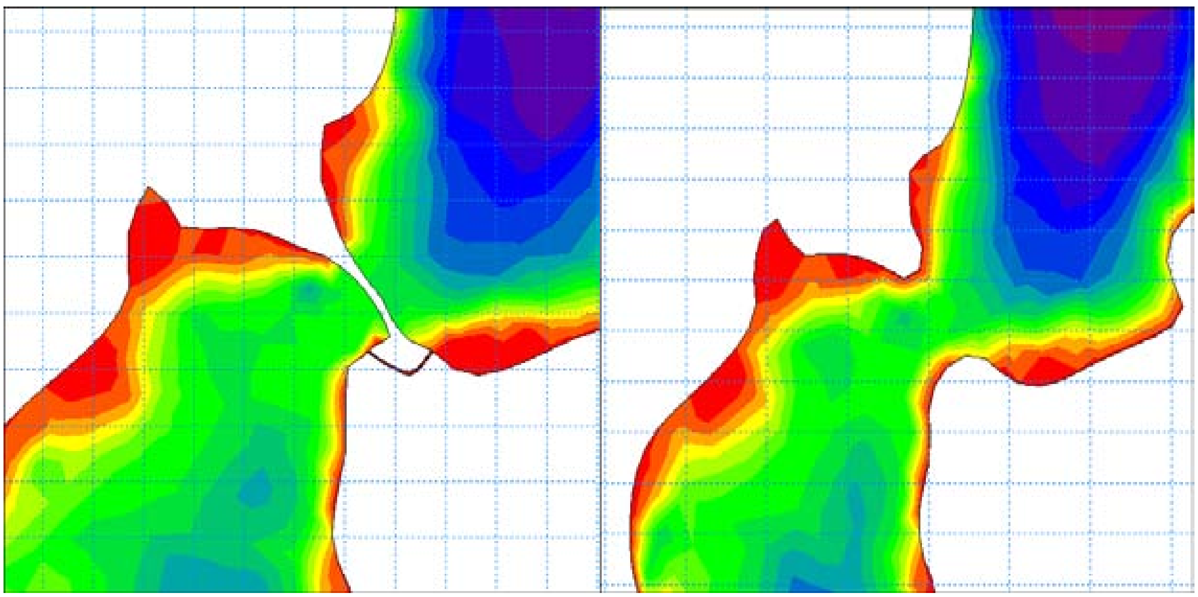
University of Manitoba
Faculty of Engineering
Department of Civil Engineering

Hydrodynamic Modeling of Lake Winnipeg and the Effects of Hecla Island



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ABSTRACT

The flow conditions of Lake Winnipeg and the effects of the Hecla Island causeway have been investigated in this study in order to determine if the causeway may potentially be responsible for changed flow conditions in this area, as well as the south basin of the lake. The investigation was performed by developing a two-dimensional hydrodynamic MIKE21 model that accurately reproduced the flow conditions of Lake Winnipeg, before and after the construction of the causeway. Specifically, this report compares the lake's flow patterns with and without the causeway implemented, as well as compares discharges through the Narrows, Mainland-Hecla, Hecla-Black and Black-Mainland channels. In addition, the hydrodynamic model served to provide a tool that helped to better understand the hydrodynamic behaviour of Lake Winnipeg including the impacts of wind set-up on the lake.

First of all, the study concludes that the currents and fluctuations that can be seen on Lake Winnipeg are caused primarily by wind stress applied to the lake. Secondly, blocking the Mainland-Hecla channel with the causeway seems to have a minor effect on the overall hydrodynamics of the south basin of the lake. Consequently, it is implausible to believe the causeway is responsible for changed conditions in this area. Finally, effects close to the causeway do seem more plausible and therefore, the causeway may potentially be responsible for changed conditions in the surrounding area. With this being said, additional research is required to determine how changes in flow patterns around the causeway may be affecting the conditions of the surrounding area including, the increase in algae and the increased erosion in this area.

ACKNOWLEDGEMENTS

I would like to extend my gratitude to Dr. Shawn Clark for giving me the opportunity to complete my undergraduate thesis and for offering his advice, knowledge and support throughout the process of completion.

I would also like to thank my family and friends who have been particularly supportive of my goals and ambitions, as this encouragement has made a world of difference in allowing me to excel at what I do best.

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1. INTRODUCTION

1.1 PROBLEM

On September 22, 2007 an article was published in the Winnipeg Free Press, which expressed the concerns of some Manitoba residents who believe that the Hecla Island causeway, built in 1971, may be responsible for many problems that are currently plaguing Lake Winnipeg. These individuals suggest that the causeway is virtually acting as a dam and therefore, is preventing water from moving between the lake's north and south basins on one of the only three channels available to flow. More specifically, these same residents propose that the addition of the causeway has changed the flow patterns throughout the south basin, from Netley Marsh to Hecla Island and consequently, algae have accumulated in the trapped water and erosion has increased in the surrounding area [1]. Figure 1.0 highlights the concerns brought forth by these Manitoba residents.

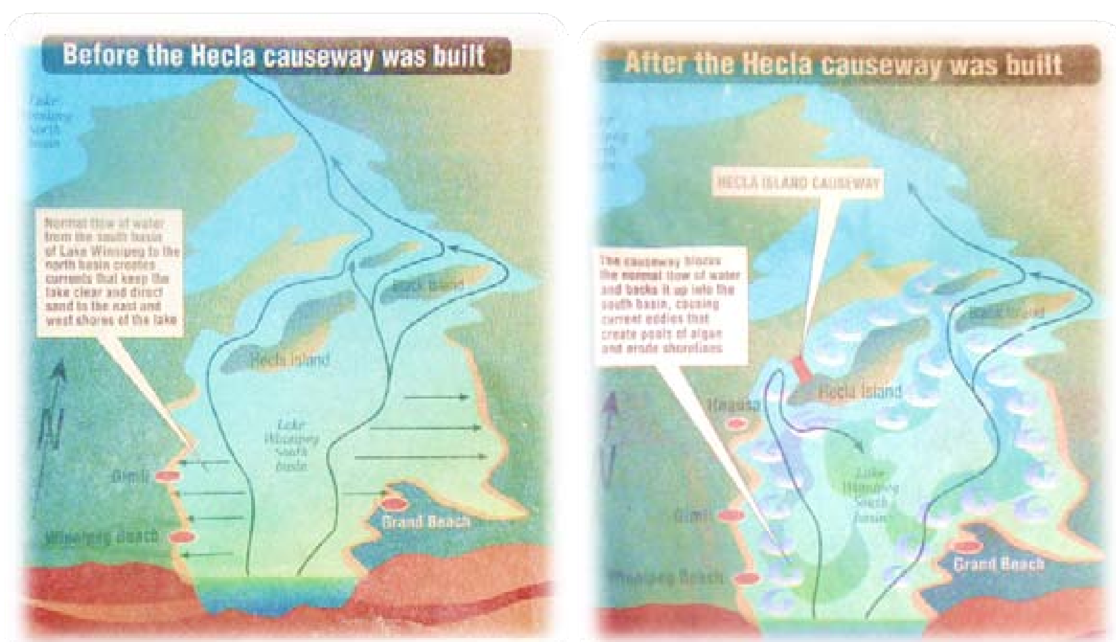

Figure 1.0: Flow patterns in Lake Winnipeg before and after Hecla Island causeway was built [1].

The photo to the left, which shows the flow patterns before the causeway was built, has a caption which reads “normal flow of water from the south basin of Lake Winnipeg to the north basin creates currents that keep the lake clear and direct sand to the east and west shores of the lake.” The photo to the right, which shows the flow patterns after the causeway was built, has a caption which reads “the causeway blocks the normal flow of water and backs it up into the south basin, causing current eddies that create pools of algae and erode shorelines.”

1.2 MOTIVATION

The health of Lake Winnipeg has been a growing concern for many years and it is evident that a solution to the lake’s woes must be considered. Therefore, the unease of the Manitoba residents with regards to the Hecla Island causeway must be seriously considered and investigated before the proposed problem can be dismissed.

In 2007, Lake Winnipeg Research Consortium acknowledged that the flow in Lake Winnipeg has most likely been affected by implementing the causeway, but declared that there was no data to back up this theory. Manitoba’s Water Stewardship department also recognized that more research would have to be done in order to determine if the causeway has negatively impacted the lake and consequently, if plans need to be implemented to minimize or diminish these undesirable effects [1]. Accordingly, it is evident that the flow conditions of Lake Winnipeg, with and without the implementation of the causeway, need to be examined. Ideally, examining the flow conditions will provide valuable information, which will aid the process of determining the effects that the Hecla Island causeway has on Lake Winnipeg.

1.3 PURPOSE

The purpose of this study is to investigate the flow patterns of Lake Winnipeg before and after the Hecla Island causeway was built. A two-dimensional hydrodynamic MIKE21 model will be developed in order to accurately reproduce the lake’s flow conditions, with and without the causeway constructed. In addition, this hydrodynamic model will serve to provide a tool that will help to better understand the hydrodynamic behaviour of Lake Winnipeg including the impacts of wind set-up on the lake. This report will compare the lake's flow patterns with and without the causeway implemented. Furthermore, discharges through each of the channels in the south basin, as well as through the Narrows will be compared with the causeway constructed and without. In addition, the report will discuss how various changes made to the conditions of the lake impact these results.

1.4 BACKGROUND

Lake Winnipeg is the tenth largest body of freshwater in the world, covering an area of 24,000km². The lake has two distinct basins, the north basin and the south basin, which are separated by the Narrows. The south basin is 40km wide, the north basin is 100km wide and the Narrows is a 2.5km wide channel. Although the lake has a large surface area, it is considered to be a shallow lake [2]. Consequently, wind affects the lake dramatically and has a significant impact on its water levels and velocities. Figure 1.1 illustrates Lake Winnipeg and the locations of the north and south basins, as well as the Narrows.

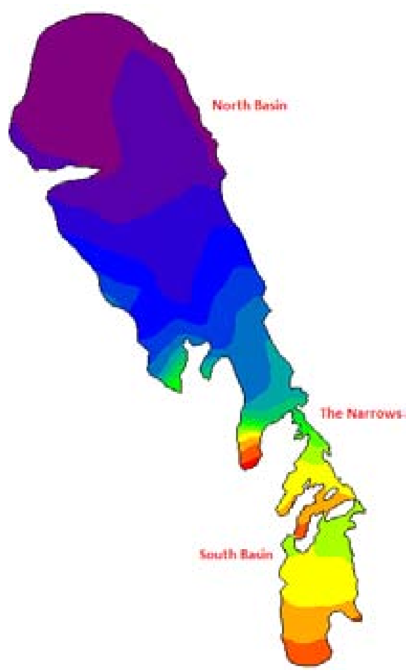

Figure 1.1: Lake Winnipeg illustrating the locations of the north and south basins, and the Narrows.

Lake Winnipeg is the third largest reservoir in the world, as Manitoba Hydro uses it to produce hydro electric power, with which they generate $350 - 580 million per year in export power sales. In addition, the lake serves a variety of recreation and commercial uses including, fishing, swimming, and boating. The recreational uses attract tourism, which generates more than $100 million per year. Many communities rely on Lake Winnipeg for fresh drinking water and the lake is also home to a variety of fish and organisms [3]. It is evident that Lake Winnipeg is important to the province of Manitoba and it's residents and therefore, the water quality is an essential matter. Figure 1.2 demonstrates the diminishing water quality of Lake Winnipeg in recent years.

Figure 1.2: Lake Winnipeg's diminishing water quality [2].

2. HYDRODYNAMIC MODEL DEVELOPMENT

2.1 MIKE21 MODELLING SYSTEM

The computer program selected for this study was MIKE21 Flow Model FM by DHI. MIKE21 Flow Model FM is a modelling system that follows a flexible mesh approach, meaning that the mesh can be refined in certain areas while being kept coarse in others. The flexible mesh is comprised of triangular and quadrilateral elements. This program can be used for studying hydrodynamics in a variety of situations. The application areas are generally problems where flow and transport phenomena are the most significant factors and where the flexible mesh feature is advantageous [4].

The modelling system is based on the numerical solution of the two-dimensional shallow water equations and therefore, consists of the continuity, momentum, temperature, salinity and density equations. It is not necessary to include temperature or salinity inputs if they are not of particular concern. The spatial discretization - the conversion of continuous space into an equivalent discrete space - is performed using a cell-centered finite volume method. In general, the MIKE21 Flow Model FM modelling system calculates a variety of variables, such as flow, based on boundary conditions that are input [4]. Some examples of boundary conditions include tributary inflows, water surface elevations and wind. This data must be obtained prior to the development of the model.

2.2 LAKE WINNIPEG MODEL

The hydrodynamic model of Lake Winnipeg, developed specifically for this study, was generated using the tools that are provided in MIKE21 and MIKE Zero; MIKE Zero is DHI's graphical user interface for setting up simulations, as well as for pre- and post-processing analysis.

2.2.1 Lake Winnipeg Mesh

This study's two-dimensional flexible mesh was developed using MIKE Zero's mesh generator, which required bathymetry data of the entire Lake Winnipeg. Two different meshes were required to perform this research. One mesh modeled the flow conditions of Lake Winnipeg before the construction of the causeway-the open mesh, while the other modeled the flow conditions of Lake Winnipeg after the construction of the causeway-the closed mesh. Developing these two separate meshes allowed for comparison of the results between the two different scenarios. Figures 2.0 and 2.1 show the two meshes that were developed, zoomed into the causeway, so that it is easy to

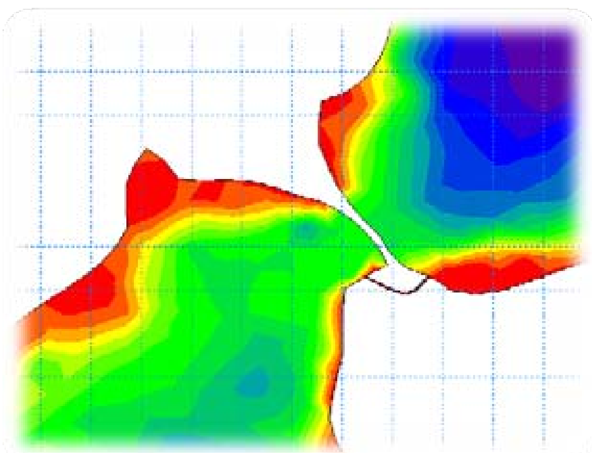

Figure 2.0: Closed mesh zoomed into causeway.

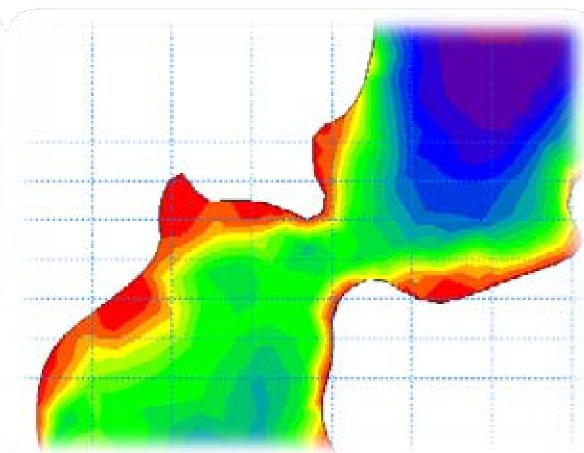

Figure 2.1: Open mesh zoomed into causeway.

depict the difference between the two. The curved line running through the causeway in Figure 2.0 models the 30m wide channel that was left open underneath the bridge connecting the causeway to Hecla Island. This channel will be referred to as the Mainland-Hecla channel in this report.

The characteristics of both meshes are extremely similar and therefore, only one mesh will be referred to for the remainder of this section. Before the mesh could be interpolated and turned into a continuous surface, appropriate node spacing, which controls the resolution of the mesh had to be determined. It was decided that the mesh should be more refined starting from just north of the Narrows and ending just south of Hecla Island. The node spacing chosen for this refinement was 500m. In addition, the Narrows and the smaller narrows were refined even further to a node spacing of 50m. Finally, the Mainland-Hecla channel was refined additionally to a node spacing of 10m. It was determined that the rest of the mesh's nodes would be spaced 5km apart. These decisions were based on the fact that it is important to have at least four to five elements spanning each part of the mesh and therefore, the smallest locations had to be refined the most. Moreover, the finer the mesh, the more accurate it becomes and therefore the mesh was chosen to be more refined in areas where it was known accuracy was important. The mesh was chosen to be coarse in locations of less importance in order to minimize computation times. When the causeway was removed to develop the open mesh, the node spacing was left at 500m through this channel. Figures 2.2 and 2.3 show the Lake Winnipeg mesh with its elements and varying resolution. It should be noted that the darker areas are the more refined locations.

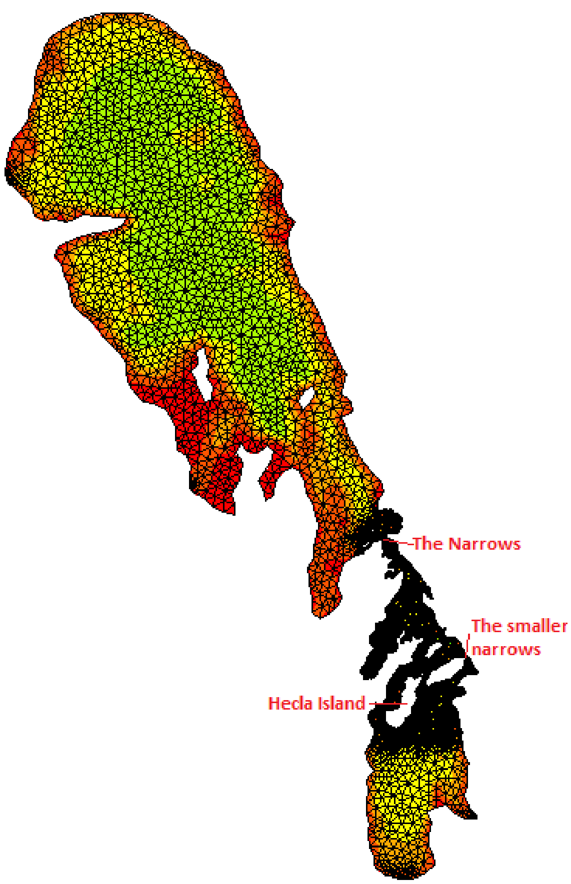

Figure 2.2: Element mesh with varying resolution.

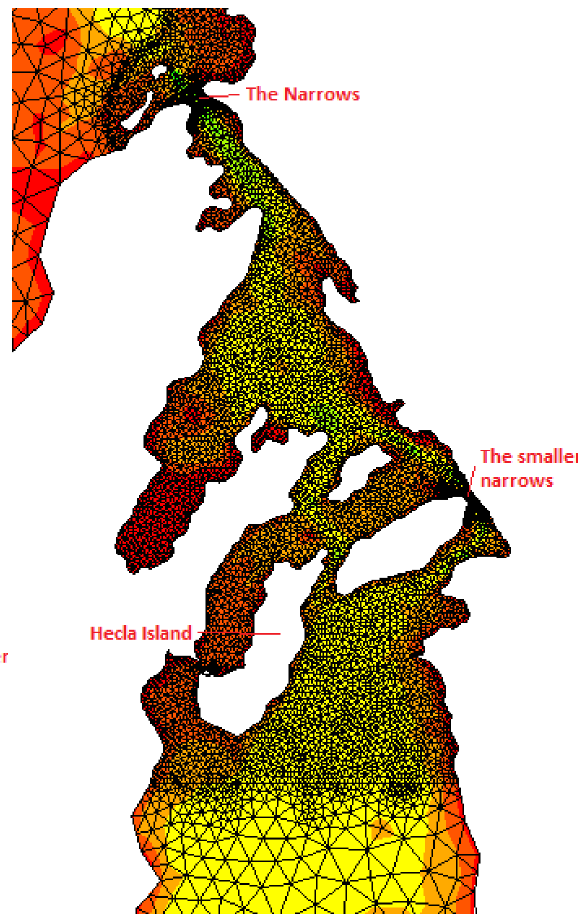

Figure 2.3: Element mesh zoomed in.

Boundary condition locations also had to be specified before the mesh could be completed. This consisted of defining arcs around the lake where the boundary conditions were to be located. Each of these arcs consisted of 2 nodes and 4 vertices. Boundary conditions will be discussed further in section 2.2.2.

In the end, the closed mesh contained 9,421 nodes and 16,625 elements. Conversely, the open mesh contained 8,456 nodes and 15,032 elements. Both meshes were constructed with a varying resolution.

2.2.2 Model Inputs

After the meshes were constructed it was necessary to input certain data that would simulate the realistic conditions of Lake Winnipeg. First, five tributary inflows were used as boundary conditions in the model. These five tributary inflows included the Red, Saskatchewan, Winnipeg, Dauphin and Icelandic rivers. Second, the water surface elevation at the lake's outlet, specifically at the Montreal Point location, was used as the sixth boundary condition in the model. Third, wind speed and direction data were input into the model in order to simulate the effects that wind has on Lake Winnipeg. In addition, bottom roughness, which in this case was Mannings n, needed to be input into the model. Figure 2.4 shows that two different values of Mannings n were used. The red area

Figure 2.4: Illustration of how Mannings n varies with domain.

has a Mannings n value of 0.031 and the purple area, which is the Narrows, has a Mannings n value of 0.0625. Finally, a drag coefficient of air had to be selected, which is empirically related to the density of air, as well as wind speed in the MIKE21 modelling system in order to reproduce the effects of wind stress over the model domain [4]. After analyzing the results from various simulations that were run with different drag coefficients it was decided that a value of 0.004 best modeled the wind stress on Lake Winnipeg. The wind stress was set to be constant over the entire domain of the model.

2.3 CALIBRATION

After all of the components to the model were developed and simulations could be run, these simulations needed to be analyzed in order to determine whether the modeled data accurately reproduced the measured data. In other words, the model needed to be calibrated. The calibration was carried out by comparing measured water surface elevation data from eight gauges around the lake to the modeled data at these same locations. These eight water surface elevation gauge stations were located at Montreal Point, Mission Point, George Island, Berens River, Matheson Island, Pine Dock, Gimli and Victoria Beach. Further calibration was carried out by comparing measured velocities through the Narrows and the Mainland-Hecla channel to the modeled data in these same locations. Finally, bottom roughness and the drag coefficient were adjusted to realistic values that best modeled the actual conditions of the lake.

Figures 2.5 through 2.12 show the comparisons between measured and modeled water surface elevations at each of the eight gauge stations around the lake from June 1-July 15. These figures demonstrate that the model does in fact reproduce the measured data accurately. In particular, the model well represents the timing and magnitude of the peaks and valleys that can be noted in the measured water surface elevation signal. In no case does the model produce unrealistic results. In addition, the figures show that the water surface elevations around the lake do not change whether the causeway has been implanted or not. The differences between the modeled results from both the open and closed meshes are insignificant.

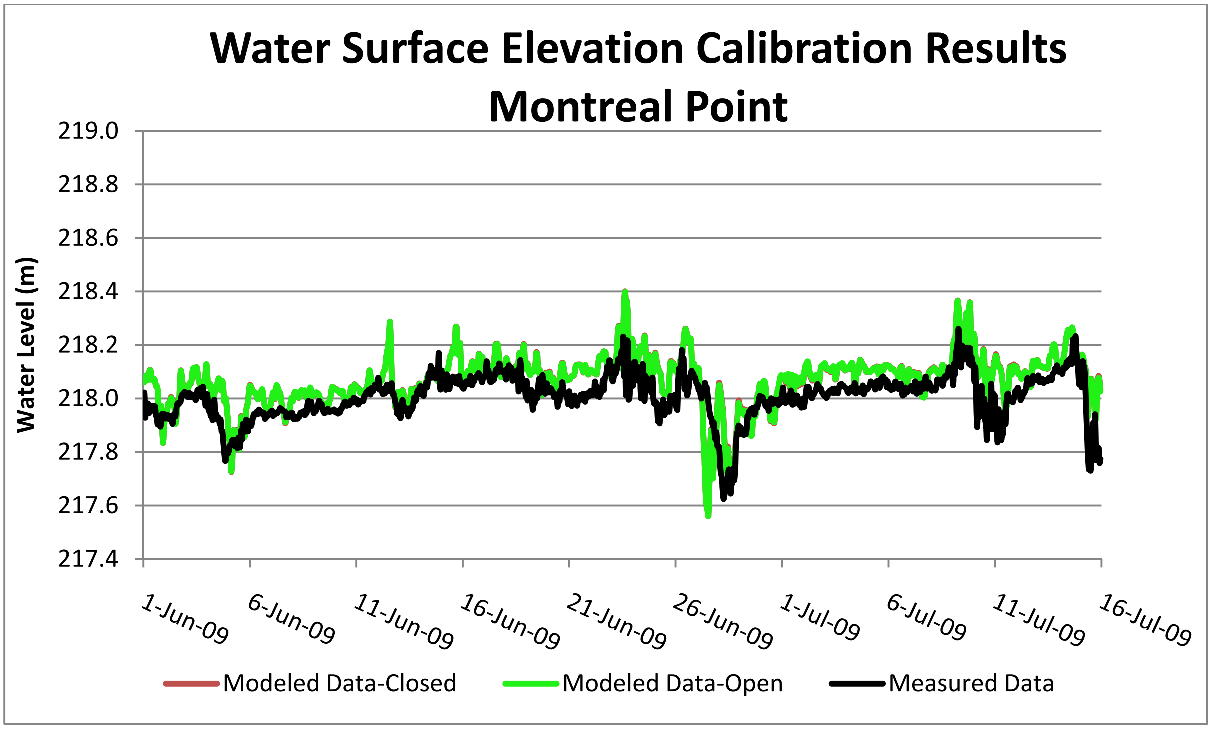

Figure 2.5: Comparison between measured and modeled water surface elevations at Montreal Point.

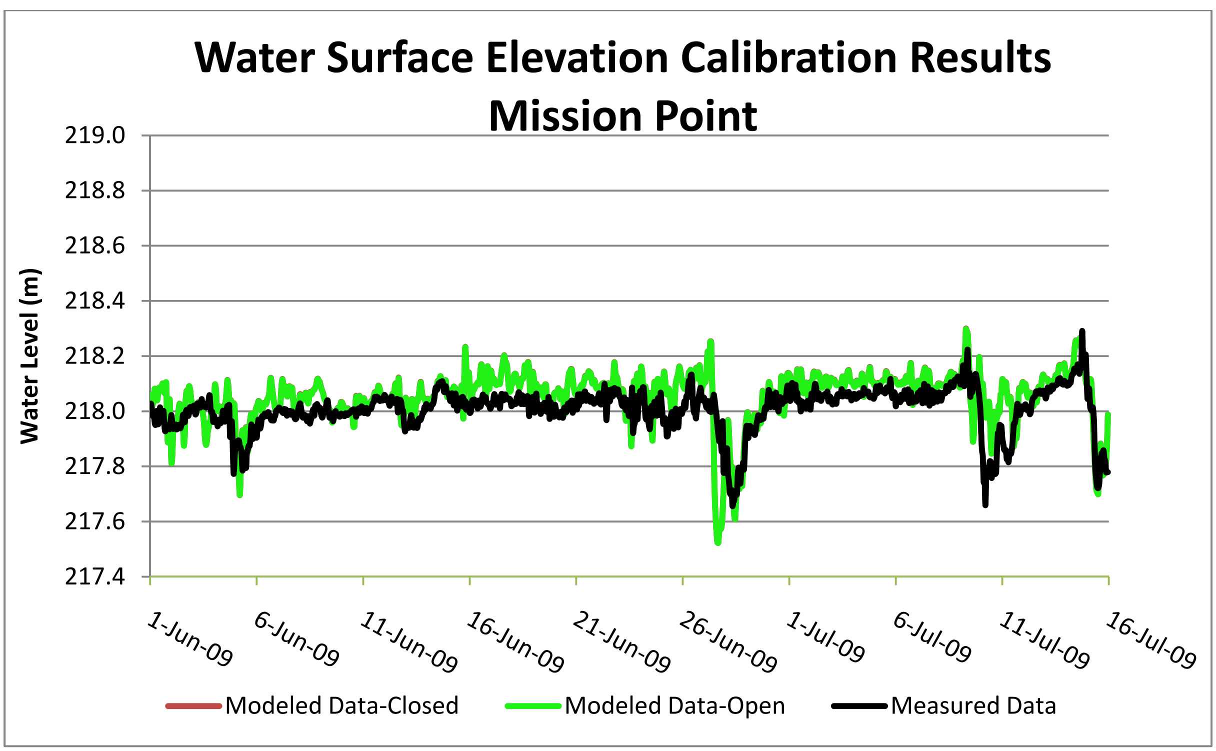

Figure 2.6: Comparison between measured and modeled water surface elevations at Mission Point.

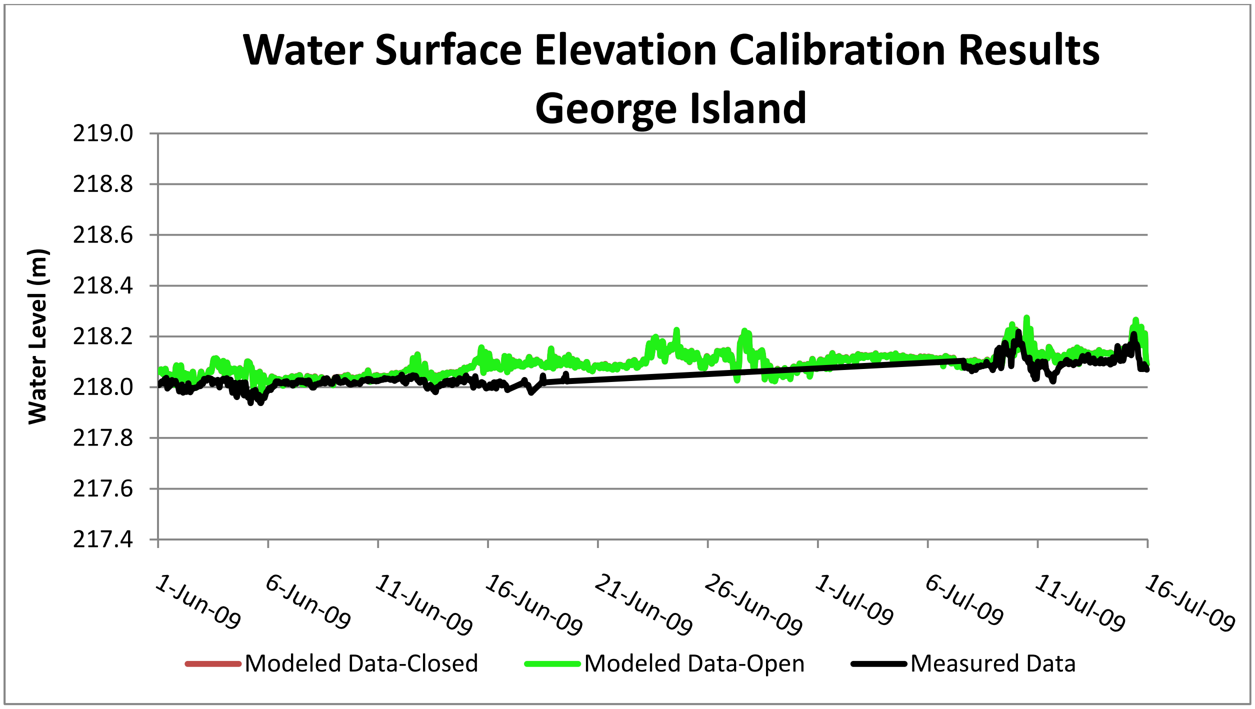

Figure 2.7: Comparison between measured and modeled water surface elevations at George Island.

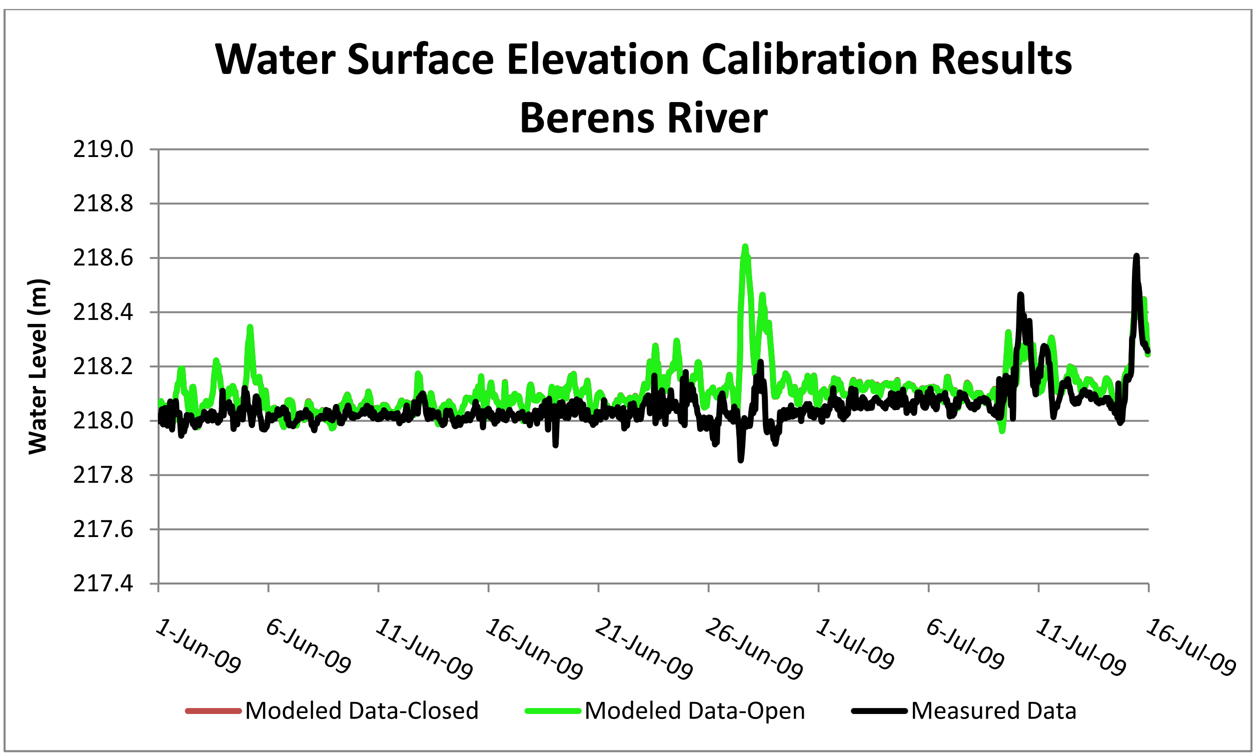

Figure 2.8: Comparison between measured and modeled water surface elevations at Berens River.

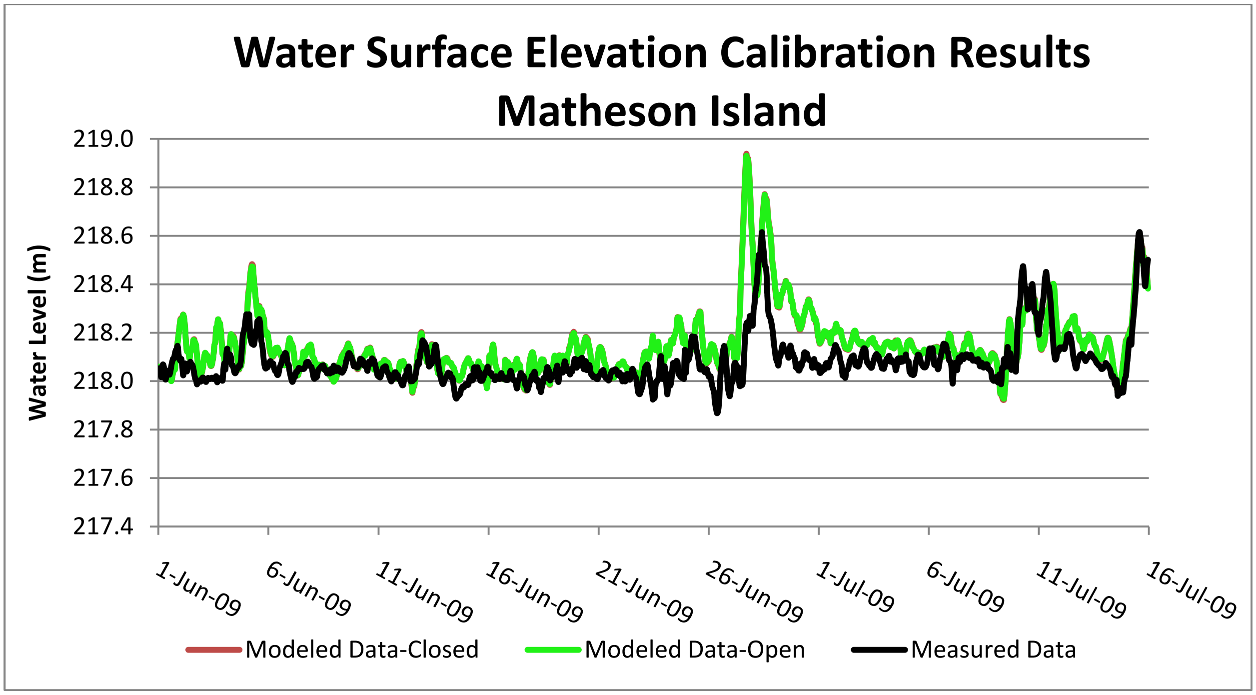

Figure 2.9: Comparison between measured and modeled water surface elevations at Matheson Island.

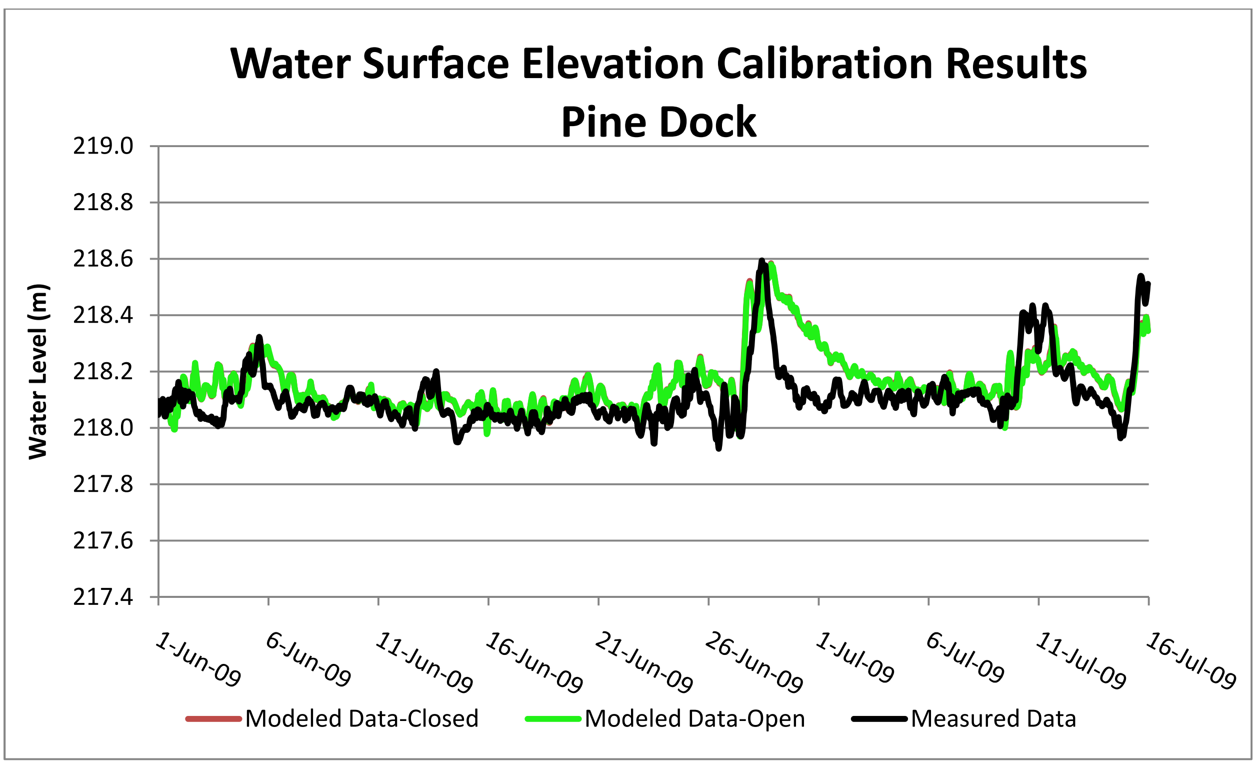

Figure 2.10: Comparison between measured and modeled water surface elevations at Pine Dock.

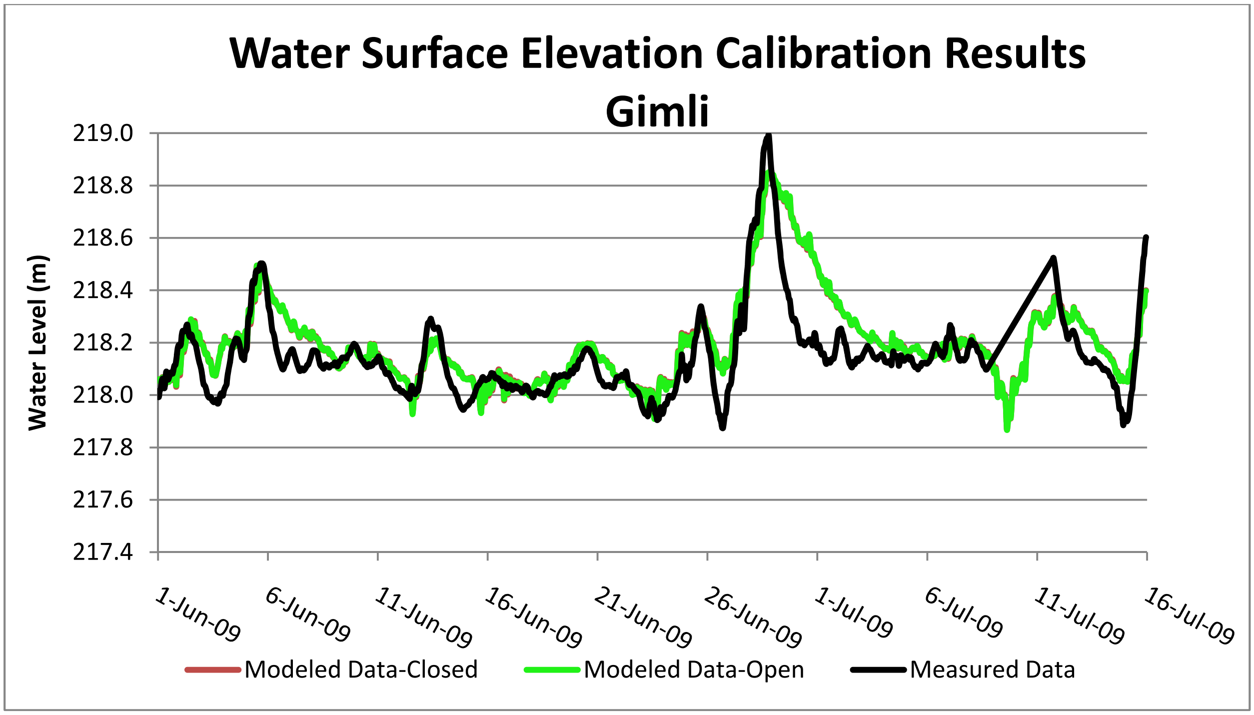

Figure 2.11: Comparison between measured and modeled water surface elevations at Gimli.

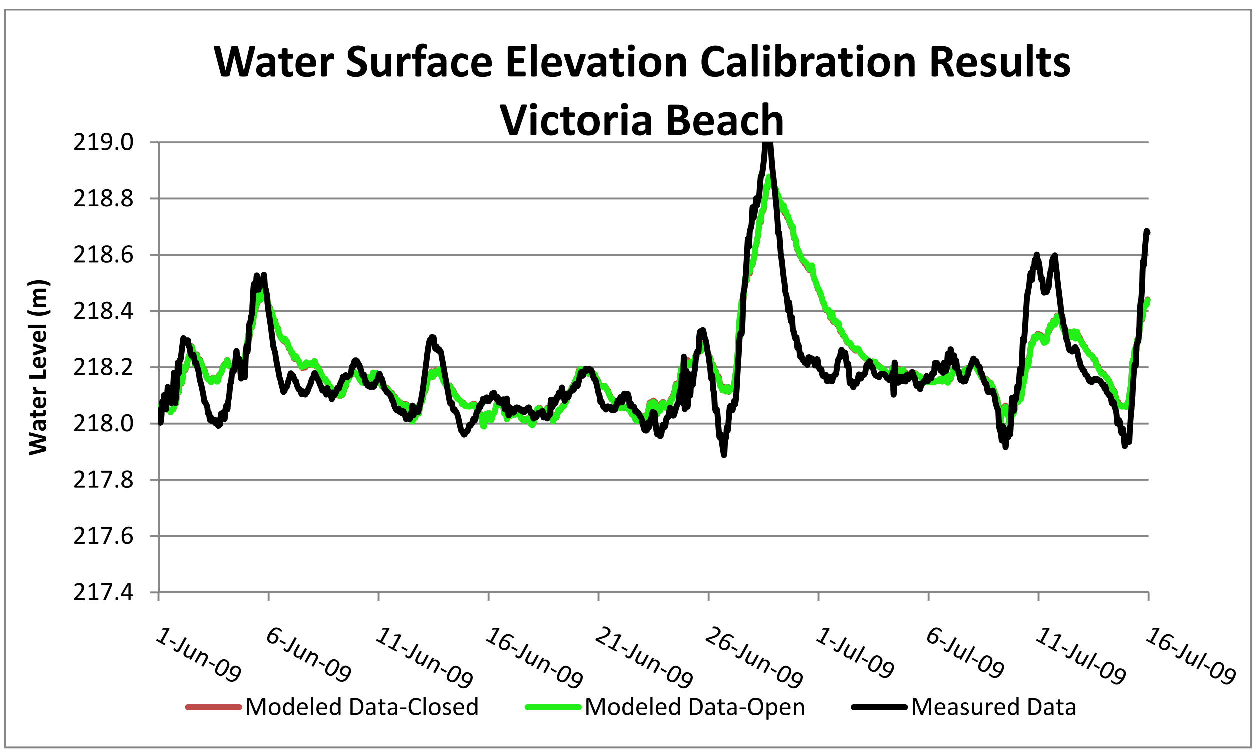

Figure 2.12: Comparison between measured and modeled water surface elevations at Victoria Beach.

Figures 2.13 and 2.14 show the comparisons between measured and modeled velocities in the Narrows specifically, the x-component and y-components of velocity, respectively. These results were not reproduced as accurately as had been hoped for and ultimately, it was not determined if this had been a problem with the model or the measured data. The results would be deemed more successful if the trends between the measured and modeled data were more similar. However, the maximum error between the measured and modeled data was only on the order of 3cm/s. Therefore, the lack of similarity between the trends was not of utmost concern. In addition, the figures do show that the velocity in the Narrows does not change whether the causeway has been implemented or not. The differences between the modeled results from both the open and closed meshes are insignificant.

Figure 2.15 compares the velocities between the measured and modeled data in the Mainland-Hecla channel. It was important that the model did accurately reproduce the measured data in the Mainland-Hecla channel as this was the location which was of particular interest for this study. After analyzing these results it was determined that the model does in fact reproduce accurate results in this location.

Figure 2.16 demonstrates the effects of Mannings n on water surface elevation. Three different values of Mannings n were simulated. One value was chosen to be more realistic, while the others were included to demonstrate how sensitive the model is to changing Mannings n. As suspected, the higher Mannings n value of 0.0625 dampens the magnitude of the water surface elevation peaks, while the lower Mannings n value of 0.01 amplifies the magnitude of the water surface elevation peaks. It can be seen that the most realistic value of 0.031 reproduces the measured data most accurately. The same conclusions can be made for the effects of Mannings n on velocity, which is shown in Figure 2.17, that were made for the effects of Mannings n on water surface elevation.

Figure 2.18 illustrates how changing the drag coefficient of air effects water surface elevation. Four different drag coefficients were simulated and a value of 0.004 was chosen, as it was reasonable and replicated the measured data most precisely. MIKE21 uses a default drag coefficient of 0.001255, which is generally used for open sea applications. However, field measurements of the drag coefficient collected over lakes indicate that the drag coefficient is larger for lakes than for open

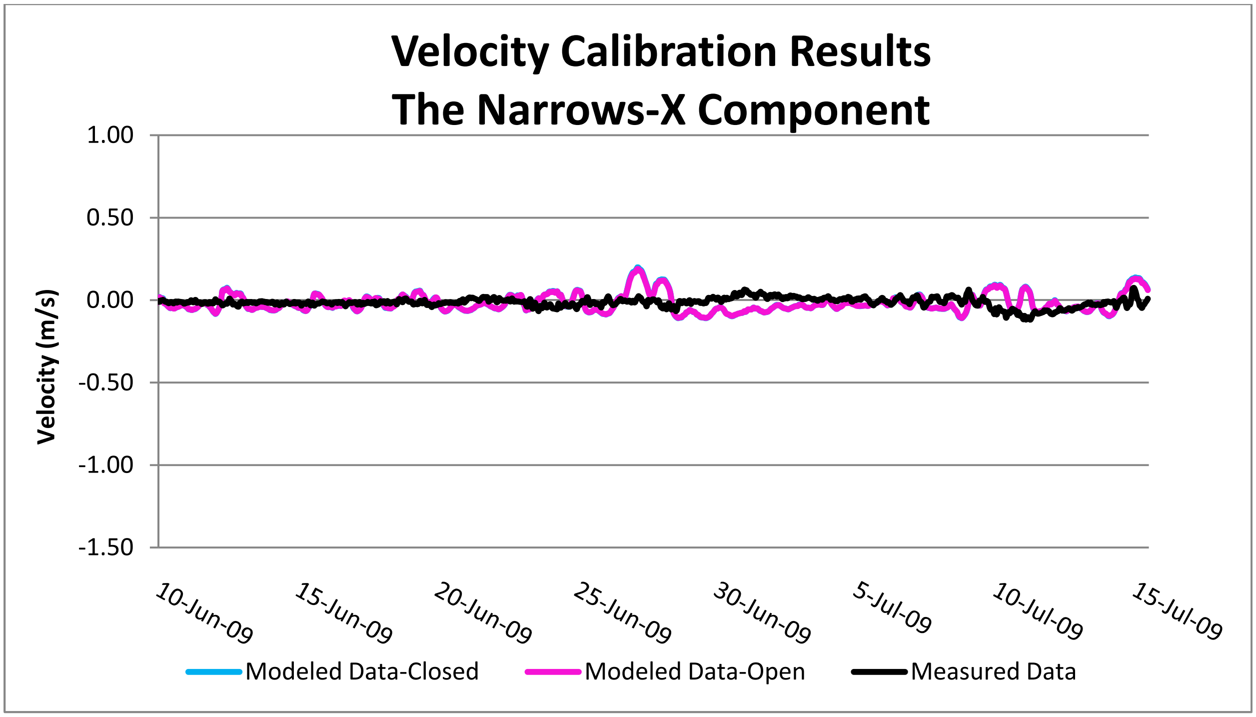

Figure 2.13: Comparison between measured and modeled velocities in the Narrows.

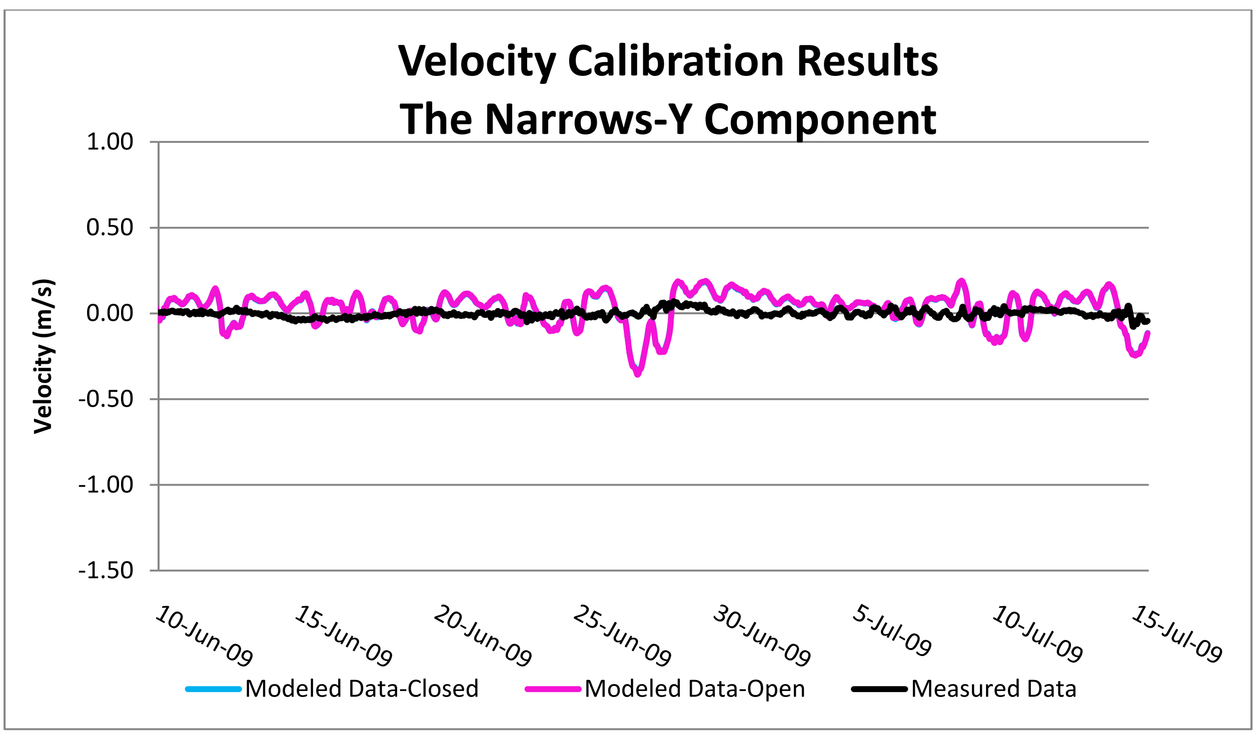

Figure 2.14: Comparison between measured and modeled velocities in the Narrows.

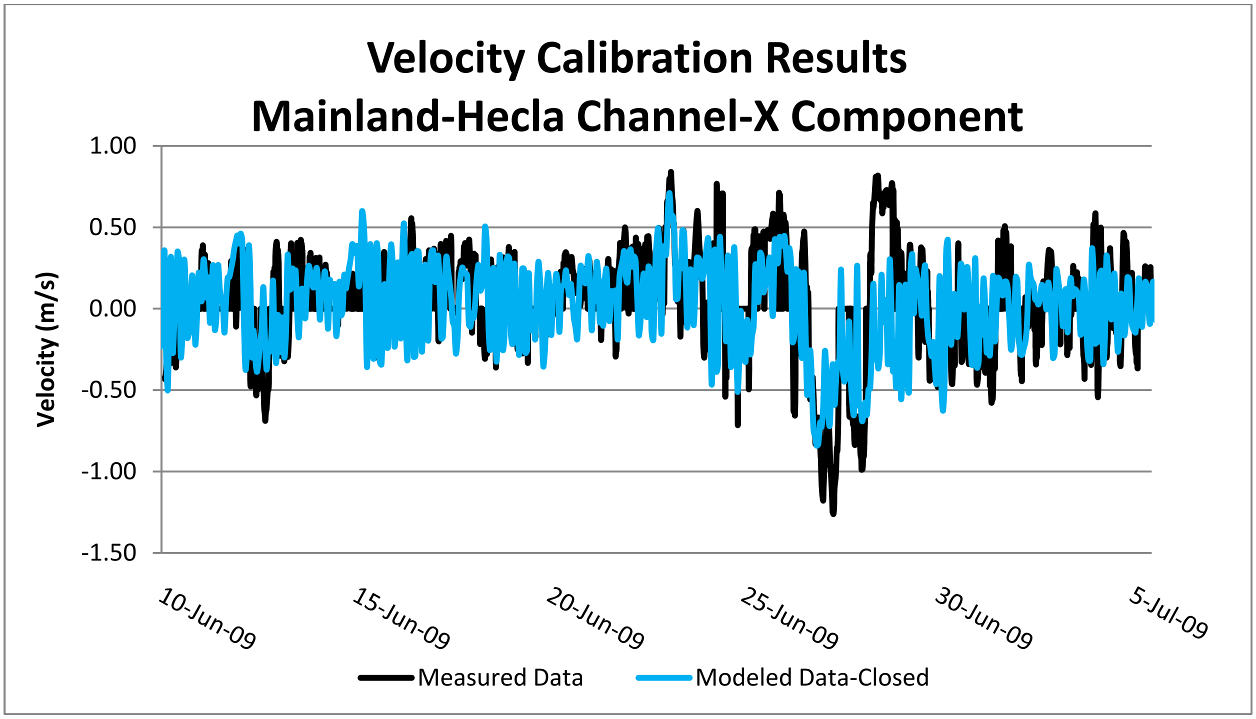

Figure 2.15: Comparison between measured and modeled velocities in the Mainland-Hecla channel.

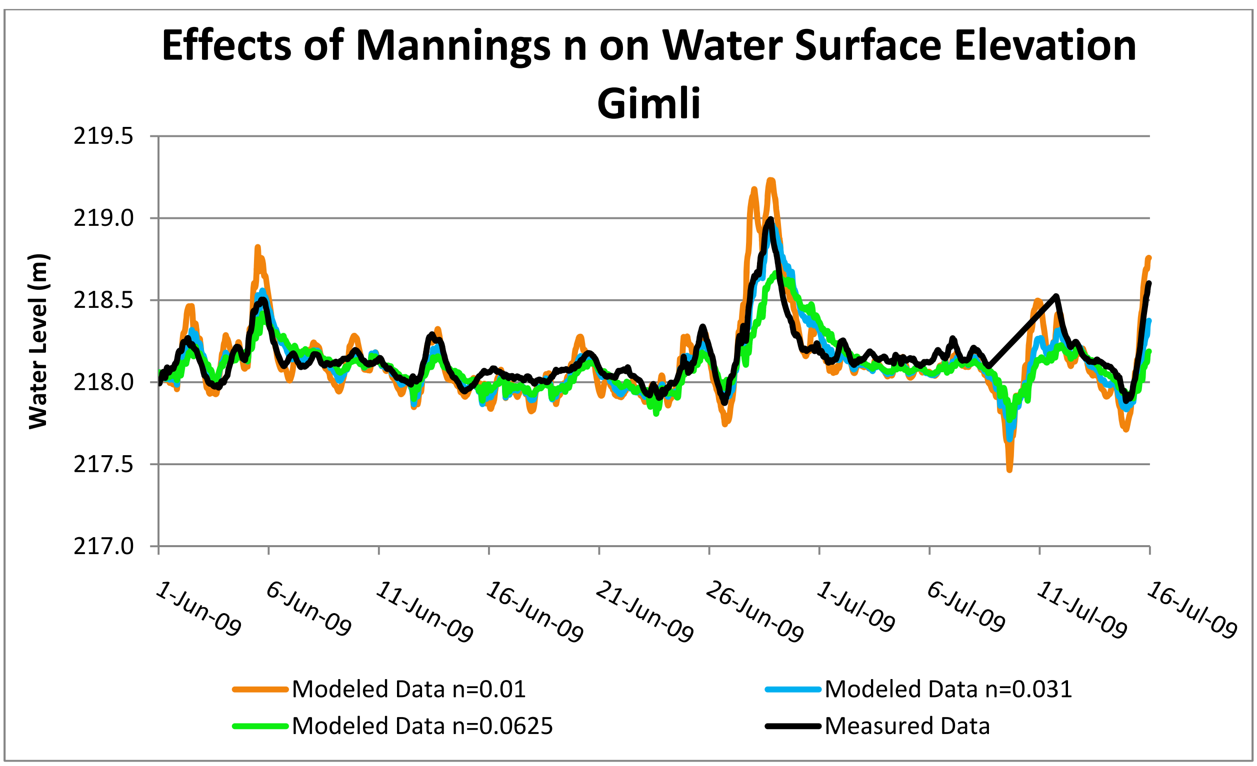

Figure 2.16: Effects of Mannings n on water surface elevation.

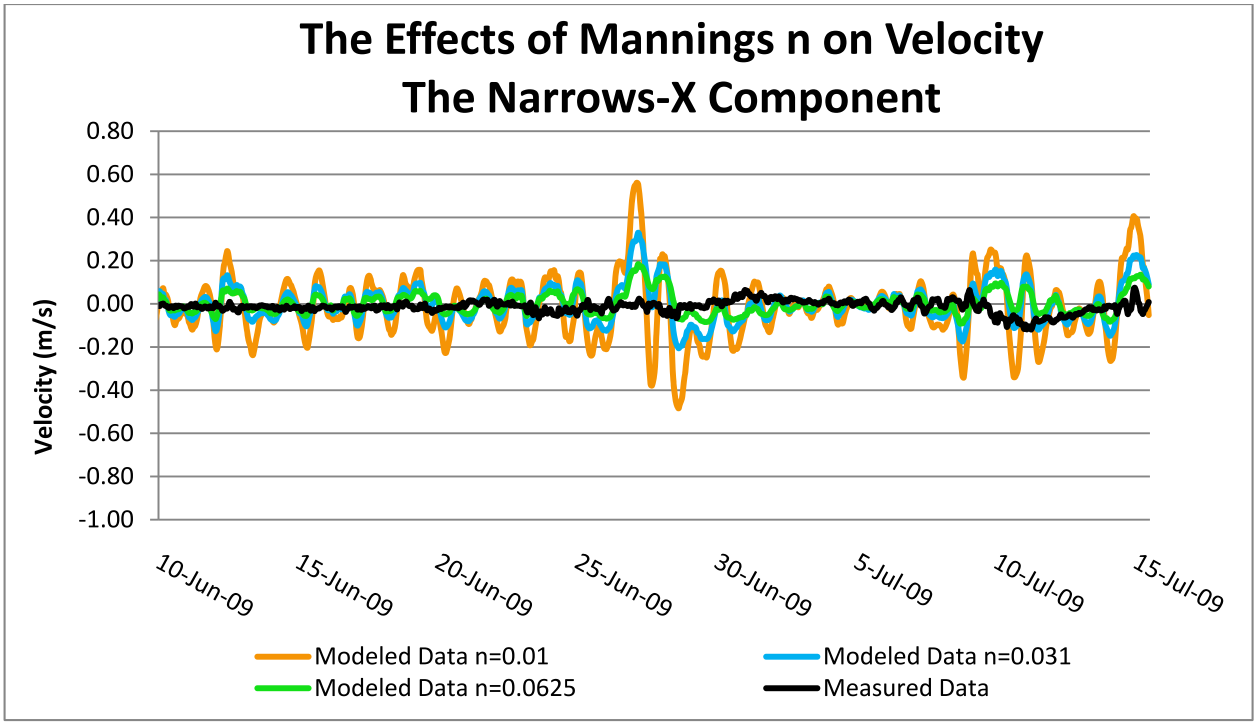

Figure 2.17: Effects of Mannings n on velocity.

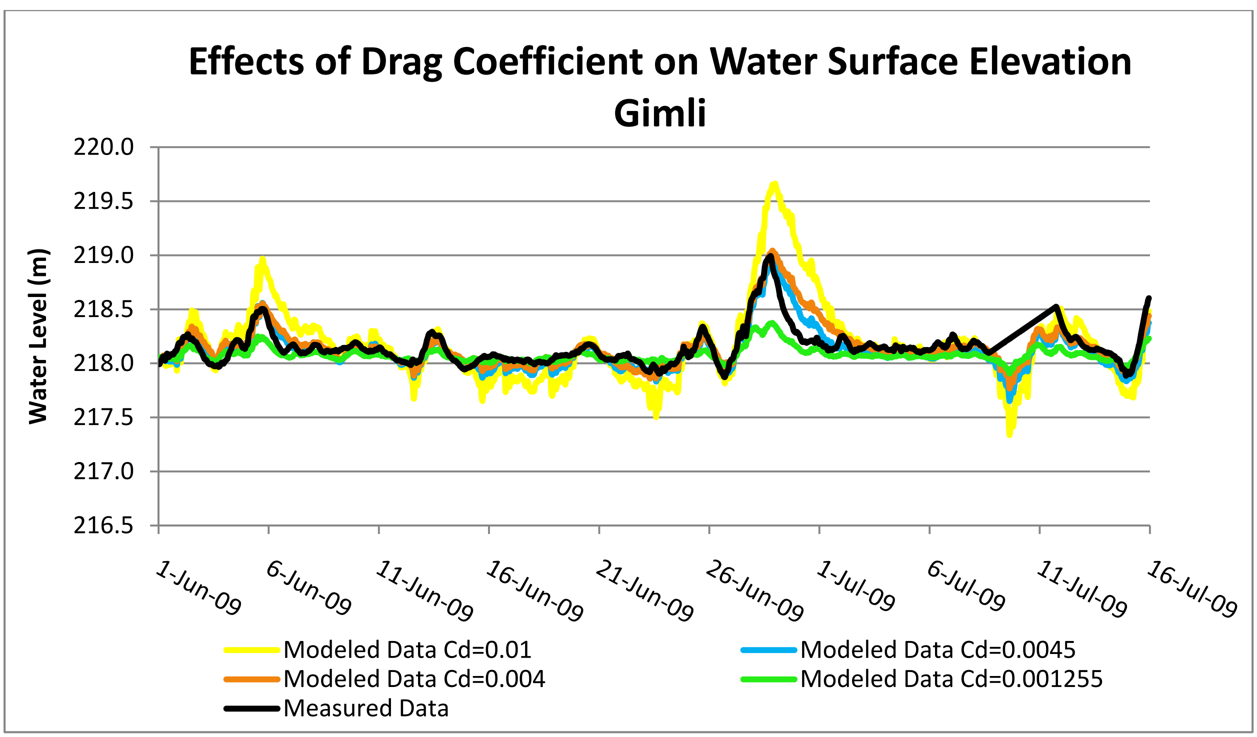

Figure 2.18: Effects of drag coefficient on water surface elevation.

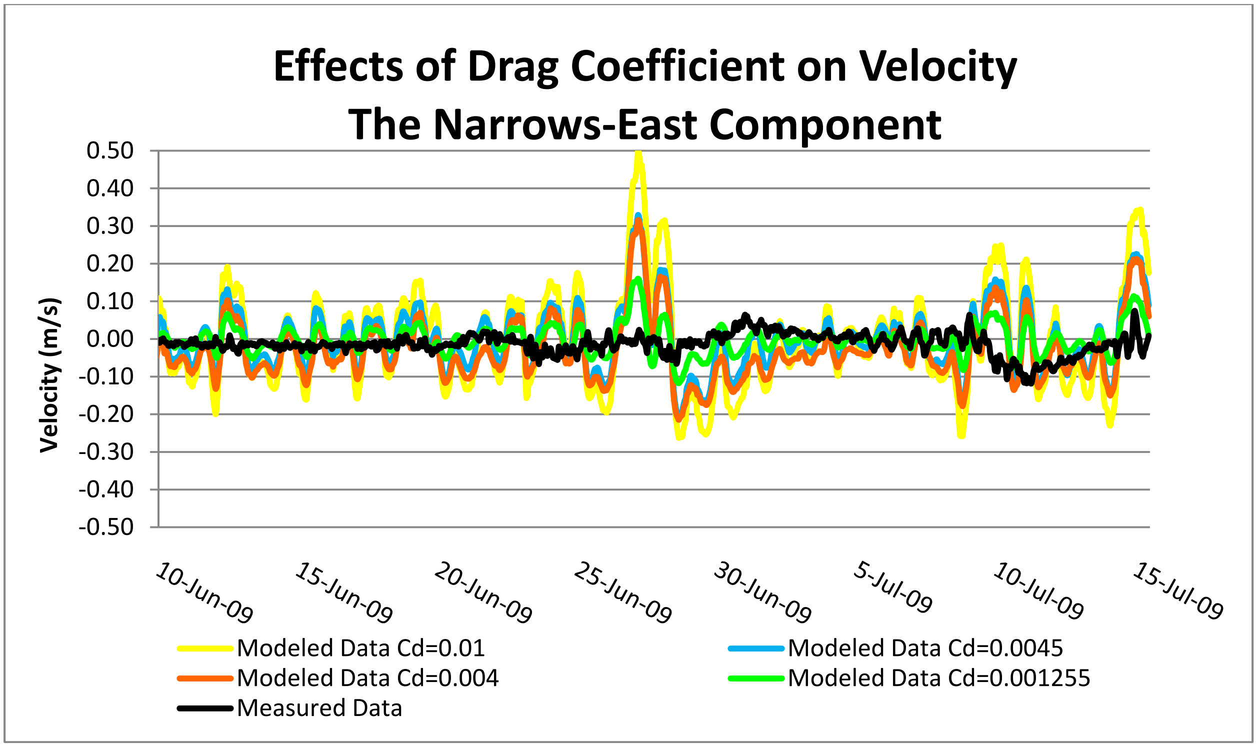

Figure 2.19: Effects of drag coefficient on velocity.

ocean data [4]. In addition, recall that Lake Winnipeg is a shallow lake and as a result, wind stress affects it significantly. Therefore, applying a higher drag coefficient of 0.004 was deemed reasonable. The other simulations shown in this figure were included to show how sensitive the model is to changing this drag coefficient. Again, the same conclusions can be made for the effects of the drag coefficient on velocity, which is shown in Figure 2.19, that were made for the effects of the drag coefficient on water surface elevation.

Finally, Figures 2.20 and 2.21 show the results from a verification simulation at the Mission Point and Victoria Beach locations, which are in the north and south basins of the lake, respectively. This simulation was completed to prove that the model could be run for any time period with any data and still produce accurate results. It is evident from these figures that the model does in fact reproduce accurate results for different time periods and data, as this simulation was run from July 23-August 30 as opposed to June 1-July 15.

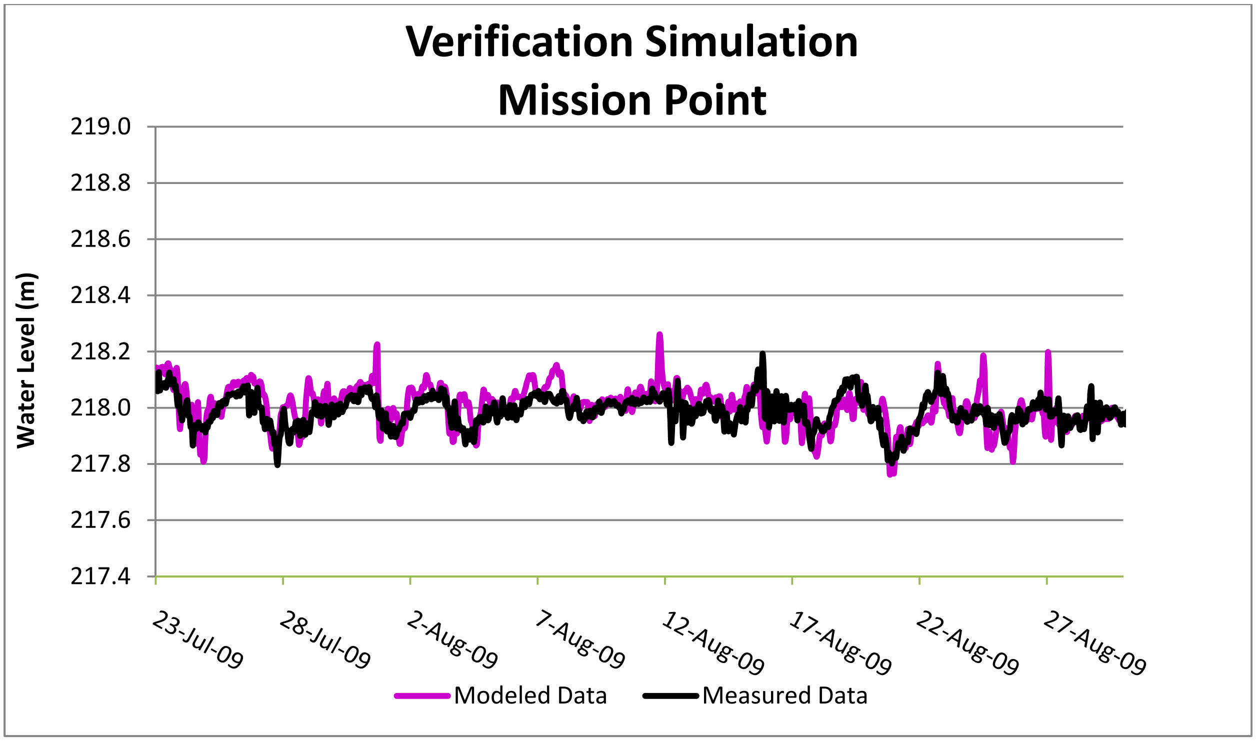

Figure 2.20: Verification simulation results at Mission Point.

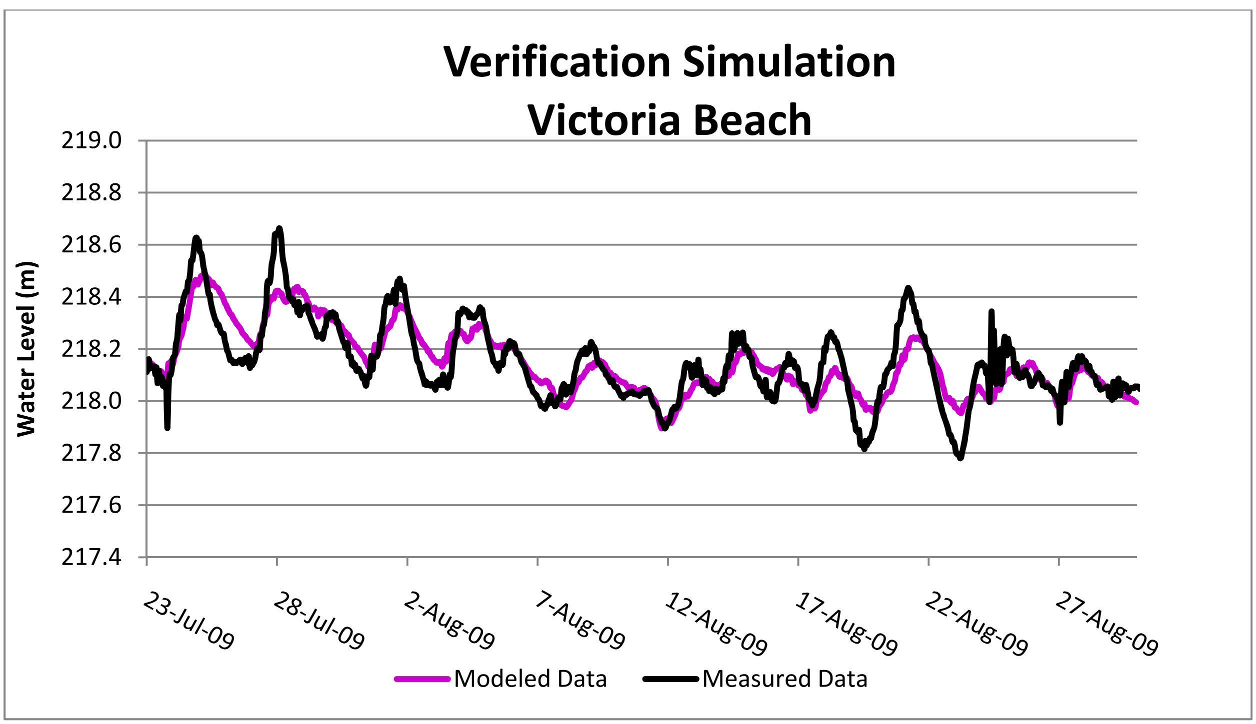

Figure 2.21: Verification simulation results at Victoria Beach.

3. RESULTS

The purpose of this study was to develop a model that would be used to compare various effects from before and after the causeway was built. In particular, this model was used to determine whether there were significant differences between circulation patterns in the south basin of the lake, as well as between discharges through specific channels. Prior to undergoing these investigations the model was used to develop a better understanding of how wind stress affects Lake Winnipeg.

3.1 EFFECTS OF WIND STRESS ON LAKE WINNIPEG

Understanding how wind stress affects the conditions of Lake Winnipeg was an important element of this study. Figures 3.0 and 3.1 illustrate the dramatic effects that wind has on water surface elevation and velocity, respectively. Particularly, these figures present the results from two simulations, one that was performed with wind stress applied to the lake and the other without wind stress applied to the lake. As suspected, the simulation that applied wind stress replicates the measured data quite closely, that is, similar trends can be identified between the two. In contrast, the simulation that did not apply wind stress does not resemble the measured data whatsoever, that is, no similarities can be identified between the two. Consequently, these graphs provide evidence to support the fact that wind stress is responsible for the most prominent changes that can be seen on Lake Winnipeg. These changing conditions include water level and velocity fluctuations, as well as circulation patterns. As such, it is important to closely examine wind effects in order to accurately reproduce or study the conditions of Lake Winnipeg.

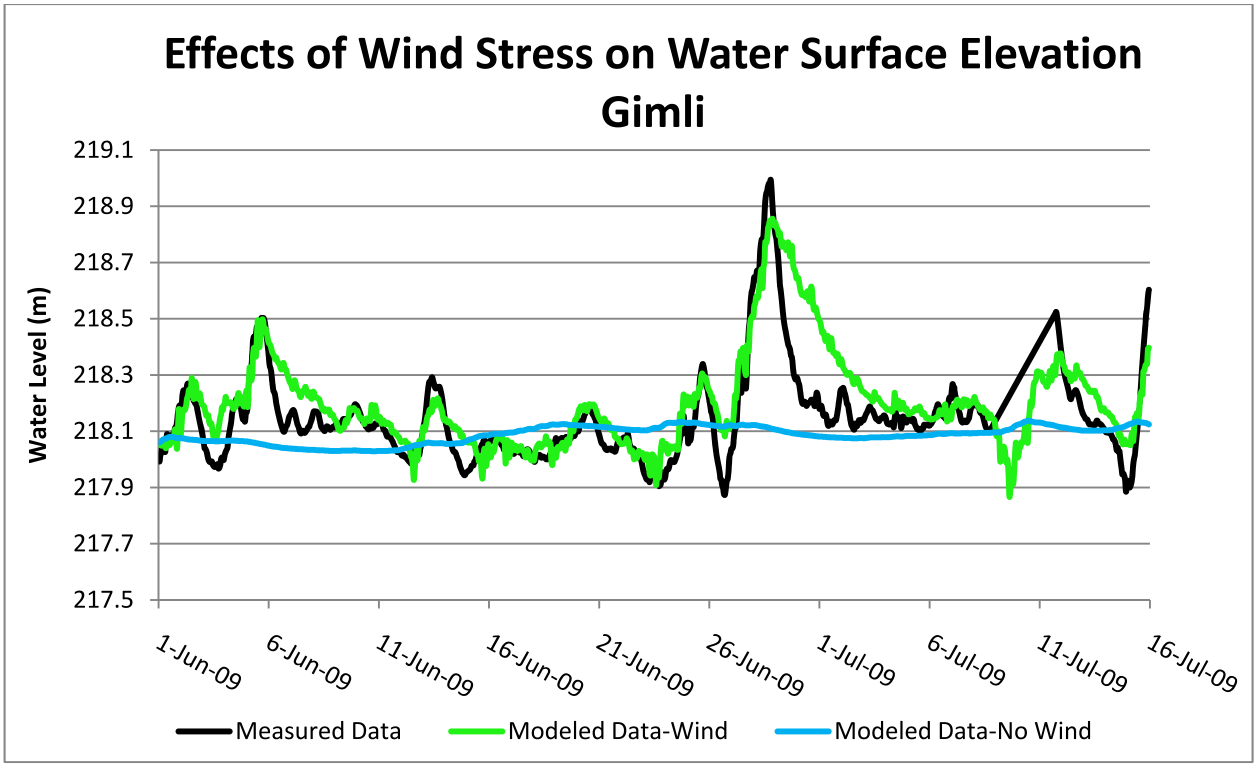

Figure 3.0: Effects of wind stress on water surface elevation.

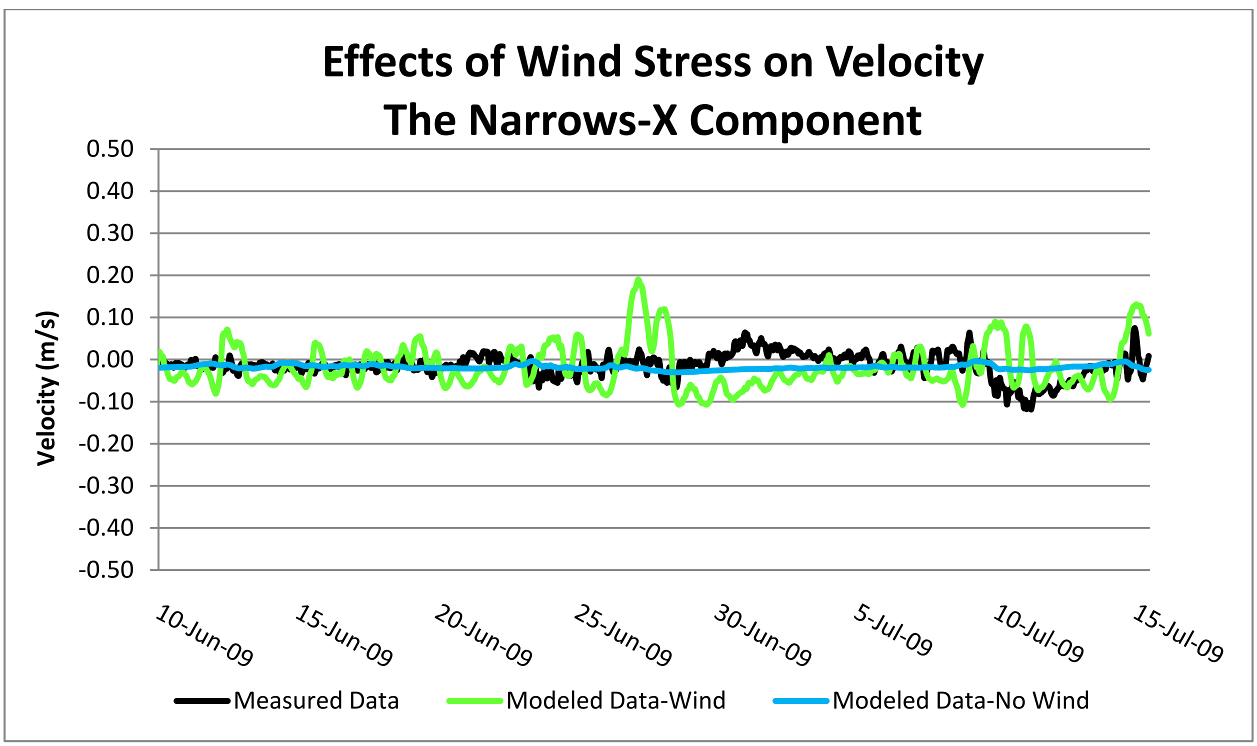

Figure 3.1: Effects of wind stress on velocity.

3.2 EFFECTS OF THE CAUSEWAY ON CIRCULATION PATTERNS

Figures 3.2 and 3.3 show the differences in the circulation patterns of the south basin, on June 23 at 9:00 AM, before and after the causeway was built. After examining these figures it is evident that there are virtually no differences between the two circulation patterns in the south basin, which excludes the Mainland-Hecla channel. Again, Figures 3.4 and 3.5 show the differences in circulation patterns, but on June 30 at 1:00 AM instead of June 23 at 9:00 AM. Once more, there are virtually no differences between the two. These figures confirm that the causeway has had very minimal effects on the flow conditions in the south basin of Lake Winnipeg.

Figures 3.6 and 3.7 are zoomed into the Mainland-Hecla channel, where the causeway has been constructed. Evidently, there are differences between these two figures. First, the causeway is virtually acting as a dam and consequently, has decreased the amount of flow getting through this channel. Secondly, the eddies in the closed mesh are bigger than the eddies in the open mesh. Finally, differences exist between the contours, which represent the current speed in this area. However, these differences are only on the order of 1cm/s and therefore, are not going to significantly impact the conditions in this area. With this being said, effects close to the causeway do seem plausible, but again are still fairly minor.

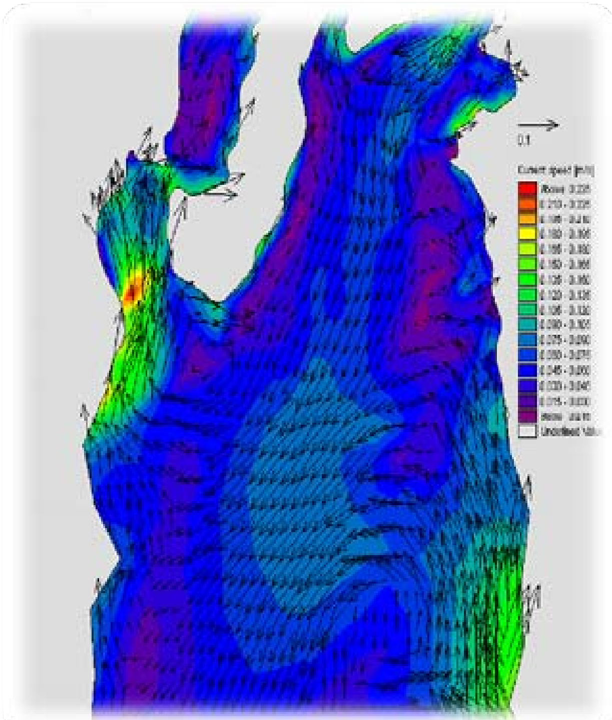

Figure 3.2: Modeled circulation pattern if no causeway had been built-June 23, hour 9.

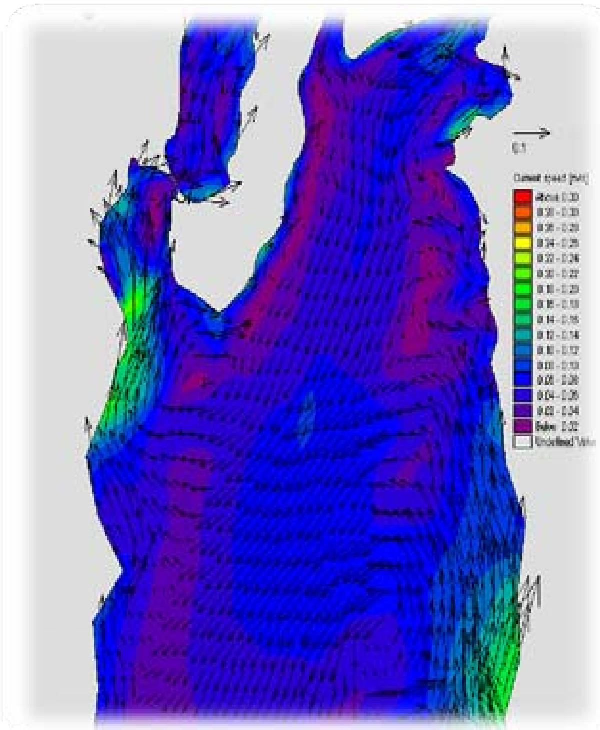

Figure 3.3: Modeled circulation pattern with the constructed causeway-June 23, hour 9.

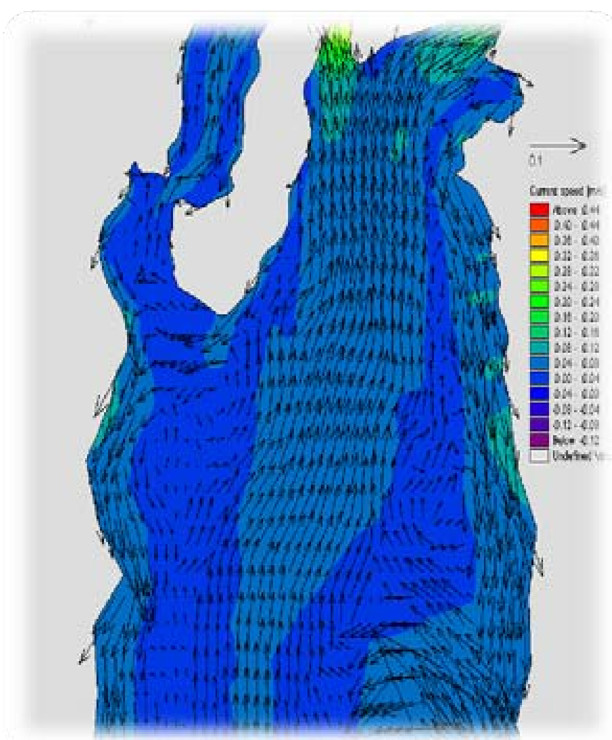

Figure 3.4: Modeled circulation pattern if no causeway had been built-June 30, hour 1.

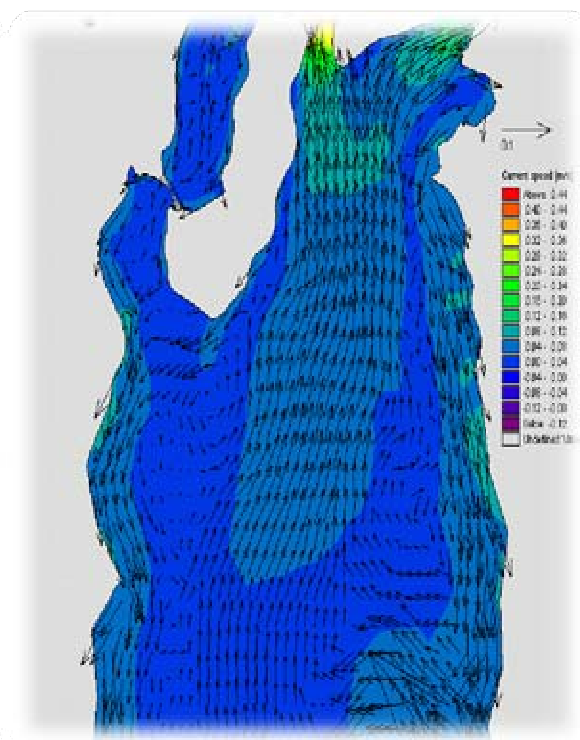

Figure 3.5: Modeled circulation pattern with the constructed causeway-June 30, hour 1.

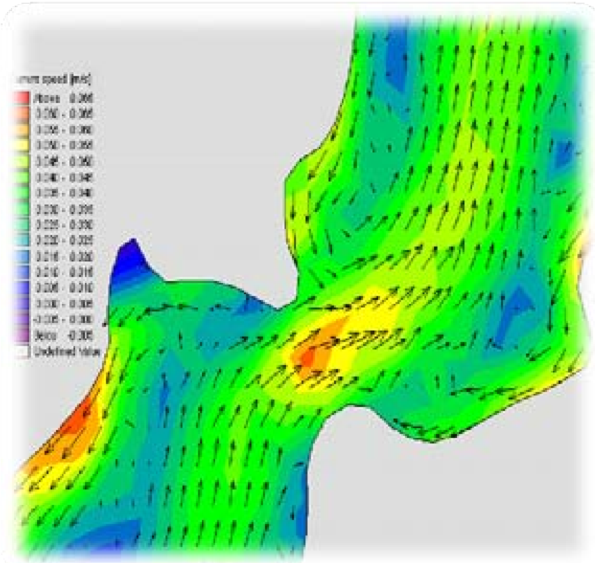

Figure 3.6: Modeled circulation pattern in the Mainland-Hecla channel if no causeway had been built-June 30, hour 1.

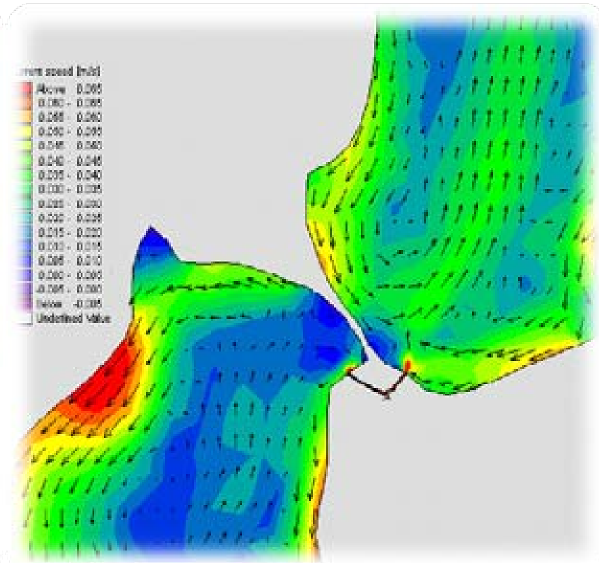

Figure 3.7: Modeled circulation pattern in the Mainland-Hecla channel with the constructed causeway-June 30, hour 1.

3.3 EFFECTS OF THE CAUSEWAY ON DISCHARGE

The differences in discharge through the Narrows, Mainland-Hecla, Hecla-Black and Black-Mainland channels were examined in this study. The locations of these channels are presented in Figure 3.8. Recall that this study was motivated by a theory that the Hecla Island causeway blocks one third of the flow in Lake Winnipeg from travelling from the south basin into the north basin. If this was the case then the flow through the Narrows would decrease by one third. With this in mind, investigating Figure 3.9 reveals that only slight differences can be distinguished between the discharge through the Narrows before and after the causeway was constructed. Had the theory been true, the magnitude of the discharge produced after the causeway was built would have been decreased by one third. Evidently, this is not the case, as it can be seen that the flow through the Narrows from both before and after the causeway was constructed are very similar, specifically, the flow has not decreased by one third.

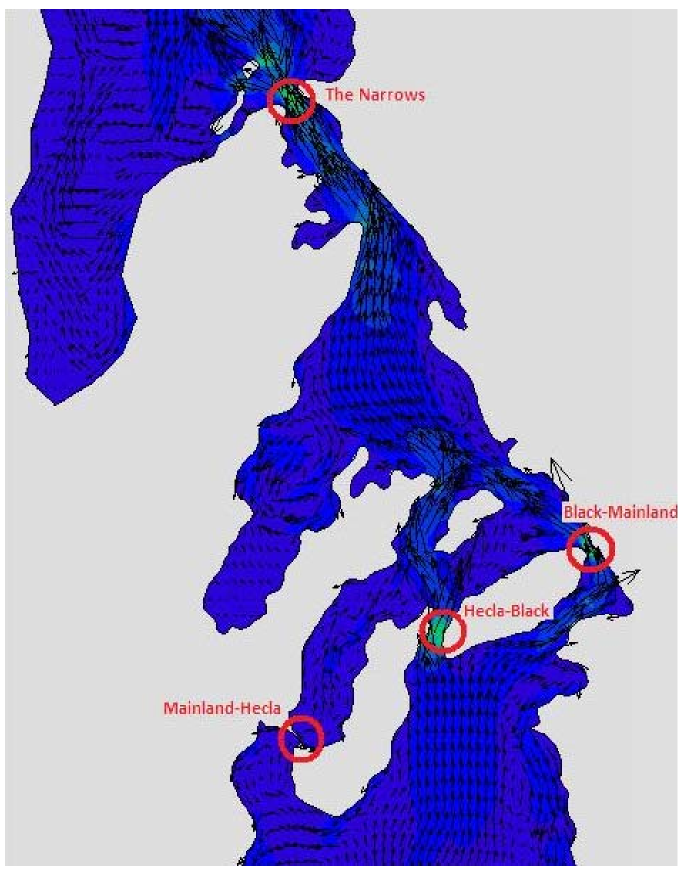

Figure 3.8: Locations of channels where discharge was examined.

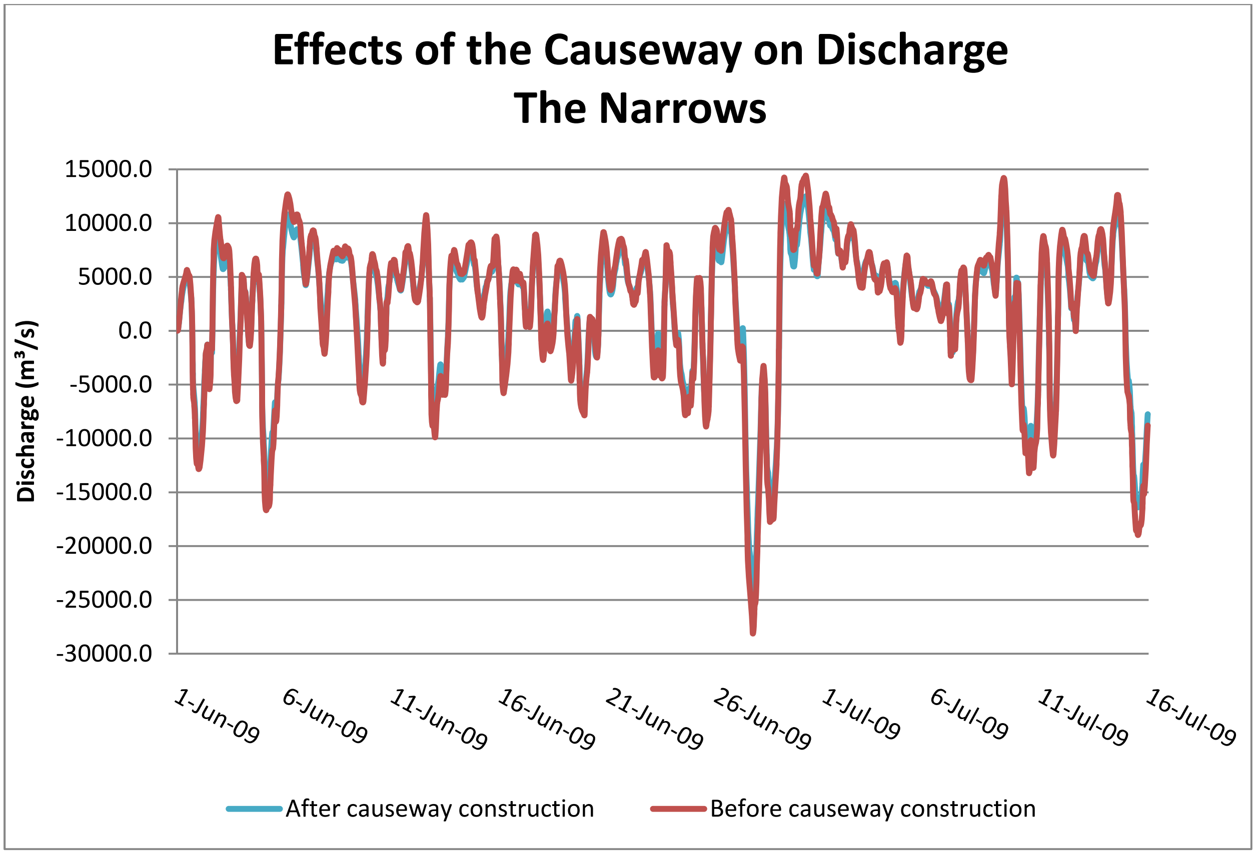

Figure 3.9: Effects of the causeway on discharge through the Narrows.

It can be seen from Table 3.0 that the average flow through the Narrows remains virtually unchanged whether the causeway is in place or not. The reasoning behind this can be noted from Figure 3.9, which shows that the flows before the causeway was constructed are more variable than the flows after the causeway was constructed. In other words, they are slightly higher in magnitude, both when water is flowing into and out of the south basin of the lake. Consequently, the average flows are very similar in both cases. However, Table 3.0 also shows that the standard deviation for the scenario with no causeway is notably higher than for the case after the causeway was constructed. What this means is that the causeway has a moderate damping effect on the flow through the Narrows. Specifically, the average does not change significantly, but the causeway seems to decrease the peak flows in either direction through the Narrows. This proves that the theory, which suggests that the flow from the south basin into the north basin of Lake Winnipeg has decreased by approximately 33%, is an over estimation.

Narrows-Open		Narrows-Closed		Difference		
						%
Average Flow (m^3/s)	2,221	Average Flow (m^3/s)	2,236	Average Flow (m^3/s)	15	0.67
Standard Deviation	7,295	Standard Deviation	6,400	Standard Deviation	-895	-12.3

Table 3.0: Comparisons of discharge through the Narrows before and after the causeway was built.

Similar differences, with respect to the decrease in discharge, can be noted for the Hecla-Black and Black-Mainland channels, which are shown in Figures 3.10 and 3.11, respectively. Conversely, the differences in discharges through the Mainland-Hecla channel, which can be observed in Figure 3.12, are more significant than through the previous channels that have been discussed. For instance, with the causeway in place the maximum amount of flow that gets through the Mainland-Hecla channel is approximately 100m^3/s. Without the causeway in place the maximum amount of flow that gets through the Mainland-Hecla channel is approximately 3200m^3/s, which is a noteworthy difference.

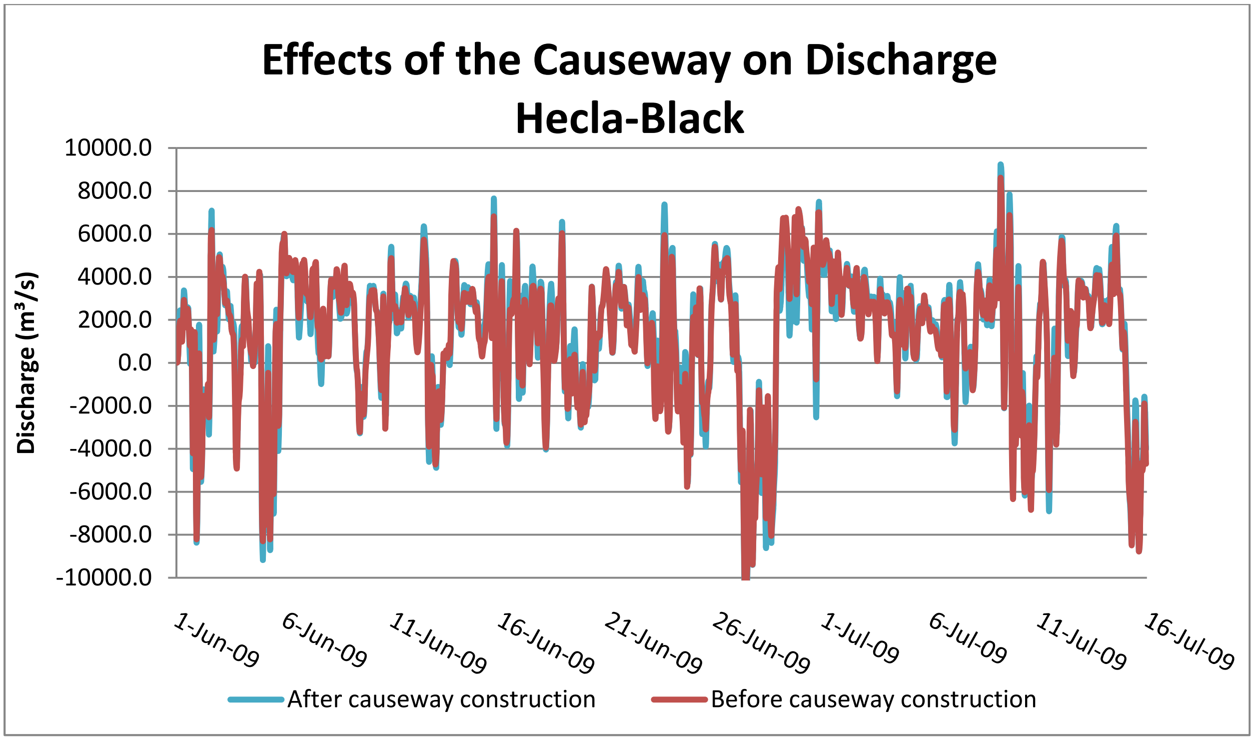

Figure 3.10: Effects of the causeway on discharge through the Hecla-Black channel.

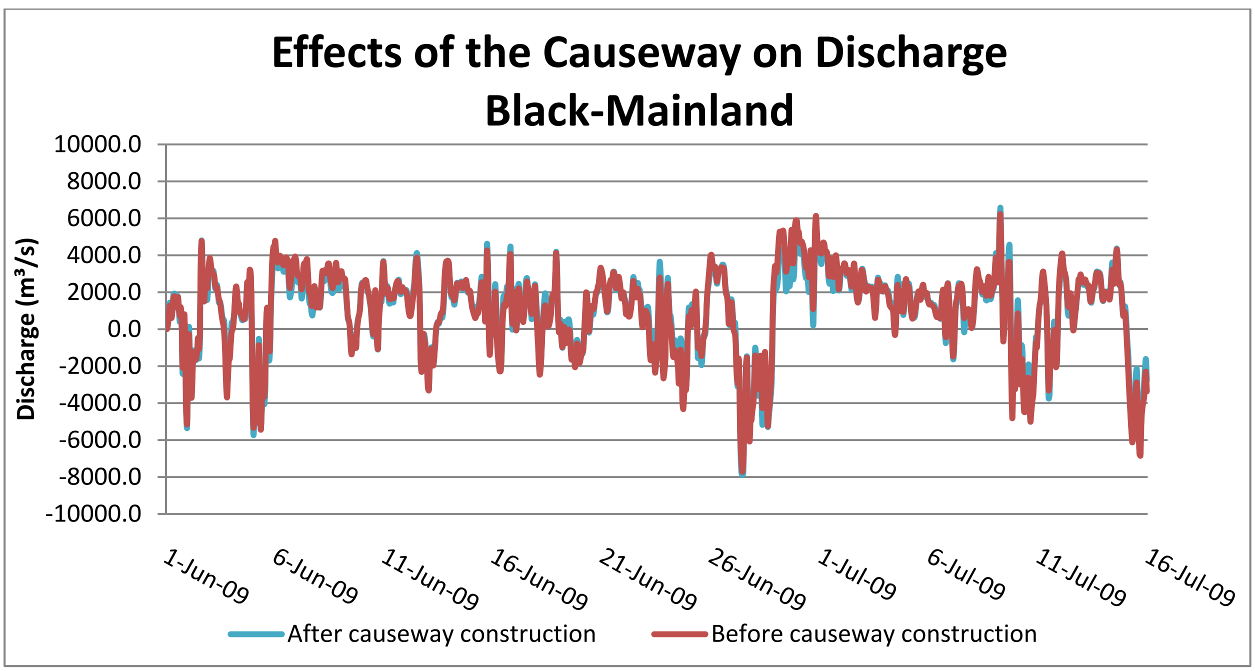

Figure 3.11: Effects of the causeway on discharge through the Black-Mainland channel.

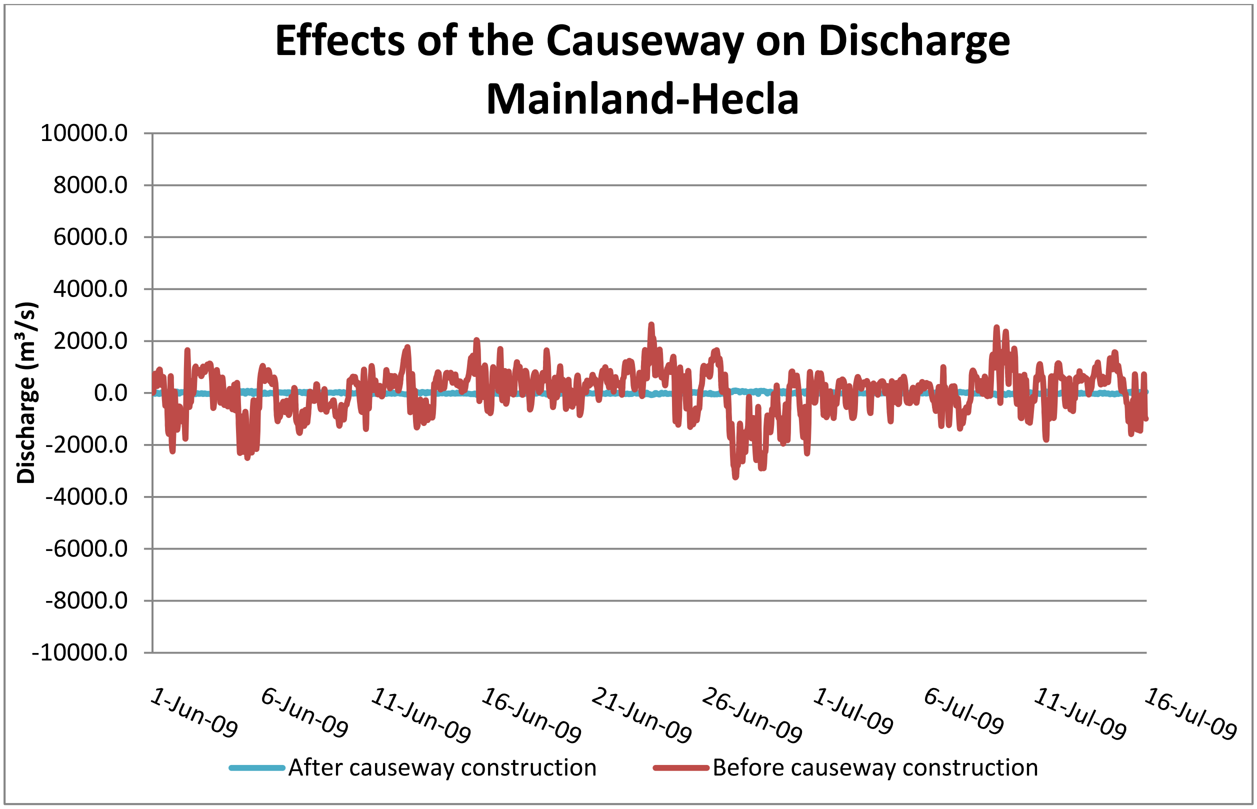

Figure 3.12: Effects of the causeway on discharge through the Mainland-Hecla channel.

Table 3.1 has been included to demonstrate the effects that the causeway has on discharge through the Mainland-Hecla channel, more precisely. In particular, Table 3.1 provides a rough estimate of the percentage of total flow that travels through each of the three channels in the south basin before and after the construction of the causeway. In addition, Table 3.1 tabulates the percentage by which the flows have increased or decreased due to the implementation of the causeway. In essence, the implementation of the causeway changes the distribution of flows through these three channels. Without the causeway constructed, 12.1% of the total flow in the south basin passes through the Mainland-Hecla channel, whereas post-construction of the causeway only 0.5% of the total flow in the south basin passes through this channel. This results in a decrease of 11.6% of the total flow in the south basin passing though the Mainland-Hecla channel. Keep in mind that 11.6% is being compared to 12.1% of the total flow that is travelling through the Mainland-Hecla channel and therefore, the change is quite significant. Another way to communicate this point would be to isolate the Mainland-Hecla channel by stating that the total amount of flow passing through this channel decreases by approximately 95% when the causeway is in place. Either way, it is evident that the flow decreases in the Mainland-Hecla channel and increases in the Hecla-Black and Black-Mainland channels. Therefore, it is reasonable to believe that the Hecla-Black and Black-Mainland channels will not be significantly impacted by an increase in flow of less than 8%. Conversely, minor effects close to the causeway do seem plausible.

Open		Closed		Difference	
	% Total Flow		% Total Flow		% Total Flow
Mainland-Hecla	12.1	Mainland-Hecla	0.5	Mainland-Hecla	-11.6
Helca-Black	49.9	Helca-Black	57.8	Helca-Black	7.9
Black-Mainland	38	Black-Mainland	41.7	Black-Mainland	3.7

Table 3.1: Comparison of the percentage of total flow that travels through each of the channels in the south basin of the lake, before and after the causeway was built.

4. CONCLUSION

Some Manitoba residents developed a theory suggesting that the Hecla Island causeway was responsible for several problems that plague Lake Winnipeg. In particular, these individuals suggested that the causeway was preventing one third of the flow from moving between the lake's north and south basins. More specifically, these same residents proposed that these changed flow conditions were also responsible for the increase in eroded shorelines and algae that have accumulated in the surrounding area.

The health of Lake Winnipeg has been a growing concern for many years and it is evident that a solution to the lake's woes must be considered. Therefore, the unease of these Manitoba residents with regards to the Hecla Island causeway had to be seriously considered and investigated before the proposed problem could be dismissed. Accordingly, this study served to investigate the flow patterns of Lake Winnipeg before and after the Hecla Island causeway was constructed in order to deem whether the proposed theory could in fact be true.

Various simulations were produced to accurately replicate the conditions that Lake Winnipeg would encounter before and after the causeway was implemented. Based on the analysis of these simulations the conclusions that have been established from this study are as follows:

- The currents and fluctuations that can be seen on Lake Winnipeg are caused primarily by wind stress applied to the lake.
- Blocking the Mainland-Hecla channel with the causeway seems to have a minor effect on the overall hydrodynamics of the south basin. Consequently, it is implausible to believe the causeway is responsible for effects of erosion and algae throughout the entire south basin.
- Effects close to the causeway do seem more plausible and therefore, the causeway may potentially be responsible for changed conditions in the surrounding area.

Further investigation of other important issues related to the theory regarding the Hecla Island causeway should be considered. For example, additional research is required to determine how changes in flow patterns around the causeway may be affecting the conditions of the surrounding area including, the increase in algae and the increased erosion in this area.

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