lower Rice Lake
- Site 2—Mississippi River at Ball Club
- Site 3—Sandy River
- Site 4—Shell River to Twin Lakes
- Site 5—Red River
- Site 6—Mississippi River at Palisade
- Site 7—Mississippi River at Little Falls

For each of the seven modeling locations, the following detailed analyses were completed.

- An assessment to identify the potential threats to the pipeline from natural and human causes at the modeling location, and an assessment to quantify the failure frequency for a full bore rupture specific to the conditions at that location (i.e., within the potential impact segment; Chapter 4.0). The maximum volume of crude oil that could be hypothetically released at each site was determined based on the pipeline specifications and topographic conditions in proximity to each modeling location. The maximum volume out was calculated as a full bore rupture, with a conservative response in the pipeline Control Center of a maximum of 10 minutes, followed by a 3-minute period to allow for valve closure, and then drain-down of the elevated segments of pipeline. The maximum 13-minute duration of Control Center response time to valve closure is a standard for safe operations and leak detection for Enbridge. The total volume out included both the initial release volume prior to shutdown (i.e., actively pumping out), as well as hydraulic drain down of the pipeline (i.e., gravity drained oil within the pipeline between the valves), following shutdown at that site.
- The trajectory of an unmitigated oil release and the associated fate or behavior of the crude oil (i.e., weathering and physical distribution [e.g., on shore, on the water surface]) was predicted for each location using two different modeling tools (see Chapters 5.0 and 6.0). The volumes used in the hypothetical release were based on the largest quantity of oil from the L3RP pipeline at that specific location. At each location, separate models were run for three flow conditions for watercourses (low, average and high) and three types of crude oil (Bakken crude oil, CLB, and CLWB). Maps of the trajectory of the release and tabular summaries of the fate of the crude oil were developed for 6, 12, 18, and 24 hours following the hypothetical release.
- The effects of the hypothetical release of crude oil at each location on key receptors in the natural and human environment were assessed using two methods. The first method involved determining the potential overlap of the predicted trajectory of an oil release on HCAs, as defined under federal law, and AOIs, as defined under state law (Chapter 7.0). The HCAs were based on the PMHSA data for each location. The types of AOIs to be considered were identified by the state and federal agencies and included databases from the MN DNR. The second method considered known effects of crude oil releases on key receptors, with a focus on ecological and human health risks. The recovery of the natural and human

environment from exposure to crude oil, based on current literature, is discussed in Chapter 8.0.

As shown in Figure 3-5 and summarized in Table 3-3, the seven representative modeling locations are well distributed along the preferred and alternate routes for L3RP. To better illustrate how the seven representative modeling locations represent different combinations of hydrological conditions, watercourse widths, water features and uses, the detailed summary of features and characteristics (i.e., site attributes) described in Table 3-1 was condensed into a simpler format (Table 3-3). As shown in this table, for each attribute and the specific categories within each attribute (other than overland flow), at least two of the representative modeling locations and typically several were representative of that specific attribute and category. This summary demonstrates that the seven representative modeling locations did include a robust diversity of site characteristics that were identified in the scoping sessions. This included the features that are representative of most of the predominant ecological units along the pipeline, as well as the major hydrological features, watercourse widths, watercourse features along the preferred and alternative routes.

It is the opinion of the authors of this report that the modeled crude oil releases under different seasonal flow conditions and the predicted trajectory and fates information at each of the seven modeled sites will adequately represent the likely outcomes of an oil release in central and northern Minnesota. In combination with a broader understanding of the literature regarding the effects of an oil release on key receptors in the natural and human environment (Section 7.1), as well of site-specific assessments of potential effects on environmentally-sensitive areas (e.g., HCAs and AOIs; Section 7.3) and on key receptors at each of the seven modeling locations (Sections 7.4 to 7.10), a wide range of potential effects on key receptors under different seasonal flows conditions and with light and heavy crude oils are considered and analyzed. Further, the authors of this report believe that modeling and assessment of effects at additional inland sites would not add proportionately to a better understanding of environmental effects stemming from hypothetical oil releases, nor would additional modeling change the conclusions of the anticipated environmental effects, should there be a release of oil.

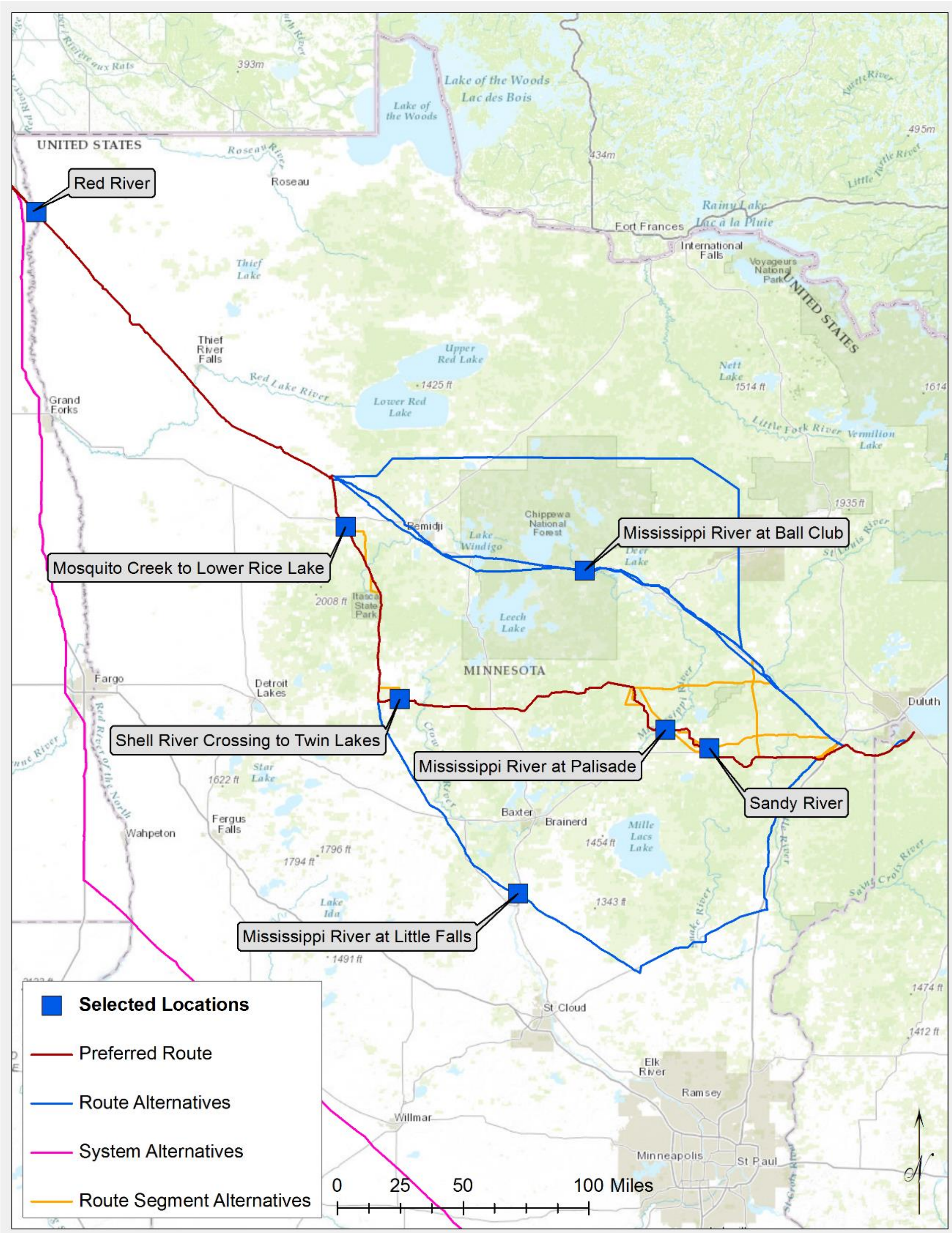

Figure 3-5 Location of Representative Sites Selected for Modeling of Hypothetical Large Releases of Crude Oil

Table 3-3 Summary of Characteristics of Each Representative Release Location

Representative Release Location		Mississippi River at Ball Club	Mississippi River at Little Falls	Mississippi River at Palisade	Mosquito Creek to Lower Rice Lake	Red River	Sandy River	Shell River Crossing to Twin Lakes
EcoProvince		Laurentian Mixed Forest Province	East Broadleaf Forest Province	Laurentian Mixed Forest Province	Laurentian Mixed Forest Province	Prairie Parkland Province	Laurentian Mixed Forest Province	Laurentian Mixed Forest Province
Site Features								
Hydrology Features	Ditch/Creek				X		X	
	Watercourse (stream/river)	X	X	X	X	X	X	X
	Lake/Pond	X			X		X	X
	Flat Water	X		X	X	X	X	X
	Rapids / Falls		X	X				
	Dams		X	X				
	Wetland/Marsh/Fen	X			X		X	X
Watercourse Width	Small (<10 m)				X		X	
	Medium (10–50 m)	X		X				X
	Large (>50 m)		X			X		

Table 3-3 Summary of Characteristics of Each Representative Release Location

Representative Release Location		Mississippi River at Ball Club	Mississippi River at Little Falls	Mississippi River at Palisade	Mosquito Creek to Lower Rice Lake	Red River	Sandy River	Shell River Crossing to Twin Lakes
EcoProvince		Laurentian Mixed Forest Province	East Broadleaf Forest Province	Laurentian Mixed Forest Province	Laurentian Mixed Forest Province	Prairie Parkland Province	Laurentian Mixed Forest Province	Laurentian Mixed Forest Province
Site Features								
Watercourse Features	Agricultural Land		X		X	X	X	X
	Forested Region	X		X			X	X
	Mississippi River	X	X	X				
	Urban Area		X					
	Wild Rice	X			X		X	X
Identified Uses	Recreational	X	X	X	X	X	X	X
	Drinking Water			X		X		
	Populated Area		X			X		
	Sensitive Ecosystem	X	X	X	X	X	X	X
Includes Overland Transport					X			

3.3.6 Description of Representative Release Locations

3.3.6.1 Site 1—Mosquito Creek to Lower Rice Lake

The Mosquito Creek to Lower Rice Lake modeling location captures both the potential for overland flow of crude oil and the downstream transport of crude oil in a very small watercourse. The hypothetical release location is in a relatively flat, forested region that forms a drainage area that has a gentle slope towards agricultural and grassland habitats. The swale collects into a narrow and seasonal water crossing that ultimately forms Mosquito Creek, a channel approximately 3 ft in width that flows to the south and west. Mosquito Creek flows through marshy grassland and sporadic forest, cutting through agriculture and nature reserves. After approximately 12.5 miles, the watercourse grows to around 35 ft in width, before entering Lower Rice Lake. Lower Rice Lake is approximately 1,600 acres in size and supports large areas of wild rice.

This modeling location represents the environmental conditions of a small quiescent watercourse that contains wetlands, marsh, and fen. The agricultural lands, nature preserve, and wild rice that may be present are representative of lands that may be used as a source of food and recreation. In addition, portions of the ecosystem have been classified as sensitive (i.e., included in the PHMSA database for HCAs and/or the State of Minnesota data base for AOIs).

3.3.6.2 Site 2—Mississippi River at Ball Club

The Mississippi River at Ball Club modeling location contains a sinuous water channel that is approximately 80 ft wide. The channel flows to the south and east through a relatively well defined channel that has a large number of oxbows. The banks are lined with extensive wetlands and forested areas adjacent to some parts of the water course. Under high river flows, the watercourse connects to White Oak Lake, before extending to the south through more sinuous channels and marshy wetlands.

This modeling location captures the environmental conditions of a quiescent watercourse of intermediate size that contains wetlands, marsh, and fen. The lake is approximately 9 miles downstream of the hypothetical release location. This location is representative of lands where food may be harvested, including fish and wild rice. In addition, the location includes an upstream portion of the Mississippi River and forested land. This region is used for outdoor recreation, and near the populated area of Deer River and sensitive ecosystems.

3.3.6.3 Site 3—Sandy River

The Sandy River modeling location is a bifurcated channel, approximately 30 ft wide, and flows to the west. The southern channel is a natural sinuous feature, while the northern channel is a straight drainage-type ditch. The waterway is mainly lined by marshy grasses and wetland with some forests. The river flows through Steamboat and Davis lakes to Flowage Lake and eventually Big Sandy Lake. The region is known to contain fish spawning habitat.

This modeling location captures a small ditch/creek type water course that enters into lakes and ponds after passing through areas with wetlands, marsh, and fen. The lakes are between approximately 6 and 12 miles downstream. The site is representative of forested and agricultural lands where food may be harvested. Due to the fish species present, this watercourse is used for recreation, specifically focused around recreational fishing. The region is known to contain sensitive ecosystems.

3.3.6.4 Site 4—Shell River to Twin Lakes

The Shell River Crossing to Twin Lakes modeling location contains a straight marshy channel, approximately 80 feet wide, that passes through forested areas that are nestled between agricultural lands. The watercourse enters the northern end of Upper Twin Lake before draining into a small reach that feeds Lower Twin Lake. There are many houses lining the lakes, with docks that provide access to swimming and boating.

This modeling location captures a medium width quiescent watercourse that enters directly into lakes after passing through areas with wetlands, marsh, and fen. The lakes are approximately 0.6 to 1.2 miles downstream of the hypothetical release location. The presence of residences with docks does make this location representative of inhabited areas that may be used recreationally. In addition, this region is known to contain sensitive ecosystems.

3.3.6.5 Site 5—Red River

The Red River is located along the border of Minnesota and North Dakota, and runs to the north into Canada. The pipeline crossing is located approximately 3 miles (4.82 km) due east of Bowesmont, North Dakota and 9 miles (14.48 km) southwest of Hallock, Minnesota adjacent to Route 16. At the proposed pipeline crossing location and downstream, the Red River is a large, wide (150–400 ft) river that flows north along a well-defined sinuous channel. The Red River passes the communities of Pembina, North Dakota and St. Vincent, Minnesota approximately 32 river miles downstream from the crossing location, and crosses into Canada approximately 34.5 miles downstream. The communities of Emerson and West Lyme, Manitoba are located on the Canadian side of the international border.

This modeling site captures a large, low-gradient (dropping approximately 6 ft in 35 river miles) watercourse, with a sinuous channel that is subject to flooding. The shore types are predominantly vegetated, often with shrubs and trees above the level of ice-scour. These waters are known to be a major area for recreation use, and also pass through or adjacent to sensitive ecosystems. The riparian banks are generally well vegetated, including some trees. Patches of forest are often present where the river meanders, although the surrounding land use is primarily agricultural. The Red River is subject to moderate to extreme flooding, particularly in the spring. Under low or average flow conditions, the stream banks are a combination of grass and soil. Under higher flow conditions the river can overtop the banks and spread into the surrounding farm and grassland.

3.3.6.6 Site 6—Mississippi River at Palisade

The Mississippi River at Palisade modeling location is a large river, approximately 250 ft wide, which flows to the south and west. The hypothetical release location is approximately 1 mile south of Palisade, MN. The sinuous channel is mostly flat water passing through a number of oxbows. There are some turbulent waters with the presence of a flood diversion dam and spillway. Under high flow rates, this small region would have very turbulent waters containing rapids from a waterfall. The banks are mainly forested, with residences and some agricultural lands on either side.

This modeling location captures the environmental conditions of a large and relatively quiescent watercourse that has predominantly forested banks. In addition, the site does include a midstream portion of the Mississippi River and forested lands. While the majority of the channel is relatively flat water, the flood diversion channel, with its dam and spillway, have the potential to result in localized turbulence, that could entrain oil if a release were to occur and crude oil was to reach the spillway. The sinuous channel is used recreationally and contains sensitive ecosystems. In addition, the watercourse is known to be a source of drinking water to residences in the area.

3.3.6.7 Site 7—Mississippi River at Little Falls

The Mississippi River at Little Falls modeling location is a large river, approximately 820 ft wide, which flows to the south. This modeling location captures the environmental conditions of a large watercourse that has predominantly forested banks. The hypothetical release location is approximately 5 miles north of Little Falls. This small urban area contains the Little Falls Dam, which has a large waterfall that induces a large amount of turbulence, which would entrain surface oil into the water column, if a release of crude oil were to travel downstream to this dam. A second dam and waterfall, known as the Blanchard Dam, is located approximately 8 miles downstream of Little Falls, providing the potential for further entrainment of crude oil into the water column in the event of a release. The shore types in this region are mainly forested, with some small portions of agricultural lands and urban areas along the banks. The waters are used recreationally and sensitive ecosystems are present.

3.4 SELECTION OF MODELING TOOLS

3.4.1 Approach

The types of models to be used to predict the trajectory and fate of hypothetical releases of crude oil were discussed at the initial meetings with the State of Minnesota and Enbridge. The types of models, including the desired output information, were also discussed during the initials meetings with state and federal agencies and Enbridge. Through these discussions, it was agreed that modeling of the trajectory and fate (i.e., behavior and weathering) of hypothetical releases would be conducted using both the OILMAP Land and SIMAP computation models.

OILMAP Land provides a two-dimensional prediction of the trajectory and fate of the released crude oil (i.e., downslope and downstream in the horizontal direction), whereas SIMAP provides a three dimensional prediction (i.e., movement in both the horizontal and vertical directions, meaning the possibility for movement within the water column and on bottom sediments). Because SIMAP calculates the trajectory and fate of crude oil in three dimensions, it is a considerably more complex model that contains more interactions and processes and requires more site-specific data than OILMAP Land. Both are state-of-the-art models used by industry, government, and academics throughout the world.

Both models have been used extensively in the United States and internationally to meet regulatory requirements and other recommendations and guidelines. The PHMSA regulations (CFR, Title 49, Parts 190-199) discuss hazardous liquid integrity management, stipulating identification of HCAs and determination of direct and indirect effects from a potential spill, which are addressed with this modeling. Regulatory requirements for pollution control in offshore waters are overseen by the Bureau of Safety and Environmental Enforcement, with 30 CFR 254 requiring worst case trajectory modeling. For inland waters, the U.S. Environmental Protection Agency (USEPA) oversees Spill Prevention, Control, and Counter-measure and Facility Response Plans. Finally, increasingly comprehensive regulations for transportation of crude by rail have begun with rulings from the U.S. Department of Transportation Federal Rail Administration. The SIMAP model also has been used on numerous Natural Resource Damage Assessments (NRDA).

As shown in Table 3-4, either the OILMAP Land or SIMAP model was used at each representative location. The choice of model for each location was based on the characteristics of the site, as well as the desired outputs from the modeling. SIMAP was chosen for two of the sites on the Mississippi River. This was primarily based on a desire by the State of Minnesota to better understand how turbulent flow could result in the entrainment of crude oil from the water surface into the water column, and the possibility for the creation of oil-mineral aggregates which have the potential to sink (i.e., "sinking oil"). The two modeling locations on the Mississippi River chosen for SIMAP include dams and waterfalls downstream of the hypothetical oil release location. OILMAP Land was used at the remaining five sites. More detailed descriptions of each of the models and their application is provided below.

Unmitigated releases (i.e., no emergency response to contain or remove released oil) were simulated at each hypothetical release location, using a range of site-specific environmental conditions over multiple seasons.

[NONPUBLIC DATA HAS BEEN EXCISED...

Table 3-4 Locations and Predicted Volume Out for the Representative Release Locations

Case #	Representative Release Location	Latitude (N)	Longitude (W)	Model Used	Predicted Volume Out (bbl)[1]
1	Mosquito Creek to Lower Rice Lake	47.4604	95.3066	OILMAP Land	
2	Mississippi River at Ball Club	47.2360	93.9596	OILMAP Land	
3	Sandy River	46.6263	93.2431	OILMAP Land	
4	Shell River to Twin Lakes	46.8196	95.0430	OILMAP Land	
5	Red River	48.70533	97.1148	OILMAP Land	
6	Mississippi River at Palisade	46.6983	93.4950	SIMAP	
7	Mississippi River at Little Falls	46.0483	94.3420	SIMAP	

NOTE:
[1] The maximum volume of oil hypothetically released at each modeling location included both the initial release volume prior to shutdown (i.e. actively pumping out), as well as hydraulic drain down of the pipeline (i.e. gravity drained oil within the pipeline between the valves), following shutdown at that site. The calculation is specific to the pipeline and topographic conditions at the modeling location.

...NONPUBLIC DATA HAS BEEN EXCISED]

As noted earlier, multiple modeling runs were completed for each of the seven release locations. A total of five release locations were modeled using OILMAP Land, while the remaining two were modeled using SIMAP (Table 3-4). This involved separate model runs for each of the two oil types (Bakken crude oil and CLB[6]) for each of the three flow conditions/seasons (high water flow—corresponding to spring; moderate water flow—corresponding to summer and fall; and low flow—corresponding to winter). In total, 42 physical fates scenarios were modeled (7 sites x 2 crude oils x 3 flow conditions/seasons).

Each of the hypothetical unmitigated releases was modeled for 24 hours, with outputs provided at 6, 12, 18 and 24 hours. The 24-hour duration for an unmitigated release was chosen as it is a conservative assumption that the release would be unmitigated for 24 hours, and that the released crude oil would travel downstream unimpeded for that length of time. A similar duration and time steps were used for the ecological and human health risk assessment for Line 3 in Canada that was submitted to the National Energy Board of Canada (Enbridge 2015).

[6] Two crude oil types were considered: Bakken crude oil and CLB. The composition of CLB varies throughout the year. Therefore, the properties of CLB during the summer and winter were determined. A Cold Lake Summer Blend (CLSB) was used for modeling of the average (summer) and high (spring) conditions, whereas CLWB was used for modeling of winter conditions.

3.4.2 OILMAP Land

OILMAP Land is a two-dimensional modeling system that is used to simulate the movement of released oil in the environment. It simulates the flow of oil or chemicals over land as it travels over the land surface and into any surface water body. The model itself has three components, including the overland release model, the surface water transport model, and the evaporative model that define the weathering of oil in the environment under specified conditions. The outputs include an assessment of overland and downstream trajectory of crude oil and resulting locations (e.g., shoreline reaches or segments) where oil may be found at specific times following a release. A simplified mass balance is provided to determine how much oil is retained on land, evaporates, is on the water surface, or oils shorelines. The trajectory results from OILMAP Land can be used in an HCA and AOI analysis, which consists of overlaying the presence of oil onto specific identified regions of interest to determine which resources potentially may be affected.

At each of the five modeling locations where OILMAP Land was used, the trajectory and fate of the hypothetical release of crude oil into riverine and lacustrine environments were modeled based upon the assumption of a full bore release and drain down (Table 3-4). Worst-case release volumes, based on a full bore release for 13 minutes and complete drain down, were calculated for each location. The methodology used to calculate release volumes may be found in Section 4.2. Three seasonal and environmental conditions were modeled, including high, average, and low river flows that represented spring, summer, and winter conditions, respectively. Two oil types were modeled for each flow/season at each site, including Bakken crude and CLB. The chemical and physical parameters of CLB were varied between warmer conditions (CLSB was used for spring, summer/fall conditions) and winter months (CLWB was used) due to changes in the composition of the oil over the course of a year.

For each of the three flow-defined seasons, scenarios for the hypothetical oil releases were run under the corresponding environmental conditions including temperature, wind speed, the concentration of total suspended solids within the water column, etc.

3.4.3 SIMAP

SIMAP is a three-dimensional modeling system that is used to simulate the physical fates of crude oil in the water. It estimates the distribution (as mass and concentrations) of whole oil and components of oil on the water surface, on shorelines, in the water column, in sediments, and evaporated to the atmosphere. This comprehensive modeling system allows for a more in depth understanding of the behavior of oil in the environment, when compared to OILMAP Land. Oil fate processes included in SIMAP are oil spreading (gravitational and by shearing), evaporation, transport, randomized dispersion, emulsification, natural entrainment, dissolution, volatilization of dissolved hydrocarbons from the surface water, adherence of oil droplets to suspended sediments, adsorption of soluble and sparingly-soluble aromatics to suspended sediments, sedimentation, and degradation.

The outputs of the SIMAP physical fates model include the distribution of the released crude oil in three dimensional space and time. This can include the cumulative area covered by a thickness of oil on the water surface, volumes of water at various concentrations of dissolved aromatics and total hydrocarbons, masses of total hydrocarbon and aromatics on surface sediments, and the lengths and location of shoreline affected by oil.

At each of the two modeling locations where SIMAP was used, the effects of potential releases into riverine environments were modeled at each location based on the assumption of a full bore release (Table 3-4). The same three seasonal and environmental conditions, two types of crude oil, and approach for determining the site-specific release volumes modeled in the OILMAP Land assessment were used for the two SIMAP sites.

4.0 PIPELINE FAILURE PROBABILITY ANALYSIS

As part of the route permitting process for L3RP, the MN DOC-EERA was directed to complete an environmental review. The review was required to include an assessment of the risk of large oil releases, including the probability of such events, modeling of oil releases, and an assessment of the potential corresponding environmental effects.

Risk is commonly defined as the product of the probability of an event occurring (i.e., an oil release) and the resulting consequence (i.e., trajectory, fate and effects) of a release. This chapter focuses on the first component of risk: the probability of a large oil release occurring.

To address the probability of a large oil release, quantitative estimates of rupture frequency were determined for each of the seven modeling locations. In linear infrastructure such as pipelines, the probability of failure over a given time period is proportional to segment length, with longer segments being associated with greater probabilities. Therefore, given that each of the seven sites were associated with river crossings, the length of the pipeline segment that was considered in the failure frequency analysis for each modeled site was established through a high resolution analysis of outflow and overland spill modeling of full-bore rupture release scenarios. Specifically, the failure frequency analysis for each site considered the longest length of pipeline around the river crossing where crude oil from a hypothetical full bore rupture was predicted to reach the immediately adjacent waterbody. This analysis took into account both direct releases into the waterbody, as well as local topography and land cover type on each side separately, as well as the associated overland flow.

Having established the segment length at each of the seven modeled sites, quantitative estimates of rupture frequency were made, based on a two-step analysis. The first step involved a Threat Assessment in which the relevant threats at each site were identified (described in Section 4.2). As part of the Threat Assessment, approaches for quantifying threat-specific rupture frequency were selected, giving consideration to threat attribute data, as well as best practice methodologies. Using these approaches, threat-specific quantitative estimates of rupture frequency were then generated in the second step of the analysis—the Frequency Analysis (described in Section 4.2).

4.1 THREAT ASSESSMENT

4.1.1 Overview of the Threat Assessment

The primary objective of the Threat Assessment was to evaluate the potential threats to the integrity of the L3RP at each of the seven modeling locations. The threat assessment approach described in ASME B31.8S (Attachment A) was used as the basis of the Threat Assessment. Threats were divided into nine categories, plus an additional category (Other Threats):

- External corrosion
- Internal corrosion
- Stress corrosion cracking (SCC)
- Manufacturing defects
- Construction defects
- Equipment failure
- Third party damage
- Incorrect operations
- Weather related and outside force
- Other threats (e.g., forest fires, concomitant failures, access restrictions, and exposure to vandalism)

As the results of the threat assessment form the basis of a subsequent analysis to provide quantitative estimates of the likelihood of failure at each of the seven sites, the other objective of the threat assessment is to establish candidate approaches for estimating failure likelihood based on the availability, quality, and completeness of the data attributes for each threat.

The results of the threat assessment showed that of all threats considered, only two (SCC and “Other” threats) are characterized as negligible (i.e., given the location, materials and design/build specifications of the L3RP, these threats do not contribute in a substantial way to the overall failure likelihood). Additionally, the threat of Equipment Failure was considered out of the scope of this assessment, since there are no non-pipe components within the study area for any of the seven modeling locations. For the remainder of threats, quantitative estimates of failure frequency were made in a separate failure frequency analysis.

4.1.2 Introduction

The primary objective of the threat assessment is to review the attributes for all potential threats to a pipeline system taking into account the design, materials, construction methods and operational variables for the pipeline system of interest. Through this review, the relevance and severity of each threat can be assessed in the context of the operating environment for the pipeline being reviewed.

As a variety of failure likelihood estimation approaches exist, with each requiring specific data sets, the threat assessment also considered the availability and type of data for each threat to assist in the selection of the optimal approach of determining the failure frequency for that threat.

This Chapter is structured as follows:

- Section 4.1.3: Scope—description of the pipeline segments being addressed by the threat assessment documented in this report, as well as a description of the future operating conditions that are likely for the pipe segments for the seven modeling locations
- Section 4.1.4: Threat Assessment Approach—identification of the threats considered and a description of the approach
- Section 4.1.5: Assessment of Threats—review of all threat attributes and an assessment of threat potential
- Section 4.1.6: Threat Potential Summary—summary of the threat potential for each threat, as well as description of the candidate approaches for estimating failure likelihood based on the availability, quality, and completeness of the data attributes for each threat

4.1.3 Scope

The threat assessment was conducted for seven separate segments of the 36 inch outside diameter (OD) L3RP. At each of the seven modeling locations, the segment length for each pipeline was determined by outflow and overland spill analysis. Specifically, the threat assessment and failure frequency analysis for each site considered the length of pipeline around the site of the hypothetical full bore rupture from which a crude oil release could affect (i.e., reach) the immediately adjacent waterbody through direct release or overland flow.

The design details of these seven pipeline segments are summarized in Table 4-1. Aerial imagery of each of the seven modeling locations is provided in Figure 4-1 to Figure 4-7.

Table 4-1 L3RP Pipe Segment Summary

Site No.	Stationing			Mile Post			Design Details				Installation	
	Start (ft)	End (ft)	Total Length (ft)	Start	End	Comment	OD (in)	WT (in)	Grade	MOP (psi)	Method	Min. Depth (ft)
Site 1: Mosquito Creek Crossing	741,337.644	743,162.474	1,824.830	396.01	396.36	Preferred Route MP	36	0.515	X70	654.26	Open trench	4
Site 2: Mississippi River at Ball Club	400,739.478	400,946.857	207.379	79.38	79.41	Miles from divergence from Preferred route, along RA-07	36	0.750	X70	728.91	HDD	40
Site 3: Sandy River Crossing	1,573,712.316	1,574,863.425	1,151.109	553.84	554.06	Preferred Route MP	36	0.750	X70	453.76	HDD	40
Site 4: Shell River Crossing	1,025,970.305	1,028,513.301	2,542.996	449.99	450.47	Preferred Route MP	36	0.750	X70	440.23	HDD	40
Site 5: Red River Crossing	64,422.101	66,010.025	1,587.924	801.65	801.93	L3RP existing corridor MP	36	0.750	X70	513.13	HDD	40
Site 6: Mississippi River at Palisade	1,488,560.525	1,490,030.446	1,469.921	537.68	537.96	Preferred Route MP	36	0.750	X70	734.68	HDD	40
Site 7: Mississippi River at Little Falls	1,355,723.087	1,357,034.285	1,311.198	67.97	68.22	Miles from divergence from Preferred route, along RA-55	36	0.750	X70	438.69	HDD	40

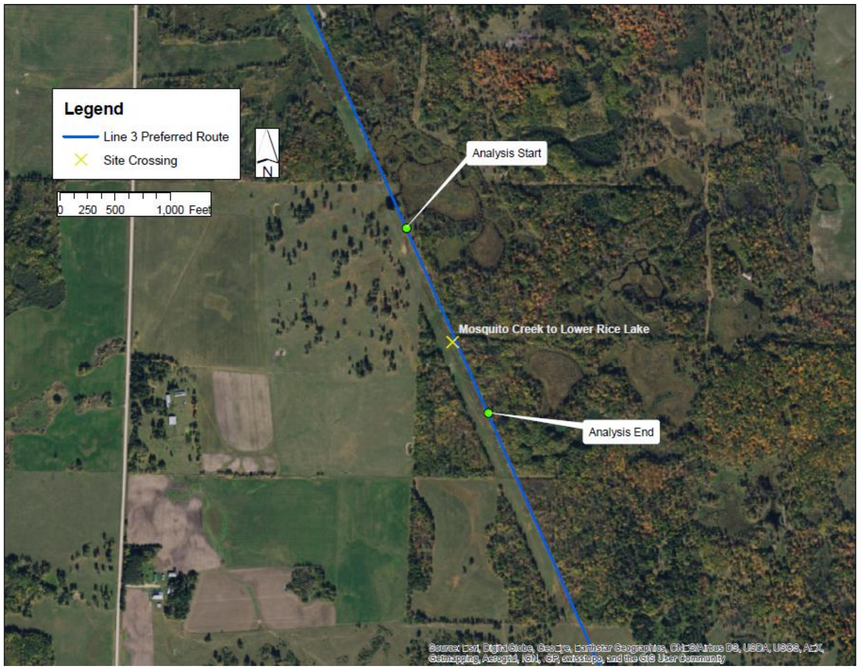

Figure 4-1 Site 1: Mosquito Creek Crossing

Figure 4-2 Site 2: Mississippi River Crossing at Ball Club

Figure 4-3 Site 3: Sandy River Crossing

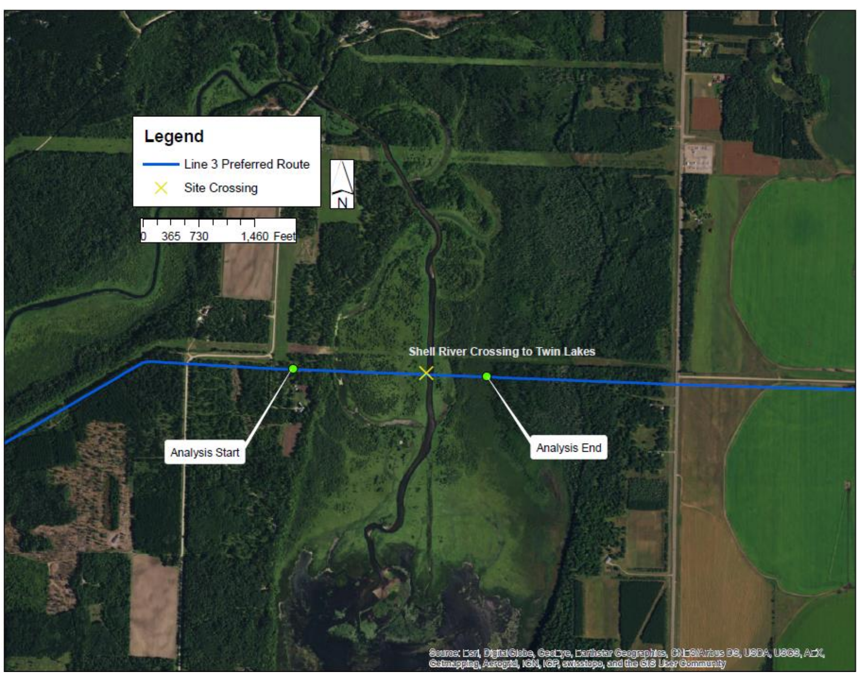

Figure 4-4 Site 4: Shell River Crossing

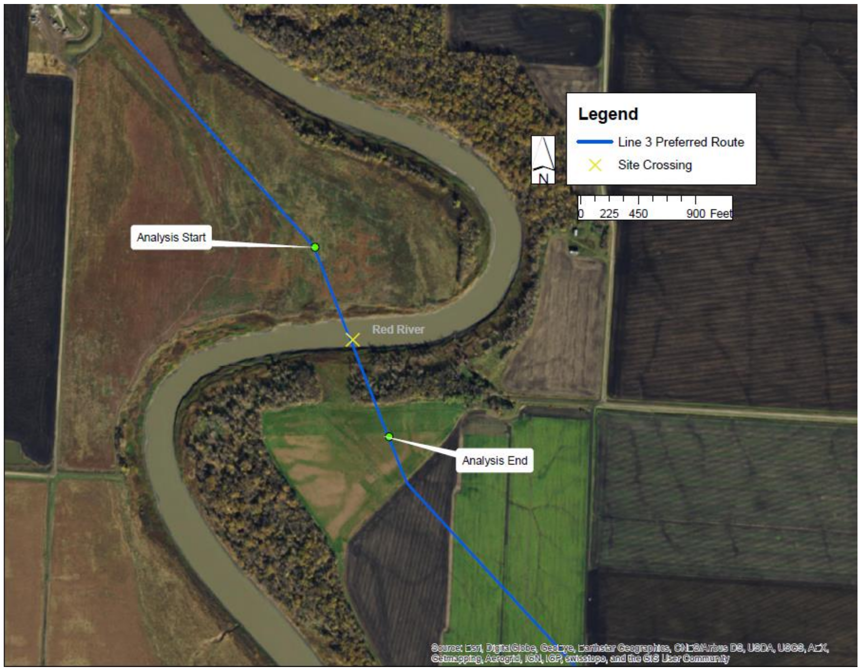

Figure 4-5 Site 5: Red River Crossing

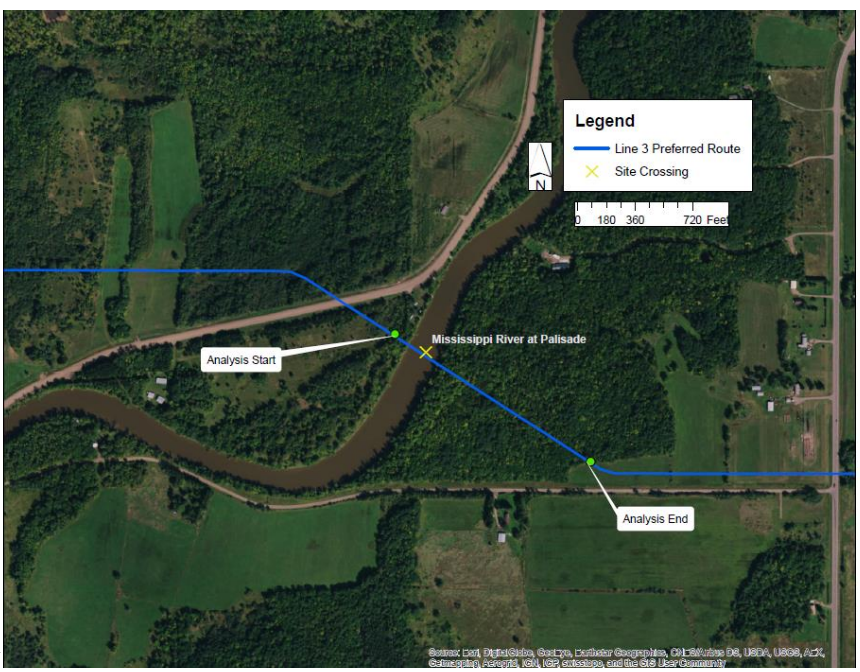

Figure 4-6 Site 6: Mississippi River Crossing at Palisade

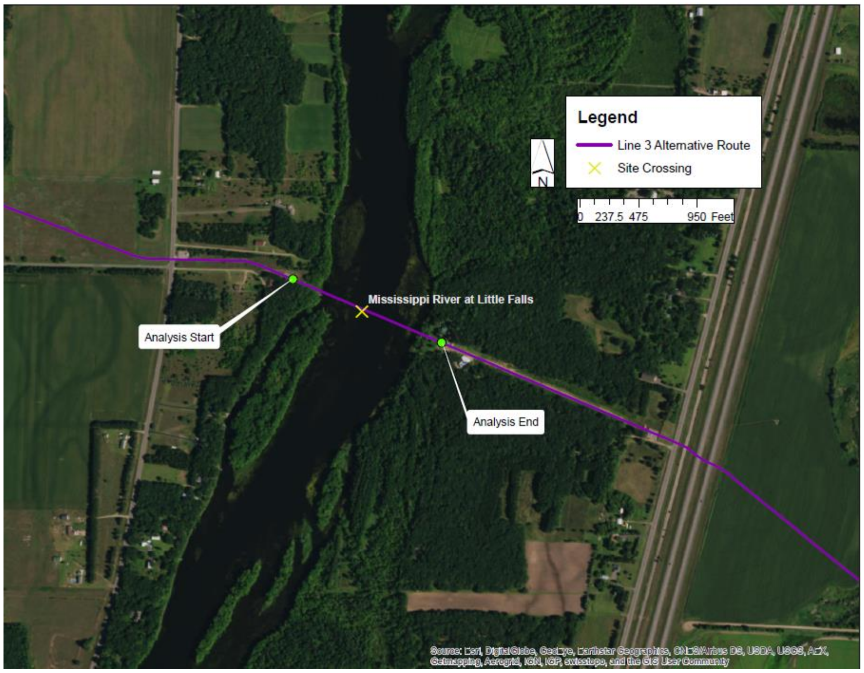

Figure 4-7 Site 7: Mississippi River Crossing at Little Falls

4.1.4 Threat Assessment Approach

The threat assessment was based on ASME B31.8S (Attachment A). Although the scope of ASME B31.8S is the management of system integrity of gas pipelines, this standard was employed as the basis of the threat assessment due to the comprehensive list of threats considered in Attachment A, and the applicability of these threats to crude oil pipelines. Based on this standard, threats are divided into nine categories, plus an additional category (Other Threats).

- External corrosion
- Internal corrosion
- SCC
- Manufacturing defects
- Welding / fabrication defects
- Equipment failure
- Third party damage
- Incorrect operations
- Weather related and outside force
- Other threats

A Threat Assessment Workshop was conducted in Enbridge's offices in Duluth, Minnesota on December 9 and 10, 2015. The list of attendees at this workshop, along with their affiliations and job titles is provided in Table 4-2.

The objectives of the workshop were to review information from sources such as maps, imagery, design records, operating data, and the opinions of subject matter experts to meet the objectives of the analysis as outlined in Section 4.1.1.

During the workshop, standardized threat assessment forms were utilized to focus the discussion. Information from the workshop and from follow-up data collection exercises is presented in Section 4.1.5.

Table 4-2 Threat Assessment Workshop Attendees

Company	Name	Title
Dynamic Risk Assessment	Jim Mihell	Chief Engineer
Dynamic Risk Assessment	Tyler Klashinsky	Integrity Engineer E.I.T
Kelly Geotechnical	Shane Kelly	Geotechnical Engineer
Wim M. Veldman Consulting Inc.	Wim Veldman	Geotechnical Specialist
Enbridge	Matt Bordson	Senior Engineer, L3R Mainline
Enbridge	Kyle Bridell	Region Engineer, Superior Region
Enbridge	Kelly Sullivan	Engineer, L3R Mainline
Enbridge	Andrew Onken	Corrosion Engineering Lead–Lake Superior Consulting
Enbridge	Andrew Nielson	Asset Lead, Pipeline Integrity
Enbridge	Claudia Schrull	Sr. Manager, Regulatory
Enbridge	David Carmona Ruiz	Engineer, Pipeline Integrity–L3RP
Enbridge	David Weir	Manager, Risk Management Modeling
Enbridge	John Pechin	Manager, Bemidji Operations, Superior Region
Enbridge	Jonathan Minton	Project Supervisor, US Regulatory Affairs
Enbridge	Matthew Martin	Engineering Specialist, L3R Mainline
Enbridge	Brent Eliason	Region Engineer, Superior Region
Enbridge	Theresa Picton	Compliance Coordinator Superior Region Operations
RPS Group	Matt Horn	Senior Scientist

4.1.5 Assessment of Threats

The attributes for each of the potential threats are discussed below.

4.1.5.1 External Metal Loss

External corrosion is a form of wall loss caused by interaction of the outside steel pipe surface with the environment. The primary form of defense against external corrosion is the external corrosion coating on the pipe. Corrosion cannot occur so long as this coating is intact, and well-bonded to the surface of the pipe. In the event of a "holiday" (an area of missing coating), or disbondment of the coating from the surface of the pipe, the secondary defense is cathodic protection, which is designed to maintain the surface of the pipeline more electro-negative than its corrosion potential. Failure of both systems can lead to areas of localized wall loss caused by corrosion.

A summary of the threat assessment for external metal loss as it relates to L3RP is provided in Table 4-3 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-3 External Metal Loss Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Coating Type	The following coating types will be used for L3RP: • Mainline pipe body coating system: Fusion Bond Epoxy (FBE) • Hot bends and field girth welds: 2-Part Liquid Epoxy • Horizonal Directional Drill (HDD) Sections: FBE with Abrasion-resistant overcoat Maximum temperature performance rating of all coatings is compatible with the 140°F maximum operating temperature.	All coating types being considered for the pipeline projects can be characterized as high-performance coating systems that form an efficient corrosion barrier, and that resist degradation with time.
Cathodic Protection	L3RP will have a remote-bed impressed cathodic protection (CP) system. Potential sources of interference such as High Voltage DC (HVDC) and High Voltage AC (HVAC) power lines, and adjacent pipelines will undergo testing to establish the most effective mitigation measures. If necessary, bonding will be completed to adjacent structures. Site-specific circumstances and plans are outlined below: • Site 1 – Mosquito Creek Crossing: – Additional existing lines parallel (4 Minnesota Pipe Line Company crude oil pipelines). Closest pipe 25 ft to L3RP – Interference testing will be completed. If necessary will bond to existing system – No potential AC interference • Site 2 – Mississippi River Crossing at Ball Club: – HVAC line running south of line which is currently mitigated for existing lines. – Great Lakes gas pipelines (2-3 lines) in vicinity but not parallel. Minimum separation distance would be 50 ft – Existing parallel Enbridge line (6 total) Min separation would be 25 ft (Enbridge Energy Partners [EEP]corridor) – Line would be bonded to EEP which fully mitigates existing lines. Site 3 – Sandy River Crossing: – No other existing lines (foreign or Enbridge-owned) – No sources of Interference (HVAC or HVDC) • Site 4 – Shell River Crossing: – Nearby overhead power line <300 ft HVDC – Far enough away that interference should not be an issue – No additional interference sources – No foreign pipelines	The proposed CP system design and testing measures represent industry best practice for cathodic protection systems.

Table 4-3 External Metal Loss Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
	• Site 5 – Red River Crossing: – 7 different parallel lines all Enbridge-owned min 25 ft separation. Plan is to bond to all 7 Lines at this location • Site 6 – Mississippi River Crossing at Palisade: – No adjacent pipelines – No foreign or Enbridge pipelines – No Sources of interference (HVAC or HVDC) • Site 7 – Mississippi River Crossing at Little Falls: – Viking parallel gas line will be minimum 50 ft away. – Testing for interference and appropriate mitigation such as bonding will be implemented if necessary	
CP Survey Plan	A Direct Current Voltage Gradient coating quality check will be completed on the L3RP following construction and within 18 months of commissioning. Annual test surveys to be completed on the L3RP. Additionally, close interval surveys will be completed every five years post construction. Rectifier readings will be completed on a minimum bi-monthly schedule. HDD sections will undergo coating quality testing after installation.	The proposed CP survey plans represent industry best practice for cathodic protection systems.
Soil Characteristics	No problematic conditions (acid rock drainage, high microbiological activity, etc.) have been identified along the L3RP.	There are no special concerns related to soil characteristics along L3RP.
Above-ground pipe	All piping within the scope of the analysis will be below-grade.	No consideration required for atmospheric corrosion or aeration cells.
Casings	There are no cased crossings within the scope of the analysis.	No consideration required for casing shorts.

Table 4-3 External Metal Loss Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Assessment Plan	Types of assessment to be performed, and assessment intervals to be used	Magnetic metal loss, ultrasonic crack detection, and high resolution geometry tool with an Inertial Mapping Unit as part of the baseline inspection will be completed within 1 year of in service. Inspection intervals will depend on previous findings, however currently planning 5 year inspection intervals for crack, corrosion and deformation tools. Features identified by in-line assessment tools will be evaluated against acceptability criteria, and those that exceed those criteria will be excavated and evaluated to assess the need for repair, replacement or recoating.
Analogue In Line Inspection (ILI) Data	During the Threat Assessment Workshop potential sources of Inline Inspection (ILI) data were discussed in consideration of: • Similar geographic region / terrain • Same CP standards and practices • Same coating systems • Reliability of ILI dataset • Preferably 15 years between installation date and inspection date	The following candidate ILI datasets were discussed in terms of their potential to provided suitable ILI analogues: • Line 64 – 2003 FBE – potential option • Line 4 in Canada – FBE Portions built in 90s and 2000s – follows same route as L3RP • To be provided

4.1.5.2 Internal Metal Loss

Internal metal loss is a form of degradation caused by corrosion, erosion, or a combination of the two. Internal corrosion is a form of wall loss caused by exposure of the inside surface of the pipe to an electrolyte (typically water). Internal corrosion may be enhanced by erosion, which is caused by sediment entrained within the product stream impinging against the internal surface of the pipe. Under extreme circumstances of sediment loading and product stream velocity, erosion can become a significant cause of metal loss without contributions from corrosion processes.

Internal corrosion can be eliminated by preventing water from coming into contact with the pipe surface. This can be achieved by eliminating water from the product stream and/or minimizing water content and maintaining turbulent flow conditions so as to keep water entrained within the product stream, thereby keeping it from coming into contact with the pipe surface. Erosion can be eliminated by maintaining the solid content of the product stream to low levels.

A summary of the threat assessment for internal metal loss as it relates to L3RP is provided in Table 4-4 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-4 Internal Metal Loss Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Product Stream Characteristics	Tariffs for L3RP were reviewed, and elements of those tariffs that are relevant to internal corrosion are as follows: • L3RP Tariff FERC No. 41.10.0: – BS&W limited to 0.5%	A CEPA study (Penspen Integrity 2013) indicates that under normal operations, oil pipelines, including dilbit pipelines with low BS&W (0.25–0.5%) are unlikely to have free water present in them and, with a sufficiently high flow velocity inside the pipe, any free water presence caused by operation upsets will be entrained in the oil by turbulent flow, and the pipe wall will continue to be oil wetted. At low BS&W levels, in conjunction with turbulent flow, water will remain entrained in oil. Therefore, internal corrosion is unlikely to occur.
Product Stream Flow Characteristics	The products to be transported through the L3RP will be operated in such a manner as to maintain fully-turbulent and steady flow.	Turbulent flow controls solids deposition, and maintains what little water exists entrained in the product stream. The product stream, in conjunction with the operating and flow characteristics should render the pipe wall in an oil-wet (i.e., non-corrosive) condition, although monitoring and the implementation of appropriate mitigation strategies, where warranted, is required. Flow rates will be monitored to confirm turbulent flow, as well as no sediment or water drop-out.
Corrosion Detection Devices	Means of monitoring for internal corrosion	The use of internal coupons and in-line inspection will be employed to monitor for internal corrosion.
Receipt Points	L3RP will receive product from Clearbrook West and Superior receipt points.	Product is monitored to confirm that it meets Enbridge's tariff.
Chemical Inhibition Program	None planned	Monitoring and the implementation of appropriate mitigation strategies will be implemented, where warranted.
Cleaning Pig Program	None planned	

Table 4-4 Internal Metal Loss Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Assessment Plan	Types of assessment to be performed, and assessment intervals to be used	Magnetic metal loss, ultrasonic crack detection, and high resolution geometry tool with an Inertial Mapping Unit as part of the baseline inspection will be completed within one year of in service. Inspection intervals will depend on previous findings, however currently planning 5 year inspection intervals for crack, corrosion and deformation tools. Features identified by in-line assessment tools will be evaluated against acceptability criteria, and those that exceed those criteria will be excavated and evaluated to assess the need for repair, replacement or recoating.
Potential source of Analogue ILI Datasets	During the Threat Assessment Workshop potential sources of In-Line Inspection (ILI) data were discussed in consideration of: • Similar product type • Similar hydraulic regime • Similar continuity of flow • Similar inhibition and pigging program • Reliable ILI dataset • Preferably >15 years between installation date and inspection date	For liquid products, the important parameters that should be included in a comparison of corrosivity are water content, erosion and erosion/corrosion, flow velocity, flow mechanism, temperature, susceptibility to under-deposit corrosion (solid deposition, MIC potential, and water chemistry), and mitigation measures (use of inhibition, biocides, or pigging). To confirm that the corrosion mechanism and corrosivity that is represented by the analogue ILI dataset is representative of that which would be expected in the L3RP, an evaluation of all of these parameters were conducted. Through this process, it was determined that ILI data obtained from Enbridge's 36 inch Line 4 would be most representative of the corrosivity conditions expected on this pipeline.

4.1.5.3 Stress Corrosion Cracking

SCC in pipelines is a type of environmentally-assisted cracking (EAC). EAC is a generic term that describes the formation of cracks caused by various factors combined with the environment surrounding the pipeline. Together these factors reduce the pressure carrying capacity of the pipeline. When water (electrolyte) comes into contact with steel, the minerals, ions, and gases in the water can attack or corrode the steel. These chemical or electrochemical reactions may result in general wall thinning, corrosion pits, and/or cracks.

SCC involves corrosive mechanisms and depends on both an aggressive environment and tensile stress. SCC in pipelines is further characterized as "high pH SCC" or "near-neutral pH SCC," with the "pH" referring to the environment on the pipe surface at the crack location and not the soil pH. (pH is the measure of the relative acidity or alkalinity of water. It is defined as the negative log [base 10] of the hydrogen ion concentration. Water with a pH of 7 is neutral; lower pH levels indicate an increasing acidity, while pH levels above 7 indicate increasingly basic solutions). SCC flaw growth can be enhanced by pressure cycling and fatigue.

In terms of perspective relative to other threats, SCC is a relatively small causal factor for gas transmission pipeline incidents in the U.S., and SCC failures on hazardous liquid pipelines have been less frequent when compared with SCC occurrences on natural gas pipelines.

Based on industry experience, susceptibility to SCC has been associated with buried pipelines that have the following threat characteristics (Baker 2005):

- SCC susceptible coating system
- Pipe in operation greater than 10 years
- Operating stress levels greater than 60% Specified Minimum Yield Strength (SMYS)
- Located within 20 miles downstream of a pump station
- Temperatures greater than 100°F (specific to high-pH SCC)

SCC is found in areas of coating damage. Vintage coating systems (i.e., pre-FBE) are considered to be generally susceptible to the type of coating damage associated with SCC.

The use of effective, high-performance coatings for new pipeline design and installation is the most practical way preventing failures due to SCC in pipelines, and FBE, liquid epoxies, and urethanes are the preferred coatings for managing this threat.

A summary of the threat assessment for SCC as it relates to the L3RP is provided in Table 4-5 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-5 Stress Corrosion Cracking Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
SCC Susceptibility	The following design and operating variables were reviewed for the L3RP: • Operating stress level – Max stress level 32.7% SMYS • Operating temperature – 140˚F max • Distance from Pump Station – Minimum distance: 8 mi (Site 6) • Coating type – Mainline pipe body coating system: FBE; Hot bends and field girth welds: 2-Part Liquid Epoxy; HDD Sections: FBE with Abrasion-resistant overcoat	All the specified pipeline coating systems are characterized as high-performance coating systems, and as such, are resistant to the formation of significant SCC. To date, no operating company has ever experienced a failure that was attributed to SCC in a pipeline that was coated with these coating systems.
Pressure cycling and fatigue	A pressure cycling and fatigue study was conducted on L3RP (Enbridge 2015). This study concluded that fatigue life in this segment was deemed to be acceptable per the requirements of D02-110 (2013) - Fatigue Design of New Pipelines.	A Fatigue Life Analysis design process accounts for the type of pipe selected, the different pressure ranges encountered throughout the pressure cycles, and the operational parameters selected by the operator. The main purpose of these calculations is to aid operators in quickly avoiding unacceptable pressure cycling. This represents industry best practice, as it allows the operator to be aware of the threat environment, and to pre-emptively mitigate potential threats before they can manifest themselves as a failure.
Assessment Plan	Types of assessment to be performed, and assessment intervals to be used	Magnetic metal loss, ultrasonic crack detection, and high resolution geometry tool with an Inertial Mapping Unit as part of the baseline inspection will be completed within one year of in service. Inspection intervals will depend on previous findings. In addition, Enbridge is currently planning 5 year inspection intervals for crack, corrosion and deformation tools. Features identified by in-line assessment tools will be evaluated against acceptability criteria, and those that exceed those criteria will be excavated and evaluated to assess the need for repair, replacement or recoating.

4.1.5.4 Manufacturing Defects

Based on historical industry experience, manufacturing defects failures have been associated primarily with pipe seam defects and hard spots[7]. Other issues related to pipe manufacture such as out-of-roundness, out-of-dimensional-tolerance conditions in preparation of pipeline ends, and high hardenability[1] have contributed to field weldability[1] problems, which in themselves have constituted a threat.

In modern pipe manufacture, with the universal adoption of continuous casting in lieu of ingot casting practices, and with the advent of High Strength Low Allow (HSLA) steel designs, hard spots have been fully eliminated; however, for the most part, the remainder of the above-listed issues are still a concern. In addition, in recent years, hydrostatic test failures and dimensional out-of-spec conditions have resulted from the production of pipe that does not meet minimum yield strength criteria.

The best way to safeguard against manufacturing defect related pipeline failures is through the application of carefully designed and executed pipe manufacturing and quality control practices, as dictated by rigorous skelp and pipe mill pre-qualification procedures and pipe purchase specifications.

A summary of the threat assessment for manufacturing defects as it relates to the L3RP is provided in Table 4-6 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

[7] See Glossary

Table 4-6 Manufacturing Defects Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Manufacturing procedure specification	Manufacturing procedure specifications reviewed for pipe to be used on L3RP addresses: • Steelmaking • Slab and skelp manufacturing • Forming • Welding • Finishing • Hydrostatic testing • Inspection • Repair • Tracking and control • Laboratory testing • Quality management system • Material tracking system • Inspection and test plan • Non-conformances • Handling, shipping, storage • Third party inspection • Marking	The manufacturing procedure specification, together with the inspection and test plan constitute key quality assurance documents that form the basis of good pipe procurement practices.
Manufacturing Process	• All sites will use 36 in. Double Submerged Arc Welded (DSAW) straight-seam pipe.	While some vintage manufacturing processes are prone to manufacturing defects, modern line pipe manufacturing processes are not associated with characteristic chronic manufacturing defects. Well-developed manufacturing procedure specifications and inspection test plans are instrumental in maintaining quality assurance.
Use of Third Party Pipe Mill Auditors	• Roving auditors + final bench at pipe mills • Third party inspector during loading and unloading	While third party audits and inspection does not guarantee quality, the effective deployment of auditors promotes a quality focus during line pipe manufacture, while alerting purchasers to potential quality problems during manufacture and prior to delivery.
Line pipe manufacturer	• Site 1: 36 inch DSAW UOE line pipe	None of the pipe mills being used are associated with

Table 4-6 Manufacturing Defects Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
	manufactured by EVRAZ, Portland. • All other sites: 36 inch DSAW UOE line pipe manufactured by EVRAZ, Camrose	documented chronic quality problems.
Pressure cycling	• A pressure cycling and fatigue study was conducted on this segment of pipeline (Enbridge Pressure Cycling Analysis L3R 2015). This study concluded that fatigue life in this segment was deemed to be acceptable per the requirements of D02-110 (2013)—Fatigue Design of New Pipelines.	Fluctuating operating pressures, that are typical of liquids pipelines, can activate pre-existing manufacturing defects. Nevertheless, the Fatigue Life Analysis design process accounts for the type of pipe selected, the different pressure ranges encountered throughout the pressure cycles, and the operational parameters selected by the operator. The main purpose of these calculations is to aid operators in quickly avoiding unacceptable pressure cycling. This represents industry best practice, as it allows the operator to be aware of the threat environment, and to pre-emptively mitigate potential threats before they can manifest themselves as a failure.
Hydrostatic test	• A review was conducted of Enbridge Specification USPCS-Spec-Hydro-005 "Specification for Pipeline Construction (USA) Pipeline Hydrostatic Testing".	The L3RP pipeline will be tested to a maximum test pressure of 2003 psi. For the seven sites being evaluated, this test pressure ranges from 272% to 457% of maximum operating pressure. These represent significant safety factors, ensuring that any manufacturing defects left after the hydrostatic test are not operating at stress levels where they would be considered to be structurally significant.

4.1.5.5 Construction Defects

Historically, construction defect failures have been associated primarily with welding defects and installation defects such as dents and buckles, which may be associated with improper ditch preparation and backfill, or with the use of excessive tie-in strains. For a given pipe material, failures from construction defects are influenced by the following factors:

- Construction practices
- Joining practices
- Joint inspection practices
- Hydrostatic inspection practices
- Inspections
- Operating pressure

A summary of the threat assessment for construction defects as it relates to the L3RP is provided in Table 4-7 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-7 Construction Defects Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Construction Practices	The following information related to construction practices proposed for L3RP were reviewed: • Welding processes: – Mechanized gas metal arc welding (GMAW)—mainline – Tie-ins—cellulosic root and hot pass with mechanized GMAW fill and cap – Weld zone assessment – 100% automated ultrasonic testing (AUT)/phased array – Potential for supplemental X-ray – Post-construction inspection – Caliper tool inspection – Post-construction pressure testing – Minimum test pressure 2003 psi Additionally, the Enbridge specification of Mainline Construction was reviewed, which addresses construction procedures related to activities such as trenching, lowering-in and backfilling.	Welding and non-destructive inspection procedures are representative of industry best practices, which maximize the use of low-hydrogen welding processes, and state-of-the-art inspection systems. Although construction specifications are comprehensive, leading to minimized potential for construction-related damage, such damage can occur, particularly on pipelines that have high diameter: wall thickness ratio. Post-construction in-line inspection is an effective measure of identifying such damage, and enabling repairs to be made before defects can grow to failure during operation. For the 7 modeling locations being evaluated along the L3RP pipeline, hydrostatic test pressure ranges from 272% to 457% of maximum operating pressure. These represent important safety factors, and help confirm that any construction defects left after the hydrostatic test are not operating at stress levels where they would be considered to be structurally significant.
Operating Pressure	• A pressure cycling and fatigue study was conducted on this segment of pipeline (Enbridge Pressure Cycling Analysis L3R, 2015). This study concluded that fatigue life in this segment was deemed to be acceptable per the requirements of D02-110 (2013) - Fatigue Design of New Pipelines.	Fluctuating operating pressures that are typical of liquids pipelines can activate pre-existing construction defects. Nevertheless, the Fatigue Life Analysis design process accounts for the type of pipe selected, the different pressure ranges encountered throughout the pressure cycles, and the operational parameters selected by the operator. The main purpose of these calculations is to prevent unacceptable pressure cycling at the earliest stages possible. This represents industry best practice, as it allows the operator to be aware of the threat environment, and to pre-emptively mitigate potential threats before they can manifest themselves as a failure.

4.1.5.6 Equipment Failure

Equipment failure is defined in the context of pipeline transmission infrastructure as failures occurring in pressure retaining components other than pipe and fittings such as valves, flanges, and gaskets. These components require the same types of quality surveillance and inspection as the pipe itself. Risk factors for equipment failure are related to operating and maintenance (O&M) procedures, and the quality management systems that detail when and how inspections and maintenance of equipment will be performed and what specific action is required.

As the pipeline segments associated with each of the seven modeling locations does not include non-pipe equipment, this threat was determined to be out of scope for this assessment.

4.1.5.7 Third Party Damage

Third party damage is defined as third-party-inflicted damage, typically caused by ground disturbance by heavy equipment, such as excavators. All pipelines experience some level of threat due to third party damage. The magnitude of this threat is a function of the effectiveness of damage prevention measures, adjacent land use and depth of cover, as well as damage resistance characteristics of the pipe. Although damage prevention measures can help to offset this threat, third party damage can never be fully neutralized. In this respect, failure susceptibility due to third party damage can be established as the product of two independent variables; the frequency of incurring a hit and the probability of failure given such a hit.

Impact frequency due to external interference has been characterized in terms of damage prevention factors; specifically (Chen and Nessim 1999a):

- Adjacent land use
- One-call system availability and promotion
- Signage placement
- Use of buried marker tape
- Response time for locate requests
- Patrol frequency
- Marking and locating methods
- Depth of cover

A summary of the threat assessment for third party damage as it relates to the L3RP is provided in Table 4-8 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-8 Third Party Damage Threat Attribute Summary

Threat Attribute	Data Evaluation	Threat Considerations
Adjacent land use	For the purposes of evaluating exposure to accidental interference, Chen and Nessim (1999) characterizes adjacent land use as commercial / industrial / high density residential / low density residential / agricultural / remote	Enbridge's damage prevention measures are representative of industry best-practice. Nevertheless, the potential for third party damage cannot be discounted.
One-call system availability and promotion	The one-call promotion practice to be employed on L3RP includes the promotion and use of an 811 call number, community involvement, and community meetings.	
Signage placement	The signage placement practice to be adopted on L3RP includes warning signs at road, railways, water crossing, both sides of pipeline, irrigation, areas where third party might occur, fence crossings, and areas of population growth (i.e., all crossings plus areas of potential activity). Sign placement also takes into account line of sight and potential activity.	
Use of buried marker tape	Buried marker tape is not used, and is not relevant to HDD crossings.	
Response time for locate requests	The response time standard for locate requests within Minnesota is within two business days.	
Patrol frequency	Patrol frequency is 26 times per year but not exceeding every 3 weeks (helicopter and fixed wing)	
Marking and locating methods	The marking and location practices to be employed on L3RP are as follows: • Excavations within 100 ft: locate and mark • Excavations within 16 ft: expose by vacuum truck • Excavations within 2 ft: expose by hand digging	
Depth of cover	All HDD installations have a minimum cover of 40 ft All trenched installations have a minimum cover of 4 ft (3 ft in rock ditch).	

4.1.5.8 Incorrect Operations

Incorrect operations failure is defined in the context of pipeline transmission infrastructure as failures that have causal factors that are related to design, as well as operation and maintenance procedures. A review of these procedures as they relate to the L3RP was evaluated by means of an Operations Questionnaire which was completed by workshop attendees during the threat assessment workshop. Results of the questionnaire are summarized below.

The threat environment associated with this threat is best evaluated through dialogue that is focused on design and operational factors related to the following attributes:

- Design attributes
  - Hazard identification
  - Maximum Allowable Operating Pressure (MAOP) potential
  - Safety systems
  - Checks
- Operations attributes
  - Operating procedures
  - Management of change procedures
  - Supervisory Control and Data Acquisition (SCADA) / communications
  - Drug testing procedures
  - Safety programs
  - Surveys / maps / records
  - Training procedures and programs
  - Mechanical error preventers

To facilitate the collection of information related to the above, an Operations Questionnaire, focused on the above attributes was administrated during the Threat Assessment Workshop. This questionnaire, along with the results of the targeted discussion associated with each of the attributes, is reproduced in Table 4-9.

Table 4-9 Operations Questionnaire

Contents

Section	Subject	Title	Questions	Possible Points
1.1	Design	Hazard Identification	4	4
1.2		MAOP Potential	1	12
1.3		Safety Systems	1	10
1.4		Material Selection	2	2
1.5		Checks	1	2
2.1	Operations	Operating Procedures	7	7
2.2		Management of Change	7	7
2.3		SCADA/Communications	1	3
2.4		Drug Testing	2	2
2.5		Safety Programs	1	2
2.6		Surveys/Maps/Records	2	5
2.7		Training	10	10
2.8		Mechanical Error Preventers	4	7
		Total	43	73

NOTES:

Survey questions for all topics other than Management of Change were based on the Incorrect Operations approach contained in *Pipeline Risk Management Manual*, Third Edition [Muhlbauer, W.K.]. Management of Change approach was based on API RP 581 Part 2 "Risk Based Inspection Technology" – Annex 2.A – Management Systems Workbook.

Scores are assigned such that higher scores are associated with the most favorable response.

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
1. Design			
1.1	Hazard Identification		
	a. Has a threat assessment been performed that entertains all possible threats?	1	1
	b. Do the results of the threat assessment reflect current conditions?	1	1
	c. Have possible hazards and risks associated with the work been identified through studies such as HAZOP, risk assessment, or reliability analysis?	1	1
	d. Are the results of the above studies available in documented form?	1	1
	Section Totals	***4***	***4***
1.2	MAOP Potential		
	Characterize the ease with which MAOP could be reached on the pipeline system (select one response only):		
	a. Routine. Routine, normal operations could allow the system to reach MAOP. Overpressure would occur fairly rapidly due to incompressible fluid or rapid introduction of relatively high volumes of compressible fluids. Overpressure is prevented only by procedure or single-level safety device.	0	
	b. Unlikely. Overpressure can occur through a combination of procedural errors or omissions, and failure of safety devices (at least two levels of safety).	5	
	c. Extremely Unlikely. Overpressure is theoretically possible (sufficient source pressure), but only through an extremely unlikely chain of events including errors, omissions, and safety device failures at more than two levels of redundancy.	10	10
	d. Impossible. Overpressure cannot occur, under any conceivable chain of events.	12	
	Section Totals	***12***	***10***

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
1.3	Safety Systems		
	Describe the safety systems that are in place (select one response only):		
	a. No Safety Devices Present. No safety devices are present to prevent overpressure.	0	
	b. On Site, One Level. A single on-site device offers protection from overpressure.	3	
	c. On Site, ≥2 Levels. Two or more independent on-site devices offer protection from overpressure.	6	5*
	d. Remote, Observation Only. Pressure is monitored from a remote location. Remote control is not possible, and automatic overpressure protection is not present.	1	
	e. Remote, Observation and Control. Pressure is monitored from a remote location. Remote control is possible, and automatic overpressure protection is not present.	3	
	f. Non-Owned, Active Witnessing. Overpressure prevention devices exist, but are not owned, maintained, or controlled by the owner of the equipment that is being protected. The owner takes steps to ensure that the safety device(s) is properly calibrated and maintained by witnessing such activities.	-2	
	g. Non-Owned, No Involvement. Overpressure prevention devices exist, but are not owned, maintained, or controlled by the owner of the equipment that is being protected. The owner does not take steps to ensure that the safety device(s) is properly calibrated and maintained by witnessing such activities.	-3	
	h. Safety Systems Not Needed. Safety systems not needed because overpressure cannot occur.	10	
	Section Totals	***10***	***5***
1.4	Materials Selection		
	Are design documents available that illustrate that all piping systems were designed with consideration given to all anticipated stresses?	1	1
	Do control documents, including material specifications and design drawings for all systems and components exist and maintained in an up-to-date manner?	1	1
	Section Totals	***2***	***2***
1.5	Checks		
	Do procedures exist that require design calculations and decisions to be checked by a licensed professional	2	1

* Less than full marks awarded reflecting less than complete independence of overpressure protection.

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
	engineer at key points during the design process?		
	Section Totals	2	1
2. Operation			
2.1	Operating Procedures		
	Do written procedures covering all aspects of pipeline operation exist?	1	1
	Are these procedures actively used, reviewed, and revised?	1	1
	Are copies of these procedures available at field locations?	1	1
	Does a protocol exist that specifies the responsibility for procedure development and approval?	1	1
	Does a protocol exist that specifies how training is performed against these procedures?	1	1
	Does a protocol exist that specifies how compliance to these procedures is verified?	1	1
	Does a document management system exist that ensures version control, and proper access to the most current procedure documents?	1	1
	Section Totals	7	7
2.2	Management of Change		
	Is there a written MOC procedure that must be followed whenever processes, procedures or physical assets are changed?	1	1
	Are authorization procedures clearly stated and at an appropriate level?	1	1
	Do physical changes, changes in operating conditions, and changes in operating procedures invoke the MOC procedure?	1	1
	Is there a clear understanding of what constitutes a 'temporary change', and does the MOC procedure address temporary changes?	1	1
	Are temporary changes tracked to ensure that they are either removed after a reasonable period of time or reclassified as permanent?	1	1
	Do the MOC procedures specifically require the following actions whenever a change is made to an operating procedure?	1	1
	Update all affected operating procedures		
	Update all affected maintenance programs and inspection schedules		

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
	Modify drawings, statement of operating limits, and any other safety information affected?		
	Notify all operations and maintenance employees who work in the area of the change, and provide training as required		
	Review the effect of the proposed change on all separate but interrelated procedures		
	When changes are made in operating procedures, are there written procedures requiring that the impact of these changes on the equipment and materials of construction be reviewed to determine whether they will cause any increased rate of deterioration or failure, or will result in different failure mechanisms in the equipment?	1	1
	Section Totals	7	7
2.3	SCADA / Communications		
	Describe the SCADA / Communications systems that are in place (select one response only):		
	a. Level 1. No SCADA system exists, or is not used in a manner that promotes human error reduction.	0	
	b. Level 2. Some critical activities are monitored; field actions are informally coordinated through a control room; system is at least 80% operational.	1	
	c. Level 3. Most critical activities are monitored; field actions are usually coordinated through a control room; system up-time exceeds 95%.	2	
	d. Level 4. All critical activities are monitored; all field actions are coordinated through a control room; SCADA system reliability (measured in up-time) exceeds 99.9%.	3	3
	Section Totals	3	3
2.4	Drug Testing		
	Does a drug testing program exist that applies to employees who play substantial roles in pipeline operations?	1	1
	Does the testing program incorporate elements of random testing, testing for cause, pre-employment testing, post-accident testing, and return-to-work testing?	1	1
	Section Totals	2	2
2.5	Safety Programs		
	Does the company's safety program incorporate the following elements? (award partial marks for compliance with only a portion of the elements):	2	2
	Written company statement of safety philosophy		

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
	Safety program designed with high level of employee participation		
	Strong safety performance record		
	Good attention to housekeeping		
	Signs, slogans, etc. to show an environment tuned to safety		
	Full-time safety personnel		
	Section Totals	**2**	**2**
2.6	Surveys, Maps, Records		
	Are surveys such as those listed below conducted on a regular basis? (award partial marks for compliance with only a portion of the elements):	3	3
	Close interval pipe-soil surveys		
	Coating condition surveys		
	Water crossing surveys		
	In Line Inspection (ILI) assessments		
	Population density surveys		
	Depth of cover surveys		
	Leak detection surveys		
	Patrols (aerial or ground-based)		
	Are detailed, clear maps and records updated regularly, and are they available to all operations staff?	2	2
	Section Totals	***5***	***5***
2.7	Training		
	Evaluate the operator training program in terms of the following elements:		
	a. Minimum training requirements are documented	2	2
	b. Incorporates testing	2	2
	c. Covers the following:		
	i. Product characteristics	0.5	0.5

Table 4-9 Operations Questionnaire

Question #	Question	Possible Score	Actual Score
	ii. Pipeline material stresses	0.5	0.5
	iii. Pipeline corrosion	0.5	0.5
	iv. Control and operations	0.5	0.5
	v. Maintenance	0.5	0.5
	vi. Emergency drills	0.5	0.5
	d. Training is job-procedure specific	2	2
	e. Incorporates requirements for scheduled re-training	1	1
	Section Totals	***10***	***10***
2.8	Mechanical Error Preventers		
	Evaluate the availability and effectiveness of the following devices designed to prevent operator error:		
	a. Lock-out devices. Installed on safety-critical valves (e.g., during blow-down and repair)	2	2
	b. Key-lock Sequence Programs. If a job procedure calls for several operations to be performed in a certain sequence, and deviations from that prescribed sequence may cause serious problems, a key-lock sequence program may be employed to prevent any action from being taken prematurely.	2	2
	c. Computer permissives. Electronic equivalent to key-lock sequence programs.	2	2
	d. Highlighting of critical instruments. e.g., painting critical valves with specific colors.	1	1
	Section Totals	***7***	***7***
Total Points		**73**	**65**

4.1.5.9 Geotechnical / Hydrotechnical Forces

This threat category is associated with outside forces associated with geophysical factors that can act on a pipeline. These outside forces can be caused by earth movement, erosion / water impingement, rock fall, flooding, etc. The primary means of preventing outside forces associated with these factors is to identify and avoid the area of potential geotechnical or Hydrotechnical activity.

The assessment of geotechnical and hydrotechnical threats involved a separate detailed study in which all information relevant to each site was integrated and evaluated. The report describing the process and findings is summarized in Attachment A.

4.1.5.10 Other Threats

During the Threat Assessment Workshop, an open discussion was held to identify potential threat mechanisms that do not fall into one of the nine categories listed in Section 4.1.4. A wide variety of operating threats were discussed, including forest fires, concomitant failures, access restrictions, and exposure to vandalism.

A summary of the threat assessment for other defects as it relates to the L3RP is provided in Table 4-10 (note that the Threat Attributes identified in this Table are those factors that influence both the causal and mitigation factors within the threat environment).

Table 4-10 Other Threats Threat Attribute Summary

<table>
<tr><th>Threat Attribute</th><th>Data Evaluation</th><th>Discussion of Threat Potential</th></tr>
<tr><td>Concomitant Failures</td><td>Concomitant failures occur where the catastrophic failure of one pipe (typically a natural gas pipe, in which rapid decompression of a compressible fluid results in the formation of a large blast crater, and in which the ensuing release of natural gas is readily ignitable), can result in the uncovering of an adjacent pipe, which may become involved in an ensuing fire.

Design considerations to address the potential for concomitant failure are addressed in Clause 4.11.6 of CSA Z662-11, which references criteria outlined in IGEM/TD/1. This Standard provides safe separation distance to existing gas pipelines as a function of diameter and soil conditions. The maximum safe separation distance published by this standard is associated with 48-inch diameter gas pipelines operating at pressures up to 1160 psi, and is listed as 12 m (39.4 ft).</td><td>A review of spacing between existing pipeline infrastructure (if any) was conducted at each site, and is summarized below:
<table>
<tr><th>Site No.</th><th>Adjacent Pipeline Considerations</th></tr>
<tr><td>1</td><td>Existing Minnesota Pipe Line Company oil pipelines with minimum 25 ft separation to L3R. Concomitant failure not considered to be a threat.</td></tr>
<tr><td>2</td><td>Great Lakes gas pipelines in vicinity will have minimum separation distance of 50 ft This meets the safe separation requirements of IGEM/TD/1. Existing Enbridge oil pipelines (6 in total) with minimum separation distance of 25 ft Concomitant failure not considered to be a threat.</td></tr>
<tr><td>3</td><td>No adjacent parallel pipelines.</td></tr>
<tr><td>4</td><td>No adjacent parallel pipelines.</td></tr>
<tr><td>5</td><td>7 separate LVP liquids pipelines with minimum separation distance of 25 ft Concomitant failure not considered to be a threat.</td></tr>
<tr><td>6</td><td>No adjacent parallel pipelines.</td></tr>
<tr><td>7</td><td>Parallel Viking gas pipeline will have minimum separation distance of 50 ft This meets the safe separation requirements of IGEM/TD/1.</td></tr>
</table></td></tr>
<tr><td>Access</td><td>Presence of segments where accessibility constraints</td><td>None such access restrictions were identified.</td></tr>
</table>

Table 4-10 Other Threats Threat Attribute Summary

Threat Attribute	Data Evaluation	Discussion of Threat Potential
Restrictions	(whether due to landowner relations or physical) are such that they act as a barrier to regular pipeline maintenance activities, such as corrosion surveys, defect excavations, etc.	
Forest fires	With respect to forest fires, experience dictates that where a pipe is buried in a cleared ROW, forest fires do not constitute a significant loss-of-containment hazard in and of themselves, since the ROW acts as a fire break, and the ground cover acts to insulate the pipe.	Industry experience indicates that forest fires are not a threat for buried pipelines. There are no above-ground sections of pipeline on L3RP, except in the immediate vicinity of pump stations and valves.
Exposure to Vandalism	Exposure to vandalism is greatest at above-ground facilities, where measures such as fenced compounds and locks are installed.	There are no above-ground sections of pipeline within the scope of work.

4.1.6 Threat Potential Summary

In this Section, a summary of threat potential is provided based on a review and analysis of the information contained in Section 4.1.5. Additionally, based on the available data for each threat, this Section provides overviews of appropriate approaches for estimating failure likelihood. A detailed description of the failure frequency estimation approach for each threat is provided in Section 4.2.

Where appropriate, assumptions that will be incorporated into the quantitative failure analysis are identified for each threat.

4.1.6.1 External Metal Loss

4.1.6.1.1 Threat Potential

It is expected that the pipeline will have some degree of exposure to the threat of external corrosion. Therefore, the threat potential for external corrosion was included in the quantitative failure frequency estimate.

4.1.6.1.2 Approach

As will be discussed in greater detail in Section 4.2.3.1, reliability approaches for providing quantitative estimates of failure likelihood exist for some threats, including corrosion. Reliability approaches have the benefit of accounting for design and material performance characteristics. In addition, for time-dependent threats such as corrosion, they accurately reflect that failure likelihood changes with time.

For the external metal loss threat, a reliability approach was used that leverages existing "analogue" ILI datasets, along with the specific design details (diameter, wall thickness, grade, operating pressure) of the L3RP at each site of interest. With this approach, it is important to confirm that the analogue datasets are representative (or slightly conservative) relative to the expected external corrosion performance of the proposed pipeline segments. In this way, the reliability parameters from the analogue ILI datasets for external corrosion feature incident rate, external corrosion feature size distribution, and external corrosion growth rate will be representative, or conservative relative the same parameters for the L3RP. To ensure that this is the case, the considerations outlined in Table 4-11 were incorporated into the assessment.

Table 4-11 Considerations for Quantitative Failure Likelihood Estimates—External Corrosion

Threat Factor	Issue	Controls	Action
Mainline Coating Type	The mainline external coating system used in the pipeline from which the analogue ILI data are taken should be representative or conservative, relative to the expected corrosion coating performance on the L3RP.	Analogue ILI datasets that are representative of FBE coating systems will address this issue.	To be addressed during selection of analogue ILI dataset
Field Joint Coating	The field joint external coating system used in the pipeline from which the analogue ILI data are taken should be representative or conservative, relative to the expected corrosion coating performance on the L3RP.	Analogue ILI datasets that are representative of high performance field joint coating systems will address this issue.	To be addressed during selection of analogue ILI dataset
Temperature effects on external coatings	Operating temperatures that exceed the maximum temperature rating of the mainline and field joint coating systems can result in significantly degraded coating performance over time	Coating systems are being specified for mainline and field girth welds are rated to withstand the expected maximum operating temperatures of the L3RP	Addressed by purchase specifications and detailed design
		Analogue ILI datasets must be selected so that they are representative of pipelines that have not been operated above the maximum temperature rating of either the mainline or field girth weld coating systems.	To be addressed during selection of analogue ILI dataset
Cathodic Protection	Ensure that CP performance in pipeline from which analogue ILI dataset is obtained is representative of CP performance expected on the L3RP.	Design measures for L3RP incorporate identification of potential sources of interference, and incorporation of appropriate mitigations	Addressed by L3RP detailed design, and in operating procedures.
		Analogue ILI datasets must be selected so that they are representative of CP design and operating practices for L3RP.	To be addressed during selection of analogue ILI dataset

Table 4-11 Considerations for Quantitative Failure Likelihood Estimates—External Corrosion

Threat Factor	Issue	Controls	Action
Soil Characteristics	Ensure that soil characteristics in pipeline from which analogue ILI dataset is obtained is representative of soil characteristics on the L3RP.	Identify any locations of highly corrosive ground conditions on L3RP, such as acid-generating rock. If present, ensure that analogue ILI dataset is representative of similar conditions.	Undertaken during threat assessment – no such highly corrosive ground conditions identified.
ILI Data	Potential for manufacturing defects to be misinterpreted as corrosion defects, leading to unrealistically high corrosion feature incidence rates and aggressive apparent growth rate distributions	Utilize a dataset from a pipeline that is old enough to mask the effects of manufacturing defects.	To be addressed during selection of analogue ILI dataset

4.1.6.2 Internal Metal Loss

4.1.6.2.1 Threat Potential

The corrosivity analysis contained in Section 4.1.5.2 indicated that the product stream in conjunction with the operating and flow characteristics should render the pipe wall in an oil-wet (i.e., non-corrosive) condition, although ongoing monitoring with a view to implementing appropriate mitigation strategies is warranted. While the threat of internal corrosion is not anticipated to be a significant contributor to overall failure likelihood for the L3RP, it is not possible to disqualify this threat entirely.

4.1.6.2.2 Approach

As will be discussed in greater detail in Section 4.2.3.1, reliability approaches for providing quantitative estimates of failure likelihood exist for some threats, including corrosion. Reliability approaches have the benefit of accounting for design and material performance characteristics. In addition, for time-dependent threats such as corrosion, they accurately reflect that failure likelihood changes with time.

For the internal metal loss threat, a reliability approach was used that leverages existing "analogue" ILI datasets along with the specific design details (diameter, wall thickness, grade, operating pressure) of the L3RP at each site of interest. Under such an approach it is important to confirm that the analogue datasets are representative (or slightly conservative) relative to the expected internal corrosion performance of the proposed pipeline segments. In this way, the reliability parameters from the analogue ILI datasets for internal corrosion feature incident rate, internal corrosion feature size distribution, and internal corrosion growth rate will be representative, or conservative relative the same parameters for the L3RP. To ensure that this is the case, the considerations outlined in Table 4-12 were incorporated into the assessment.

Table 4-12 Considerations for Quantitative Failure Likelihood Estimates—Internal Corrosion

Threat Factor	Issue	Controls	Action
Water Content	Elevated water content can result in stratification in some flow regimes, and may result in enhanced corrosivity	• Control BS&W to 0.5% max, reflecting standards for transmission pipelines. • Maintain turbulent flow to entrain what little water that exists in the product stream flow, causing pipe wall to remain in oil-wet condition.	• 0.5% BS&W reflects current tariff specifications. • Hydraulic design of L3RP ensures turbulent flow. • Flow rates will be monitored to ensure turbulent flow, and to ensure that no sediment or water drop-out occurs
		Ensure that BS&W and hydraulic flow regime in pipeline from which analogue ILI dataset is obtained is representative of conditions in L3RP.	To be addressed during selection of analogue ILI dataset
Deposit of Solids	Solid deposition can result in under-deposit corrosion	• Control BS&W to 0.5% max, reflecting standards for transmission pipelines. • Maintain turbulent flow to entrain what little solids that exists in the product stream, and to prevent deposition of solids	• 0.5% BS&W reflects current tariff specifications. • Hydraulic design of L3RP ensures turbulent flow. • Flow rates will be monitored to ensure turbulent flow, and to ensure that no sediment or water drop-out occurs
		Ensure that BS&W and hydraulic flow regime in pipeline from which analogue ILI dataset is obtained is representative of conditions in L3RP.	To be addressed during selection of analogue ILI dataset
Corrosion Monitoring	Regardless of interpreted susceptibility to corrosion based on product composition and flow characteristics, monitoring is required to ensure that the pipeline remains in a condition that is not susceptible to internal corrosion.	Corrosion detection devices	• The use of internal coupons and in-line inspection will be employed to monitor for internal corrosion. • Flow rates will be monitored to ensure turbulent flow, and to ensure that no sediment or water drop-out occurs
ILI Data	Potential for manufacturing defects	Utilize a dataset from a pipeline that is old	To be addressed during selection of

Table 4-12 Considerations for Quantitative Failure Likelihood Estimates—Internal Corrosion

Threat Factor	Issue	Controls	Action
	to be misinterpreted as corrosion defects, leading to unrealistically high corrosion feature incidence rates and aggressive apparent growth rate distributions	enough to mask the effects of manufacturing defects.	analogue ILI dataset

4.1.6.3 Stress Corrosion Cracking

4.1.6.3.1 Threat Potential

Based on industry experience, susceptibility to SCC has been associated with coatings other than the following:

- FBE
- Urethane and liquid epoxy
- Extruded polyethylene
- Multi-layer or composite coatings

The threat potential for SCC is anticipated to be negligible (i.e., this threat will not contribute in a substantial way to overall failure likelihood), since the coating systems used on the L3RP are limited to those listed above.

4.1.6.4 Manufacturing Defects

4.1.6.4.1 Threat Potential

Enbridge's pipe procurement program specifies rigorous controls to confirm the quality of line pipe to be supplied to the L3RP Project. Although line pipe for LVP pipelines is not required to have proven notch toughness, pipe with minimum notch toughness values of 29.5 ft-lbs (40 J) will be used. Additional controls will be implemented that include supplier pre-qualification practices that focus on technical and quality criteria, as well as third party pipe mill quality surveillance. While the threat of manufacturing defects is not anticipated to be a significant contributor to overall failure likelihood for the L3RP, it is not possible to disqualify this threat entirely.

4.1.6.4.2 Approach

The threat of manufacturing defects does not lend itself to failure likelihood estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters (Section 4.2.3). Despite the fact that this threat is not anticipated to contribute significantly to overall failure likelihood, an attempt will be made to achieve an estimate of failure frequency based on industry operating experience of recent installations of hazardous liquids pipelines.

4.1.6.5 Construction Defects

4.1.6.5.1 Threat Potential

Enbridge's construction practices that will be used in the construction of the L3RP Project specifies rigorous controls to confirm the quality of the pipeline installation, including welding processes. In addition, quality checks will be employed, including 100% NDT using phased array ultrasonics and/or X-ray inspection, as well as 100% inspection with a pipe size and deformation tool after installation to confirm that the pipeline is free of dents, buckles, and excessive out-of-round conditions. The use of a mechanized low hydrogen welding process, in which procedural variables are tightly controlled, is an effective means of maintaining weld quality and procedural control.

While the threat of construction defects is not anticipated to be a significant contributor to overall risk for the L3RP, it is not possible to disqualify this threat entirely.

4.1.6.5.2 Approach

The threat of construction defects does not lend itself to failure likelihood estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters (Section 4.2.3). Despite the fact that this threat is not anticipated to contribute significantly to overall failure likelihood, an attempt will be made to achieve an estimate of failure frequency based on industry operating experience of recent installations of hazardous liquids pipelines.

4.1.6.6 Equipment Failure

As the pipeline segments associated with each of the seven modeling locations do not include non-pipe equipment, this threat was determined to be out of scope for this assessment.

4.1.6.7 Third Party Damage

4.1.6.7.1 Threat Potential

All pipelines experience some level of threat due to third party damage, the magnitude of this threat being a function of the effectiveness of damage prevention measures, adjacent land use, depth of cover, material properties, and pipeline design. Although damage prevention measures can help to offset this threat, third party damage can never be fully neutralized, and so this is expected to be one of the primary threats in contributing to overall pipeline failure likelihood.

4.1.6.7.2 Approach

A reliability model exists that considers all the parameters of damage prevention measures, adjacent land use, depth of cover, material properties and pipeline design; this model will be used in the failure frequency analysis (Section 4.2) (Chen and Nessim 1999). The reliability approach employs a fault tree model to estimate hit frequency, and a separate stochastic model to predict probability of failure, given a hit.

4.1.6.8 Incorrect Operations

4.1.6.8.1 Threat Potential

All pipelines experience some level of threat due to incorrect operations, the magnitude of this threat being a function of the effectiveness of design-related and operations/maintenance related practices and measures. Although design, operations and maintenance practices can help to offset this threat, incorrect operations can never be fully neutralized, and so this is expected to be one of the primary threats in contributing to overall failure likelihood.

4.1.6.8.2 Approach

The threat of incorrect operations does not lend itself to failure likelihood estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters (Section 4.2.3). Reflecting this fact, an attempt will be made to achieve an estimate of failure frequency based on operating incident data, related to this threat, modified by the results of the Operations Questionnaire that was administered during the Threat Assessment Workshop (Table 4-9).

4.1.6.9 Geotechnical / Hydrotechnical Forces

To assess the degree of threat that a pipeline will be exposed to, a thorough evaluation of information related to the potential for geotechnical and hydrotechnical threats was undertaken at each of the seven modeling locations within the scope of work. A description of the threat potential and the approach by which estimates of failure likelihood were derived is provided in Attachment A.

4.1.6.10 Other Threats

During the Threat Assessment Workshop, an open discussion was held to identify potential threat mechanisms that do not fall into one of the nine categories listed above. The following potential threats were reviewed:

- Potential for concomitant failure associated with adjacent pipelines
- Access restrictions
- Forest fires
- Exposure to vandalism

As discussed in Section 4.1.5.10, none of the "Other Threats" were found to represent significant potential for failure.

4.2 QUANTITATIVE FREQUENCY ANALYSIS

4.2.1 Overview and Summary

To be consistent with the assessment of full bore ruptures in the consequence analysis, the frequency analysis focused on the occurrence of ruptures (as opposed to smaller leaks). Based on the guidance provided in the Threat Assessment, the frequency analysis undertook to estimate rupture frequency using optimal approaches for each threat. These approaches included:

- Methods based on Industry Incident Data—PHMSA Hazardous Liquids Database, 2010–2015 (threats assessed using this method included manufacturing defects, construction defects and incorrect operations)
- Methods based on mechanistic, reliability approaches (external corrosion, internal corrosion, and third party damage)

- Site-specific evaluation of hydrotechnical and geotechnical hazards (weather related and outside forces)

The annual probability of a large oil release (i.e., a full bore rupture) was determined for each of the seven modeling locations for L3RP. The length of the pipeline segment that was considered in the failure frequency analysis for each modeling site was established through outflow and overland spill modeling of full-bore rupture release scenarios for the modeling site. Specifically, the failure frequency analysis for the site considered the length of pipeline around the site of the hypothetical full bore rupture from which a crude oil release could affect (i.e., reach) the immediately adjacent waterbody through direct release or overland flow.

The annual probability values, as well as the average annual return periods (defined as the inverse of the annual probability values) at each modeling site are summarized in Table 4-13.

Table 4-13 Annual Probability of Rupture and Average Return Period within the Potential Impact Segment of Each of the Seven Modeling locations

Site Number	Annual Probability of Rupture	Average Return Period (yr)
1—Mosquito Creek	3.402×10^{-06}	293,945
2—Mississippi River at Ball Club	3.961×10^{-07}	2,524,615
3—Sandy River	1.939×10^{-06}	515,730
4—Shell River	4.388×10^{-06}	227,894
5—Red River	2.781×10^{-06}	359,583
6—Mississippi River at Palisades	2.527×10^{-06}	395,726
7—Mississippi River at Little Falls	2.287×10^{-06}	437,254

Of note, for linear infrastructure, such as pipelines, the probability of incurring a failure is proportional to segment length (i.e., the longer the segment that is being considered, the greater is the likelihood of incurring a failure at some point along that segment). This is reflected in the above results, with the longest potential impact segment (the 2,543 ft-long segment associated with the Shell River crossing), having the greatest probability of failure.

The likelihood of a large oil release occurring ranges from 3.96×10^{-07} to 4.39×10^{-06}; this is equivalent to average annual return periods that range from 227,894–2,524,615 years.

4.2.2 Introduction

This Section describes the approach and the results of a quantitative failure frequency assessment at seven modeling locations along the L3RP pipeline:

- Site 1—Mosquito Creek Crossing
- Site 2—Crossing of the Mississippi River at Ball Club

- Site 3—Sandy River Crossing
- Site 4—Shell River Crossing
- Site 5—Red River Crossing
- Site 6—Crossing of the Mississippi River at Palisades
- Site 7—Crossing of the Mississippi River at Little Falls

As described in the Threat Assessment (Section 4.1), seven threats were identified, and are addressed by the quantitative failure frequency analysis contained in this Section:

- External corrosion
- Internal corrosion
- Third party damage
- Manufacturing defects
- Construction defects
- Incorrect operations
- Geotechnical / hydrological forces

In the remainder of this chapter, the approach used to complete the failure frequency analysis is first described. Results of the failure frequency analysis are then described.

4.2.3 Failure Frequency Approach

For the purposes of the failure frequency analysis described here, the term "failure" refers to loss-of-containment of the L3RP pipeline. To be consistent with the assessment of full bore ruptures in the consequence analysis, the frequency analysis focused on the occurrence of ruptures (as opposed to smaller leaks).

In the following section of this chapter, quantitative estimates of annual failure probability for a full bore rupture were determined on a threat-by-threat basis. As was discussed in the Threat Assessment (Section 4.1), the most appropriate method for estimating failure frequency was identified for each threat, taking into account the type and availability of data, and the methods available that are applicable to failure estimation for each threat.

4.2.3.1 Quantitative Approach for Estimating Failure Frequency

As outlined below, there are a variety of approaches for making quantitative estimates of pipeline failure likelihood. One method is to use industry incident statistics as the basis for the making the estimate. Another method is to estimate failure likelihood based on a first-principles approach, known as "reliability methods". A third method, specific to the estimation of failure frequency related to geohazards, employs an approach that expresses the frequency of loss of containment as the product of the potential for the geohazard to occur, the frequency of occurrence, the unmitigated system vulnerability, and the effects of the mitigations used in the segment.

One of the challenges of making quantitative estimates of failure likelihood on a new pipeline using industry incident statistics is that without careful selection and filtering of data, industry failure statistics are not directly applicable to modern pipeline designs, materials, and operating practices. As a result, industry failure statistics tend to over-state failure frequencies associated with new pipelines.

A review of industry failure statistics suggests that the majority of pipeline failures occur on pipelines that were installed in the 1970s or earlier (Mihell and Rout 2012). These pipelines were developed prior to the advent of several technologies that have enhanced pipeline reliability, such as:

- Continuous casting of steel slabs
- Thermomechanical controlled processing (TMCP) technology for skelp production (i.e., steel that is rolled or forged into narrow strips and ready to be made into pipe by being bent into a cylindrical shape and welded)
- HSLA steel design
- Low sulfur steels
- Inclusion shape control
- High toughness steels
- Implementation of quality systems and the use of highly constrained process control variables during pipe manufacture
- Highly-constrained mechanized welding processes using low-hydrogen welding processes
- Use of only non-destructive inspection methods
- High performance coating systems such as fusion bonded epoxy coatings
- Design-phase identification of internal corrosion threat factors and design of mitigation plans through internal corrosion modeling
- Identification of HVAC interference effects and development of mitigation plans through diagnostic testing of cathodic protection systems
- Implementation of quality management systems during design, construction and operations

Another challenge associated with the use of industry failure databases as the basis of a quantitative failure frequency assessment is that they do not address site-specific threats for a pipeline segment, such as geotechnical hazards.

Reliability methods have been widely adopted in the nuclear and aerospace industry, where they are used to identify and manage threats. In recent years, the pipeline industry has moved towards adopting this as a tool for risk studies. Pipeline industry research organizations such as the Pipeline Research Committee International (PRCI) and European Pipeline Research Group (EPRG) have developed reliability-based models for various threats. Reliability models employ limit state functions for the specific damage mechanism of interest in which the load variables and resistance variables are characterized in terms of probability density functions. This enables us to use reliability modeling techniques such as Monte Carlo Analysis to characterize the probability of incurring a failure on a pipeline. Reliability methods provide a powerful tool to make accurate, quantitative predictions on likelihood of failure over the expected lifespan of a pipeline.

Figure 4-8 illustrates how reliability methods can be utilized to quantify the probability of failure, based on a defendable approach.

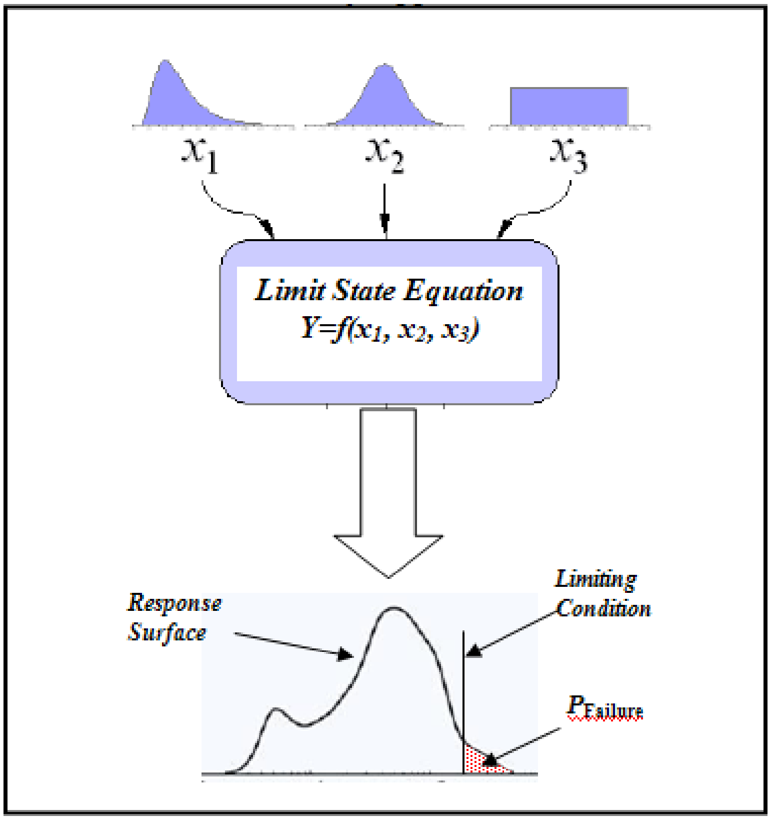

Figure 4-8 Reliability Approach

In the pipeline industry, reliability models exist for the most significant threats, including third party damage, internal corrosion and external corrosion.

The basis of every reliability model is a limit state equation that describes the failure conditions for the mechanism being considered. Furthermore, at least one of the input variables to this limit state equation must be characterized as a probability density function, as illustrated in Figure 4-8.

Therefore, a reliability approach is not possible for some threats, such as incorrect operations, where these probability density functions are not available. For these threats (which usually constitute second-order threats, in terms of failure likelihood magnitude), an alternative is to employ industry failure statistics, incorporating techniques such as the careful selection and filtering of incident data and/or means of accounting for differences in materials, design and operations that are characteristic of modern pipelines. For geotechnical threats, the likelihood of failure can be characterized in terms of expected magnitude and associated frequency of occurrence, thereby enabling pipeline reliability to be established at each geotechnically-active site.

The approach used in estimating failure frequency for each threat is described in the remainder of this section.

4.2.3.2 External Corrosion

The reliability approach for external corrosion employs the application of an analogue ILI dataset, taking into account the design and materials for the L3RP (Mihell and Rout 2012).

As the wall thickness of the pipe segments vary between the seven modeling locations, a separate analysis was conducted for each wall thickness (in all cases, the pipe grade was X70) (Table 4-14). To provide a conservative assessment, the highest maximum operating pressure of any of the seven modeling locations for the L3RP was used in the analysis. The combinations of diameter, wall thickness, grade and maximum operating pressure that were used in the analysis are summarized in Table 4-14.

Table 4-14 Design Parameters Employed in Analysis

Diameter (in.)	Wall Thickness (in.)	MOP (psi)	Segments Represented
36	0.750	734.7	Sites 2,3,4,5,6,7
36	0.515	734.7	Site 1

4.2.3.2.1 Selection of Analogue ILI Data

Based on Mihell and Rout (2012), to estimate defect incidence rate, defect size distribution, and defect growth rate distribution, it is important that the analogue ILI dataset is representative of the degradation process and performance characteristics of the coating system to be used in with the L3RP.

After a review of candidate ILI datasets, the external wall loss feature list of interacted features (6t x 6t interaction rule) from the 2010 in-line inspection of Enbridge's Line 4 (BU-QU) was chosen.

As outlined in Mihell and Rout (2012), to reduce over-conservativism in the analysis, candidate ILI datasets were reviewed to remove wall loss data that cannot be attributed to active corrosion (e.g., benign manufacturing features). One effective method that can be used to screen for active wall loss is to use data derived from pit-matching for the same pipeline of separate in-line inspections. However, because pit-matched data was not available, and as described in Section 4.2.3.2.2, a conservative approach to determining corrosion growth rate was used.

Beyond the quality of ILI data, several other factors were considered in selecting the Line 4 dataset:

- Coating type (FBE in both Line 4 and in the proposed L3RP pipelines)
- Coating specification (i.e., the same Enbridge coating specification will apply to both Line 4 and the proposed L3RP pipelines)
- Operating environment (Western Plains are common to Line 4 and L3RP pipelines)
- Cathodic protection and other operating standards (i.e., the same Enbridge standards apply to Line 4 and L3RP pipelines)

Another important consideration was that the Line 4 data set represents fusion bond epoxy coated pipeline segments that were 11 years old at the time of inspection, having been installed in 1999, thereby enabling sufficient time for evidence of corrosion susceptibility to manifest itself on the ILI logs.

4.2.3.2.2 Reliability Approach

The reliability approach described in Mihell and Rout (2012) was used to estimate failure frequency as a function of pipeline age.

A Monte Carlo approach was developed to assimilate distributions derived from size and growth rate distributions derived from the analogue ILI dataset, and apply those distributions against the modified ASME B31G failure limit state criterion, which, for the purposes of the analysis, was rearranged to determine flaw depth at failure:

Equation 1

$$d_f = \mathrm{MIN}\left[(0.8t), \left(\frac{t(\sigma_{op} - \bar{\sigma})}{0.85\left(\frac{\sigma_{op}}{M} - \bar{\sigma}\right)}\right)\right]$$

Where,

d_f = Depth at failure
t = Wall thickness
σ_{op} = Operating stress
$\bar{\sigma}$ = Flow stress
$M = \sqrt{1 + 0.6257\frac{L^2}{Dt} - 0.003375\left(\frac{L^2}{Dt}\right)^2}$
(for $L \leq \sqrt{50Dt}$)
$M = 3.3 + 0.032\frac{L^2}{Dt}$
(for $L > \sqrt{50Dt}$)
L = Defect length

In the Monte Carlo analysis, the variables of pipe diameter, pipe wall thickness, yield strength, and operating pressure specific to each of the pipeline design combinations (Table 4-14) were used and a separate reliability analysis was completed for each combination of variables. Corrosion feature incidence rates and the distribution parameters for corrosion feature length and depth were determined from the analogue ILI data, as were corrosion feature growth rates.

When using ILI data for the purposes of establishing these parameters, it is important to recognize that the quantities derived represent values at a particular point in time (i.e., the date of last inspection). Furthermore, these quantities are subject to tool measurement error. Corrosion feature depth is therefore considered characteristic of the depth after some period of time. When applied to a new pipeline, the depth distribution must be adjusted downwards (accounting for some assumed corrosion growth rate) when the modeled pipeline age is less than that from which the analogue ILI data was obtained. Similarly, the depth distribution must be adjusted upwards when the modeled pipeline age is greater than that from which the analogue ILI data was obtained. This is illustrated in Figure 4-9, which shows how the flaw distribution flattens and translates with time (t). Specifically, as time increases, the mean of the flaw depth distribution and the standard deviation of the flaw depth distribution increase.

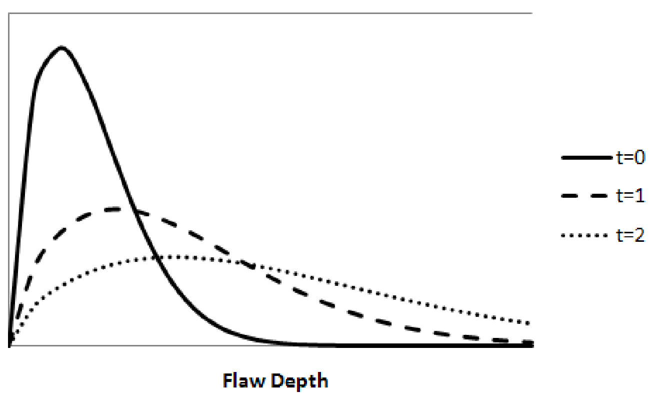

Figure 4-9 Illustration of How Flaw Depth Distribution Changes With Time

In the absence of any other information pertaining to how flaw depth growth rate varies with time, a linear growth rate assumption can generally be considered a reasonable, yet conservative approximation, since it ignores the polarizing effects of the accumulation of corrosion product.

The high-performance coating systems that are characteristic of modern pipelines, such as fusion bond epoxy are not susceptible to time-dependent coating degradation to the extent that older vintage coating systems are. Therefore, it was considered realistic to assume that any coating damage that is inferred from the presence of a corrosion feature was created at the time of installation, and that the areal extent of coating damage, and hence the potential for increases in wall loss area (i.e., length and width) does not change appreciably with time.

In the Monte Carlo simulation, corrosion feature depth, as a function of time, and feature length are sampled stochastically, based on the probability density functions for those parameters derived from the analogue ILI dataset. A further stochastic adjustment on flaw depth is made to account for the tool error associated with the ILI tool from which the analogue data was derived. Because correlations derived from <Tool-Predicted> to <In-Ditch Measurement> data pairs were not available for the analogue dataset, a standard tool measurement error of ±10% wall thickness, 80% of the time was used. In statistical terms, this corresponds to a normal error distribution having a mean of 0, and a standard deviation of 7.8% of the wall thickness.

Assuming a linear flaw depth growth model, the stochastically-sampled flaw depth estimate was adjusted to account for the difference between the age of the analogue pipeline at the time that the ILI data was acquired, and the modeled age of the new pipeline:

Equation 2

$$\overset{o}{d}_A = \frac{\overset{o}{d} \cdot T_A}{T_{ILI}}$$

Where,

$\overset{0}{d}_A$ = Stochastically sampled flaw depth at the specific time assumed in the analysis
$\overset{0}{d}$ = Stochastically sampled flaw depth, derived from the analogue ILI dataset (incorporating stochastic adjustment for analogue ILI tool error)
T_A = Year of operation for the pipeline that is being assumed in the analysis
T_{ILI} = Year of operation for the analogue pipeline when the ILI assessment was completed.

For the purposes of the Monte Carlo simulation, all pipe parameters that are contained in the limit state function shown in Equation 1 (i.e., pipe wall thickness, operating stress level, and flow stress) correspond to each of combination of pipeline design variables reported in Table 4-14.

Failure is predicted when the stochastically sampled flaw depth derived from Equation 2 exceeds the flaw depth that defines the limiting condition (derived from Equation 1). When the Monte Carlo simulation is performed through multiple iterations, the probability of failure for the given year of analysis is defined as the proportion of those iterations that return a failure prediction. This probability is defined as the probability of failure, given the presence of a corrosion feature, $P_{f,F}$. The overall probability of failure for a given pipeline segment in the year of operation being considered in the analysis is defined as:

Equation 3

$$P_{f,DS} = \rho_{ILI} \cdot \frac{D_N}{D_{ILI}} \cdot L_{DS} \cdot P_{f,F}$$

Where:

$P_{f,DS}$ = Probability of failure for the pipeline segment

ρ_{ILI} = Corrosion feature density per unit length of pipeline derived from the analogue ILI dataset

D_N = Diameter of the pipeline

D_{ILI} = Diameter of the pipeline from which the analogue ILI data was derived

L_{DS} = Length of the pipeline segment

$P_{f,F}$ = Probability of failure, given the presence of a corrosion feature.

4.2.3.2.3 Determination of Leak and Rupture

To support a risk analysis, the output from the failure frequency analysis must be relevant to the fates and effects analysis (Chapters 6.0 and 7.0). Therefore, the results of a failure frequency analysis must specify more than frequency of occurrence; instead, the frequencies of occurrence must be tied to an outcome, with the outcome being the volume of the crude oil release. As discussed in Chapter 3.0, a release volume corresponding to a most-credible worst-case scenario, involving a rupture was determined for each of the seven modeling locations.

In the reliability analysis for external corrosion failure likelihood, the proportion of ruptures are determined by first calculating the critical through-wall flaw size as a function of material properties and operating parameters of the pipeline segment. The NG-18 flaw equation was used to determine the critical through-wall flaw size (Eiber and Leis 2001):

Equation 4

$$K_c^{\,2} = \frac{12 \cdot C_v \cdot E}{A_c} = \frac{8 \cdot c \cdot \bar{\sigma}^2}{\pi} \ln \sec\left[\frac{\pi \cdot M_T \cdot \sigma_h}{2 \cdot \bar{\sigma}}\right]$$

The above relationship is commonly used to determine the maximum size defect that will leak rather than rupture. At high fracture toughness values, it represents a flow-stress or plastic instability criterion (typical of the failure mode of most corrosion features), whereas at lower fracture toughness values, it may represent a conservative representation of the leak/rupture boundary for corrosion features.

As illustrated in Figure 4-10, the cumulative distribution function for flaw length, derived from the analogue ILI dataset was compared against the critical through-wall flaw length for each set of pipeline design variables modeled. Using this approach, the proportion of features that have the potential to penetrate through-wall at a length greater than the critical through-wall flaw length can conservatively be said to have the potential to fail in rupture mode, while the remainder of the flaws will fail as leaks.

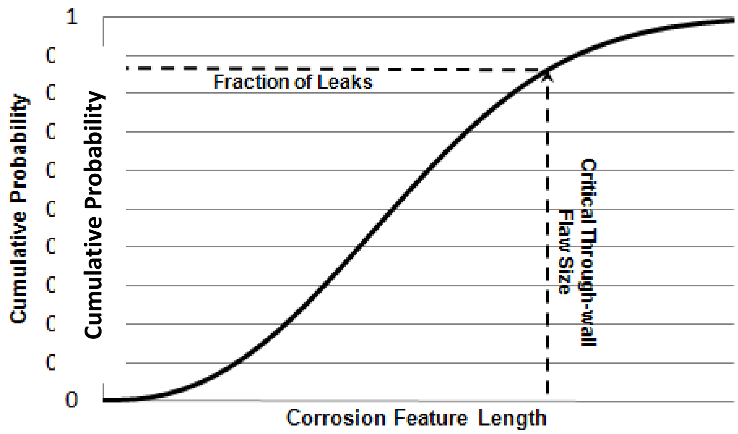

Figure 4-10 Determination of Fraction of Leaks and Ruptures from Corrosion Feature Length CDF and Critical Through-Wall Flaw Size

Because critical through-wall flaw length is a function of wall thickness and operating pressure, the proportion of leaks was determined for each combination of pipeline design variables modeled, based on the feature length distribution obtained from the analogue ILI dataset.

4.2.3.2.4 Results—Unmitigated Analysis

By performing a separate analysis for each year of operation, and for each dynamic segment, an external corrosion reliability plot was generated for each year of operation for each wall thickness for the L3RP for the 7 modeling locations out to 20 years after installation. It is important to note that in the unmitigated analysis, each corrosion feature is allowed to grow throughout the full time period covered for the analysis. This represents a significantly conservative assumption, as in reality, several measures will be employed to mitigate corrosion, including:

- Regular cathodic protection surveys will be conducted, and any lows will be immediately remediated
- ILIs will be completed on a regular basis, and any features that exceed the acceptance criteria established in CFR 49 Part 195 will be excavated, examined, and repaired or re-coated
- In practice, even when left unmitigated, corrosion growth rates tend to decline with the passage of time due to the accumulation of corrosion products. This natural tendency for decreasing corrosion growth rates with time has been disregarded in the analysis.

Two sets of analyses were performed; one for 36-inch diameter, 0.515-inch wall thickness (Site 1), and one for 36-inch diameter, 0.750-inch wall thickness (Sites 2,3,4,5,6,7).

The reliability plot for the 0.515-inch wall thickness case is presented in Figure 4-11. As can be seen from this plot, the estimated rupture frequency is essentially zero (less than 10^{-40}) for at least the first 20 years of operation. No reliability plot has been provided for the 36-inch diameter, 0.750-inch wall thickness case, as finite (non-zero) values were not obtained through the 20 year analysis period. This reflects a lack of failure sensitivity of both of the L3RP design cases to the expected probability distributions that characterize corrosion feature initiation and growth over that 20 year period.

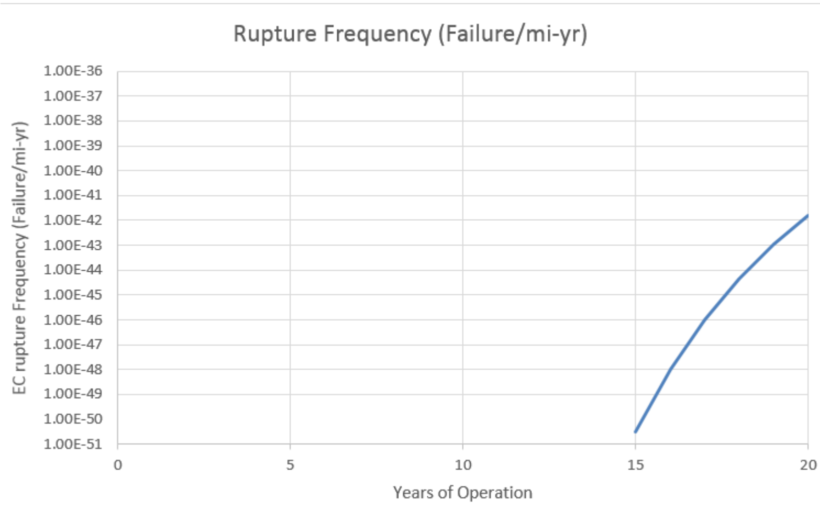

Figure 4-11 External Corrosion Reliability Plot: 36" L3RP 0.515" WT

4.2.3.2.5 Results—Consideration of Operations and Maintenance

The analysis of unmitigated external corrosion failure likelihood demonstrates the relative lack of sensitivity of external corrosion rupture frequency over time, relative to the planned five-year ILI reassessment interval. Specifically, the rupture frequency attributed to the threat of external corrosion is essentially zero for the first 20 years of operation for each of the L3RP design cases evaluated. This 20-year period reflects a time period during which 5 ILIs (including a baseline inspection) for wall loss are planned to occur. Given this lack of time-sensitivity to failure, relative to the planned ILI interval, it is reasonable to expect that any external corrosion features that may initiate will be detected and monitored for pre-emptive repair so that they can be mitigated before they can reach a critical size for failure. Given this circumstance, it is not possible to arrive at a finite value of expected failure frequency over the long term. Nevertheless, a failure frequency value of 10^{-08} ruptures/mi.yr (which the analysis shows to be conservative) will be assigned to this threat, and will be applied to all seven modeling locations.

4.2.3.3 Internal Corrosion

The reliability approach for internal corrosion is consistent with the approach described for external corrosion. However, in regard to the selection of candidate analogue ILI data, the considerations required to evaluate and compare the corrosion conditions for the L3RP with those of the candidate analogue datasets are different than those employed for an assessment of external corrosion.

4.2.3.3.1 Selection of Analogue ILI Data

One of the simplest methods to perform screening for internal corrosion is to view orientation charts for internal wall loss features. Where water drop-out and accumulation is an essential aspect of the internal corrosion mechanism that is associated with the product and flow characteristics being considered (as is the case here), wall loss that is associated with internal corrosion should be expected at the bottom of the pipe, as illustrated in Figure 4-12.

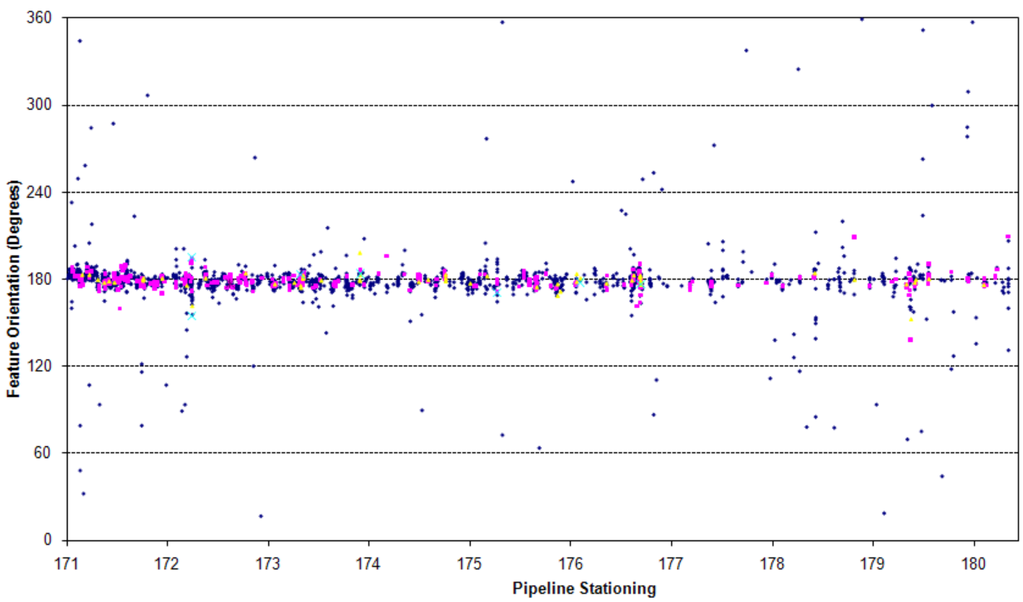

Figure 4-12 Six O'Clock Orientation Typical of Water Drop-out and Accumulation

On the other hand, a random distribution of internal wall loss features around the circumference of the pipe, with no apparent trends relative to inclination angle or receipt points might be more representative of benign manufacturing imperfections, as is represented in Figure 4-13.

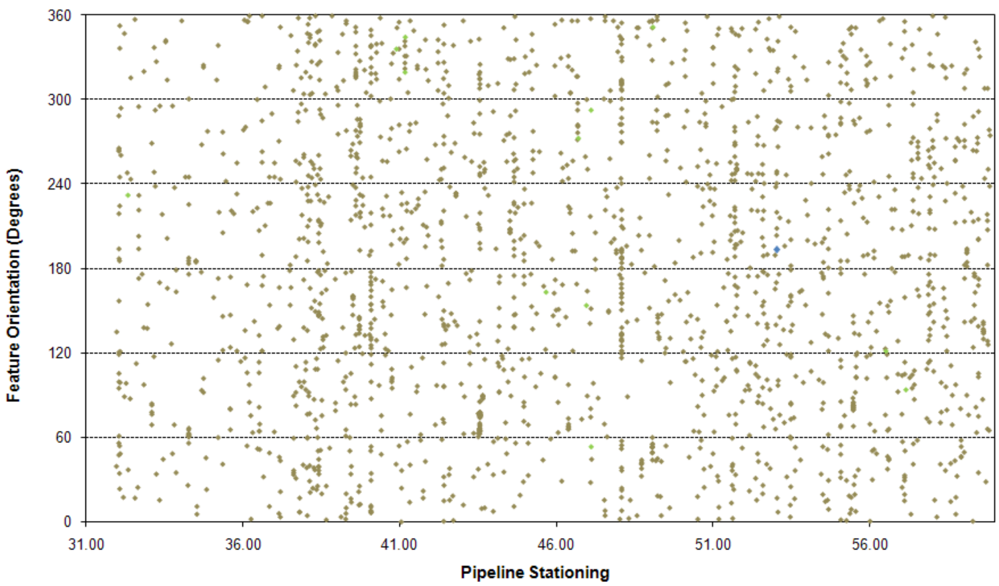

Figure 4-13 Random Wall Loss Orientation Typical of Manufacturing Imperfections—No Apparent Active Internal Corrosion

Internal corrosion evaluation techniques are largely based on product stream characteristics and flow rates. For liquid products, the important parameters that should be included in a comparison of corrosivity are water content, erosion and erosion/corrosion, flow velocity, flow mechanism, temperature, susceptibility to under-deposit corrosion (solid deposition, MIC potential, and water chemistry), and mitigation measures (use of inhibition, biocides, or pigging).

To ensure that the corrosion mechanism and corrosivity that is represented by the analogue ILI dataset is representative of that which would be expected in the L3RP, an evaluation of all of these parameters was conducted. Through this process, it was determined that ILI data obtained from Enbridge's 36-in. Line 4 would be most representative of the corrosivity conditions expected on the L3RP, since Line 4 transports similar products with similar tariffs in similar hydraulic regimes. A review of historical operating conditions on Line 4 indicates that like the proposed L3RP, the product flows in a fully-turbulent regime. Line 4 has historically transported both conventional and heavy crude oil and dilbit, with a tariff of 0.5% basic sediment and water (BS&W), which is the same tariff assigned to the L3RP.

4.2.3.3.1.1 Line 4 ILI Data

Approximately 10,000 km/year of ILI data from the 36-inch Line 4 was reviewed (i.e., approximately 1,000 km of 36-inch Line 4, having an average age of approximately 10 years at the time of inspection), with no evidence of active internal corrosion. The fully-turbulent mode of flow that is characteristic of 36-inch Line 4 and that will also be characteristic of the L3RP results in full entrainment of what little water is present at a BS&W content of less than 0.5%.

In such circumstances, water cannot stratify or accumulate adjacent to the pipe wall, and the internal surface of the pipeline remains in an oil-wet condition. This condition is not associated with internal corrosion.

Regular assessments for corrosion on the L3RP will be completed at no more than 5-year intervals. Given the demonstrated lack of failure-sensitivity to the initiation and growth of internal corrosion over a time period that is approximately double the inspection interval, it was concluded that it is not possible to arrive at a finite value of expected failure frequency for this threat. Nevertheless, a failure frequency value of 10-08 ruptures/mile/year (which the analysis shows to be conservative) will be assigned to this threat, and will be applied to all seven modeling locations.

4.2.3.4 Third Party Damage

The approach used for determining the reliability of a pipeline from the perspective of third party damage was based on the approach developed by Chen and Nessim (1999a). In this approach, failure frequency can be established as the product of two independent variables; the frequency of incurring a hit by an excavator, and the probability of failure given such a hit:

Equation 5

$$FF_{3PD} = F_H \cdot P_{F,H}$$

Where,

FF_{3PD} = Failure frequency due to third party damage
F_H = Excavator hit frequency (hits/km.yr)
$P_{F,H}$ = Probability of failure, given a hit

Chen and Nessim (1999b) demonstrated that machines smaller than excavators do not significantly affect predicted failure probability. Based on this finding, only impacts by large machines such as excavators are addressed by this model.

4.2.3.4.1 Determination of Impact Frequency Due to Third Party Activity

The impact frequency due to third party activity was determined by using a fault tree model developed by Chen and Nessim (1999b). This fault tree model is illustrated in Figure 4-14 and Table 4-15.

Figure 4-14 Impact Frequency Fault Tree

Table 4-15 Probability Values for Fault Tree Modeling

No	Event	Conditions	Probability
B1	Excavation on pipeline alignment	Commercials/Industrial	0.52/km-year
		High density residential	0.26/km-year
		Low density residential	0.36/km-year
		Agricultural	0.076/km-year
		Remote	0.06/km-year
B2	Third-party unaware of one-call	Advertising via direct mail-outs and promotion among contractors	0.24
		A1+Community meetings	0.10
		Community meetings only	0.50
B3	Right-of-way signs not recognized	Signs at selected crossings	0.23
		Signs at all crossings	0.19
		All crossings plus intermittently along route	0.17
B4	Failure of permanent markers	No buried markers	1.00
		With buried markers	0.10
B5	Third-party chooses not to notify	Voluntary	0.58
		Mandatory	0.33
		Mandatory plus civil penalty	0.14
		Right-of-way agreement	0.11
B6	Third-party fails to avoid pipeline	N/A	0.40
B7	ROW patrols fail to detect activity	Semi-daily patrols	0.13
		Daily patrols	0.30
		Bi-daily patrols	0.52
		Weekly patrols	0.80
		Biweekly patrols	0.90
		Monthly patrols	0.95
		Semi-annual patrols	0.99
		Annual patrols	0.996
B8	Activity not detected by other employees	N/A	0.97
B9	Excavation prior to operator's response	Response at the same day	0.02
		Response within two days	0.11
		Response within three days	0.20

Table 4-15 Probability Values for Fault Tree Modeling

No	Event	Conditions	Probability
B10	Temporary mark incorrect	By company records	0.20
		By magnetic techniques	0.09
		By pipe locators/probe bars	0.01
B11	Accidental interference with marked alignment	Provide route information	0.35
		Locate/mark	0.17
		Locate/mark/site supervision	0.03
		Pipe exposed by hand	0.06
B12	Excavation depth exceeding cover depth	Cover depth = 0.8 m (2.5 ft)	0.42
		0.9 m (3 ft)	0.25
		1.2 m (4 ft)	0.08
		1.5 m (5 ft)	0.07
		1.8 m (6 ft)	0.06

The fault tree model was used in conjunction with design, installation and operations data for the L3RP that was supplied during the Threat Assessment Workshop.

4.2.3.4.2 Determination of Failure Probability, Given Excavator Impact

Given a failure in the measures to prevent the accidental contact of an excavator with the pipeline, a loss of containment may occur due to gouge-in-dent or puncture mechanisms, or alternatively a failure may not occur. The frequency of having a gouge-in-dent or puncture failure, given a contact with an excavator, is a function of whether or not the pipeline resistance (a function of grade, wall thickness, and toughness) is greater or less than the driving forces for failure (a function of excavator force, bucket tooth dimensions, operating pressure). Where the resistance of the pipeline to failure exceeds the driving forces, no failure will occur. Otherwise, failure will occur.

Where failures occur that are related to external interference, the mode of failure is more likely to be gouge-in-dent than puncture (Fuglem et al. 2001; Eiber and Leis 2001). This is in part due to the fact that less force is required to cause a gouge-in-dent failure than is required to puncture a pipeline.

The model that determines the probability of failure, given a hit was derived based on the work reported in Fuglem et al. (2001), utilizes a Monte Carlo analysis to assimilate the probability distributions of the various parameters employed. An overview of the approach is provided below.

4.2.3.4.2.1 Test for Gouge-in-Dent

Gouge-in-dent failure has been empirically described by the NG-18 Q-Factor Relationship (Eiber and Leis 2001).

Equation 6

$$\sigma_h = \sigma_{fl}\left[\frac{(Q - C_2)^{0.6}}{C_3}\right]$$

Where,

σ_h	= Hoop stress at failure (ksi or MPa)
σ_{fl}	= Flow stress (ksi or MPa)
	= Y.S. + 10 ksi or Y.S. + 68.9 MPa
C_2	= a constant
	= 300 ft-lbs/in or 16 J/mm
C_3	= a constant
	= 90 (ft-lbs/in)0.6 or 4.80 (J/mm)0.6

Equation 7

$$Q = c_{v,2/3}\left[\frac{R\,t}{D\,d_g\,c_g}\right]$$

Where,

$C_{v,2/3}$	= 2/3 upper-shelf charpy toughness (ft-lbs or J)
R	= Pipe radius (in. or mm)
t	= Wall thickness (in. or mm)
D	= Maximum dent depth at the time of defect introduction (in. or mm)
d_g	= Depth of gouge (in. or mm)
c_g	= ½ gouge length (in. or mm)

The input parameters utilized in the analysis are described below.

4.2.3.4.2.2 Flow Stress (σfl)

As defined above, flow stress is a function of yield strength. Yield strength distribution parameters were obtained from Fuglem et al. (2001), which indicates that yield strength is normally distributed, with distribution parameters as follows:

μ	= 1.1(SMYS)
COV	= 0.035(SMYS)

4.2.3.4.2.3 Charpy Toughness (cv)

The toughness for the L3RP was conservatively estimated at 40J (29.5 ft-lb), full-size, which corresponds to the minimum specified value for pipe that will be ordered for this pipeline. This is considered quite conservative, since modern pipeline materials easily exceed this value.

4.2.3.4.2.4 Pipe Radius (R)

Pipe radius is a function of pipe diameter (D). Pipe diameter distribution parameters were obtained from Fuglem et al. (2001), which indicates that pipe diameter is normally distributed, with distribution parameters as follows:

μ = 1.0 (nominal diameter)
COV = 0.0006 (nominal diameter)

4.2.3.4.2.5 Wall Thickness (t)

Wall thickness distribution parameters were obtained from Fuglem et al. (2001), which indicates that wall thickness is normally distributed, with distribution parameters as follows:

μ = 1.0 (nominal wall thickness)
COV = 0.01 (nominal wall thickness)

4.2.3.4.2.6 Ultimate Tensile Strength (UTS)

Ultimate tensile strength distribution parameters were obtained from Fuglem et al. (2001) which indicates that ultimate tensile strength is normally distributed, with average and standard deviation values on API 5L X70 pipe of 639.2 MPa (92.7 ksi) and 22.4 MPa (3.2 ksi), respectively.

4.2.3.4.2.7 Excavator Force (Fd)

Maximum Excavator Force Capacity (Fd, kN) has been shown to be a function of excavator mass (mex, tonnes) (Roovers et al. 2000).

Equation 8

$$F_d = 14.2 \cdot m_{ex}^{0.928}$$

Driver and Zimmerman (1998) presented a distribution of excavators by machine mass. This is the same excavator mass distribution that was employed in Fuglem et al. (2001); specifically the entire excavator mass distribution may be applied for Class 1 and Class 2 locations, while a sub-set of that distribution (i.e., excluding excavator masses in excess of 40 tonnes) is applicable to Class 3 and 4 locations. By performing cumulative probability transformations of the excavator mass distributions, and applying Equation 8, sixth-order polynomial curve fits can be made to the data for both the Class 1/2 and Class 3/4 datasets, as illustrated in Figure 4-15 and Figure 4-16. These regression functions were incorporated directly in the Monte Carlo simulations.

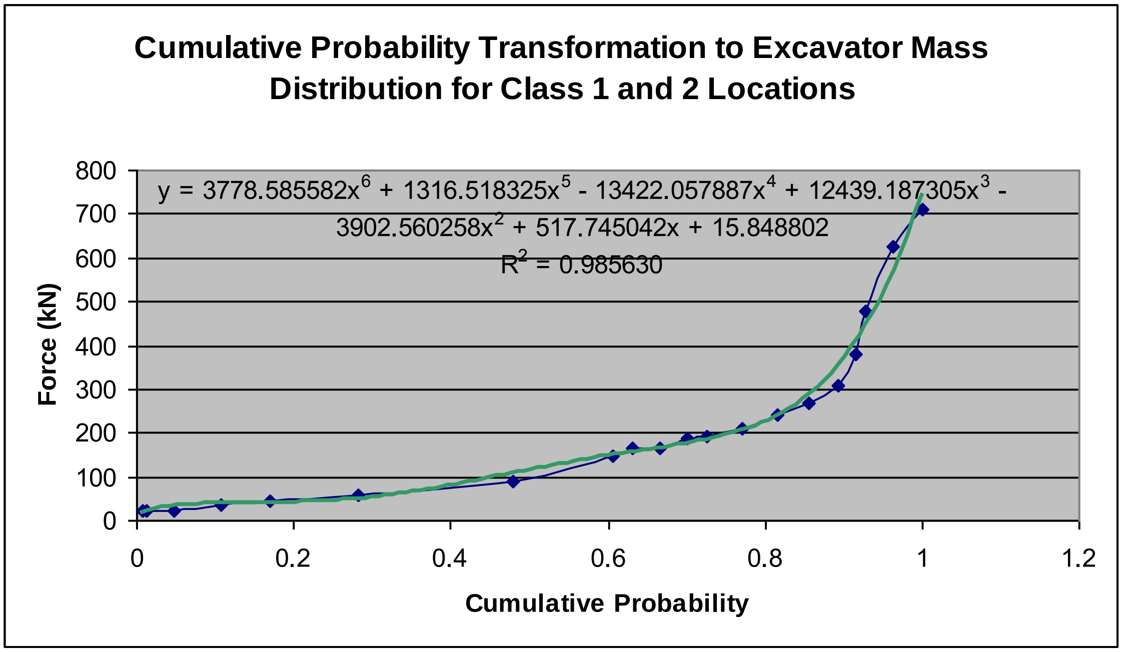

Figure 4-15 Excavator Mass Distribution, Class 1 and 2 Locations

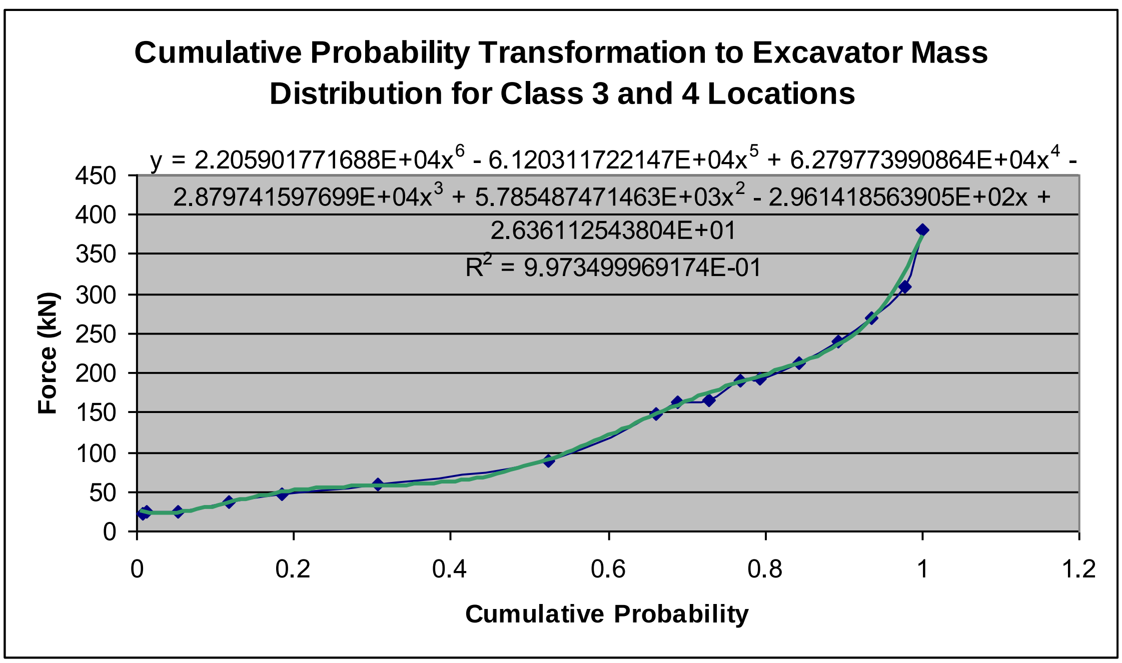

Figure 4-16 Excavator Mass Distribution, Class 3 and 4 Locations

4.2.3.4.2.8 Excavator Tooth Dimensions: Length (L) and Width (W)

The excavator bucket tooth size parameters tooth length (L, mm) and tooth width (W, mm) have been shown to be a function of excavator mass (mex, tonnes) (Roovers et al. 2000).

Equation 9

$$(L + W) = 29.4 \cdot m_{ex}^{\ 0.400}$$

Equation 10

$$L = 24.6 \cdot m_{ex}^{\ 0.420}$$

These parameters were therefore derived as functions of the excavator mass distribution.

4.2.3.4.2.9 Dent Depth (H)

Dent depth has been shown to be a function of pipe diameter, ultimate tensile strength, excavator tooth Length, wall thickness, operating pressure (Pop) and excavator force (Roovers at al. 2000).

Equation 11

$$P_r = \sqrt{t^3 \cdot UTS \cdot L}\left[1 + 0.7\left(\frac{P_{op} \cdot D}{t \cdot UTS}\right)\right]$$

Where,

UTS = Ultimate Tensile Strength (MPa),
L = Tooth Length (mm),
P_{op} = Maximum Operating Pressure (MPa),
D = Pipe Diameter (mm),
t = Pipe Wall Thickness (mm),
P_r = Pipeline Resistance Parameter (mm(N)0.5), where:

Equation 12

$$\text{If } P_r \le 2000\ mm \cdot \sqrt{N} : H = \left(\frac{F_d}{0.007 \cdot P_r}\right)^2$$

Equation 13

$$\text{If } P_r > 2000\,\text{mm}\cdot\sqrt{\text{N}} : H = \left(\frac{F_d}{0.31\cdot\sqrt{P_r}}\right)^2$$

Where,

F_d = Denting Force (kN),

H = Dent depth, measured after damage under pressure (i.e., after re-rounding under pressure) (mm).

A relationship exists between H and Ho (the dent depth prior to re-rounding under pressure) (Roovers et al. 2000):

Equation 14

$$H_o = 1.43 \cdot H$$

4.2.3.4.2.10 Gouge Depth (dg)

In Fuglem et al. (2001), reference was made to a judgment-based decision to assume that the gouge depth distribution could be defined as a random variable described by a Weibull distribution having μ = 0.5 mm and σ = 0.5 mm. Conversations with researchers who were involved in full-scale experimental testing of third party damage revealed an unpublished dataset showing that gouge depth is a function of excavator force. A straight-line regression was found to fit this dataset having the form:

Equation 15

$$\text{Gouge Depth (in)} = 3.268\times10^{-4}\cdot F_d(\text{kN}) - 5.851\times10^{-3}$$

It should be noted that the 50th percentile force from Figure 4-17 is approximately 100 kN. If this value is substituted into Equation 15, a gouge depth of 0.027" is obtained, which corresponds very closely to the mean value of 0.5 mm that is cited in Fuglem et al. (2001).

Accordingly, it was decided to correlate the gouge depth distribution to the excavator force distribution by means of Equation 15.

4.2.3.4.2.11 Half Gouge Length (cg)

Fuglem et al. (2001) and Eiber and Leis (2001) were referenced to establish a basis for a gouge length distribution. It was determined that unlike gouge depth, gouge length is independent of other variables such as excavator force. In Fuglem et al. (2001), the gouge length distribution was described using a Weibull distribution having a mean of 6.0 in., and a COV of 1.25. Gouge length was described as having an approximate value of 3 in., and an upper-bound value of 25 in. (Eiber and Leis 2001). It was noted that the dataset compiled in Eiber and Leis (2001) was derived from mechanical damage defects that failed in-service, and so the upper-bound gouge length may be taken as a statistical outlier. On the basis of this review, it was decided to describe the gouge length distribution as a Weibull distribution, having the shape parameters a = 1.2 and β = 3.2. This distribution is illustrated in Figure 4-17.

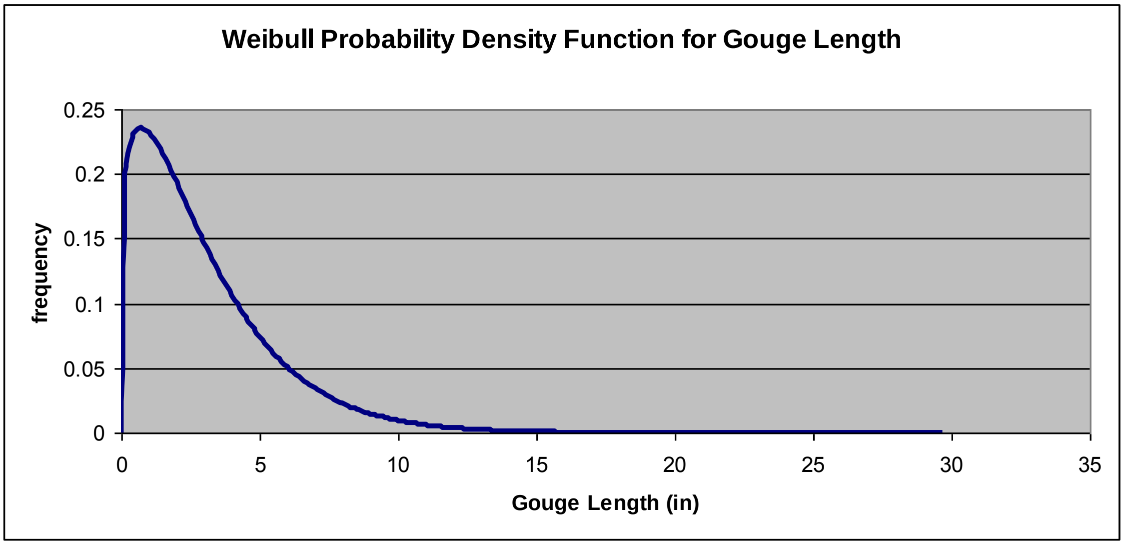

Figure 4-17 Gouge Length Distribution

Because gouges may be randomly oriented with respect to the axis of the pipe, a gouge orientation factor is applied against the gouge length. This is derived by recognizing the fact that the projected length of a gouge on the pipe axis is proportional to the cosine of the angle between the gouge and the pipe axis. The gouge length orientation factor; therefore, varies between 0 and 1 and is equal to the cosine of a uniform distribution of random angles between 0 and π/2 radians. A cumulative probability transformation on this distribution was performed, and a second order polynomial curve fit was derived for this function, as depicted in Figure 4-18.

This polynomial function was incorporated directly within the Monte Carlo simulation.

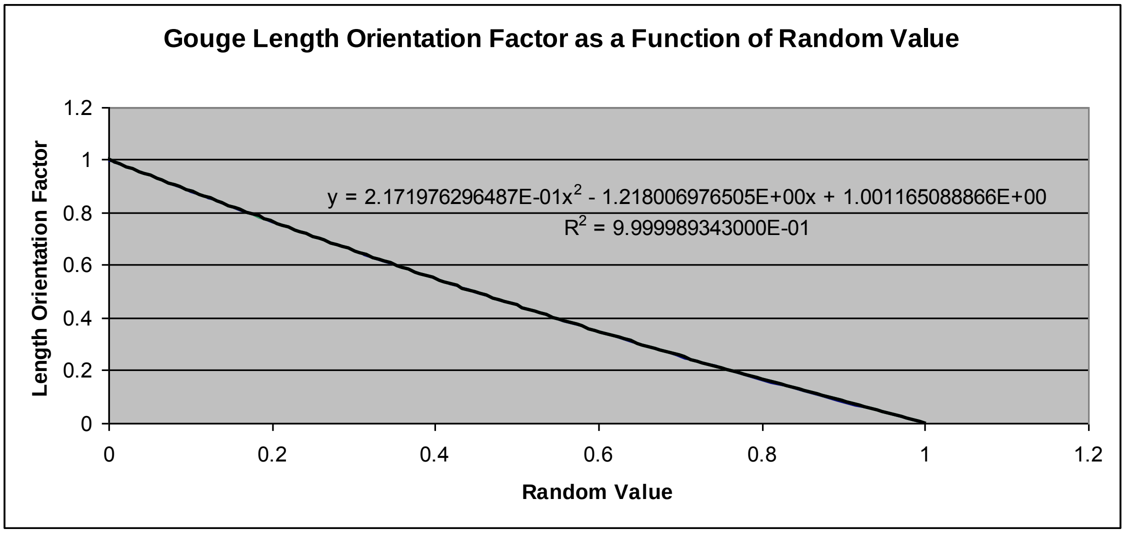

Figure 4-18 Gouge Length Orientation Factor

4.2.3.4.2.12 Off-Angle Force Reduction Factor

When the excavator force is applied normal to the pipeline, the full penetrating force of the excavation equipment can be brought to bear against the pipeline. When the applied force is at an angle θ to the pipe, the component of the maximum applied force that is directed towards penetration of the pipeline is equal to FMax Cos θ, as illustrated in Figure 4-19.

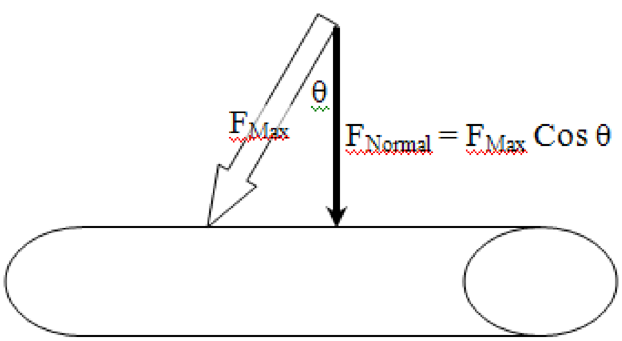

Figure 4-19 Off-Angle Force Reduction Factor

As presented by Fuglem et al. (2001), since the angle of the application of excavator force may be equally likely to be any angle between 0 and 90°, the off-angle force reduction factor is best described as a uniform distribution between 0 and 1.

4.2.3.4.2.13 Operator Control Factor

As discussed in Fuglem et al. (2001), the operator of a piece of excavation equipment will, in most cases, apply a load that is considerably less than the maximum quasi-static load. The typical actual capacity at which the machine is used will depend on the soil type and how aggressively the operator digs. It may also be expected that an operator may dramatically cut back on the load if he detects a foreign object. This may be particularly true for gouge-in-dent type damage, which is inflicted more gradually than puncture damage. Because of the uncertainty regarding the distribution of applied force, the approach by Fuglem et al. (2001) was used to calibrate the model against "Probability of Failure, Given a Hit" data for the operator control factor.

4.2.3.4.2.14 Test of Failure Due to Puncture

Puncture failure has been empirically described by the model described by Chen and Nessim (1999b).

Equation 16

$$R = \left[1.17 - 0.0029 \cdot \left(\frac{D}{t}\right)\right] \cdot (L + W) \cdot t \cdot \sigma_u + E_R$$

Where:

- R = The resistance to puncture (N)
- D = Pipe diameter (mm)
- t = Wall thickness (mm)
- L = Excavator tooth length (mm)
- W = Excavator tooth width (mm)
- σ_U = Ultimate tensile strength (MPa)
- E_R = Model error (N)

This is the same limit state equation used to define puncture resistance in Fuglem et al. (2001).

4.2.3.4.2.15 Input Parameters

With the exception of the operator control factor, all of the input parameters that are required for the puncture model have been defined in the discussion on the gouge-in-dent model. To avoid repetition, only the operator control factor will be described in this section.

As was done for the gouge-in-dent model, due to the lack of certainty regarding the distribution that describes the degree of operator control, the puncture model was calibrated against "Probability of Failure, Given a Hit" data contained in Fuglem et al. (2001).

4.2.3.4.2.16 Monte Carlo Simulation

Monte Carlo simulation is a numerical approach for arriving at a solution when the variables within a mathematical expression are best described as random variables derived from probability density functions, rather than discrete values, as is the case with a conventional deterministic analysis. When used as part of a reliability analysis, the mathematical expression is known as a "limit state equation", and the usual objective of the analysis is to estimate the probability of an event or "limiting condition" occurring.

The limiting condition is usually one which describes the onset of failure, or some other undesirable event. In the case at hand, two limit state equations are used; one to define the onset of gouge-in-dent failure (Equation 6) and the other to define the onset of failure due to puncture (Equation 16).

The probability of failure given a hit due to gouge-in-dent is obtained by employing a Monte Carlo Simulation to determine the frequency of occurrence (over a set number of iterations) of events where the operating hoop stress due to internal pressure (σh) exceeds the operating stress at failure, as defined in Equation 6. Similarly, the probability of failure given a hit due to puncture is obtained by employing a Monte Carlo Simulation to determine the frequency of occurrence (over a set number of iterations) of events where the factored excavator force exceeds the resistance, R, as defined in Equation 16.

The overall probability of failure given a hit is determined by executing the Monte Carlo Simulations for gouge-in-dent and puncture simultaneously, and determining the frequency of occurrence (over a set number of iterations) of events where either the limit state for gouge-in-dent or puncture is exceeded.

4.2.3.4.3 Calibration

Calibration of this model was undertaken as described in the Sections describing the operator control factor for each of the two limit states. This approach is consistent with what was carried out in Fuglem et al. (2001), and it was achieved utilizing the calibration data from that study.

4.2.3.4.4 Leaks and Ruptures

It has been reported that the respective percentages of leak and rupture for third party damage failures are 75% and 25%, based on the mechanical damage incidents reported to the U.S. Department of Transportation during 1984 to 1992 (Chen and Nessim 1999b). Accordingly, third party damage failure rates established by the reliability approach described above are sub-divided into leaks and failures in accordance with this guideline.

4.2.3.4.5 Results

The length-averaged third party damage rupture frequency values for each of the seven modeling locations are summarized in Table 4-16.

Table 4-16 Third Party Damage Summary

Site	Third Party Damage Rupture Frequency (Ruptures/mi.yr)
1—Mosquito Creek	1.026×10^{-06}
2—Mississippi River at Ball Club	6.680×10^{-08}
3—Sandy River	6.680×10^{-08}
4—Shell River	6.680×10^{-08}
5—Red River	8.183×10^{-08}
6—Mississippi River at Palisades	6.680×10^{-08}
7—Mississippi River at Little Falls	1.733×10^{-07}

4.2.3.5 Manufacturing Defects

Manufacturing Defects failures are those that are attributed to pipe as a direct result of the presence of pipe body or seam weld defects.

The threat of manufacturing defects does not lend itself to failure frequency estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters. Therefore, the approach that was used to estimate the frequency of occurrence for this threat applies a failure frequency derived from industry failure statistics for modern (1980 installation or later) pipeline materials, design, and installation practices.

4.2.3.5.1 Failure Frequency for Manufacturing Defects

4.2.3.5.1.1 Analysis if Incident Data

The PHMSA Hazardous Liquids incident database (2010–present, current to December 31, 2015) was filtered for onshore, pipelines installed since 1980. For the purposes of isolating only those incidents associated with pipelines (i.e., not including facilities), the PHMSA incident database was filtered so that it included only those incidents that were related to "Onshore Pipelines, Including Valve Sites".

For the purposes of the "Pipelines Only" analysis, failures related to non-pipe equipment were not considered, thereby providing a suitable basis for estimating failure rates associated with pipeline ROWs.

To highlight failures characterized as "ruptures", a filter was applied to the "Release Type" field of the PHMSA flagged hazardous liquids incident database. The *Instructions for Form PHMSA F700-1 Accident Report—Hazardous Liquid Pipeline Systems* defines the term "leak" as follows: "Leak means a failure resulting in an unintentional release of the transported commodity that is often small in size, usually resulting in a low flow release of low volume, although large volume leaks can and do occur on occasion."

Conversely, the term "rupture" is defined as follows: "Rupture means the pipeline facility has burst, split, or broken and the operation of the pipeline facility is immediately impaired. Pipeline ruptures often result in a higher flow release of larger volume. The terms "circumferential" and "longitudinal" refer to the general direction or orientation of the rupture relative the pipe's axis. They do not exclusively refer to a failure involving a circumferential weld such as a girth weld, or to a failure involving a longitudinal weld such as a pipe seam."

For the purposes of categorization, failures that were characterized as "Mechanical Puncture" were included within the "Rupture" category.

Once the above filters were applied, the number of ruptures that were associated with materials defects over the reporting period was counted.

4.2.3.5.1.2 Analysis of Mileage Data

The PHMSA Liquid Annual Data for the years 2010 and higher were filtered so that they represented infrastructure mileage for onshore liquids pipelines. Further filters were applied so that mileage data could be broken down by year of installation.

4.2.3.5.2 Calculation of Failure Frequency

To express pipeline incident frequency in a manner that is independent of timeframe or length of infrastructure, failure frequency estimates are conventionally expressed in normalized terms, using units of failures per mile per year of operation. To provide results in such normalized terms, this was calculated as follows:

Equation 17

$$FF_R = \frac{I_R}{L \times A}$$

Where,

- FF_R = Failure frequency (ruptures/mi.yr)
- I_R = Incident count obtained from the PHMSA flagged hazardous liquids incident database 2010–present (# ruptures)
- L = Average length of infrastructure in miles (i.e., infrastructure length values averaged over the PHMSA Liquid Annual Data for the years 2010 and higher)
- A = Number of years of incident data represented by the PHMSA flagged hazardous liquids incident database (for the "2010–present" database used, this value was 6 years)

Based on the above analysis, the failure frequency for Materials Defects was determined to be 2.775×10^{-06} ruptures/mi-yr.

4.2.3.6 Construction Defects

Construction defects failures are those that are attributed to construction or installation defects, such as girth weld defects.

The threat of construction defects does not lend itself to failure frequency estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters. Therefore, the approach that was used to estimate the frequency of occurrence for this threat applies a failure frequency derived from industry failure statistics for modern (1980 installation or later) pipeline materials, design, and installation practices.

4.2.3.6.1 Failure Frequency for Construction Defects

The PHMSA Hazardous Liquids incident database (2010–present, current to December 31, 2015) was sorted and failure frequency was calculated as described in Section 4.2.3.5.1. Once the above filters were applied, the number of ruptures that were associated with construction defects over the reporting period were counted.

Based on this analysis, the failure frequency for construction defects was determined to be 5.551×10^{-06} ruptures/mi- yr.

4.2.3.7 Incorrect Operations

Failures due to incorrect operations are related to human error and procedural error during the operation of a pipeline. The threat of incorrect operations failures does not lend itself to failure frequency estimation using a reliability approach due to the lack of a limit state model that is supported by probability distributions for its input parameters. In consideration of this fact, estimates of failure frequency were based on operating incident data related to this threat, modified by the results of the operations questionnaire that was administered during the Threat Assessment Workshop. This approach is similar to that described in the second edition of API RP 581 "Risk Based Inspection Technology", where operations-related failure frequency is obtained by multiplying a baseline operations-related failure rate by a management systems adjustment factor, as highlighted below:

Equation 18

$$FF_{IO} = FF_{IO,\,Baseline} \times AF_{MS}$$

Where,

FF_{IO}	= Incorrect operations failure frequency (ruptures/km yr)
$FF_{IO,\,Baseline}$	= Baseline rupture frequency for incorrect operations derived from industry failure statistics
AF_{MS}	= Operational Management Systems Adjustment Factor (0.1 – 10.0)

4.2.3.7.1 Baseline Failure Frequency for Incorrect Operations

The PHMSA Hazardous Liquids incident database (2010–present, current to December 31, 2015) was sorted and failure frequency was calculated as described in Section 4.2.3.5.1. Once the above filters were applied, the number of ruptures that were associated with incorrect operations over the reporting period were counted. Included in that count were all first and second party external interference incidents, since failures associated with first and second party damage can be considered as principally related to process failure and human error.

Based on this analysis, the failure frequency for incorrect operations was determined to be 2.775×10^{-06} ruptures/mi- yr.

4.2.3.7.2 Operational Management Systems Adjustment Factor

During the threat assessment, an operations questionnaire was administered. That questionnaire covered topics that were intended to gauge the performance of Enbridge operations in terms of the causal factors of failures related to incorrect operations. As detailed in the threat assessment, the results of the questionnaire were evaluated and scored, resulting in a score of 65 out of a possible 73 points (i.e., 89.0%).

Adopting the quantitative failure frequency estimation approach of API RP 581, an operational management systems adjustment factor is derived in accordance with the following expression:

Equation 19

$$AF_{MS} = 10^{[-0.02 P_{Score} + 1]}$$

Where,

P_{Score} = the percent score obtained on the Operations Questionnaire.

Based on a P^{Score} value of 89.0%, AFMS was determined to be 0.166.

From Equation 18, the adjusted incorrect operations rupture frequency was therefore determined to be 4.607×10^{-07} ruptures/km yr.

4.2.3.8 Geotechnical / Hydrotechnical Threat

To assess the degree of threat that a pipeline will be exposed to threats associated with geotechnical and hydrological factors, an evaluation of these factors was completed at each of the seven modeling locations. The review included published information (textbooks and reports), including soils maps, topographic maps, hydrological maps, pipeline alignment sheets, and incident reports related to ground movement, hydrological and geological events and floods.

A full description of the approach that was adopted for the determination of failure frequency is provided in Attachment A.

Failure likelihood estimates, expressed in terms of annual rupture probability were derived for each geohazard or hydrotechnical hazard identified at each site. The combined annual probability of pipeline rupture for all threats was then determined as the statistical "OR" function of all probability values associated with each threat for each site. The combined annual probability of rupture associated with geohazards / hydrotechnical hazards for each site is summarized in Table 4-17.

Table 4-17 Geohazard / Hydrotechnical Hazard Annual Probability of Rupture

Site	Annual Rupture Probability
1—Mosquito Creek	0.000
2—Mississippi River at Ball Club	5.000×10^{-08}
3—Sandy River	5.000×10^{-09}
4—Shell River	1.105×10^{-07}
5—Red River	1.050×10^{-07}
6—Mississippi River at Palisades	6.000×10^{-08}
7—Mississippi River at Little Falls	6.000×10^{-08}

4.2.4 Summarized Estimates of Failure Frequency

In Section 4.1, threat-specific estimates of failure frequency were provided for each unique combination of design variables associated with the L3RP at each of the seven modeling locations. Knowing the failure frequency associated with a given segment of pipeline (expressed in units of failures per mile per year of operation), the annual probability of failure over that segment length can be determined as:

Equation 20

$$P_f = 1 - (1 - FF)^{SL}$$

Where,

Pf = Annual probability of failure over a defined segment of length SL (miles)
FF = Failure Frequency (failures per mile per year of operation)

For multiple threats, the combined annual probability of failure is expressed as:

Equation 21

$$P_{Comb} = P_{f\,,\,Threat1}\ U\ P_{f\,,\,Threat2}\ U\ P_{f\,,\,Threat3}\ ...U\ P_{f\,,\,Threatn}$$

Where the operator U represents the statistical "OR" function.

From the above relationships, a summary of annual failure probability values for each of the seven modeling locations is provided for all threats identified in the threat assessment based on the threat-specific failure frequency values identified in Section 4.1. Results are provided below for each modeling site.

4.2.4.1 Mosquito Creek

The threat-specific failure annual probability of failure values for the L3RP at the Mosquito Creek modeling site are provided in Table 4-18.

Table 4-18 Failure Probability Summary L3RP, Mosquito Creek

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.346	3.460×10^{-09}
Internal corrosion	1.000×10^{-08}		3.460×10^{-09}
Third party damage	1.026×10^{-06}		3.549×10^{-07}
Manufacturing defects	2.775×10^{-06}		9.602×10^{-07}
Construction defects	5.551×10^{-06}		1.921×10^{-06}
Incorrect operations	4.607×10^{-07}		1.594×10^{-07}
Geotechnical/hydrological forces	-		0.000
All threats combined			$\mathbf{3.402 \times 10^{-06}}$

4.2.4.2 Mississippi River at Ball Club

The threat-specific failure annual probability of failure values for the L3RP at the Mississippi River at Ball Club modeling site are provided in Table 4-19.

Table 4-19 Failure Probability Summary L3RP, Mississippi River at Ball Club

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.039	3.900×10^{-10}
Internal corrosion	1.000×10^{-08}		3.900×10^{-10}
Third party damage	6.680×10^{-08}		2.605×10^{-09}
Manufacturing defects	2.775×10^{-06}		1.082×10^{-07}
Construction defects	5.551×10^{-06}		2.165×10^{-07}
Incorrect operations	4.607×10^{-07}		1.797×10^{-08}
Geotechnical/hydrological forces	-		5.000×10^{-08}
All threats combined			**3.961×10^{-07}**

4.2.4.3 Sandy River

The threat-specific failure annual probability of failure values for the L3RP at the Sandy River modeling site are provided in Table 4-20.

Table 4-20 Failure Probability Summary L3RP, Sandy River

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.218	2.180×10^{-09}
Internal corrosion	1.000×10^{-08}		2.180×10^{-09}
Third party damage	6.680×10^{-08}		1.456×10^{-08}
Manufacturing defects	2.775×10^{-06}		6.050×10^{-07}
Construction defects	5.551×10^{-06}		1.210×10^{-06}
Incorrect operations	4.607×10^{-07}		1.004×10^{-07}
Geotechnical/hydrological forces	-		5.000×10^{-09}
All threats combined			**1.939×10^{-06}**

4.2.4.4 Shell River

The threat-specific failure annual probability of failure values for the L3RP at the Shell River modeling site are provided in Table 4-21.

Table 4-21 Failure Probability Summary L3RP, Shell River

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.482	4.820×10^{-09}
Internal corrosion	1.000×10^{-08}		4.820×10^{-09}
Third party damage	6.680×10^{-08}		3.220×10^{-08}
Manufacturing defects	2.775×10^{-06}		1.338×10^{-06}
Construction defects	5.551×10^{-06}		2.676×10^{-06}
Incorrect operations	4.607×10^{-07}		2.221×10^{-07}
Geotechnical/hydrological forces	-		1.105×10^{-07}
All threats combined			**4.388×10^{-06}**

4.2.4.5 Red River

The threat-specific failure annual probability of failure values for the L3RP at the Red River modeling site are provided in Table 4-22.

Table 4-22 Failure Probability Summary L3RP, Red River

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.301	3.010×10^{-09}
Internal corrosion	1.000×10^{-08}		3.010×10^{-09}
Third party damage	8.183×10^{-08}		2.463×10^{-08}
Manufacturing defects	2.775×10^{-06}		8.353×10^{-07}
Construction defects	5.551×10^{-06}		1.671×10^{-06}
Incorrect operations	4.607×10^{-07}		1.387×10^{-07}
Geotechnical/hydrological forces	-		1.050×10^{-07}
All threats combined			**2.781×10^{-06}**

4.2.4.6 Mississippi River at Palisades

The threat-specific failure annual probability of failure values for the L3RP at the Mississippi River at Palisades modeling site are provided in Table 4-23.

Table 4-23 Failure Probability Summary L3RP, Mississippi River at Palisades

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.278	2.780×10^{-09}
Internal corrosion	1.000×10^{-08}		2.780×10^{-09}
Third party damage	6.680×10^{-08}		1.857×10^{-08}
Manufacturing defects	2.775×10^{-06}		7.715×10^{-07}
Construction defects	5.551×10^{-06}		1.543×10^{-06}
Incorrect operations	4.607×10^{-07}		1.281×10^{-07}
Geotechnical/hydrological forces	-		6.000×10^{-08}
All threats combined			$\mathbf{2.527 \times 10^{-06}}$

4.2.4.7 Mississippi River at Little Falls

The threat-specific failure annual probability of failure values for the L3RP at the Mississippi River at Little Falls modeling site are provided in Table 4-24.

Table 4-24 Failure Probability Summary L3RP, Mississippi River at Little Falls

Threat	Annual Failure Frequency (ruptures/mi.yr)	Segment Length (mi)	Annual Rupture Probability
External corrosion	1.000×10^{-08}	0.248	2.480×10^{-09}
Internal corrosion	1.000×10^{-08}		2.480×10^{-09}
Third party damage	1.733×10^{-07}		4.298×10^{-08}
Manufacturing defects	2.775×10^{-06}		6.882×10^{-07}
Construction defects	5.551×10^{-06}		1.377×10^{-06}
Incorrect operations	4.607×10^{-07}		1.143×10^{-07}
Geotechnical/hydrological forces	-		6.000×10^{-08}
All threats combined			$\mathbf{2.287 \times 10^{-06}}$

5.0 MODELING OF OIL RELEASES

This chapter contains a description of the computational models used for different scenarios (Sections 5.1.1 and 5.1.2, respectively), the key assumptions made for these simulations (Section 5.2), and the input data sources, processing, and assumptions for environmental and chemical data (Section 5.3). Trajectory and fates results are presented in Chapter 6.0; results are organized by location, then type of crude oil and season.

Hypothetical oil releases from the proposed preferred and alternate pipeline routes for the L3RP were modeled using the OILMAP Land and SIMAP computation models that have been developed by RPS. The L3RP route is depicted in Figure 5-1.

Large releases of crude oil were simulated from five representative release locations along the pipeline using the OILMAP Land computation model. Two additional locations were selected for more comprehensive three dimensional modeling using the SIMAP modeling system. Modeling of large releases of crude oil at these seven locations provided quantitative predictions of the trajectory and fate of released oil under a range of environmental conditions (in-stream flows and seasons) and a range of crude oils (i.e., light and heavy crude oils). The rational for the selection of the two computational models; and the selection of a specific modeling system for different locations, are provided in Chapter 3.0. Details are also provided on the criteria used to select preferred locations for modeling of large releases of crude oil; how a specific range of conditions were determined for each hypothetical release (i.e., volume of the release, flow conditions, types of crude oil); and the types of output desired.

Information on the trajectory and fate of crude oil for these hypothetical releases was used to assess a wide range of potential effects on key receptors under different seasonal flows conditions and with light and heavy crude oils. The assessment of potential environmental effects included site-specific assessments of potential effects on environmentally-sensitive areas (e.g., HCAs and AOIs; Section 7.3), and on key receptors at each of the seven modeling locations (Sections 7.4 to 7.10).

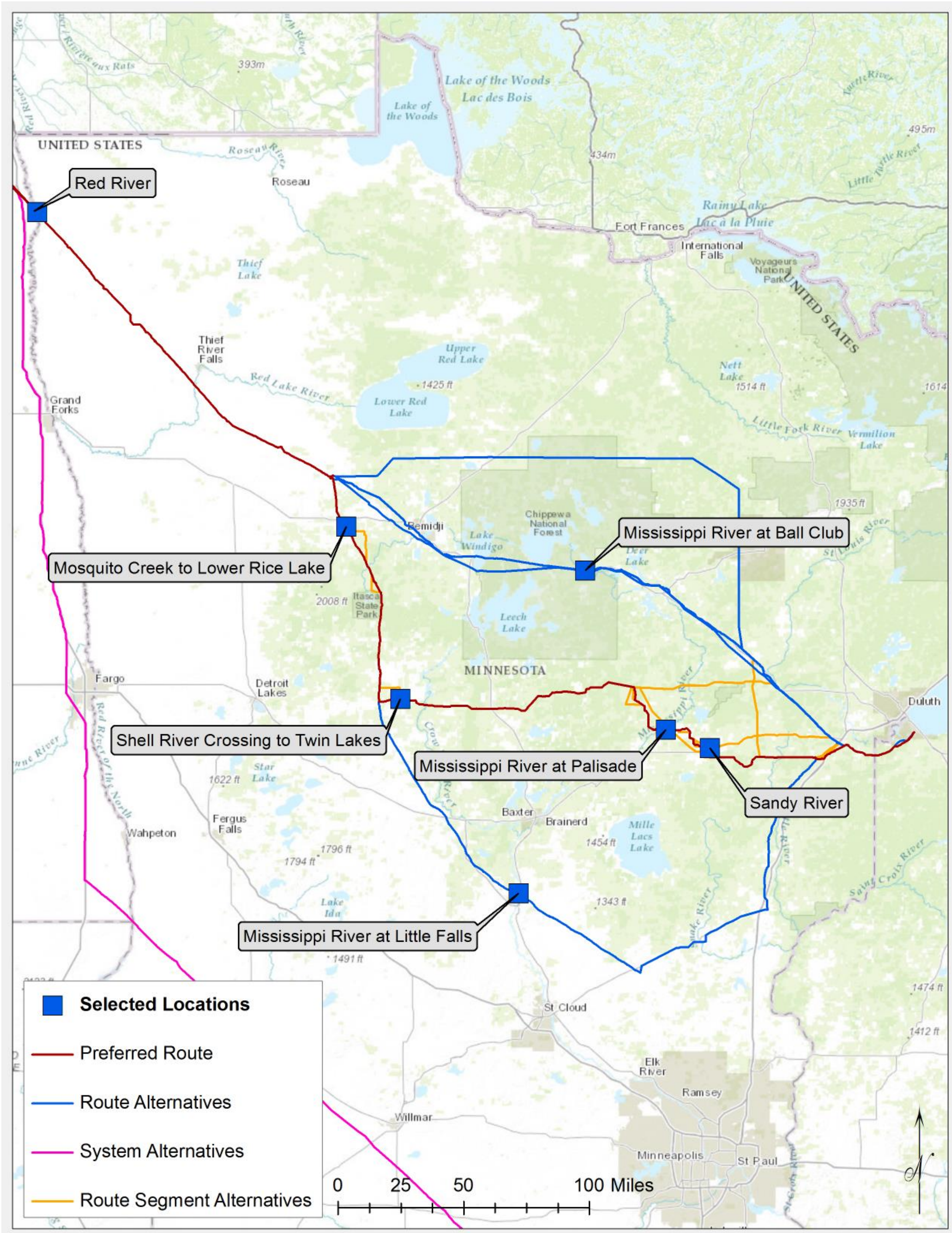

Figure 5-1 Map of the Enbridge Line 3 Replacement Pipeline Route, Preferred and Alternative Routes, and Selected Hypothetical Release Locations for Modeling

Of note, seasonal variations in river flow rate, temperature, wind speed, and snow and ice cover are expected at each of the modeled locations and would affect the trajectory and fate of a crude oil release. Because river discharge controls the downstream velocity of water and, therefore, the potential transport of oil, a hydrologic analysis was conducted to characterize seasonal differences at each hypothetical release location. Historical stream discharge (flow) data was used to determine the monthly average flow rate for each location. The seasonally appropriate environmental conditions that would be present during each of these months were then identified for use in modeling. The combination of multiple environmental conditions and oil types modeled at each location provide a realistic range of anticipated seasonal conditions upon which to base the hypothetical release scenarios. The three seasons modeled bound the range of likely conditions spanning high to low river flow rate, temperature, ice cover, and wind speed.

Months representing the average, maximum, and minimum river flow rates were identified, and the corresponding temperatures and wind speeds during those seasons were used in the modeling. The average monthly river flow rate month was considered representative of baseline conditions. As mean flow can occur in two seasons, typically observed around summer and fall, the month with the warmest temperature (i.e., August) was selected to represent the maximum amount of evaporation, potentially resulting in the largest exposure to hydrocarbon vapors in air as a potential trigger for human health effects. The month with the highest flow rate represented the spring freshet (i.e., a spring thaw and increased river flow rates from snow and ice melt typically occurring between April and June), a result of rising temperatures and snowmelt. The month with the lowest flow rate represented the winter (i.e., January–March), and was typified by freezing conditions and probable snow cover on land and ice cover on water.

5.1 DESCRIPTION OF MODELING TOOLS

The OILMAP Land modeling system was used to predict the trajectory and fate of hypothetical large releases of crude oil at five modeling locations: Mosquito Creek to Lower Rice Lake, Mississippi River at Ball Club, Sandy River, Shell River to Twin Lakes, and Red River (Table 3-5).

5.1.1 OILMAP Land

The OILMAP Land model simulates the flow of oil or chemicals from a given rupture point along a pipeline (Figure 5-2). The release is modeled as it propagates over the land surface and then into any surface water network until the entire amount of product is released. Oil flow over land is governed by the physical characteristics and slope of the land surface. The overland model calculates an oil mass balance that includes losses from oil adhesion to land over the oiled path, the formation of small puddles, oil pooling in large depressions on the land surface, and oil evaporation to the atmosphere.

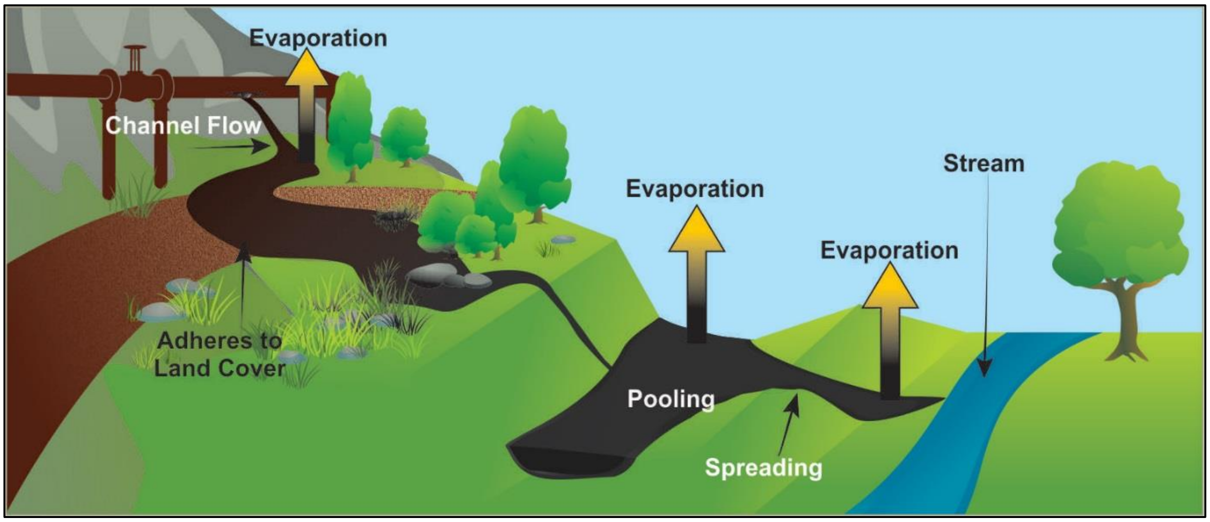

Figure 5-2 Conceptual Diagram of the Land Transport Model Depicting the Possible Fate of Oil as it Moves Over the Land Surface in OILMAP Land

In many cases, oil may reach a watercourse. The flow of oil within a watercourse is governed by surface currents, which require a different modeling approach (Figure 5-3). The water transport model simulates the downstream movement of oil on the water surface in streams at a defined velocity. As oil moves downstream, estimates of the amount of oil lost to the shore from adhesion and to the atmosphere by evaporation are made. Any oil entering a lake is allowed to spread over the water surface of the lake in a radial pattern to a minimum thickness that reflects the density and viscosity of the released oil.

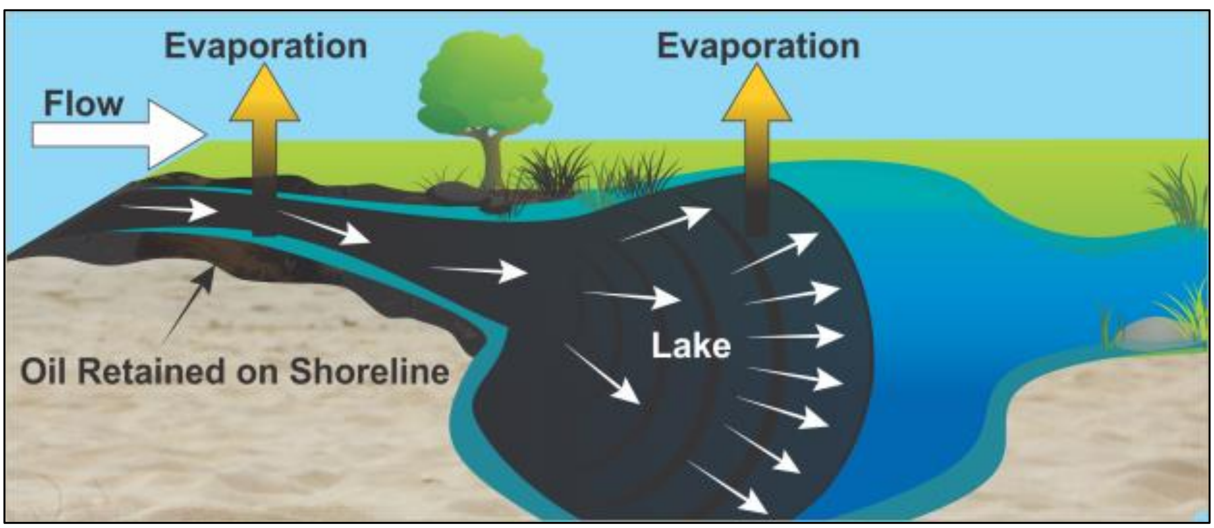

Figure 5-3 Conceptual Diagram of the Downstream Transport Model Depicting the Possible Fate of Oil Entering the Surface Water Network in OILMAP Land

While OILMAP Land does provide an indication of the downstream extent of oiling and mass balance of oil within the modeled 24-hour period, it is not able to provide detailed predictions of 3-D oil fate and transport. Therefore, complex processes such as entrainment of oil into the water column, dissolution of soluble fractions of hydrocarbons, and emulsion formation were not modeled for the five hypothetical release sites that were simulated with the OILMAP Land system. Two additional release locations on the Mississippi River were modeled using SIMAP to characterize a more comprehensive investigation of 3-D trajectory and fates process within the water column (Section 5.1.1.5).

5.1.1.1 Overland Release Model

For the purpose of the OILMAP Land computational model, the overland flow of oil is simulated using a square land elevation grid. Starting at the release location, the model searches the eight neighboring cells to determine the steepest down slope direction. The adjacent cell with the lowest elevation becomes the next starting location (Figure 5-4). This process repeats successively until a flat or depression area is reached. In a flat area, the model searches (i.e., looks beyond adjacent cells) to determine the minimum distance path to a next lowest cell. In a depression area, the area assumed to fill with liquid until the elevation of the surface of the pool equals the elevation of a grid cell on its boundary. At this point the boundary of the pool is breached, and the grid cell becomes the next starting point for farther down slope movement of oil. The lowest elevation cell becomes the next starting location.

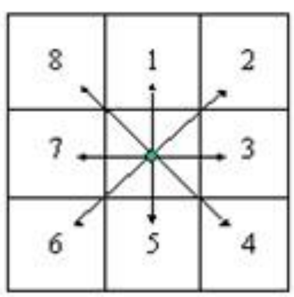

Figure 5-4 Diagram Showing How the OILMAP Land Model Searches the Eight Neighboring Cells to Determine the Steepest Down Slope Gradient and Resulting Direction of Flow

As a release path is established, the release area is calculated and the loss of oil is computed as a function of three process terms (i.e., adherence, pooling, and evaporation; Figure 5-2). Adherence, or depression storage, is the process by which oil is lost to the ground surface and vegetation as it spreads overland. Depression storage values vary by land type (as a function of surface area, roughness, etc.) and oil type (as a function of viscosity). Depression storage represents both the puddling of oil within small surface depressions on a scale smaller than the elevation grid, and physical adhesion of oil on surfaces. Pooling is larger-scale process by which oil is trapped within depressions in the local topography (i.e., depressions that can be resolved at the resolution of the available elevation grid). Such depressions are assumed to fill with oil before additional down slope transport occurs. Evaporation is the process by which the volatile portion of the liquid oil becomes a gas that enters the atmosphere.

In the first calculation, the rate of oil loss to adhesion and puddle formation is dependent primarily on the physical characteristics of the land surface (vegetation type, land cover, slope) and the physical and chemical characteristics of the released product. A data grid specifying land cover type is used to determine the amount of oil retention on each grid cell. As oil traverses the land, a variable loss rate is calculated based upon changes in land cover type. Oil retention loss values vary by land type and oil type, with values spanning five orders of magnitude (between 0.02 and less than 200 mm) (Table 5-1). These loss rates for oil are based on surface hydrologic studies (ASCE 1969; Kouwen et al. 2002; Schwartz et al. 2002). The puddling or depression storage portion of the rate of oil loss represents the loss of oil based upon predicted sub-elevation grid scales within a grid cell, as elevation may have some heterogeneity within the scale of a single elevation grid cell.

Land cover was only used in the Mosquito Creek scenarios, as oil was assumed to enter directly into the river channels at the other four modeling locations for the OILMAP Land computational modeling. In the Mosquito Creek scenarios, a 0.5 mile stretch of grassland/herbaceous cover (during spring through fall) or snow/ice land cover (during winter months) extended downslope from the hypothetical release site to the waters of Mosquito Creek. Snow would retain a larger proportion of oil, than the grassland/herbaceous ground cover. A more complete description of the effects of snow cover may be found in Section 5.3.2.5.

Table 5-1 Range of Oil Retention Values for Each Land Cover Type, for a Light and Heavy Oil

OILMAP Land Code	Description	Light Oil (mm)	Heavy Oil (mm)
19	Unknown—data gaps, cloud cover, etc.	0.6	3.8
31	Bare rock/sand/clay	0.7	4.5
41	Deciduous forest	2.0	13.4
42	Evergreen forest	2.0	13.4
43	Mixed forest	2.0	13.4
51	Shrubland	0.6	3.8
71	Grasslands/herbaceous	0.6	3.8
82	Row crops	0.6	3.8
91	Woody wetlands	33.8	225.4
92	Emergent herbaceous wetlands	33.8	225.4
97	Tundra	0.7	4.5
98	Barren land	0.7	4.5
99	Snow/ice	*see section 5.2	

Table 5-1 Range of Oil Retention Values for Each Land Cover Type, for a Light and Heavy Oil

OILMAP Land Code	Description	Light Oil (mm)	Heavy Oil (mm)
103	Wetland	33.8	225.4
108	Impervious Surface	0.02	0.2

The second loss calculation includes oil lost to pooling on the land surface. This is defined as the volume of oil that would be retained within depressions defined by the land elevation grid. Released oil would need to fill the calculated volume of the depression before any additional oil would be allowed to travel downslope. When combined, the oil lost to the ground is the sum of adhesion, puddling and pooling.

The third loss calculation includes the evaporation of oil into the atmosphere. Evaporative loss is dependent upon the chemical and physical parameters of the oil, as well as the shape (i.e., surface area) of the release, and other environmental conditions. Some or all of the available/remaining released product may evaporate. The total amount of oil retention and loss during a release simulation includes both losses to the ground in addition to the evaporative loss to the atmosphere.

The leading edge of a release travels with a specific velocity (V), as the oil travels over the land surface. The velocity of the oil is determined using Manning's Equation, which uses the slope of the land surface and the width of the oil plume:

$$V = 1/n\ R^{2/3}\ S^{1/2}$$

Where R is the hydraulic radius and S is the slope, and n is a dimensionless number that characterizes the flow resistance from surface roughness. The hydraulic radius is a slope dependent metric of cross sectional area of flow divided by the wetted perimeter. It is calculated iteratively at each time step and is based upon flow rate. Typically R is approximately 0.122 m, which corresponds with velocity calculation that is dependent upon slope alone:

$$V = 4.92\ S^{1/2}\ \text{(meter/sec)}$$

Down-slope speed never reaches more than a few meters per second and has a minimum of 0.001 m/s. The maximum advance rate is limited by the release rate of the released oil.

In many cases, the elevation grid defining the land surface is not of sufficient resolution to define channels that direct the path of the oil. The width of the flow path increases as the slope of the land surface decreases and downslope velocity slows. Conversely, the path width decreases to a narrower channel with increasing land surface slope and increasing downslope velocity. The model uses the land surface slope to calculate the path width of the oil. It is typically around 1 m, and cannot exceed the dimension of the land elevation grid cells.

The total volume of oil loss is equal to the sum of adherence and puddling, pooled oil, and evaporation. If total oil loss equals the total release volume during overland flow, then the release is terminated at this point. If the release volume is not a limiting factor, release propagation over land terminates when the leading edge encounters a surface water feature, or when the model's set duration is reached (i.e., 24 hours for modeling described here).

As noted earlier, the total volume of oil loss on land was only applied to the Mosquito Creek scenarios. The remaining six sites involved immediate release of oil into water.

5.1.1.2 Surface Water Transport Model

For the purpose of the OILMAP Land computational model, once the released product encounters a surface water feature during the high flow in spring or the average flow in summer, it is transported through the surface water network at a velocity defined by the speed and direction of each stream segment. As oil is transported down the surface water network, there are two potential loss terms including adhesion of the released product to the stream shoreline and loss of the released product through evaporation to the atmosphere. The modeled portions of the downstream release model and the factors influencing a release in surface waters are illustrated in Figure 5-3.

During winter conditions, the surface water transport model assumes complete ice coverage (100% ice cover) of the water surface. Any oil that makes its way to the watercourse from a land spill is predicted to not enter the water body due to the coverage of ice. However, if a hypothetical release were to occur into the watercourse from an underground/underwater crossing then the model assumes all of the oil would enter into the water column itself. In this case, oil is assumed to rise through the water column and be trapped by the ice cover at the surface. The model assumes that evaporation is completely prevented (0% evaporation) due to the layer of ice on the water surface.

For the winter modeling scenarios, it is assumed that the speed of the downstream transport of oil within river sections is at the same speed as the local water velocity. However, oil is assumed to pool under the ice in lakes, due to the lower velocity. These conservative approximations maximize the extent of potential oiling. A more complete description of the effects of ice cover may be found in Section 5.3.2.6.

The distance oil is allowed to travel downstream during any season is limited by one of three factors, including:

- Adherence of all available released product on the water surface to the stream bank as shoreline oiling
- Loss of all available /remaining released product to evaporation

- Reaching a user-specified travel time limit (i.e., model duration)

User-specified travel times are typically defined in release response plans as the time required to respond to a catastrophic release. Note that the model may not run for the full user-specified travel time limit (i.e., in the case of the modeling for L3RP this was 24 hours) if either of the second two criteria are met before this point.

The amount of oil adhering to the stream shoreline varies according to the stream shore type and oil type. Five different stream shore types were defined, each with a specified bank width and range of oil retention thickness, based upon the type of oil (Table 5-2). Oil volume lost to the shoreline is calculated as the product of the length of the shoreline oiled, the specified bank width, and the oil retention thickness, which is controlled by the density and viscosity of the oil.

Table 5-2 Typical Shoreline Oil Loss Values in Oil Thickness

Shore Type	Shore Width (m)	Light Oil (mm)	Heavy Oil (mm)
Bedrock	0.5	1	4
Soil	1	2	15
Sand/Gravel	2	3	20
Grass	5	4	25
Marsh	20	6	40

Oil movement across lakes is simulated based on lake size, shape, and water flow characteristics. Oil is assumed to spread radially across the lake surface until it covers the entire lake, or until the oil slick reaches a specified minimum thickness. If the minimum thickness is reached, spreading stops and the oil travels no farther. The minimum slick thickness is dependent upon the oil type, as density, viscosity, and other chemical and physical parameters control the behavior of oil on the water surface. Typical values for minimum slick thickness range from microns (μm) to millimeters (mm). In the case of the OILMAP Land computational model, if oil covers the entire lake surface before reaching the minimum thickness, the remaining oil is allowed to continue to move down any out-flowing streams at the velocity defined for that specific stream segment.

Dissolution—the process where water-soluble components of oil diffuse out of the oil and into the water—is not addressed by the OILMAP Land computational model. Dissolution is considered by SIMAP; accordingly this modeling system was used for the two modeling locations on the larger sections of the Mississippi River where dissolution and entrainment of oil was identified as a concern.

5.1.1.3 Evaporation in Overland and Surface Water Models

Evaporation is the process where volatile components of the oil diffuse out of the oil and enter a gaseous phase in the atmosphere. Oil evaporates as it spreads over land and water. The most volatile hydrocarbons (i.e., those having a low carbon number) evaporate most rapidly, typically in less than a day and sometimes in under an hour (McAuliffe 1989). As oil evaporates its composition changes, affecting its density and viscosity, as well as subsequent evaporation. As lighter components evaporate off, the remaining "weathered" oil becomes more viscous. As the oil continues to weather and, particularly, if it forms a water-in-oil emulsion, evaporation will be substantially decreased.

OILMAP Land uses a method called the Evaporative Exposure Model[8] of Stiver and Mackay (1984), which is used in oil release models of all kinds, both water and land based, to predict the volume fraction evaporated.

Several simplifying assumptions are made in modeling that directly affects the amount of oil predicted to evaporate. In general, the rate of evaporation depends on surface area, oil thickness, and vapor pressure, which are functions of the composition of the oil, wind speed, and air and land temperature. The mass of oil evaporated is particularly sensitive to the surface area of the spreading oil and the time period over which evaporation is calculated. On the land surface, the exposed surface area and evaporation time are functions of the slope, which is defined by the elevation grid. Steeper slopes cause the oil to travel faster but along a narrower path, while a lower slope slows the speed of advance and increases the width of the oiled path. In general, evaporation from surface and shoreline oil increases as the oil surface area, temperature, and wind speed increase.

In the stream network, the surface area of oiled water is a function of the total length of the oiled reach of the stream, times the average width of the same reach. The total length oiled is a function of stream velocity. The surface area of the oil surface then defines the rate of evaporation. Oil loss to evaporation is assumed to continue until the simulation is terminated. Termination may occur for a number of reasons, including:

- Oil loss to the ground surface, stream banks, and evaporation exceeds the volume released
- Release reaches its minimum thickness on a lake surface
- Release reaches either a dead end in the stream network or the coastline
- User-specified travel time limit (i.e., model duration) is reached

[8] The Evaporative Exposure Model of Stiver and Mackay (1984) is used to determine the rate of evaporation for spills of hydrocarbons and petroleum mixtures. The model uses the specified oil type's physical and chemical characteristics to determine the rate of evaporation, which includes the initial boiling point, the gradient of the distillation curve (i.e., the relationship between the oils liquid temperature and the fraction of oil condensed), and relationships between Henry's Law Constant, along with environmental parameters including temperature and wind speed.

In reality, oil will continue to evaporate from the ground or water surface, increasing the total evaporation amount. This conservative calculation of evaporative loss used in the OILMAP Land modeling system is consistent with a worst-case scenario approach.

For a release on the water surface, the gravitational spreading of the released oil occurs very rapidly (within hours) to a minimum slick thickness. Thus, the area exposed to evaporation is high relative to the oil volume. Evaporation proceeds faster than dissolution. Thus, most of the volatiles and semi-volatiles evaporate, with a smaller fraction dissolving into the water.

Evaporation is faster as the wind speed increases. However, above about 12 knots (6 m/s) of wind speed and in open water, white caps begin to form and the breaking waves entrain oil as droplets into the water column. Higher wind speeds (and turbulence) increase entrainment and results in smaller droplet sizes. These fates processes are not captured in the OILMAP Land model. More sophisticated (3D) modeling of oil transport and fate such as SIMAP take these factors into account.

5.1.1.4 Use of the OILMAP Land Modeling System for the L3RP

OILMAP Land was used for five of the seven modeling locations to predict the trajectory and fate of a large release of crude oil under different seasonal flow conditions and with different types of crude oil. The modeled scenarios did not include any response activities (i.e., unmitigated). The OILMAP Land modeling system was used to predict the expected downstream extent of oil transport (i.e., maximum downstream distance of a release at a specific time period) and the predicted mass balance of oil over the first 24 hours following the hypothetical release, including time steps at 6 and 12 hours. The mass balance reflects the amount of shoreline retention, evaporation, and oil remaining on the water surface over the first 24 hours following a release, or until no further oil is predicted to remain on the river surface (i.e., all oil is predicted to have evaporated or adhered to shorelines before 24 hours had passed). If there was oil on the river surface after 24 hours and the release was left unmitigated, it would continue downstream, and would continue to oil shorelines and evaporate until no oil remained. As an emergency response would be initiated soon after a release, the 24 hour time limit is considered appropriate and consistent with the conservative approach taken in this assessment.

5.1.1.5 Uncertainties in the OILMAP Land Modeling System

The OILMAP Land model is a simplified modeling system that was developed over many years to provide a conservative approximation of the maximum extent and maximum shoreline oiling that may be possible in the event of a release. However, there are limits to the complexity of processes that are modeled, as well as gaps in the underlying data that were used. As has been discussed, some simplifications have been made regarding steady-state currents and the behavior of oil on water and under ice. Additionally, the model does not take into account the influence of wind on the transport of oil on water. There is a degree of uncertainty related to the terrain, as these datasets do not contain the full-scale horizontal resolution (i.e., <1 cm) that may affect an actual release. Furthermore, the assumptions of 100% shoreline oil retention and land retention values do err on the side of conservatism. Finally, the radial spreading of oil in lakes is a simplification that would err on the side of maximum surface oiling and maximum extent. While OILMAP Land may simplify real world releases, results from several actual releases on land compared well to the modeled predictions (Fontenault 2015; and other unpublished work).

5.1.2 SIMAP

The SIMAP modeling system was used to predict the trajectory and fate of hypothetical large releases of crude oil at two modeling locations on the Mississippi River: Mississippi River at Palisade and Mississippi River at Little Falls (Table 3-5).

The SIMAP modeling system was developed by RPS. It originated from the oil fate and biological effects submodels in the NRDA Models for Coastal and Marine Environments (NRDAM/CME) and Great Lakes Environments (NRDAM/GLE), which ASA developed in the early 1990s for the U.S. Department of the Interior for use in "type A" NRDA regulations under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). The most recent version of the type A models, the NRDAM/CME (Version 2.4, April 1996) was published as part of the CERCLA type A NRDA Final Rule (Federal Register, May 7, 1996, Vol. 61, No. 89, p. 20559-20614). The technical documentation for the NRDAM/CME is in French et al. (1996). This technical development involved several in-depth peer reviews, as described in the Final Rule.

While the NRDAM/CME and NRDAM/GLE were developed for simplified natural resource damage assessments of small releases in the U.S., SIMAP is designed to evaluate fate and effects of both real and hypothetical releases in marine, estuarine, and freshwater environments worldwide. Additions and modifications to SIMAP were made to increase model resolution, allow modification and site-specificity of input data, allow incorporation of spatially and temporally varying current data, evaluate subsurface releases and movements of subsurface oil, track multiple chemical components of the oil, enable stochastic modeling, and facilitate analysis of results.

The fates and effects models in the SIMAP modeling system are described below. Detailed descriptions of the algorithms and assumptions in the model are provided in French McCay 2002, 2003, 2004, and 2009. The model has been validated with more than 20 case histories, including the Exxon Valdez and other large releases (French and Rines 1997; French McCay 2003 and 2004; French McCay and Rowe 2004), as well as test releases designed to verify the model (French et al. 1997).

SIMAP estimates the distribution of whole oil and oil components (as mass and concentrations) on the water surface, on shorelines, in the water column, and in sediments. Oil fate processes in SIMAP are oil spreading (gravitational and by shearing), evaporation, transport, randomized dispersion, emulsification, entrainment (natural and facilitated by dispersant), dissolution, volatilization of dissolved hydrocarbons from the surface water, adherence of oil droplets to suspended sediments, adsorption of soluble and sparingly-soluble aromatics to suspended sediments, sedimentation, and degradation.

Oil is a mixture of hydrocarbons of varying physical, chemical, and toxicological characteristics. Thus, oil hydrocarbons have varying fates and effects on organisms. In the SIMAP model, oil is represented by component categories, and the fate of each component is tracked separately. The "pseudo-component" approach (Payne et al. 1984 and 1987; French et al. 1996; Jones 1997; Lehr et al. 2000) is used, where chemicals in the oil mixture are grouped by physical-chemical properties, and the resulting component category behaves as if it were a single chemical with characteristics typical of the chemical group.

The most toxic components of oil to aquatic organisms are low molecular weight aromatic compounds (monoaromatic and polycyclic aromatic hydrocarbons, MAHs and PAHs), which are both volatile and soluble in water. Their acute toxic effects are caused by non-polar narcosis, where toxicity is related to the octanol-water partition coefficient (Kow), a measure of hydrophobicity. The more hydrophobic the compound, the more toxic it is likely to be. However, as Kow increases, the compound also becomes less soluble in water, so there is less exposure to aquatic organisms. The toxicity of compounds with log (Kow) values greater than about 5.6 is limited by their very low solubility in water and consequent low bioavailability (French McCay 2002; Di Toro et al. 2000). Thus, the potential for acute effects is the result of a balance between bioavailability, toxicity once exposed, and duration of exposure. French McCay (2002) contains a full description of the oil toxicity model in SIMAP. French McCay (2003, 2009) describes the implementation of the toxicity model in SIMAP.

Because of these considerations, the SIMAP fates model focuses on tracking the lower molecular weight aromatic components divided into chemical groups based on volatility, solubility, and hydrophobicity. In the model, the oil is treated as comprising eight components (Table 5-3).

Table 5-3 Definition of Four Distillation Cuts and the Eight Pseudo-Components in SIMAP (MAHs; benzene + toluene + ethybenzene + xylene, BTEX; PAHs)

Characteristic	Volatile and Highly Soluble	Semi-Volatile and Soluble	Low Volatility and Slightly Soluble	Residual (non-volatile and very low solubility)
Distillation cut	1	2	3	4
Boiling point (°C)	< 180	180–265	265–380	> 380
Molecular weight	50–125	125–168	152–215	> 215
Log (K_{ow})	2.1–3.7	3.7–4.4	3.9–5.6	> 5.6
Aliphatic pseudo-components: number of carbons	volatile aliphatics: C4 - C10	semi-volatile aliphatics: C10 - C15	low-volatility aliphatics: C15 - C20	non-volatile aliphatics: > C20
Aromatic pseudo-	MAHs:	2 ring PAHs: C4-	3 ring PAHs: C3-,	≥ 4 ring aromatics:

Table 5-3 Definition of Four Distillation Cuts and the Eight Pseudo-Components in SIMAP (MAHs; benzene + toluene + ethybenzene + xylene, BTEX; PAHs)

Characteristic	Volatile and Highly Soluble	Semi-Volatile and Soluble	Low Volatility and Slightly Soluble	Residual (non-volatile and very low solubility)
component name: included compounds	BTEX, MAHs to C3-benzenes	benzenes, naphthalene, C1-, C2-naphthalenes	C4-naphthalenes, 3-4 ring PAHs with $\log(K_{ow}) < 5.6$	PAHs with $\log(K_{ow}) > 5.6$ (very low solubility)

Six of the components (i.e., all but the two non-volatile residual components representing non-volatile aromatics and aliphatics) evaporate at rates specific to the pseudo-component. Solubility is strongly correlated with volatility, and the solubility of aromatics is higher than aliphatics of the same volatility. The MAHs are the most soluble, the two-ring PAHs are less soluble, and the three-ring PAHs slightly soluble (Mackay et al. 1992). Both the solubility and toxicity of the non-aromatic hydrocarbons are much lower than for the aromatics, and dissolution (and water concentrations) of non-aromatics is safely ignored. Thus, dissolved concentrations are calculated only for each of the three soluble aromatic pseudo-components.

This number of components provides sufficient accuracy for the evaporation and dissolution calculations, particularly given the time frame (minutes) over which dissolution occurs from small droplets and the rapid resurfacing of large droplets. The alternative approach of treating oil as a single compound with empirically-derived rates (e.g., Mackay et al. 1980; Stiver and Mackay 1984) does not provide sufficient accuracy for environmental effects analyses because the effects to water column organisms are caused by MAHs and PAHs, which have specific properties that differ from the other volatile and soluble compounds. The model has been validated both in predicting dissolved concentrations and resulting toxic effects, supporting the adequacy of the use of this number of pseudo-components (French McCay 2003).

The lower molecular weight aromatics dissolve from the whole oil and are partitioned in the water column and sediments according to equilibrium partitioning theory (French et al. 1996; French McCay 2004). The residual fractions in the model are composed of non-volatile and insoluble compounds that remain in the "whole oil" that spreads, is transported on the water surface, strands on shorelines, and disperses into the water column as oil droplets or remains on the surface as tar balls. This is the fraction that composes black oil, mousse, and sheen.

5.1.2.1 Oil Fate Model Processes

Because oil contains many chemicals with varying physical-chemical properties and the environment is spatially and temporally variable, the oil rapidly separates into different phases or parts of the environment; specifically:

- Surface oil

- Emulsified oil (mousse) and tar balls
- Oil droplets suspended in the water column
- Oil adhering to suspended particulate matter in the water
- Dissolved lower molecular weight components (MAHs, PAHs, and other soluble components) in the water column
- Oil on and in the sediments
- Dissolved lower molecular weight components (MAHs, PAHs, and other soluble components) in the sediment pore water
- Oil on and in the shoreline sediments and surfaces

The oil fate processes simulated by SIMAP in near shore and riverine environments are shown schematically in Figure 5-5.

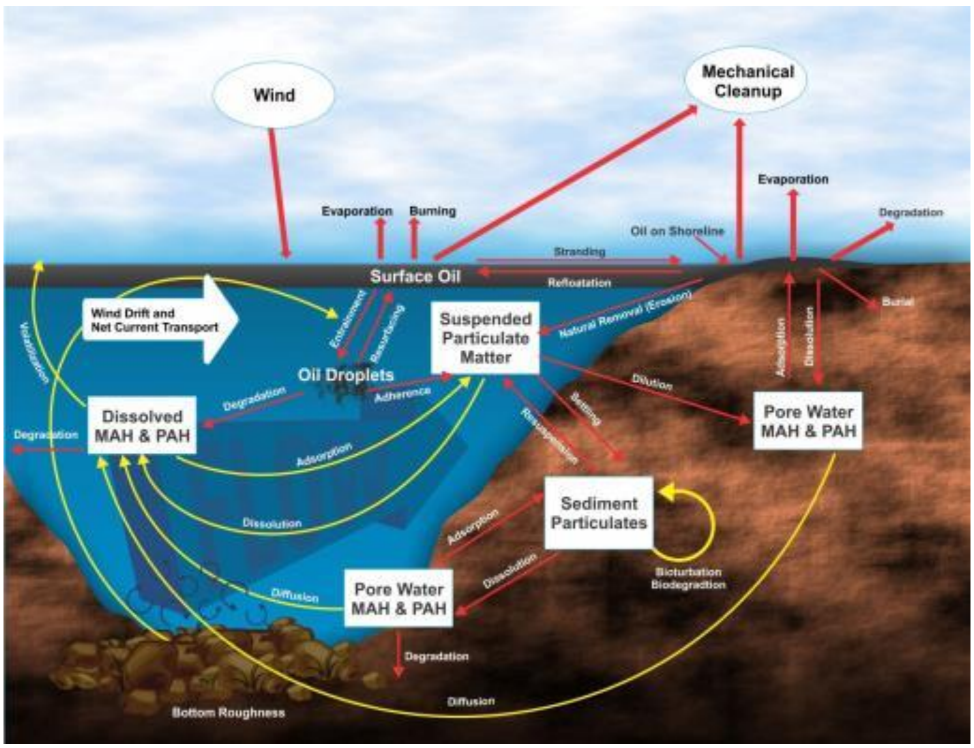

Figure 5-5 Oil Fates Processes in Lakes and Rivers That are Simulated by SIMAP

- **Spreading** is the thinning and broadening of surface slicks caused by gravitational forces and surface tension. This occurs rapidly after oil is released on the water surface. The spreading rate is faster when oil viscosity is lower at higher temperatures. Viscosity increases as oil emulsifies.
- **Transport** is the process where oil is carried by currents.
- **Turbulent dispersion** is the process by which turbulence ("sub-scale" currents that mix oil in three dimensions) spreads oil components on the surface and into the water column.

- **Evaporation** is the diffusion of volatile compounds from oil into a gaseous phase in the atmosphere. Evaporation from surface and shoreline oil increases as the oil surface area, temperature, and wind speed increase. As lighter components evaporate, the remaining "weathered" oil becomes more viscous.
- **Emulsification** is the mixture of water into the oil, such that the oil forms a matrix with embedded water droplets. The resulting mixture is commonly called mousse, which is technically a water-in-oil emulsion. The rate of emulsification increases with increasing wind speed and turbulence on the surface of the water. Viscosity increases as oil emulsifies.
- **Entrainment** is the process by which waves break over surface oil and carry oil droplets into the water column. At higher wind speeds (about 12 knots, or 6 m/s) or where currents and bottom roughness induce turbulence in a river or stream, wave heights may reach a threshold where they break. Thus, entrainment becomes increasingly important (higher rate of mass transfer to the water) with higher wind speeds.
- **Resurfacing** of entrained oil occurs rapidly for larger oil droplets. Smaller droplets resurface when the wave turbulence decreases. The smallest droplets do not resurface, as typical turbulence levels in the water keep them indefinitely suspended. Local winds at the water surface can also prevent oil from surfacing.
- **Dissolution** is the diffusion of water-soluble components out of the oil and into the water. Dissolution rate increases as the surface area of the oil relative to its volume increases. Since the surface area to volume ratio is higher for smaller spherical droplets, smaller droplet sizes have higher dissolution rates.
- **Volatilization** of dissolved components from the water to the atmosphere occurs as they mix, diffuse to the water surface boundary, and enter the gas phase. Volatilization rates increase with increasing air and water temperature.
- **Adsorption** of dissolved components to particulate matter in the water occurs because the soluble components (MAHs and PAHs) preferentially adsorb to particulates when the latter are present. The higher the concentration of suspended particulates, the more adsorption occurs. Also, the higher the molecular weight of the compound, the less soluble it is, and the more it tends to adsorb to particulate matter.
- **Adherence** is combination of oil droplets with particles in the water. If the particles are suspended sediments, the combined oil/suspended sediment agglomerate is heavier than the oil and the surrounding water. If turbulence subsides, the oil-sediment agglomerates will settle.
- **Sedimentation (settling)** is the process where oil-sediment agglomerates and particles with adsorbed sparingly-soluble components (MAHs and PAHs) settle to the bottom sediments. Sedimentation can be an important oil pathway in near shore areas when waves are strong and subsequently subside. Generally, oil-sediment agglomerates transfer more PAHs to the bottom than sediments with PAHs adsorbed from the dissolved phase in the water column.
- **Resuspension** of settled oil-sediment agglomerates and particles with adsorbed sparingly-soluble components (MAHs and PAHs) may occur if current speeds and turbulence exceed threshold values for overcoming cohesive forces.
- **Diffusion** is the process where dissolved compounds move from higher to lower concentration areas by random motion of molecules and micro-scale turbulence. Dissolved components in bottom and shoreline sediments can diffuse out to the water column where concentrations are relatively low. Bioturbation, groundwater discharge, and hyporheic flow of water through stream-bed sediments can greatly increase the rate of diffusion from sediments (see below).
- **Hyporheic flow** is the movement of water through stream bed sediments, induced by pressure differentials associated with stream bed irregularities or groundwater discharge.

- **Dilution** occurs when water of lower concentration is mixed into water with higher concentration by turbulence, currents, or shoreline groundwater.
- **Bioturbation** is the process by which benthic fauna mix the surface sediment layer while burrowing, feeding, or passing water over their gills. In open-water soft-bottom environments with minimal or no pollution, bioturbation effectively mixes the top 10 cm of the sediment layer.
- **Degradation** is when oil components are changed either chemically or biologically (biodegradation) into another compound. Degradation occurs through breakdown to simpler organic carbon compounds by bacteria and other organisms, photo-oxidation by solar energy, and other chemical reactions. Higher temperature and higher light intensity (particularly ultraviolet wavelengths) increase the rate of degradation.
- **Stranding and refloatation** occur when floating oil meets the shorelines and then refloats as water levels rise, allowing the oil to move further down current or downstream.

5.1.2.2 Overview of Processes Affecting a Release of Oil

Following a release of oil on the water surface, gravitational spreading occurs very rapidly (within hours) to a minimum thickness. Thus, the area exposed to evaporation is high relative to the oil volume. Evaporation proceeds faster than dissolution. Thus, most of the volatiles and semi-volatiles evaporate, with a smaller fraction dissolving into the water. Degradation (photo-oxidation and biodegradation) also occurs at a relatively slow rate compared to these processes.

As mentioned previously, evaporation is faster as the wind speed increases. Above about 12 knots (6 m/s) of wind speed and in open water conditions, white caps begin to form and the breaking waves entrain oil as droplets into the water column. These processes are modeled in SIMAP and higher wind speeds (and turbulence) increase entrainment and results in smaller droplet sizes. From Stoke's Law, larger droplets resurface faster and form surface slicks. Thus, a dynamic balance evolves between entrainment and resurfacing. As high- wind events occur, the entrainment rate increases. When the winds subside to less than 12 knots, the larger oil droplets resurface and remain floating. Similar dynamics occur in turbulent streams.

The smallest oil droplets remain entrained in the water column for an indefinite period. Larger oil droplets rise to the surface at varying rates. While the droplets are under water, dissolution of the light and soluble components occurs. Dissolution rate is a function of the surface area available. Thus, most dissolution occurs from droplets, as opposed to from surface slicks, since droplets have a higher surface area to volume ratio, and they are not in contact with the atmosphere (and so the soluble components do not preferentially evaporate as they do from surface oil).

If oil is released or driven underwater, it forms droplets of varying sizes. The more turbulent the conditions, the smaller the droplet sizes. From Stoke's Law, larger droplets rise faster, and surface if the water is shallow. Resurfaced oil behaves as surface oil after gravitational spreading has occurred. The surface oil may be re-entrained. In most cases, the smallest droplets remain in the water permanently. As a result of the higher surface area per volume of small droplets, the dissolution rate is much higher from subsurface oil than from floating oil on the water surface.

Because of these interactions, the majority of dissolved constituents (which are of concern because of potential effects on aquatic organisms) are from droplets entrained in the water. For a given release volume and oil type/composition, with increasing turbulence either at the water surface and/or at the stream bed: there is an increasing amount of oil entrained; the oil is increasingly broken up into smaller droplets; there is more likelihood of the oil remaining entrained rather than resurfacing; and the dissolved concentrations will be higher. Entrainment and dissolved concentrations increase with (1) higher wind speed, (2) increased turbulence from other sources of turbulence (waves on a beach, rapids, and waterfalls in rivers, etc.), and (3) subsurface releases (especially under higher pressure and turbulence.

These processes that increase the rate of supply of dissolved constituents are balanced by loss terms in the model: (1) transport (dilution), (2) volatilization from the dissolved phase to the atmosphere, (3) adsorption to suspended particulate material (SPM) and sedimentation, and (4) degradation (photo-oxidation or biologically mediated). Other processes slow the entrainment rate: (1) emulsification increases viscosity and slows or eliminates entrainment, (2) adsorption of oil droplets to SPM and settling removes oil from the water, (3) and stranding on shorelines removes oil from the water. Thus, the model-predicted concentrations are the resulting balance of all these processes and the best estimates based on our quantitative understanding of the individual processes.

5.1.2.3 Oil Fate Algorithms

The algorithms used to model oil fate processes are described in French McCay (2004). Lagrangian elements (spillets) are used to simulate the movements of oil components in three dimensions over time. Within the model, releases of oil are broken down into many thousands of discrete or individual elements (i.e., Lagrangian Elements referred to as spillets) that are forced and tracked individually throughout the modeled domain. Surface floating oil, subsurface droplets, and dissolved components are tracked in separate spillets. Transport is the sum of advective velocities based on the input on watercourse currents to the model, surface wind drift, vertical movement according to buoyancy, and randomized turbulent diffusive velocities in three dimensions. The vertical diffusion coefficient is computed as a function of wind speed in the surface wave-mixed layer. The horizontal and deeper water vertical diffusion coefficients are model inputs.

The model separates oil (whole and as pseudo-components [Section 5.1.2]) into different phases or parts of the environment. SIMAP considers: surface slicks; emulsified oil (mousse) and tar balls; oil droplets suspended in the water column; dissolved lower molecular weight components (MAHs and PAHs) in the water column; oil droplets adhered and hydrocarbons adsorbed to suspended particulate matter in the water; hydrocarbons on and in the sediments; dissolved MAHs and PAHs in the sediment pore water; and hydrocarbons on and in the shoreline sediments and surfaces.

The algorithms used to calculate these fates processes are briefly described in the subsections below.

5.1.2.3.1 Transport

Spillets are moved in three dimensions over time. For each model time step, the new vector position of the spillet center is calculated from the old location plus the vector sum of east-west, north-south, and vertical components of advective and diffusive velocities:

$$Xt = X\,t\text{-}1 + \Delta t\ (\,Ut + Dt + Rt + Wt\,)$$

where Xt is the vector position at time t, Xt-1 is the vector position the previous time step, Δt is the time step, Ut is the sum of all the advective (current) velocity components in three dimensions at time t, Dt is the sum of the randomized diffusive velocities in three dimensions at time t, Rt is the rise or sinking velocity of whole oil droplets in the water column, and Wt is the surface wind transport ("wind drift"). The magnitudes of the components of Dt are scaled by horizontal and vertical diffusion coefficients (Okubo and Ozmidov 1970; Okubo 1971). The vertical diffusion coefficient is computed, based on Thorpe (1984), as a function of wind speed in the surface wave-mixed layer (which ranges from centimeter scales in rivers and near lee shorelines to potentially meters in large water bodies away from shore when wind speeds are high). Rt is computed by Stokes law, where velocity is related to the difference in density between the particle and the water, and to the particle diameter. The algorithm developed by Youssef and Spaulding (1993) is used for wind transport in the surface wave-mixed layer (Wt, described below).

5.1.2.3.2 Shoreline Stranding

The fate of released oil that reaches the shoreline depends on characteristics of the oil, the type of shoreline, and the energy environment. The stranding algorithm is based on work by CSE/ASA/BAT (1986), Gundlach (1987), and Reed and Gundlach (1989) in developing the COZOIL model for the U.S. Minerals Management Service. In SIMAP, deposition occurs when an oil spillet intersects shore surface. Deposition ceases when the model determines that the volume holding capacity for the shore surface is reached. The model does not allow subsequent oil coming ashore to remain on the shore surface. It is assumed to be refloated by rising water, and carried away by currents and wind drift SIMAP then removes the remaining shoreline oil exponentially over time. Data for holding capacity and removal rate are taken from CSE/ABA/BAT (1986) and Gundlach (1987), and are a function of oil viscosity and shore type. The algorithm and data are provided in French et al. (1996).

5.1.2.3.3 Spreading

Spreading determines the areal extent of the surface oil which, in turn, influences its rates of evaporation, dissolution, dispersion (entrainment), and photo-oxidation, all of which are functions of surface area. Spreading results from the balance among the forces of gravity, inertia, viscosity, and surface tension (which increases the diameter of each spillet). The model also considers two other processes that can influence the spreading of an oil release: turbulent diffusion (which spreads the spillets apart); and entrainment followed by resurfacing, which can spatially separate the leading edge of the oil from resurfaced oil transported in a different direction by subsurface currents.

For many years, Fay's (1971) three-regime spreading theory was widely used in oil spill models (ASCE 1996). Mackay et al. (1980, 1982) modified Fay's approach and described the oil as thin and thick slicks. Their approach used an empirical formulation based on Fay's (1971) terminal spreading behavior. They assumed the thick slick feeds the thin slick and that 80–90% of the total slick area is represented by the thin slick. In SIMAP, oil spillets on the water surface increase in diameter according to the spreading algorithm empirically-derived by Mackay et al. (1980, 1982). Sensitivity analyses of this algorithm led to the discovery that the solution was affected by the number of spillets used. Thus, a formulation was derived to normalize the solution under differing numbers of surface spillets (Kolluru et al. 1994). Spreading is stopped when an oil-specific terminal thickness is reached.

5.1.2.3.4 Evaporation

The rate of evaporation depends on surface area, thickness, vapor pressure, and mass transport coefficient which, in turn, are functions of the composition of the oil, wind speed, and temperature (Fingas 1996, 1997, 1998, 1999; Jones 1997). As oil evaporates, its composition changes, affecting its density and viscosity, as well as subsequent evaporation. The most volatile hydrocarbons evaporate most rapidly, typically in less than a day and sometimes in under an hour (McAuliffe 1989). As the oil continues to weather, and particularly if it forms a water-in-oil emulsion, evaporation will be significantly decreased.

The evaporation algorithm in SIMAP is based on accepted evaporation theory, which follows Raoult's Law that each component will evaporate with a rate proportional to the saturation vapor pressure and mole fraction present for that component. The pseudo-component approach (Payne et al. 1984; French et al. 1996; Jones 1997; Lehr et al. 2000) is used, such that each component evaporates according to its mean vapor pressure, solubility, and molecular weight. The mass transfer coefficient is calculated using the methodology of Mackay and Matsugu (1973), as described in French et al. (1996).

5.1.2.3.5 Entrainment

As oil on the water surface is exposed to wind and waves, or if oil moves into a turbulent area of a stream or river, it is entrained (or dispersed) into the water column. Entrainment is a physical process where globules of oil are transported from the water surface into the water column due to breaking waves or other turbulence. It has been observed that entrained oil is broken into droplets of varying sizes. Smaller droplets spread and diffuse in the water column, while larger ones rise back to the surface.

5.1.2.3.5.1 Entrainment by Breaking Surface Wave Action

In open waters, breaking waves created by the action of wind and waves on the water surface are the primary sources of energy for entrainment. Entrainment is strongly dependent on turbulence and is greater in areas of high wave energy (Delvigne and Sweeney 1988).

Delvigne and Sweeney (1988), using laboratory and flume experimental observations, developed a relationship for entrainment rate and oil droplet size distribution as a function of turbulent energy level and oil viscosity. Entrained droplets in the water column rise according to Stokes law, where velocity is related to the difference in density between the particle and the water, and to the particle diameter. The data and relationships in Delvigne and Sweeney (1988) are used in SIMAP to calculate the mass and particle size distribution of entrained droplets. Particle size decreases with higher turbulent energy level and lower oil viscosity. The natural dispersion particle sizes observed by Delvigne and Sweeney (1988) are confirmed by field observations by Lunel (1993a, 1993b).

Entrained oil is mixed uniformly throughout the wave-mixed zone. Vertical mixing is simulated by random placement of particles within the wave-mixed layer each time step. Settling of particles does not occur in water depths where waves reach the bottom (taken as 1.5 times wave height). Wave height is calculated from wind speed, duration, and fetch (distance upwind to land), using the algorithms in CERC (1984). Wave height is on the scale of centimeters in small rivers and streams and near lee shorelines; whereas it may increase to meters in open waters under windy conditions.

5.1.2.3.5.2 Entrainment by Bottom Roughness in Streams

When modeling oil releases in rivers, entrainment of oil into the water column by turbulent flow over bottom structures and around obstacles must be taken into consideration. It is clear that in rapid flow where turbulence is large, rocks or other obstacles may break the surface and a plunging wake may occur where the possibility of entrainment increases. Delvigne (1993) demonstrated that breaking wave dispersion to fast flow past an obstacle, such as a pile, generates a plunging wake. This is sufficiently similar to breaking waves from alternative sources of turbulence such as the fast flow past an obstacle, flow over a dam, cataract with a hydraulic jump, or a vessel crossing an oil slick. In the breaking wave model, the dispersion of energy leads to the plunging of oil into water and the formation of oil droplets.

To relate this more generally to a river formulation, an energy dissipation relationship was developed. In this formulation, energy dissipation is proportional to the stream flow rate and bottom roughness, and is inversely proportional to the local depth. The generation and propagation of turbulent energy through the water column due to bottom roughness is applied with a typical quadratic stress equation to the plunging flow (Anderson et al. 1995). The dispersed mass of oil is determined by scaling the surface area covered by oil at the dispersion source and the range of oil droplet sizes, which is a function of the dispersion energy.

5.1.2.3.6 Emulsification (Mousse Formation)

The formation of water-in-oil emulsions, or mousse, depends on oil composition and turbulence level. Emulsified oil can contain as much as 80% water in the form of micrometer-sized droplets dispersed within a continuous phase of oil (Daling and Brandvik 1988; Fingas et al. 1997). Viscosities are typically much higher than that of the parent oil. The incorporation of water also dramatically increases the oil/water mixture volume.

SIMAP uses the Mackay and Zagorski (1982) emulsification scheme for floating oil. Water content increases exponentially, with the rate related to the square of wind speed and previous water incorporation. Viscosity is a function of water content. The change in viscosity feeds back in the model to the entrainment rate.

5.1.2.3.7 Dissolution

Dissolution is the process by which soluble hydrocarbons enter the water from a surface slick or from entrained oil droplets. The lower molecular weight hydrocarbons tend to be both more volatile and more soluble than those of higher molecular weight. For surface slicks, since the partial pressures tend to exceed the solubility of these lower molecular weight compounds, evaporation accounts for a larger portion of the mass than dissolution (McAuliffe 1989), except perhaps under ice. Dissolution and evaporation are competitive processes. The dissolved component concentration of hydrocarbons in water under a surface slick shows an initial increase followed by a rapid decrease after some hours due to the evaporative loss of components. Most soluble components are also volatile and direct evaporation (volatilization) from the water column depletes their concentrations in the water. Dissolution is a particularly important weathering process where evaporation is low (dispersed oil droplets and ice-covered surfaces). Dissolution can be substantial from entrained droplets because of the lack of atmospheric exposure and because of the higher surface area per unit of volume.

SIMAP uses the model developed by Mackay and Leinonen (1977) to calculate dissolution from a surface slick. The slick (spillet) is treated as a flat plate, with a mass flux (Hines and Maddox 1985) related to solubility and temperature. It assumes a well-mixed layer with most of the resistance to mass transfer lying in a hypothetical stagnant region close to the oil. For subsurface oil, dissolution is treated as a mass flux across the surface area of a droplet (treated as a sphere) in a calculation analogous to the Mackay and Leinonen (1977) algorithm. The dissolution algorithm was developed in French et al. (1996).

5.1.2.3.8 Volatilization from the Water Column

SIMAP uses the procedure outlined by Lyman et al. (1982), based on Henry's Law and mass flux (Hines and Maddox 1985) to calculate volatilization from the water column. The volatilization depth for dissolved substances is limited to the maximum of one half the wave height. Wave height is computed from the wind speed and fetch (CERC 1984). The volatilization algorithm was developed in French et al. (1996).

5.1.2.3.9 Adsorption and Sedimentation

Aromatics dissolved in the water column are carried to the sediments primarily by adsorption to suspended particulates and subsequent settling. The ratio of adsorbed (C_a) to dissolved (C_{dis}) concentrations is computed from standard equilibrium partitioning theory as:

$$C_a / C_{dis} = K_{oc} \, C_{ss}$$

K_{oc} is a dimensionless partition coefficient and C_{ss} is the concentration of SPM in the water column expressed as mass of particulate per volume of water. As a default, the model uses a mean value of total suspended solids of 10 mg/l (Kullenberg 1982); alternatively data on suspended sediment concentrations in a watercourse can be used as model input.

Sedimentation of oil droplets occurs when the specific gravity of oil increases over that of the surrounding water. Several processes may act on entrained oil and surface slicks to increase density: weathering (evaporation, dissolution and emulsification), adhesion or sorption onto suspended particles or detrital material, and incorporation of sediment into oil during interaction with suspended particulates, bottom sediments, and shorelines. Rates of sedimentation depend on the concentration of suspended particulates and the rates of particulate flux into and out of an area. In areas with high suspended particulate concentrations, rapid dispersal and removal of oil is found due to sorption and adhesion (Payne and McNabb 1984).

Kirstein et al. (1987) and Payne et al. (1987) used a reaction term to characterize the water column interactions of oil and suspended particulates. The reaction term represents the collision of oil droplets and suspended matter, accounting for both oiled and unoiled particulates. The model formulation developed by Kirstein et al. (1987) is used to calculate the volume of oil adhered to particles. In the case where the oil mass is larger than the adhered sediment (i.e., the sediment has been incorporated into the oil), the buoyancy of the oil droplet will control its settling or rise rate. Within SIMAP, the Stoke's law formulation is used to adjust the vertical position of these particles. If the mass of adhered droplets is small relative to the mass of the sediment it has adhered to, the sediment settling velocity will control the fate of the combined particulate.

5.1.2.3.10 Degradation

Degradation may occur as the result of photolysis or photo-oxidation, which is a chemical process energized by ultraviolet light from the sun, and by microbial breakdown, termed biodegradation. In SIMAP, degradation occurs on the surface slick, deposited oil on the shore, the entrained oil and aromatics in the water column, and oil in the sediments. SIMAP employs a first order decay algorithm, with a specified (total) degradation rate for each oil type: surface oil, water column oil, and sedimented oil (French et al. 1999).

5.1.2.4 The Application of SIMAP for Effects Assessment

For both of the Mississippi River locations that were modeled with SIMAP, multiple release scenarios were run to simulate the expected behavior of two oil types (Bakken crude or CLB/CLWB) under three seasonal and environmental conditions (high-, average-, and low-river flow, representing spring, summer, and winter, respectively). This resulted in a total of 12 SIMAP trajectory and fates scenarios (2 locations x 2 oils x 3 seasons). The intent was to provide a range of representative trajectories and fates to understand the range of potential effects that may be anticipated under varying geographic and environmental conditions.

A deterministic modeling approach was used to provide a prediction of a representative individual release, based on specific parameters for each single event. The deterministic trajectory simulations provided representative estimates of the oil's fate and transport for a specific set of environmental conditions. Each scenario assumed that the total volume of released oil for the release location (Table 3-5) was released in a series of spillets over 10 minutes, where the trajectory, fate, and effects were tracked for the following 24 hours after the release. All modeled releases were assumed to be unmitigated, meaning that no response efforts were undertaken (e.g., booming, burning, skimming, collection).

The results of the deterministic simulations provide a time history of oil weathering (i.e., mass balance) over the 24 hour duration for the spill modeling, expressed as the percentage of released oil on the water surface, on the shoreline, evaporated, entrained in the water column, and decayed. In addition, times series snapshots of the individual trajectories showing location of floating surface oil, shoreline oil, and the concentration of dissolved aromatics in the water column (surface and profile view) are provided. Summary figures of results are provided for each combination of release location, oil type, and modeled season (Section 6.2).

As was discussed in the OIMLAP Land Application (Section 5.1.1), the SIMAP modeling results were used to assess potential environmental effects through two major methods: an overlay of the predicted trajectory of the oil release of HCAs and AOIs; and an assessment of effects on key receptors of the natural and human environment.

5.1.2.5 Uncertainties in the SIMAP Modeling System

The SIMAP model has been developed over many years to greatly increase the types and amount of information to simulate the fates and effects of oil releases. However, as in all science, there are limits to the complexity of processes that can be modeled, as well as gaps in knowledge regarding the environment that is affected. As described in the preceding sections, assumptions based on available scientific information and professional judgments were made in the development of the model.

The major sources of uncertainty in the oil fates processes considered by SIMAP are:

- Oil contains thousands of chemicals of differing physical and chemical properties that determine their fate in the environment. The model must of necessity treat the oil as a mixture of a limited number of components, grouping chemicals by physical and chemical properties.
- The fates model contains a series of algorithms that are simplifications of complex physical-chemical processes. These processes are understood to varying degrees.

- Information on physical parameters including but not limited to hydrodynamics, water depth, river width, total suspended solids concentration, and wind speed were based on the available data for the release location and the predicted downstream trajectory. When data was lacking, previous experience and sources from other similar locations were used to determine the parameter values that were implemented in the model. In some cases, professional judgment was required to make appropriate assumptions.

In addition, in the unlikely event of an actual oil release, the fates and effects will be strongly determined by the specific environmental conditions, and a myriad of details related to the event. Thus, the results are a function of the scenarios simulated and the accuracy of the input data used. The goal of the SIMAP modeling was not to forecast every detail that could potentially occur, but to describe a range of possible consequences so that an informed analysis could be made as to the likely effects of oil releases under various scenarios. The model inputs are designed to provide representative conditions to inform such an analysis for the scenarios considered.

5.2 KEY ASSUMPTIONS

The OILMAP Land and SIMAP modeling was based on a number of assumptions relating to the type of release event (i.e., full bore rupture, release of oil into watercourses), the volume of oil released, the duration of the release and subsequent downstream movement prior to mitigation (i.e., 24 hours), and the types of crude oil released. Each of these are discussed below.

5.2.1 Full Bore Rupture is an Unlikely Event

A full bore rupture means that the pipeline is severed or burst, such that the opening is equivalent to the cross-sectional area of the pipe (regardless of the mechanism leading to the rupture) and crude oil is assumed to spill freely from this opening. By design, and as a result of Enbridge's pipeline operation and maintenance programs (Enbridge 2014), a full bore rupture pipeline incident is considered to be a highly unlikely event. The selection of full bore, and the calculation of release volumes based on a full bore rupture, is therefore a highly conservative assumption.

5.2.2 Identification of Representative Hypothetical Release Scenarios

Even in the event of a full bore rupture incident, crude oil releases to land often result in only small areas of land (i.e., a few hectares) becoming contaminated by released oil. This is not to suggest that such effects would not be consequential. Rather, it justifies the selection of crude oil releases that enter watercourses (rivers or lakes) as being a conservative choice with respect to the fate, transport, and potential effects of released oil. With a larger spatial distribution, unmitigated releases of oil into water would have greater potential to cause adverse effects to larger numbers of ecological and human receptors. Therefore, this analysis focused on scenarios that result in the release of crude oil to watercourses as a conservative assumption.

Seven locations, each adjacent or close to a watercourse, were selected for modeling of hypothetical large releases of crude oil. The selection of these seven modeling locations was guided by consideration of the following engineering and environmental/socio-economic risk factors (Section 3.3.3):

- Located so that crude oil release volumes could potentially enter a watercourse; this included selection of locations where the hypothetical release of oil would either occur directly into a watercourse or would travel a short distance overland into a watercourse
- Located where shut-off valves would not overly restrict the volume of oil that could potentially be released (i.e., the hydraulic drain down of pipeline would be a substantial contributor to the oil release volume)
- Include sites along both the preferred and alternate routes
- Representative of the geographic and environmental conditions and land uses along the proposed ROW for the pipeline to allow for an evaluation of the range of potential effects to the natural and human environment along the pipeline
- Include a range of watercourse types (e.g., size, flow, energy level) and water bodies, including wetlands
- Support evaluation of potential effects to environmentally sensitive resources (e.g., spawning grounds for fish, wild rice lakes, or other sensitive habitats)
- Represent areas of expressed concern by Native American tribes, the general public, and/or state and federal agencies
- Support evaluation of potential effects to traditional use, other human use or infrastructure (e.g., potable water intakes or treatment facilities)

Based on a review of potentially sensitive hypothetical release locations and collaboration with the MN DNR and MN PCA (Sections 3.3.4 and 3.3.5), the scenarios were narrowed to seven general areas:

- Site 1—Mosquito Creek to Lower Rice Lake
- Site 2—Mississippi River at Ball Club
- Site 3—Sandy River
- Site 4—Shell River to Twin Lakes
- Site 5—Red River
- Site 6—Mississippi River at Palisade
- Site 7—Mississippi River at Little Falls

Modeling of hypothetical release scenarios at these seven locations was completed to predict the potential trajectory of released oil, the fate of released oil, and the potential effects of accidental oil releases on the natural and human environment. The intent of these analyses for each modeling location was to infer a range of potential effects that may occur at other locations in Minnesota with similar biophysical and human use characteristics.

5.2.3 Crude Oil Release Volume

At each of the seven identified potential release locations, the environmental effects of a hypothetical full-bore pipeline rupture were evaluated.

For each hypothetical release scenario, other than the Mosquito Creek land release, it was conservatively assumed that released oil would enter directly into the watercourse with no retention of oil on land. These circumstances would produce a scenario where most of the estimated volume of released crude oil would enter the aquatic environment close to the point of release. Making the assumption that the damage to the pipeline occurred near a topographic low point maximizes the hypothetical release volume (due to drain-down of the pipeline following the initial volume that was released under pressure before the pipeline was shut down), but also implies that the hypothetical release occurred in proximity to a watercourse. This is a conservative assumption, due to the potential for watercourses to effectively and rapidly transport released crude oil away from the release location.

The hypothetical release scenario is modeled such that a change in pipeline flow characteristics due to the rupture would be detected at the Control Center and the pipeline would be shut down (see next paragraph). For the purposes of this analysis, it is assumed that the location of the full-bore rupture would be at a low point (e.g., in proximity to a watercourse) between two control valves, and that oil would continue to drain by gravity from the pipeline, between the location of the rupture and the nearest valves.

The crude oil release volume was calculated as a full bore rupture, with a conservative response in the pipeline Control Centre of a maximum of 10 minutes, followed by a 3-minute period to allow for valve closure, and then drain-down of the elevated segments of pipeline. The maximum 13-minute duration of Control Center response time to valve closure is a standard for safe operations and leak detection for Enbridge. 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, this is a conservative assumption, since a response through to valve closure would be expected to occur in less than 13 minutes in a full bore rupture leak scenario.

The maximum volume of oil that could be hypothetically released at each site was determined based on the pipeline specifications and topographic conditions in proximity to each modeling location; the maximum volume out included both the initial release volume prior to shutdown (i.e., actively pumping out), as well as hydraulic drain down of the pipeline (i.e., gravity drained oil within the pipeline between the valves), following shutdown at that site. The maximum volume of oil that could hypothetically be released from the L3RP at each modeling location is summarized in Table 3-5.

The release duration is the amount of time required for the released oil volume to be released from the ruptured pipeline, including drain-down. The OILMAP Land and SIMAP modeling systems use a constant release rate based upon the defined total release volume and duration of release. The release duration was calculated using the release volume, pipeline diameter, pipeline shutdown time, pipeline design flow rate, and elevation profile of the pipeline.

5.2.4 24 hour Unmitigated Oil Release

The analysis was carried out following a highly conservative assumption that the release would be unmitigated for 24 hours, and that the released crude oil would travel downstream unimpeded for that length of time. This is a conservative assumption because Enbridge would immediately mobilize a response that would contain and collect oil in the event that a release were to be detected. The 24-hour time frame is consistent with guidance from the USEPA, which stipulates a 27-hour period, representing 24-hours for arrival and 3-hours for deployment (USEPA 2003). As such, modeled results should not be interpreted as representative of expected effects, but rather as an unlikely, unmitigated worst-case potential outcome.

Crude oil release simulations that reach the 24 hour time limit may still have oil remaining on the surface of the river or lake that has not adhered to a shoreline or spread to the defined minimum thickness. If there was oil on the water surface after 24 hours, it could (if not mitigated) continue to move downstream, further oiling shorelines until it either evaporated or stranded. The simulations assumed the releases were unmitigated for the modeled 24 hour period (i.e., no benefits of emergency response operations were incorporated into the model). In a real-life scenario, emergency response procedures would mitigate the effects of the modeled incidents.

5.2.5 Crude Oil Types

The range of product types expected to be shipped in the L3RP may range from light crude oils such as those in the Alberta Light Sweet Crude category, to heavy oils such as conventional heavy crude oils and diluted bitumen products. The physical and chemical characteristics of light and heavy crude oils are quite different, although the characteristics of diluted bitumens are very similar to those of heavy conventional crude oils (Zhou et al. 2015). Therefore, two crude oil types were selected for their representative characteristics and conservatively high potential for effects to serve as the basis for the analysis. The two oil types include Bakken Crude Oil (a light conventional crude oil with a high aromatic content) and CLB (a diluted bitumen). The characteristics of these oils are detailed in Section 5.3.1 of this document.

5.3 INPUT DATA SETS

5.3.1 Oil Property Data

A range of product types are expected to be shipped in the L3RP pipeline, including heavier oils such as diluted bitumen and lighter oils such as Alberta Light Sweet Crude light crudes, with similar product characteristics to Bakken oils. The chemical and physical characteristics of these oil types are quite different. To account for these differences, two representative product types were selected for this modeling assessment that bound the range of anticipated products that may be shipped: the heavier diluted bitumen CLB and the lighter Bakken Crude oil. The differences between these oils will result in a range of potential outcomes related to the trajectory, fate, and effects of releases under varying environmental conditions.

CLB is a diluted bitumen with a high viscosity and density, falling in the upper range of characteristic values allowed by the pipeline tariff specifications for Enbridge. This product exhibits generally mid-range density and viscosity characteristics for the range of diluted bitumen products. Seasonal variations in environmental temperatures affect the viscosity of the diluted bitumen, which directly affects the ability to pump the fluid through the pipeline. To address this, the amount of diluent added to Cold Lake bitumen is varied through the year to attain a viscosity that meets shipping requirements. The largest amount of diluent is added to the bitumen during winter to reduce the viscosity to a level suitable for shipping at low temperatures. As a consequence, the density, viscosity, and aromatic content changes through the year. During the winter months, CLB has a lower density and viscosity and a greater aromatic content, when compared to the summer months.

As the chemical and physical characteristics of the CLB will vary seasonally, CLSB and CLWB were considered in the modeling of hypothetical releases. CLSB was used for spring and summer scenarios, while the CLWB was used for winter scenarios.

Bakken Crude Oil is produced in North Dakota, Montana, and the bordering Canadian provinces of Manitoba and Saskatchewan. Bakken crude is a light crude oil with an API gravity generally between 40° and 43° and a sulfur content less than 0.2 wt.%. Bakken is a relatively light crude oil with low density, low viscosity, and a high aromatic content.

The chemical and physical characteristics of each representative product, including chemical and physical properties, were derived from publicly available data from Environment Canada's Oil Properties database, technical data reports, assays, and other related project work (Enbridge 2014; S.L. Ross 2010; ESTC 2016; Exxon Mobil 2015; CrudeMonitor 2016). The level of detail, including the type of variables and number of analytes measured did vary between data sources. When specific oil property data was not available, the properties from similar oil types were assumed (ESTC 2016). For all three oils, minimum oil slick thicknesses were determined based on Coastal Response Research Center categories and observations of releases compiled by RPS ASA (2013) and the previous work of Allen and Dale (1997), McAuliffe (1987), NRC (1985, 2002) and the Bonn Agreement (Daling et al. 1999).

5.3.1.1 Physical Properties of the Oils

The physical properties of the three crude oils considered in modeling of hypothetical releases at each of the seven modeling locations are shown in Table 5-4.

Table 5-4 Physical Properties of the Three Crude Oils

Oil Property	Bakken Crude	Cold Lake Winter Blend	Cold Lake Summer Blend
Oil Type	Crude	Emulsion	Emulsion
Minimum Slick Thickness (μm)	0.1	10.0	10.0

Table 5-4 Physical Properties of the Three Crude Oils

Oil Property	Bakken Crude	Cold Lake Winter Blend	Cold Lake Summer Blend
Surface tension (dyne/cm)	27.3	27.1	27.1
Pour Point (°C)	-55.0	-45.0	-45.0
API Gravity	41.80	22.69	20.73
Density (g/cm^3) at 16°C	0.81650	--	--
Density (g/cm^3) at 15°C	--	0.91770	0.92950
Viscosity (cP) at 10°C	3.88	--	--
Viscosity (cP) at 15°C	--	150.0	342.0
Viscosity (cP) at 30°C	2.49	--	--

5.3.1.2 Chemical Properties of the Oils

The chemical properties of CLB were estimated using information from the Crude Monitor (2016) for the period of 2009 through 2016 (Figure 5-6). Seasonal variations in the fractional composition of the whole oil was used to determine volume of BTEX and the total hydrocarbon concentration (THC), by pseudo-component, of CLWB and CLSB. These results provide the variability and ultimately the ratio of BTEX and THC between winter and summer blends. BTEX concentrations (modeled as AR1) that were measured directly for the Exxon Mobil (2015) assay were used for CLWB, and the ratio of winter to summer calculated from Crude Monitor (2016) was used to scale BTEX values for the CLSB. Additional aromatic concentrations (AR2 and AR3) for CLWB were available from direct measurements for the S.L. Ross (2010) assay. For CLSB, the winter to summer ratio was used to scale the S.L. Ross (2010) values for AR2 and AR3. The total hydrocarbon breakdown (THC1, THC2, and THC3) for CLWB was determined from distillation data (Exxon Mobil 2015). The aliphatic breakdown (AL1, AL2, and AL3) was calculated by difference (e.g., AL1 = THC1 – AR1). For CLSB, the THC was again scaled based upon the winter to summer ratio from Crude Monitor (2016). Together, this analysis provides a breakdown of the chemical composition of CLB by pseudo-component for the winter and summer blends.

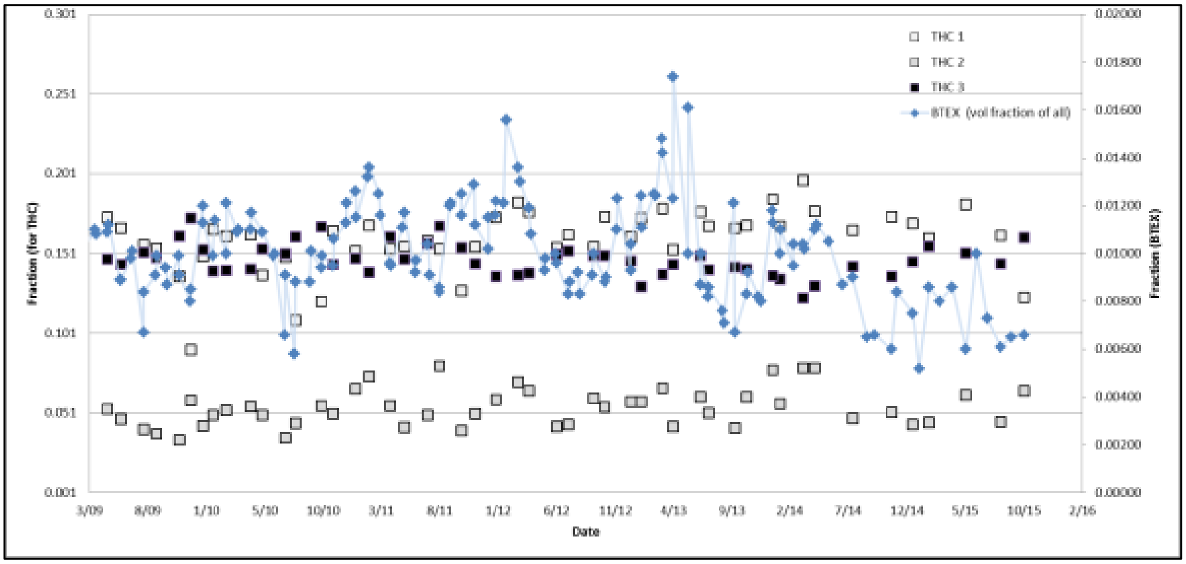

Figure 5-6 Fractional Composition of the THC and BTEX (AR1) Components in CLB from 2009 through 2016 (CrudeMonitor 2015)

The aromatic, aliphatic, and total hydrocarbon concentration and percentage composition of fresh whole oil for the three crude oils considered in modeling of hypothetical releases at each of the seven modeling locations are shown in (Table 5-5). BTEX content peaks in winter month blends and can make up greater than 1.6% of the fractional volume of the whole oil.

Table 5-5 Aromatic (AR), Aliphatic (AL), and Total Hydrocarbon Concentration (THC) and Percentage Composition of Fresh Whole Oil for the Three Crude Oils

Oil Type	Oil Component	% AR	% AL	% THC[1]
Bakken Crude	**1** (AR = BTEX & MAHs >C8-C10) (AL = >C6-C10)	0.029300	0.250700	0.280000
	2 (AR = MAHs and PAHs >C10-C12) (AL= >C10-C12)	0.022045	0.167955	0.190000
	3 (AR = PAHs >C12-C16) (AL = >C12-C16)	0.037668	0.242332	0.280000
Cold Lake Winter Blend	**1** (AR = BTEX & MAHs >C8-C10) (AL = >C6-C10)	0.012460	0.213302	0.225762
	2 (AR = MAHs and PAHs >C10-C12) (AL= >C10-C12)	0.000880	0.059265	0.060145
	3 (AR = PAHs >C12-C16) (AL = >C12-C16)	0.004400	0.136629	0.141029
Cold Lake	**1**	0.009003	0.154127	0.163130

Table 5-5 Aromatic (AR), Aliphatic (AL), and Total Hydrocarbon Concentration (THC) and Percentage Composition of Fresh Whole Oil for the Three Crude Oils

Oil Type	Oil Component	% AR	% AL	% THC[1]
Summer Blend	(AR = BTEX & MAHs >C8-C10) (AL = >C6-C10)			
	2 (AR = MAHs and PAHs >C10-C12) (AL= >C10-C12)	0.000748	0.050367	0.051115
	3 (AR = PAHs >C12-C16) (AL = >C12-C16)	0.004300	0.133538	0.137838

NOTE:
[1] THC is the sum of AR and AL. (Numbers of carbons in the included compounds are listed, e.g., >C8-C10 indicates greater than 8 carbons and including 9- and 10-carbon hydrocarbons.)

In some cases, additives are combined with the oil to reduce drag or turbulence in a pipeline, allowing it to pump at lower pressure. Additives are mainly comprised of polymers, solid-particle suspensions, biological additives, and surfactants that serve as drag-reducing agents or polymers. These compounds make up only a very small portion of the total volume of shipped product (i.e., oil) moving through the pipeline and are measured at part-per-million (ppm) levels. Because of this, the ultimate trajectory, fate, and effects would not be significantly different between a crude oil with or without these agents. This modeling exercise did not take any additive substances into account.

5.3.2 OILMAP

5.3.2.1 Elevation Data

The OILMAP Land model uses land elevation data to determine the overland pathways of releases occurring in the terrestrial environment. The elevation data are stored in a grid (raster) format and the model calculates the down slope pathway by determining the direction of steepest slope, as the leading edge of the release moves from grid cell to grid cell.

The ability of the model to accurately determine the overland release pathways is in large part controlled by the vertical and horizontal resolution of the elevation grid.

The horizontal resolution refers to the size of the individual grid cells of the elevation data in north-south and east-west directions. As the horizontal resolution increases it is possible to include smaller terrain features in the elevation data in the OILMAP Land model. This may include roads, ditches, and other smaller-scale features. As each horizontal grid cell is assigned a single elevation value, small-scale features can be flattened or smoothed in the larger grid cell and have limited effects on the elevation, especially when the resolution of the horizontal elevation data is course.

The vertical resolution refers to the level of precision available for each cell's elevation value. Sub-meter precision is critical for accurate modeling of flow over a land surface. Without the small sub-meter variations in the elevation surface, larger areas of no apparent elevation change may be present. In this case, the surface flow model will have greater difficulty in determining an overland flow direction, as multiple cells need to be crossed to find the downslope gradient.

Elevation data was obtained from the U.S. Geological Survey (USGS) National Elevation Dataset (USGS 2015). These data have either a 1/3 arc second (approximately 32.8 ft [10 m]) or 1 arc second (approximately 98.4 ft [30 m]) horizontal resolution and were primarily used as a reference for the topography surrounding the various rivers modeled. The higher resolution data covered all portions of land within the U.S., while the coarser one arc second resolution data was used to define the small portion of Canadian land area north of the release location. Elevation data used for modeling was obtained from the MN DNR (MN DNR 2014). The elevation data used was a digital elevation model (DEM) that was derived from LiDAR data. The DEMs have a 9.8 ft (3 m) horizontal resolution and 0.4 in (1 cm) vertical resolution. The Accuracy of the raw LiDAR data is reported as less than 9.8 ft (1 m) in the horizontal and less than 5.9 in (15 cm) in the vertical. They were used in OILMAP Land overland modeling at the Mosquito Creek site and for the stream crossing analysis at all sites. Land elevation maps for all sites modeled in OILMAP Land are presented below (Figure 5-7 through Figure 5-11).

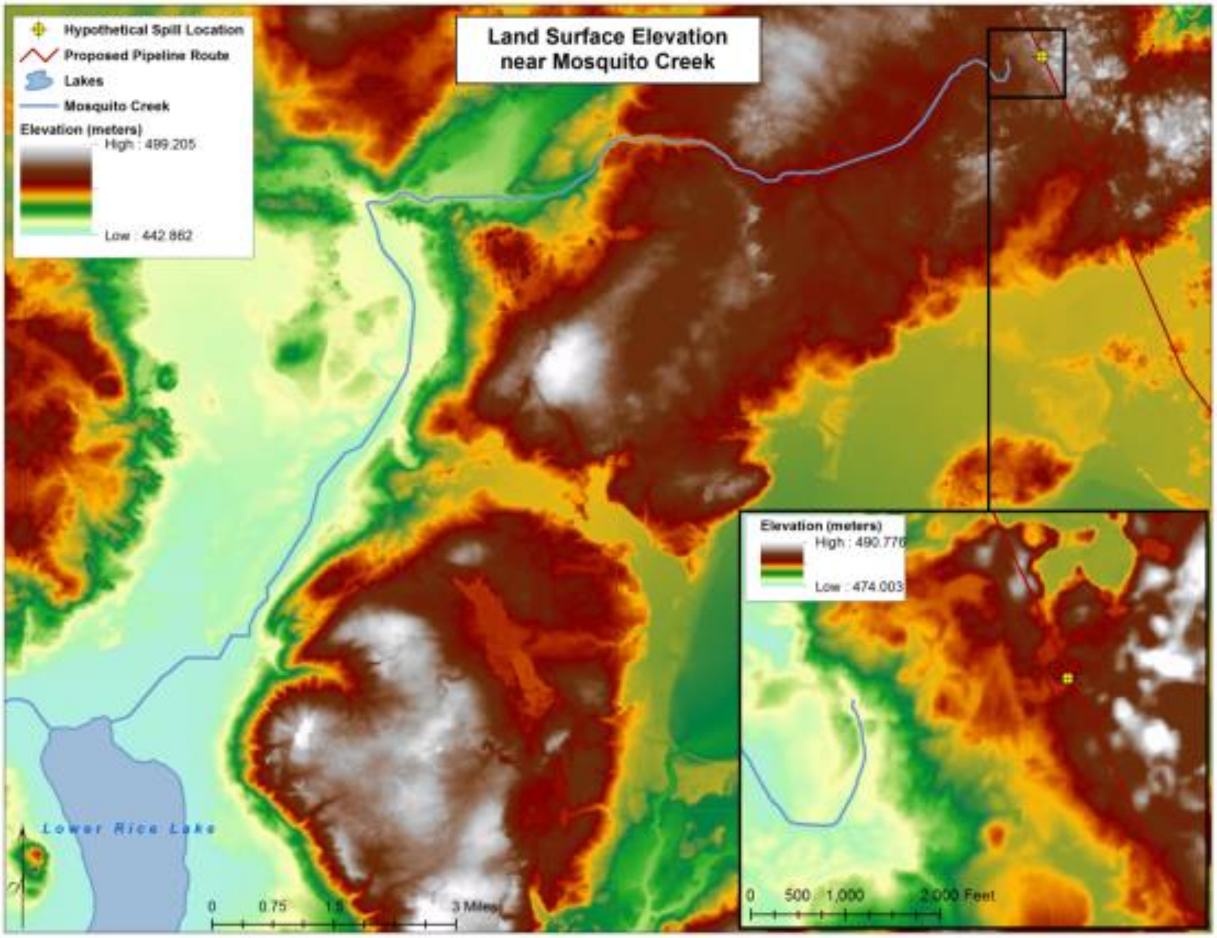

Figure 5-7 Land Surface Elevation (m) for the Mosquito Creek Release Location

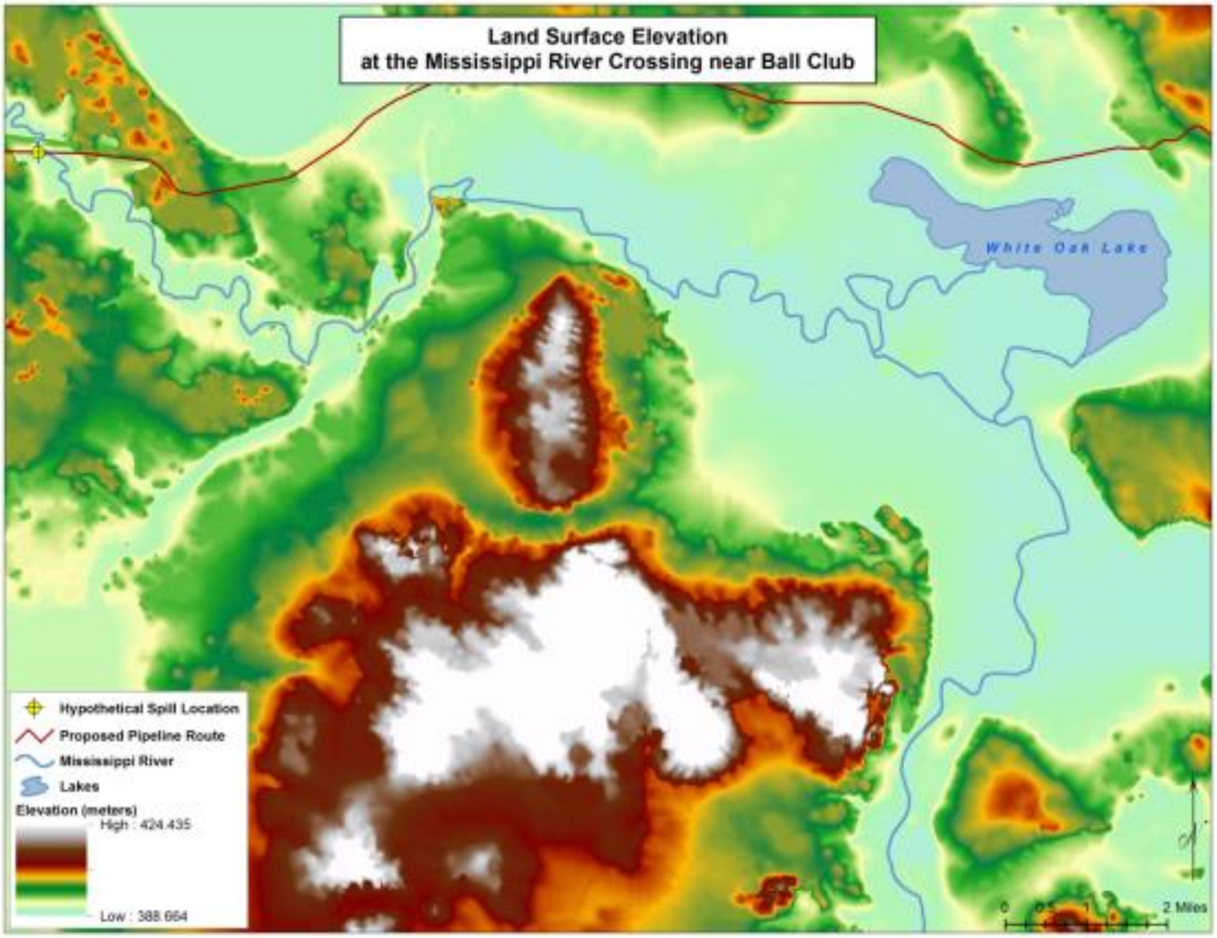

Figure 5-8 Land Surface Elevation (m) for the Mississippi River at Ball Club Release Location

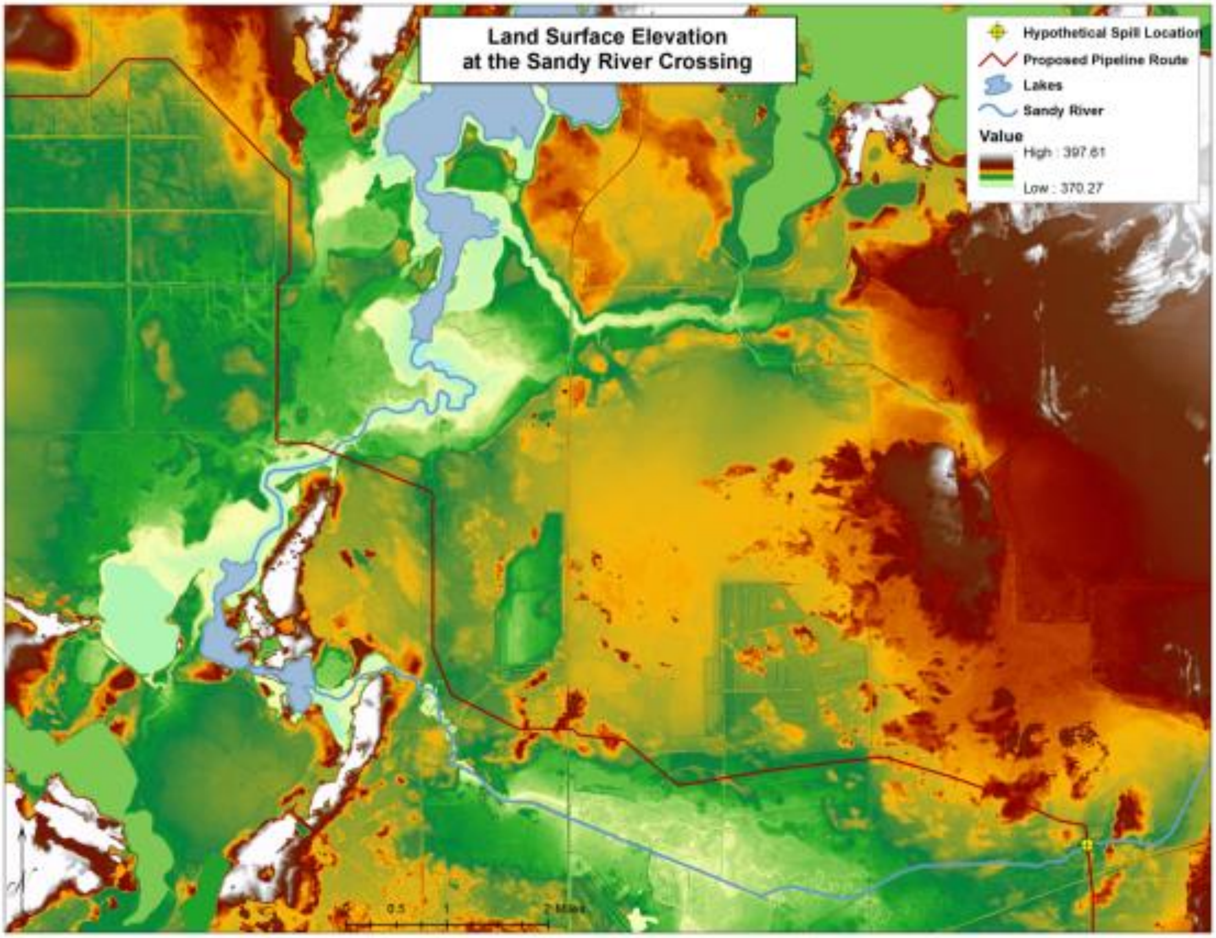

Figure 5-9 Land Surface Elevation (m) for the Sandy River Release Location

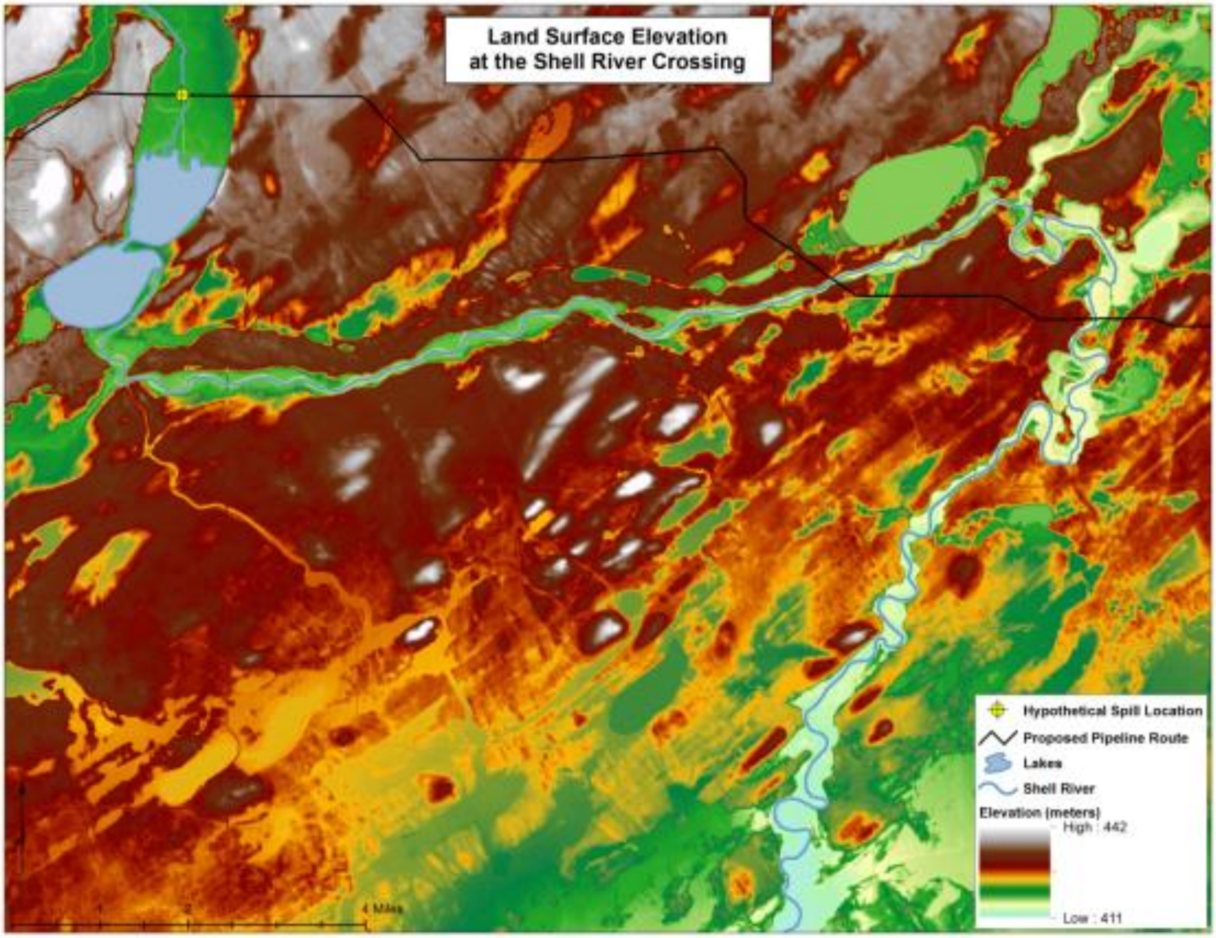

Figure 5-10 Land Surface Elevation (m) for the Shell River to Twin Lakes Release Location

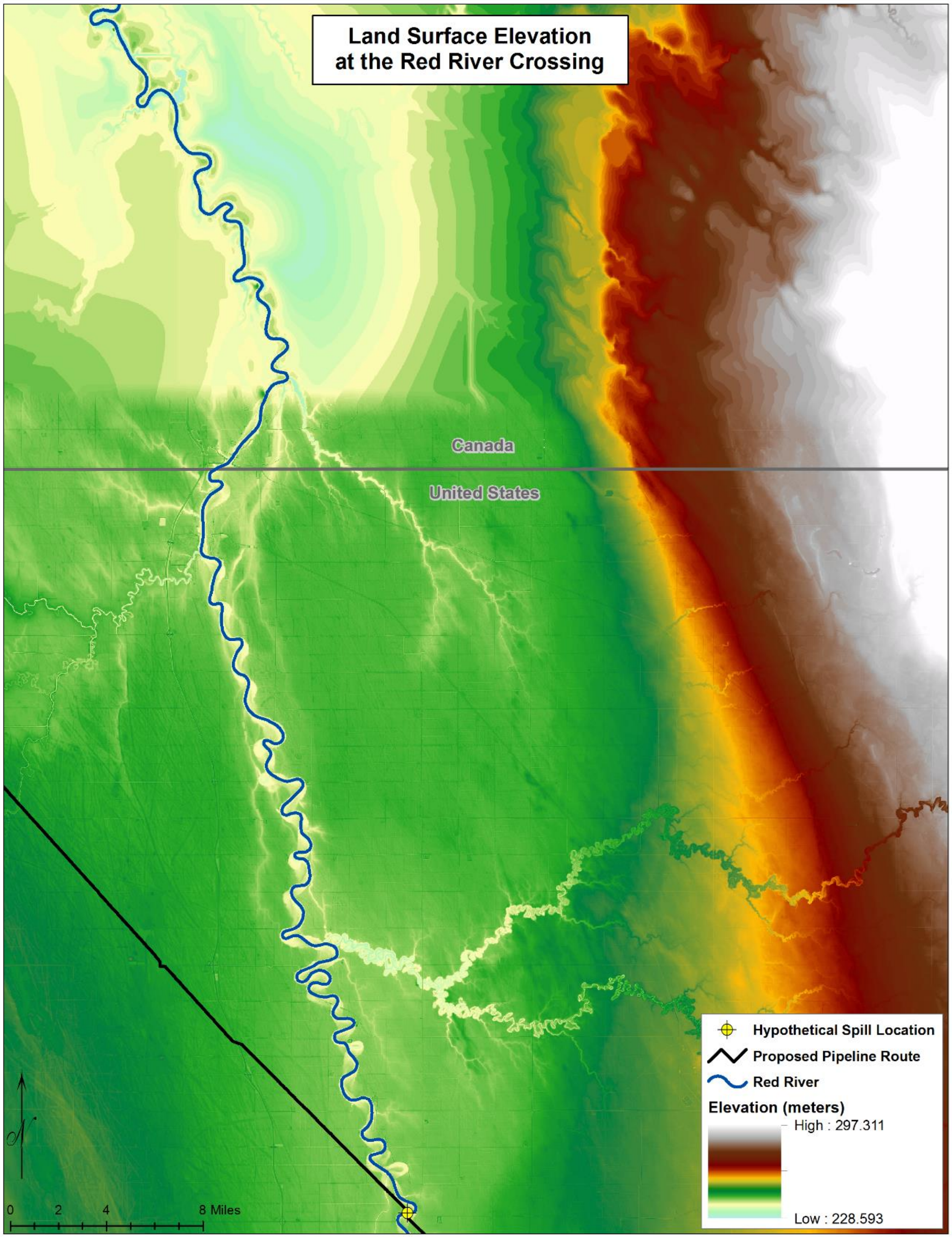

Figure 5-11 Land Surface Elevation (m) for the Red River Release Location. Elevation Data for Canadian Land is at a Coarser Resolution than the U.S.

5.3.2.2 Surface Water Data

The OILMAP Land release model uses data for networked streams and lakes to model the pathways of oil once it reaches surface water. Streams and rivers are represented in the model as a polyline feature of the stream centerline, which has been digitized according to the flow direction. The streams must be networked in a way such that the model can determine where each single stream segment joins the next, as the downstream movement of oil is modeled. Lakes are represented as polygon features, and connect to the streams that both feed and drain them, as appropriate.

Each individual stream segment has its own defined stream velocity and width. Therefore, the model calculates an appropriate downstream transport as a river or stream changes. As an example, a section of a river may widen and slow, and be followed by a narrower and faster reach. The OILMAP Land model uses the location specific river velocity to more accurately model the oil pathway and fate in the stream network.

Surface water data were derived from multiple sources. Stream centerlines, stream polygons and lake polygons were derived from the USGS high resolution National Hydrography Dataset (NHD) (USGS 2014). This data provides geospatial vector data, at a 1:24,000 scale, describing hydrographic features such as lakes, reservoirs, rivers, streams and canals in the form of a linear drainage network. Stream centerlines, networking, and flow information was used from the USEPA's NHDPlus version 2 data (NHDPlus v2; Horizon Systems 2012). NHDPlus integrates the USGS's medium resolution (1:100,00 scale) NHD, the 1/3 arc-second resolution National Elevation Database (NED), and National Watershed Boundary Dataset (WBD) to improve stream networking information, and estimate stream flow and velocity for every stream segment. Stream centerlines for the Canadian portion of the Red River were taken from the National Hydro Network (NHN) of Canada.

NHDPlus includes an estimated monthly and annual average stream flow rate and velocity for each stream segment. Flow is estimated using the Extended Unit Runoff Method (EROM). This method determines flow based on estimate of accumulated runoff based on the elevation data, evaporative loss, and various adjustments based on gages in the region. The velocities are calculated based on the estimated flow using the Jobson Method (Jobson 1996).

The Canadian NHN data does not have the same flow rate and velocity information as the NHDPlus data for the U.S. watercourses. In order to estimate the river velocity for the Canadian portion of the Red River, flows and velocities were calculated separately using a similar process as in the NHDPlus data. The contributing drainage area for each stream segment was determined based on the elevation data. An equation was then used to determine flow, as a function of drainage area, based on the NHDPlus data. The flow for the NHN streams was calculated based on these relationships for each flow period. The flow was then used to determine the velocity for each stream segment using the Jobson Method. A major input to this relationship is the stream slope. However, the resolution of the elevation data in Canada was not adequate to define a unique slope for each stream segment. Instead the overall change in elevation was used to determine an average slope. The result of these calculations was stream velocities that matched well with the NHDPlus data and a seamless stream network for the US and Canadian portions of the Red River.

The stream centerline network was originally extracted for each river from the NHDPlus network to maintain the networking and flow and velocity information found there. The stream centerlines were adjusted to be more accurately aligned using the NHD high-resolution stream centerlines as well as aerial photography. Stream widths were calculated based on the NHD high-resolution stream polygons where available (USGS 2014) using a series of transects along the river centerline. Where not available, stream widths were measured for each stream segment based on aerial photographs. Stream shore types were determined based on aerial photographs and land cover data (see next section). Low and average flow scenarios used the visible shore types, while high flow scenarios assumed the shore type of the surrounding land cover above the stream bank. Lake polygons were derived from the high resolution NHD dataset. The size and shape of some of the lakes were updated for different seasons based on aerial photographs.

River velocity varied between seasons for each hypothetical release site. The mean monthly river velocities for the identified seasons/months are presented in Table 5-6.

Table 5-6 Mean River Velocity Modeled for Each OILMAP Land Release Site and Season

Case #	Release Site	River Flow	Season	Corresponding Month	Average River Velocity (m/s)
1	Mosquito Creek to Lower Rice Lake	Low	Winter	February	0.16
		Average	Summer	July	0.21
		High	Spring	April	1.03
2	Mississippi River at Ball Cub	Low	Winter	March	0.12
		Average	Summer	August	0.31
		High	Spring	April	0.47
3	Sandy River	Low	Winter	March	0.13
		Average	Summer	July	0.24
		High	Spring	April	0.35
4	Shell River to Twin Lakes	Low	Winter	March	0.25
		Average	Summer	August	0.35
		High	Spring	April	0.54
5	Red River	Low	Winter	February	0.31
		Average	Summer	August	0.44
		High	Spring	April	1.02

5.3.2.3 Land Cover Data

The OILMAP Land model uses land cover data to vary the amount of oil that adheres to the land surface as oil moves down slope. The land cover data are used in a gridded format, with each grid cell value representing the type of land cover at that specific location. Land cover code values are then matched to the categories that define oil retention, so that the loss by retention can be accurately calculated as oil flows over the land surface.

The land cover data used was the National Land Cover Database ([NLCD] 2011), created by the Multi-Resolution Land Characteristics Consortium (Homer et al. 2015). The NLCD 2011 is based on a decision-tree classification of 2011 Landsat satellite data with 30-m resolution.

The NLCD 2011 data was transformed to the appropriate coordinate system. The dataset required reclassification of land cover classes to assign them to OILMAP Land values. The classification conversions for the NLCD 2011 data are provided in Table 5-7.

Table 5-7 Mapping Used to Convert the NLCD 2011 Land Cover Categories to OILMAP Land Classification Scheme

NLCD 2011 Code	NLCD 2011 Description	OILMAP Land Code	OILMAP Land Description
11	Open water	5	Water
12	Perennial snow/ice	12	Perennial ice/snow
21	Developed, open space	21	Low intensity residential
22	Developed, low intensity	21	Low intensity residential
23	Developed, medium intensity	22	High intensity residential
24	Developed, high intensity	22	High intensity residential
31	Barren land (rock/sand/clay)	31	Bare rock/sand/clay
41	Deciduous forest	41	Deciduous forest
42	Evergreen forest	42	Evergreen forest
43	Mixed forest	43	Mixed forest
51	Dwarf scrub	51	Shrubland
52	Shrub/scrub	51	Shrubland
71	Grasslands/herbaceous	71	Grasslands/herbaceous
72	Sedge/herbaceous	92	Emergent herbaceous wetlands
73	Lichens	98	Barren land
74	Moss	98	Barren land
81	Pasture/hay	81	Pasture/hay
82	Cultivated crops	82	Row crops
90	Woody wetlands	91	Woody wetlands

Table 5-7 Mapping Used to Convert the NLCD 2011 Land Cover Categories to OILMAP Land Classification Scheme

NLCD 2011 Code	NLCD 2011 Description	OILMAP Land Code	OILMAP Land Description
95	Emergent herbaceous wetlands	92	Emergent herbaceous wetlands

For each seasonal scenario, the release was simulated using both Bakken Crude and CLSB/CLWB oil types. Along with the varying chemical and physical properties of the two oil types, other model settings were adjusted for each oil type such as oil retention values for the shore type and the minimum thickness on lake surfaces. The oil retention values used by OILMAP Land for the shore and oil types are provided below (Table 5-8).

Table 5-8 Shoreline Retention Values Applied for Both Oils and Multiple Shore Types

Shore Type	Total Shore Width (m)	Oil Retention Thickness (mm)		Oil Volume Retained (m^3 per km of river)	
		Bakken Crude	Cold Lake Blend	Bakken Crude	Cold Lake Blend
Rock / Concrete	0.5	1	4	0.5	2
Soil	1	2	15	2	15
Sand	2	3	20	6	40
Grass	5	4	25	20	125
Marsh	20	6	40	120	800

Overland trajectory modeling was conducted only for the Mosquito Creek site. The land cover and lake surface oil retention thicknesses used in the model are presented in Table 5-9.

Table 5-9 Land and Lake Surface Retention Values Applied for Both Oils at the Mosquito Creek Site *

Land Cover Type	Oil Retention Thickness (mm)	
	Bakken Crude	Cold Lake Blend
Deciduous Forest	2	13.4
Pasture / Hay	0.6	3.8
Snow [1]	69.6	139.2
Vegetated Lake	0.28	1.68
Lake Surface	0.001	0.1
Under Ice in Lake	1.9	10.6

Table 5-9 Land and Lake Surface Retention Values Applied for Both Oils at the Mosquito Creek Site *

Land Cover Type	Oil Retention Thickness (mm)	
	Bakken Crude	Cold Lake Blend
NOTE: 1 Snow cover based on average February snow depth of 34.8 cm		

Maps depicting the shore types and corresponding river velocities modeled for each release location and season are presented below in Figure 5-12 through

Figure 5-29.

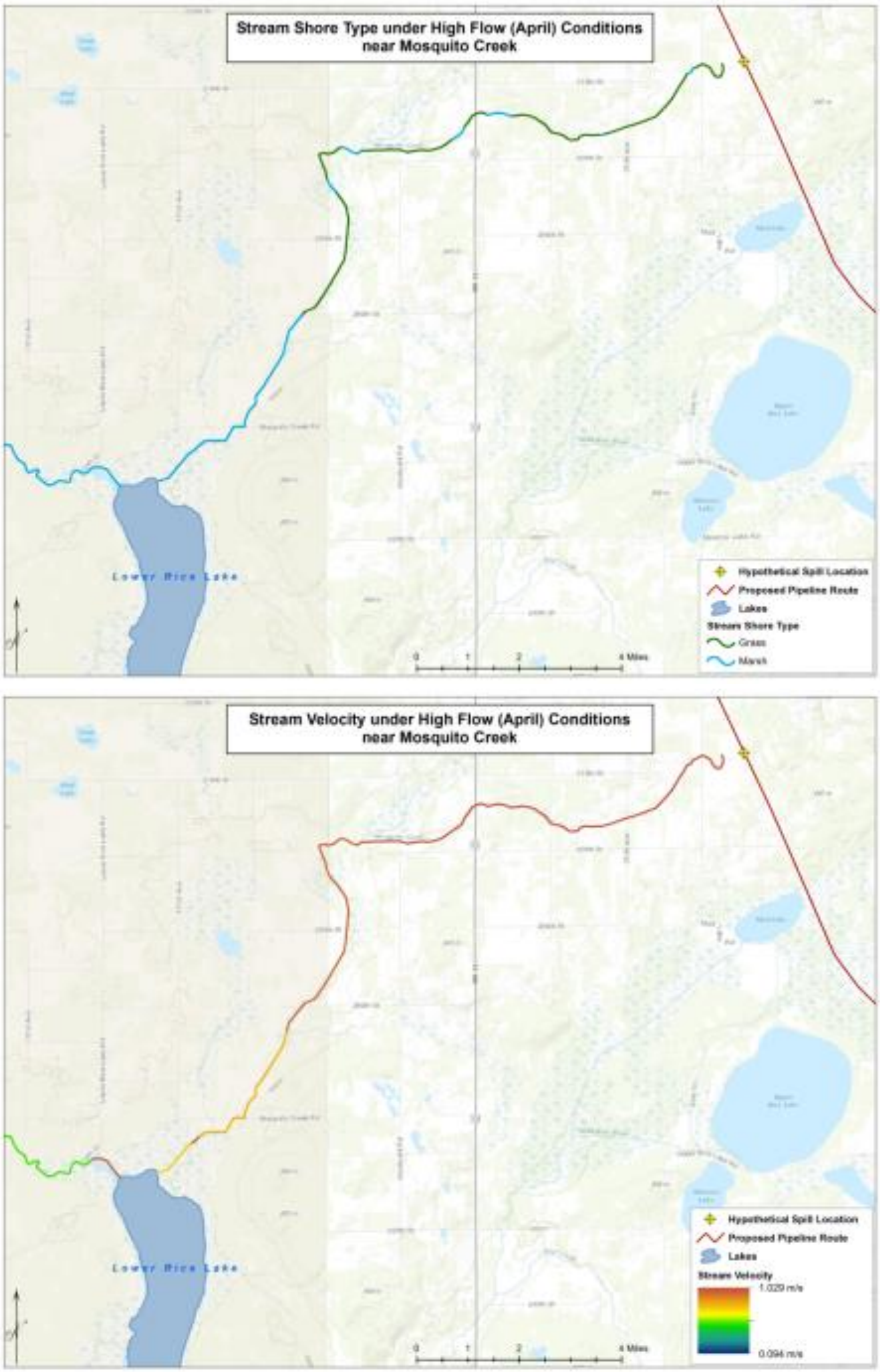

Figure 5-12 Stream Shore Type (top) and Velocity (bottom) Modeled Under High Flow Conditions for the Mosquito Creek Release Location

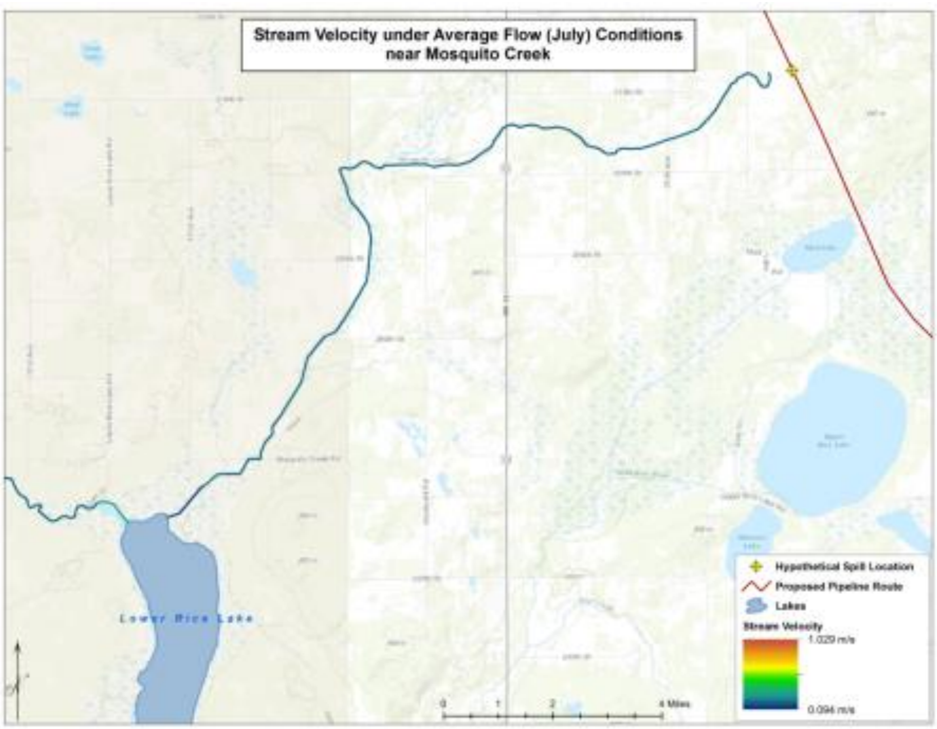

Figure 5-13 Stream Shore Type (top) and Velocity (bottom) Modeled Under Average Flow Conditions for the Mosquito Creek Release Location

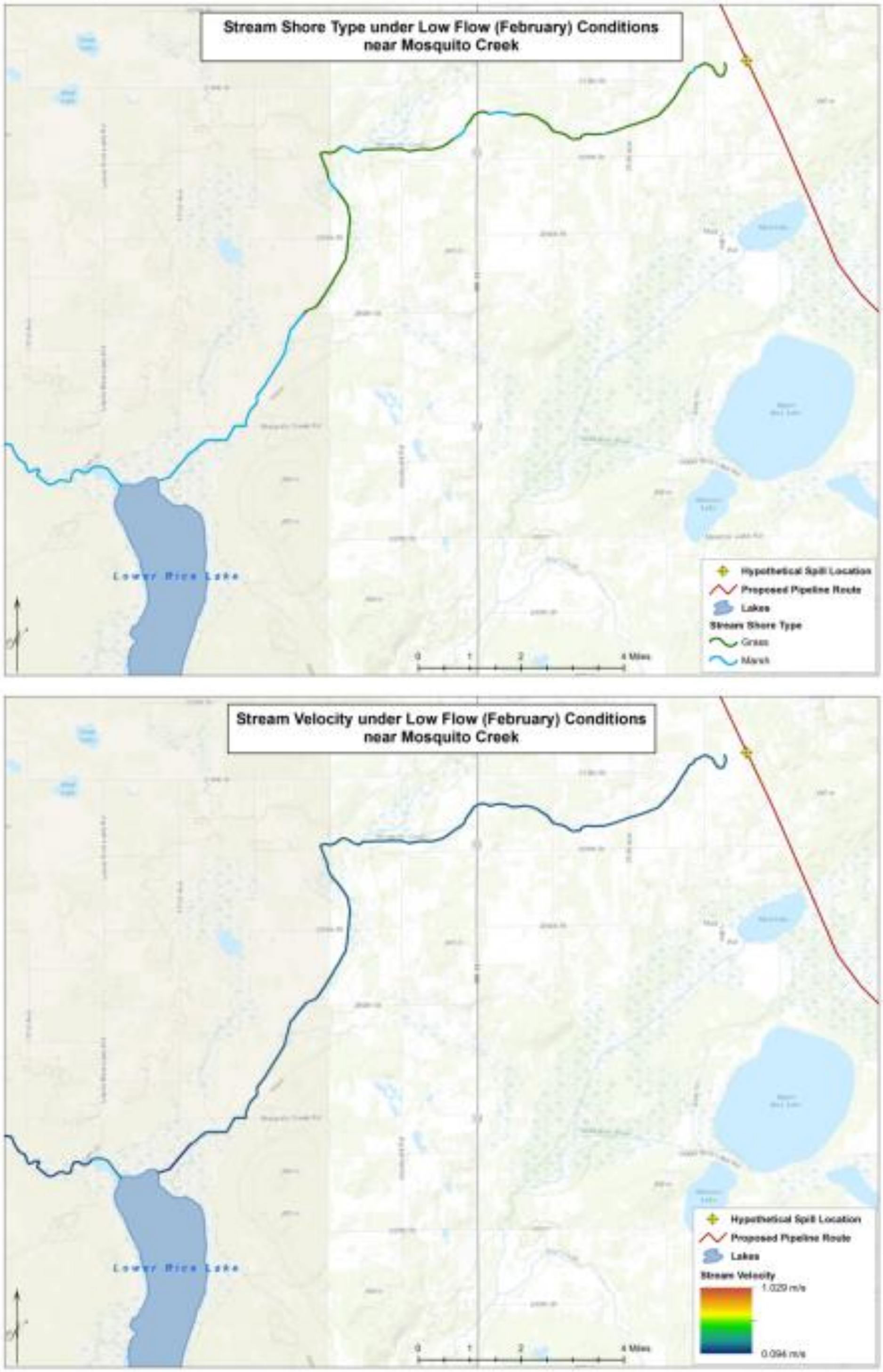

Figure 5-14 Stream Shore Type (top) and Velocity (bottom) Modeled Under Low Flow Conditions for the Mosquito Creek Release Location

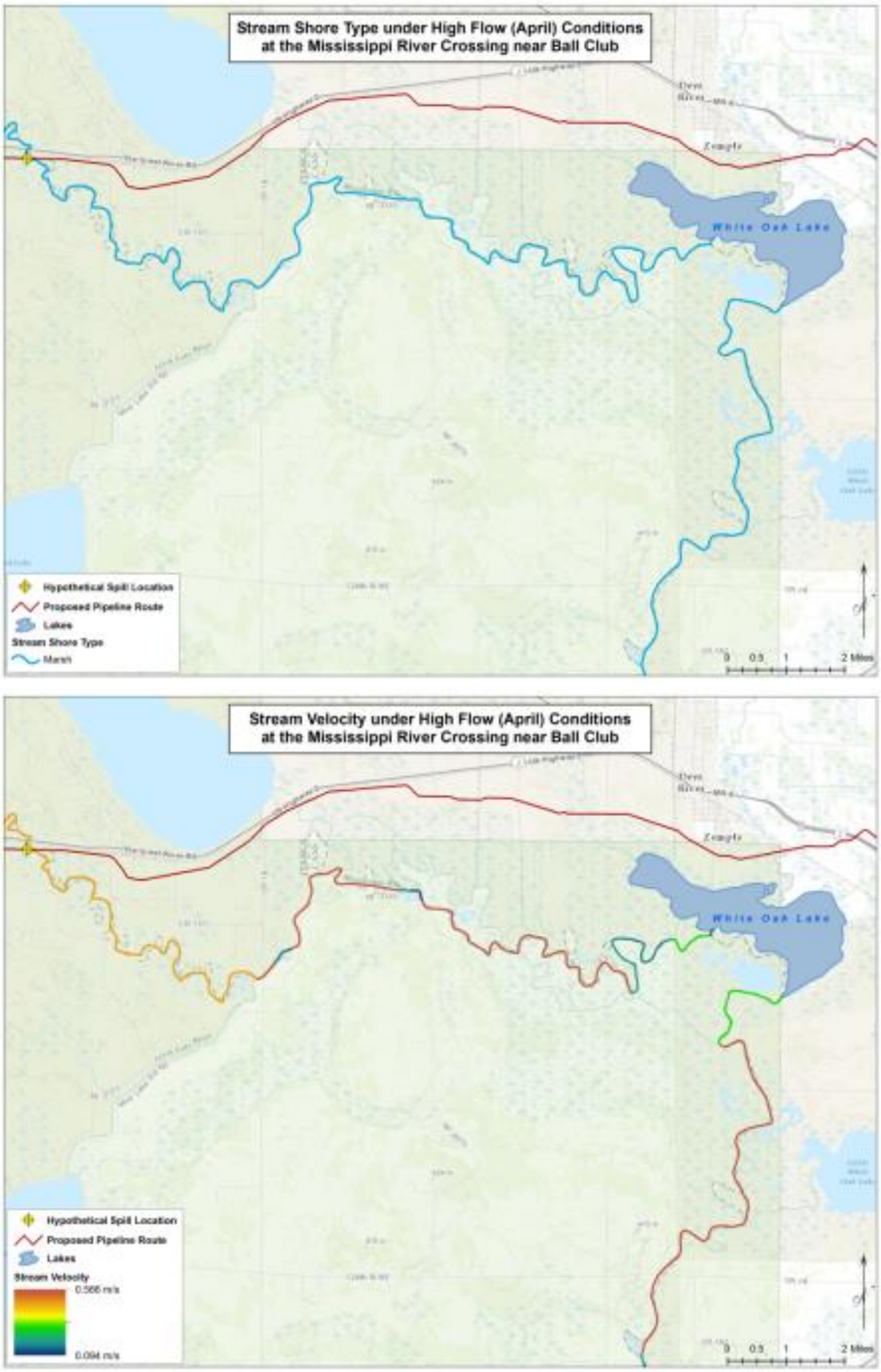

Figure 5-15 Stream Shore Type (top) and Velocity (bottom) Modeled Under High Flow Conditions for the Mississippi River Near Ball Club Release Location

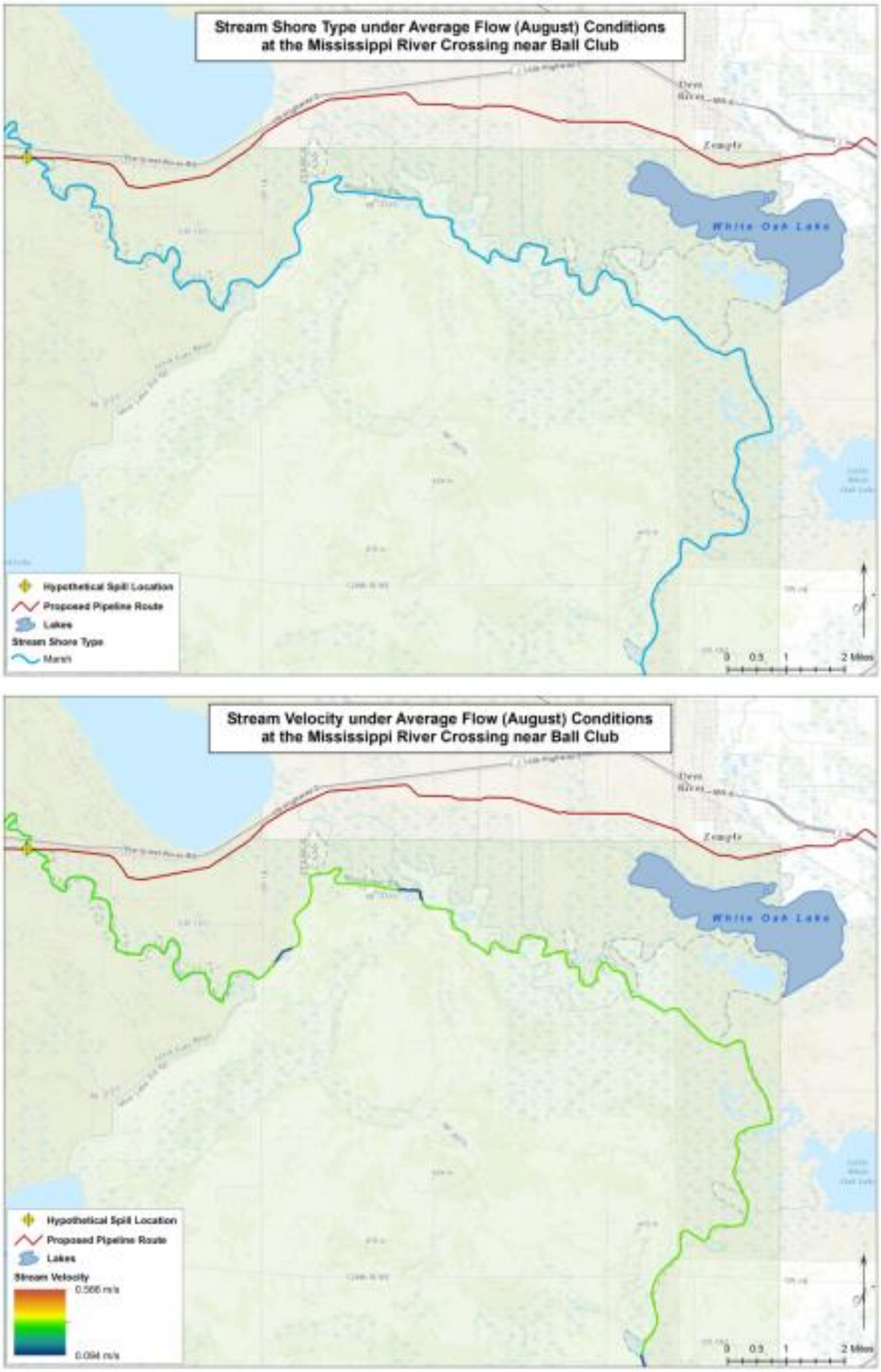

Figure 5-16 Stream Shore Type (top) and Velocity (bottom) Modeled Under Average Flow Conditions for the Mississippi River Near Ball Club Release Location

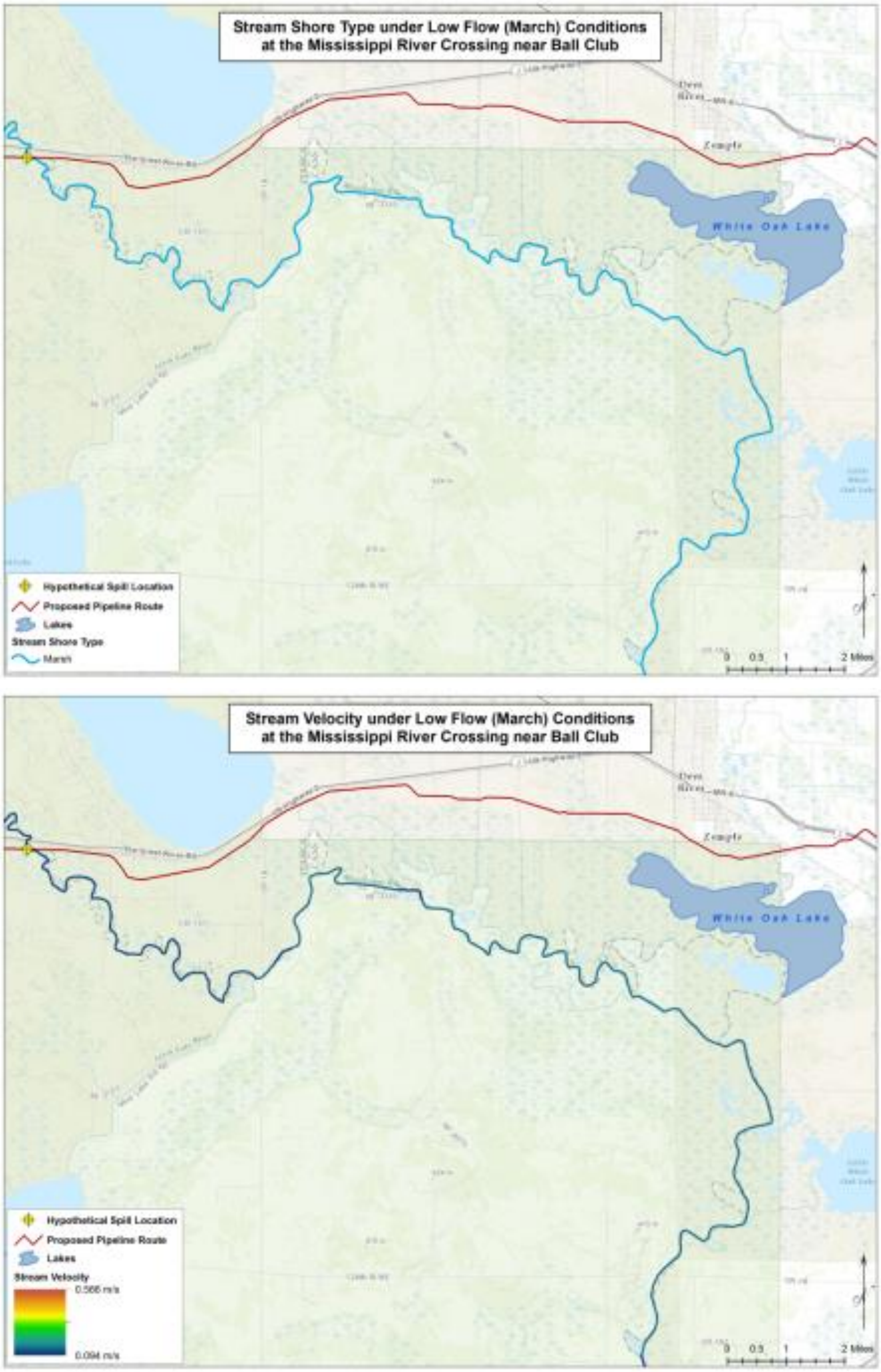

Figure 5-17 Stream Shore Type (top) and Velocity (bottom) Modeled Under Low Flow Conditions for the Mississippi River Near Ball Club Release Location

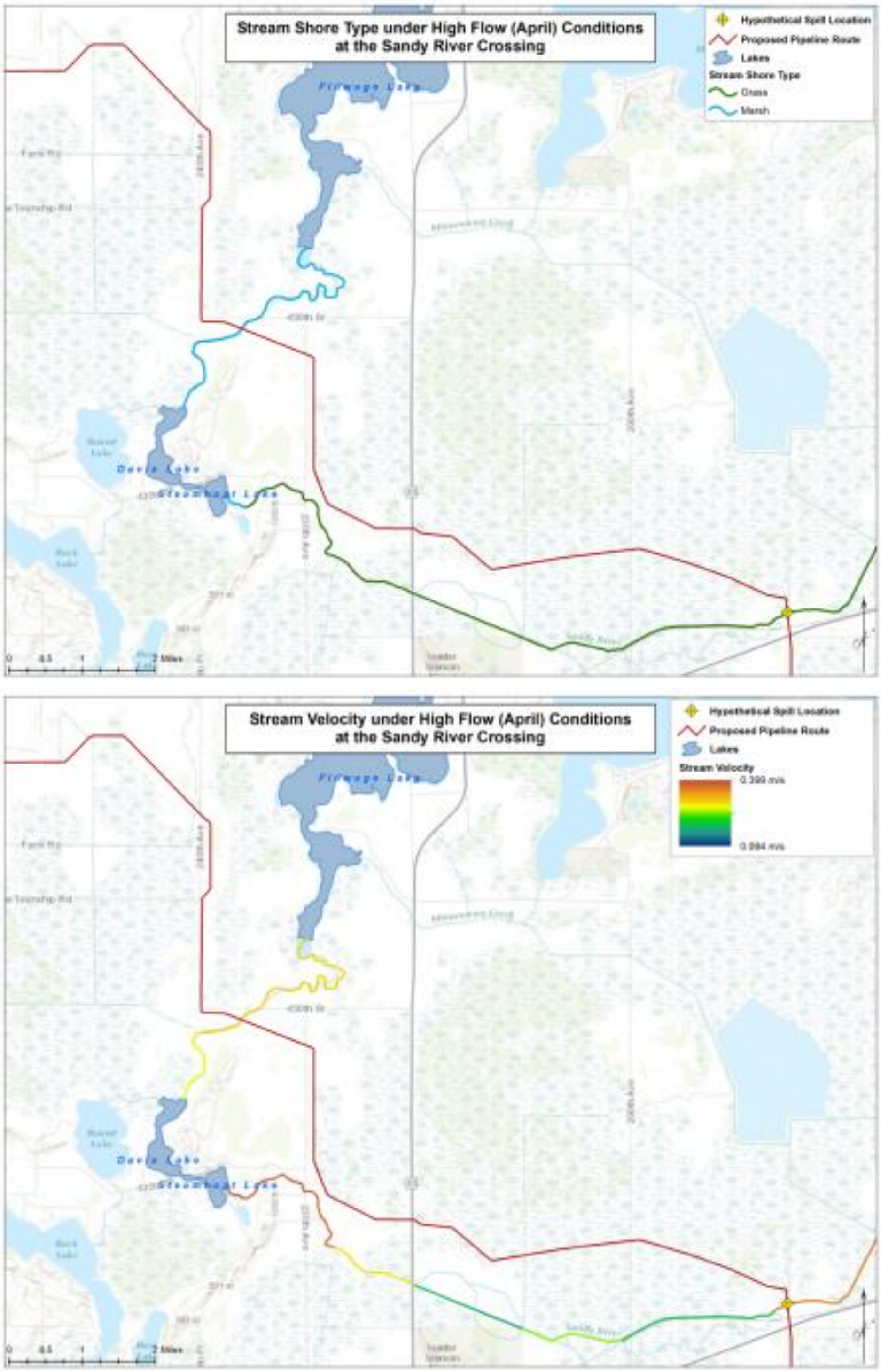

Figure 5-18 Stream Shore Type (top) and Velocity (bottom) Modeled Under High Flow Conditions for the Sandy River Release Location

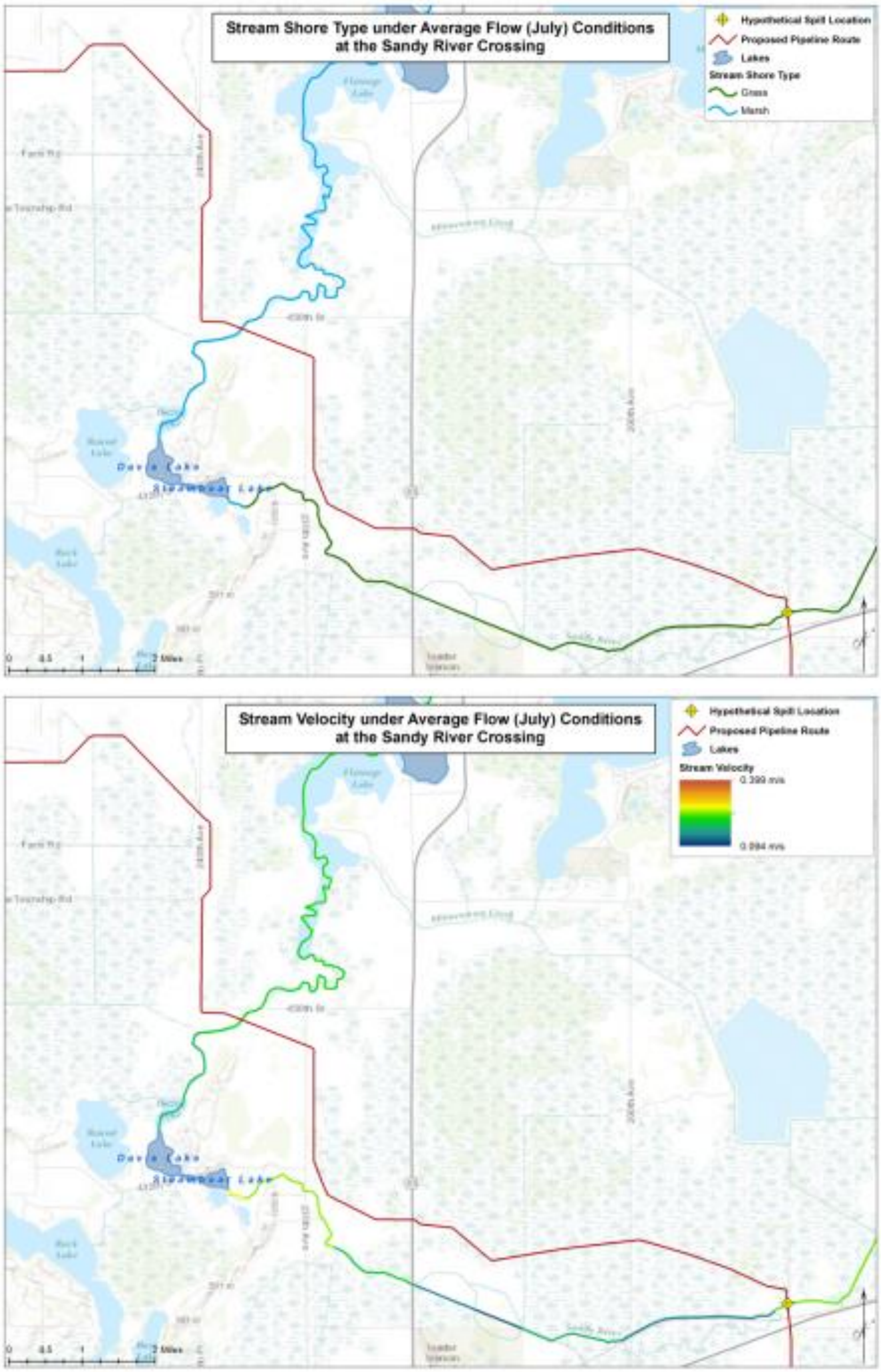

Figure 5-19 Stream Shore Type (top) and Velocity (bottom) Modeled Under Average Flow Conditions for the Sandy River Release Location

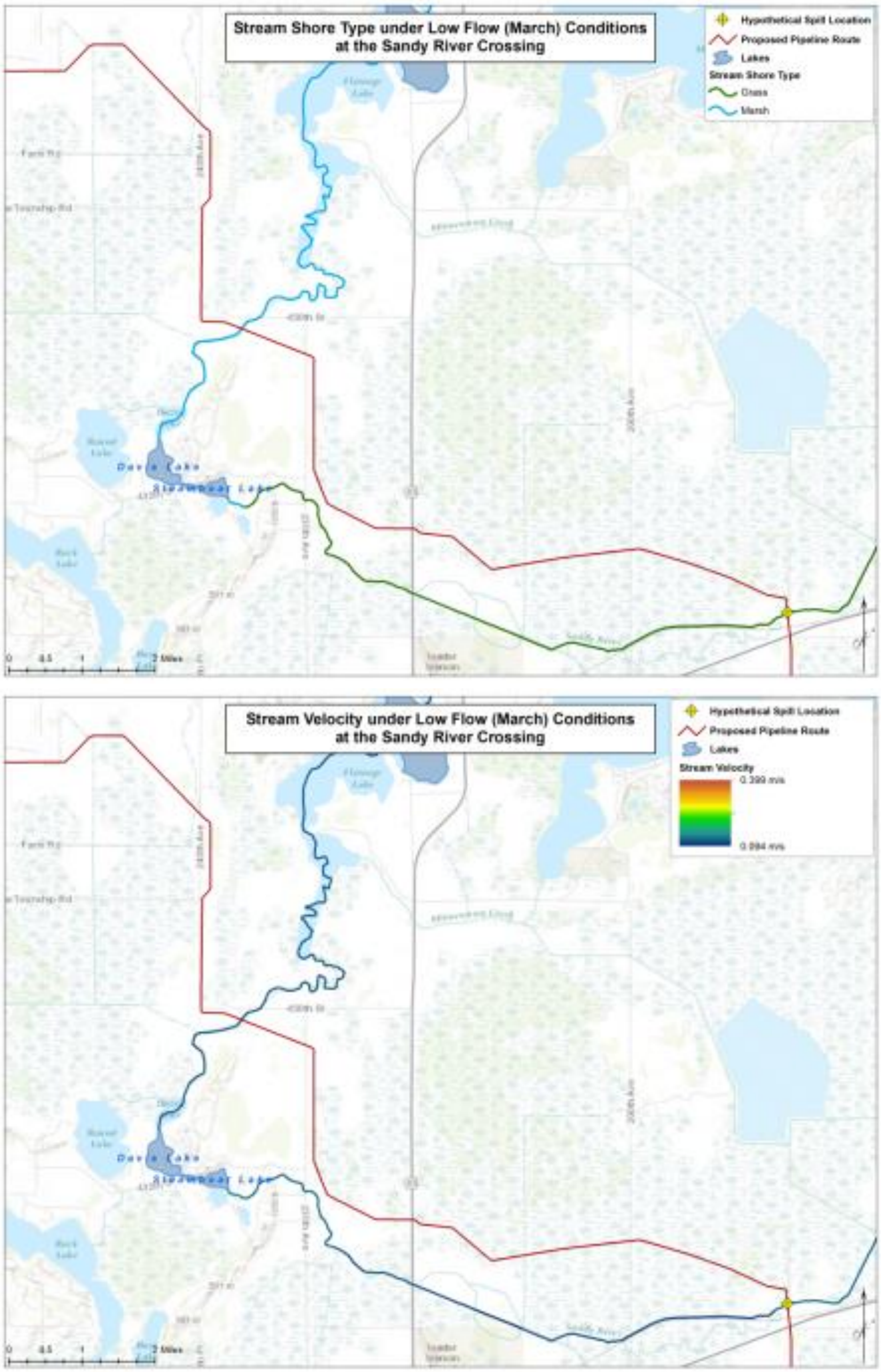

Figure 5-20 Stream Shore Type (top) and Velocity (bottom) Modeled Under Low Flow Conditions for the Sandy River Release Location

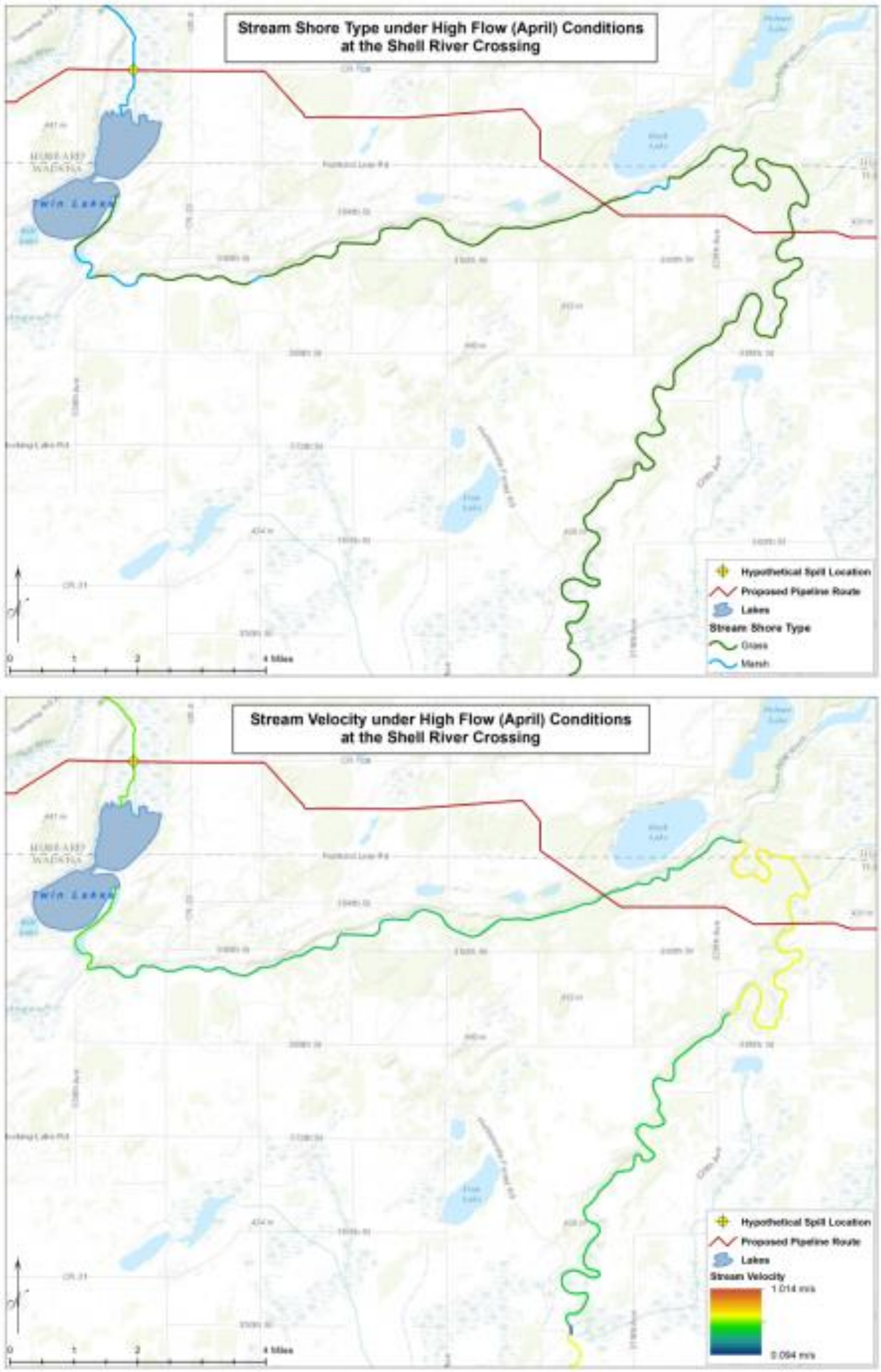

Figure 5-21 Stream Shore Type (top) and Velocity (bottom) Modeled Under High Flow Conditions for the Shell River to Twin Lakes Release Location

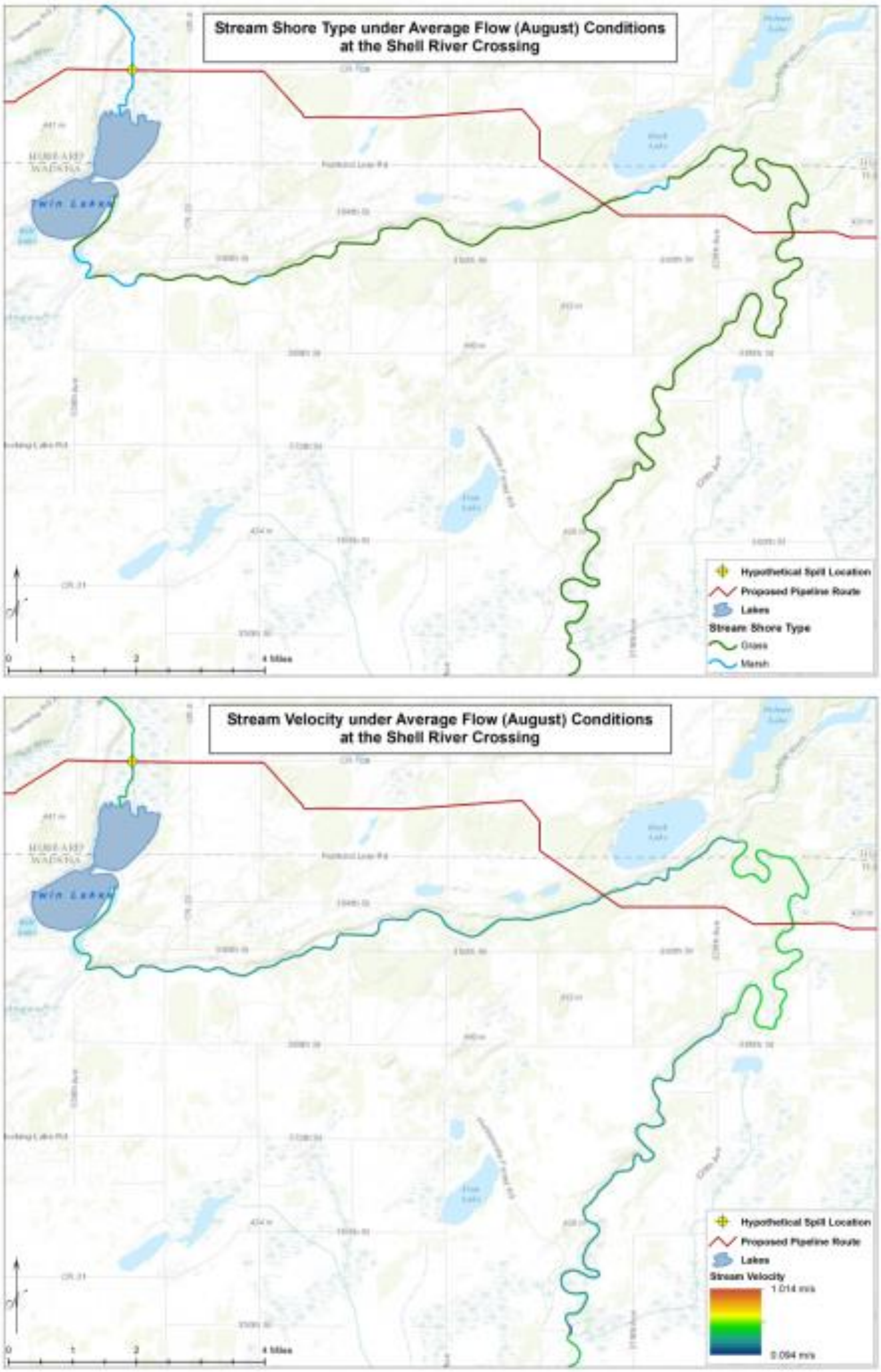

Figure 5-22 Stream Shore Type (top) and Velocity (bottom) Modeled Under Average Flow Conditions for the Shell River to Twin Lakes Release Location

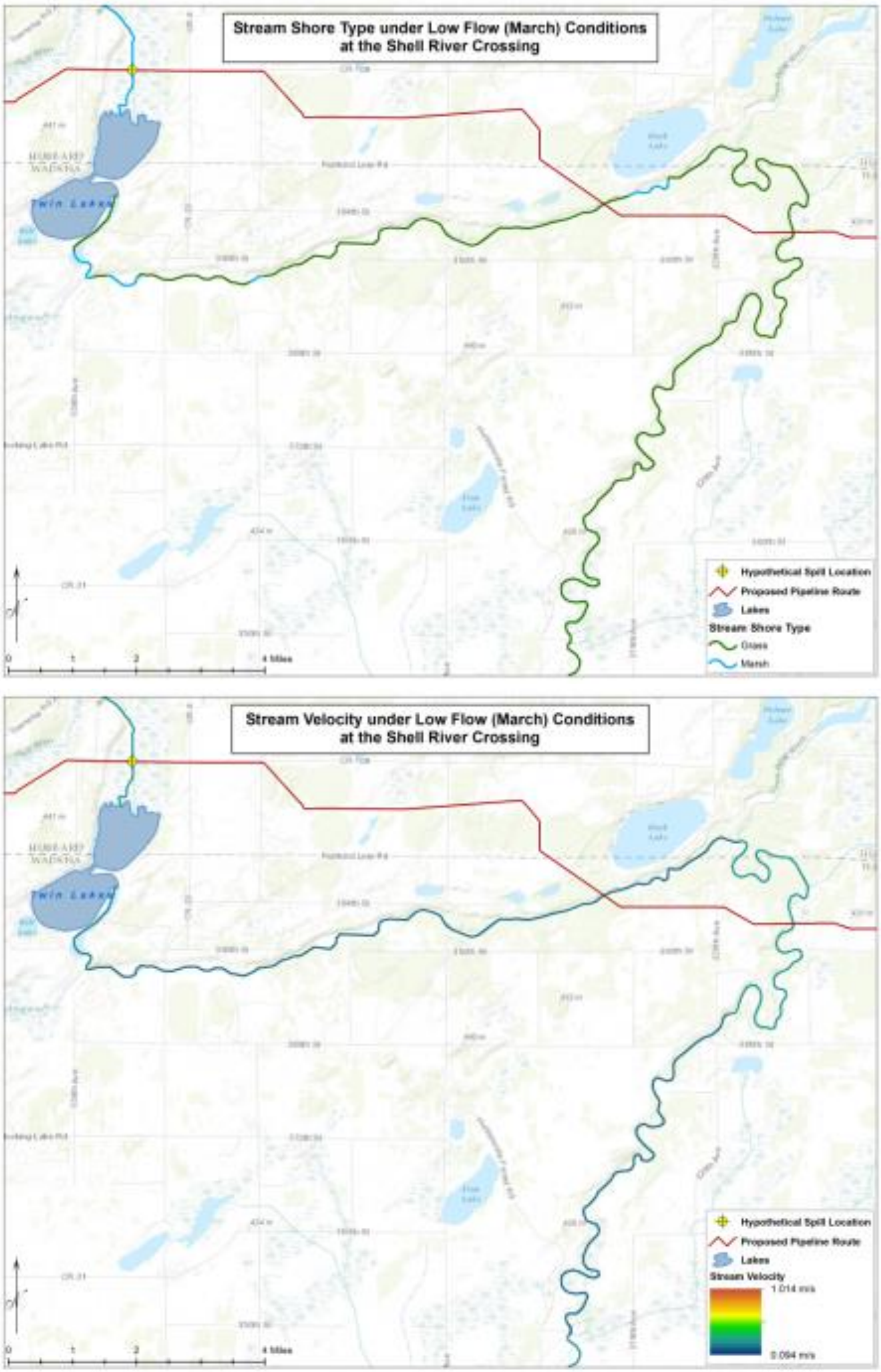

Figure 5-23 Stream Shore Type (top) and Velocity (bottom) Modeled Under Low Flow Conditions for the Shell River to Twin Lakes Release Location

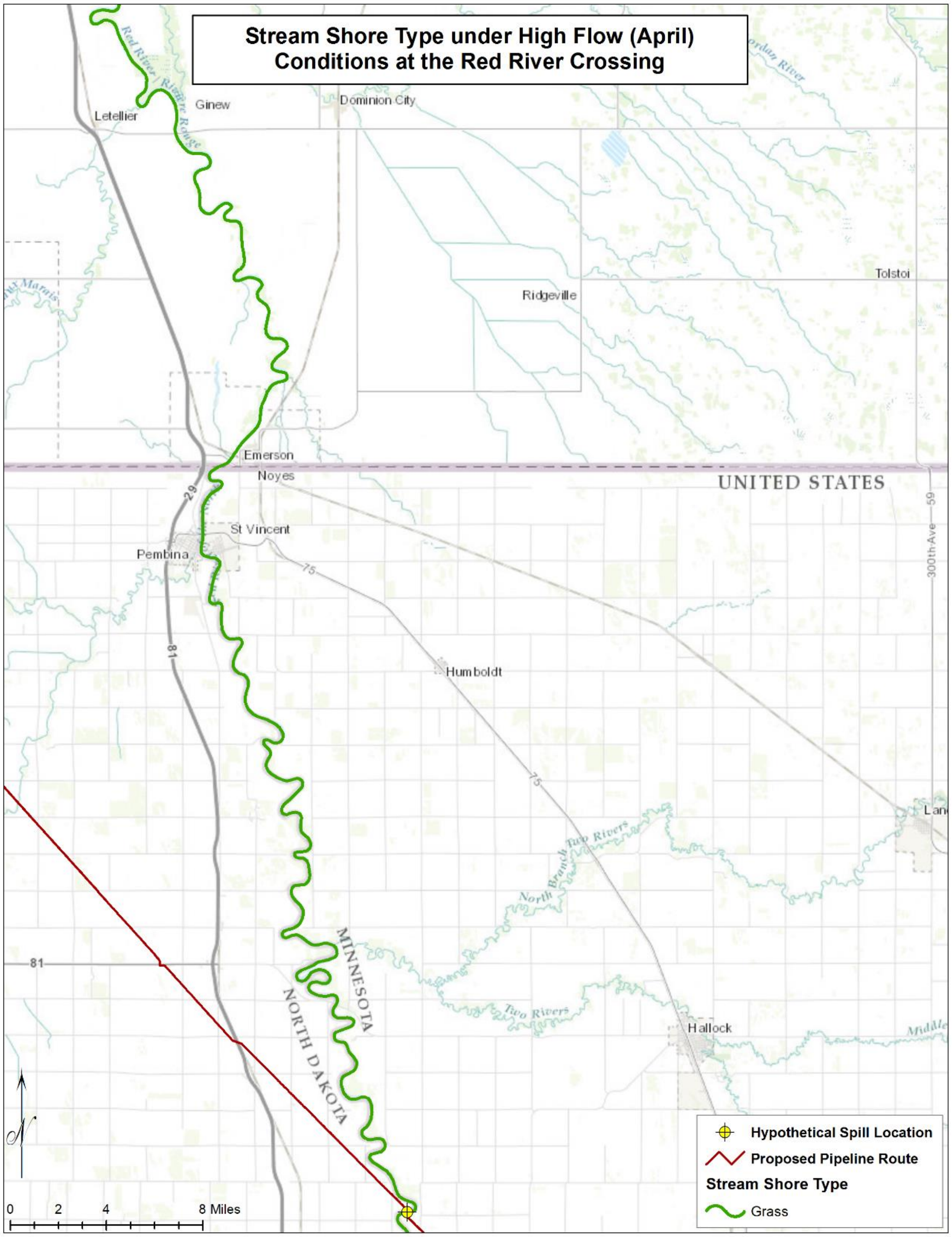

Figure 5-24 Stream Shore Type Modeled Under High Flow Conditions for the Red River Release Location

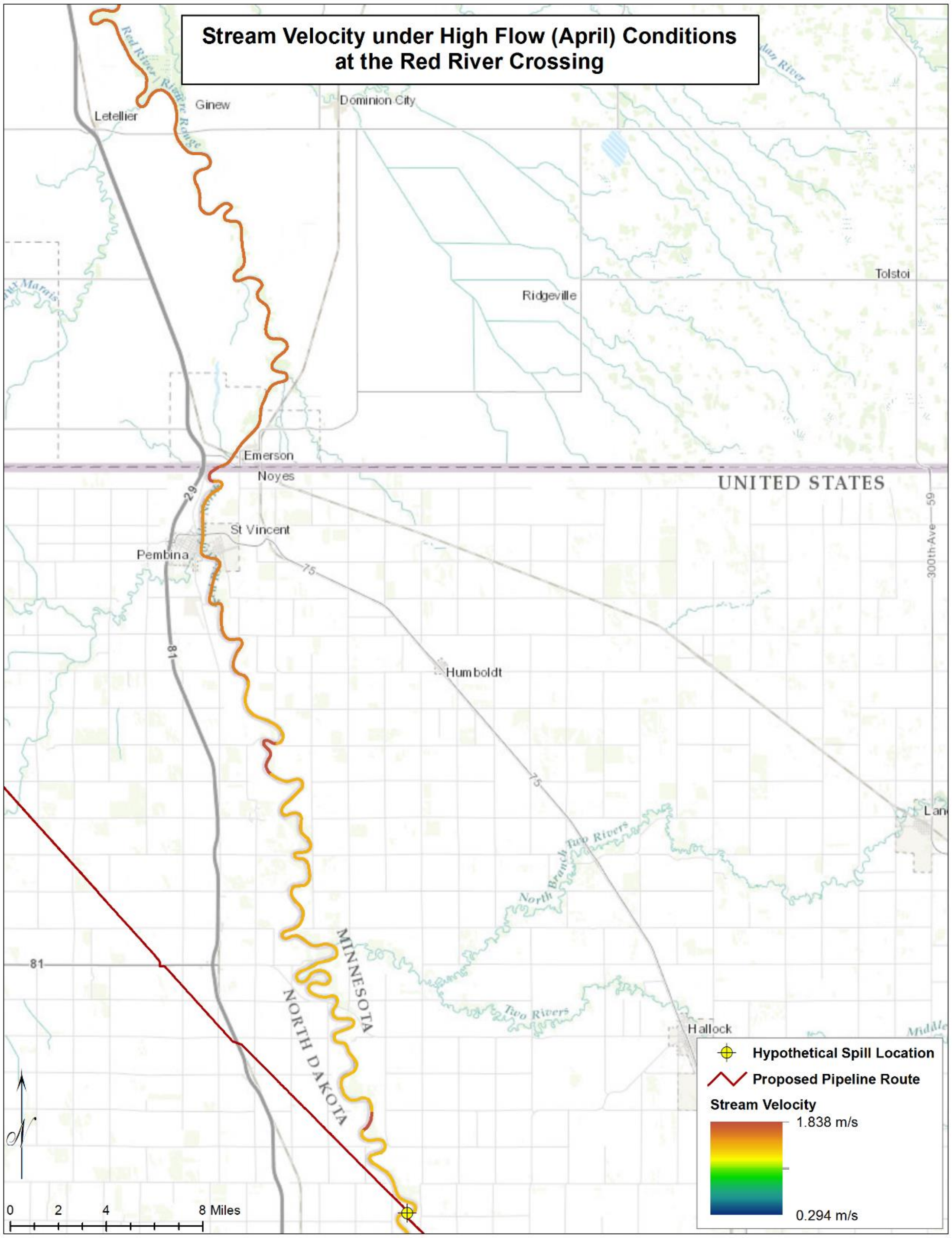

Figure 5-25 Stream Velocity Modeled Under High Flow Conditions for the Red River Release Location

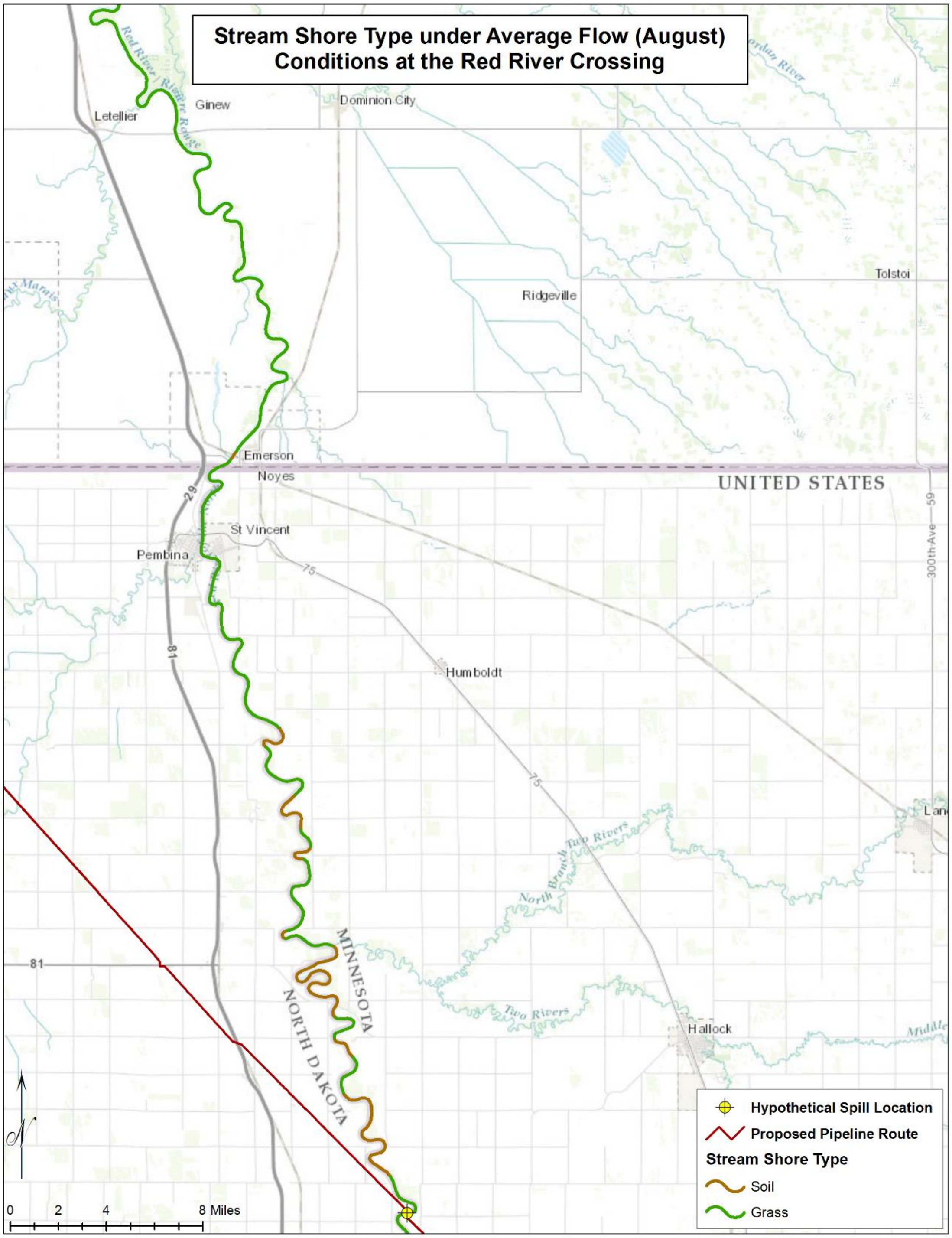

Figure 5-26 Stream Shore Type Modeled Under Average Flow Conditions for the Red River Forks Release Location

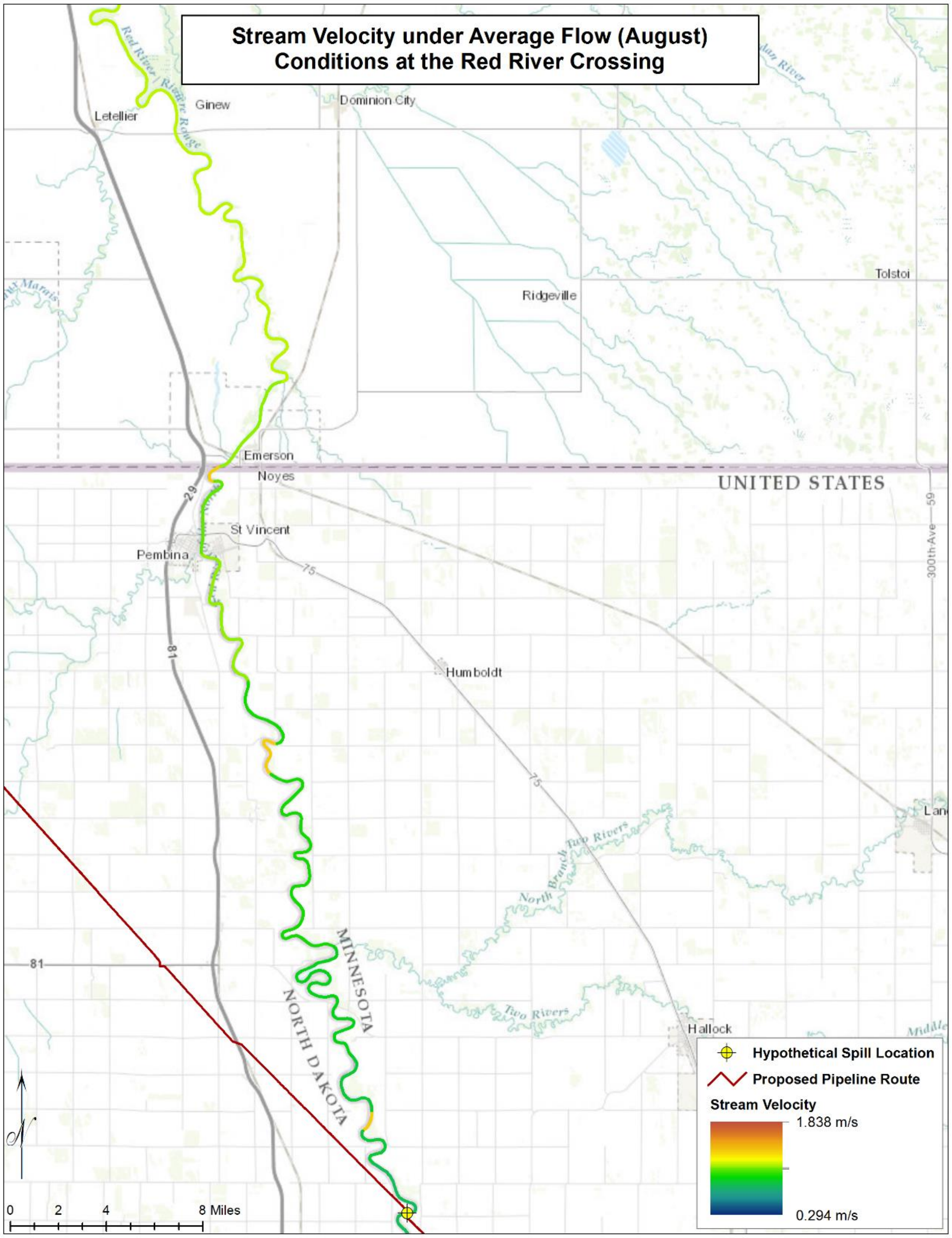

Figure 5-27 Stream Velocity Modeled Under Average Flow Conditions for the Red River Release Location

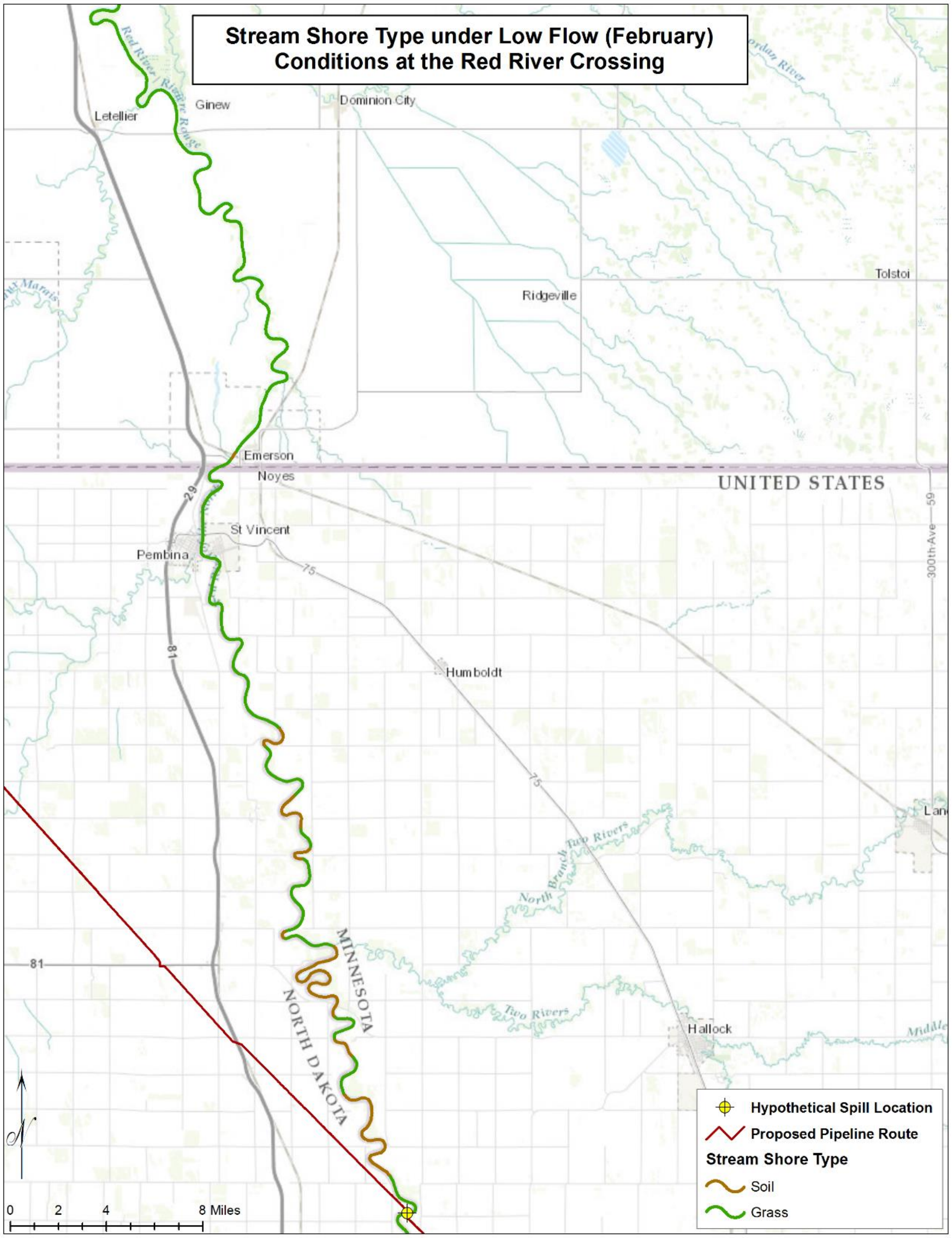

Figure 5-28 Stream Shore Type Modeled Under Low Flow Conditions for the Red River Release Location

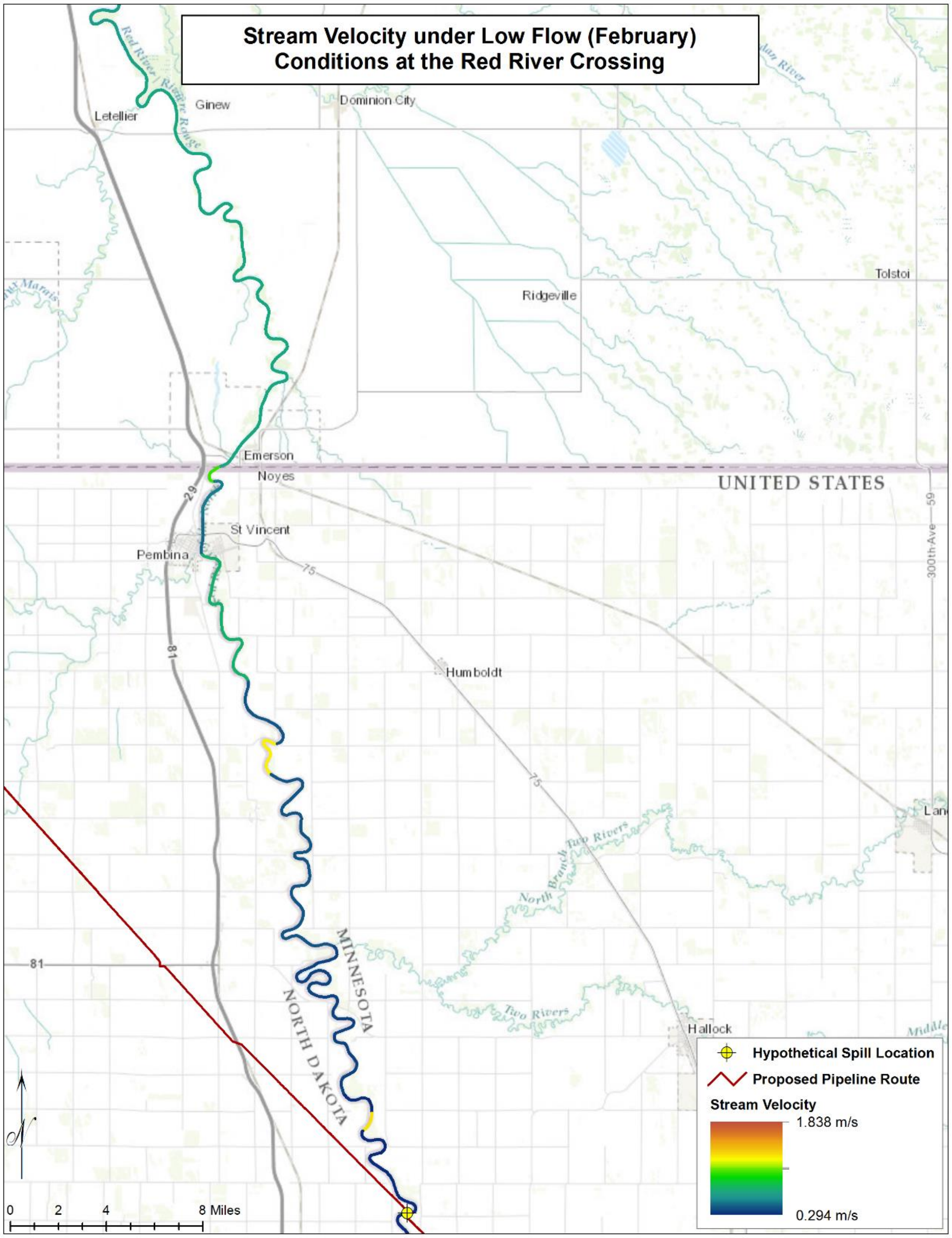

Figure 5-29 Stream Velocity Modeled Under Low Flow Conditions for the Red River Release Location