Appendix D

Summary of Hydrodynamic, Sediment Transport, and Wave Modeling

Spirit Lake Sediment Site

Prepared for
U. S. Steel Corporation

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1.0 Introduction

The purpose of this Appendix to the Feasibility Study (FS) is to describe the modeling effort undertaken by Barr and Deltares to better understand the hydrodynamic and sediment transport processes that govern Sprit Lake. A number of modeling software packages were used, which are all generally united under the umbrella of the Delft3D modeling suite developed and maintained by Deltares (2010). Multiple tools were necessary due to the complex nature of Spirit Lake and the need to consider several important processes, each of which was best addressed by an effort targeted at that phenomenon. This Appendix describes each of these modeling efforts, and provides details of how these models were constrained by, and calibrated to, field observations made during the Sediment Remedial Investigation (RI: Barr, 2013).

The overarching goal of the modeling presented in this Appendix was to provide a tool where the bed could be modified within Spirit Lake, to predict the functionality of potential Project Alternatives proposed in the main body of this FS. In other words, a tool that is capable of predicting hypothetical situations, thus aiding in estimating their feasibility. The conceptual model described in the main body of the feasibility study was developed from field observations, and served as the starting point for this modeling effort. Thus, the conceptual model provides the basis for the development of the computational model, not the converse. This approach (i.e. data before predictions) provides the foundation for hydrodynamic modeling efforts in Spirit Lake. A model that can be shown to reasonably predict conditions that are known to exist over a range of conditions provides a sound basis for the simulation of potential future designs.

The modeling effort was divided into several phases, the details of each are described by sections of this Appendix:

1. Data analysis and refinement of the RI conceptual model with particular attention to those data most valuable for model construction and calibration;
2. Development of the numerical morphodynamic (hydrodynamics and sediment transport) model of Spirit Lake, including calibration to RI data;
3. Addition of wave and vegetation modules to the calibrated morphodynamic model of Spirit Lake, with additional local wave modeling at specific locations;
4. Evaluation of potential for impacts associated with ice formation; and
5. Additional model analyses with newly available St. Louis River discharge data.

1.1 Spirit Lake Physical System

Spirit Lake is a relatively complex system that is heavily influenced by a number of factors ranging from the flow of the St. Louis River, to Lake Superior water level, to wind-wave dynamics. A comprehensive field study was conducted as a part of the RI that captured the details of these processes during both river flood and low water conditions (Barr, 2013). These data served as the basis for the Site conceptual model described elsewhere in this FS.
This conceptual model and the data serve as the basis for the modeling described in this Appendix. While a comprehensive review of Site data is not included here, certain aspects of the data are worth reviewing for clarity. In particular, several data sets are critical for development of model boundary conditions:

1. **Bathymetric scans (2011 & 2012)**
2. **Hydrodynamic data**
   a. St. Louis River discharge (from Scanlon, MN)
   b. Water surface elevation (from on-site measurement station)
   c. Flow velocity (from multiple methods at several locations)
   d. Wave height
3. **Meteorological data**
   a. Wind speed and direction
4. **Sediment data**
   a. Bed sediment characteristics
   b. Water column suspended sediment

These data are summarized briefly in the following sections to provide context for the model boundary conditions discussed later in this Appendix.

### 1.1.1 Bathymetric Scans

Bathymetric scanning was undertaken in Spirit Lake in both October 2011 and August 2012. These scans happen to have occurred on either side of the 500-year return period flood of June 2012, providing a valuable resource for model development and calibration.

Spirit Lake is relatively shallow throughout its central and western extent, and is characterized by a relatively deep river channel along the eastern shore of the lake. A dredged channel exists in the north-central portion of the lake dating to industrial use of the Site, and a deep “hole” is located within the Wire Mill area in the north west corner near the peninsula ([Figure D-1](#)). This was dredged sometime during the facility operation to create a water intake feature for the former plant operations.

The major flood of June 2012 led to both erosion and deposition of sediment in Spirit Lake. Erosion was focused in a relatively narrow region in the south-central portion of the lake, and the pattern of this erosion reflects focusing of flood flow (and associated higher velocity currents) into the main body of the lake ([Figure D-2](#)). As the flood flow entered the main body of the lake significant sediment deposition occurred throughout the central portion of the lake due to lateral spreading and velocity decrease.

### 1.1.2 Hydrodynamic Data

Several types of hydrodynamic data were collected during the RI, which serve to both bound the model runs (e.g. river discharge, water surface elevation) and validate model predictions (e.g. flow velocities and wave height).
1.1.2.1 River Discharge

River discharge data were obtained from both the USGS gauging station located on the St. Louis River at Scanlon, MN, and from the operations records of the Fond du Lac Dam as provided by Minnesota Power. While the USGS data provide a long-term record for St. Louis River flow (Figure D-3), the Fond du Lac Dam data are considered a more realistic representation of the flow through Spirit Lake because the data are recorded downstream of the two hydropower reservoirs that separate Spirit Lake and Scanlon. Both data sets have been used for the modeling presented in this Appendix.

The USGS record shows that three major floods (near to or exceeding 1,000 m$^3$/s) have occurred in the past century—in 1950, 1979, and 2012. Moderate flooding, with discharge between 500 – 1,000 m$^3$/s, is more common, and has occurred in approximately 1/3 of the past 60 years. Despite these relatively frequent flood events, the typical summer/fall/winter discharge of the St. Louis River is smaller than 50 m$^3$/s. This discharge record implies two very different regimes occur in Spirit Lake: one where periodic river floods dominate, and another (much more common) where the river discharge plays a small role in the overall morphology of the lake.

1.1.2.2 Water Level

The water surface elevation in Spirit Lake is controlled by several factors: Periodic Lake Superior water level changes, wind/weather related water level changes, and St. Louis River discharge.

The first of these—periodic Lake Superior level variation—is very important in Spirit Lake. Such water level changes in Spirit Lake are associated with seiche formation in Lake Superior, and are a well-documented phenomenon caused by oscillation of long-period waves from east to west within the large lake. Figure D-4 shows a spectral analysis of water level measured in Spirit Lake (Barr 2013) that indicates how the dominant (most common) frequency of lake level changes occurs every 8 hours, with less dominant 2 and 4 hour periods. More important for morphological evolution than the lake level, however, are periods when lake level is changing (i.e.: change in lake level with time, and thus rate of either draining or filling the lake). In practice, these three frequencies of lake level variation interact with each other, and lead to a periodic velocity pattern that is discussed in the next sub section.

The weather can cause changes in the level of Spirit Lake, due to phenomena known as either set-up or set-down of lake level. This behavior is associated with major wind events, and occurs in Spirit Lake due to sustained uni-directional wind blowing on the surface of Lake Superior. When winds are relatively strong out of the west for a period of several days, Lake Superior water is pushed to the east, and water levels can drop in both lakes for several days. Conversely, easterly winds lead to short-term local increases in lake level. These water level changes are not as important as those associated with seiche dynamics, as they are less common. However, major storms often lead to larger lake level changes than does the seiche.

Finally, and most intuitively, high St. Louis River discharge leads to significant (0.1 – 1 m) variation in lake level. However, increased velocities associated with river flood are typically significantly more important than lake level in dictating morphologic evolution during such periods.
1.1.2.3  Flow Velocity

Flow velocity was documented via two methods: (1) continuous records over several weeks from upward-oriented acoustic Doppler current profiler (ADCP) devices, and (2) instantaneous measurements at several points in time, along several transects (Figure D-5). These data show how both river flooding and lake level changes can affect flow patterns in Spirit Lake.

During low river discharge, overall velocity magnitudes are relatively small—on the order of 0.05 – 0.1 m/s. The dominant velocity pattern during low river discharge is associated with filling and emptying of Spirit Lake due to Lake Superior seiche. This is reflected as periodic alternation between northward and southward flow with an approximately 8h period. This phenomenon is particularly evident in a vector plot of flow velocity near Unnamed Creek between November 9 – 11, 2011 (Figure D-6). During low flow periods the reduced river flow is directed primarily through the eastern river channel, with velocity magnitudes generally below the threshold for sediment movement.

Detailed measurements of velocity during the flood of 2012 are not available, due to loss of equipment during the flood. Two ACDPs were located within the main path of the flow. Buos attached to the ADCPs were detached from the ADCPs by the force of the flow and carried downstream where they were found in the area between Morgan Park and the Riverside Marina. The loss of equipment indicates the dominance of flood flow in velocity patterns during flood events.

1.1.2.4  Wave Height

Wave data were recorded in four locations (Figure D-5). During the measurement period in the fall of 2011 wave heights in the middle of Spirit Lake only exceeded 0.2 m once, and were typically much smaller (< 0.05 m). Waves recorded in the central portions of the lake were generally higher than those nearer the Unnamed Creek and Wire Mill Pond outfall, where wave height never exceeded a few centimeters.

These minimal waves are too small to have an effect on the bottom sediments, though they reflect relatively mild wave formation conditions present during the measurement period. More sustained easterly winds could drive larger wind wave formation, but because Spirit Lake is sufficiently small and shallow that wave heights cannot exceed 0.5m in that water body. A range of potential wave-generating winds were investigated with the wave modeling presented later in this Appendix.

1.1.3  Meteorological Data

The primary meteorological data needed for the modeling presented in this Appendix are wind direction and speed. These data in combination with the geometry of the lake are important for modeling wave influence. The primary source of wind data is the NOAA weather station at the Richard I Bong Airport, in Superior WI, which is approximately 7.5 km east of Spirit Lake. Additionally, wind direction and speed were collected at an onsite weather station, though this record is not long enough to produce a statistically reasonable representation of site conditions through multiple seasons and years. The two records were compared, however, and indicate that the Bong Airport data reasonably represent the wind conditions at Spirit Lake.
Figure D-7 shows a wind rose derived from the Bong Airport data, which indicates that the record is dominated by either northeasterly or southwesterly winds. Of these two end members, the northeasterly winds, which rarely exceed 10 m/s and average approximately 5 m/s, are the most important for wave formation on the western, impacted, margin of Spirit Lake.

1.1.4 Sediment Data

Two types of sediment data were collected during the RI: 1) bed sediment samples; and 2) suspended fine grained sediment concentration. The former are useful for parameterizing the potential for sediment cohesiveness (and thus erosion potential), as well as for parameterizing the overall sediment grain size distribution in the system. The latter are used to construct a site-specific relationship between river discharge and suspended sediment load.

The bed of Spirit Lake is dominated by silt and clay sized particles (mean grain size < 62 µm). Coarser particles (sand sized) were found on the bed in a few places where flow velocities are higher, such as in the main St. Louis River channel. Determination of whether sediments will behave cohesively or non-cohesively was made via plotting the grain size data on a ternary sand-silt-clay diagram. Figure D-8 shows that the majority of the bed sediment samples fall in the cohesive field of the diagram (non-shaded), and that the majority are clay to silt dominated. The implication of sediment grain size data for the modeling presented in this Appendix is that cohesive bed erosion and sediment transport laws are appropriate.
2.0  Modeling Software

As noted above, several modeling packages/approaches were needed to address the wide range of important processes that operate within Spirit Lake. Multiple approaches were needed, as no one modeling tool was capable of evaluating all potential questions that might arise of the Project alternatives presented in the FS. However, all methods ultimately have a calibrated Delft3D hydrodynamic model at their core.

2.1  Delft3D

The core numerical model of Spirit Lake used in this FS was developed in the Delft3D software suite—a fully integrated suite of open source modeling tools that can be used to address a wide range of natural phenomena and interactions from hydrodynamic processes, to sediment transport, waves, water chemistry, and vegetation. More information about Delft3D, and the flow equations in particular, can be found in the Delft3D user manual (Deltares, 2013), or to the Delft3D Open Source Community web portal (oss.deltares.nl/web/delft3d).

The Delft3D modeling includes several sub components that were used in this analysis (FLOW, SED-ONLINE, SWAN, and VEG), the parameterization and calibration of which will be discussed as they are introduced later in the document. Their output forms the boundary condition for the additional modeling tools described below.

2.2  SWAN/XBeach

The SWAN module of Delft3D, while powerful, is not designed to simulate the effects of individual waves in the swash zone. Thus, we employed an additional wave modeling tool, XBeach, to make a number of detailed simulations in regions where impacted sediment exists (Rolevink, et. al., 2010).
3.0 **Morphodynamic Model (FLOW and SED ONLINE)**

A numerical morphodynamic model was developed which uses the hydrodynamic (FLOW) and sediment transport (SED-ONLINE) modules of Delft3D, as the basis for evaluation of project alternatives. Hydrodynamics and sediment transport are coupled together in this approach at each time step, so that the bed is constantly updated during the simulation of hydrodynamic processes. This is particularly important when significant morphological changes are expected, such as during river flood.

During low flow conditions the hydrodynamic boundary conditions (river currents and waves) were observed to be relatively small, with flow velocities on the order of 10 cm/s and wave heights of a few centimeters, as discussed above. These conditions are not likely to mobilize the bed sediments significantly. However, during flood events the river discharge increases significantly and thus flow velocities in Spirit Lake become large. Significant morphological changes were measured after the June 2012 flood, with erosion/deposition up to a meter in certain areas of Spirit Lake. Because the present model was designed to reproduce bed stability and morphological change, the setup and calibration of the model was focused on matching the pre- to post-flood morphological changes as well as possible.

### 3.1 Computational Grid and Bathymetry

The model grid was set up to include Spirit Lake and all surrounding areas potentially subject to flooding during high flow events. Additionally, the model grid was designed to be aligned with likely flow paths, in this case the main river channel along the eastern shore of Spirit Lake and curvilinear paths through the central portion of the Lake. Special attention was given to the dredged channel. The resulting computational grid is shown in Figure D-9. Grid cell edges are generally in the range of 30 – 60 m in length. This grid alignment was designed to optimize the numerical solution of flows that follow its geometry and not to promote flow in certain orientations.

The model bathymetry was created using the bed levels measured in October 2011, prior to the flood event. At locations where bathymetric data were absent, depths were estimated using best engineering judgment and local knowledge. An initial erodible layer of sediment 0.2 m thick was applied to the bed to allow for potential erosion below the initial bathymetry.

### 3.2 Boundary Conditions

#### 3.2.1 Hydrodynamics

The hydrodynamic conditions in Spirit Lake are a result of water level variations, wind shear on the water surface, and river inflow into the lake. The hydrodynamic forces were imposed as numerical boundaries via:

1. Water levels at the two northern open boundaries of the domain;
2. River discharge at the southern open boundary; and
3. Wind, translated into drag at the water surface (using the Smith and Bank wind drag formulation).
The water level boundary conditions employ the locally measured water levels, while the discharge data at Scanlon were used as the initial upstream boundary. Additional model runs employ the Fond du Lac discharge data as their upstream boundary condition. Wind speeds, which are most important for wave-related model runs, are based on Bong Airport meteorological data.

### 3.2.2 Sediment Load

One of the most difficult boundary conditions to specify for modeling in river systems is the sediment load. This estimation is complicated by the fact that sediment loading data are much more difficult to measure than water discharge, and therefore they are less frequently available. Some data are available from Scanlon, MN, though they are separated from Spirit Lake by two hydropower reservoirs, and thus are unlikely to provide an accurate picture of St. Louis River sediment loads at Spirit Lake. Two records were evaluated as potential boundary conditions:

1. **Turbidity measurements that were obtained during the 2012 flood at Scanlon.** These data imply 50,000 – 200,000 m$^3$ of sediment were delivered to Spirit Lake during the flood. This estimate is much smaller than the total amount of sediment deposition estimated from the bathymetric surveys (700,000 m$^3$), and therefore implies additional sources of sediment to the system, particularly during flood. In any case, this discrepancy indicates that the Scanlon turbidity measurements are not suitable as the upstream boundary condition.

2. **Long term sediment concentration measurements at Scanlon.** Unfortunately, this time series did not include the 2012 flood event during model development. The flood of 1979, however, gives an indication of the concentrations observed for high discharge events. By assuming a linear relation between discharge and sediment concentration, a sediment concentration for the June 2012 flood event can be estimated. Integrating the sediment load over time with the second record still leads to an underestimation of the total sediment influx, again implying that additional sources of sediment exist between Scanlon and Spirit Lake.

An appropriate boundary condition for the model, therefore, requires higher sediment loads than the Scanlon records would suggest, particularly during times of flood. To estimate the load reasonably, we relied on the well-understood distinction between wash load (finest grain sizes, never settle in channelized flow) and suspended bed material load (bed material suspended in the flow during high river discharge). Thus, some fraction of wash load mud was presumed to travel through the system at all times—low and flood flow. At higher sediment concentrations (above 50 mg/l) the system was assumed to obtain additional sediment load via erosion. Preliminary model runs indicated that the sediment load from the Scanlon record, underestimated the total sediment volume deposited within the model domain during the 2012 Flood. To account for the underestimation of Spirit Lake sediment volumes by the Scanlon records, a multiplier in the formulation that increased the flood sediment load above that implied by correlation with discharge was used. Based on comparing sediment volume results from the model with the measured data, this value was found to be 5.

This approach was the best fit to the extreme circumstances of the flood of 2012, and is likely a reasonable approximation for other extreme events of this nature.
3.2.3 Bed Roughness

The bed roughness of the initial hydrodynamic model was specified via a Chézy coefficient of 40 m\(^{1/2}\)/s in the upstream river portions of the model domain and 60 m\(^{1/2}\)/s in the shallower Sprit Lake portion of the model. These values were determined via iterative comparison of model predictions with observed water levels and velocities. Both Manning-type and Chézy formulations were evaluated, and the latter determined to better reproduce observed water levels and flow velocities. This iterative process was also used to determine that the addition of a numerical process for Horizontal Large Eddy Simulation was appropriate for Spirit Lake, which estimates a horizontal turbulent viscosity and more accurately reproduces observed flow velocities.

3.2.4 Sediment Characteristics

The characteristics of the Spirit Lake sediments were determined primarily from the field data collected during the RI (Barr, 2013). Two sediment transport formulations were used for the modeling (1) silt transport was based on the Van Rijn (2007) non-cohesive transport law, and (2) mud transport/erosion was modeled via the Parthenaides-Krone formulation (Partheniades, 1965).

Bed sediment characteristics include:

1. Predominantly mud-sized sediment (D\(_{50}\) < 63 \(\cdot\) m)
2. Organic content of 5 – 10 %
3. Moderate compaction (dry density of 500 kg/m\(^3\))
4. Weakly cohesive bed, with relatively high silt:clay ratio (relatively low erosion parameter of \(10^{-5}\) kg/m\(^2\)/s, settling velocity of 0.5 mm/s, and critical shear stress of 0.1 Pa)

The upstream sediment input into Spirit Lake was parameterized by:

1. Three size fractions
   - very fine mud (wash load, settling rate 0.001 mm/s)
   - fine mud (settling rate 0.05 mm/s)
   - coarse mud (settling rate 0.5 mm/s)
2. weakly cohesive (when deposited; erosion parameter of \(10^{-3}\) kg/m\(^2\)/s)
3. Bed density (when deposited) of 500 kg/m\(^3\).
4. critical shear stress (when deposited) of 0.1 Pa

For sediment transport modeling, the most critical calibration parameters are the settling velocity and critical shear stress for erosion. While these parameters can be predicted with some accuracy for relatively coarse sediments (sands), they are not as easily predicted for cohesive materials like those common in Spirit Lake, making calibration important. Values used in the final calibrated model were derived through a sensitivity analysis in which input parameters were varied, and results compared with the measured bathymetric change as a result of the June 2012 Flood.
3.3 Morphodynamic Model Results

As noted above, the primary calibration for the modeling involved comparison of model predictions to observed bathymetric changes that occurred during the 2012 flood. This is fortunate, as flood scenarios are typically the most difficult both to observe and model, despite having the most significant impacts on bed stability. The flood-calibrated model was then run with the low-flow conditions observed in fall 2011 to assess its robustness over a range of flow conditions.

3.3.1 June 2012 Flood Scenario

The model was run over a three month period (May – July 2012). The upstream boundary condition for this model scenario was the river hydrograph shown in Figure D-10. Initial bed elevation was specified by the fall 2011 bathymetric scanning, and an initial bed layer was available for erosion.

Figure D-11 shows model predictions of depth-averaged velocity in Spirit Lake (with Unnamed Creek area inset) at the moment of highest discharge (June 21, 2012). The arrows in the figure indicate the flow direction and magnitude. The map indicates how the highest velocities are concentrated within the river channel south of Spirit Lake. After entering Spirit Lake, the flow spreads out across the width of the lake and slows significantly. Depth averaged velocities are as high as 2.5 m/s in the main river channel (thalweg), with velocities nearer 1m/s where the flow enters the lake, and velocities less than 0.5 m/s along the western margin of the lake during this period.

The most important result of the 2012 flood simulation is the comparison between modeled and measured bed level changes shown in Figure D-12. As noted above, this comparison is used as calibration for the various model input parameters, and thus represents ‘ground truth’ for the performance of the model. Figure D-12 shows a map-view of this comparison. The model accurately predicts overall patterns of sedimentation and erosion and also captures the overall magnitude (thickness) of deposition. The model does not capture the minor erosion observed near the north-central edge of the lake, in the area of the dredged channel. The model over-predicts erosion at the southern end of the domain where the river channel enters Spirit Lake. While these discrepancies may be due to processes not included in this version of the model (such as vegetation), the subtle differences are more likely due to a mismatch between the observation and simulation periods. That is, the bathymetric scans span the 10-month period between October 2011 and August 2012, whereas the model only simulates the 3-month period between May and July 2012. This time period was chosen due to the understanding developed during the RI that little morphodynamic change occurs during periods of low flow where sediment loads and river currents are minimal.

3.3.2 Fall 2011 Low Flow Scenario

To evaluate the robustness of the calibrated model under other conditions, the model was used to simulate the intensive RI observation period in the fall of 2011. Simulation of this time period was valuable for evaluating how the model would handle seiche processes, in particular, as they are significantly more important when river discharge is low.
Figure D-13 shows a comparison between measured and predicted water levels and velocities during a 2-day portion of the low flow model run. All measurements are from the Unnamed Creek area. The predicted water levels tend to be slightly smoother than the short-term (2-hour) measured water level fluctuations, particularly those early on 12 November. The overall trends, as well as the magnitude of the 8-hour seiche fluctuations, however, are well captured by the model predictions. This minor smoothing of the 2-hour fluctuations is not significant to the overall model morphodynamics, as they are of short enough duration that neither significant velocities, nor sediment transport is associated with them.

The lower two panels of Figure D-13 show a feather plot of velocity as measured (top) and predicted (bottom) by the model off Unnamed Creek. Both the color and length of the vectors indicate velocity, while orientation indicates direction of flow (where straight up is equivalent to north). Velocities alternate from northwestward to southeastward flow and rarely exceed a tenth of a meter per second. While the phase of the velocity is not always in sync between measurements and predictions, the overall magnitudes and periodic changes are consistent. Low magnitude velocities like those observed in the Unnamed Creek area are traditionally the most difficult to reproduce numerically, as they fall near the lower limit of model resolution in time and space. Thus, the favorable comparison between overall magnitude and direction constitutes an acceptable validation of the model predictions. Even if the phase is slightly different, the net effect of the predicted velocity fluctuations and directions will be indistinguishable from the natural phenomenon.

3.3.3 Sensitivity Analysis

A common approach in numerical modeling is to evaluate model sensitivity to changes in various specified input parameters—particularly those parameters that are either difficult to measure, or are unique to the numerical environment and thus unmeasurable (such as horizontal eddy viscosity). Five parameters were evaluated for model sensitivity:

1. **river/lake bed roughness**: This is parameterized in the model via a Chézy coefficient. The value was varied between 40 and 90 m$^{1/2}$/s (relatively rough to smooth bed character).

2. **horizontal viscosity**: This parameter is important for reproducing large-scale circulatory patterns, particularly in a setting like Spirit Lake where flow width changes significantly. Delft3D handles this behavior via a numerical process called Horizontal Large Eddy Simulation (HLES). The values for horizontal viscosity were varied between 0.2 and 10 m$^{2}$/s.

3. **vertical discretization**: Delft3d is capable of simulations that resolve variation in velocity (and other parameters) with depth. Both depth-averaged (2D) and depth resolving (3D, with 10 model cells distributed through the flow) simulations were run.

4. **grid size/shape**: Model simulations were run with additional, hypothetical, St. Louis River cells added, such that numerical reflection of the water level boundary condition (a phenomenon unique to the model) could be minimized.
5. **boundary condition smoothing:** This applies to the water level boundary condition. Simulations were run using both the ‘raw’ measured data and a slightly smoothed version where the shortest term fluctuations were dampened.

The result of these analyses showed that the model results were relatively insensitive to roughness, horizontal viscosity, and depth resolution. Thus, reasonable values for roughness and horizontal viscosity were chosen, and all simulations reported in this document are depth-averaged (2D). The analysis of grid size/shape and boundary condition smoothing showed that better matches to observed water level records (with respect to phase, in particular) were achieved with both a numerically extended St. Louis River and modestly smoothed water level boundary conditions. None of the results from within this hypothetical river extension are valid, but it is designed to be far from the region of interest. Boundary condition smoothing is a common numerical technique—one that is made necessary by the discrete time step required for numerical solutions. Provided the major morphodynamically important fluctuations remain in the boundary condition time series, the effect of such smoothing is negligible.

### 3.4 Summary

Initial hydrodynamic and sediment transport model development, in combination with insight from the conceptual model, indicated that Spirit Lake is dominated by two important flow regimes: High river flow and low river flow. These regimes are distinct in that the dominant processes controlling sediment movement, deposition, and erosion potential are either dictated by river flow patterns (during high flow) or other secondary processes such as seiche (during low flow).

Magnitudes of sediment transport can be relatively large during river flood, though impacts associated with river flow patterns are focused in the southernmost and central portions of the lake, not in areas that are the focus of this FS. During low flow periods, filling and draining of the Lake due to periodic water level changes causes small velocity fluctuations, which lead to negligible sediment transport everywhere in the Lake.

These results do not include the effects of vegetation or wave influence. However, even without these potentially important processes, the model predictions are consistent with observations, implying that the morphodynamic evolution of Spirit Lake is dominated by river flow and seiche processes, while waves and vegetation play a significantly smaller secondary role. The following sections of this Appendix discuss how other processes are included in the modeling, and the degree to which they impact the model predictions.
4.0 Vegetation Modeling

Vegetation can play a significant role in the morphodynamic evolution of natural systems. The presence of vegetation in the water column can lead to both slowing and constriction of the flow, potentially leading to either sheltered areas that enhance sediment deposition or local velocity increases (enhancing erosion). Therefore, it is important to evaluate the role of vegetation in Spirit Lake to understand its potential influence on sediment transport, particularly with the potential for inclusion of new vegetation in the Project alternatives.

4.1 Vegetation Model Setup

A number of techniques exist for modeling the effects of vegetation on hydrodynamic and sediment transport processes. In general, they all involve numerically increasing the bed. An increase in bed roughness by itself, however, can lead to an underestimate of the sheltering effect and associated increased sedimentation that vegetation typically causes. Thus, the effects of vegetation are incorporated in the Delft3D model via a numerical technique referred to as the "trachytope" method, in which an additional flow resistance term is included (Delft3D, 2013; Baptist, 2005).

4.1.1 Vegetation Area Definition

Figure D-14 shows a vegetation map for the Unnamed Creek and Wire Mill areas that was produced as part of the RI (Barr, 2013). This map was used as basis for defining vegetation areas for the numerical modeling. Three vegetation scenarios were modeled:

1. Vegetation distribution based only on the map shown in Figure D-14.

2. The vegetation distribution obtained via the RI survey, combined with an estimate for the presence of vegetation in other portions of Spirit Lake based on satellite imagery (Figure D-15).

3. Vegetation distribution depending on the local (mean) water depth, assuming vegetation is present in all areas where the water depth is less than 1m (Figure D-16).

4.1.2 Vegetation Characteristics

Estimates of vegetation height, density, size, and rigidity were required for implementation of vegetation in Delft3D. A list of vegetation species present in Spirit Lake was developed as a component of the RI (Table 1). The list included nine different species with various characteristics. As can be seen in Table 1, the parameter range is generally quite large for individual species (particularly vegetation density), and often larger than the range between different species. To assess the sensitivity of these various vegetation characteristics, a range of stem density ($n$) values were used in the model (ranging between 0.1 – 10 m/m$^2$).

The result of this vegetation sensitivity analysis was that the various species had an overall similar morphological effect. Therefore, rather than assume particular values for each species to be distributed in the model, one numerical vegetation type that combined average characteristics of all species was used.
Vegetation height was assumed to be equal to the water depth at all locations—an assumption supported by a number of experimental simulations that showed the model to be relatively insensitive to vegetation height.

### Table 1  Vegetation species and characteristics

<table>
<thead>
<tr>
<th>Vegetation species</th>
<th>$h_v$ [m]</th>
<th>$D_v$ [mm]</th>
<th>$n$ [m/m$^2$]</th>
<th>Rigidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vallisneria Americana</td>
<td>0.3 – 2</td>
<td>3 – 10</td>
<td>20 – 100</td>
<td>not</td>
</tr>
<tr>
<td>Ceratophyllum demersum</td>
<td>0.3 – 2</td>
<td>2 – 20</td>
<td>3 – 100</td>
<td>not</td>
</tr>
<tr>
<td>Potamogeton richardsonii</td>
<td>0.3 – 1</td>
<td>1 – 2.5</td>
<td>10 – 100</td>
<td>not</td>
</tr>
<tr>
<td>Nymphaea odorata</td>
<td>&lt; 2.5</td>
<td>0.3 – 1</td>
<td>30 -60</td>
<td>flexible</td>
</tr>
<tr>
<td>Sparganium angustifolium</td>
<td>0.5 – 1</td>
<td>2 – 3</td>
<td>25 – 250</td>
<td>flexible</td>
</tr>
<tr>
<td>Najas flexilus</td>
<td>0.5 – 1</td>
<td>0.2 – 0.6</td>
<td>1 – 25</td>
<td>Not</td>
</tr>
<tr>
<td>Potamogeton epihydrous</td>
<td>0.5 – 2</td>
<td>1 – 2</td>
<td>3 – 40</td>
<td>not</td>
</tr>
<tr>
<td>Stuckenia pectinata</td>
<td>0.3 – 1</td>
<td>1 – 2</td>
<td>3- 40</td>
<td>not</td>
</tr>
<tr>
<td>Sagittaria rigida</td>
<td>0.5 – 2</td>
<td>Var</td>
<td>Var</td>
<td>flexible</td>
</tr>
</tbody>
</table>

Note: columns 2 – 4 give vegetation height ($h_v$), diameter ($D_v$), and density ($n$), respectively.

#### 4.2 Vegetation Modeling Results and Summary

The primary validation of the modeled vegetation scenarios was via comparison of the cumulative erosion and sedimentation patterns between the three cases listed above and the measured bathymetric changes through the 2012 flood. The best match between modeled and observed results was obtained using the first vegetation scenario, in which vegetation distribution was based only on the RI survey. Figure D-17 shows the measured changes (left panel), the hydrodynamic and sediment model without vegetation (center panel), and the model results using this vegetation distribution (right panel). The primary area where addition of vegetation to the model showed an effect was in the central portion of the model, immediately south and southeast of the man-made spit. The match between simulation and observation, particularly with respect to the magnitude of deposition between the spit and Spirit Island, was improved in this area by addition of vegetation.

Overall, the addition of vegetation to the model did not change the predictions of sedimentation patterns. This is due to the relatively small role that vegetation plays in this system presently. The vegetation simulations improved the match to observations in vegetated areas, but confirmed that present-day sedimentation patterns in Spirit Lake are dominated by river and seiche processes. However, should restoration plans call for significant new vegetation, the model is capable of including these effects.
5.0 Wave Modeling

Waves can lead to significant remobilization and transport of sediment in certain environments, and therefore consideration of their potential effects in Spirit Lake was an important component of model development. Waves can affect bed sediment by elevating near-bed shear stresses during their passage along the water surface. Waves may also create currents (e.g.: “longshore” currents) potentially capable of sediment transport. Data collected during the RI (Barr, 2013) illustrated that wave generated currents were not important within Spirit Lake.

Wave heights within Spirit Lake were measured during both the 2011 and 2012 RI field campaigns. Significant wave heights during these campaigns were found to be low typically, on the order of a few centimeters (see Section 2). However, significant wave events have been observed during other site visits, and the meteorological station documented periodic high wind events capable of generating larger waves. Therefore the aim of the wave modeling was to quantify potential effects of more extreme waves on bed stability and sediment redistribution, as well as wave interaction with river currents.

Three numerical approaches were used to evaluate the magnitude and potential effect of waves in Spirit Lake, each of which are discussed in this Section:

1. Finite Depth Wind Wave Model: A simplistic numerical model used to create preliminary wind-wave characteristics and to check outputs from other wave models.

2. SWAN (Simulating Waves Nearshore): A third-generation wave model which computes random, short crested waves in coastal regions and inland waters.

3. XBeach: A 2-dimensional model for calculating wave propagation in shallow water near shore environments.

5.1 Meteorological Conditions

Aside from bathymetry and basin geometry, wind characteristics are the key driver of wave formation. Data from the Bong Airport was evaluated to develop a set of wind speed and direction data that would represent strong to severe events to establish a design event. From these data four test cases were developed (Table 2).
5.2 Finite Depth Wind Wave Model

Wave height in a shallow setting like Spirit Lake is limited by the depth of the water, as increasingly large waves experience elevated drag on the bottom, and become unstable. The Finite Depth Wind Wave Model (FDWWM; Kamphuis, 2010) was used to estimate the largest physically reasonable waves possible for a given fetch length, wind speed, and depth. The output of this model provided validation and corroboration for the more sophisticated modeling techniques presented below. The inputs used for this modeling were a maximum fetch length for Spirit Lake of roughly 2.3 km in the NNE-SSW direction, and an average water depth of 2 m. Wind speeds/directions are listed in Table 2.

Results of the model (Table 3) indicated characteristic wave heights of 0.2 – 0.4 m, with a wave period of approximately 2 seconds. These are reasonable values based on site observational experience, and are comparable to those found in other settings with relatively limited fetch length and shallow bathymetry, like Spirit Lake. It is expected, as seen in data collected during the RI, that actual wave heights in the study area would be smaller, due to wave refraction and shoaling. As waves propagate into shallow water their wave lengths and wave heights change as the waves “feel” the bed, and these changes are referred to as wave refraction and wave shoaling. In addition, vegetation and other natural debris within Spirit Lake would act to dissipate wave energy—phenomena not included in the FDWWM. Given the assumptions/simplifications described above, the results of the Finite Depth Wind Wave Model are considered to be the upper limit for wave height and period in Spirit Lake.

Table 2  Wind conditions used for wave modeling. Wind direction is defined in the nautical convention (north = 0 degrees, east = 90 degrees).

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind Speed [m/s]</th>
<th>Wind Origin [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>67.5</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>67.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>U [m/s]</th>
<th>θ [°]</th>
<th>Hs [m]</th>
<th>T [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 4</td>
<td>10</td>
<td>45</td>
<td>0.34</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>67.5</td>
<td>0.42</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>45</td>
<td>0.23</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Note: U, t, Hs, and T indicate wind speed, wind direction, predicted significant wave height, and predicted wave period, respectively.
5.3 SWAN

5.3.1 Model Setup

The SWAN wave model is set up within the Delft3D modeling suite (Delft3D – Wave) and uses the same computational grid as the flow model (see Figure D-8). This component of the wave modeling program was used because the FDWWM discussed above only makes predictions for a particular fetch, water depth, and wind speed. SWAN was used to model the entire wave field within Spirit Lake, including how wave dynamics were affected by islands, shallow areas, and river currents.

For most applications SWAN does not need intensive calibration, and is considered robust for nearly all applications (Deltares, 2013). However, for the modeling described herein, the expected wave characteristics (height, length and period) are relatively small compared to typical SWAN applications. Thus, certain wave model settings have been adjusted from their default values. These settings are described in the following sub sections.

5.3.1.1 Bottom Friction

Default wave dissipation by bottom friction in SWAN is parameterized using the common formulation of Hasselmann, et. al. (1973). Two different bottom friction coefficients are commonly applied with this formulation: Swell type waves use a bottom friction coefficient of 0.038 m²s⁻³, and wind waves a bottom friction of 0.067 m²s⁻³. Recent research, however, has shown that the value for wind waves might be too high. Van Vledder, et. al. (2010) stated that the two characteristic values have been used for years despite no theoretical foundation having been found for needing a distinction between wave types. It was found that the value for swell waves worked well for both swell and wind type waves, and thus proposed 0.038 m²s⁻³ as a default bottom friction coefficient value. The Van Vledder, et. al. approach was used for the Spirit Lake model.

5.3.1.2 Convergence Settings

A few numerical settings that influence iteration procedure had to be changed from the default implementation of SWAN in Delft3D. Due to the relatively weak wave forcing in Spirit Lake (compared to oceanic environments, for example), the numerical convergence criteria needed to be set more restrictively. Setting the convergence criteria to a stricter value involved longer computation times, but resulted in more accurate prediction, as the difference between the wave height and period in two consecutive iteration steps was smaller. The default setting for relative change in wave height and period between two consecutive iteration steps is 0.02 (expressed as a fraction of the predicted quantity, such as significant wave height). However, for this model it was set to 0.01. Thus, a value of 0.01 required that the difference between the calculated values for successive numerical iterations must be less than 1% of the mean value of all computed values. For most SWAN applications these settings are not very important. However, for low-energy wave conditions (like those in Spirit Lake), stricter convergence criteria are critical.

For similar reasons, the percentage of the wet grid cells where the above criteria was required to be met was increased from a default of 98% to a stricter value of 99%.
5.3.1.3 **Frequency Domain Settings**

Due to the relatively small wave periods expected in Spirit Lake (Table 3), the default SWAN frequency domain needed to be modified. High frequency waves are more common in Spirit Lake than in more typical SWAN applications. Therefore the maximum frequency was increased to 2.5 Hz (from a default of 1 Hz), thus including waves with a period as short as 0.4 seconds (as opposed to the default of 1 second). In addition, relatively long waves cannot form in Spirit Lake, so the minimum frequency was increased from the default value of 0.05 Hz to 0.1 Hz. This restricted the wave periods modeled to less than 10 seconds instead of 20 seconds. The number of frequency bins was also increased to better discretize the expected wave frequency range.

5.3.2 **SWAN Model Results**

The SWAN simulations were run to represent simplistic extreme wind condition cases, so as to develop an understanding of the maximum potential wave conditions that are possible in Spirit Lake. Coupling the low flow hydrodynamics with SWAN produced a 2-month long modeling period, which is much longer than any one sustained wind pattern observed in the meteorological record. However, this simulation provided ample time for full development of the wave field when a single wind speed from a single direction was applied for the length of the model. In addition to allowing waves to fully develop, the long run period also allowed for wave conditions to be modeled over changing water levels, which can have an effect on wave conditions. For the modeling time period, the water level varied from +0.3 to -0.3 meters relative to the mean water level.

The SWAN modeling results showed significant wave heights that vary from 0.1 to 0.3 meters, while the period varies from 1 to 2 seconds. As expected, the largest wave heights were found associated with Case 2 wind speeds of 12 meters per second, a result comparable to the FDWWM results presented in Table 3. Maps of important wave characteristics for Case 2 are given in Figure D-18. Local geometry and bathymetry within Spirit Lake had a role in wave propagation; though nowhere did wave heights exceed the maximum height of 0.42 meters predicted by the FDWMM (Table 3), due to generally shallower depths than those used as input to the FDWMM.

The central result of the SWAN modeling was a spatial distribution of maximum wave heights, periods, and propagation directions that were consistent with the physical bounds predicted by the FDWWM. The SWAN results showed how the wave field in Spirit Lake was affected by both local bathymetry and the overall geometry of the shoreline (e.g., Spirit Island, man-made spit, etc.). The results of the SWAN modeling, however, were not directly applicable to prediction of nearshore wave phenomena. This is due to the fact that SWAN, though a powerful spectral wave modeling tool, does not model individual waves. Rather, the validated SWAN results are used in the following sub section as a boundary condition for a nearshore wave model targeted at the region of interest.

5.4 **XBeach Nearshore Wave Modeling**

XBeach was used to assess the effects of individual waves on nearshore sediment stability and transport. XBeach is an open source shoreline process model. Designed to simulate short term “storm type” wave events, XBeach was developed to evaluate rapid shoreline change on short time scales using a particular
wave climate (in contrast to SWAN, which is targeted at large-scale wave field generation, and not at individual wave dynamics). XBeach was designed to operate over time scales on the order of a few days, which is comparable in duration to the strong wind/storm events that impact Spirit Lake. The output of the SWAN model was used as input to XBeach.

### 5.4.1 Spirit Lake XBeach Model Setup

The XBeach model domain was adapted from the Delft3D model described above. Figure D-19 illustrates the curvilinear grid that was created to focus on the nearshore areas of the Unnamed Creek and Wire Mill Deltas. Both deltas were included into one domain so that the effects of landforms on wave propagation and shoaling could be taken into account.

Wind-wave results from SWAN were applied as boundary conditions at the “seaward” (eastern) boundary. In addition to this boundary condition, larger “storm” waves were applied at the boundary to simulate potential worst-case scenarios. Inputs included initial water level elevation, wave height, wave length, peak wave period, and average wave direction, as predicted by SWAN. The XBeach input parameters are shown in Table 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>Significant Wave Height [m]</th>
<th>Wave Frequency [1/s]</th>
<th>Wave Direction [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.3</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.3</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>0.3</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.3</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 4 XBeach input values

For the analyses described in this section, XBeach was used to calculate the wave induced bottom shear stresses. These shear stresses were then used to identify areas of potential sediment erosion.

### 5.4.2 XBeach Model Results

Results of the various XBeach model runs (Cases 1-4) showed that the waves propagating from offshore Spirit Lake were significantly affected by shoaling across the shallow water depths in the nearshore area. This shoaling limits the amount of wave energy that reaches the study area and ultimately the shoreline. The highest wave induced bed shear stresses occurred very near the shoreline, in < 0.3 m water depths, where breaking occurs. Figure D-20 shows the spatial distribution of wave related shear stresses for Case 1. High shear stresses were restricted to the near shore regions, and were highest just north of the Wire Mill outlet. Only in the shallowest water, less than 30 centimeters, did shear stresses exceed the critical value for potential sediment disturbance (0.1 Pa).

The implication of the XBeach modeling results, as well as each of the models used to provide the boundary conditions, is that sediments in the Project site are generally very stable under even relatively extreme wind/wave conditions. The wind roses of Figure D-7 indicated that winds like those used as input to the XBeach model (10 m/s) were exceeded less than 1% of the time over the 6-year period.
meteorological record. Thus, simulation of such winds as sustained over 2 months is extremely conservative. During this conservatively extreme simulation bed shear stresses were large enough to mobilize sediment only immediately adjacent to the shoreline in water less than 0.3 m deep.
6.0 Summary

This Appendix describes a linked series of models that were constructed, calibrated, and validated to produce an evaluation tool that includes the physical processes most critical for the assessment of bed stability in Spirit Lake. Results of this modeling effort compare well with observations of the system made during the RI, and corroborate the conceptual site model developed from those observations and published in the RI Report. In particular, the linked models reproduce the erosion and sedimentation patterns observed through the flood of record on the lower St. Louis River, which indicates they are well suited to evaluation of Project alternatives under extreme conditions.

Several important physical phenomena that operate in Spirit Lake are illustrated by the model results and summarized in this section.

6.1 River and Seiche Currents

The largest potential for morphodynamic change (and thus sediment impact) occurs during large flow/flood events. During these events the St. Louis River overtops the primary channel along the eastern edge of the Spirit Lake and flow moves through the central portion of the lake. This flow path increases bed shear stresses through the lake, and delivers more sediment throughout the site. During the 500-year flood event of June 2012 flow through Spirit Lake deposited as much as one meter of new sediment in some areas while removing bed sediment in other areas. The Project site was not affected by erosion during this event, but significant new sediment deposition occurred. The model reproduced this effect.

During low flow periods, little to no morphodynamic changes occur. During low flows the St. Louis River carries very little sediment load, and higher velocity river flow is concentrated in the main river channel along the eastern shore of Spirit Lake. Seiche dynamics are the largest influence on flow patterns within Spirit Lake during low river flow, due in part to the presence of the dredge channel that extends from the downstream end of Spirit Lake into the lake. This channel acts to provide an easy conduit for flow during the filling and draining of the lake associated with periodic seiche. During the falling period of a seiche, increased water velocities and bed shear stresses occur in offshore areas near the dredged channel, but velocities remain below the critical threshold for sediment movement.

6.2 Vegetation Effects

Vegetation affects flow patterns and velocities within Spirit Lake, and thus influences the distribution of sediment accumulation and impact. Addition of vegetation to the hydrodynamic and sediment transport model showed that river and seiche flow patterns dominate sedimentary patterns throughout most of Spirit Lake, but that denser vegetation near the man-made spit leads to a reduction of sedimentation in that area. Further, field observations coupled with this modeling indicated that high flow events are likely to remove vegetation, resulting in deposition and erosion patterns that are governed by flow. The fact that addition of vegetation to the model improved the match between prediction and observation only modestly indicates that Spirit Lake was not particularly vegetated prior to the 2012 flood. At the very least, vegetation was not exerting a major influence on flow patterns prior to the flood.
6.3 Wave Effects

Wave modeling indicated that even extreme wind conditions produced characteristic waves that were incapable of impacting sediments throughout the vast majority of Spirit Lake. Evaluation of individual waves using XBeach illustrated that in the Project site bed shear stresses remain negligible except for where wave breaking occurs in 0.30 m of water or less. This is due to the elevated bed shear stresses that accompany breaking waves. Field observations indicate that even in this swash zone sediments are presently relatively stable with coarser bed sediments having created an armoring layer.

6.4 Application to Project Alternatives

The numerical models described in this document represent an important tool for evaluating potential Project designs and strategies. Each of the important processes identified in the RI as potentially disturbing impacted sediments are included in the models, and their modeled behavior compared well with observations made during the RI. As project design advances, the models described in this document will be useful for evaluating the potential effects of future extreme events, as well as for evaluating how revegetation might affect flow patterns in Spirit Lake.
7.0 References


Roelvink D, et. al., eds., 2010. XBeach Model Description and Manual.


Figure D-1 2012 Spirit Lake Bathymetric Survey
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Grey area = non-cohesive
I sand dominated
II clay dominated
III silt dominated
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