HYDRODYNAMIC AND MORPHOLOGIC MODELING OF ALTERNATIVE DESIGN SCENARIOS FOR SHIPPAGAN GULLY, NEW BRUNSWICK CANADA

Mitchel Provan[1], Ioan Nistor[2], Andrew Cornett[3] and Alain Drouin[4]

This paper describes a comprehensive study comprising field measurements and numerical modeling of hydrodynamic and sedimentary processes undertaken to help assess alternative engineering measures for promoting and maintaining a stable and safe navigation channel through a dynamic tidal inlet. Shippagan Gully is a dynamic tidal inlet located on the Gulf of St-Lawrence near Le Goulet, New Brunswick, Canada. The tidal lagoon transects the Acadian Peninsula, hence the flows through the inlet are controlled by the tidal phase lag between the two open boundaries. Due to the nature of this phase lag, the ebb flows through Shippagan Gully, which regularly exceed 2 m/s, are typically twice as strong as the flood flows. As a consequence of this imbalance, the hydrodynamic and sedimentary processes at the inlet, and the morphologic features produced by these processes, are strongly dominated by the ebb flows. Over the past decades, shipping activities through Shippagan Gully have been threatened due to sediment deposition along the east side of the inlet which has caused the channel to narrow and shift westward. The objective of the present study was to develop an improved numerical model of the hydrodynamic and sedimentary processes at Shippahan Gully, and then apply the model to assess different engineering interventions for stabilizing the inlet and improving navigation safety.

INTRODUCTION

Shippagan Gully is a narrow channel at the mouth of a dynamic tidal inlet located on the Gulf of Saint Lawrence near the Le Goulet village, New Brunswick, Canada (see **Error! Reference source not found.**). It is a particularly interesting and complex tidal inlet due to the fact that its tidal lagoon bisects the Acadian Peninsula and is open to the sea at two locations which generate an appreciable phase-lag in the tidal cycle. Due to the nature of this phase lag in tidal forcing, the ebb flows through Shippagan Gully, which can exceed 2 m/s, are roughly twice as strong as the flood stage velocities. As a consequence of this imbalance, the hydrodynamic and sedimentary processes at the inlet, and the morphological features produced by these processes, are strongly dominated by the ebb flows. Due to the ebb flow domination, this inlet cannot be classified or analyzed using traditional methods such as Escoffier curve analysis (Escoffier, 1940, 1977) or the tidal prism analysis (O'Brian, 1931). The tides at Shippagan Gully are semi-diurnal, and the tidal range is generally on the order of 2m or less.

For many years Shippagan Gully has served as an important navigation route, providing boaters from communities in the Acadian Peninsula and the Bay des Chaleurs with direct access to the open waters of the Gulf of St-Lawrence. The fishing industry, a very important element of the local economy, relies on safe navigation through the inlet. However, over the last few decades, significant volumes of sediment have accumulated within the inlet due to natural processes. These accumulations have constricted the navigation channel, making it more difficult and riskier for fishing vessels to pass safely through the inlet on their way to and from the Gulf of St-Lawrence. Many of the larger vessels which once relied on the inlet for safe and sheltered passage can no longer safely navigate the constructed channel. These vessels must now circumnavigate the Acadian Peninsula, thus considerably lengthening their journey and forcing passage through the rough waters off Miscou Point.

[1] Graduate Student, Civil Engineering, University of Ottawa, 161 Louis Pasteur St. CBY A115, Ottawa, Ontario, K1N 6N5, Canada

[2] Associate Professor, Civil Engineering, University of Ottawa, 161 Louis Pasteur St. CBY A115, Ottawa, Ontario K1N 6N5, Canada

[3] Program Leader, Marine Infrastructure, Energy & Water Resources, National Research Council Canada, 1200 Montreal Rd M-32, Ottawa, Ontario K1A 0R6, Canada

[4] Engineer, Public Works & Government Services Canada, 1550 d'Estimauville Avenue, Quebec City, Quebec, G1J 0C7, Canada

Figure 1. Geographical location of the Shippagan Gully inlet and of the Acadian Peninsula near Le Goulet, New Brunswick (navigation route through the Acadian Peninsula shown in red). (Good Earth, 2013).

The nearshore wave climate at the site features significant wave heights ranging from 0.5 up to ~4m, and peak wave periods from 3 to 11s. The historical evolution of the inlet provides clear evidence of a wave-driven net longshore sediment transport flowing from NE to SW. This is consistent with the fact that the local wave climate is dominated by waves approaching from easterly direction. Waves also approach the site from the south and southeast, but waves from these directions tend to occur less frequently and/or tend to be less energetic.

Shippagan Gully has been maintained by man-made coastal structures since the late 1800's in an effort to stabilize its position and promote its navigability. In 1882, two 300m long jetties were initially constructed on either side of the inlet mouth. Engineering drawings dating from the late 19th century show periodic extensions of the east jetty, as sediment accumulated on its east face and ultimately passed around its seaward limit and into the inlet. Throughout the mid-20th century, several engineering works were completed at Shippagan Gully, most notably during the 1960's and 1970's. A new jetty was constructed on the east side of the inlet near the inlet mouth (see **Error! Reference source not found.**). This new structure was built on the west side of the older eastern jetty, its angle differing such that it was nearly parallel to the shoreline. The second major coastal works undertaken in the 1960's and 1970's was the two phases construction of a 600m long curved, vertical sheet pile training wall within the inlet (also seen in **Error! Reference source not found.**). As a result of this new construction, a sheltered small craft harbour was formed between the west jetty and curved training wall.
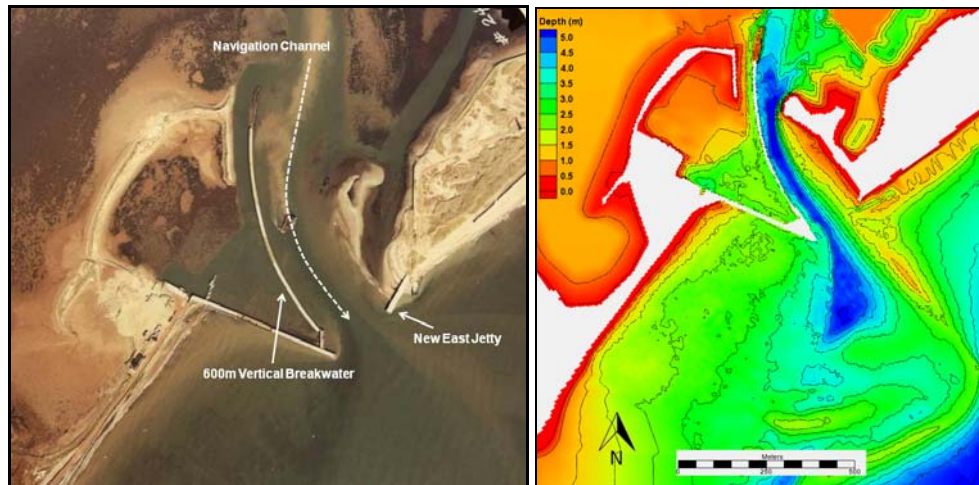
Figure 2. Aerial photograph (1980) showing coastal works completed in late 1960's and early 1970's (left) and interpolated 2010 bathymetry of Shippagan Gully inlet and ebb shoal region (right).

No significant coastal works have been undertaken at Shippagan Gully since the 1970's. As such, natural morphologic processes have taken hold of the inlet over the past 30 years, resulting in its present state. Sediment continues to be deposited along the eastern side of the navigation channel causing the navigation channel to migrate westwards, towards the training wall. At present, the navigation channel is less than 75m wide at its narrowest point, where it is constricted by a large sand spit that has formed along the eastern side of the inlet mouth, as shown in the interpolated bathymetry in **Error! Reference source not found.** (right). Furthermore, navigable depths in the offshore region are highly variable and often dangerously low due to the presence of a high dynamic crescentric ebb shoal, which is curved towards the SW direction.

In 2010, Public Works and Government Services Canada (PWGSC), acting for Fisheries and Oceans Canada (DFO), commissioned the National Research Council (NRC) to develop a numerical model to assess the current and potential future evolution of coastal processes at Shippagan Gully. The methods and results of this initial study are described in Logan *et al.*, 2012. In 2012, NRC was again retained by PWGSC to conduct further in-depth numerical simulations of the coastal processes at Shippagan Gully and help assess engineering solutions to mitigate the sedimentation problem and to ensure a safer and adequate navigation channel. The main objectives of this current study are (1) to improve the resolution and precision of the numerical model using new features in the CMS numerical model (Buttloph et. al., 2006; Lin et. al., 2011; Reed et. al., 2011; We et. al., 2011) and (2) use the improved model to estimate the future hydrodynamic and morphology changes at Shippagan Gully for a number of inlet configurations in relation to the *status-quo* as well as the deployment of several engineering solutions.

FIELD INVESTIGATION

Several field investigation campaigns have been conducted at Shippagan Gully to collect data used to calibrate and validate the numerical model. Velocity measurements were obtained from the site in August 2010 and again in June 2012. The August 2010 measurements were recorded throughout the inlet using an Electromagnetic Current Meter (ECM) suspended from a motor boat and measurement positions were recorded using a global positioning system (GPS). Additional velocity data was collected using an Acoustic Doppler Current Profiler (ADCP) in June 2012. The ADCP instrument was suspended from a boat that moved slowly across the water surface and the boat position was recorded using a GPS within the ADCP instrument. The ADCP measurements were processed such that they could be used to validate the numerical model. The data processing included computing a series of depth-averaged and spatially averaged velocity vectors.

Twenty-one sediment samples were collected and analyzed during three separate field investigations at Shippagan Gully. The first set of sediment samples was collected during the site visit in August 2010, during which various samples were taken from the beaches located NE and SW of the inlet and on the beach located along the east side of the inlet. A second set of sediment samples was collected during a

site visit in June 2012. During this site visit, additional sediment samples were taken from the beach located NE of the inlet, within the inlet (along the eastern beach) and at the reattachment point on the beach located SW of the inlet. The third and final set of sediment samples was collected from the seabed in 10 different locations within the inlet and on the ebb shoal area. The beaches NE and SW of the inlet are comprised of non-cohesive sediments with D_{50} ranging from 0.17 up to ~18mm. The field data suggests that the ebb shoal contains a wide range of sands and fine gravels, with grain sizes ranging from 0.15 to ~10mm. Within the inlet mouth, where peak velocities regularly exceed 2m/s, the navigation channel is armoured with a blend of coarse sand and gravel with particle sizes ranging from 1mm up to 85mm.

Over the past several decades, PWGSC has conducted annual hydrographic surveys of this navigation channel. Collected survey data typically had a horizontal resolution of ~1m and covered the navigation channel from the bridge located at the NW edge of the tidal lagoon and extending offshore of the entrance in the Shippagan Gully, including a portion of the ebb shoal. This bathymetric data was used to prepare the bathymetric map along the navigation channel and quantify the changes in bathymetry over various periods of time.

NUMERICAL MODEL SETUP

CMS-Model and Computational Domain

The Coastal Modelling System (CMS) is an integrated suite of numerical models developed by the Coastal Inlets Research Program (CIRP) of the United States Army Corps of Engineers (USACE) for simulating flow, waves, sediment transport, and morphology change in coastal areas (Sanchez et al., 2012). The system is specifically designed for practical applications related to navigation channel performance and sediment management for coastal inlets and adjacent beaches. CMS is composed of two different models: (1) a model which calculates hydrodynamics and sediment transport (CMS-Flow) and (2) a wave model (CMS-Wave). Both models operate on a rectangular finite difference grid with variable grid spacing, such that areas of interest can be modeled at a high resolution without significantly sacrificing computation time.

CMS-Flow is a coupled hydrodynamic and sediment transport model capable of simulating depth-averaged circulation, salinity and sediment transport due to tides, wind and waves. The hydrodynamic model solves the conservative form of the shallow water equations and includes terms for the Coriolis force, wind stress, wave stress, bottom stress, vegetation flow drag, bottom friction and turbulent diffusion. The CMS-Flow model domain for this study, shown in Figure 3, covers the entire tidal lagoon, up to the bridge at Shippagan and extends approximately 3km in the offshore direction, out to a depth of ~12m. In the longshore direction the CMS-Flow grid covers a stretch of coastline 6km in length with Shippagan Gully at its centre, providing ample shoreline to either side of the inlet for the investigation of longshore sediment transport.
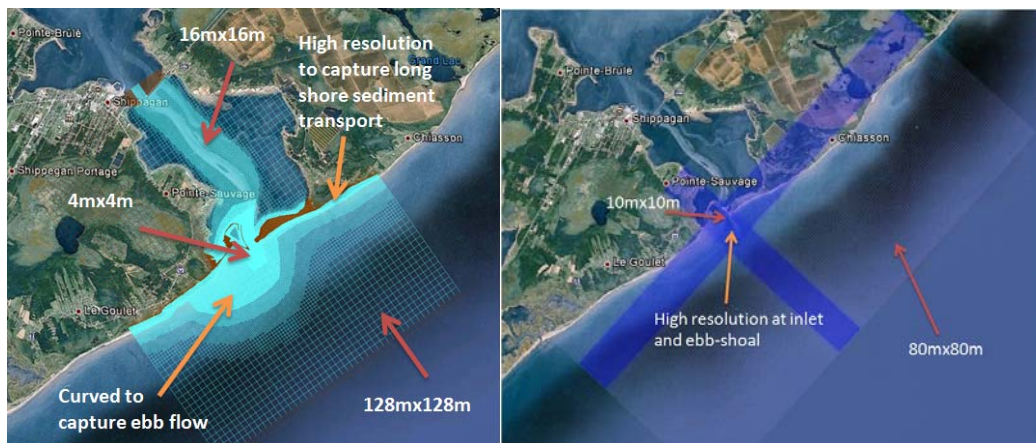

Figure 3. CMS-Flow computational grid (left) and CMS-Wave computational grid (right).

The model domain has three boundaries where water level fluctuations are prescribed: the northwest limit of the tidal lagoon, the northeast longshore limit and the southwest longshore limit. The offshore (southeast) boundary of the numerical model was set as a closed boundary in order to force the currents to travel in the longshore direction. This re-created the existing longshore tidal current in the Gulf of St-Lawrence. **Error! Reference source not found.** shows the computational grid for the CMS-Flow model that was developed for this study. The grid consists of approximately 120,000 computational cells and utilizes the telescoping grid option to produce a high resolution (4mx4m) grid around the inlet, while maintaining a lower resolution (128mx128m) offshore of the inlet.

CMS-Wave is a spectral wave transformation model that solves the steady-state wave-action balance equation on a non-uniform Cartesian grid. It considers wind wave generation and growth, diffraction, reflection, dissipation due to bottom friction, whitecapping and breaking, wave-wave and wave-current interactions, wave run-up, wave setup and wave transmission through structures (Lin et al., 2008). The CMS-Wave grid developed for this study contains approximately 72,000 computational cells and is shown in **Error! Reference source not found.**. The grid describes a numerical domain that extends approximately 5km in the offshore direction and 2km inside of the lagoon. The offshore boundary of the CMS-Wave domain included the location where information on the local wave climate was known; specifically, a node from the MSC50 wave hindcast developed by Environment Canada (Swail et al., 2006). The domain includes approximately 14km of coastline, stretching from a point 6km southwest of the inlet to a point 8km northeast of the inlet. The cell sizes vary from 80mx80m at the offshore boundary to 10mx10m over the ebb shoal and within the inlet.

Model Boundary Conditions
Measured water level data was sparsely available near Shippagan Gully. However, a tidal prediction model for the Gulf of St-Lawrence is maintained by the Canadian Hydrographic Services (CHS) which provided tidal constituents at a 5km grid spacing throughout the entire St-Lawrence estuary. A regional tidal model was developed based on the TELEMAC modelling system (Hervouet et al., 2000). Using 30 tidal constituents provided by the CHS, a full year of water level fluctuations was generated along each of the three above mentioned TELEMAC model boundaries. The TELEMAC model was then used to obtain corresponding water level fluctuations at the locations of the three CMS-Flow model boundaries.

Information on the wave climate at the site was developed from analysis of the MSC50 Atlantic Wave Hindcast produced by Environment Canada (Swail et al., 2006). The MSC50 hindcast provides hourly estimates of wave height, period and direction across the entire Gulf of St-Lawrence with a 0.1° resolution over a 54-year period from 1954 to 2008. The hindcast has previously been successfully calibrated and validated against available buoy data. Data for a MSC50 hindcast grid point located 5km offshore the inlet in a water depth of 16m was analyzed to define the local wave climate. The wave conditions were separated into 30° directional bins and the peak over threshold method was employed to establish extreme wave conditions for each bin, associated with various return periods from 1 to 25 years. From this analysis, it was found that significant wave heights near Shippagan Gully rarely exceed 3m and peak wave periods rarely exceed 12s. As shown in **Error! Reference source not found.**, the wave climate is dominated by waves approaching from the east (ESE to ENE); however, waves approaching from the south are also common.
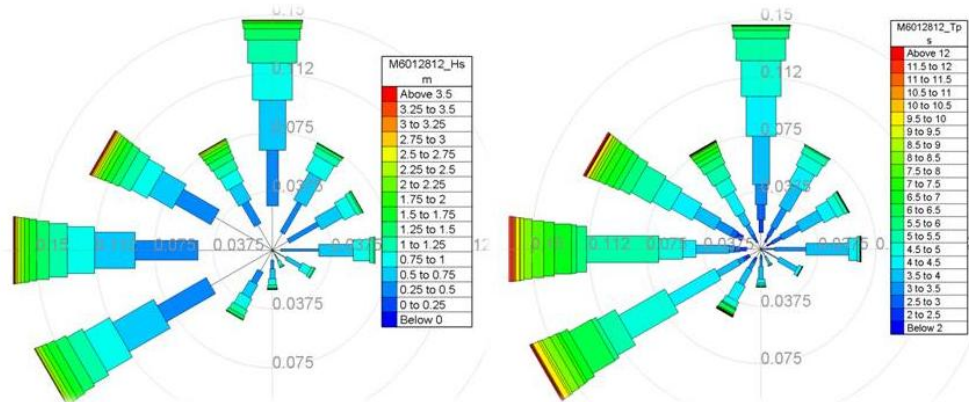
Figure 4. Significant wave height rose (left) and peak wave period rose (right) at a location 5km offshore for Shippagan Gully.

MODEL CALIBRATION AND VALIDATION

The CMS-Flow model required calibration and validation to ensure that it provided fairly realistic simulation of the flows and morphologic trends at Shippagan Gully. The model calibration and validation was split into two separate tasks: to capture the hydrodynamic features and to simulate the morphology changes. The hydrodynamic calibration was performed such that the model replicated with good precision the flow conditions (water levels and current speeds) observed during a field investigation conducted in August 2010. The calibration involved making adjustments to the bottom friction factor used in different regions of the computational domain to minimize the overall differences between the model's predictions and the velocities observed during the site visits. The accuracy of the model predictions was quantified using the root mean square error (RMS). The RMS error for the best performing calibration run was 0.209 m/s. Following the successful calibration of the hydrodynamic features, a validation procedure was conducted to verify whether the model was able to correctly predict flow velocities for other periods of time. The validation used ADCP velocity measurements collected on June 14, 2012. The CMS-Flow model was configured with 2012 bathymetry and was forced using estimated boundary conditions from June 13, 2012 to June 15, 2012. As with the calibration, an RMS error statistic was calculated for the hydrodynamic validation by comparing measured velocities to the modeled velocities. The average RMS error was 0.157 m/s for the hydrodynamic validation of the CMS-Flow model. This error was deemed acceptable, given that the errors are similar to those obtained during the hydrodynamic calibration.

After completing the hydrodynamic calibration and validation, a morphologic calibration was also completed to ensure that the numerical model was capable of reproducing the morphologic trends at Shippagan Gully. A time period of 2004-2006 was chosen for the morphologic calibration and the period of 2004-2010 was chosen for the validation. The calibration was completed by iteratively adjusting the sediment transport scaling parameters and adjusting the spatial distribution of the initial sediment grain size until a satisfactory match was obtained between the measured morphology change and modeled morphology change for the period between 2004 and 2006. The optimized initial D_{50} map, shown in **Error! Reference source not found.**a, consists of areas of coarse sediment sizes (D_{50}~50mm) in locations where high ebb velocities are experienced. Sediments with D_{50}~25mm were assumed over the ebb shoal where the ebb jet emerges from the inlet mouth. A gradual transition was assumed between the gravels located at the inlet and the medium sands (D_{50}~0.35mm) located over most of the computational domain away from the inlet.
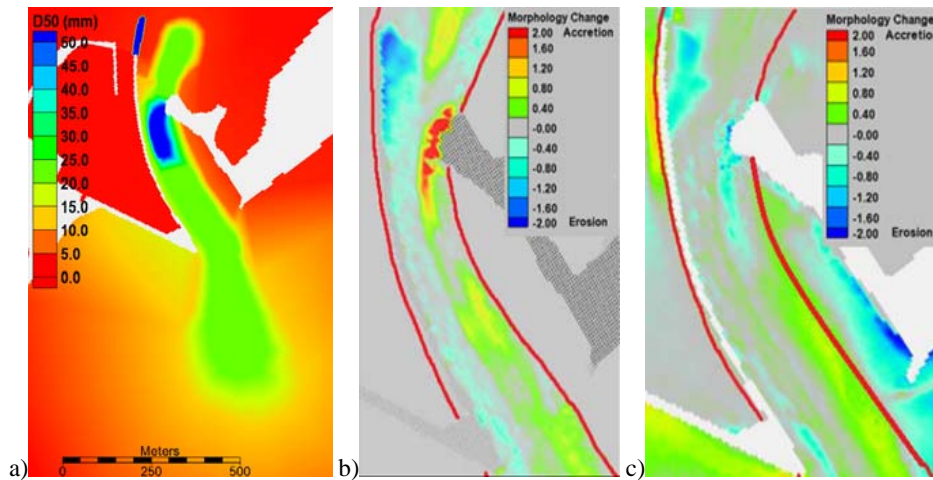
Figure 5. (a) Optimized D$_{50}$ map with (b) measured and (c) modeled changes in seabed elevation from 2004-2010 (blue = erosion, green/yellow/red = deposition, grey = no change).

Once the calibration was completed, a validation run was conducted to ensure the model could reproduce the morphology trends over a long time period. The validation period spanned from 2004-2010 and the modeled results are shown in **Error! Reference source not found.**c, along with the measured bathymetry change. The measured changes could only be derived for the area covered by both hydrographic surveys, which had a focus on the navigation channel (outlined in red in **Error! Reference source not found.**b), which only represents a small sub-set of the entire model domain. Overall, the model was able to predict the correct erosional and depositional trends occurring in the correct locations within the inlet. While the trends are relatively well modeled, the magnitudes of these trends need to be treated with caution given the complexity of the sediment transport and the long durations of modeled periods. It should be noted that the numerical model was not able to predict the deposition observed at the north-western tip of the sand spit that has formed on the eastern side of the inlet.

RESULTS AND DISCUSSION

Baseline Results for Existing Conditions
The first simulation that was modeled using the calibrated CMS model was conducted for the existing condition (*status quo*). This scenario represents the case where no intervention is made at the Shippagan Gully inlet; meaning no changes made to the existing bathymetry or structures. Included in the *status quo* scenario is a representation of the collapsed jetty on the east side of the inlet mouth in its current state, the curved wharf on the west side of the inlet and the 100m length of rubble extending north from the northern tip of the curved wharf. This scenario was modeled using both long-term (six year) boundary conditions and short-term (25 hours) storm simulations.

The flow field predicted by the numerical model at instants with strong flood and ebb currents are shown in **Error! Reference source not found.**. These velocities are representative of the maximum velocities which occur within the inlet during non-storm conditions. The highest velocities within the inlet occur during the ebb flow, with depth-averaged velocities reaching magnitudes of up to 2.1 m/s at the narrowest section of the channel. The sand spit to the east side of the inlet causes a noticeable narrowing of the channel, which produces a concentration of the current and hence a corresponding increase in velocity at, and immediately south of the channel constriction. The ebb current is non-uniform across the inlet mouth and is much weaker (0.1-0.3 m/s) on the eastern part of the inlet mouth near the sand spit. In fact, while the tide is ebbing, the water on the eastern side of the inlet mouth flows slowly into the inlet from south to north, opposite to the main ebb flow exiting through the western side of the inlet mouth. In other words, a bi-directional flow with a counter-clockwise circulation occurs within the inlet mouth during ebb flows. The highest velocities reached during the

flood stage (1.1 m/s) are located near the narrowest point of the inlet, at the same location where the maximum ebb flow velocities are observed. It is important to note that the maximum flood velocities are almost half of the maximum ebb velocities. This strong imbalance between the ebb and flood flows is due to the fact that the tidal lagoon bisects the Acadian peninsula and is open to the sea at two locations where there is an appreciable phase lag in the tidal cycle.
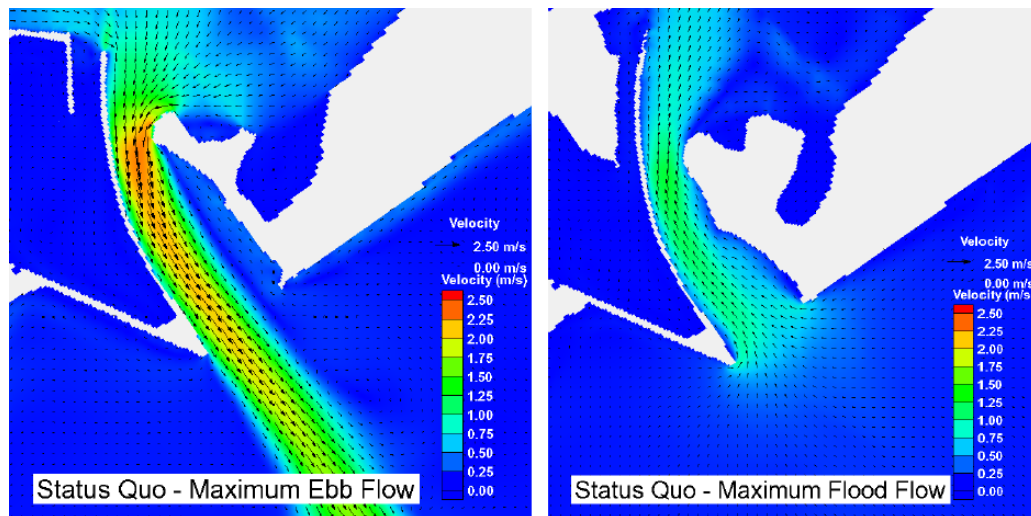

Figure 6. Depth-averaged velocities and flow pattern during strong ebb and flood tides for the status quo scenario.

The hydrodynamic field was also modeled for several scenarios including idealized storms approaching from east (90°), south-east (135°) and south (180°) directions. The residual current (net time-averaged currents) was calculated for each storm. The easterly storm (**Error! Reference source not found.**a) generates a longshore current present both near the shore and over the ebb shoal, flowing from NE to SW on both sides of the inlet. The strong ebb jet emerging from the inlet mouth is deflected towards the west by the easterly storm waves. For the case of the southerly storm (see **Error! Reference source not found.**b), as expected, the longshore current on both sides of the inlet reverses and flows from SW to NE. The strong ebb jet is deflected towards the east in this case and the residual circulation of the ebb shoal is generally weaker and shows more variation. In all cases, the residual currents within the inlet mouth are bi-directional; flowing strongly towards the Gulf of St. Lawrence on the west side of the inlet along the edge of the sand spit. This prominent clockwise circulation within the inlet mouth has likely contributed to the growth and northwards elongation of the sand spit that has formed on the eastern side of the inlet mouth and which now threatens safe navigation through Shippagan Gully. These results show that the residual currents flowing in and out from the inlet mouth are weaker during storms from the east direction than during storms from the southeasterly or southerly directions.

The long-term morphology change result for the status quo scenario is shown in **Error! Reference source not found.**a. A map defining the morphology change was developed by subtracting the seabed elevation at the start of the simulation from the seabed elevation at the end of the simulation period, on a cell by cell basis. Thus, positive change denotes deposition (increased bed elevation), while negative change denotes erosion (decreased bed elevation). Based on the model results for the status quo, deposition will continue within the navigation channel and along the eastern edge of the channel, thereby increasing the narrowing of the navigation channel. Based on the net sediment transport results, the model suggests that most of the deposition in the channel is due to longshore sediment transport travelling from the NE and entering the inlet.
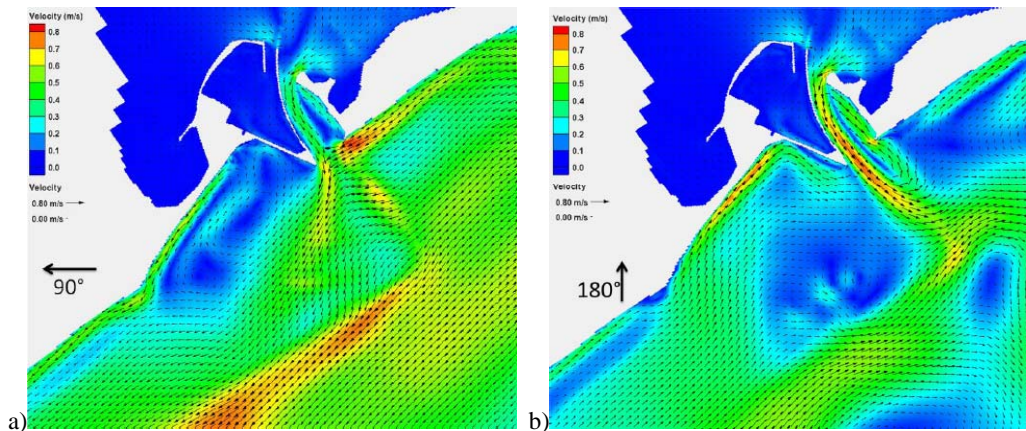
Figure 7. Residual currents for idealized storm with waves approaching from the: (a) east (90⁰) and (b) south (180⁰).

The morphology change results for storm waves approaching from the east (90°) and south (180°) show how the wave direction influences deposition within and offshore of the inlet. The numerical model results indicate that easterly storms, which are the most common at Shippagan Gully, mainly deposits sediment offshore of the inlet with reduced amounts of deposition within the navigation channel and along the east side of the inlet. The southerly storms deposit the most amount of sediment along the east side of the inlet with virtually no deposition offshore of the inlet. A net sediment transport plot for the southerly storms (**Error! Reference source not found.**b) shows sediment entering the east side of the inlet. Therefore, sediment enters the east side of the inlet regardless of the approaching wave direction, where it is then deposited.
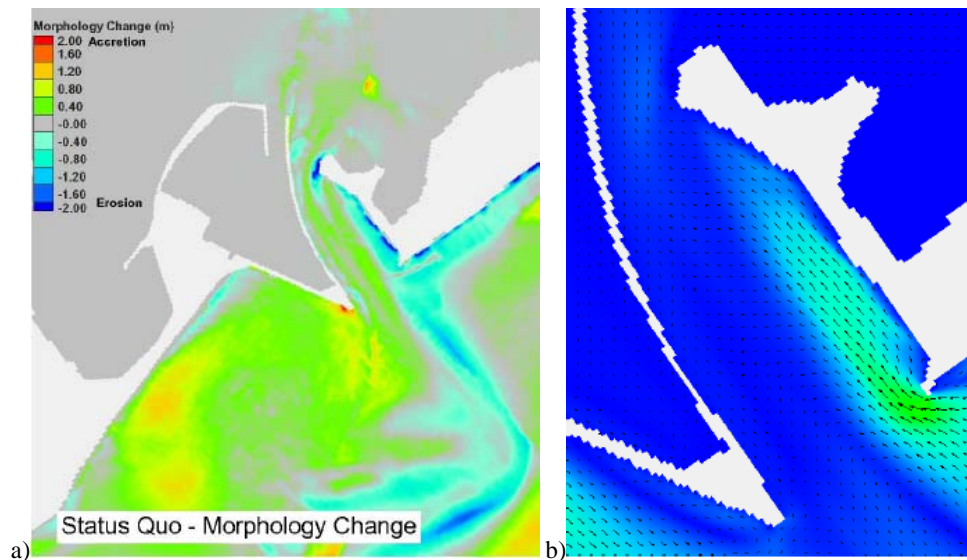

Figure 8. (a) Morphology change results for the status quo scenario and (b) net sediment transport plot for the southerly storms.

Comparison to Phase I Results

Before modeling the new inlet configurations, the best performing scenarios from the Phase I study were modeled using the current refined CMS model to assess the impact of the model refinement, primarily the change in spatial resolution within the model and the implementation of multiple grain size sediment transport. A comparison between the morphology change results of the Phase I model and the current refined model (refer to **Error! Reference source not found.**) shows significant discrepancies between the two models. The significant differences could be due to several factors including:

- The different spatial resolution used in each model;
- The improvements in how sediment transport, and therefore morphology change, is calculated in the new version of the model; and
- The different initial seabed sediment properties assumed in each model.

The changes in how sediment transport is calculated in each model are likely the main reason behind the different morphology change results. The simplistic sediment transport algorithm used in the Phase I model may result in a build-up of deposition in areas with large assumed D_{50} values. After a storm event in the Phase I model, the longshore sediment transport deposited within the inlet did not retain the proper sediment size once it was deposited. Instead, the deposited sediment took on the sediment size of the area of where it was deposited. The strong ebb flow was subsequently not able to erode the storm deposition, since the sediment was now of a much larger size. This led to a build-up of sediment in areas where the seabed D_{50} was larger than what could be re-mobilized by the ebb flow (as seen in the center of the inlet mouth in **Error! Reference source not found.**). This spurious sediment accumulation is seen in virtually all of the Phase I results. The multiple grain size sediment transport algorithm employed in the current CMS model is able to erode fine sediment deposited in areas where larger bed sediments are assumed. The Phase II model is believed to provide a better, more realistic representation of the sediment transport processes occurring at Shippagan Gully, thereby increasing the accuracy of the morphology change results.
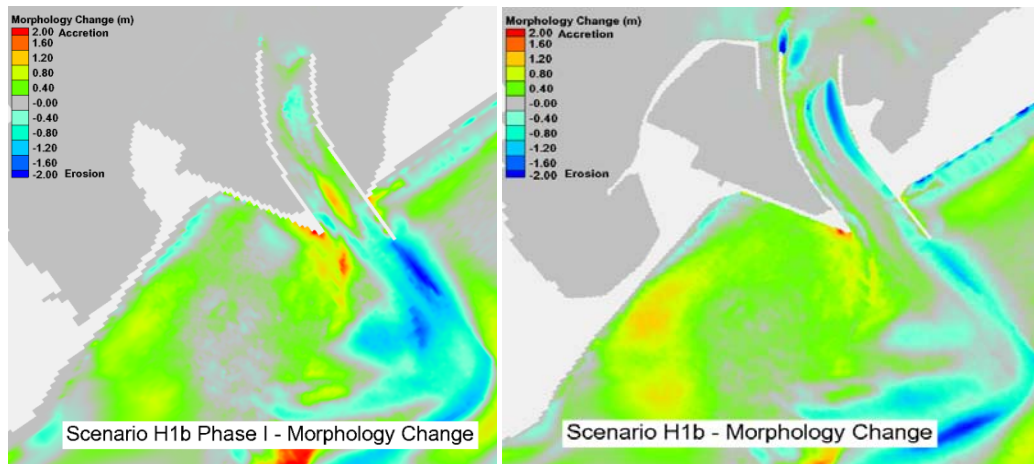

Figure 9. Comparison of morphology change model results for Phase I (left) and the current model (right).

Modeled Inlet Configurations

A total of twenty-one inlet configurations were modeled using the refined, validated and calibrated CMS numerical model. The various scenarios were comprised of different combinations of dredging work, new jetties, new training walls and/or new revetments. The overall aim was to stabilize and widen the navigation channel passing through the inlet mouth in order to improve navigability and increase navigation safety. Since minimizing future maintenance costs was also a priority, it was also important to find a solution for which sediment deposition within the navigation channel would be minimal.

A number of jetty orientations were modeled in order to analyze the effects of placing a jetty on the east side of the inlet mouth. Through the simulations, it was found that a curved, shore perpendicular jetty was optimal at trapping and redirecting the longshore sediment transport approaching from the NE direction. In addition, the shore perpendicular jetty provided a means of sheltering the inlet from easterly approaching storm waves. Overall, placing a shore perpendicular jetty on the east side of the inlet helped reduce the amount of deposition along the east side of the channel for all modeled scenarios.

Two different types of shore stabilizing structures, a vertical training wall and a sloped rock revetment, were modeled along with the shore perpendicular jetty in an attempt to stabilize the eastern shore of the inlet. The vertical training wall was set to a height of +3m above still water level and was oriented

parallel to the existing wharf (shown in **Error! Reference source not found.**). The width of the inlet was adjusted in the various scenarios by altering the distance between the new training wall and the existing wharf. The maximum inlet width that was modeled was 130m and the minimum was a tapering inlet width that started at 110m at the inlet mouth and gradually reduced to 80m at the northern end of the inlet. The rock revetment was set with a 1.5:1 slope and was set at a maximum height of +3m above MWL, similar to the vertical training wall. The bathymetry in these scenarios was adjusted such that a minimum depth of 4m was obtained throughout the entire inlet channel. This was done to ensure an even flow across the entire inlet width as well as providing a deep, wide channel for ships to navigate. Both the training wall and revetment were found to be effective means of reducing sediment deposition within the inlet. Out of the scenarios that were modeled, the configuration that decreased most the deposition within the inlet was the scenario with a gradually tapering inlet width, even though all of the tested scenarios offered an improvement over the status quo.

The best performing inlet configuration needed to take into account the maximum velocities occurring within the inlet, a navigation constraint, as well as the quantity of sediment deposited within the inlet. If ebb velocities are too low, the ebb flow will not be able to effectively scour sediment deposited by storms. However, if ebb velocities are too high, they disturb navigation conditions throughout the inlet. Therefore, the optimal inlet configuration needs to provide a good balance between the maximum allowable velocity for navigation and the amount of sediment deposition within the inlet. The best performing scenario incorporates a curved jetty place on the east side of the inlet mouth and a rock revetment on the east side of the inlet, providing the inlet with a constant 110m width. As shown in **Error! Reference source not found.**, the model results indicate that this configuration reduces both the maximum ebb velocity and the deposition within the inlet, greatly improving the navigability of the inlet. The maximum ebb velocity is reduced to 1.75 m/s (from 2.1 m/s) and the deposition within the inlet is reduced by 20%.
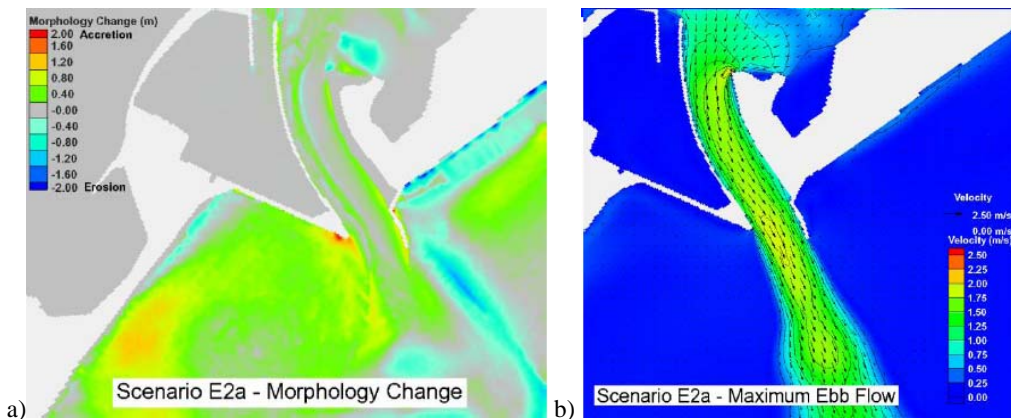

Figure 10. Model results for the best performing scenario; (a) morphology change results and (b) maximum ebb flow plot.

CONCLUSION

The present study was successful in investigating the hydrodynamic characteristics and morphological evolution of this complex tidal inlet using of the CMS-Flow and CMS-Wave numerical models. A number of conclusions can be drawn from this analysis:

- Model results show that the maximum velocity within the inlet during the ebb flow (of 2.1 m/s) and flood flow stages (1.1 m/s) occur at the location where the sand spit on the east side of the inlet causes a narrowing of the channel. It is also important to note that the maximum flood flow is approximately half of the maximum ebb flow. The model results show that during both the flood and ebb flow there is no seaward flow on the east side of the inlet. This indicates that the water current on the eastern side of the inlet mouth is rarely, if ever, directed towards the sea.
- The morphology change results show that deposition will continue to occur along the east side of the navigation channel if the status quo is maintained. This deposition is problematic because it causes the narrowing of the navigation channel.

- Implementing the telescoping grid and multiple grain size sediment transport options in the CMS model resulted in improvements in the morphology change results. This is likely due to the more sophisticated sediment transport algorithm employed in this model version that allows sediment to retain its originally specified grain size regardless of where it is deposited.
- The ideal inlet configuration will decrease flow velocities and sediment deposition within the inlet in order to provide boaters with a safe, navigable channel. The recommended scenario has a 110m wide channel, which is additionally dredged to -4.0m below the MWL, with a rock revetment lining the east side of the channel. A shore perpendicular jetty is proposed for the east side of the inlet mouth to trap and divert the NE to SW direction longshore sediment transport and to protect the inlet mouth from easterly storm waves. The model results show that this inlet configuration reduces both the inlet velocities by 20% and sediment deposition within the inlet by 20%.

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