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Lake St. Martin Outlet Channel Sediment Transport Modelling to Manage Excess Sediment Concentrations During Commissioning

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STATEMENT OF LIMITATIONS AND CONDITIONS

Limitations

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1.0 INTRODUCTION

1.1 Background

The first operation of the Lake St. Martin Outlet Channel (LSMOC) will occur during commissioning of the project. During this phase, the various components of the project, including the Water Control Structure (WCS), channel and drop structures, will be brought into operation. Water will be conveyed from Lake St. Martin (LSM) into the LSMOC and released into Lake Winnipeg through this system for the first time. Initial releases of flow will be capable of mobilizing and transporting loose sediments present on the channel bed following construction. This is anticipated to cause an increase in the concentrations of total suspended solids (TSS) in the channel and could lead to deposition of sediment in Sturgeon Bay.

Commissioning is planned to occur during summer months. This would be outside the windows of restricted activity prescribed by the Department of Fisheries and Oceans (DFO) for the project. DFO's intent with these prescribed windows is to protect fish and fish habitat from the effects of mobilization of sediments into Sturgeon Bay. Nevertheless, MI's Environmental Assessment Team has requested that the design and operation of the LSMOC comply during commissioning with limits of TSS concentration for sediment leaving the channel. An upper bound of the 24-hour average TSS concentration has been prescribed by MI to be 25 mg/l during this phase.

Numerical sediment transport modeling was undertaken to examine the predicted increase in TSS concentrations and associated sediment deposition in Sturgeon Bay during scenarios representative of commissioning. The modelling also focussed on the impact that controlled gate operation measures can have to limit the increase in TSS concentrations.

Future operations of the LSMOC during flood periods will also have the potential to mobilize sediments. However, the risks during future operations will differ from those during commissioning. Those risks are being addressed separately and are therefore excluded from this report. Nevertheless, the results of the analyses of the commissioning will provide valuable information to support the development of operating strategies for future operations of the LSMOC.

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1.2 Objectives and Structure of This Report

The objectives of this work are as follow:

- Estimate the TSS concentrations and total volume/mass of sediment leaving the LSMOC during project commissioning and to determine the fate of the eroded channel sediment on entering Lake Winnipeg.
- Develop, analyze and compare commissioning strategies that could be utilized to control the release of sediment from the channel and maintain the TSS at the channel outlet below the required threshold.
- Select and recommend a preferred commissioning strategy.

This report commences with a brief overview in Section 2.0 of the approach adopted for the various analyses described herein, and in particular, the application of a powerful numerical model. Section 3 describes the development and key features of the upstream portion of the system and the modeling to simulate it.

Section 4 describes the downstream portion of the study area in Lake Winnipeg and the modelling required to represent it. Section 5 summarizes the results of the model simulations, including the combined outputs of both upstream and downstream model components. Section 6 summarizes the findings and the key conclusions from this work.

It will be noted in the report that some aspects of the analyses are as yet incomplete, due to the need for more time than was available. Each of those shortfalls in analysis are identified, and when more definitive results are available, this report will be updated.

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2.0 OVERVIEW OF APPROACH TO ANALYSIS

The hydraulic system of the LSMOC and its release of flow into Lake Winnipeg is complex. KGS Group believes that the best approach to quantitative analysis of this system would require the application of a leading-edge numerical model. The well-known software developed by the Danish Hydraulic Institute (DHI), called MIKE21, was selected for this task. MIKE21 is a leading software in the field of numerical modeling of complex hydraulic phenomena. KGS Group has extensive prior experience with MIKE21 and has developed strong skills in practical applications.

The deployment of MIKE21 focused on the potential for erosion, sediment transport, and deposition during the commissioning of the LSMOC. Both the hydrodynamic (HD) module and the mud transport (MT) modules of MIKE21 were required for this work. The HD module simulates the variations in water levels and velocities in response to the applied boundary conditions and a variety of other forcing functions, such as wind and wave action. The MT module is used to analyze the erosion, transport, settling, and deposition of cohesive sediment. This module is recommended for use when the bed material is composed of fine-grained silt and clay with particle sizes that are less than 0.063 mm. Since the majority of the bed material in the study area is expected to have particle sizes less than this limit, the MT module was selected.

To enhance the capabilities of the in-house modelling team for this important and complex analysis, KGS Group retained the world-renowned consulting services of DHI. This provided KGS Group with access to very experienced modelers who specialize in sediment transport modelling using MIKE 21. The expertise and advice from DHI guided many of the assumptions made and the methodology followed during model development and calibration.

Two separate numerical models were developed and utilized in this study. The first was a model of the LSMOC, which extended from the WCS to the channel outlet. The model geometry included the designed cross sections of the key portions of the channel, as well as the eight drop structures. The second model focused on Sturgeon Bay in Lake Winnipeg. This downstream model included the LSMOC outlet, the outlet of the Dauphin River, and approximately 24 km of Lake Winnipeg north of the LSMOC outlet.

Results from the LSMOC model were used as input to the downstream model of Sturgeon Bay. The modelling process involved simulating a set of conditions with the LSMOC model and extracting the resulting flow and time series of TSS concentrations at the channel outlet. That data was then used as the input to the downstream model of Sturgeon Bay to assess the dispersion of the incoming sediment load and its potential settlement in the lake. Further details on the models are provided in Sections 2.0 and 3.0.

It should be noted that wind and wave effects were not included in the numerical analysis. The extent of the TSS plume and deposition zone would change if these variables were included. In general, it would be expected that wind and waves would disperse the suspended sediments into broader areas, potentially further diluting the TSS plume concentrations away from the outlet and reducing the average depth of deposition. This complication will continue to be reviewed as design progresses.

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3.0 LSMOC MODEL DEVELOPMENT

3.1 Mesh Development

A finite element mesh was developed to carry out the two-dimensional calculations of hydrodynamics and sediment transport within the channel. It consisted of triangular elements that ranged in size. Sizes of elements within the mesh were carefully selected to adequately capture all features of the study area, including the channel bathymetry, drop structures, and channel outlet. Sensitivity analyses of various mesh sizes were undertaken to determine its effects on the model results. The final mesh configuration was adopted to optimize model resolution and computational time. A comparison of the modelled inflow to the modelled outflow indicated that the selected mesh resolution was able to adequately maintain continuity throughout the model domain with minimal error (<2%). The selected sizes of the elements were from:

- 30 m^2 on the channel bed and on local zones immediately upstream and downstream of the drop structures to
- 60 m^2 on the side slopes of the channel

The final mesh is shown in Figure 1. The expanded view of one typical drop structure is included in the figure.

Once the key features of the LSMOC were incorporated into the mesh, and appropriate sizes of elements were established, the data was exported from the previously developed Digital Elevation Model (DEM) of the channel. It was then imported into the MIKE 21 model for interpolation of elevations of each element of the mesh. MIKE 21's internal numerical procedures were used to interpolate and assign appropriate ground elevations into the mesh.

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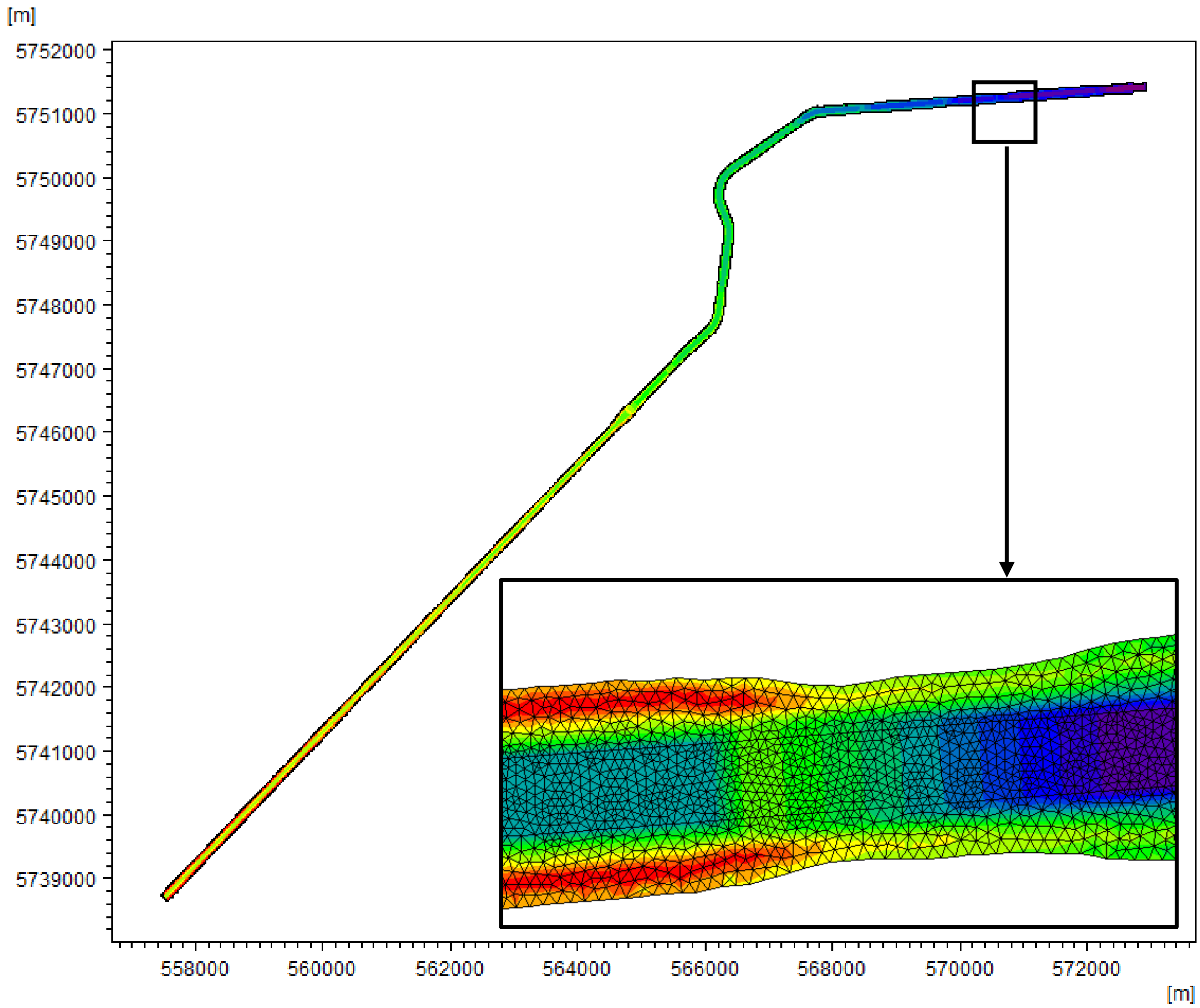
FIGURE 1: MODEL MESH FOR LSMOC



3.2 Hydrodynamic Module

3.2.1 INITIAL CONDITIONS

During commissioning, it is anticipated that the LSMOC will be watered up gradually. The pools upstream of each drop structure will be filled to the elevations of each crest. This filling process is anticipated to disturb loose sediments in the channel. It could lead to temporarily high TSS concentrations in the channel. It is expected that once all the pools are filled, the water control structure gates will be closed. This is intended to provide sufficient time for suspended sediments to deposit and TSS concentrations to return to baseline values. Initial conditions for all simulations of sediment transport were therefore based on conditions assuming a "watered" channel after this initial stabilization. This stabilized condition was then adopted as the starting point for the analysis of various scenarios of commissioning.

3.2.2 BOUNDARY CONDITIONS

A "boundary condition" is a modelling jargon used to represent the condition that controls the numerical operation of the simulation model. It can be a prescribed inflow to, outflow from, or water levels at the inlet/outlets, depending on the intention of the modeler. In the case of the model of the LSMOC, the upstream boundary condition was prescribed as inflow to represent releases of water through the Water Control Structure (WCS). At the channel outlet at Lake Winnipeg, the downstream boundary condition consisted of a prescribed water level to represent Lake Winnipeg. For the purposes of this modelling, it was expected that commissioning of the LSMOC will occur during non-flood conditions. This boundary condition was set to a long-term average water level on Lake Winnipeg of El 217.5 m.

3.2.3 HYDRAULIC ROUGHNESS OF THE CHANNEL

The Manning's n value of the channel was selected to be 0.028 to be consistent with that used in the one-dimensional HEC-RAS model of the channel. This value represents a composite representation of the channel bed. It takes into account the increased hydraulic roughness that will exist on the upper portion of the channel side slopes where vegetation will grow. It is anticipated that vegetation will not grow on the channel bed or on the portions of the side slopes up to 1 m below the crest elevations of the drop structures. When flow is released through the channel, the water level will rise above the crest elevations, resulting in increased flow resistance by the vegetated portions of the channel. The composite n-value assigned is considered appropriate for the overall nature of the wetted perimeter of the channel.

Riprap will be placed as protection against erosion downstream of the WCS, and on, and downstream of, the eight drop structures. The Manning's n value assigned to these short regions was 0.04.

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3.3 Mud Transport Module

3.3.1 INITIAL CONDITIONS

3.3.1.1 Quantity of Residual Sediment After Construction

It is anticipated that there will be some erodible material remaining in the channel subsequent to construction. Some of that material may be readily transported as TSS during commissioning. Prediction of an accurate volumetric estimate of the erodible material is influenced by a number of factors including the:

- anticipated construction methodologies including the level of cleanup performed in the channel prior to initial operations;
- duration of the channel construction works;
- seasons of construction;
- weather conditions during construction;
- typical behavior of the exposed surfaces of the soil stratums at the channel slopes and at the base of the channel;
- durations and intensities of wetting and drying cycles of the exposed slopes during construction.

The complexities and subjective nature of estimating the quantity of loose sediment which may erode during commissioning required the development of reasonable assumptions. For the purpose of this sediment modeling assessment, a 5 mm thick layer of loose fine particles uniformly distributed across the channel was considered representative. This was styled after a similar approach that had been applied recently by Manitoba Hydro. This involved the analysis of the various channels at the Keeyask Generating Station on the Nelson River in northern Manitoba. Similar assumptions had been used to estimate the TSS concentrations that could be anticipated during testing and commissioning of the turbines and spillway gates.

The 5 mm layer of erodible sediment was applied as representative of both the channel base and side slopes along the full length of the LSMOC. In practice, due to the various factors described above, it is recognized that some areas of the channel may have a thicker layer of erodible sediment, while other areas may have less. For example, less thickness would be expected in areas of established vegetation or where the channel bed is located in bedrock. Nevertheless, an average of 5mm over almost the full length of the channel was considered reasonable.

The areas directly downstream of the water control structure and at and downstream of each of the eight drop structures will be armored with riprap. The riprap in those areas will be screened such that it contains a limited amount of fines subject to erosion. Therefore, the 5mm layer was not applied in those regions.

3.3.1.2 Initial TSS Concentration

As described in Section 2.3.1, it is anticipated that the LSMOC will be watered up during commissioning. Furthermore, it is also anticipated that there will be adequate time for any particles suspended by the watering up process to settle within the channel prior to discharging flows into Lake Winnipeg. For this reason, the initial TSS concentration in the channel was assumed to be zero. It should be noted that the water from Lake St. Martin will have a relatively low level of TSS concentration. However, for the purposes of this study that background TSS concentration has been considered as zero, both for the initial conditions as well as for the remainder of the simulation, as described further in Section 3.3.5. In the monitoring of the actual commissioning process, the measured TSS of the water in LSM at the time would become the base for considering the uptake of TSS from the LSMOC.

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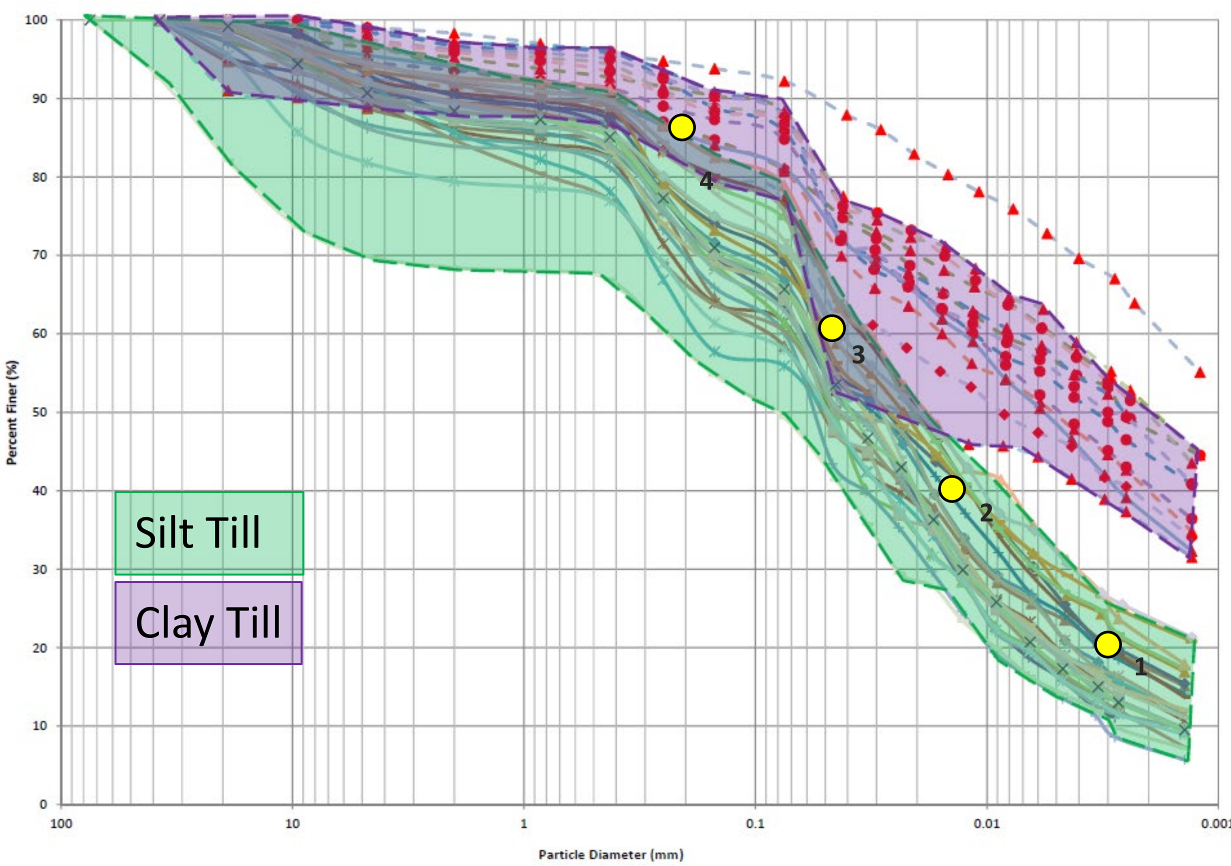
3.3.2 SIZE GRADATION OF MATERIAL ON CHANNEL BED

Geotechnical investigations have indicated that silt till, clay till, and clay are present in the natural soils along the length of the LSMOC. The typical size gradation curves for the silt till and clay till are shown on Figure 2. It was assumed that the gradation of the disturbed bed material would be similar to that of the in-situ material and that the gradation would be relatively consistent along the entire length of the channel.

For the purposes of this assessment, only the distribution of the silt till was considered because clay tills and clay make up a much lower percentage of the channel. However, if the clay tills and clay gradations were considered, the results could yield slightly greater TSS concentrations due to the increased proportion of fine material. Regardless, this assumption is not expected to influence the conclusions of this work, as it is expected that the TSS concentrations would still be within a manageable range and can be mitigated through strategic channel operation.

Four representative size fractions were selected to simplify the gradation curve for modelling purposes. These fractions are shown by the yellow dots on Figure 2. The ranges in sizes are described further in Section 3.3.3 and in Table 1. It is acknowledged the four selected fractions do not cover the range of the size gradations in its entirety, and that some particles could be larger or smaller. However, past experience has demonstrated that selecting four fractions in this manner provides a good representation of the physical environment. It is considered a reasonable compromise between computational efficiency and modest gains in accuracy that would be achieved using more than four size fractions. The inclusion of even smaller clay particles may suggest an increase in TSS concentration. But the addition of these small sizes would have to be offset by inclusion of larger particles as well, to be a fair representation of the nature of the soils. So, the outcome in TSS is believed to be a relative balance between increased small sizes and increased volumes of larger sizes that would not erode or would deposit within the channel. For these reasons, the selected ranges of fractions were deemed to be a suitable representation of the actual bed material.

FIGURE 2: GRAIN SIZE DISTRIBUTION SUMMARY



3.3.3 SELECTED PROPERTIES OF SILT TILL

Four fractions were defined to represent the material in the channel bed, as described above. The fractions were selected from the size gradation curves that best represent the silt till found at the site. The key physical properties that were selected to correspond to each of the fractions are summarized in Table 1. The settling velocities of the particles were calculated using Stokes' Law. The critical shear stresses for deposition were estimated based on past experience and engineering judgement. The relative volumetric proportions of each fraction are summarized in Table 2. This applied to both the residual layer of 5mm thickness, as well as the underlying material within the bed of the channel.

TABLE 1: SUMMARY OF SELECTED PROPERTIES FOR SILT TILL

Fraction	Particle Type	Grain Size (mm)	Settling Velocity (m/s)	Critical Shear Stress for Deposition (Pa)
1	Clay	0.0029	5.0×10^{-6}	0.4
2	Fine Silt	0.015	0.000145	0.4
3	Coarse Silt	0.045	0.0007	0.4
4	Fine Sand	0.2	0.0295	0.6

3.3.4 BED PARAMETERS

As described in Section 3., it has been assumed that a 5 mm layer of erodible sediment existed initially on the base and sides of the channel. The areas downstream of the water control structure and drops structures that have been armored with riprap were excluded. The bed layer is composed of the four representative fractions described in Section 3.3.3. The proportion of each of these fractions within the bed layer are summarized in Table 2.

TABLE 2: PROPORTION OF FRACTIONS IN BED LAYER

Fraction	Proportion of Bed Layer	Particle Type
1	30%	Clay
2	20%	Fine Silt
3	27.5%	Coarse Silt
4	22.5%	Fine Sand

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Field observations and testing of in-situ material in the LSMOC guided the strategy of representing the susceptibility of the 5-mm thick residual layer to erosion. The testing allowed the samples to dry for an extended period of time. Once dry, the samples were rewetted, and it was found that the material then softens and erodes quickly. Consequently, the 5mm thick layer of disturbed bed material was represented as a soft mud layer, which can readily erode when wetted.

The physical parameters adopted to describe both the 5-mm layer and the underlying bed material are summarized in Table 3. Typically, these parameters are calibrated by comparing model results to recorded TSS data. However, since this is a “greenfield” project and no recorded data exists, these parameters were selected on the basis of expert opinion, documentation in the MIKE 21 manual, past experience, engineering judgement and sensitivity testing.

TABLE 3: SUMMARY OF ADOPTED PHYSICAL PARAMETERS TO REPRESENT CHANNEL BED

Parameter	Description	Proportion of Bed Layer
Bed Layer Density	Dry density of bed	1000 kg/m^3
Power of Erosion (α)	Parameters used in the equation that defines the rate of erosion (E): $E = E_0 e^{\alpha(\tau_b - \tau_c)}$	4
Erosion Coefficient (E_0)		5x10^{-6} kg/m^2/s
Critical Shear Stress (τ_c)	The minimum shear stress at which erosion can occur	0.6 Pa
Bed Roughness (k)	The resistance against flow, which depends on the bed form and grain size of the insitu bed material	0.01 mm

3.3.5 BOUNDARY CONDITIONS OF TSS CONCENTRATION

At the upstream end of the model, a boundary condition that represents the incoming TSS concentration is used, as described in Section 3.3.1.2 for the initial conditions. For the purpose of this study, it has been assumed that this inflow TSS concentration from LSM remains at zero for the full duration of the simulations. As a result, the model simulations represent only the incremental TSS concentrations directly caused by the erosion of the channel bed.

Similarly, the downstream end of the model in Lake Winnipeg also adopts a TSS concentration of zero as the boundary condition in Lake Winnipeg. All elevated TSS concentrations therefore represent erosion from the LSMOC.

3.4 Model Calibration

3.4.1 HYDRODYNAMIC CALIBRATION

There is no available hydrodynamic data to allow a formal calibration of the model. Consequently, water surface profiles computed by the previously developed one-dimensional HEC-RAS model were used to verify the computed profiles of the MIKE 21 model. Water profiles calculated by the MIKE 21 model were compared to those generated by the HEC-RAS model for a range of flows between zero and the design flow (326 m^3/s). Comparisons of the profiles computed by the two models are shown in Figures 3 and 4. These results indicate that the models are in good agreement and the difference in water levels between the two models is limited to 10 cm. Both models also calculated nearly equal results for average velocity. No additional calibration was considered necessary for the hydrodynamic model.

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FIGURE 3: LSMOC HYDRODYNAMIC CALIBRATION – 326 M^3/S

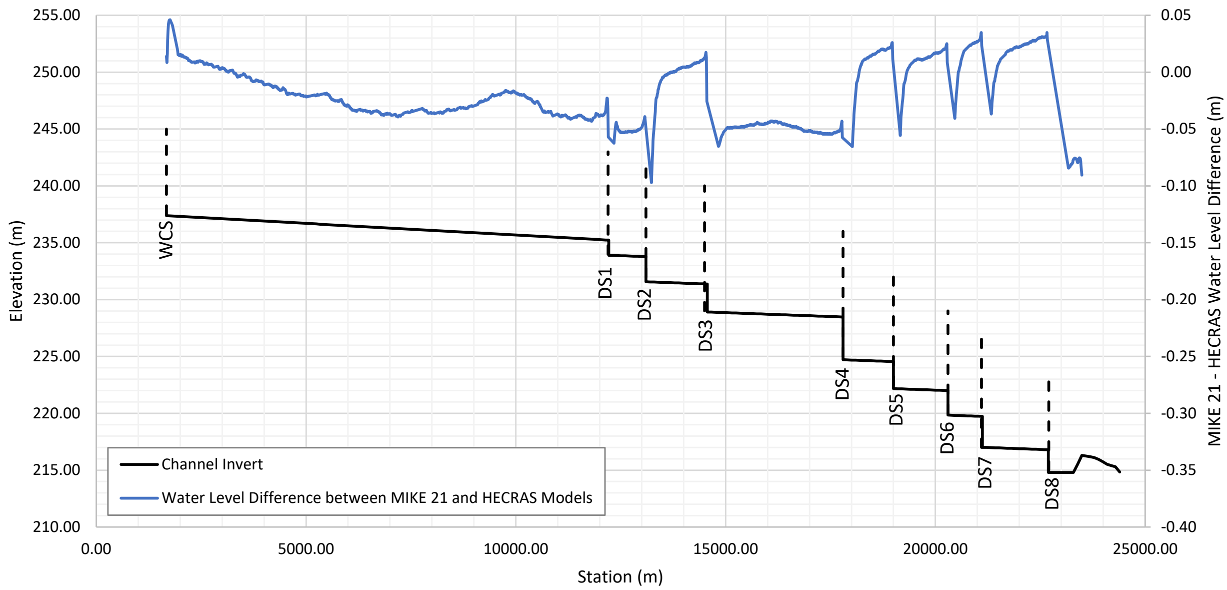
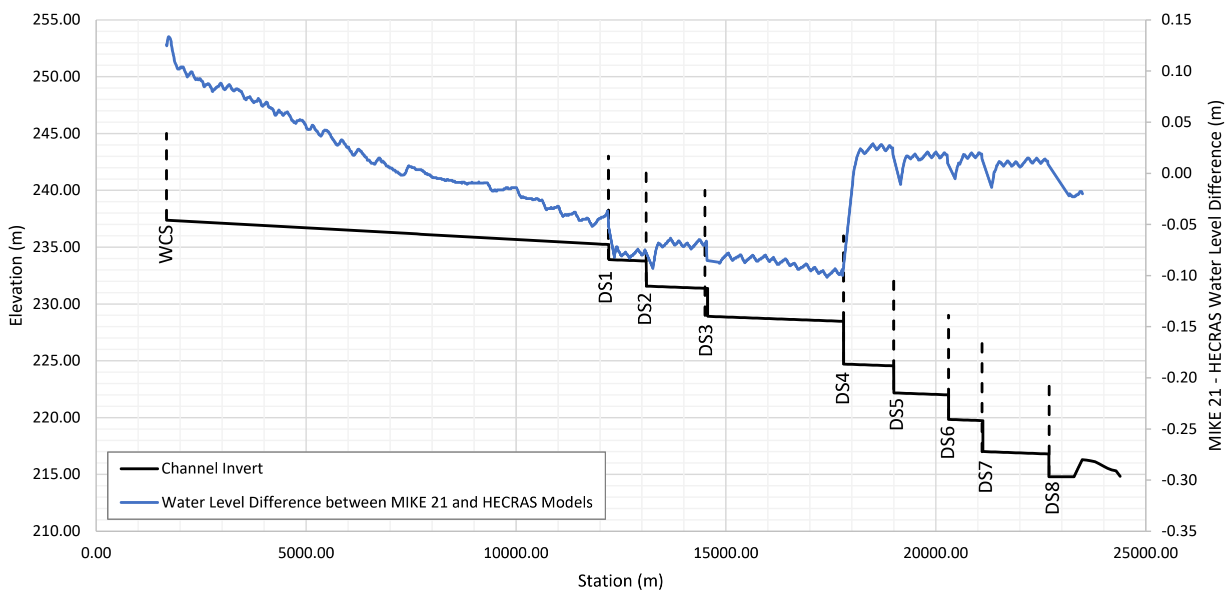


FIGURE 4: LSMOC HYDRODYNAMIC CALIBRATION – 160 M^3/S



3.4.2 CALIBRATION OF MUD TRANSPORT MODEL

Many of the parameters in the mud transport model are typically selected and refined during model calibration using recorded water quality data. However, the channel has not yet been constructed and no water quality data is therefore available. Consequently, a formal calibration of the mud transport model was not possible. Instead, the following measures were taken when selecting the various model parameters:

- Evaluation of geotechnical data, including material testing and lab experiments.
- Consultation with DHI's sediment transport modelling experts.
- Qualitative comparison of model results to TSS measurements recorded at Reach 1 in 2011 and 2014.
- Extensive sensitivity testing of all model parameters.

In spite of the strong basis for selecting the model parameters, they are inherently challenging to predict given the variability that could occur in the physical environment. For this reason, it is recommended that the model be further verified during commissioning, following first operations of the LSMOC. Initial records of TSS data in LSM, in the channel and in Lake Winnipeg would form the basis of this extension of model verification. Further calibration of the model should also be undertaken prior to being adopted to study alternate strategies of operation during future years.

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4.0 DEVELOPMENT OF MODEL OF STURGEON BAY

4.1 Development of Finite Element Mesh

A computational mesh of finite elements representing Lake Winnipeg had been previously developed for other aspects of this project, including the analyses of the flow systems and the spectral waves. It was repurposed for application to the sediment transport modelling described herein. To reduce computational time, the extent of the mesh was reduced to only include Sturgeon Bay, including approximately 24 km of the Lake Winnipeg's north basin to the north of the LSMOC outlet. The mesh was designed such that small elements were used to model the hydrodynamics and sediment transport near the LSMOC. This would ensure accuracy in the critical areas where much of the transport and deposition is expected to occur. Larger elements were used in more remote locations of the outlet area to increase computational efficiency. The overall computational mesh is shown on Figure 5.

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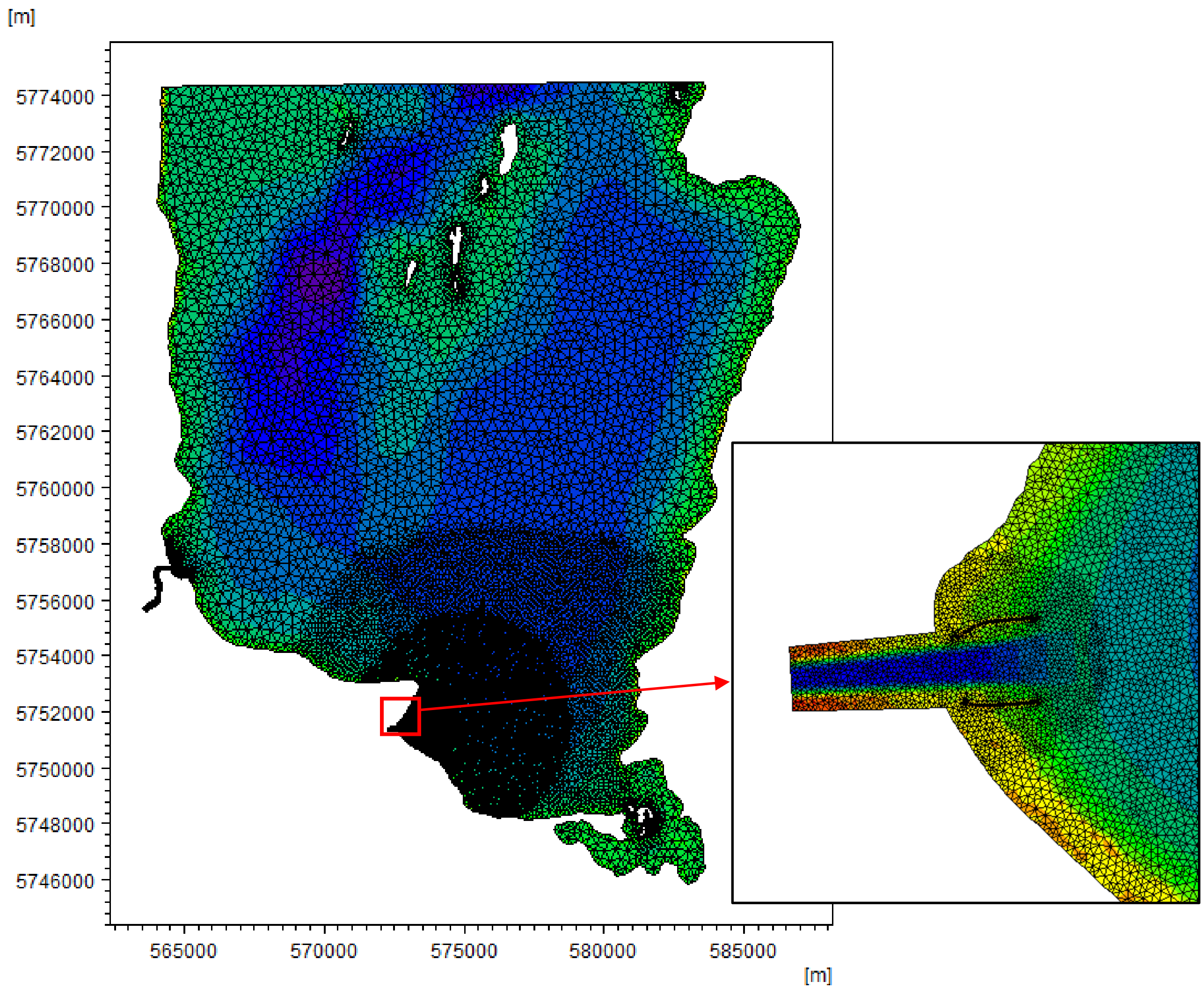
FIGURE 5: COMPUTATIONAL MESH – STURGEON BAY



4.2 Hydrodynamic Module

4.2.1 INITIAL CONDITIONS

The initial model conditions consider that Lake Winnipeg is at its average level of El 217.5 m and the LSMOC is closed.

4.2.2 BOUNDARY CONDITIONS

The Sturgeon Bay model has two upstream flow boundaries that represent inflows from Dauphin River and the LSMOC. The Dauphin River inflow was set to a constant release of 50 m^3/s. This is representative of a low to mid-range flow for the Dauphin River, which will have a high probability of being experienced at the time of commissioning. The inflow hydrograph for the LSMOC was set equal to the outflow hydrograph computed by the LSMOC model for any given scenario.

The downstream extent of the model is a water level boundary condition. It is set to the average Lake Winnipeg water level of El 217.5 m.

4.3 Mud Transport Module

4.3.1 INITIAL CONDITIONS OF SEDIMENT CONCENTRAION

The sediment concentration in both LSM and in the LSMOC were initialized at zero. As described in Section 3.0, water entering the LSMOC from LSM, as well as water in Lake Winnipeg was considered to have a TSS concentration of zero, both initially and throughout the remainder all simulations.

4.3.2 SELECTED PARAMETERS FOR MUD TRANSPORT MODEL

The parameters adopted for the mud transport module of the Sturgeon Bay model were selected to be consistent with those representing the LSMOC. However, a distinct difference between the two models is that the bed in the Sturgeon Bay model was assumed to be non-erodible. Significant erosion in Sturgeon Bay is considered unlikely and analysis of that aspect was excluded from the terms of reference for this work. The purpose of the Sturgeon Bay model was to define the transport and deposition of sediments being flushed from the LSMOC. An analysis of project impacts on shoreline morphology and substrates is documented in the report “Lake St. Martin Outlet Channel Post-Project Shoreline Morphology Assessment” (Zuzek, 2021).

4.3.3 BOUNDARY CONDITIONS

A time series of TSS concentrations of each sediment fraction at the outlet of the LSMOC were extracted from the results generated by the LSMOC model. This data was then used as the incoming sediment concentration into the Sturgeon Bay model. For simplicity, it was assumed that no additional TSS would be introduced to Lake Winnipeg through the Dauphin River.

At the downstream extent of the model, a zero gradient boundary condition was used.

4.4 Model Calibration

The hydrodynamic calibration of the Lake Winnipeg model had been carried out previously as part of the spectral wave analysis and is documented in KGS Group’s Post-project Shoreline Morphology Assessment (Zuzek, May 2021). No additional calibration was considered necessary for this analysis.

Given that the channel is not yet constructed, no water quality data is yet available to carry out a calibration of the sediment transport model. For this reason, the various parameters for the Sturgeon Bay model were selected to be consistent with the LSMOC model.

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5.0 MODEL RESULTS

5.1 Base Case

The base case is intended to represent an uncontrolled commissioning scenario whereby the WCS gates are fully opened over the course of 12 hours to achieve the full design flow. Although commissioning is not anticipated to occur during a flood event, achieving full design flow in the LSMOC would be possible for short duration until the north basin water level recedes in response to the changing flow condition conveyed by the Lake Manitoba and Lake St. Martin Outlet Channels. If the Lake St. Martin water level is too low at the start of the selected commissioning period, it may not be possible to achieve the full design flow in the channel. In this case, more sediment would remain in the channel and would likely be flushed during subsequent operations of the channel at higher flows. Alternatively, if the channel must be commissioned during flood conditions, it is possible that gates would be opened faster than the simulations described herein and the TSS concentration would increase accordingly. Analysis of impacts of commissioning on lake water levels requires further review and should be undertaken with the overall water balance model developed by MI.

Once full flow is achieved, the flows would be held constant until the majority of the sediment is flushed from the channel and the TSS concentration at the channel outlet returns to near zero. The WCS gates would then begin to close and channel flows would recede. It is expected that fully closing the gates could take approximately 13 days and would be governed by the maximum rate of closure permitted to maintain stable side slopes in the channel under rapid drawdown conditions.

The computed flow conditions for the base case and the resulting TSS concentration at the channel outlet are shown on Figure 6. This case is considered to be hydraulically efficient, since it occurs quickly and does not require a large draw down on Lake St. Martin. However, it results in a rapid increase in channel velocity and shear stress, which mobilizes a large amount of sediment quickly. The results have indicated that fully opening the channel to reach the full design flow of 326 m^3/s over the course of 12 hours will result in a peak TSS concentration of approximately 1200 mg/L at the channel outlet.

It will take approximately 2 days for the TSS concentration to return to zero at the channel outlet. During this time, an estimated 5.3 million kilograms of sediment is transported from the channel into the lake. A portion of the initial sediment layer remains in the channel because:

- the shear stresses were not sufficient to cause it to erode or
- it eroded and was subsequently deposited elsewhere in the channel. Some deposition occurred upstream of the drop structures, particularly Drop Structure 1 which forms a deep upstream pool. Additional deposition tended to occur downstream of the drop structures in recirculation zones that developed on the sides of the channel.

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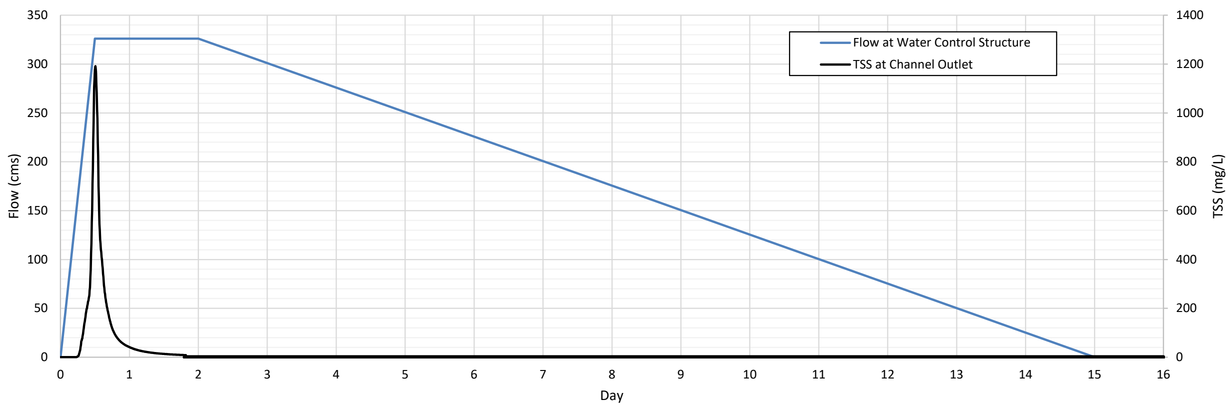
FIGURE 6: TSS CONCENTRATION AND CHANNEL INFLOW – BASE CASE



LSMOC model results, including the TSS concentration and flows over a period of time, were extracted at the channel outlet location and subsequently used as inputs to the Sturgeon Bay model to assess sediment dispersion and deposition in the lake. The sediment dispersion for the base case is shown in Figure 7. The results indicated that the incoming sediment gets discharged towards the eastern bank of Sturgeon Bay and then circulates both to the north and south. After sixteen days, when channel flows have receded to zero, the sediment has dispersed a distance of approximately 14 km away from the LSMOC outlet. At this time, the majority of the TSS plume has reduced to a concentration of 2 mg/L or less, with some small local areas having concentrations of up to 8 mg/L.

Sediment deposition resulting from the base case scenario is shown in Figure 8. The results indicated that the coarser sediments (sands) get deposited near the outlet and the finer material is generally deposited within 10 km of the outlet, depositing over an area of about 15 km^2. Some of the finest sediments remain in suspension after 30 days.

The computed depth of deposition is small, (less than 2mm), and is considered to be temporary in nature. Any potential sediment input to Sturgeon Bay from the LSMOC is expected to contribute to the existing natural sediment budget of the lake and, subsequently, be subjected to the same natural shoreline processes that currently sort and distribute sediment in the various regions of the lake. As a result, measurable impacts on the existing substrate are considered unlikely.

It should be noted that wind and wave effects were not included in this analysis. The extent of the TSS plume and deposition zone would change if these variables were considered. In general, it would be expected that wind and waves would disperse the suspended sediments into broader areas, potentially further diluting the TSS plume concentrations away from the outlet and reducing the average depth of deposition. This process will continue to be reviewed as design progresses.

In addition, the simulation only considered an average Lake Winnipeg water level of 217.5 m. If Lake Winnipeg were higher or lower during the commissioning period, water velocities in the vicinity of the outlet would either increase or decrease accordingly. This would affect the overall dispersion and deposition in the lake.

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FIGURE 7A: TSS CONCENTRATION IN STURGEON BAY – BASE CASE

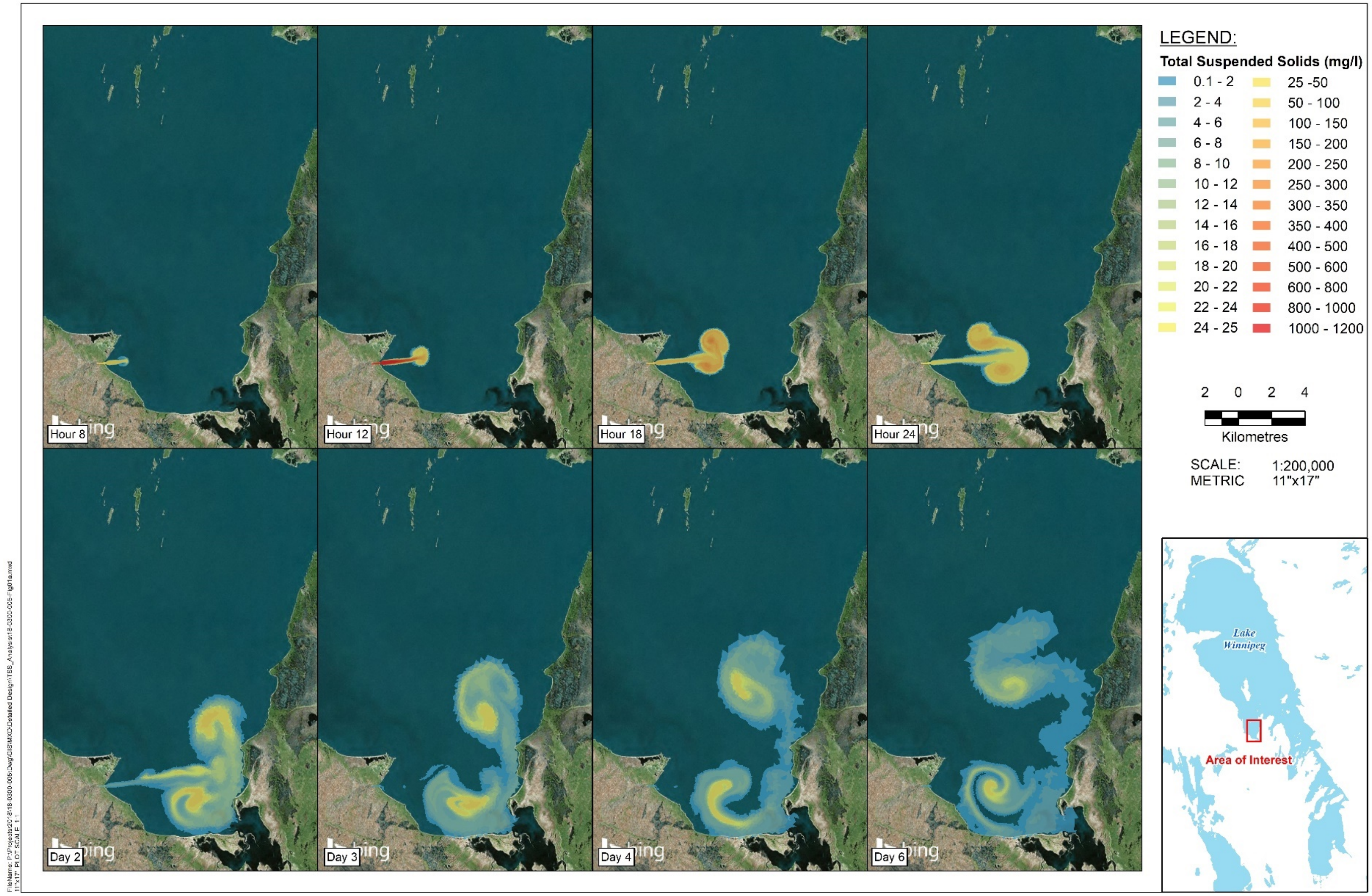


FIGURE 7B: TSS CONCENTRATION IN STURGEON BAY – BASE CASE

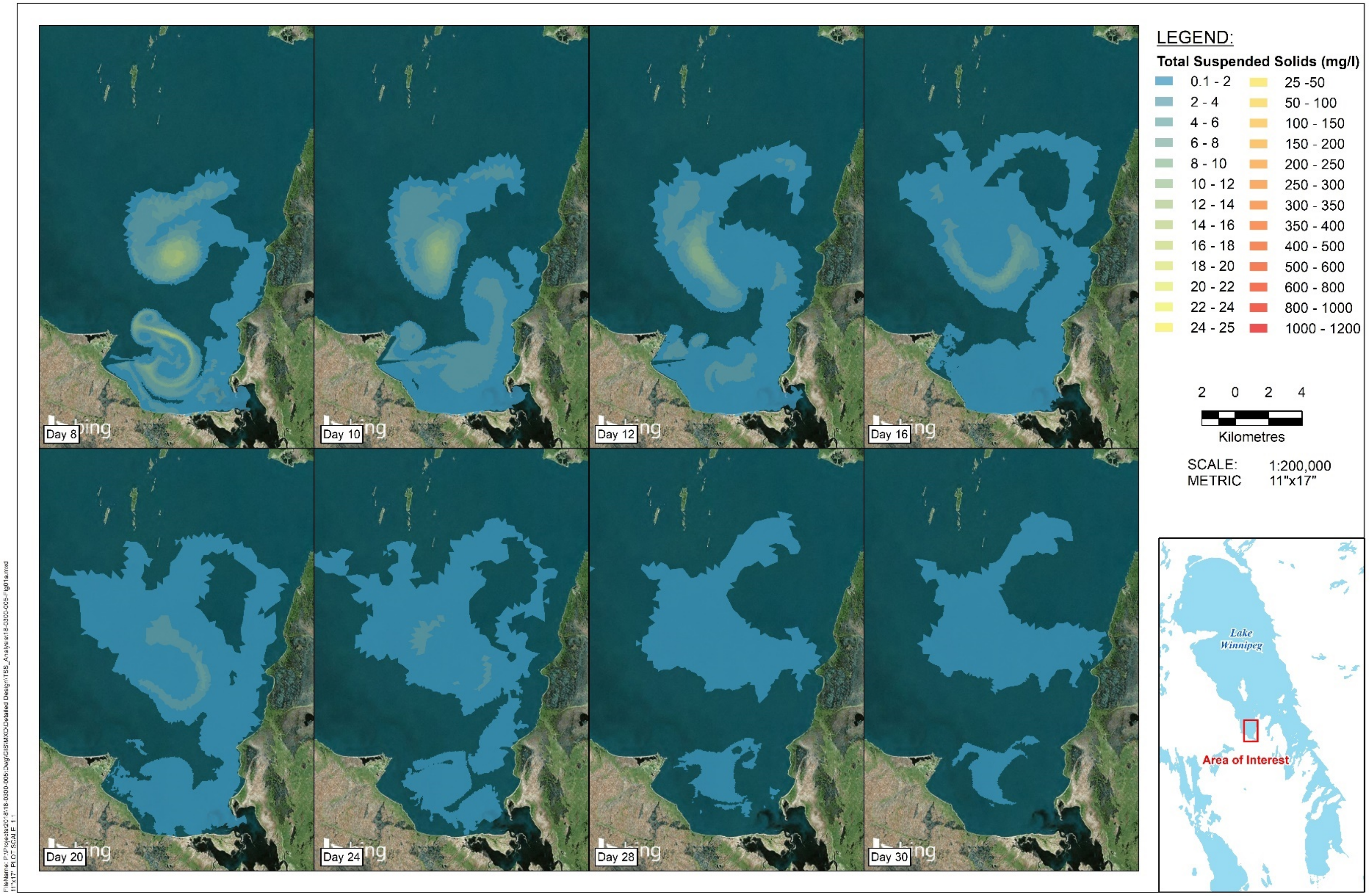


FIGURE 8A: DEPOSITION OF SEDIMENT IN STURGEON BAY – BASE CASE

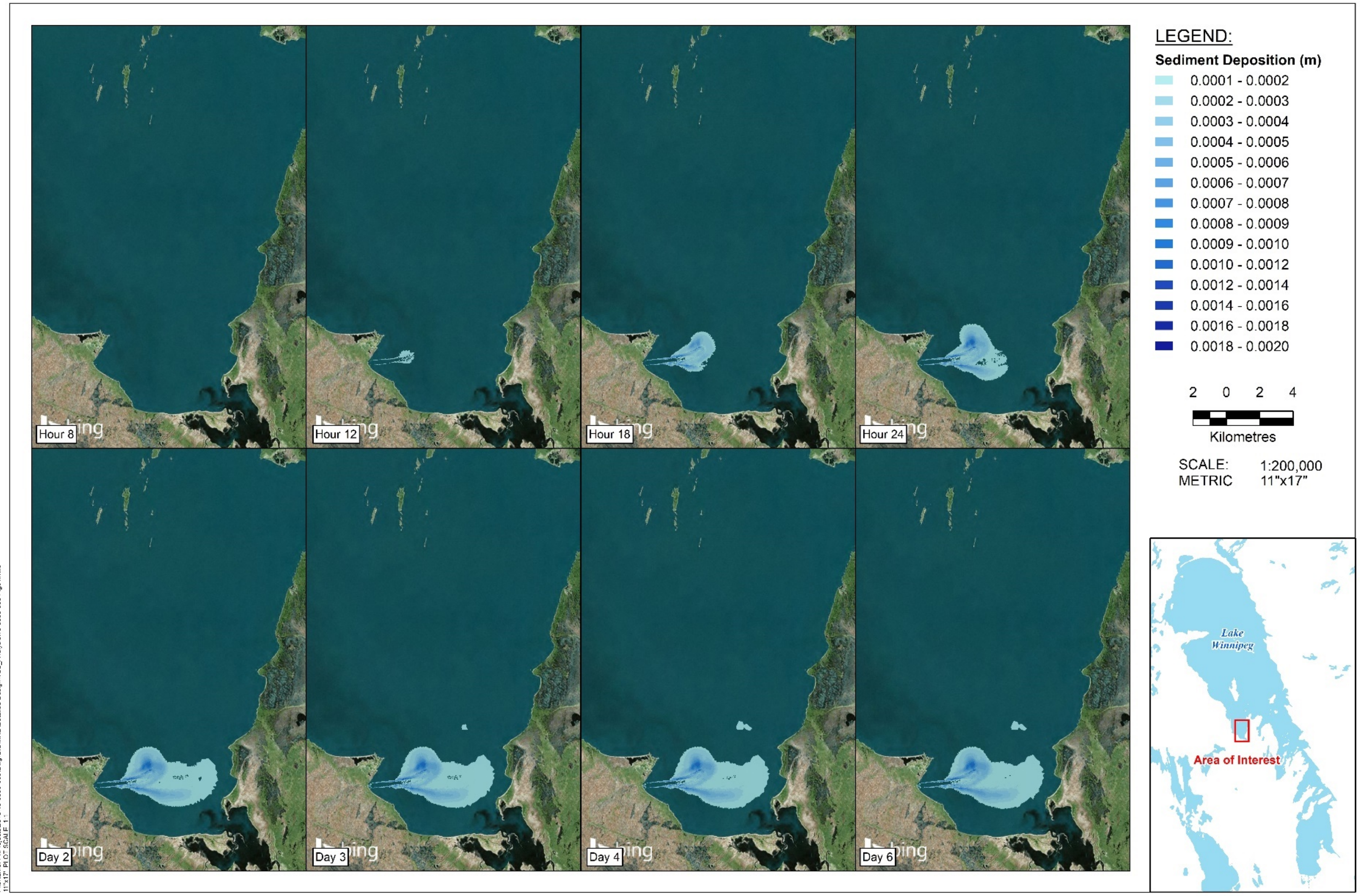
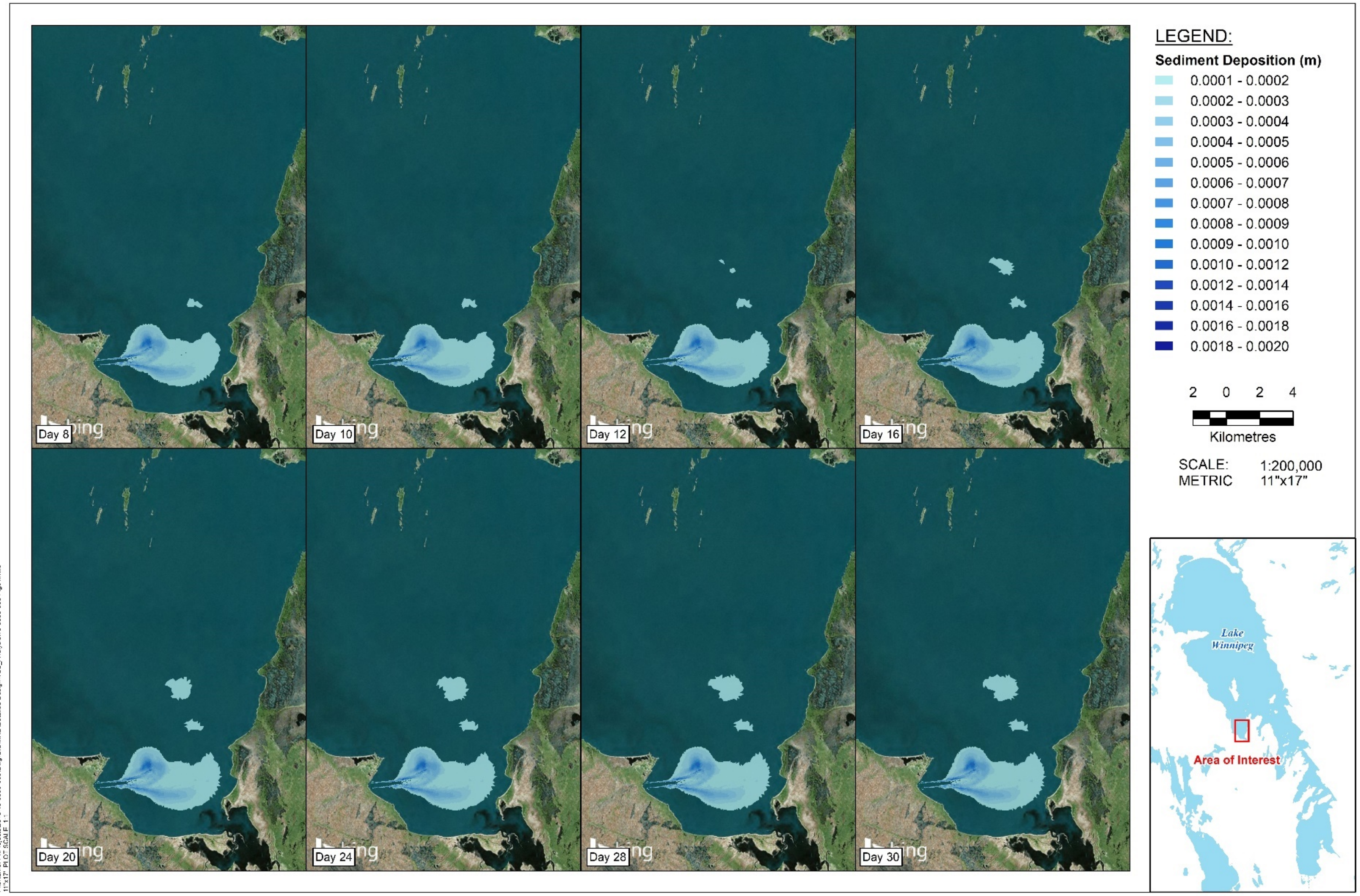


FIGURE 8B: DEPOSITION OF SEDIMENT IN STURGEON BAY – BASE CASE



5.2 Mitigation Case

The simulation of the base case resulted in a TSS concentration that notably exceeded the desirable threshold of 25 mg/L. Consequently, a second scenario, representing a possible means of mitigation, was developed. The intent was to provide guidance on how the channel could be commissioned but still maintain TSS concentrations at the outlet of LSMOC below 25 mg/L. This scenario requires the channel inflow to be ramped up slowly over a period of 24 days until the maximum flow is achieved. The inflow would be ramped up at the slowest rate at flows for which the channel is particularly susceptible to erosion (generally between 50 and 140 m^3/s). When flows are either above or below this critical zone, flows would be ramped up more quickly to reduce the time and outflow volumes required from LSM to successfully commission the channel. After 28 days, the WCS gates would begin to close and channel flows would recede. It is expected that fully closing the gates could take approximately an additional 13 days. It would be governed by the maximum rate of closure permitted to maintain stable side slopes under rapid drawdown conditions.

As described for the base case, commissioning is not anticipated to occur during a flood event. Considering the significantly longer period of operation for the mitigation case compared to the base case, it is anticipated that the maximum flows conveyed by that channel could be limited based on lake levels and not gate opening. Analysis of impacts of commissioning on lake water levels requires further review and should be undertaken with the system water balance model is fully developed by MI. If the design flow of 326 m^3/s cannot be achieved during commissioning, some of the loose sediment that would have otherwise flushed into the lake under the base case scenario would remain in the channel.

The flow conditions for the mitigation case and resulting TSS at the channel outlet are shown on Figure 9. The results have indicated that fully opening the channel to reach the design flow of 326 m^3/s over the course of 24 days will allow the TSS concentration at the channel outlet to largely be maintained below 25 mg/L. After 28 days, the TSS concentration at the channel outlet would return to zero. During this time, an estimated 5.3 million kilograms of sediment would be transported from the channel into Sturgeon Bay.

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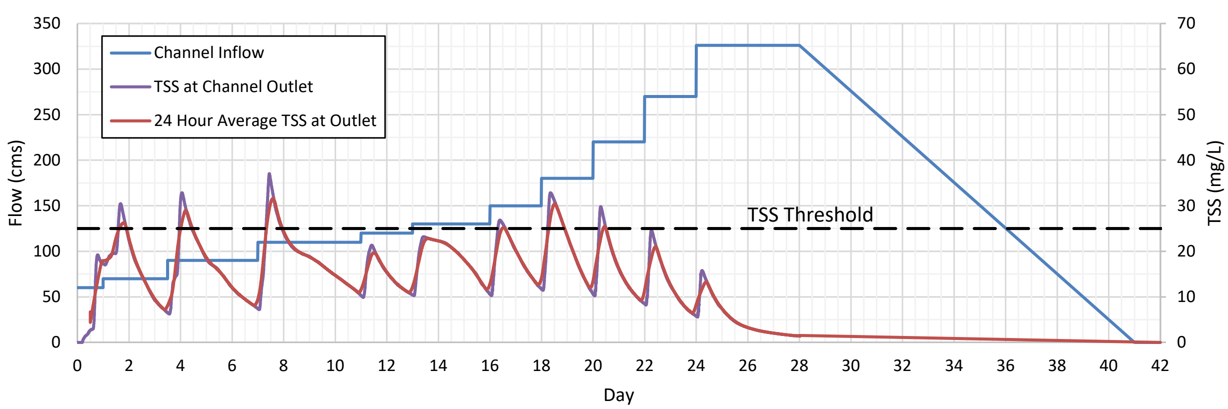
FIGURE 9: TSS CONCENTRATION AND CHANNEL INFLOW – MITIGATION CASE



The sediment dispersion for the mitigation case is shown in Figure 10. The results indicated that the incoming sediment gets discharged towards the eastern bank of Sturgeon Bay and then circulates both to the north and south. After 28 days it is anticipated that the WSC gates would start to be closed and channel flows would start to recede. At this point, the sediment is computed to have dispersed over a distance of approximately 18 km from the outlet of the LSMOC. At that time, the majority of the TSS plume would have reduced to a concentration of approximately 1 mg/L above the background concentration, with small local areas having concentrations of up to 2 mg/L. After 7 weeks, the sediment plume is computed to have largely dissipated into the lake. The remaining concentrations at that point are estimated to be generally less than 1 mg/L above the background concentration.

Sediment deposition resulting from the base case is shown in Figure 11. The results indicated that the coarse sediments (sands) would be deposited near the outlet. Some of the fine material would be deposited up to 9 km from the outlet, depositing over an area of 14 km^2 after 28 days. The computed deposition does not increase notably after 28 days. Similar to the base case, the deposition depth is small, (typically less than 1 mm), and is believed to be temporary in nature.

Similar to the base case, wind and wave effects were not included in this analysis. The extent of the TSS plume and deposition zone would change if these variables were considered. In general, it would be expected that wind and waves would disperse the suspended sediments into broader areas. This would further dilute the TSS concentrations in the plume and reduce the average depth of deposition. This aspect will continue to be reviewed as design progresses.

In addition, the simulation only considered an average Lake Winnipeg water level of 217.5 m. If Lake Winnipeg were higher or lower during the commissioning period, water velocities in the vicinity of the outlet would either increase or decrease accordingly. This would affect the overall dispersion and deposition in the lake.

Results of the analysis demonstrate that controlled operations of the LSMOC during commissioning is a feasible mitigative strategy to maintain TSS concentrations at the outlet within acceptable limits. However, as described in Section 3.5.2, parameters that control sediment transport are inherently challenging to predict given the variability that could occur in the physical environment. For this reason, detailed, real-time monitoring of turbidity and TSS along the channel and in Lake Winnipeg will be necessary during commissioning to verify model results. It is likely that adjustments to operations will subsequently be required, as deemed necessary based on observed field conditions, to maintain TSS levels below the agreed levels of concentration to be identified in the environmental license for the project. A more extensive calibration of the MIKE21 model should also be undertaken prior to being adopted for study of alternate strategies of operation during future years.

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FIGURE 10A: TSS CONCENTRATION IN STURGEON BAY – MITIGATION CASE

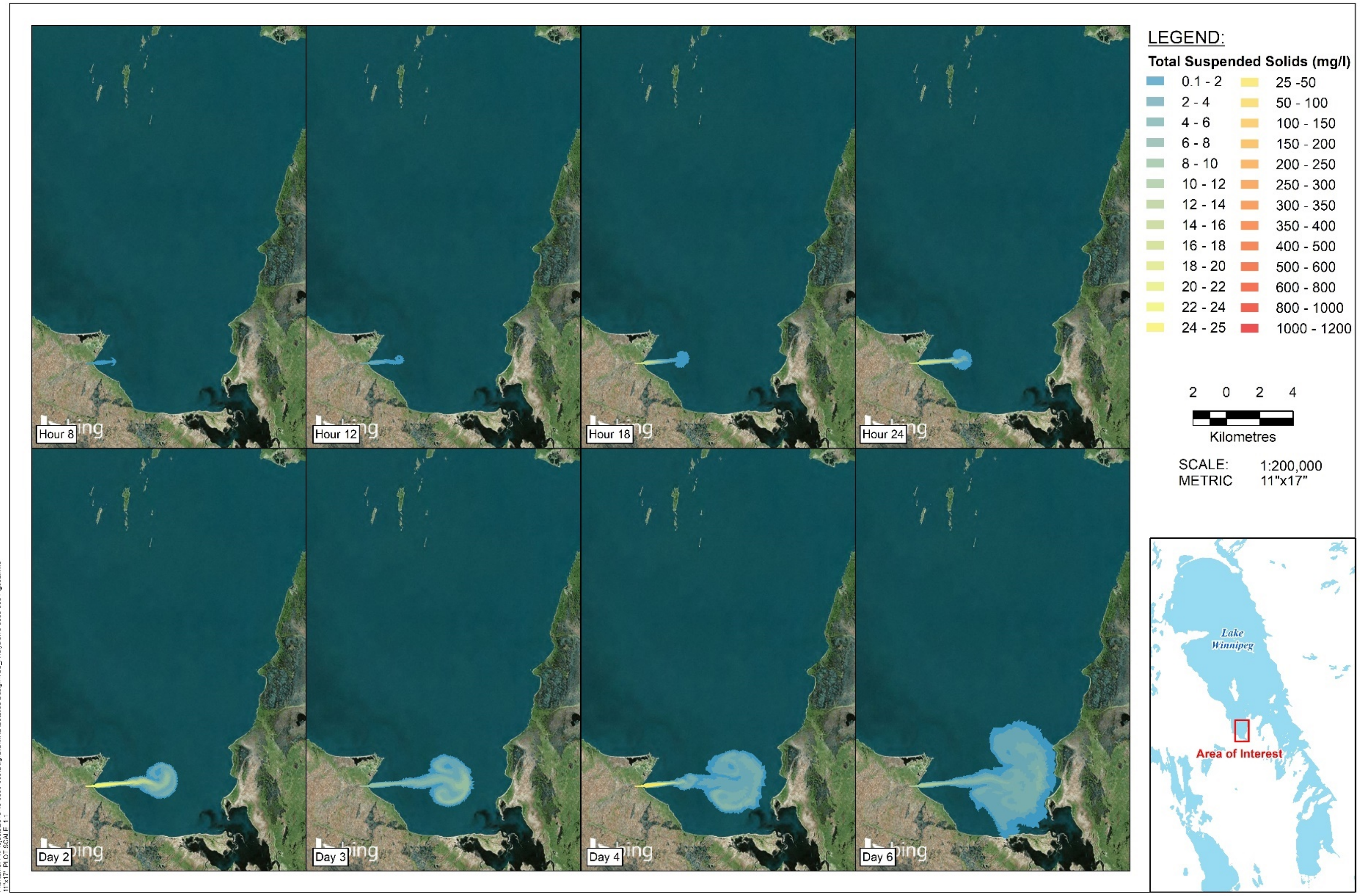


FIGURE 10B: TSS CONCENTRATION IN STURGEON BAY – MITIGATION CASE

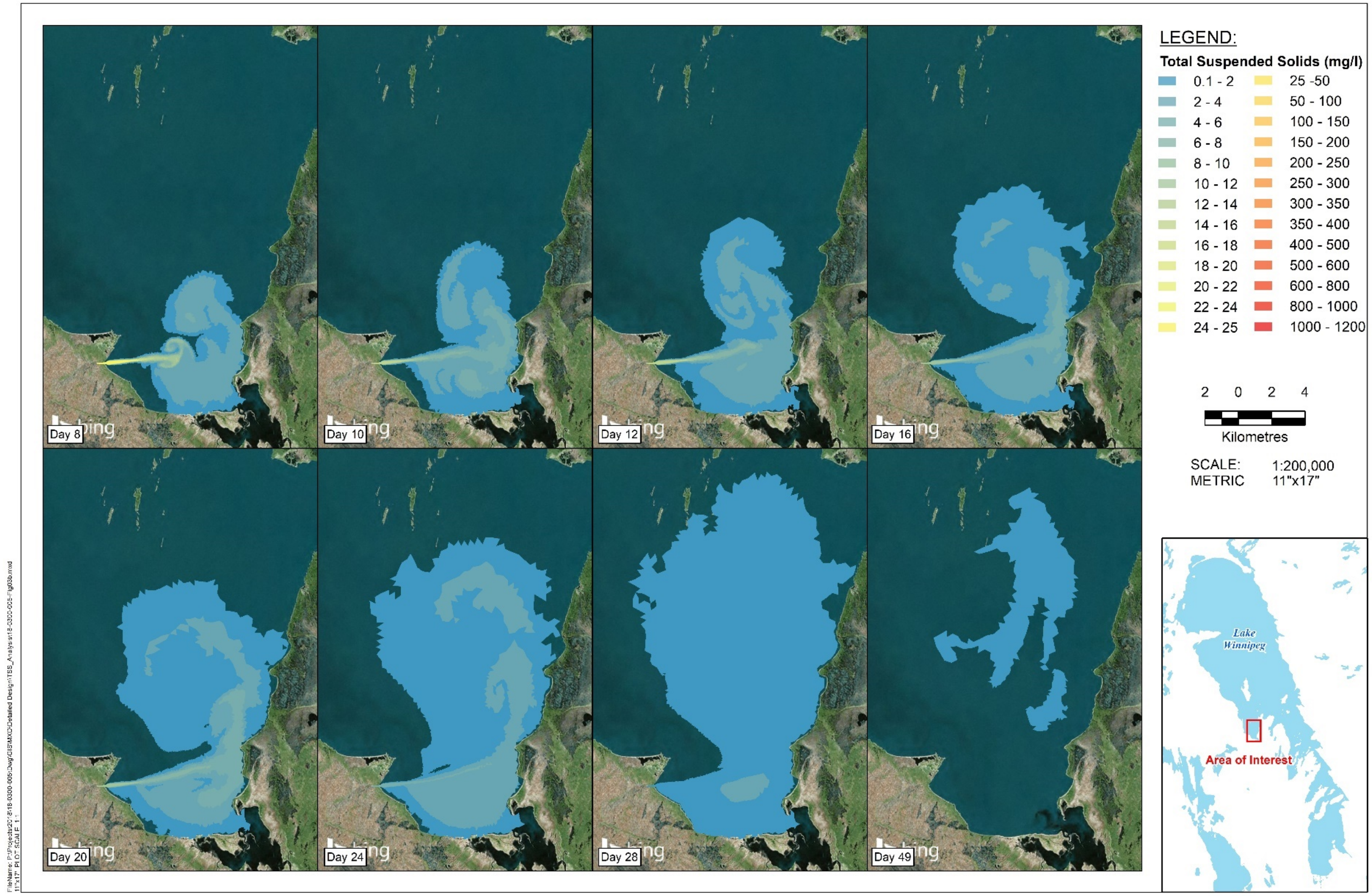


FIGURE 11A: SEDIMENT DEPOSITION IN STURGEON BAY – MITIGATION CASE

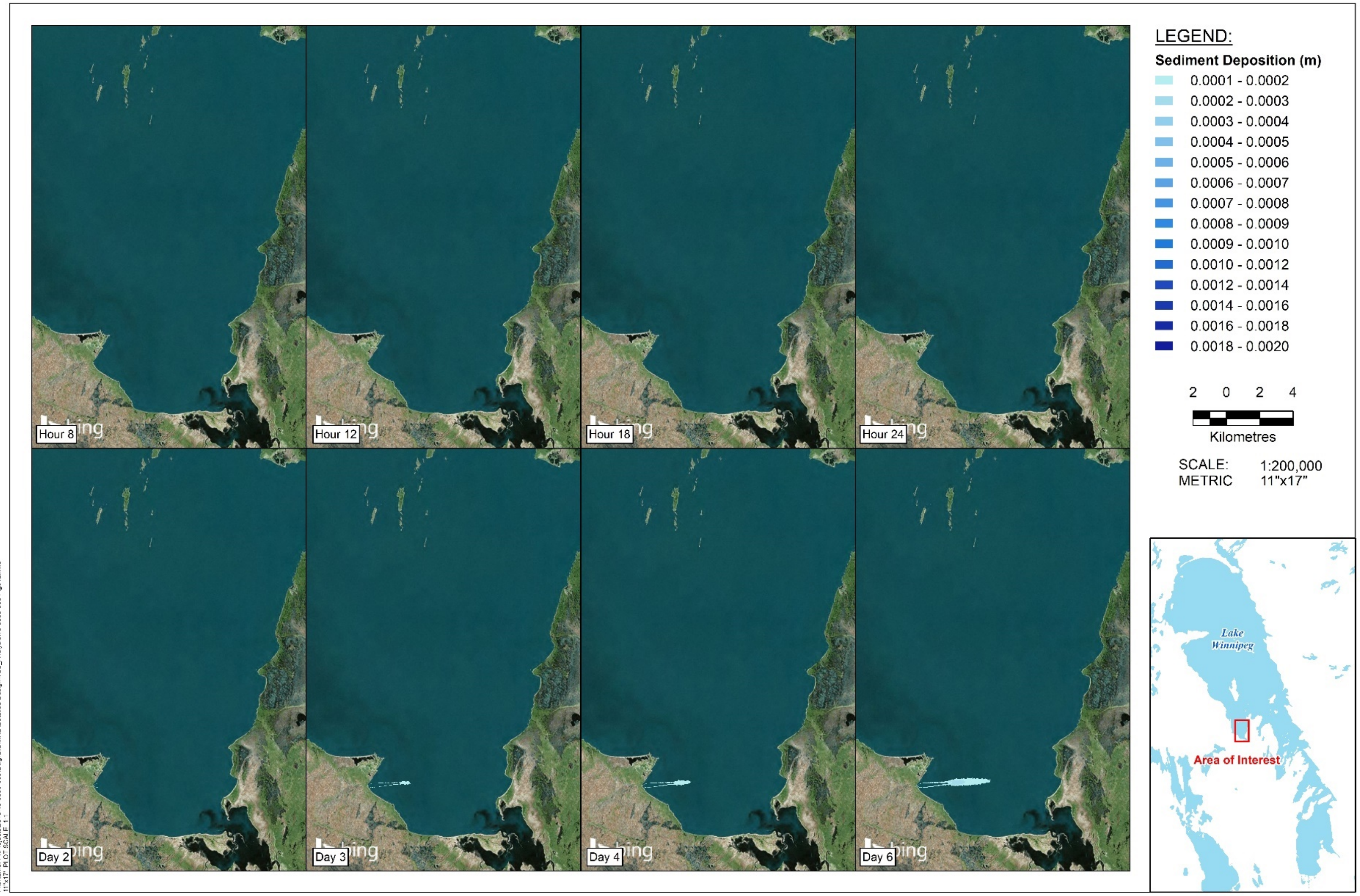
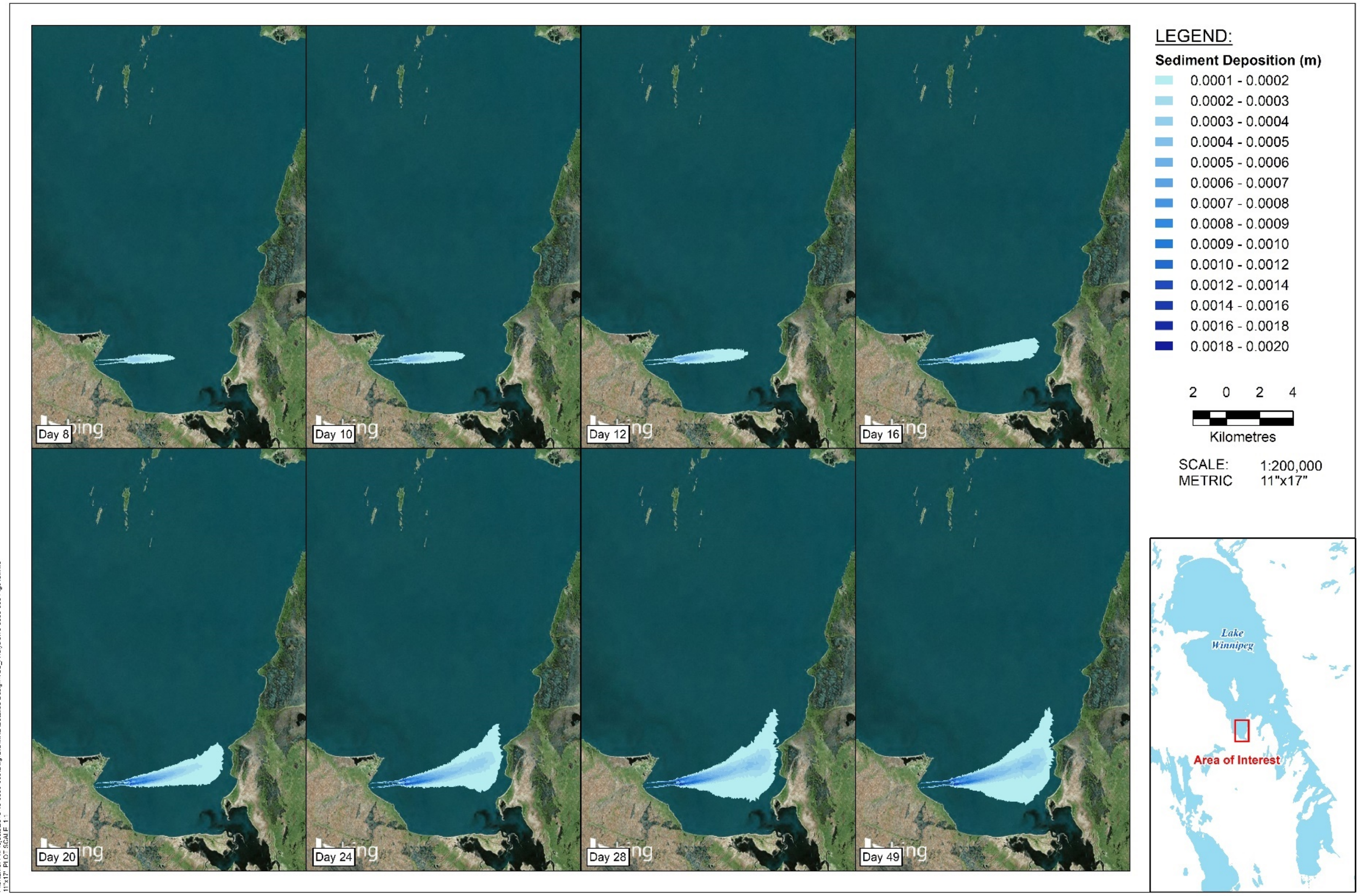


FIGURE 11B: SEDIMENT DEPOSITION IN STURGEON BAY – MITIGATION CASE



6.0 SUMMARY AND CONCLUSIONS

Numerical sediment transport modeling was undertaken to examine the increase in TSS concentrations and associated sediment deposition in Sturgeon Bay. This focussed on scenarios representative of commissioning, as well as the impact that controlled gate operation measures can have to limit the increase in TSS concentrations during that process. A 5 mm thick layer of loose fine particles uniformly distributed across the channel was estimated to be available for erosion and potential transport prior to commissioning the channel. This layer was assumed to have the same grain size distribution as the in-situ material and would be consistent along the entire length of the channel.

Two scenarios were simulated with the sediment transport model, including:

- ***Base Case –*** The gates of the water control structure at the upstream end of the LSMOC are opened fully over 12 hours until the design flow of 326 m^3/s has been reached. The gates remain fully open until all sediment is flushed from the channel and the TSS concentration at the channel outlet has returned to near zero.
- ***Mitigation Case*** – The gates of the water control structure are systematically opened over a period of approximately four weeks to allow sediments to be flushed more gradually and reduce TSS concentration at the channel outlet to approximately 25 mg/L or less.

The following conclusions were made from the results of these simulations:

- Under the base case conditions, the peak TSS concentration at the channel outlet was estimated to be 1200 mg/L and approximately 5.3 million kilograms of sediment was estimated to be flushed from the channel. The sediment entering Sturgeon Bay would discharge towards the eastern bank and then circulate both to the north and south. After sixteen days, the sediment is estimated to have dispersed a distance of approximately 14 km from the LSMOC outlet. At this time, the majority of the TSS plume is estimated to have reduced to a concentration of less than 2 mg/L, with some small local areas having concentrations of up to 8 mg/L. The coarse sediments (sands) would be deposited nearest the LSMOC outlet. The of the finer material would be deposited within 10 km of the outlet, over a computed area of approximately 15 km^2. Some of the finest sediments would remain in suspension after sixteen days. The average depth of deposition over the area of the plume is small, (less than 2mm), and it is believed that it would be temporary in nature.
- Under the mitigation case, the TSS concentration at the channel outlet was generally limited to 25 mg/L by strategically and gradually opening the WCS gates over a period of 24 days. During this time approximately 5.3 million kg of sediment was estimated to be flushed from the channel into Sturgeon Bay. After 28 days, when it is anticipated that closure of the WSC gates would commence, the sediment in Sturgeon Bay would have dispersed over an estimated distance of 18 km from the LSMOC outlet. At this time, the majority of the TSS plume would have reduced to a concentration of approximately 1 mg/L, with small local areas having concentrations of up to 2 mg/L. After 7 weeks, the sediment plume is estimated to have largely dissipated into the lake and remaining concentrations are generally less than 1 mg/L. Sediment deposition is estimated to occur up to 9 km from the outlet, with sediments depositing over an estimated area of 14 km^2 after 28 days. The deposition would not increase notably

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after 28 days. The depth of deposition would be is small, (typically less than 1 mm), and is considered to be temporary in nature.

- The model results clearly demonstrate that TSS concentration at the channel outlet can be managed through a strategic commissioning strategy, with gradual opening of the WSC gates. Detailed, real-time monitoring of turbidity and TSS along the channel and in Lake Winnipeg will be necessary during commissioning. This will be needed to verify model results and provide guiding information for the gate operations at the WCS to maintain TSS concentrations below acceptable levels.
- In both cases, any potential sediment input to Sturgeon Bay from the LSMOC is expected to contribute to the existing natural sediment budget of the lake and, subsequently, be subjected to the same natural shoreline processes that currently sort and distribute sediment in the various regions of the lake. As a result, measurable impacts on the existing substrate are believed to be unlikely.
- Wind and wave effects were not included in this analysis. The predicted extent of the TSS plume and deposition zone would change if these variables were considered in the analysis. In general, it would be expected that wind and waves would disperse the suspended sediments into broader areas. Further dilution of the TSS concentrations in the plume would be expected with a corresponding reduction in the average depth of deposition. This aspect will continue to be reviewed as design progresses.
  The simulations only considered an average Lake Winnipeg water level of 217.5 m. If Lake Winnipeg were higher or lower during the commissioning period, water velocities in the vicinity of the outlet would either increase or decrease accordingly. This would affect the overall dispersion and deposition in the lake.
- Analysis of impacts of commissioning on water levels in LSM requires further review and should be undertaken with the water balance model developed by MI.
- Parameters that control sediment transport are inherently challenging to predict. It is therefore recommended that the model be further verified during commissioning following first operations of the LSMOC. This would be based on recorded actual TSS data in LSM, in the channel and in Lake Winnipeg. A more extensive calibration of the model should also be undertaken prior to being adopted for study of alternate modes of operation during future years.

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