



# RESILIENT INFRASTRUCTURE

June 1–4, 2016



## ASSESSING CURRENT AND FUTURE MACKENZIE RIVER FREIGHT VOLUMES IN THE CONTEXT OF CLIMATE CHANGE IMPACTS

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### ABSTRACT

The Mackenzie River is a major freight transportation route that connects many remote communities in the Northwest Territories and parts of Nunavut to southern Canada's transportation network. The river is only navigable during the summer months, from mid-June until sometime in late-September to mid-October, when it is clear of ice. However, the water conditions of the river have changed significantly in recent years. Although water levels always decrease as the delivery season moves into fall, these reductions have been occurring much faster, in turn reducing barge loading capacities as well as operational speeds. In addition, based on simulations of ice breakup and water volumes in the Mackenzie River basin, the sailing season opening dates are anticipated to shift earlier in the future. In the end, the main impact of climate change on river transport is not definitive events but rather, increased variability in events. This research aims to account for those abovementioned climate changes in the freight volume scheduling process, and conducts a numerical analysis based on the projections of future water conditions from climate simulation models as well as predicted freight volumes from time-series analysis and forecast models. The results of the numerical analysis can help local government and waterway transportation companies to better understand how freight scheduling strategies could account for climate changes that affect regional waterway transportation and, hence, optimize their operational schedules to take advantage of good water conditions while reducing financial cost.

Keywords: Freight Transportation, Climate Change, Water Transportation, Transport Schedule.

### 1. INTRODUCTION

The Mackenzie River, shown in Figure 1, serves as a major freight transportation route connecting remote communities in the Northwest Territories and parts of Nunavut to the southern Canada's freight network. Water conditions of the river have changed significantly in recent years, threatening what was once a highly reliable mode of freight delivery. Although water levels and volumes always decrease as the delivery season moves into fall, these reductions have been occurring much faster. According to William Smith, VP Logistics and Business Development at the Northern Transportation Company Limited (NTCL), a major freight transportation company on the Mackenzie River (personal communication, December 4, 2015), water levels at the north end of the river were much lower than previous years from the beginning of September onwards through the rest of the season in 2014. As a result, much anticipated freight delivery to communities located at the north end of the river did not occur. This situation in 2014 suggests that transportation companies on the Mackenzie River must consider changes to their delivery strategies and resulting scheduling, in order to adapt to changing water conditions. Particularly, companies must consider changes to freight transport historically carried out towards the end of the summer delivery season (i.e. September and October) in order to decrease the likelihood of non-delivery (such as that experienced in 2014). Although scheduling freight delivery earlier to take place during good water conditions could improve transportation reliability, there will be an extra cost to implement new schedules. Tows and barges need to be set up earlier than usual if the freights are planned

to be delivered sooner. Besides, waterway freight transportation companies will need to explain to their customers why the transportation schedules are planned earlier and persuade them to deliver their freights to the terminals by an earlier deadline. Therefore, balancing the additional cost of implementing new schedules and the benefit of utilizing good water conditions is critical when deciding freight delivery plans.



Figure 1: Geographical location of the Mackenzie River

Based on future water condition projections from climate simulation models, this research aims to account for potential climate changes in the freight volume scheduling process and determine an alternative schedule that better aligns with predicted water conditions. The model applied in this study factors in the additional cost of rescheduling freight delivery to earlier dates as well as the benefit of utilizing better water conditions. Time-series analysis is used to assess trends in waterway freight volumes supplied by NTCL, from 2002 to 2015, to estimate future waterway freight volumes. Mackenzie River stream flow forecasts from Dr. Thian Gan’s research group at the University of Alberta (2016) were used to estimate future water conditions, and therefore, freight delivery conditions, in this research. The results of the analysis can help local government and waterway freight companies better understand how current waterway freight volumes may not be feasible under climate change, and how freight deliveries might be planned with this consideration. It may lead to the crafting of policies and services that encourage waterway freight carriers to plan and operate accordingly to better utilize water conditions. The results can also inform waterway freight companies in planning schedules and contracts to take advantage of the Mackenzie River water conditions best suited for freight transport, and therefore better serve the communities to which they deliver.

This paper is organized as follows: Section 2 contains a brief literature review. Section 3 presents the waterway freight volume analysis and prediction. Section 4 describes the cost function used in the rescheduling of bi-monthly freight volumes based on projections of future water conditions, which is presented in Section 5 along with a numerical analysis.

## 2. LITERATURE REVIEW

This section provides an overview of previous research on the impact of climate changes on inland waterway transportation and total logistic transportation cost.

The surface temperature of the Earth has shown a tendency to increase more rapidly in recent years (Jones et al. 2007). One major impact of the temperature increase on inland rivers is water shortage, resulting in decreased water levels and discharges (Ho 2010). Jonkeren et al. (2007) studied the impacts of climate change on inland water transport on the Rhine River, and found that there is a considerable negative effect of water levels on freight price per ton and a positive effect on load factor. In Jonkeren et al.’s other research (2011) on inland waterway transport in the Rhine area, his group estimated that under extreme climate situations, a significant amount of freight would be transferred

via modes other than waterway, including rails, roadways, etc. In addition, Olsen et al. (2005) found that costs to inland navigation can be significant, potentially with diminished river flows and even closures, as in their study of the Middle Mississippi River. In their paper, they also recommended transportation managers to monitor climate conditions and adapt policies in case of significant changes.

In previous research, the total logistic transportation cost function was used broadly in freight assignment models and as a tool to analyze and evaluate the performance of freight transportation networks and delivery plans. Sheffi et al. (1988) included transportation costs, stationary inventory costs, and in-transit inventory costs in the total logistics cost function used in their research on transportation mode choice between a given origin and destination. Daganzo et al. (2005) categorized freight transportation cost into three types in his book: holding cost, transportation cost, and handling cost. Holding cost includes the rent for space, machinery needed for storage, and maintenance costs for the equipment. Transportation cost is the cost produced during transportation, including the driver wages, fuel consumption, etc. Handling cost is the cost for loading and unloading in the terminals. In 2013, Rodrigue et al. (2013) categorized total logistic cost into terminal cost, line-haul cost, and capital cost in their book. Loading, unloading, and transshipment costs are included in the terminal cost; labour and fuel are included in the line-haul cost; as for the capital cost, the purchase of fixed assets and any enhancement of fixed assets are included. In general, the handling cost at terminals, including the loading and unloading cost and the cost of equipment and maintenance, as well as travel costs, including fuel consumptions, labour, cost of time, etc., are considered in the freight transportation cost.

However, in contrast to inland waterways analyzed in other previous research, located in higher-density geographic areas, the Northwest Territories are sparsely populated; as a result, many of the communities served by the Mackenzie River system have no other cost-effective delivery options in the summer (delivery by air is very costly) due to a lack of all-weather road access. As a result, this research focuses on this waterway delivery route, aiming to find ways to balance the additional cost of implementing new schedules according to water condition changes and the benefit of utilizing good water conditions to minimize the total generalized cost to respond to potential climate changes. Thus, in the cost function, besides the handling cost and travel cost mentioned above, the additional cost of implementing new schedules and those related to transportation delays and freight not successfully transported within one delivery season due to low water conditions are included as well.

### **3. FREIGHT DATA ANALYSIS**

This section introduces the data analysis for historical NTCL freight volume data. We introduce the dataset, trend test, time series model, intervention analysis, and all analysis results.

#### **3.1 Dataset**

Data on freight volumes delivered to northern communities by NTCL between January 2002 and July 2015 were taken from tow letters provided by NTCL. The tow letters provided a rich set of information, which included tug and barge departure dates from Hay River (where their major loading terminal is located), type of freight carried (such as fuel, ship gears, anchor, deck goods, etc.), freight volumes (in tons), and the final destinations of the freight. More than 70 destinations are identified in the tow letters, but many have very small delivery volumes; rather, there are a few destinations that have the highest volumes. Based on total volume heading to these destinations and their occurrence frequency since 2002 to 2015, 14 major locations are identified, to which more than 80 percent of total freight volumes are destined. Six major locations are along the Mackenzie River — Tulita, Norman Wells, Fort Good Hope, Aklavik, Inuvik, and Tuktoyaktuk. The rest (Sachs Harbour, Holman, Paulatuk, Kugluktuk, Roberts Bay, Cambridge Bay, Gjoa Haven, and Taloyoak) are in the north Inuvik region and north Kitikmeot region and must be delivered by ocean barges transshipped at Tuktoyaktuk from river barges. For the purposes of this research, all major locations beyond the Mackenzie River are combined as one destination labeled the Arctic Region. Based on freight types recorded in tow letters, freight transported via the Mackenzie River is categorized into two major classes: fuel and dry cargos. Dry cargos include freight such as construction materials, mining equipment and gear, non-perishable food items, personal vehicles, etc. Bi-monthly fuel and dry cargos heading to major destinations along the river and Arctic Region as well as volumes of all destinations were extracted as time-series from 2002 to 2015.

### 3.2 Seasonal Kendall Trend Test For Volume Data

Trend tests are usually applied to determine whether upwards or downwards trends are present in a subject dataset. The results of such tests can provide guidance on choosing appropriate models for further analysis, such as ARIMA models. For a time-ordered dataset, the Mann-Kendall trend test can be used to assess whether there is a monotonic (increasing or decreasing) trend over time in this dataset within a certain level of significance. However, the traditional Mann-Kendall trend test does not account for seasonality (Hirsch et al. 1982). Since waterway freight data, like most transportation volume data, shows significant seasonality due to the annual pattern of water conditions in the Mackenzie River, the seasonal Kendall trend test was used to test monotonic trends in freight volume data.

The seasonal Kendall trend test results for the freight volumes indicated that total volumes transported via the river showed a significant decreasing trend over time at a 99% confidence level. As for the major destinations, only volumes destined for Tuktoyaktuk and the Arctic Region showed a significant decreasing trend at a 99% confidence level. One reason for the volume decrease of these two destinations is that since 2008 summer, another marine transportation company expanded their sealift services to Kitikmeot communities via the Northwest Passage (“Around Nunavut” 2008). According to Darren Locke from the Government of Northwest Territories’ Department of Transportation (personal communication, November 24, 2015), new scheduled services from Eastern Canada through the Northwest Passage are believed to have reduced NTCL’s deliveries to these regions.

### 3.3 ARIMA Model and Intervention Analysis

Autoregressive Integrated Moving Average (ARIMA) models can be used to represent and forecast data in time series. Data that is a stationary time series has constant mean, variance, etc., over time. A non-stationary series needs to be transformed into a stationary series before applying ARIMA models. The common way to transform a non-stationary series into a stationary one is differencing (O’Connell and Koehler 2005). First and second differences are usually adequate for most data (O’Connell and Koehler 2005). An ARIMA model includes three terms  $(p, d, q)$ , where  $p$  represents the order of autoregressive (AR) model,  $d$  represents the number of differences to obtain a stationary series in the case of non-stationary series, and  $q$  is the order of moving average (MA) model. Since seasonality is found in freight data, seasonal ARIMA models were applied to analyze and forecast the total volumes transported via the Mackenzie River. Besides  $(p, d, q)$  in the ARIMA model, three extra terms  $(P, D, Q)_s$  are included in the seasonal ARIMA model as well, where  $s$  is the number of seasons until same pattern shows again,  $P$  is the order of AR term in the seasonal part,  $Q$  is the order of MA term in the seasonal part, and  $D$  represents the number of differences with lag  $s$ .

Since a shock in 2008 was identified in the trend test and a significant decrease in the total volumes after 2008 was observed, a transfer function was added in the ARIMA model to represent the impact of this shock. We can observe change in NTCL delivery volumes before and after 2008 in Figure 2. Note that Figure 2 shows volumes as a proportion of the historical maximum annual volume instead of absolute volumes. The transfer function to model this sudden drop is specified in Eq. 1.

$$[1] \quad TC = \omega I_t$$

Where,  $\omega$  is the intervention parameter, representing the expected changes of mean in one period before and after the intervention;  $I_t$  is a step function specified in Eq. 2.

$$[2] \quad I_t = \begin{cases} 0, & \text{if } t < T \\ 1, & \text{if } t \geq T \end{cases}$$

Where  $T$  is the year of intervention; here,  $T = 2008$ .

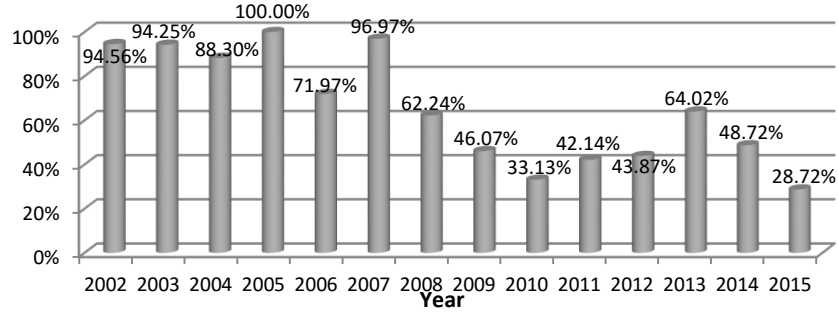


Figure 2: NTCL total freight volumes (as a proportion of the maximum annual total volume observed)

As described in 3.1, freight is categorized as fuel or dry cargo. Seasonal ARIMA models were applied on both bi-monthly total fuel volumes and total dry cargo volumes transported by NTCL via the river. Freight volume data are extracted and organized bi-monthly; as a result, each year is divided into 24 periods, from the first half of January to the second half of December, such that  $s = 24$ .  $ARIMA(0,0,0)(1,1,0)_{24}$  is chosen for both fuel and deck data series according to their sample autocorrelation and partial sample autocorrelation. The integration of ARIMA model and transfer function is thus specified in Eq. 3.

$$[3] \quad y_t = \varphi(y_{t-24} - y_{t-48}) + y_{t-24} + a_t + \omega I_t$$

Where,  $y_t$  is the original observation at time period  $t$ ;  $a_t$  is the white noise at time  $t$ ,  $a_t \sim N(0, \sigma^2)$ ;  $\varphi$  is the parameter in the seasonal AR model. Estimations of parameters  $\varphi$  and  $\omega$  for fuel and dry cargo volume data series are presented in Table 1.

Table 1: Parameter Estimation Results of ARIMA Model and Transfer Function

	Fuel		Dry Cargos	
	Value	$p$ -Value	Value	$p$ -Value
$\varphi$	-0.462	<0.0001	-0.575	<0.0001
$\omega$	-830.11	0.1014	-314.98	0.0096

The  $p$ -value of  $\omega$  for fuel volume data is 0.1014, indicating that this parameter is considered to be statistically significant at a 90% confidence level. Despite this somewhat marginal significance, we still retain this term in the following forecasting process. Also,  $\omega$  is negative, indicating that there is a drop on mean of data series before and after the intervention. The absolute values of the  $\omega$ s indicate the average changes of mean per unit time before and after the intervention, and in our models, it represents that the fuel volume decreased about 830 tons per half month on average, while the dry cargos dropped about 315 tons per half month on average. Based on the ARIMA model chosen, the forecast of fuel and dry cargo volumes in 2025 were obtained. These forecasted volumes for 2025 are used as the base schedule in the numerical analysis (Section 5). The base schedule represents the anticipated bi-monthly freight delivery volumes when transport companies continue with “business as usual” in the future. The added cost of freight rescheduling is the difference between base schedule and revised schedule.

#### 4. GENERALIZED COST FUNCTION

For the purposes of modeling, we use a generalized cost function to describe the costs of rescheduling freight volumes to take better advantage of anticipated future water conditions. It accounts for the costs associated with implementing new schedules, transportation delays, and unsuccessfully delivered freight in one delivery season.

In the cost function, we use  $d_{i,j}^q$  to represent the volume (in tons) of freight type  $q$  rescheduled from time period  $j$  to period  $i$ . In addition, we use  $l_i^q$  to represent the volume of freight type  $q$  not delivered in time period  $i$ , and use  $v_i^q$  to represent the volume delivered in time period  $i$ . If the capacity of freight  $q$  ( $C_i^q$ ) is larger than the total volume requiring transport in this period (including volumes allocated to this period  $\sum_j d_{i,j}^q$ , and volumes not delivered in the

preceding period  $l_{i-1}^q$ ),  $l_i^q$  should be zero, as all freight demanding transport in this period was satisfied; otherwise,  $l_i^q$  is equal to total volume requiring transport minus the capacity (actual volume transported). If the total volume requiring transport is smaller than or equal capacity,  $v_i^q$  equals the total volume requiring transport, otherwise,  $v_i^q$  is the capacity. Let us assume that  $l_0^q$  equals zero, which means that the season does not start with freight undelivered from the previous year. Then,  $l_i^q$  and  $v_i^q$  can be defined mathematically using Eq. 4 and Eq. 5 respectively.

$$[4] \quad l_i^q = \begin{cases} 0, & \text{if } l_{i-1}^q + \sum_j d_{i,j}^q \leq C_i^q \\ l_{i-1}^q + \sum_j d_{i,j}^q - C_i^q, & \text{if } l_{i-1}^q + \sum_j d_{i,j}^q > C_i^q \end{cases} \quad (i \in I)$$

$$[5] \quad v_i^q = \begin{cases} l_{i-1}^q + \sum_j d_{i,j}^q, & \text{if } l_i^q = 0 \\ C_i^q, & \text{if } l_i^q \neq 0 \end{cases} \quad (i \in I)$$

Where  $I$  is the set containing all (discrete) time periods.

We assume that there are four cost components to consider in the rescheduling model. These include: handling costs ( $C_H$ ), accounting for the costs associated with loading and unloading freight, including associated equipment and maintenance; travel cost ( $C_T$ ), representing fuel consumptions, labour, transport time, etc.; costs associated with moving freight delivery volumes to a different time period ( $C_R$ ); and costs due to delays ( $C_D$ ), which includes lateness (i.e. delivery in a time period later than the one intended), and cost penalties due to total non-delivery of freight by the end of the summer delivery season by water. The major component of  $C_R$  consists of the cost of actions required to reschedule freight to other periods, such as rearranging tows and barges to accommodate new plans, modifying customer contracts and logistics plans. Therefore, the total cost can be expressed as follows:

$$[6] \quad C = C_H + C_T + C_R + C_D$$

The benefits of delivering freight in good water conditions can be reflected in two aspects in the cost function. First, if water levels decrease faster over a season in the future, it is likely that water levels in late September and early October will be poor for tug and barge operations, and therefore, freight intended to be transported at this time would possibly experience high delays and possible non-delivery by end of season. By rescheduling these late-season volumes to earlier time, the costs of freight delays and non-deliveries might be significantly reduced. Second, the travel time of a tow in good water conditions (i.e. high water levels) is likely to be much smaller than in less-ideal conditions. A major reason for this is when water conditions are low, barges have to be anchored and be dragged one by one to pass hazard sections in the river, including rapids and ramparts (Mulder and Williams 2006).

The handling cost is considered to be linearly related to the total volume transported within the delivery season for each freight type, while travel cost is considered to be linearly related to total travel time in each period in this model. Handling cost and travel cost are shown in Eq. 7 and Eq. 8 respectively.

$$[7] \quad C_H = \sum_q \beta^q \sum_i v_i^q \quad (i \in I)$$

$$[8] \quad C_T = \sum_i \theta \cdot n_i \cdot t_i \quad (i \in I)$$

Where,  $\beta^q$  is the unit cost for setting up transportation for goods type  $q$ ;  $\theta$  represents value of time;  $n_i$  is the number of tows completed in period  $i$ ; and  $t_i$  is travel time in period  $i$ .

Rescheduling cost is considered to be related not only to the volume of freights rescheduled from other time periods, but also related to the amount of time that freights are moved earlier compared to base schedule, and is defined by Eq. 9.

$$[9] \quad (C_R)_i^q = \vartheta^q \cdot \sum_j (t_{i,j} \cdot d_{i,j}^q) \quad (i \in I)$$

Where,  $\vartheta^q$  is a parameter to convert this time-related term to monetary values for freights  $q$ ;  $t_{i,j}$  is the time difference between period  $i$  and period  $j$ .

There are two types of cost to account for in the delay cost in our research. First, before the last available transportation period in the season  $i_{end}$ , if some freight cannot be delivered by the end of some periods, they still can be arranged to be transported in the following periods. The cost for freight transportation delays is specified as the first sub-function in Eq. 10. If there are still some freights that are not transported, these freights then will not be successfully delivered within the delivery season via waterway, and the cost to deal with those leftover freights is defined as the second sub-function in Eq. 10. For time periods after the delivery season, we define the delay cost as zero, shown as the third sub-function in Eq. 10.

$$[10] \quad (C_D)_i^q = \begin{cases} \varphi_1 \cdot t_i^{delay} \cdot l_i^q, & (i < i_{end}, i \in I) \\ \varphi_2 \cdot l_{i_{end}}^q, & (i = i_{end}) \\ 0, & (i > i_{end}, i \in I) \end{cases}$$

Where,  $\varphi_1, \varphi_2$  are parameters to convert the term to monetary values for freight  $q$ ;  $t_i^{delay}$  is the average delay of a ton of goods that cannot be delivered in period  $i - 1$  and needs to wait to be transported in period  $i$ , and on average we assume it has been delayed for a time of  $\frac{L_i}{2}$ , where  $L_i$  is the length of time period  $i$ ;  $i_{end}$  is the last time period within the delivery season.

This cost function is then applied to obtain the optimal transport schedule for year 2025 based on the stream flow projections and freight volume projections for 2025 in the numerical analysis (Section 5).

## 5. NUMERICAL EXAMPLE

The network and rescheduling model used in this example are introduced in section 5.1, while methods applied to obtain capacities of fuel and dry cargos are described in 5.2. The results are discussed in 5.3.

### 5.1 Model Setup

The network used here in this numerical example is an abstracted and simplified network, with only one origin and destination, with a single waterway route connecting them. According to William Smith (personal communication, December 4, 2015), fuel deliveries are typically planned out well in advance of the season (six months to a year), and contracted dry cargo deliveries (for mining and other industrial operations) can be planned out in advance as well. However, delivery demand for some personal dry cargos, such as cars, is variable and may not be known in advance, making it difficult to do early planning. Based on this information, we have assumed three types of freight: fuel, contracted cargo, and “unscheduled” cargo. Since deliveries of the first two freight types are planned in advance, we consider that it would be more cost-effective to reschedule these types of freight compared with the last. Demands for delivery of the third freight class are usually quite small compared to fuel and contracted dry cargos (William Smith, NTCL, personal communication, December 4, 2015). Thus, we have assumed for this analysis that 90% of all dry cargo is the contracted type while 10% is the “unscheduled” cargo, and this remains true into the future (of course this depends heavily on the future of mining and oil & gas explorations in the Northwest Territories).

Compared with historical stream flows, stream flows projected for the year 2025, provided by Dr. Thian Gan’s research group at the University of Alberta (2016), start to rise and decrease at earlier times (See Figure 3). According to historical volume data and stream flow data, no deliveries happen when stream flow is lower than 6000 m<sup>3</sup>/s. In Figure 3, predicted stream flows in September and October 2025 are lower than 6000 m<sup>3</sup>/s, meaning that deliveries cannot be made at these times. In this example, we assume that barge operators would like to ensure that all freight is successfully delivered by the end of the season. We also assume that transport companies are able to estimate their delivery capacities for every period based on anticipated stream flows, and they do not want any unnecessary delays, meaning the volume assigned to a certain period will be less or equal the capacity. Therefore, we can simplify the cost function of Eq. 6. The handling cost will be the same for every possible schedule, since it is linearly related to the total volume transported within the delivery season, which remains constant (i.e. we assume it is an exogenous quantity). We assume that we will find new schedules where all freight is delivered by the end of the season. Therefore, only travel cost and rescheduling cost need to be considered. The parameters to transfer time-related terms into generalized

cost can be omitted in this example, since the left two terms are both time-related. The objective function and constraints are set up in Eq. 11 through Eq. 15.

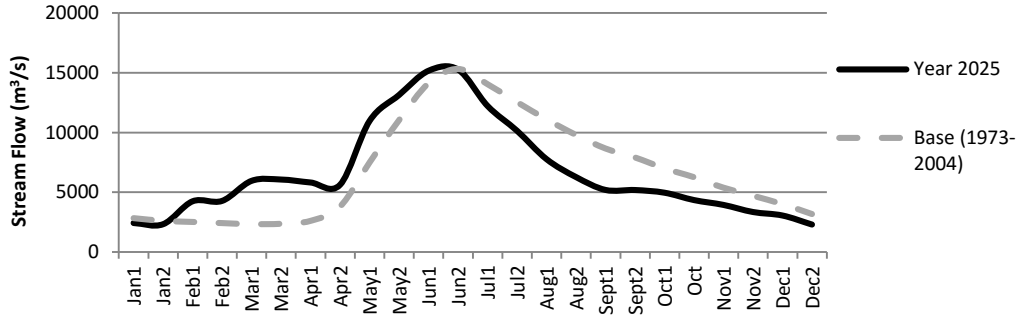


Figure 3: Predicted and historical stream flows at Fort Simpson in the Mackenzie River (from Dr. Thian Gan (2016))

$$[11] \quad \text{Minimize } C = \sum_i n_i \cdot t_i + \sum_q \sum_i \sum_j \vartheta^{q'} \cdot (t_{i,j} \cdot d_{i,j}^q)$$

Subject to:

$$[12] \quad d_{i,j}^q \geq 0, \forall i, j, q$$

$$[13] \quad \sum_i d_{i,j}^q = p_j$$

$$[14] \quad \sum_j d_{i,j}^1 \leq C_i^1$$

$$[15] \quad \sum_{q=2}^3 \sum_j d_{i,j}^q \leq \sum_{q=2}^3 C_i^q$$

Where  $\vartheta^{q'}$  is a factor reflecting the inflexibility of freight  $q$  to be rescheduled to another time period, and the higher the value is, the more difficult it is to reschedule the freight. Because the third type of freight is considered more difficult to reschedule than the first and second types of freight, in this example, we arbitrarily assume  $\vartheta^{1'}$  and  $\vartheta^{2'}$  are 1, while  $\vartheta^{3'}$  is 25. For the travel time of one trip in time period  $i$  ( $t_i$ ), we arbitrarily assume that if the difference of the maximum stream flow and stream flow in this period is larger than 3000, the travel time will increase 15% to reflect impacts of water conditions on the travel time. Eq. 12 stipulates that volumes rescheduled from period  $j$  to period  $i$  should be non-negative. Eq. 13 specifies that all freight originally from time period  $j$  in new schedules should equal the total volume assigned to period  $j$  in base schedule. Eq. 14 and Eq.15 specify that demand for each freight type reassigned to any period should be less or equal the capacity ( $C_i^q$ ) of this freight type in this period. According to Section 3.3, freight data are only categorized into fuel and dry cargos. Since capacities for every period were estimated based on historical freight data as well as historical and projected stream flows, capacities are only estimated for fuel and dry cargos as a whole. Therefore, the total amount of freight from the second and third type in a certain period should be less or equal the capacity for dry cargos in this period. Eq. 15 presented the mathematical form of this constrain.

## 5.2 Estimates of Capacity

Waterway freight delivery capacities in each time period of 2025 were roughly estimated with historical volume data and a comparison of the historical stream flow profile and predicted stream flow profile for 2025. In Figure 3, the predicted stream flow profile, although very similar to the historical stream flow profile, seems to start to increase and decrease about half a month earlier than historical ones. Hence, we assumed that the ratio of capacity in period  $m$  in 2025 and historical capacity in period  $m + 1$  is the same as the ratio of the stream flow in period  $m$  in 2025 and the historical stream flow in period  $m + 1$ . Historical bi-monthly volumes in the 85th percentile are assumed as the historical capacities, in order to remove outliers. In addition, no deliveries happen when stream flow is lower than 6000 m<sup>3</sup>/s, based on historical volume data and stream flow data. The predicted capacities for fuel and dry cargos are shown in Figure 4.



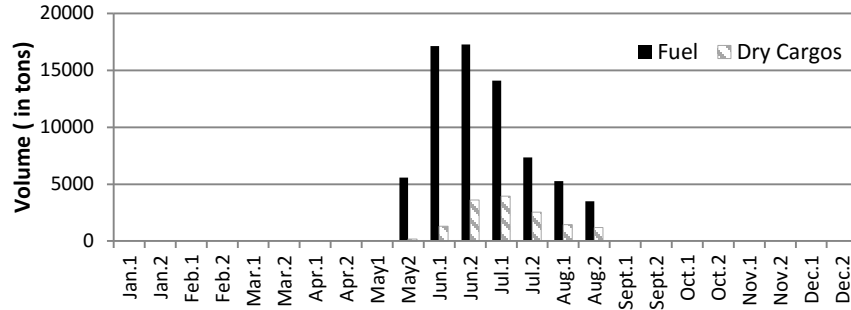


Figure 4: Predicted capacities for fuel and dry cargos in 2025

### 5.3 Numerical Results

The results of freight rescheduling are shown in Figure 5. It can be observed that freight assigned for delivery in September and October in the base schedule has been rescheduled to earlier periods. Persuading customers to have their goods ready for shipment several months earlier than they currently do would likely be very difficult. However, due to limited capacity in late July and August as a result of low stream flow, some of the freight assigned to September and October must be rescheduled to late June or early July to ensure successful delivery. Hence, in Figure 5, freight volumes in early July are significantly higher than in other periods during the delivery season. In addition, since the third-type freights are more difficult to reschedule than the second type, in the last period available for transportation, the third type freights originally assigned to September and October were first arranged for transportation in this period. To ensure that the capacity of dry cargos in this period will not be exceeded, some of the second-type freights originally assigned to this period are rescheduled to an earlier period.

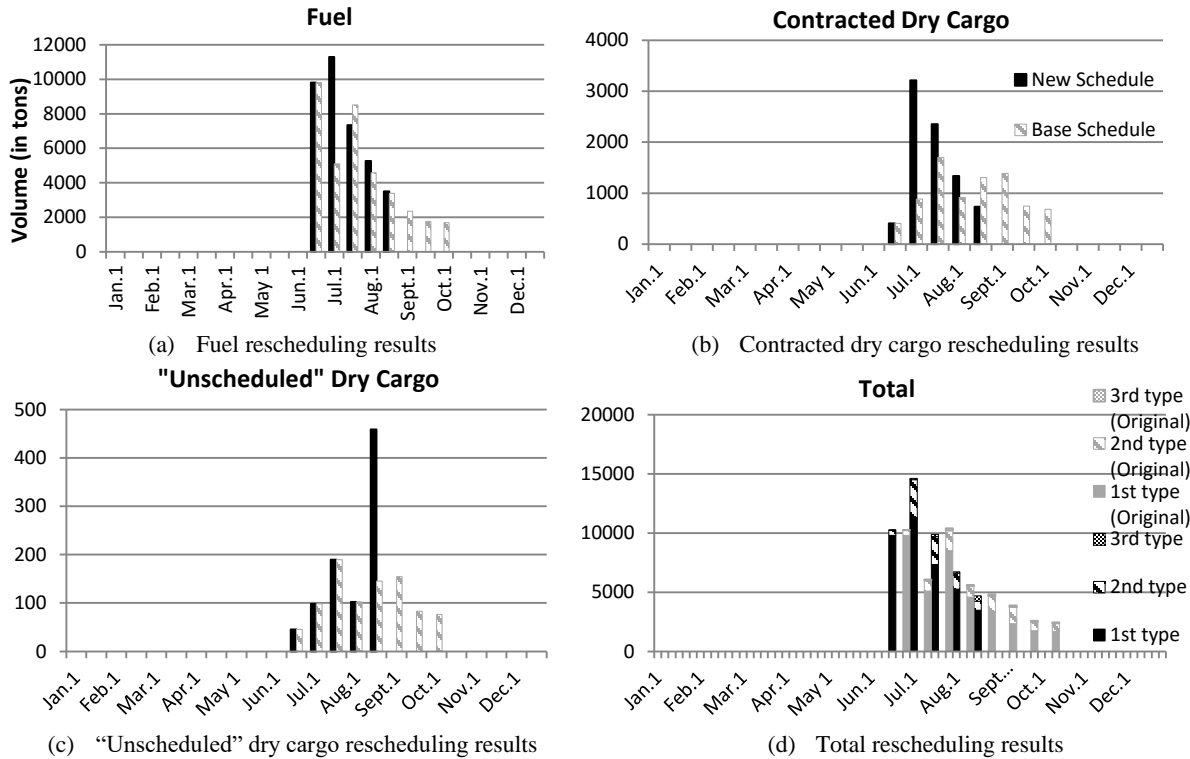


Figure 5: 2025 Freight rescheduling results

The results also show that the new shipping schedule is a more compressed schedule compared to the original one, which may require faster barge unloading at community landing sites. This may require some investments (either capital or operational) to accommodate these increased rates of delivery.

The results in this analysis reveal that future waterway freight transportation capacities in September and October may be insufficient to transport freight expected for delivery in those late-season months. This indicates a need to change freight volume transport schedules so that there is a higher probability that all freight can be successfully delivered if low water conditions occur in September and October. Therefore, local government and waterway transportation companies need to monitor future climate changes and prepare alternative schedules accordingly.

## 6. CONCLUSIONS

This paper provides an assessment of how forecasted future freight volumes along the Mackenzie River might be modified to account for the impacts of climate change on water conditions. The cost function applied in this study factors in the additional cost of rescheduling freight delivery to earlier dates as well as the benefit of utilizing better water conditions. By minimizing the total generalized cost, we can determine more cost-effective (costs as defined above) transport schedules, which take better advantage of future anticipated water conditions and therefore, provide a higher likelihood of successful delivery. A trend test and time-series model were applied to assess trends in historical waterway freight data and to provide forecasts of future freight volumes. The forecasts were then used in the freight rescheduling numerical analysis. Results suggest that if stream flows start to increase and drop earlier every year as predicted, waterway transport capacities towards the end of the delivery season will be reduced. Specifically, September and October deliveries will be most significantly affected. Our results may encourage local governments to more closely monitor the impacts of climate change on freight transport operations, and encourage waterway freight operators to evaluate their anticipated scheduling and delivery contracts in order to minimize the likelihood of non-delivery. In this analysis, the delivery capacity of every period was only roughly estimated based on historical flow stream profile and projected flow stream profile. Future research on the capacity of the existing marine infrastructure can help to provide more realistic estimates of delivery capacity in each period.

## ACKNOWLEDGEMENT

This work was sponsored by Transport Canada's NEXTAW (Network of Expertise on Transportation in Arctic Waters) initiative. We would like to thank NTCL for providing freight volumes data, and the Government of Northwest Territories (GNWT) for their continued support. We would also like to thank Dr. Thian Gan and members of his research group for providing the future Mackenzie River stream flow simulation results.

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