Ice Effects on Flow Distributions in the Mackenzie Delta

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The Mackenzie Delta (the Delta) is a highly complex hydrodynamic system that consists of many interconnected rivers, streams, and lakes. Part of the complexity of the system can be attributed to the low water surface gradients, variable river inflows, ice jamming events and changes in sea level (due to the effects of storm surge and tides). The ability to reliably predict the distribution of flows in the Delta and to the Beaufort Sea under open water and ice conditions is critical to the operational ocean modelling of waves and sea ice used in marine forecasting. This paper presents a one-dimensional network model of the major channels of the Delta, built upon the University of Alberta’s River1D hydrodynamic and ice process model. The current model of the Delta channel network consists of ten hydraulically significant channels, thirteen junctions, inflows from the Makenzie and Peel Rivers, and outflows to five locations at the Beaufort Sea. The model has been calibrated and verified for open water conditions using measured flows for three separate pseudo-steady state flow scenarios. Specified hypothetical ice cover conditions were simulated to determine how the presence of ice could impact the distribution of flows within the major channels of the Delta and to the five outflow locations at the Beaufort Sea.
1. Introduction

Located in the Northwest Territories, the Mackenzie Delta (the Delta) is a highly complex hydrodynamic system that consists of many interconnected rivers, streams, and lakes. The Delta, shown in Figure 1, starts at Point Separation, approximately 25 km downstream of the community of Tsiigehtchic. The major channels of the Delta include the Middle, East, Peel, West, Napoiak, Neklek, Reindeer, and Kumak Channels. The multi-channel reach of the river starting at Point Separation and extending nearly 40 km downstream has been described elsewhere as the “Turtle” (Beltaos et al., 2012; Morley, 2012). Within the “Turtle”, there is a channel to the west (or left) which forms the back of the “Turtle”. Beltaos et al. (2012) referred to this channel as the “Left Channel of the Turtle” or for brevity the “Left Channel”. In this paper, this channel will also be referred to as the “Left Channel”. The Left Channel connects to the Peel Channel via a small channel referred to herein as the Peel Mackenzie Connector.

The complexity of this delta system can be partly attributed to the low water surface gradients, variable river inflows and changes in sea level (due to the effects of storm surge and tides). This can cause changes in flows distributions within the Delta and in some cases channels may even experience flow reversal (Terroux et al., 1981; Mackay, 1963). This greatly affects freshwater, sediment, and nutrient flow into the Beaufort Sea. Because of its northern location, the Delta flows are further complicated by the presence of river ice for a prolonged period of the year. Although flows are measured where they enter the Delta, flows entering the Beaufort Sea via the many delta channels are not measured. It is very difficult to continuously measure discharge in these outflowing channels since it is not possible to establish unique stage-discharge relationships (typically used to determine discharge) due to the tidal influences. A hydraulic model provides an important tool to estimate open water and ice affected flows within the Delta and to the Beaufort Sea.

A previous hydraulic model of the Delta was developed using Environment Canada’s ONE-D model (Fassnacht, 1997). An internal Environment Canada report (Kerr & Miyagawa, 1996) indicates that the model was calibrated and verified for the open water season (May to October) between 1982 and 1993 but the model had limited winter calibration, did not include geometry in the outer Delta, and had yet to be used to simulate larger dynamic storm surge events. The current status of this model is not known.

The Mackenzie Delta Hydraulic Model (MDHM) originally was developed as part of the Canadian Polar Year (IPY) project entitled “Study of Canadian Arctic River-delta Fluxes” (IPY-SCARF) in order to develop a better understanding of how flows are distributed within the Delta and to the Beaufort Sea. Building on IPY activities, the Beaufort Regional Environmental Assessment (BREA) study “Modeling of Freshwater Flows to the Beaufort Sea for improved Offshore Prediction by the Metarea Ocean Forecast System, 2012-2015” provided additional funding to enhance the model to account for off-channel storage and specified ice conditions in order to represent flow distributions to the Beaufort Sea for all seasons and flow scenarios.

The current version of the model has been calibrated and verified for open water conditions but has yet to be calibrated for ice conditions due to poor availability of winter discharge data (Morley et al., 2011). This paper reports on the current status of the MDHM and on the results of three hypothetical ice cover scenarios, developed to represent typical winter and breakup ice
conditions in the Delta, in order to investigate how ice conditions may affect flow distributions within the Delta and to the outflows to the Beaufort Sea.

2. Model Description
The MDHM has been built upon the University of Alberta’s River1D hydrodynamic model. The River1D model has recently been enhanced with the capability of simulating dynamic wave propagation in multi-channel networks. The main advantage of this new hydrodynamic component is that channel junctions are modelled without the assumption of constant water levels across a given junction, as is the case in most existing 1-D network models. Instead, River1D takes into account the significant physical effects at junctions (such as gravity forces and channel resistance) which are critical to dynamic unsteady flow applications, such as ice jam formation/release and severe storm surge events. These physical effects become more important when horizontal scales are large relative to vertical scales (Shabeyek, 2002), as is the case in natural channel networks such as the Delta.

The current configuration of the MDHM, shown in Figure 1, consists of ten hydraulically significant channels, thirteen junctions, inflows from the Mackenzie and Peel Rivers, and outflows to five locations at the Beaufort Sea. Model inflow boundaries were placed at the locations of established Water Survey of Canada (WSC) hydrometric monitoring stations: Peel River above Fort McPherson (10MC002) and Mackenzie River at Arctic Red River (10LC014). The model outflow boundaries are located where the West, Napoiak, Reindeer, Kumak and East Channels enter the Beaufort Sea. Morley (2012) included the Kumak Channel as part of the Middle Channel based on reports that over 90% of flow from the Middle Channel enters the Kumak Channel.

The development of a comprehensive hydraulic model of this network requires detailed channel bathymetry for all channels. However, due to the Delta’s large size and remote location, only limited cross-section data is available. For this reason, it was decided to employ a ‘limited geometry approach’ for this version of the MDHM by approximating channel cross-sections as rectangular. Hicks (1996) demonstrated in the absence of detailed cross-section survey data, that a reliable hydraulic model can still be developed assuming rectangular channel cross-sections. The current version of the model is defined using 2069 rectangular cross-sections that were developed from channel centerline locations and channel widths measured from georeferenced digital colour air photos (Nafziger et al., 2009) at 500 m intervals using a geographic information system (GIS). The extracted widths were then smoothed for input to the model using a 15 point moving average.

The model has been calibrated and verified for open water conditions using measured flows for three separate pseudo-steady state flow scenarios. The scenarios are classified as pseudo-steady state since measured flows for the scenarios were collected over a range of dates, during which time the measured total inflow to the Delta varied between 8 and 28%. For each scenario, the model was run to a steady state using constant flow at the inflow boundaries (based on average inflow to the Delta during the scenario period) and constant water level at the downstream boundaries. Due to the lack of cross-sectional data, the calibration of the model was accomplished by assuming a bed Manning coefficient, \( n_b \), of 0.025 and adjusting the bed slopes
in the model until the model flows agreed well with the observed flows for one of the open water flow scenarios. The model calibration was then validated with the two remaining open water flow scenarios. For the calibration scenario, the error between observed and modelled flows, expressed as percentage of the total inflow to the Delta was within 4%. For the validation scenarios, the maximum error was 5%. The 5% error was associated with the scenario where the total inflow to the Delta varied by 28%. Given the variation in the total inflow to the Delta during the periods used in the calibration and validation scenarios, the agreement between the measured flows and models flows is considered to be very good.

3. Model Application

The model was set up to simulate four hypothetical steady state scenarios: three ice covered scenarios and one open water scenario. In order to isolate the effects of the hypothetical ice conditions on flow distributions within the Delta, the same inflow and outflow boundary conditions were used for all four scenarios. Beltaos (2012) compiled historical peak breakup flows reported at Mackenzie River at Arctic Red River (10LC014) along with the severity of the breakup. For severe to very severe breakup years, the peak breakup discharge ranged between 28,800 and 30,500 m$^3$/s. Based on these historical flows, a value of 30,000 m$^3$/s was input to the model at the Mackenzie River inflow boundary. Mean monthly flows at Peel River above Fort McPherson (10MC002) and Mackenzie River at Arctic Red River (10LC014) indicated that in spring the flows entering the Delta via the Peel River represented approximately 10% of the total inflow to the Delta. Based on this, 3,300 m$^3$/s was input to the model at the Peel River inflow boundary. For all four scenarios, the water surface elevation was set to sea level at all five outflow boundaries. The three ice scenarios were designed to represent typical ice affected conditions observed in the Delta, while the open water scenario was simulated as a basis for comparison to the ice affected scenarios.

For the first ice scenario, the ice thickness and roughness were set to a constant value throughout the model. This scenario, shown in Figure 2, was created to represent the intact ice cover conditions in later winter prior to spring breakup and is referred to herein as the “Late Winter Scenario”. Based on temporal ice thickness data collected near Mackenzie River at Arctic Red River (10LC014) as reported by Beltaos et al. (2012), a late winter ice thickness of 1.0 m was selected. A sheet ice Manning coefficient, $n_i$, of 0.020 was assumed based on the range of values given by Nezhikovskiy (1964) for smooth ice covers.

The second ice scenario was created in order to simulate the type of ice jamming that has been previously observed during breakup in the Delta. In 2006, an ice jam developed in the Middle Channel between Tsiigehtchic and Rosses Island, located approximately 79 km downstream of Tsiigehtchic (Morley, 2012). In 2008, an ice jam developed in the Middle Channel. On May 21, 2008, the jam started to develop with its toe approximately 44 km downstream of Point Separation and by May 22, the head of jam had reached Point Separation (Beltaos and Carter, 2009). Maps developed from satellite images acquired during breakup 2008 (van der Sanden and Drouin, 2011) indicate that by May 22 rubble ice had also accumulated in the East Channel, Left Channel and Peel Mackenzie Connector. The rubble in the East Channel resulted in a 12 km jam with the toe of the jam located about 70 km downstream of Tsiigehtchic (Morley, 2012). Shear wall height data, a rough indicator of the ice jam thickness, collected after the jam in the Middle
Channel had released, varied between 3.3 m and 5.3 m (Beltaos et al., 2012). In 2009, a similar jamming configuration developed in the Turtle area of the Delta. Morley (2012) reported that on May 27, 2009, a 36 km jam developed in the Middle Channel (toe of jam about 71 km downstream of Tsiigehtchic) and a 21 km jam developed in the East Channel (toe of jam about 73 km downstream of Tsiigehtchic).

Based on these observations, a hypothetical ice jamming scenario was created, as shown in Figure 3. In this scenario, it was assumed that an ice jam had developed in the Middle Channel, the Left Channel, the Peel Mackenzie Connector and in the first 10 km of the East Channel. The toe of the jam was located 70 km downstream of Tsiigehtchic and the head of the jam was at Point Separation, with open water upstream of the head of the jam. For the scenario, it was also assumed that the ice cover remained intact downstream of the jam in the Middle/Kumak (including Napoiak, Reindeer, Neklek) and East Channels and that the winter ice cover in the Peel River had retreated to 50 km downstream of Peel River above Fort McPherson (10MC002). This scenario is called the “Turtle Jam Scenario”.

The ice jam in the “Turtle Jam Scenario” was modelled using an ice thickness of 4.3 m (based on the range of shear wall data collected during breakup 2008). Beltaos (2001) obtained the following relationship for composite-flow Manning coefficient, \( n_c \):

\[
 n_c \approx (0.063 \text{ to } 0.075)t^{1/2}h^{-1/3}
\]  

[1]

Where \( t \) = thickness of the jam and \( h \) = the depth of water under the jam. For under ice depths between 9 m and 16 m, a jam thickness of 4.3 m, the values of \( n_c \) produced by this equation range from 0.05 (16 m depth) to 0.08 (9 m depth). This translates to an under ice jam Manning coefficient ranging from 0.075 to 0.10 (assuming \( n_b = 0.025 \)). Based on these calculations and initial simulations of this scenario where the depth under the jam ranged between 9 m and 16 m with an average depth of approximately 15 m, the under ice jam Manning coefficient, \( n_j \), was set to 0.08 in the model. For this scenario the intact ice cover thickness and ice Manning coefficient were based on the “Later Winter Scenario” and were set to 1.0 m and 0.020, respectively.

The third ice scenario was designed to represent an ice configuration that may occur after a jam that had previously formed in the Turtle became shorter due to thermal recession at the head of the jam. This scenario, shown in Figure 4, is called the “Receding Jam Scenario”. The ice configuration for this scenario was based on the map developed from satellite imagery obtained on May 29, 2008 (van der Sanden and Drouin, 2011). The map indicates that by this date, the rubble ice in the Middle Channel and Left Channel had receded to about 25 km downstream of Point Separation. In this scenario, the ice was configured such that the Peel River/Peel Channel was clear for the first 100 km downstream of the inflow boundary, the East Channel was open for the first 50 km, and the ice jam that had formed in the Turtle in the “Turtle Jam Scenario” had remained in place with its toe remaining at 70 km downstream of Tsiigehtchic but the head of the jam had receded to 25 km downstream of Point Separation. The ice jam and intact ice thickness and roughness values used in this scenario are the same as those in the “Turtle Jam Scenario”.
4. Results and Discussion

Table 1 presents the flow distribution results for all four scenarios at the output locations shown in Figure 1. The flow distribution results are also reported as percentage of the total inflow to the Delta (33,300 m³/s). Figure 5 compares the proportioning of flows to the five outlets at the Beaufort Sea for the four model scenarios.

4.1 East Channel
Flows entering the upstream end of the East Channel appear to be affected by the presence of ice in the Delta. In the “Open Water Scenario” the percentage of total inflow diverted into the East Channel is 6% (1960 m³/s). This percentage ranges from 7 to 9% (2270 to 3150 m³/s) for the ice scenarios. The results suggest that conditions similar to the “Receding Jam Scenario” produce the largest diversion of flows from the Middle Channel to the East Channel. This is likely due to the combined effect of high water levels at the junction and the lack of ice obstructing the flow in the East Channel downstream of the junction. Although the results suggest that more flow enters the East Channel when the Delta is ice affected, the amount of flow that reaches Kittigazuit Bay at Station 10LC013 via the East Channel remains relatively constant, varying only from 29 to 30% of the total inflow for all four scenarios. This may be due to a decrease in flow being transferred from the Middle Channel to the East Channel via the Neklek Channel. In the “Open Water Scenario” the Neklek Channel transfers 8000 m³/s (24% of total inflow) from the Middle Channel to the East Channel; this transfer drops to as lows 6910 cms (21% of total inflow in the ice scenarios). Although the presence of ice changes the distribution of flows to the East Channel, it does not appear to affect the amount of flow ultimately reaching the Beaufort Sea at Kittigazuit Bay.

4.2 Peel River / Peel Channel / West Channel
The presence of ice appears to have a significant effect on the transfer of flow from the Peel River to the Left Channel via the Peel Mackenzie Connector. In the “Open Water Scenario”, 1330 m³/s (4% of total inflow) diverges into the Peel Mackenzie Connector. The flow only drops to 1060 m³/s (3% of total inflow) for the “Late Winter Scenario” but the model results for the “Turtle Jam Scenario” suggest that the presence of a jam in the Turtle could cause a reversal of flow in the Peel Mackenzie Connector, resulting in 120 m³/s leaving the Left Channel to enter the Peel Channel via the Peel Mackenzie Connector. This flow reversal in the Peel Mackenzie Connector is consistent with visual observations made during breakup 2008 (Beltaos et al., 2012). The “Receding Jam Scenario” suggests that even once a jam has receded in the Turtle, and the Peel Mackenzie Connector is no longer experiencing a flow reversal, that the amount of flow leaving the Peel River to the Left Channel is still significantly less (1% of total inflow or 5% of Peel River inflow) than the amount leaving in the “Open Water Scenario” (4% of total inflow or 40% of Peel River inflow). The model results suggest that the amount of flow entering the Beaufort Sea at Shallow Bay can increase from 6% of the total inflow during open water conditions to between 7 and 10% during ice affected conditions.

4.3 Middle Channel / Kumak Channel / Napoiak Channel / Reindeer Channel
The results of the “Open Water Scenario” suggest that between Point Separation and the downstream end of the Turtle, the Mackenzie River loses only 2% of the total inflow to the Delta to the Peel and East Channels during open water conditions. When a simple ice cover is present this loss increases to 4% of the total inflow. The jam scenarios suggest that this loss can increase
to as much as 8 or 9% when a jam is present in the Turtle area. As discussed above, this is the result of increased flows to the East Channel and either reduced flows from the Peel or a transfer of flow from the Mackenzie to the Peel due to a flow reversal in the Peel Mackenzie Connector when the Delta is ice affected. However, the results suggest that the presence of ice does not seem to have much of an effect on the percentage of flow reaching the Beaufort Sea via the Kumak Channel. In the “Open Water Scenario”, 35% of the total inflow to the Delta reaches the Beaufort Sea via the Kumak Channel. The amount only drops by 1 to 2% of the total inflow when ice is present. This appears to be due to less flow being transferred to the Neklek and Reindeer Channels during ice affected conditions compared to open water conditions. In the “Open Water Scenario”, 23% of the total inflow is diverted to the Reindeer Channel but this percentage drops to 21% in both jam scenarios. The ice appears to have the opposite effect on the flows in the Napoiak Channel. For all three ice scenarios, more flow is diverted to the Napoiak Channel during ice affected conditions (7 to 8% of total inflow) compared to the open water conditions (6% of total inflow).

5. Summary and Future Work

The MDHM has been developed using a version of River1D that has been recently enhanced with the capability of simulating dynamic wave propagation in multi-channel networks. The MDHM was used to simulate four hypothetical steady state scenarios in order to investigate the possible effects of ice on the distribution of flows within the Delta and to the Beaufort Sea. Three ice scenarios were developed to represent typical ice affected conditions in the Delta while an open water scenario was used as a basis for comparison to the ice scenarios. The scenario results suggest that the presence of ice in the Delta does have an effect on the flow distributions within the Delta and to the Beaufort Sea in comparison to the open water conditions. The key findings are:

- The presence of ice appears to result in more flow entering the upstream end of the East Channel; however, the total flow reaching Kittigazuit Bay remains relatively constant in all four scenarios due to less flow diverted from the Middle Channel to the East Channel via the Neklek Channel.
- The scenario results suggest that not only does the presence of ice reduce the amount of flow transferred from the Peel River to the Left Channel via the Peel Mackenzie Connector, ice jamming conditions may even result in a flow reversal in the Peel Mackenzie Connector. The results suggest that, due to the reduction in flow transferred to the Left Channel, flows to Shallow Bay may increase by up to 4% of the total inflow to the Delta during ice affected conditions compared to open water conditions.
- The results suggest that the percentage of the total inflow within the Turtle area lost to the East and Peel Channels may increase from 2% during open water conditions to as much as 9% during ice affected conditions; however, the percentage of the total inflow reaching the Beaufort Sea via the Kumak Channel is relatively unaffected due to less flow leaving the Middle Channel downstream of the Turtle via the Reindeer and Neklek Channels.

The ability to reliably predict the distribution of flows in the Delta and to the Beaufort Sea under open water and ice conditions is critical to the operational ocean modelling of waves and sea ice used in marine forecasting. This paper introduces the possible effects on flow distributions with
the Delta and to the Beaufort Sea due to changing ice conditions throughout the year. However, quality winter field data is still needed to validate the model under ice affected conditions. Future work will include the addition of secondary Delta channels and natural channel geometry in order to improve the model’s predictive capabilities.

Acknowledgements

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References


Figure 1. Location map of the Mackenzie Delta, MDHM channels, and output locations.
Figure 2. Ice configuration for the “Late Winter Scenario”.
Figure 3. Ice configuration for the “Turtle Jam Scenario”.

Figure 4. Ice configuration for the “Receding Jam Scenario”.
Figure 5. Outflows to the Beaufort Sea represented as a percentage of the total inflow to the Delta for the model scenarios.
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<th>Output Location</th>
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