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Rethinking Business-As-Usual: Mackenzie River Freight Transport in the Context of Climate Change Impacts in Northern Canada

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ABSTRACT

The Mackenzie River is a major transportation route serving many remote northern Canadian communities and mining sites. The river is only navigable during the summer and early fall, when clear of ice. However, the river's water conditions have changed significantly in recent years, and are expected to continue to do so, resulting in increased uncertainty for waterway transport. This paper presents a model for providing guidance to shipping companies, customers, and government on how shipping patterns may need to evolve to effectively adapt to changing climate conditions. Future freight volumes are forecasted using time series analysis. Then, logistics cost optimization is used to incorporate predicted water flow profile changes in shipping companies' future delivery schedule planning. Results indicate that future waterway freight delivery capacities in September and October may be insufficient to transport forecasted volumes, and shipping companies may be advised to arrange for increased delivery activities in June and July. If delivery capacities are constrained by equipment and crew availability rather than water conditions in the first half of the shipping season, shipping companies may also need to take advantage of earlier anticipated ice breakup to begin the delivery season earlier. Incorporating this method for climate change adaptation in freight schedule planning may aid both shipping companies and government agencies in rethinking current practices. The method is particularly suitable for a region where harsh environmental conditions, climate change, and extreme remoteness have an overwhelming impact on operations, and logistical delays are considered quite differently from supply chains further south.

***Keywords*:** Inland waterway transportation; climate change impacts; climate change adaptation; freight delivery schedule planning; Arctic transportation; Northern Canada.

1. INTRODUCTION

This paper discusses climate change adaptation needs in freight schedule planning on the Mackenzie River in the Northwest Territories (NWT) of Canada, intending to provide guidance to shipping companies, customers, and government on how freight delivery patterns may need to evolve in order to effectively adapt to future climate conditions. Specifically, we incorporate predicted water flow profile changes in shipping companies' future delivery schedule planning. The Mackenzie River is a major transportation route connecting remote northern communities to southern Canada's transportation network (Mariport Group Ltd., 2011). In recent years, water conditions on the Mackenzie River have changed significantly, threatening this once highly reliable freight delivery route. According to William Smith, VP Logistics and Business Development at the Northern Transportation Company Limited (NTCL), a major shipping company operating on the Mackenzie River, water levels at the north end of the river from August 2014 to the end of the season were significantly lower than previous years (personal communication, December 4, 2015). Consequently, this severely impacted NTCL's tug-and-barge operations, such that deliveries planned to communities located towards the north end of the river did not occur. To adapt to these changing water conditions, shipping companies must consider changes to their delivery strategies and resulting scheduling. Although planning freight deliveries earlier in the season during good water conditions could improve delivery reliability, there are significant internal and external costs to implement such changes. Therefore, balancing the additional costs involved with planning new schedules against the benefits of taking advantage of better water conditions is necessary for greater efficiency.

In this research, we first forecast future freight volumes using time series modeling. Then, delivery capacities are estimated using historical waterway freight data as well as historical and future stream flow profiles. A logistics cost optimization model is developed to determine alternative marine shipping schedules that better align with predicted water conditions, in particular, factoring in the benefits of taking advantage of high water levels and stream flows. We also conduct a sensitivity analysis of the cost function parameters. Numerical results indicate that companies will need to consider changes to freight deliveries historically made towards the end of the delivery season, in order to decrease the likelihood of non-delivery (such as that experienced in 2014[1]). In particular, companies should consider starting the shipping season a few weeks earlier (and take advantage of earlier ice break-up) and place more equipment and crew during the earlier part of the season. The results can help shipping companies, customers, and government agencies better understand how current shipping practices will require rethinking in order to effectively adapt to climate change impacts. It may provide guidance to shipping companies and their customers on how their delivery schedule planning may be modified to better serve future demands in changing conditions. It may encourage government agencies to help facilitate these new delivery schedules by establishing policies to set up marine navigation aids earlier in the season. It also encourages government to support the development

[1] In September and October 2014, water levels on the Mackenzie River near Fort Good Hope dropped to levels significantly lower than previous years, resulting in massive delays and many non-deliveries. This ultimately resulted in large financial losses for the shipping companies.

of alternate modes of transport, to guard against economic losses in cases of unexpected waterway delivery failures in late-season months. This method was developed specifically for this northern context where harsh environmental conditions, climate change impacts, and extreme remoteness overwhelmingly impact operations, and logistical delays are considered quite differently from supply chains further south.

2. BACKGROUND

The Mackenzie River is a major freight transport route in the Northwest Territories (NWT), serving communities and mine sites in both the NWT and Nunavut (Figure 1). The river, which is considered to be ultra-shallow operating conditions, is only navigable when it is clear of ice, from about early June through late-September or early-October. Because of the ultra-shallow conditions, there are several hazard points on the river that are difficult (if not impossible) to pass under low water conditions. Due to the remoteness of this river, there is very little supporting infrastructure; there are no locks, and very few docks. However, the Canadian Coast Guard does install navigational buoys in the spring, after (river ice) break-up, before the start of the summer shipping season.

In 2010, the annual tonnage of freight delivered on the river was estimated to be in the range of 40,000-50,000 tons (PROLOG Canada & EBA Engineering Consultants Ltd., 2010). In addition, due to its the remote northern location and short operating season, there are only several shipping companies that provide freight delivery services on the Mackenzie River. In addition to several very small operators with limited delivery range, there are two major companies operating on the river: Cooper Barging Service Limited (CBSL) and Northern Transportation Company Limited (NTCL) (Transport Canada, 2012). CBSL's river terminal is located in Fort Simpson, while NTCL's is located in Hay River (see Figure 1). However, NTCL has had the most significant share of freight volumes on this river, with about 3-4 times the annual delivery volumes of CBSL (PROLOG Canada & EBA Engineering Consultants Ltd., 2010), as well as the greatest delivery range.

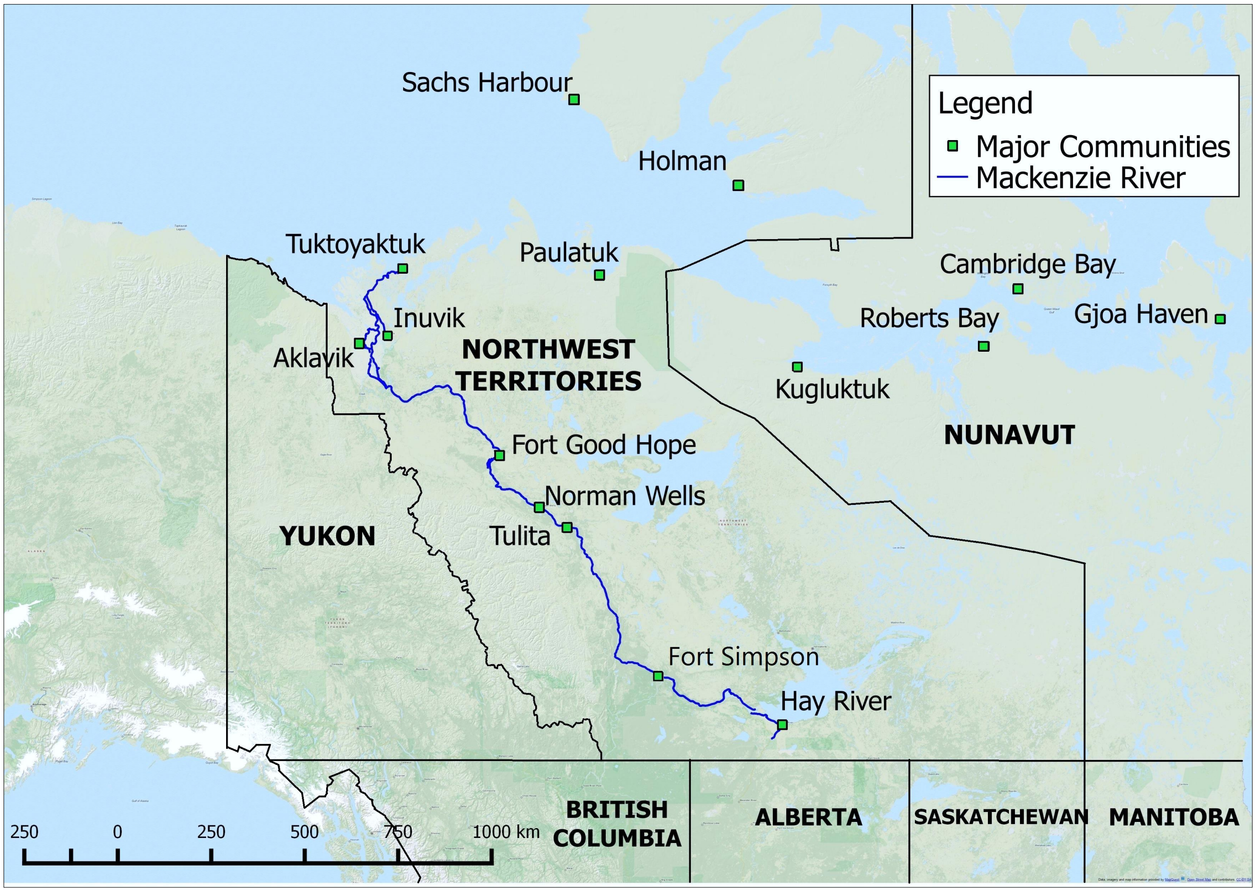


Figure 1: Mackenzie River and key communities, Northwest Territories

Freight is transported on the Mackenzie using tugs and barges. Up to six loaded barges are pushed downstream (i.e. north, towards the Beaufort Sea) by a single tug boat. There are three types of barges used by NTCL (Series 800, Series 1000, Series 1500a/1500b), with maximum loading capacity varying from 900-2200 tons (Northern Transportation Company Ltd., 2016). NTCL has ample storage capacity at their Hay River terminal, with more than 67 acres of indoor and outdoor space (Northern Transportation Company Ltd., 2016).

In addition to the river, freight is also transported in this region by road and air. The road network consists of all-weather roads and winter roads that are typically operated between mid- to late December and early to mid-April of the following year (Department of Transportation, GNWT, 2016a). The road network is very sparse, and consists largely of winter roads; only one-third of the land area in the Northwest Territories is within 100 kilometers of all-weather roads (Department of Transportation, GNWT, 2011a). The Government of Northwest Territories (GNWT) has been investing in the upgrading and expansion of transportation infrastructures, including in the expansion of the all-weather roadway system, to provide better services for local communities and mining activities (Department of Transportation, GNWT, 2016b). An all-weather highway connecting Inuvik to Tuktoyaktuk (Figure 1) is currently under construction, and another all-weather section to connect Wrigley and Norman Wells (the Mackenzie Valley Highway) was in the planning stages (Department of Transportation, GNWT, 2016c) although it was more recently stalled due to funding issues (Quenneville, 2016). The NWT also has 27 government-operated airports to provide year-round links to the rest of Canada and the world (Department of Transportation, GNWT, 2016d; PROLOG Canada & EBA Engineering Consultants Ltd., 2011). However, the unit cost of freight transport by road (all-weather or winter) is about twice that of waterway, while the unit cost via airlift is about 10 times higher (Department of Transportation, GNWT, 2011b). Considering its relatively low cost, historically high reliability during the summer operating months, and good accessibility to remote communities, for many types of high volume goods (exceptions including perishable foods and high-value/low-volume items such as electronics), transport via waterway has been the most cost-effective and reliable method for decades. However, this has come into question in more recent years due to the effects of climate change; hence, investments by government to provide more modal alternatives in the transportation system. Transportation technologies such as airships have also been considered for some time as a potentially viable means of transport, to reduce the high cost of food in the north and support natural resource extraction activities (Prentice, 2016).

Climate change has significantly altered conditions in northern Canada. Due to complex feedback mechanisms in the atmosphere-ocean-ice system in high northern latitudes, the rate of temperature increase in circumpolar Arctic areas is at least twice that of other low altitude areas (IPCC, 2007; Environment & Natural Resources, GNWT, 2008). Compared to global average surface temperature increases, annual temperatures in Inuvik have increased an additional 2.25 Celsius over the past 100 years (Environment & Natural Resources, GNWT, 2008). The warming climate in northern Canada has delayed river freeze-up in the fall and led to thinner ice and an earlier spring melt (Environment & Natural Resources, GNWT, 2008). Additionally, local precipitation patterns have become more variable from year to year (Environment & Natural Resources, GNWT, 2008). Due to these changing precipitation patterns and spring run-off conditions, Aklavik and Fort Good Hope have experienced significant flooding events in the spring and early summer. In addition, low water levels later in the summer and early fall have restricted barge traffic and caused significant delays or cancellations of deliveries to communities (CBC News, 2014). It should be noted that the 2014 summer delivery season was one of the worst on record, and NTCL has been experiencing significant management and operational issues (Quenneville, 2016).

3. LITERATURE REVIEW

Businesses (buyers, suppliers, logistics companies, etc.) have gained greater awareness of the need to address and manage risks in the supply chain network, to improve their resilience in changing and volatile conditions, and ultimately reduce potential financial losses (Jüttner, Peck, & Christopher, 2003; Kırılmaz & Erol, 2017). Supply chain risk management (SCRM) is a relatively new topic (in existence since about 2000) covered in both the academic literature and by the industry (Jüttner, Peck, & Christopher, 2003; Tang & Musa, 2011; Paulsson, 2004). Much of this literature is focused on (often qualitative) solutions from the perspective of suppliers and buyers (Kilubi, 2016). The literature that covers the logistic supply chain itself has been largely relegated to models of network design – namely, where to locate facilities within the supply chain; Jabbarzadeh et. al. (2016) provide an excellent overview of the literature. Despite the importance of this body of literature, its relevance to how to build robust freight delivery networks in highly sparse environments like the NWT under climate change impacts, from the perspectives of (unimodal) shipping companies and the government, is relatively low.

Although the impacts of climate change on inland waterway transportation in northern Canada has been observed for some time (Dillon Consulting Ltd., 2007), particularly with respect to delivery delays and cancellations on the Mackenzie River due to low water levels in late summer and early fall (Environment & Natural Resources, GNWT, 2008), there has been limited research attention to this particular subject. Most previous research studying the relationships between climate change and inland waterway freight transportation costs has focused on rivers in Europe and the U.S., due to the fact that rivers typically carry enormous freight volumes (several scales of magnitude larger than on the Mackenzie), and modal competition (from rail and road) is a serious concern. Because modal competition is limited on the Mackenzie corridor, freight volumes are comparatively small, and the river is very shallow and only navigable 4-5 months of the year, the geographic and operating context of the Mackenzie River is vastly different from those studied in Europe and the U.S. and the existing literature provides limited insight. However, there are still some features that are important to cover here.

Olsen, Zepp, & Dager (2005) indicated that the impacts of shipping cost increases, due to diminished flows and even closures, on the navigability of the Middle Mississippi River may be significant. Hence, they recommended managers to monitor water conditions for significant changes, and engineers to consider different climate scenarios in navigation project feasibility studies. On the Rhine River in Europe, low water levels were observed to have a significant impact on (increased) freight price per ton, but little impact on price per trip, through a regression analysis (Jonkeren, Rietveld, & Ommeren, 2007). The authors estimated low water levels over 20 years could result in an average annual welfare loss of approximately 28 million euros. Beuthe et al. (2014) use simulation to determine transport costs and freight mode shifts to rail and road from the Rhine and Danube, due to lower water depths brought on by climate change. Another study confirmed that ships' carrying capacities may be severely limited under low water levels, which would also increase travel times due to adverse effects on ship hydrodynamics (Schweighofer, 2014). Jonkeren, Jourquin, & Rietveld (2011) constructed several climate change scenarios based on global temperature increases and changes in wind direction, on the Rhine River in the Netherlands. Despite that the Rhine River has historically served as a highly reliable, safe and cost-efficient freight delivery route connecting major ports in the Netherlands and Germany to the hinterlands, the authors found that under extreme climate situations, a significant amount of freight would shift from the river to rail and truck. Koetse and Rietveld (2009) examined the broader empirical literature on the effects of climate change on transport. They discuss the various infrastructure disruptions that can be caused by climate change, noting that changes in temperature and precipitation will lead to lower river water levels.

The total logistics transportation cost function has been used broadly in freight assignment models and as a tool to evaluate the performance of freight transportation networks and delivery plans. Sheffi, Eskandari, & Koutsopoulos (1988) included transportation costs, stationary inventory costs, and in-transit inventory costs in a total logistics transportation cost function to determine mode choice. Daganzo (2005) introduced the holding cost component in addition to handling and transportation costs which includes storage space rent, machinery costs, etc. Additionally, Rodrigue, Comtois & Slack (2013) included terminal cost, line-haul cost, and capital cost in their function. In summary, various cost components are included in the cost function depending on application purpose; however, handling and transportation costs are always included.

In this paper, we introduce a freight delivery context not commonly covered in the existing literature, and provide a method for managing freight transportation risks (of non-delivery and delays). More specifically, our method incorporates predicted water flow profile changes into shipping companies' future delivery schedule planning. In addition to handling and transportation costs, rescheduling and delay costs are introduced to account for the additional cost of implementing new schedules and the benefit of utilizing good water conditions. This work is meant to provide assistance and support for future schedule planning activities by freight companies, and policy decisions on waterway (and other transport system) operations for governments.

4. FREIGHT DATA ANALYSIS

In this section we present forecasted future freight volumes on the Mackenzie River, based on historical freight data (2002-2015) provided by NTCL. The historical data was used to identify the major destinations served via waterway, freight volumes to these major destinations, and total volumes delivered. A seasonal Kendall trend test was applied to determine if monotonic trends existed in the volumes. Then, ARIMA models and intervention analysis were used to estimate future freight volumes.

4.1 Data set

Freight volumes delivered by NTCL to communities along the Mackenzie, between January 2002 and July 2015, were extracted from tow letters provided by NTCL. The tow letters provided a rich set of information, including tug and barge departure dates from Hay River (NTCL's main southernmost terminal, see Figure 1), type of freight carried, freight volumes, and more. Although NTCL is one of several operators on the Mackenzie, it has an overwhelming share of the volume of freight delivered, and the largest geographic coverage by far.

More than 70 destinations are identified in the tow letters. Based on the total volumes and frequency to destinations between 2002 and 2015, 14 major destinations – to which more than 90% of total freight volumes are destined – are identified (Figure 1). Six are on the Mackenzie River, including Tulita, Norman Wells, Fort Good Hope, Aklavik, Inuvik, and Tuktoyaktuk. The remainder (Sachs Harbour, Holman, Paulatuk, Kugluktuk, Roberts Bay, Cambridge Bay, Gjoa Haven, and Taloyoak) are in the north Inuvik and Kitikmeot regions. Freight destined for these eight destinations must be transshipped at Tuktoyaktuk from river barge to ocean going barge. Because this work focuses on Mackenzie River operations, all major locations beyond Tuktoyaktuk are combined into a single destination entitled "Arctic Region". The tow letters also classify freight into two major classes: fuel and dry cargo. Dry cargo includes items such as construction materials, mining equipment, non-perishable food items, personal vehicles, etc. Twice-monthly fuel and dry cargo volumes to all destinations are analyzed as time-series from 2002 to 2015.

4.2 Seasonal Kendall trend test

Trend tests are applied to determine whether upwards or downwards trends are present in a dataset. The results can provide guidance on choosing appropriate models for further analysis. Because the Mackenzie River freight volumes exhibit annual seasonality, the seasonal Kendall trend test was used to assess whether a statistically significant monotonic (increasing or decreasing) trend is present in the dataset over time (Hirsch, Slack, & Smith, 1982).

The seasonal Kendall trend test results indicate that the volumes transported by NTCL have a decreasing trend significant at a 99% confidence level. However, destination-specific volumes for Tuktoyaktuk and the Arctic Region only show significant decreasing trends (99% confidence). Since the summer of 2008, there has been an expansion in sealift services to the Kitikmeot communities (Nunavut) via the Northwest Passage (Around Nunavut, 2008). According to Darren Locke of the Government of the Northwest Territories (personal communication, November 24, 2015), in 2008, new scheduled services from Eastern Canada through the Northwest Passage reduced NTCL's deliveries to these regions.

4.3 ARIMA model and intervention analysis

Autoregressive Integrated Moving Average (ARIMA) models are used to represent and forecast data in stationary time series, which have constant means, variances, etc., over time. A non-stationary series can be transformed into a stationary one through differencing (O'Connell & Koehler, 2005). Several different models (including logistic regression) can and have been used to model data with seasonality. However, regression models require data for explanatory variables, which would include water levels amongst many others describing the demand (and capacity) behind the realized volumes. Given the absence of this information, we chose to fit a seasonal ARIMA model, and then forecast freight volumes transported on the Mackenzie River.

Since the trend test identified a shock in 2008, observed with a significant decrease in total volumes after 2008, a transfer function (T_f) is added to the ARIMA model to represent the impact of this shock (Eq. 1):

$$T_f = \omega I_t \tag{1}$$

where ω is the intervention parameter, representing the expected change of the mean before and after the intervention, and I_t is a step function specified in Eq. 2:

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

where T is the intervention year; in our case, $T = 2008$.

As described previously, freight is categorized as fuel or dry cargo. Seasonal ARIMA models are applied on both fuel and dry cargo volumes transported by NTCL. Because freight volumes are assessed on a twice-monthly basis, each year is divided into 24 periods. The ARIMA model (with transfer function) applied to both fuel and dry cargo volumes is specified in Eq. 3:

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

where y_t is the original observation (of volumes) in time period t; a_t represents white noise in t, $a_t \sim N(0, \sigma^2)$, and φ is the parameter for the seasonal autoregressive model. The estimated values for φ and ω, for both fuel and dry cargo volumes, are shown in Table 1.

Table 1: Parameter Estimates for ARIMA Model and Transfer Function

	Fuel		Dry Cargo	
	value	p-value	value	p-value
φ	-0.462	<0.0001	-0.575	<0.0001
ω	-830.11	0.1014	-314.98	0.0096

The parameters are estimated using maximum likelihood. Although the other parameters are highly statistically significant, the p-value of ω for fuel is 0.1014, indicating that it is statistically significant at just below 90% confidence level. Despite its borderline marginal significance, we still retain the term for our forecast. Also, all ω values are negative, indicating that fuel and dry cargo volumes, on average, decreased after 2008. The absolute values indicate that fuel volumes decreased about 830 tons per half-month after 2008, while dry cargo volumes dropped about 315 tons per half-month. Using the above ARIMA model parameters, forecasts of fuel and dry cargo volumes are obtained for the year 2025 (Figure 2). Note that Figure 2 shows volumes as a proportion of the historical maximum annual volume instead of absolute volumes, to protect NTCL data confidentiality.

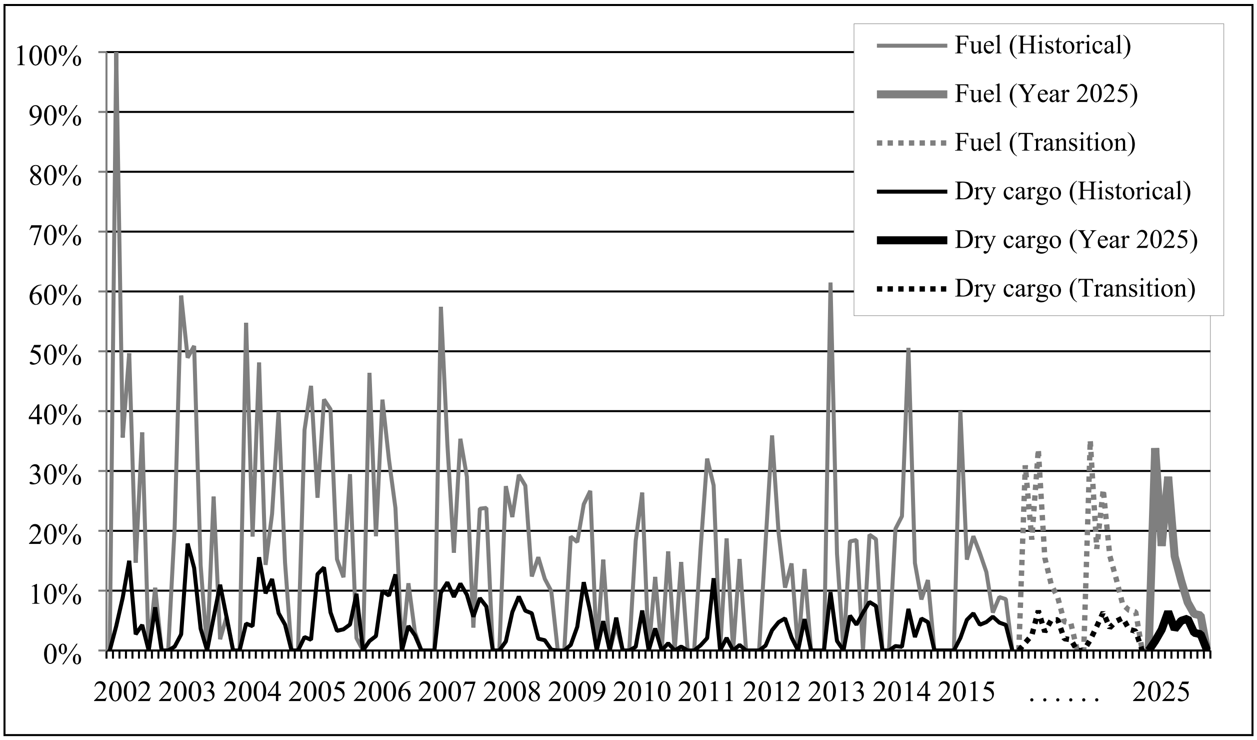


Figure 2: Historical and forecast waterway freight volumes.

It is observed that the large majority of cargo volumes transported by NTCL on the Mackenzie River consists of fuel. The 2025 forecast volumes are used as the base schedule in the following analysis. It represents anticipated twice-monthly freight delivery volumes if a shipping company like NTCL were to continue with "business as usual" freight delivery activities in 2025.

5. SCHEDULE PLANNING MODEL

In this section, in following other uses of the total logistics cost function (Daganzo, 2005), we present an optimization model that incorporates forecasted future water conditions (as a result of climate change) in freight delivery strategy planning on the Mackenzie River. The results of model application to two capacity scenarios, as well as a sensitivity analysis of the model's key input parameters, are also presented.

5.1 Generalized cost function and optimization model

According to William Smith of NTCL (personal communication, December 4, 2015), fuel and dry cargo deliveries for mining and other industrial operations are often contracted well in advance of the summer delivery season (6 months to 1 year), and make up a large majority of the cargo volumes seen on the Mackenzie. However, delivery requests for community supplies, personal vehicles, residential building materials, etc. are variable and not often known well in advance, making early planning difficult (despite their relatively small volumes). Therefore, for our modeling purposes, we have assumed three types of freight: fuel, contracted cargo, and "unscheduled" cargo. Since deliveries of the first two types are usually known well in advance, we assumed that it would be easier (i.e. cheaper) for a shipping company to reschedule this freight compared to the latter. Let us say that q represents freight type ($q = 1$ is fuel; $q = 2$ is contracted cargo; $q = 3$ is "unscheduled" cargo). As mentioned above, "unscheduled" cargo volumes are typically very small compared to fuel and contracted cargo volumes. However, due to a lack of information on the exact proportions of each type of cargo, we assume for modeling purposes that 90% of all dry cargo is contracted while 10% is "unscheduled", and that this remains true in 2025 (of course, this depends heavily on the future of mining and petroleum explorations in the NWT).

The model is built on an abstracted and simplified network, with one origin and destination connected by a single waterway route. We define $d_{i,j}^{q}$ to represent the volume (in tons) of freight q "rescheduled" from time period j to period i, and denote the delayed volume (volume not successfully transported within the required time period) of q in period i as l_i^q. If the capacity of q $\left(C_i^q\right)$ is larger than the total volume requiring transport in period i (which includes volumes assigned to this period, $\sum_j d_{i,j}^{q}$, and volumes delayed from the preceding period, l_{i-1}^{q}), then l_i^q is zero, as all freight demanding transport in this period is successfully delivered. Otherwise, l_i^q equals the total volume requiring transport minus the actual volume transported (equaling capacity). Let us set $l_0^q = 0$, meaning that the season does not start with freight undelivered from the previous year. Then, l_i^q can be defined as shown in Eq. 4:

$$\mathrm{l}_i^q = \begin{cases} 0 & \text{if } \mathrm{l}_{i-1}^{q} + \sum_j \mathrm{d}_{i,j}^{q} \leq \mathrm{C}_i^q \\ \mathrm{l}_{i-1}^{q} + \sum_j \mathrm{d}_{i,j}^{q} - \mathrm{C}_i^q & \text{if } \mathrm{l}_{i-1}^{q} + \sum_j \mathrm{d}_{i,j}^{q} > \mathrm{C}_i^q \end{cases}, \ (\mathrm{i} = 1,..,\mathrm{I}) \tag{4}$$

Where I is the final annual time period, such that $I = 24$ represents the second half of December.

Since the total volume requiring transport may either be delivered during the assigned period or delayed to a subsequent one, the summation of delayed volume (l_i^q) and transported volume (denoted as v_i^q) in period i always equals the total volume requiring transport in this period ($l_{i-1}^{q} + \sum_j d_{i,j}^{q}$). Then, v_i^q can be defined as:

$$\mathrm{v}_i^q = \mathrm{l}_{i-1}^{q} + \sum_j \mathrm{d}_{i,j}^{q} - \mathrm{l}_i^q \tag{5}$$

A total generalized cost function is developed with the quantities defined in Eqs. 4 and 5, for use as our objective function. There are four components to consider in this cost function: handling (C_H), accounting for costs associated with loading/unloading freight; travel (C_T), representing fuel consumption, labor, transport time, etc.; C_R, cost associated with moving freight to a different time period; and delay (C_D), which assigns a cost to delayed freight (i.e. delivered in a time period later than the one originally intended) and freight undelivered by the end of the marine delivery season. Therefore, the total generalized cost function is expressed as:

$$\mathrm{C} = \mathrm{C}_H + \mathrm{C}_T + \mathrm{C}_R + \mathrm{C}_D \tag{6}$$

We assess all costs in day·tons.

The impacts of delivering freight in poorer water conditions are reflected in two aspects of this cost function. Firstly, if water levels drop at a faster rate through the delivery season, it is likely that water levels in late September and early October will be poor for tug and barge operations. In turn, freight intended to be transported at this time are more likely to experience delay and non-delivery. By rescheduling these late-season volumes to an earlier period, delays and non-deliveries may be significantly reduced. Secondly, the travel time of a tow (tug and barges) in good water conditions (i.e. high water levels) is smaller than in less-ideal conditions. This is because barges must be anchored and pushed one by one through hazard sections (rapids and ramparts) when water levels are low (Department of Transportation, GNWT, 2011b).

Handling cost is a linear function of the total volume transported within the delivery season for each freight type (Eq. 7), while travel cost is a linear function of total travel time in each period (Eq. 8):

$$(C_H)_i^q = \alpha^q \cdot v_i^q \ (i = 1,2,\ldots I) \tag{7}$$

where α^q represents the time spent to handle freight q at terminals (days), and

$$(C_T)_i^q = t_i \cdot v_i^q \ (i = 1,2,\ldots I) \tag{8}$$

where t_i is the averaged travel time for a single trip in period i (days).

Rescheduling cost, defined in Eq. 9, is considered to be a function not only of the freight volume rescheduled from other time periods, but also the amount of time that freight is scheduled earlier/later compared to the base schedule.

$$(C_R)_i^q = \vartheta^q \cdot \sum_j \left(t_{i,j} \cdot d_{i,j}^q\right) \ (i = 1,2,\ldots I) \tag{9}$$

Where, ϑ^q is a parameter representing demand uncertainty of freight type q (the higher the value, the more costly it is to reschedule). We have assumed that this parameter value for fuel and contracted cargo is low because deliveries are typically planned out well in advance. However, because demand for "unscheduled" cargos $(q = 3)$ is more uncertain, we assume that ϑ^3 is much higher $(\vartheta^3 \gg \vartheta^1, \vartheta^2)$. Parameter $t_{i,j}$ represents the number of time periods between i and j (in days).

Delay costs (C_D) consist of two types of costs. If freight cannot be delivered within the period scheduled, it may still be delivered in subsequent periods before the end of the water delivery season (i_{end}). The cost for such delays is represented by the first part of Eq. 10. However, if freight is not delivered by i_{end}, it is considered a non-delivery, as it must wait to be transported either by winter roads or in the following summer delivery season. The cost of non-delivery is included in the second part of Eq. 10. To avoid double counting the non-delivery delay cost, this type of delay will be only taken into account once in the last delivery season time period (I). Therefore, for time periods between i_{end} and $I - 1$, delay cost is zero (third part of Eq. 10).

$$(C_D)_i^q = \begin{cases} \varphi_1 \cdot \Delta_i \cdot l_i^q, & (i = 1,2,\ldots i_{end} - 1) \\ \varphi_2 \cdot l_{i_{end}}^{\ q}, & (i = I) \\ 0, & (i = i_{end},\ldots I - 1) \end{cases} \tag{10}$$

φ_1 and φ_2 represent the unit costs of delays and non-deliveries (the higher the values, the higher the cost attributed to delays and non-deliveries), respectively, while Δ_i is the delay for freight that cannot be delivered in period $i - 1$ and must wait for delivery in period i (in days). We assume that if freight is delayed for a period, it is delayed $\frac{L_i}{2}$, where L_i is the length of time period i.

The optimization model (Eq. 11) minimizes the total logistics cost (Eq. 6). Since capacities have been estimated for fuel and dry cargo (the latter which includes both contracted and "unscheduled" cargos), here we use Q to represent either fuel (indicated as cargo type 1) or dry cargo (cargo type 2) for delayed volumes $\left(l_i^Q\right)$ and delivery capacities $\left(C_i^Q\right)$.

$$\text{Min C} = \sum_q \sum_i ((C_H)_i^q + (C_T)_i^q + (C_R)_i^q + (C_D)_i^q) \tag{11}$$

Subject to:

$$d_{i,j}^q \geq 0, \forall i,j,q \tag{12}$$

$$\sum_i d_{i,j}^q = p_j^q, \forall j, q \tag{13}$$

$$l_0^Q = 0, \forall Q \tag{14}$$

$$l_i^1 = \max\left(0, l_{i-1}^{\ 1} + \sum_j d_{i,j}^1 - C_i^1\right), \forall i \tag{15}$$

$$l_i^2 = \max\left(0, l_{i-1}^{\ 2} + \sum_{q=2}^{3} \sum_j d_{i,j}^q - C_i^2\right), \forall i \tag{16}$$

The ARIMA model forecasted volume of freight q (tons) in period j is represented by p_j^q. Eq. 12 stipulates that volumes rescheduled from period j to i are non-negative. Eq. 13 specifies that in the new schedule all freight rescheduled from period j (even if divided up and rescheduled to multiple periods) should equal the total volume originally assigned to period j in the base schedule. Eq. 14 ensures that the season does not start with undelivered dry cargo or fuel. Eqs. 15 and 16 specify that l_i^Q $(Q = 1 \text{ or } 2)$ is always the largest of zero or the total volume requiring transport $(l_{i-1}^{\ Q} + \sum_q \sum_j d_{i,j}^q)$ minus the delivery capacity (C_i^Q).

5.2 Numerical Analyses

In this section, we determine future planning-level freight delivery scheduling strategies under anticipated climate change impacts, using the optimization model introduced in Eqs. 11-16. A sensitivity analysis is also conducted to investigate the impacts of input parameter values to the optimization results.

5.2.1 Inputs and assumptions

Since loading/unloading time is typically 1-2 days per origin/destination, it was assumed that the time spent for loading/unloading per trip is $\alpha^q = 4$ days (Eq. 7). According to the Canadian Coast Guard, tug-and-barge speeds are lower at lower stream flows and water levels (Canadian Coast Guard, 2013). However, there is no empirical information on the relationship between stream flow and vessel travel speed. Therefore we assume that if the predicted stream flow in one period is 3000 m^3/s less than the maximum stream flow, travel time in this period will increase 15% due to reduced travel speeds. Parameter ϑ^q reflects the demand uncertainty for freight type q; the higher the value, the more costly it is to reschedule q. Since "unscheduled" cargo has higher demand uncertainty than fuel and contracted cargo, we assume $\vartheta^1$and ϑ^2 are 1, while ϑ^3 is 2. Parameters φ_1 and φ_2 represent the costs of transport delays and non-deliveries in Eq. 10. Due to a lack of information for populating φ_1 and φ_2, we assume values of 2 and 200 respectively to reflect that 1) the consequences of delays are severe and therefore costly, and 2) the consequences of non-delivery within the shipping season are far more severe than transport delays. In Section 5.2.4 we explore the sensitivities of the model results to these parameter values.

5.2.2 Estimates of delivery capacities

We further assume that tug-and-barge delivery capacities are only restricted by water conditions, and adequate equipment and crew are always available and ready. Future delivery capacities in each period are estimated based on historical volume data, provided by NTCL, as well as historical and future predicted stream flow profiles provided in a research report for Transport Canada (Gan, Kuo, Scheepers, Pervin, & Wang, 2016). The predicted stream flow profile for 2025 was observed to increase and decrease about two weeks earlier than the historical profile. By combining historical freight volumes and stream flow data, we observed that no deliveries occurred when stream flows were lower than 6000 m^3/s. We also assume that delivery capacities are greater at higher stream flows. Hence, we represent period delivery capacities using Eq. 17:

$$C_k^q = \begin{cases} \frac{V_{k+1}^q}{H_{k+1}} \cdot P_k & \text{if } P_k \geq 6000 \\ 0 & \text{if } P_k < 6000 \end{cases} \tag{17}$$

where C_k^q represents the predicted capacity for freight q in period k (in tons per period); $V_{k+1}^{\,q}$ is the historical capacity for q in $k+1$ (tons per period); P_m represents the predicted stream flow in period k (m^3/s), and H_{k+1} is the historical stream flow in period $k+1$ (m^3/s). Note that we use k to represent periods here, differentiating representation of periods from which freight can be rescheduled from (i) and to (j). Capacity is often considered a random variable; the average, median, or values in a certain percentile can be chosen as the deterministic capacity (Minderhoud, Botma, & Bovy, 1997). Here, historical twice-monthly volumes in the 85th percentile are chosen as the deterministic historical capacities. Figure 3 (where May2 and Jun.1 represent the second half of May and the first half of June respectively, and so on) shows projected year 2025 capacities for May2 to Aug.2. 2025 waterway delivery capacities are otherwise projected to be zero throughout the year, due to the stream flows in these months being lower than 6000 m^3/s. This includes the months of September and October. It can be observed in Figure 3 that, based on water conditions alone, delivery capacities are greatest in June and the first half of July.

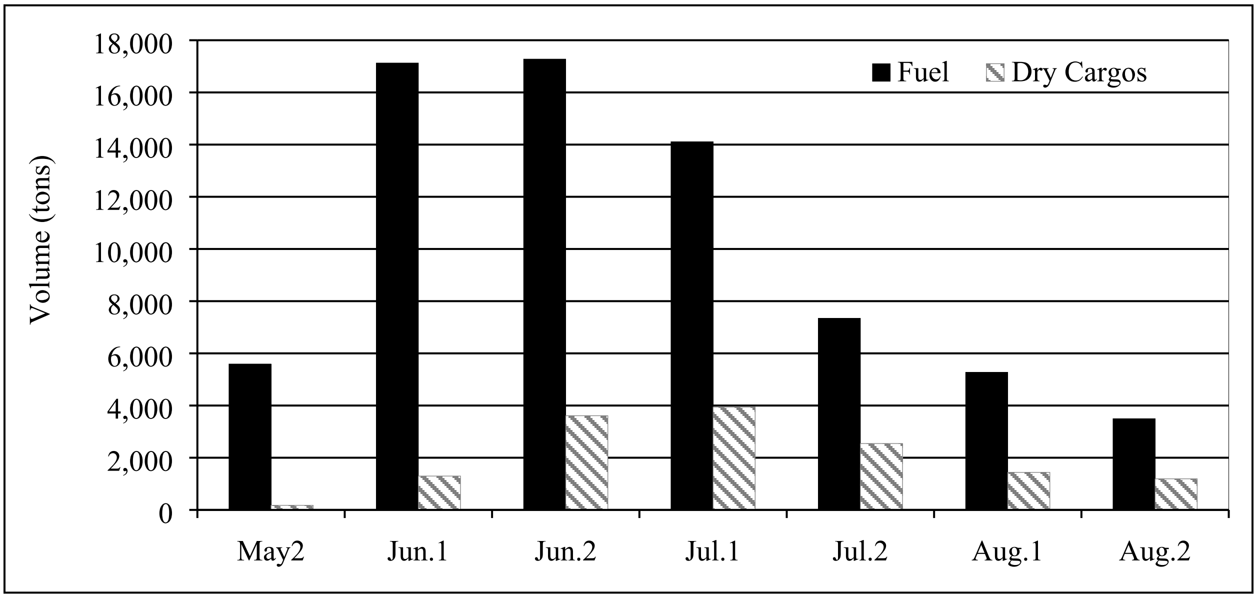
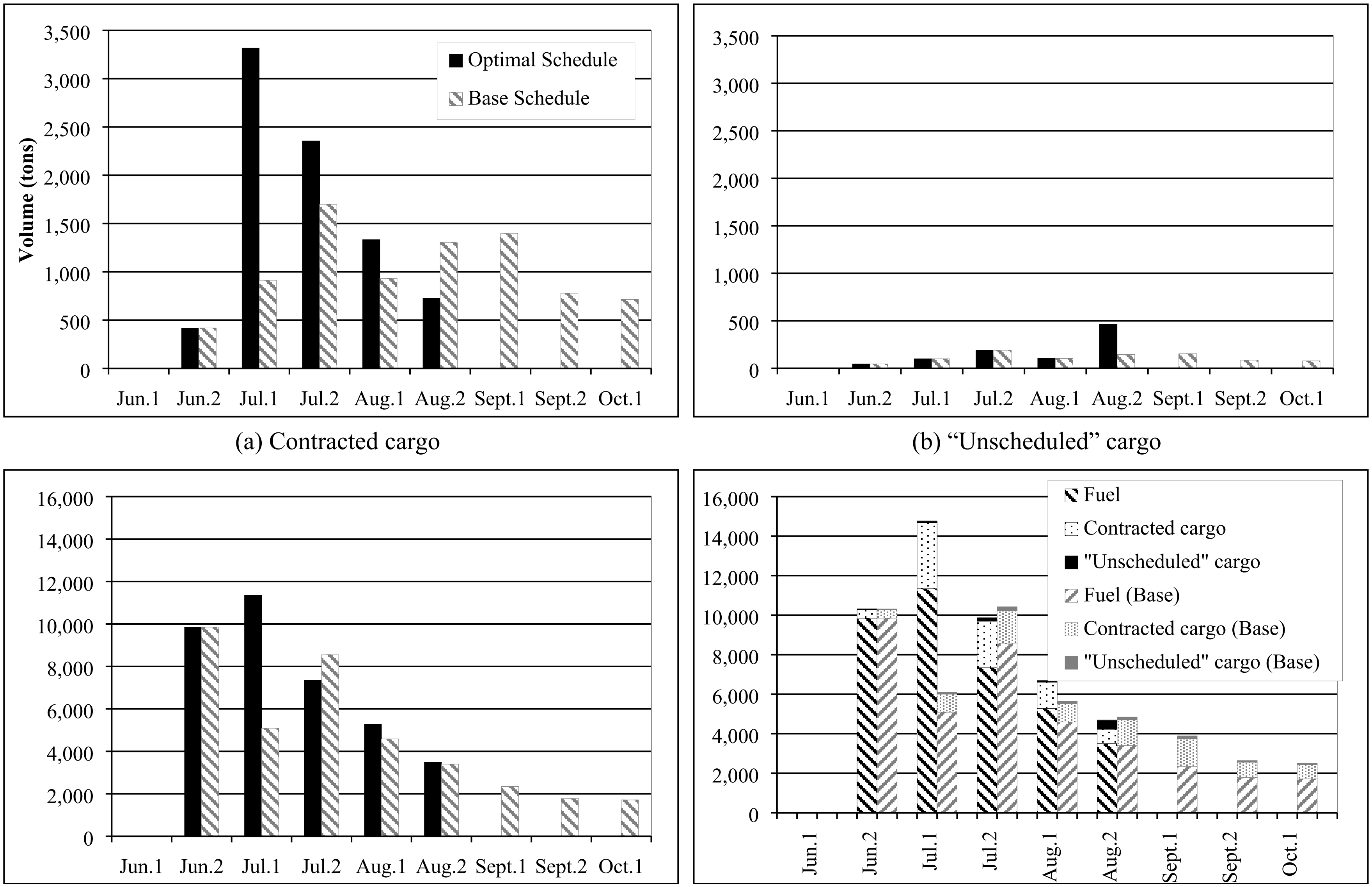


Figure 3: Predicted 2025 capacities (per half-month period) for fuel and dry cargo.

5.2.3 Numerical Results

A new high-level delivery plan for the year 2025, accounting for changes to stream flow, is obtained using the optimization model introduced in 5.1. The total cost (Eq. 6) of the optimal schedule is about 40% lower than that of the base schedule. The results are shown in Figure 4. Let us reiterate here that the results are not meant to determine specific future delivery scheduling strategies, but rather, to demonstrate to shipping companies, customers, and government that they must consider the need for climate change adaptation measures in the waterway freight system – specifically, actions to accommodate freight deliveries earlier in each season than currently done.



(a) Contracted cargo

(b) “Unscheduled” cargo

(c) Fuel

(d) Total

Figure 4: 2025 schedule planning results.

Again we observe that fuel makes up the dominant proportion of cargo volumes on the Mackenzie River. We further observe that all freight assigned to September and October in the base schedules (for all freight types) have been moved to earlier periods in the delivery season. Because capacity in late July and August is also impacted by reduced stream flows, some freight originally meant for delivery in September and October were rescheduled even earlier to late June or early July, to ensure successful delivery. Hence, freight volumes in the first half of July (Jul.1) are significantly higher than other periods within the season. These results suggest that future capacities in September and October are insufficient to transport freight currently expected for delivery in those late-season months.

Secondly, since "unscheduled" cargo is more difficult to reschedule than contracted cargo, "unscheduled" cargo originally assigned to September and October are first arranged for delivery in the latest periods allowable (Figure 4(b)). To ensure that the dry cargo delivery capacity in this period is not exceeded, some contracted cargos originally assigned to this period are then rescheduled to earlier periods to accommodate "unscheduled" cargo (Figure 4(a)). Also, in the optimized schedule, the summer water delivery season begins in the second half of June (Jun.2), unchanged from the current schedule. This indicates that it may not be necessary to begin the season earlier; instead, shipping companies can arrange a more intense delivery schedule through June and July. For instance, companies may want to fully utilize the capacities dictated by water conditions in July, to ensure successful deliveries of freight originally assigned to late season months.

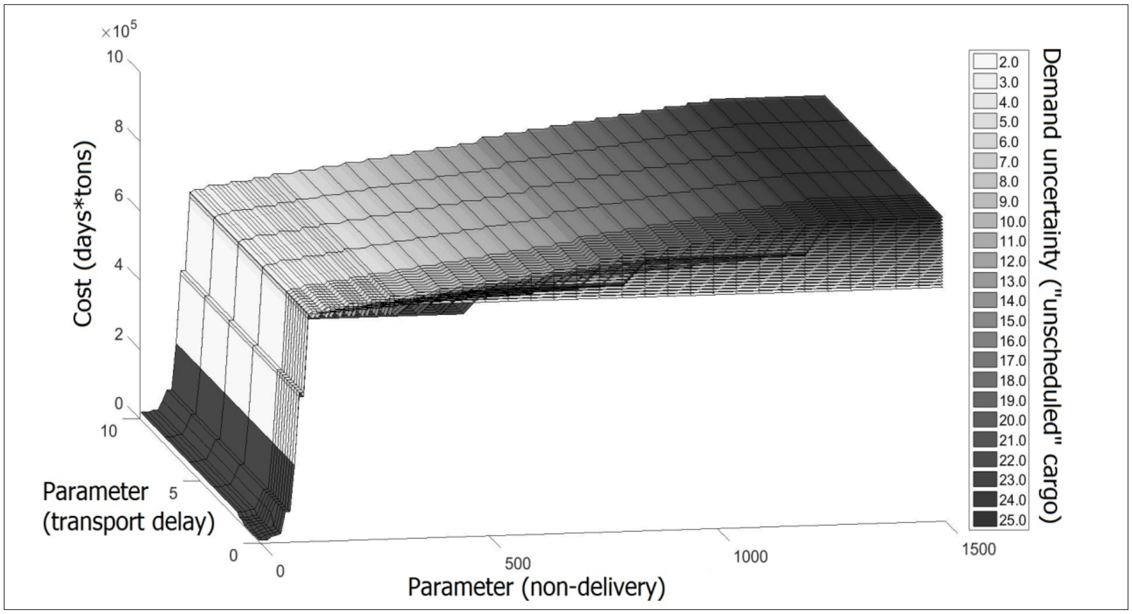
Thirdly, we go back to the big spike in optimized contracted and fuel cargo volumes observed in the first half of July (Jul.1). The optimized volumes assigned to Jul.1 are approximately three times that of the base schedule, and is due to the fact that capacities in the first half of July (as dictated by water conditions alone) are quite high compared to the projected volume levels of the base schedule. As a result, the optimization will assign more volumes to this time period. However, given the excellent water conditions at this time, capacity may in fact be constrained by companies' equipment and crew availability, and customers' storage capacities, in addition to other logistical considerations, rather than water levels. As a result, we explore this further in Section 5.2.5. These results are useful in demonstrating that shipping companies and their customers should consider planning their freight demand and deliveries as early as possible, and government agencies should consider supporting further development of alternate transport modes in case of waterway freight delivery failures in late-season months, to reduce both non-deliveries of freight and financial losses.

5.2.4 Sensitivity Analysis

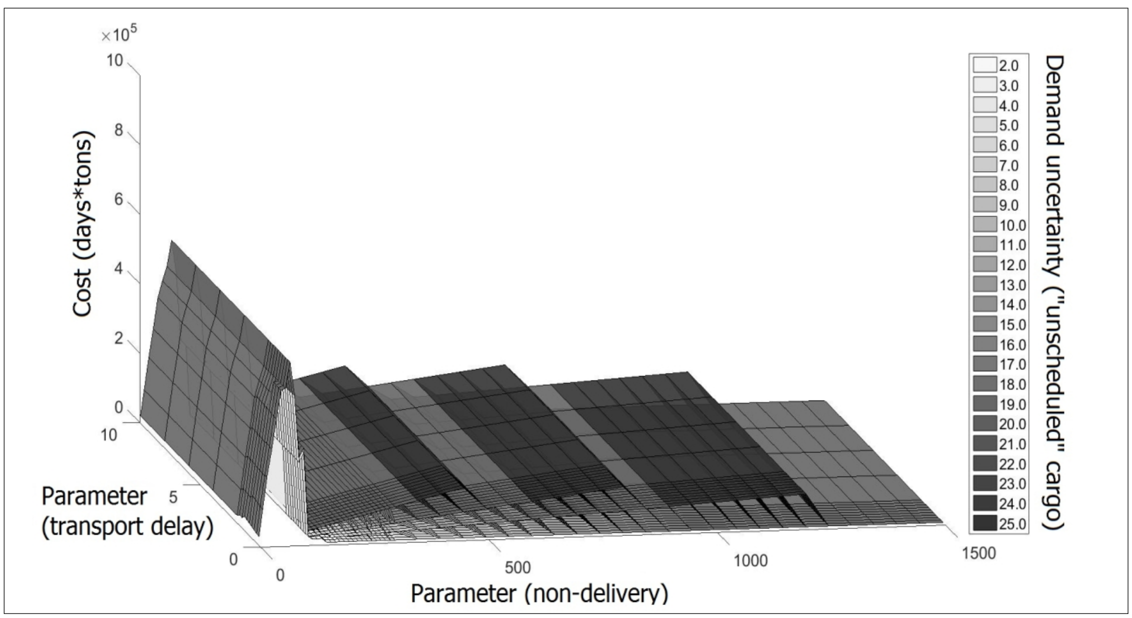
A sensitivity analysis is conducted to assess how the values of the parameter for demand uncertainty of "unscheduled" cargo (ϑ^3), cost parameter for transport delay (φ_1), and cost parameter for non-delivery (φ_2) impact schedule optimization. Since demand uncertainty of fuel (ϑ^1) and contracted cargo (ϑ^2) are set at 1 (representing relatively low rescheduling difficulty) in the numerical analysis, the same parameter for "unscheduled" cargo (ϑ^3) should be larger than 1 to reflect the greater difficulty of rescheduling "unscheduled" cargos. Therefore, ϑ^3 values from

2 through 25 are explored, with step size 1. The range of values explored for φ_1 is 0.2 to 10, using a step size of 0.2 from 0.2 to 2, and 2 from 2 to 10. The range explored for φ_2 is 10 to 1500, with step size 10 between 10 and 300, and 50 between 300 and 1500.

Figure 5 shows the optimization results with respect to rescheduling cost (Figure 5a) and delay cost (Figure 5b). The different cost parameters values of "unscheduled" cargo uncertainty (ϑ^3) are represented by shades varying from white to black as shown to the right of the chart. Values of the parameters for transport delay (φ_1) and for non-delivery (φ_2) are represented on the z and x axes, respectively. It can be observed that both rescheduling and delay costs change little as the parameter for transport delay changes, suggesting that scheduling solutions are not very sensitive to this parameter. However, when the non-delivery parameter is larger than 80, the total cost results for different values of unscheduled cargo uncertainty (ϑ^3) begin to differentiate, as seen in the emergence of the "layers". In Figure 5a, some layers remain flat, indicating that increasing values of the transport delay and non-delivery parameters do not impact rescheduling costs. It can also be observed that darker layers (higher values of ϑ^3) level out at larger values of the non-delivery parameter. The reason is that the larger the values for ϑ^3, the greater the rescheduling cost, and hence, the greater the benefits needed to overcome these costs. The cost benefits are primarily due to the avoidance of non-deliveries, as the volumes are successfully rescheduled and delivered at an earlier time. Moreover, if the benefits of rescheduling volumes of freight type q to an earlier period (i.e. from j to i) are greater than the rescheduling costs, it is worth rescheduling q. As shown in Figure 5b, at a certain critical value of the non-delivery cost parameter, the benefits of rescheduling certain types of freight begin to outweigh rescheduling costs. It becomes cost-effective to reschedule portions (or all) of cargo type q to other periods with available capacity, resulting in a steep drop in delay costs (shown in Figure 5b).



(a) Rescheduling costs



(b) Delay costs

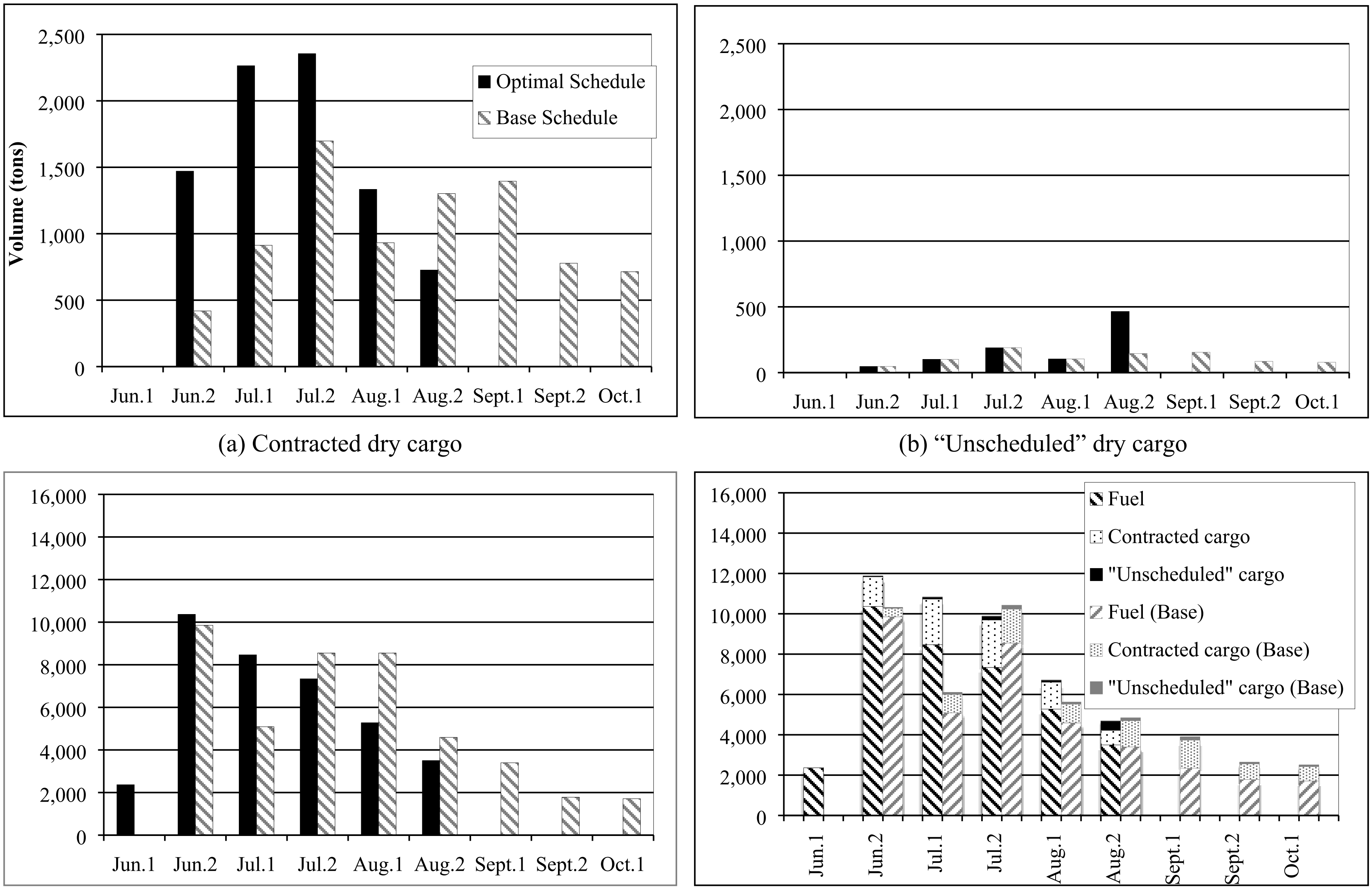
Figure 5: Sensitivity analysis results.

To summarize, this sensitivity analysis reveals that 1) optimal solutions are not highly sensitive to the transport delay parameter (φ_1); 2) the larger the "unscheduled" cargo demand parameter (ϑ^3), the larger the benefits required to compensate for rescheduling "unscheduled" cargo; and 3) delay costs drop sharply rather than continuously, as the non-delivery cost parameter increases, reflecting parameter thresholds where the optimization model provides a more drastic reallocation of volumes to minimize costs, and where delay cost savings of rescheduling freight outweigh the actual cost of rescheduling.

The results highlight a need for more research on the difficulties of schedule planning under uncertain future demand and climate change impacts, and empirical studies on how to determine appropriate parameter values in total logistics transportation cost models.

5.2.5 Alternative scenario

In the previous scenario, delivery capacities in June and July are very high as we assume they are dictated by water conditions alone – unencumbered by logistical considerations such as equipment, crew, and storage availability constraints. As a result, significant freight volumes were rescheduled from later months into June and July – particularly the first half of July, which experienced a great spike in volumes. However, during the early part of the season when excellent water conditions allow for much shipping activity, it is more likely that delivery capacity is limited by logistical elements such as equipment, crew and storage. Therefore, we explore an alternate scenario where delivery capacities in the earlier half of the season (June and July) are restricted by these logistical constraints. We assume that capacities in June and July are limited to 60% of the previously estimated capacities based on water conditions alone (see Figure 3). The capacities for all subsequent months remain the same as in the previous analysis. The results of this capacity constrained scenario are shown in Figure 6.



(a) Contracted dry cargo

(b) “Unscheduled” dry cargo

(c) Fuel

(d) Total

Figure 6: 2025 schedule planning results, alternative scenario.

The total generalized cost of the optimal schedule in this alternate scenario (with more limited capacities in June and July) is about 8% greater than that of the previous scenario. As shown in Figure 6, re-assignment of "unscheduled" cargo remains the same as in the previous scenario due to the difficulty (i.e. high cost) of rescheduling. As for fuel and contracted cargo, since the capacities in June and July have been reduced, volumes that were concentrated into the first half of July (Jul.1) in the previous scenario have been reassigned even earlier into June. About 1000 tons of contracted cargo was assigned to the second half of June (Jun.2 – Figure 6(a)) instead of the first half of July (Jul.1) as in the previous scenario. Moreover, some amount of fuel is assigned as early as the first half of June (Jun.1 – Figure 6(c)), which was not done in the previous scenario. Historically, the summer shipping season has opened sometime during the first half of June, or even in the second half. In this further constrained scenario, we observe the need to open the shipping season earlier than usual, and take advantage of earlier ice break-up and high water levels.

Overall, the results suggest that continuing with current delivery season opening dates in the future may not allow for adequate capacity to successfully transport NTCL's projected freight volumes, under projected water levels coupled with logistical constraints. As a result, the summer shipping season may need to open earlier to accommodate these demands. However, the season start date is dependent on when the Canadian Coast Guard finishes installing navigational buoys once waterways are clear of ice. Therefore, these results may encourage governmental agencies to more closely consider their schedules for setting up navigational aids and buoys in the late spring/early summer.

6. CONCLUSIONS & FUTURE WORK

This research provides an assessment on how climate change may impact shipping scheduling strategies on the Mackenzie River in future years. It also provides guidance and suggestions to shipping companies, customers, and the government on how shipping patterns may need to evolve in order to effectively adapt to future climate conditions. Freight volume data are first analyzed and forecasted using time series analysis methods. Then, an optimization model is developed to incorporate predicted future water flow profile changes in shipping companies' delivery schedule planning. A numerical analysis is conducted for two capacity scenarios, as well as a sensitivity analysis of input parameters. The results indicate that waterway freight transportation capacities in September and October of the year 2025 may be insufficient to deliver freight successfully in those late-season months, and that good water conditions in June and July will need to be better utilized in order to accommodate projected shipping demands. The sensitivity analysis results emphasize the need for more research on the difficulties of schedule planning under uncertain future demand and climate change impacts, and empirical studies on how to determine appropriate parameter values in total logistics transportation cost models. In particular, the results highlight the larger impacts of uncertain demand compared with other logistics cost components.

The results of this work can help shipping companies, customers, and government agencies better understand how current shipping practices may need to be revised, in effectively adapting to the impacts of climate change. Shipping companies may consider starting the shipping season a few weeks earlier (by taking advantage of earlier ice break-up and higher water levels), place more equipment and crew during the earlier part of the season (again, to take advantage of good water conditions), or both. However, because the season start date is dependent on when the Canadian Coast Guard finishes installing navigational buoys, private operators like NTCL will need to work very closely with government to ensure an efficient and timely start to each delivery season. In addition, government agencies can help facilitate a more reliable freight transportation system in the NWT, through the setting of appropriate policies and regulations, and investments in infrastructure for alternate freight delivery modes. The results also suggest that customers may consider offsetting the risk of delays and non-deliveries later in the summer delivery season, by planning for earlier delivery and storage.

There are several ways by which this work may be extended and improved. Firstly, the modeling work can be improved through application of a network-level model that considers multiple destinations. Secondly, more consultation and cooperation with companies such as NTCL will be helpful in setting a cost model that more realistically reflects real operational considerations and challenges. Thirdly, a stochastic optimization model may be developed to account for variations in inputs and shipping conditions. Fourthly, delivery capacities estimation using predicted stream flow profiles may be refined through an interdisciplinary effort between transportation and water resource engineers. Finally, in order to perform further, evidence-based research on transportation issues in the Mackenzie River corridor, it would be beneficial for researchers, governments, and private operators to cooperate in the collection of high-quality data. This would be particularly helpful for estimating values of parameters such as those used in this study.

This paper has presented a new climate change adaptation strategy for freight schedule planning, with application to the Mackenzie River. The strategy was developed particularly for this northern context where environmental conditions have an overwhelming impact on operations, and logistical delays are considered quite differently from supply chains further south. Specifically, the results highlight the need for earlier-season planning of navigational aid, and equipment and crew placement to take advantage of reliably better marine navigation conditions.

7. ACKNOWLEDGEMENTS

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Increasing Mackenzie River water level variability due to climate change impacts barge transport

A logistics cost optimization model incorporates predicted water flow changes in delivery schedules

Results indicate that deliveries will need to occur earlier in the shipping season

Results can help shipping companies, customers, and government adapt to future climate conditions