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# Modeling multimodal freight transportation scenarios in Northern Canada under climate change impacts

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A B S T R A C T

In Canada's Northwest Territories, goods are delivered to remote communities and natural resource extraction sites by inland barge, trucks, and for some goods, air. Combinations of all-weather and winter roads are used in the winter months, while river barge transport and all-weather roads are used in the summer. However, Northern Canada is disproportionately impacted by climate change, which results in greater variability in water level conditions on the Mackenzie River from year to year. This in turn critically affects tug-and-barge operations on the river. This paper investigates Mackenzie River Corridor freight delivery performance – with a focus on the river route – considering how variations in river water conditions can impact network operations and operational costs. We investigate the impacts of water level variation on shippers' route choice decisions, waterway supply capacity and the resulting overall performance of the freight transport system. Model outcomes provide insights into how the multimodal transportation network may be utilized and perform (quantified by delays and generalized costs) under different water level scenarios. The overarching purpose of the analysis is to provide guidance for infrastructure investment decision-making and business case development, to maintain an effective freight transportation network in the face of on-going climate change impacts.


## 1. Introduction

In the Northwest Territories (NWT) of Canada, particularly along the Mackenzie River Corridor, goods are delivered to remote communities and natural resource extraction sites by different modes depending on the season. River transport and all-weather roads are used in the summer, combinations of all-weather and winter roads are used in the winter months, and highly expensive air transport can be used year-round. However, Northern Canada is heavily and disproportionately impacted by climate change, which also results in greater variability in conditions from one year to the next. Water conditions on the Mackenzie River are no exception to this phenomenon. Water conditions critically affect tug-and-barge operations on this river, which is considered an "ultra-shallow" inland waterway, and is a historically heavily relied-upon mode of goods transport. A recent study demonstrated the Mackenzie River flow regime to have changed over the past four decades due to climate variation, with decreases in maximum spring flows, and rise in cold season base flows (Yang, Shi, & Marsh, 2015). Also, critically low water levels on the Mackenzie in the summer of 2014 made that delivery season one of the worst in many years, with severe delays, much undelivered (by barge) freight, and barges "trapped" downstream. We anticipate conditions such as those experienced 2014 to occur more frequently in future years; as a result, measures to better adapt to greater variations in water conditions is necessary for waterway freight transport to continue. The purpose of this paper is to examine Mackenzie River Corridor freight delivery performance – particularly that of the marine route – considering how variations in river water conditions affect network operations.

A model is built to investigate the operational and cost impacts of water level variation on shippers' route choice decisions, waterway supply capacity and the resulting overall performance of the freight transport system connecting remote communities along the Mackenzie River and coastal communities in the Beaufort Sea. We consider a multimodal transportation system including waterway, all-weather roads, and winter roads. We construct water levels scenarios and waterway capacity scenarios based on historic water levels data to study the impacts of climate uncertainty (Jonkeren, Rietveld, & van Ommeren, 2007). The former is used to assess shippers' potential choice of delivery mode based on perceived and anticipated waterway delivery reliability (with respect to delays as well as the probability of non-delivery). The waterway freight capacity scenario tree is constructed based on historical water levels, barge loading capacities and drafts, fleet availability, and geographic characteristics. Resulting scenario delays and generalized costs are assessed to measure system performance, and provide insights into how the multimodal transportation network may be utilized and perform under different water conditions scenarios. This analysis may provide the Government of the Northwest Territories guidance about where transportation infrastructure investments may be most

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needed, and help provide business cases for these investments, in order to maintain an active and competitive transportation network that can help to stabilize living costs as well as promote economic activities in the face of on-going and rapid climate change impacts.

## 2. Context & background

The transportation system in Northern Canada must be as reliable and cost-effective as possible, despite the harsh climate conditions, in order to keep remote but well-established communities, natural resource extraction sites, and research stations connected to major supply chains in the south. It is also important to the Government of Canada in exercising its sovereignty over Arctic lands and waters (Government of Canada, 2015). The Mackenzie River – the longest and largest river system in Canada, with a watershed that covers almost 20% of the country – is a major historic transportation route through the Northwest Territories. The river flows northbound, starting from Great Slave Lake and emptying at Tuktoyaktuk into the Beaufort Sea. Transportation on the Mackenzie River corridor consists of the river itself during the summer ice-free season, winter roads that are constructed on a frozen foundation of ice and snow in the winter season (December through March/April), plus a network of all-weather roads. There is a plan to connect the entire corridor by all-weather road within the next decade.

Tugs and barges are used to deliver a variety of community supplies (personal and commercial), equipment for natural resources development and other ancillary goods, and bulk fuel along the Mackenzie River and to coastal communities in the Beaufort Sea. Dry cargo (community resupply) for the Mackenzie River and Western Arctic communities originates in Edmonton, Alberta. Petroleum, Oil and Lubricants (POL) is delivered from refineries in Edmonton, the United States, and other offshore sources in Europe or Asia (S A, 2015).

The transportation network connecting communities along the river and those in the Arctic coastal region (including the Kitikmeot Region of Nunavut) that have typically been served via the Mackenzie River freight delivery system[1] are shown in Fig. 1.

Freight deliveries on the network shown in Fig. 1 originate upstream (i.e. south) along the river or from British Columbia and Yukon via Inuvik. There are several waterway freight transportation companies that operate on the Mackenzie River, with the largest being the Northern Transportation Company Limited (NTCL). NTCL's main terminal is located in Hay River. Here, goods arrive via rail or truck, are transshipped to barges, and then delivered to communities and mine sites downstream on the river and to coastal communities in the Beaufort Sea. Although they deliver to over 80 destinations, major destinations having annual volumes over (and sometimes, well over) 2000 tons each, consisting of 86% of NTCL's total annual freight volumes (Northern Transportation Company Ltd., 2015a, 2015b), are identified in Fig. 1. The coastal communities identified by the orange shading in Fig. 1 are reached by transshipping to an ocean-going barge at Tuktoyaktuk. Another operator on the Mackenzie River is Cooper Barging Service Limited (CBSL; www.cooperservices.ca/); all-weather road is used to access their terminal at Fort Simpson, where goods are transshipped to river barge and delivered to communities along the river to Norman Wells.

Deliveries to Inuvik can be made year-round via the Dempster Highway from Dawson City, Yukon. In addition, during the winter months, some communities along the river can also be reached by winter roads.

## 3. Literature review

There has been much recent attention in the literature on climate change impacts on transportation systems performance, and transportation network resiliency in the face of both major weather events as well as growing variability in day-to-day operating conditions. Much of this literature focuses on dense urban networks, as well as important interurban (freight delivery) networks. Koetse and Rietveld (2009) indicated that there are three major methods used to examine the influence of climate change on transport. The first is to compare the performances of transport systems in regions with very different climate conditions, although difficulties arise in identifying and controlling for other factors that impact these systems such as economic situations and physical conditions. The second is to assess seasonal variations in transportation systems performance and travel behavior due, in turn, to variations in and cycles of weather and demand. The third is to consider the instantaneous impacts of weather on travel behavior, which are likely to be clearly visible but very short-term as well.

Another approach taken by Jonkeren, Jourquin, and Rietveld (2011) was to construct climate scenarios based on different levels of global temperature increases and extents of change in atmospheric circulation (i.e., wind direction) to characterize climate change on the Rhine River in the Netherlands. Climate change has impacted water levels on the Rhine River, a historically highly reliable, safe, and cost effective freight delivery route connecting major ports in the Netherlands and Germany to the hinterlands. In fact, inland waterways such as the Rhine and Danube are vulnerable to many types of extreme weather events (Schweighofer, 2014). With low water levels, vessels' cargo carrying capacity may be limited, while sailing times may increase due to low water effects on ship hydrodynamics (Schweighofer, 2014).

Jonkeren et al. (2007) looked at the freight price effects and therefore, welfare effects, of low water levels (impacting trip capacities) on freight transport along the Rhine River. They estimated that the average annual welfare loss over 20 years, due to low water levels, was about 28 million euros (Jonkeren et al., 2007). Cost implications of climate change and adaptation were further studied in 2013 (Jonkeren, Rietveld, Ommeren, & Linde, 2013). In addition, European river delivery modes compete heavily with parallel truck and rail routes, and therefore, freight mode shift (to rail and truck, away from waterways) due to increasing delays and travel time unreliability is a significant concern in this dense and demand-heavy European network. Previous studies exhibit considerable differences in the effects of attributes used to explain freight route and mode choice. The most commonly considered attributes of mode and route choice are cost, travel time (or speed), and travel time reliability (Cullinane & Toy, 2000; Wigan, Rockliffe, Thoresen, & Tsolakis, 2000). Hendrickx and Breemersch (2012) documented the interdisciplinary ECCONET project, which aimed to comprehensively account for the impacts of climate change on transportation infrastructure for economic evaluation and policy implications. Simulation was used to determine freight modal shifts to rail and road, from the Rhine and Danube, due to climate change (Beuthe, Jourquin, Urbain, Lingemann, & Ubbels, 2014).

The Government of Canada has also been concerned about climate change in the north, the impacts to all aspects of northern life and activities, and adaptation measures (Warren & Lemmen, 2014; Lemmen & Bourque, 2008). The physical and economic impacts of warming, with particular focus on the transportation system, were explored as early as 1993, using a scenario approach based on global circulation models (Shinghal & Fowkes, 2002). The authors used analytic models to assess the impacts of these climate change scenarios, and mention that data availability was a significant issue. More recently, Borkovic, Nolet, and Roorda (2014) assessed the financial risk in continued sole reliance on winter roads for diamond mining transport. They looked at the impacts of climate change on winter road duration and load capacity, and in turn, the economic impacts of air lifting goods not able to be delivered by winter road.

In this paper, we present an analysis procedure that can provide assessments of future variations in waterway shipping conditions due to climate change, that impact the traditional mode of river freight transport. We represent the multimodal network in order to study the effects of climate variation not only on demand (through modal shifts) but also on waterway capacity.

[1] These communities in the NWT and Nunavut were traditionally connected via the Mackenzie River and air only; however, with the opening of the Northwest Passage, since 2009 these communities have also been reached by sealift from the east.


**Fig. 1.** Mackenzie River Transportation Corridor (background source: Esri).

## 4. Impact of water level information on demand

### 4.1. Water level scenarios

Climate change is affecting water levels on the Mackenzie River by decreasing maximum spring flows (Yang et al., 2015), causing ice breakup earlier in the year, and decreasing late summer flows. However, time series of water levels also show greater variations in conditions and extremes from one year to the next <redacted reference>. Because there is a lack of data on estimated future water levels, we generate scenarios of water levels based on historic data from 1962 to 2014, to input into the model and observe how the freight transport system may respond to these environmental conditions changes.

Water levels vary along the Mackenzie River. In addition to its description as "ultra-shallow draft", it has many "hazard" sections, some of which can be difficult to traverse even in good conditions. Navigational hazards are caused by rocks, shoals, and other obstacles on the Mackenzie River (Government of Canada, 2008). The most difficult points for tug-and-barge systems to cross (i.e. the narrowest shelf) will determine barge drafts and therefore, load capacities. When water levels are lower, meaning there is less depth to accommodate barge drafts safely, barges must be loaded at lower capacities. In addition, traversing hazardous sections can take several times longer under low water conditions. Greater variations in water levels from one year to the next will cause greater variation in freight transport capacity and delivery times, and create more uncertainties in operations planning. Therefore, for this analysis, we must understand some features of water level variability on the Mackenzie River.

Historical and real-time water levels and flows are available from the Water Survey of Canada's website (Water Survey of Canada, 2014a). The Water Survey of Canada reports water level and flow data in near real-time (i.e. within 3 to 4 h of measurement) from over 1700 hydrometric stations on rivers, streams and lakes across Canada (Water Survey of Canada, 2014b). Based on data from active stations on the Mackenzie River, the lowest monthly average water levels at the beginning of the shipping season are usually recorded at the station nearest to Fort Good Hope. This is consistent with the experiences of freight operators on the Mackenzie River. In fact, in September 2014, NTCL suspended operations beyond Fort Good Hope due to low water and subsequent inability to pass the severe hazards section there (Canadian Broadcasting Corporation, 2014). Because a significant amount of freight transport demand is to locations downstream of Fort Good Hope, we use this point as a reference for all operations along the river.

Cluster analysis was used to identify groups of similar shipping season water levels scenarios, based on records from Fort Good Hope over 52 years from 1963 to 2014 (Water Survey of Canada, 2014a). Summer water level scenarios were identified through K-means clustering, with the pseudo-F statistic used to identify the most appropriate number of scenarios. The pseudo-F statistic is one of several metrics used (and most commonly) to decide the optimal K-value in K-means clustering analysis (Caliński, 1974), representing the ratio of cluster variance to within-cluster variance. In this work, the optimal K-value was found to be five, when the pseudo-F statistics for all K-values were compared. The clustering results for water levels at Fort Good Hope are shown in Fig. 2. The average monthly water levels are also shown, and are used as a baseline scenario in the generalized cost analysis.

The analysis yielded five water level scenarios (at Fort Good Hope) from the 52 years of data. It can be observed that water levels drop as the summer shipping season progresses – they are highest in June/July (the shipping season typically starts early June) and steadily decrease towards October (season typically ends late-September or early to mid-October). It is observed that clusters 1, 3, and 4 are most similar

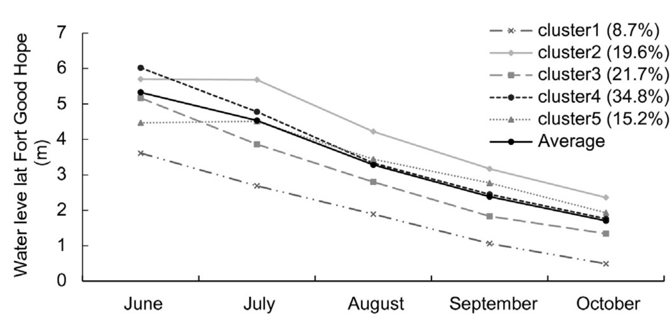


**Fig. 2.** Water level scenarios.

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in trend, insofar as they represent water levels that steadily decrease through the season. Cluster 2 represents the highest overall water level conditions (therefore the best general conditions for waterway freight transport) while cluster 1 represents the lowest (and worst freight transport conditions; it also has the smallest probability of having been observed over the 52 years of data). Cluster 5 exhibits the smallest range of water levels of all clusters found; cluster 5 water levels are relatively small (compared with the other clusters) at the beginning of the season but relatively high towards the end. The clusters with the lowest overall water levels (1 and 2) may possibly provide some representation of future water conditions, given the decreasing trends in water levels observed <redacted reference >.

### 4.2. Shippers' route choice decisions

Barge transport on the Mackenzie has historically been a highly reliable and cost-efficient mode of delivery to remote communities and mine sites. However, as explained above, low water levels and the subsequent impacts on hazardous sections of the river restrict barge load capacities and increase barge travel times (even resulting in non-delivery). When water levels fall below threshold levels, barge loads must be reduced accordingly for safe operation and navigation. Although these events were relatively uncommon in the past, with climate change, environmental conditions impacting transportation on the Mackenzie River have become more variable and difficult to predict in more recent years. As a result, customers may consider alternative transport modes when poor navigation conditions are anticipated, resulting in higher shipping costs, likelihood of delay, and non-delivery. Therefore, how might we account for the impact of this variability and uncertainty in conditions on the Mackenzie River on the future mode choices of shippers – shippers that have, historically, relied solely on barges to deliver their goods?

We propose a utility function to describe how shippers might consider Mackenzie River barge transport against the other available modes for freight delivery, when faced with changing environmental conditions that cause greater delivery uncertainty along the marine route. We populate this utility function with variables found to be of importance in route choice under climate conditions uncertainty from the previously cited literature. The utility function includes delivery cost (as set by operators), an uncertainty level regarding delay and non-delivery of goods based on anticipated water conditions, and a component to account for the cost of waiting for winter delivery (by winter road). Shippers will typically have some estimate of when their goods will be delivered based on schedules provided by barge operators, as well as their own past experiences. Reliability in freight transport can be described by the proportion of delivery units arriving by their scheduled time (Shinghal & Fowkes, 2002). The uncertainty term is meant to represent the opposite of reliability, and therefore is defined as the proportion of delivery units not arriving by their scheduled time. Waterway transport capacity in a given time period (say, one month) is determined by barge load carrying capacity and barge travel time, which are both impacted by water level conditions. Above a critical water level, capacities are unaffected, as the water levels should provide enough depths at hazards to allow for barge transport with no delays (caused by low water). However, below this level, transport capacities will decrease according to prevailing water levels. According to tow letters provided by NTCL, the number of tows (i.e. tugs with barges) per month decline with water levels below 4.2 m (Northern Transportation Company Ltd., 2015a, 2015b). Therefore, in this research we adopted 4.2 m as the critical water level for barge movement.[2]

**Table 1**
Shippers' uncertainty about delivery routes involving the waterway.

| Uncertainty level $R_A^t$ | | | | | | |
|---|---|---|---|---|---|---|
| Water level scenario | | June | July | August | September | October |
| S1 | Cluster1 (8.7%) | 0.14 | 0.36 | 0.55 | 0.75 | 0.88 |
| S2 | Cluster2 (19.6%) | 0.00 | 0.00 | 0.00 | 0.25 | 0.44 |
| S3 | Cluster3 (21.7%) | 0.00 | 0.08 | 0.33 | 0.56 | 0.68 |
| S4 | Cluster4 (34.8%) | 0.00 | 0.00 | 0.21 | 0.42 | 0.58 |
| S5 | Cluster5 (15.2%) | 0.00 | 0.00 | 0.18 | 0.34 | 0.54 |
| | Average | 0.00 | 0.00 | 0.22 | 0.43 | 0.59 |

When shippers make route choice decisions, they will form an opinion (based on their previous experiences) about delivery conditions and possible problems based on estimates of anticipated water conditions in the upcoming shipping season. Data showing the historical relationship between load capacity and tow numbers with water levels can be used as a proxy for their past shipping experiences. Furthermore, we assume that their uncertainty regarding delivery conditions is measured by the difference between the anticipated water level and the threshold water level of 4.2 m mentioned previously. The larger the difference, the more uncertain shippers are about delivery conditions. This is in addition to the idea the anticipated water level is itself uncertain. However, for this work, uncertainty is defined to be zero when the anticipated water level is higher than the threshold. "Uncertainty" values are shown in Table 1 as calculated by Eq. (1).

$$R_A^t = \begin{cases} 1 - \dfrac{w_t'}{w} & \text{if } w_t' < w \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Where $R_A^t$ is the barge delivery uncertainty level in month $t$, $w_t$ is the anticipated water level in month $t$, and $w$ is the water level threshold (4.2 m).

The deterministic utility function for delivery on each available route is shown in Eq. (2). It is assumed that all shippers prefer to have their goods delivered during the summer shipping season, rather than waiting several months past the end of the summer season for delivery on winter roads. This is captured in a waiting cost term.

$$V_k^t = \alpha \cdot C_k + \tau \cdot T_k + \beta \cdot Un_k^t + \gamma \cdot W_k \tag{2}$$

where

$V_k^t$: deterministic portion of utility of route $k$ in month $t$,
$C_k$: shipping price (CAD/ton) on route $k$,
$T_k$: schedule time on route $k$,
$Un_k^t$: pre-season uncertainty regarding reliability of route $k$ in month $t$, where $Un_{waterway}^t = R_A^t$.
$W_k$: cost of waiting for winter shipping (i.e., non-delivery),
$\alpha, \tau, \beta, \gamma$: coefficients of cost, time, uncertainty, and waiting cost.

The above route utilities are used in a logit model to calculate the shares of freight that would be sent for delivery on route $k$. Waterway route shipping costs are obtained from rate tables published by two major operators on the Mackenzie River – NTCL (Northern Transportation Company Ltd., 2015a, 2015b) and Cooper Barging (Cooper Barging Service Limited, 2012). As indicated in Table 2, NTCL operates Route 1 while Cooper operates Route 2, as per the descriptions in Section 2. For the purposes of this analysis, we assume that the cost of all-weather truck transport and winter roads is twice that of waterway transport by NTCL. This assumption is based on anecdotal conversations with NTCL, trucking companies, and the GNWT that shipping by truck can be up to several times more expensive than shipping by barge.[3]

[2] Although NTCL is only one company that operates on the Mackenzie, they historical have had an enormous share of the freight market, with about 3–4 times the delivery volumes of the next largest operator on the Mackenzie (PROLOG Canada & EBA Engineering Consultants Ltd., 2010). In addition, NTCL uses the largest vessels and has by far the largest reach, as its delivery range covers the entire Mackenzie and into the Beaufort Sea, while other operators have a much smaller delivery range on the Mackenzie.

[3] Mackenzie River barge transport has been a heavily relied upon freight transport mode for decades, because it is the most inexpensive mode of transport for high volume, low value goods. Reliability was on par, if not possibly greater, than truck transport. However, with more recent climate change impacts, the reliability of this marine mode has deteriorated greatly. Hence, this paper investigates the tradeoff between barge transport (as a low cost but somewhat low reliability mode) against truck transport (high cost, high reliability).

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**Table 2**
Route cost (CAD/ton) and travel times (days) between study area origins and destinations.

| Route type | Origin inside study area | Destinations | | | | | |
|---|---|---|---|---|---|---|---|
| | | Tulita | Norman Wells | Fort Good Hope | Inuvik | Tuktoyaktuk | Aklavik |
| Waterway NTCL (Route 1) | Hay River | 231[a]/4 | 231[a]/5 | 276[a]/6 | 330[a]/8 | 371[a]/9 | 350[a]/8 |
| Waterway Cooper (Route 2) | Fort Simpson | 261[b]/3.5 | 261[b]/4.5 | – | – | – | – |
| Winter road (Route 3) | Dawson City | – | – | – | | 742/5 | 700/5 |
| Winter road (Route 4) | Hay River | 462/2 | 462/3 | 552/3 | – | – | – |
| All weather (Route 5) | Dawson City | – | – | – | 660/4 | – | – |

Note: "-" indicates no route available.
[a] Transport Rates in NTCL Route (Northern Transportation Company Ltd., 2015a).
[b] Transport Rates in CBSL Route (Cooper Barging Service Limited, 2012).

However, overall these assumptions are made in the absence of shipping rates, while general travel time estimates were provided (through discussions) by staff at the Government of the Northwest Territories (NWT). It is also noted that these costs and times include transport only within the NWT but not from the freight's true point of origin. Because we are only concerned with transport costs within NWT, we assume that all freight is from the same origin. In addition, we look at comparative costs from entry into NWT and entry point into the Mackenzie River network; if delivery to Hay River is set as the baseline, deliveries to all other origin points on the network are calculated relative to this. Therefore, the travel time and cost from origin to each major destination on the network are shown in Table 2.

We make some further assumptions to calculate mode shares. We assume utility function coefficients take values of $\alpha=-0.03$, $\tau=-1$, $\beta=-10$, and $\gamma=-1$. Although these are assumed values, they are based on logic informed by our many meetings with the stakeholders (government and shipping companies). For example, it would be expected that a large proportion of the freight demand (which is comprised only of freight that has historically been transported via river barge) would be assigned to waterway routes when water levels are anticipated to be high), and assigned to the alternative routes when water levels are low.

Demands to the six destinations listed in Table 2 are based on freight delivery volumes data from 2002 to 2014 provided by NTCL (Northern Transportation Company Ltd., 2015a, 2015b). The average annual volume of freight delivered is about 56,000 tons, with almost 60% of this typically delivered in June and July, and less than 20% in September and October. The average monthly volume on NTCL routes observed from 2002 to 2014 are assumed to be the NTCL route demand share at the average water levels recorded during the same month. Based on the observed NTCL route volumes and calculated market share, the total demand to each destination was obtained. The total demand is assumed to be fixed. The calculated market shares for all other routes were then used to determine each route's demand volumes.

Fig. 3 shows the September delivery market shares of all routes available to Norman Wells according to the route choice model introduced above, under the five water level scenarios that may be anticipated by shippers. Norman Wells is only reachable by water in the summer, and winter roads from December to March/April (airlift is also possible but not considered here due to the excessively high cost of shipping high volume low value goods by air). The results in Fig. 3 indicate that shippers planning September deliveries will tend to choose waterway routes (Route 1 or Route 2) when they anticipate high water levels (scenarios S2 and S5). However, they will switch to truck route (Route 4) when they anticipate low water level scenarios (S1).

Fig. 4 shows the monthly waterway routes shares under six anticipated scenarios. The results in Fig. 4 indicate that most shippers choose the waterway routes in June and July, but some will switch to the truck route in September and October, particularly under low water level anticipated scenarios (S1 and S3).

## 5. Impact of water level variations on waterway transportation capacity

### 5.1. Tug-and-barge trip load capacity

As previously mentioned, a barge cannot be utilized at full capacity when water levels are lower than required to accommodate the draft. For instance, if a permitted vessel draft is 1.2 m, then the 1000-series mid-sized barge operated by NTCL can only carry 532 tons, which is 53% of its full carrying capacity (1005 tons) according to load and draft data from NTCL (Fig. 5). A tug on the Mackenzie River will typically push several barges on one trip; therefore, the total trip load is based on the number of barges and how much they are loaded. The relationship between load and draft for 1000-series barges, according to the NTCL tow letters, is plotted in Fig. 5. Although there are other (smaller and larger) barges used by NTCL, Cooper Barging, and other operators on the Mackenzie River, 1000-series barges make up the large majority of NTCL's fleet; as a result, for this analysis we assume all barges operating on the Mackenzie are 1000-series barges. Under keel clearance (UKC), the minimum water level required for vessel operations on rivers, is used to calculate minimum required water levels. UKC values usually depend on factors such as river conditions, vessel types and operational speeds. According to the Canadian Coast Guard's UKC guidelines, a value of 1.06 m is used in planning navigation on the Mackenzie. For a specific load factor, the minimum safe water level equals the sum of a vessel's draft and its UKC.

The load carrying capacity of a single barge is expressed as a function of water level in Eq. (3), and based on Fig. 5. It should be noted that this function is only applicable for load carrying capacities up to the 1000-series barge maximum of 1005 tons. According to Eq. (3), which was developed through linear regression analysis, the minimum required water level is 1.59 m for an empty barge and 2.56 m at maximum load (1005 tons).

$$c=\begin{cases}0 & w<1.59\\ 947.75w-1504.44 & 1.59\le w\le 2.65\\ 1005 & w>2.56\end{cases}\tag{3}$$

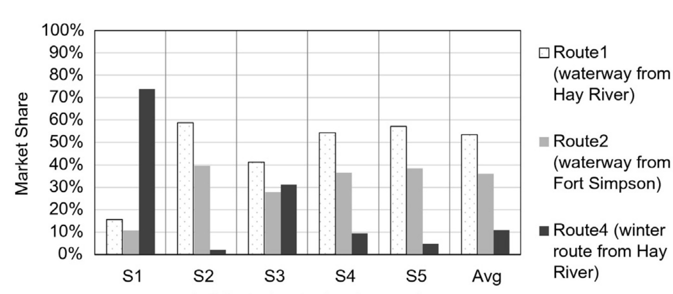


**Fig. 3.** Freight market shares to Norman Wells in September under anticipated water level scenarios.

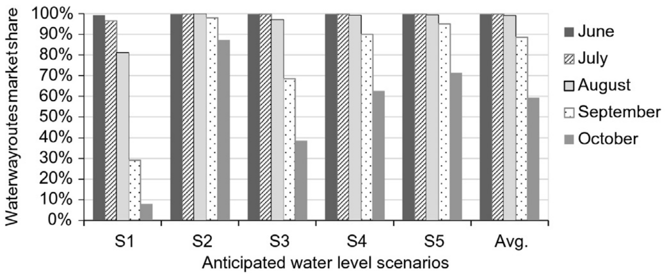


**Fig. 4.** Waterway demands under anticipated water level scenarios.

**Table 3**
Single tug-and-barge trip freight capacity of waterway routes.

| Water level scenario ID | Monthly capacity on Route 1/Route 2 (ton) | | | | |
|---|---|---|---|---|---|
| | June | July | August | September | October |
| S1 | 6030/5025 | 6030/5025 | 1721/1434 | 0/0 | 0/0 |
| S2 | 6030/5025 | 6030/5025 | 6030/5025 | 6030/5025 | 4394/3661 |
| S3 | 6030/5025 | 6030/5025 | 6030/5025 | 1380/1150 | 0/0 |
| S4 | 6030/5025 | 6030/5025 | 6030/5025 | 4906/4088 | 982/818 |
| S5 | 6030/5025 | 6030/5025 | 6030/5025 | 6030/5025 | 1949/1624 |
| Average | 6030/5025 | 6030/5025 | 6030/5025 | 4531/3776 | 650/542 |

where $c$ is the load carrying capacity of a single barge (ton/barge), and $w$ is the river water level (m).

According to NTCL, it is typically the case that six barges are used on a single trip (Route 1); for CBSL (Route 2) this number is typically five. Thus, the single trip load carrying capacity is six times that of an individual barge's load carrying capacity on the NTCL route, and five times that on the CBSL route.

Based on water level scenarios identified in Section 4.1, the single trip supply capacities of Routes 1 and 2 are shown in Table 3.

From Table 3, we can see that in June and July barges can be operated at full carrying load capacity in every water level scenario. However, barges cannot be operated at full load carrying capacity after July in Scenario S1, or after August under S3 or S4. We can see that barge load carrying capacity is most impacted by water level variations in September and October.

### 5.2. Tug-and-barge trip travel time

Navigational hazards, such as rocks, shoals, and other obstacles, are well known to impact tug-and-barge speeds on the Mackenzie River in low water level conditions. Tugs must reduce their speeds when taking barges over these hazard sections. In addition, they may also be required to take barges across one by one, which requires anchoring barges to make many trips back and forth across the hazard section. Accordingly, in Table 4, we assume the need for speed reductions across these hazard sections at various water levels. Assumptions are based on anecdotal information from NTCL, as there is a lack of data on this relationship.

Hazard locations and lengths on the Mackenzie River were entered into a GIS network (S A, 2015). The network includes a breakdown of the Mackenzie River into (operationally homogeneous) sections, the lengths of these sections (km), section type (hazard or normal), and exact hazard locations. According to the operators' experiences on the Mackenzie River, the average speed that a tug-and-barge can be operated on a "normal" section is 10 knots (18.52 km/h). Then travel times (in hours) between origins to each possible destination under the different water level scenarios can be obtained. It should be noted that the travel time here is only the barge operation time on the river, and does not

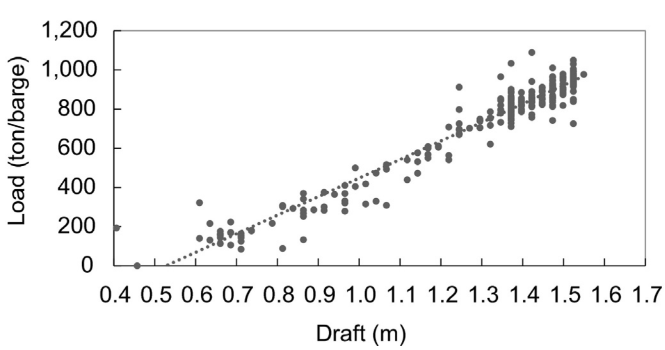


**Fig. 5.** Barge loads (ton) versus draft.

include time required for other activities such as crew rests and loading/unloading at each stop. To account for these, we assume that a tug-and-barge sails for a maximum of 12 h each day.

To evaluate freight delivery costs on a network with multiple origins and destinations, we assume a simplified delivery pattern. On waterway routes (1 and 2), each freight delivery trip is assumed to go to only one destination and then make the return trip to the origin from the final destination.[4] Based on NTCL fleet information published online (www.ntcl.com), we assume that 10 groups of barges, at six barges per group, are operated at any given time. Thus, there are 10 groups of barges assigned to different destinations, and the equipment assignment consists of the number of tugs and barges assigned to each destination, based on historical volumes. It is also assumed that the return trips for empty barges (upstream) take 70% of the time to travel downstream, loaded. Based on this assumption, the trip frequency to a destination (trips/month) in a month is found by dividing 30 days by 1.7 times the single trip sailing time (day), then multiplied by the equipment assignment factor. For the CBSL route (Route 2), it is assumed two groups of barges at five barges per group are operated at the same time to different destinations. One group of barges is assigned to each destination. The monthly trip frequencies to each destination for Route 1 and Route 2 are obtained for the five water level scenarios.

### 5.3. Capacity scenario trees

The monthly capacities of the two waterway routes equal the product of a single trip load carrying capacity and trip frequency in a month, as expressed by Eq. (4). Based on the single trip load carrying capacities and trip frequencies, the monthly capacities on Route 1 and Route 2 to each destination are calculated. Capacity scenarios to each destination were generated based on the water level scenarios introduced in Section 4.1. As an example, the monthly freight transport capacities to Norman Wells for Routes 1 and 2 are shown in Fig. 6.

As mentioned previously, the equipment assignment varies for each destination. The differences in supply capacity for Tulita and Norman Wells on Route 1 reflect both equipment limitations and travel time differences. Based on volumes, more equipment is assigned to Norman Wells than Tulita, but the trip frequency to Tulita is greater. Capacity to Tulita on Route 2 is larger than on Route 1; despite that Route 2 is served by fewer tugs and barges, travel times are lower (Hay River to Fort Simpson on route 2 is served by truck rather than barge, which is much faster). There is one group of six barges assigned to Tulita in Route 1, and one group of five barges assigned in Route 2 in each month. Although the equipment assigned to Tulita is the same each month on both Routes 1 and 2, capacity drops after June in some scenarios because of low water causing higher travel times, and in turn, fewer trips. In June, Route 2 capacity to Norman Wells is smaller than Route 1 capacity because there are 3 tugs and 18 barges assigned to Route 1, but only one group of six barges to Route 2. In addition, it can be observed

[4] This assumption is not found to be entirely unreasonable; the NTCL tow letters indicate that most tows traveled to several (smaller) destinations clustered nearby, or 1–2 major destinations. Given that we are only considering major destinations in this work, each cluster of small destinations is considered one major destination.

**Table 4**
Water levels and assumed associated speed reductions over hazardous sections.

| Water level (m) | Hazard section speed reduction (%) |
|---|---|
| $w<1.5$ | 90 |
| $1.9>w\geq 1.5$ | 70 |
| $2.7>w\geq 1.9$ | 40 |
| $3.2>w\geq 2.5$ | 25 |
| $4.2>w\geq 3.2$ | 10 |
| $w\geq 4.2$ | 0 |

that Scenario 1 and 3 capacities towards the end of the season are very close to zero. There have been (a few) years when the shipping season has been cut quite short due to very low water levels, the most recent being 2014.

## 6. Overall system performance

In this section we measure system performance under combinations of the demand and capacity scenarios introduced in Sections 4 and 5.

### 6.1. Delays

All monthly freight demand for a given route will be delivered if demand is less than the capacity; otherwise, some deliveries will be delayed to the following month. Monthly delay is defined as the freight volume that cannot be transported during the initial month that service was demanded, because the monthly capacity was reached. It is assumed that this demand will be added to the demand for the following month. In contrast, truck routes are assumed to experience no delay because we assume that trucking companies have enough fleet to accommodate as much demand as needed. On waterway routes, the following equation for $t=1\ldots5$ (where $t=1$ is June and $t=5$ is October) is used to calculate the monthly delay under a demand scenario A (as introduced in 4.1) on Route k for supply scenario s:

$$\Delta^{A}_{t,s,k}=\begin{cases} d^{A}_{t,k}+\Delta_{t-1,s,k}-y_{t,s,k} & if \quad d^{A}_{t,k}+\Delta_{t-1,s,k}-y_{t,s,k}>0 \\ 0 & if \quad d^{A}_{t,k}+\Delta_{t-1,s,k}-y_{t,s,k}\leq 0 \end{cases} \tag{4}$$

where

$\Delta^{A}_{t,s,k}$: monthly delay for demand scenario $A$ and supply capacity scenario s at the end of month $t$ (where $A=1\ldots5$ and $t=1\ldots5$) on route $k$,

$d^{A}_{t,k}$: route $k$ demand in month $t$ for demand scenario $A$,

$\Delta_{t-1,s,k}$: delay at the end of month $t-1$ of the trunk scenario where the branch capacity scenario $s$ is from on route $k$,

$y_{t,s,k}$: route $k$ supply capacity in month $t$ of capacity scenario s.

The total delay in supply scenario $s$ over route $k$, for each demand scenario $A$, is calculated in Eq. (5).

$$\Delta^{A}_{s,k}=\sum_{t}\Delta^{A}_{t,s,k} \tag{5}$$

where $\Delta^{A}_{s,k}$ is the total delay for demand scenario $A$ and supply capacity scenarios on route $k$, and $\Delta^{A}_{t,s,k}$ is the monthly delay for demand scenario $A$ and supply capacity scenario $s$ at the end of month $t$ on route $k$.

According to the equations above, monthly delays and total season delay for each waterway route can be calculated using the monthly demands and capacities described in the previous sections. Fig. 7 shows the total delays on waterway routes for the demand and capacity scenario combinations. We note here that demand scenario S1 and capacity scenario S1 are related given that they are based on the same water level cluster. Therefore, there is a higher likelihood of seeing the resulting delay scenario, than, say, the results of demand scenario S1 occurring with capacity scenario S2. However, the purpose here is not to calculate or assess the probability of these occurrences, but rather, the delay and cost impacts if these permutations were to occur. In addition, the validity of this analysis is also supported by the fact that in many seasons, there is a large discrepancy between the water

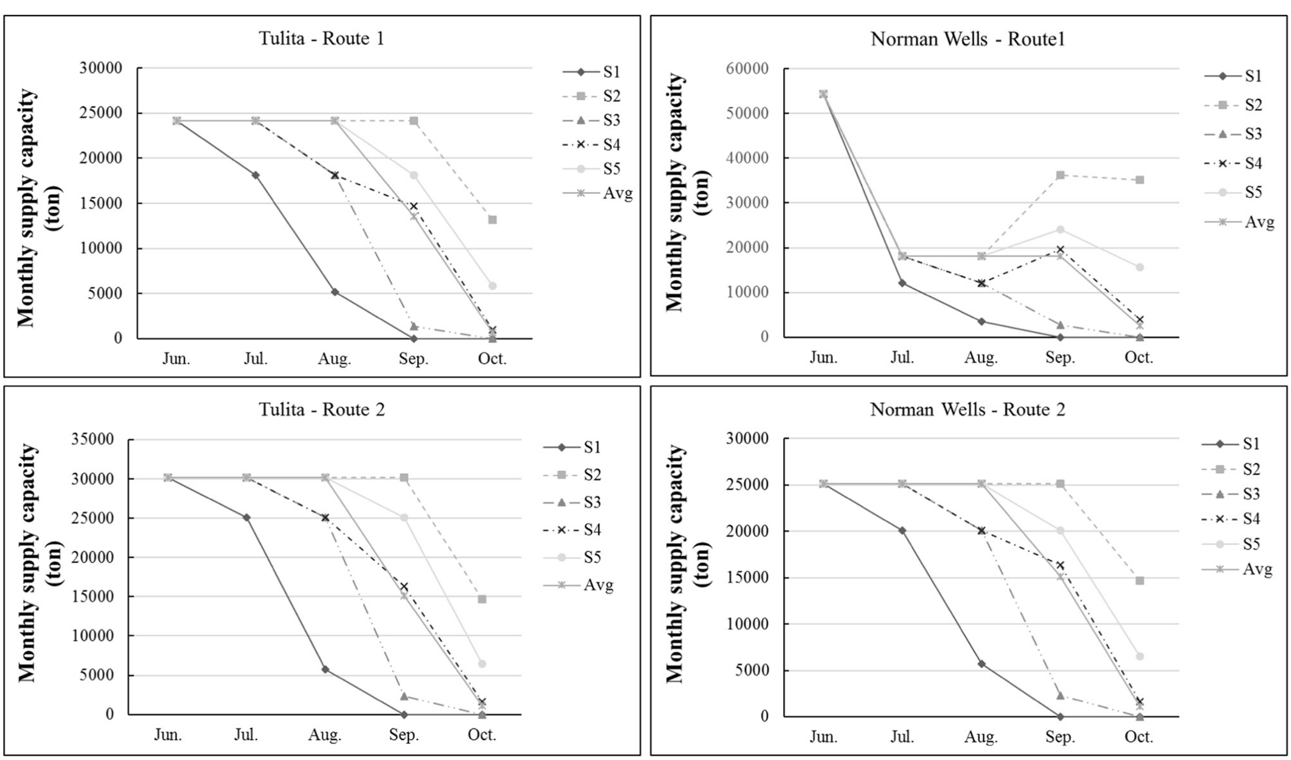


**Fig. 6.** Monthly capacity to Tulita and Norman Wells scenario trees for Route 1 and Route 2.

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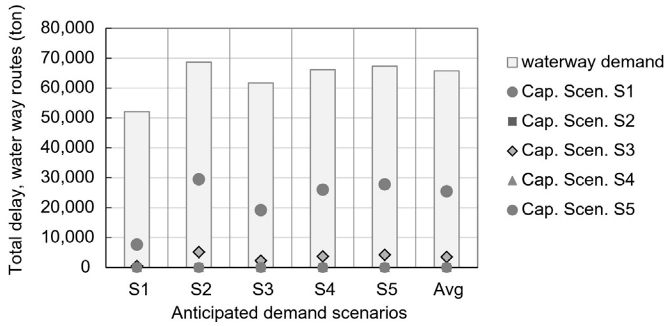


**Fig. 7.** Total delays on waterway routes.

conditions that are predicted to occur versus those which actually occur. Oftentimes, there has been little pre-season prediction due to lack of data, and demand is planned without extensive consideration of water levels.

In Fig. 7, we can observe that the largest delays are incurred under capacity scenario S1 (the lowest capacity scenario, as it is based on the lowest water profile, occurring with probability 8.7%), and S3, as expected, over all demand scenarios. As for demand scenarios, demands under S2 and S5 will result in the largest overall delays among all demand scenarios. These results indicate that the greatest delay occurs when anticipated water conditions (which determine shipper's mode/route choices) and realized waterway capacities differ significantly.

According to Fig. 7, we can see that the greatest total delay on waterway routes occurs under capacity scenario S1 and demand scenario S2. Total waterway delay includes monthly delay to each destination along all waterway routes. Fig. 8 shows the temporal (monthly) and geographical distribution of the greatest delay scenario (capacity scenario S1 and demand scenario S2). The figure indicates that there is no delay anticipated in June, July, or August, but significant amounts in September and October. June and July have high water levels that result in high waterway supply capacities, but water levels decrease closer to September and onward, resulting in poorer waterway supply capacities. As for the geographical dimension, we can see that Norman Wells will have the most delay under a low waterway capacity, high demand scenario.

Fig. 9 shows total delay and demand on Routes 1 and 2 under capacity scenario S1. We observe that the total delay on Route 1 is much larger than that of Route 2, because Route 1 volumes far exceed those of Route 2 and therefore whenever capacities are exceed, the consequences are more extreme. However, if we consider delay relative to demands, Route 2 delays are proportionately higher than those of Route 1, meaning that freight sent on Route 2 has a higher likelihood of delay in low-water seasons. We know that water level scenario S1 represents the lowest water levels of all five scenarios. In S1, most shippers, anticipating low water conditions, move their freight deliveries to all-weather roads and winter roads. Therefore, relatively small freight volumes are assigned to routes 1 and 2, and hence, the smallest delays are experienced under these scenarios. Conversely, greater delays will be experienced when more freight is sent to these routes by shippers anticipating somewhat better water conditions. The demand "leftover" at the end of the summer shipping season (October) is freight undelivered in that summer delivery season. This freight must wait for delivery opportunities when winter roads are constructed and opened in December (sometimes January), the following summer marine shipping season, or be airlifted (extremely costly). Fig. 9 also shows undelivered freight volumes (labeled "unserved demand") at the end of the season for waterway routes 1 and 2. If demands are higher on a given route, unserved demand volumes are likely to be greater as well.

### 6.2. Generalized cost

In this section we introduce a cost function to compare the Mackenzie River corridor multimodal freight network performance under the different demand and supply scenarios introduced. The cost function includes delivery fees paid to operators, cost of monthly delay, and cost of non-deliveries, as shown in Eq. (6).

$$C^{AB} = \lambda \cdot \sum_k \sum_j \left( C_{j,k} \cdot Th_{j,k}^{AB} \right) + \delta \cdot \sum_t \Delta_{t,j,k}^{AB} + \sigma \cdot \Delta_5^{AB} \tag{6}$$

where

$C^{AB}$: generalized total cost for demand scenario $A$ and capacity scenario B;

$C_{j,k}$: transport cost to destination $j$ on route $k$ (CAD/ton);

$Th_{j,k}^{AB}$: throughput to destination $j$ on route $k$, demand scenario $A$ and capacity scenario $B$ (ton);

$\Delta_{t,j,k}^{AB}$: average weighted monthly delay for demand scenario $A$ and capacity scenario $B$ at end of month $t$, to destination $j$, on route $k$;

$\Delta_5^{AB}$: undelivered demand on route $k$ (ton) at the end of the shipping season, for demand scenario $A$ and capacity scenario $B$,

$\sigma, \lambda, \delta$: parameters.

For the above cost function, we assume that non-deliveries wait seven months for the next shipping season to be delivered. The values of $\delta$, $\sigma$, are one and seven months, respectively. According to the waterway travel costs listed in Table 2 and travel times to each destination, the average cost per month-ton is \$1533 CAD, and we set $\lambda = 1/1533$. Fig. 10 displays the generalized costs calculated for each anticipated demand scenario and capacity scenario combination, as a fraction of the total generalized costs of baseline scenario (with average anticipated demand and capacity scenarios). The reason that these are reported as fractions is because the absolute cost values contain little meaning, and rather, it is their relative values that are important. Note that the

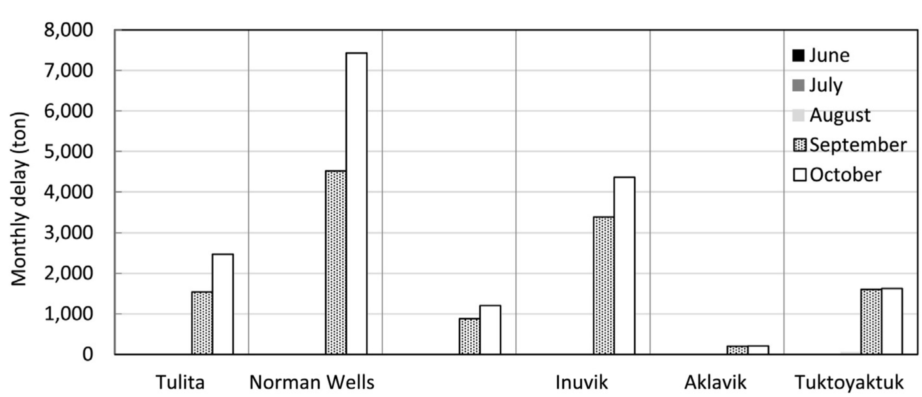


**Fig. 8.** Monthly delay to Norman Wells for capacity scenario S1 and demand scenario S2.

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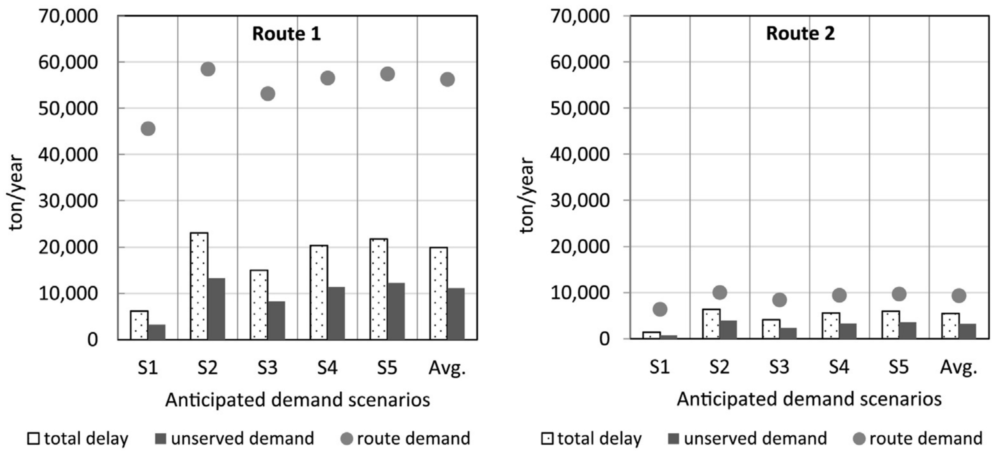


**Fig. 9.** Waterway delay and waterway demand for capacity scenario S1.

bars (for Figs. 10-12) are measured on the y-axis on the left, while the points are measured on the y-axis to the right.

Using the equations above, we calculate the total generalized costs under demand and capacity scenario combinations, as shown in Fig. 10. For all demand scenarios, capacity scenario S1 always results in the highest total generalized cost among all capacity scenarios. There is little difference between the total generalized costs of capacity scenarios S2, S4, and S5. For capacity scenario S1, the highest generalized cost occurs under demand scenario S2. We observe that the greatest generalized cost occurs simultaneously with the highest delay, because the cost function of Eq. (6) gives a significant weight to delays and end-of-season non-delivery. Because it is assumed that freight delivery by truck on winter and all-weather roads (when available) experience negligible delays, demand scenario S1 has the lowest costs of all five demand scenarios, as a large majority of freight is sent on these alternative routes given poor anticipated water conditions. However, the relatively high cost of monthly delays and non-delivery on water is reflected in the overall high cost proportions assigned to the waterway routes in demand scenarios S2 and S5, which have high waterway demand. The results show that the generalized cost is impacted by both demand shift and waterway supply capacity. Under high waterway capacity conditions, the more waterway demand share is, the less the generalized cost is. Under low waterway capacity conditions, the more the waterway demand share is, the more the generalized cost is.

A weighted average cost for each demand scenario is obtained from Fig. 10, and the capacity scenario tree probabilities in Table 1. Fig. 11 shows the proportions of transport and delay costs in the total weighted average cost for each demand scenario. Comparing the transport cost in Fig. 11 and waterway demand proportions in Fig. 10, we can see that transport costs decrease as the demand on waterway routes increases, because of the high costs of transportation by truck. However, unserved demands increase as waterway demands increase.

Fig. 12 shows the weighted average transport costs for water and truck modes, for each demand scenario. The proportions of waterway and truck transport costs are reflections of the demands for each of these modes in each demand scenario. Therefore, a greater the average truck transport cost is for a demand scenario, the greater the demand is for truck routes. However, despite that truck transport is much more costly than waterway transport, it can be observed that demand scenarios in which more goods are transported by truck end up having smaller average total costs, due to the fact that waterway shipping can experience significant delays under low water conditions. This suggests that if lower and more variable water conditions are anticipated, with no additions to shippers' (i.e., NTCL or Cooper) operating fleets, trucks may gain more freight market share in the Mackenzie Corridor to reduce the overall costs of shipping.

Fig. 12 also suggests that if great water level variations are anticipated in the future, making barge transport increasingly difficult, truck transport is an increasingly attractive option despite its much greater per unit cost. This would support the case for the federal and territorial governments' investments in the all-weather Mackenzie Valley Highway.

To demonstrate the modeling procedure and obtain results such as those seen above, many key assumptions were made, which we would like to list here. Firstly, assumptions were made regarding the

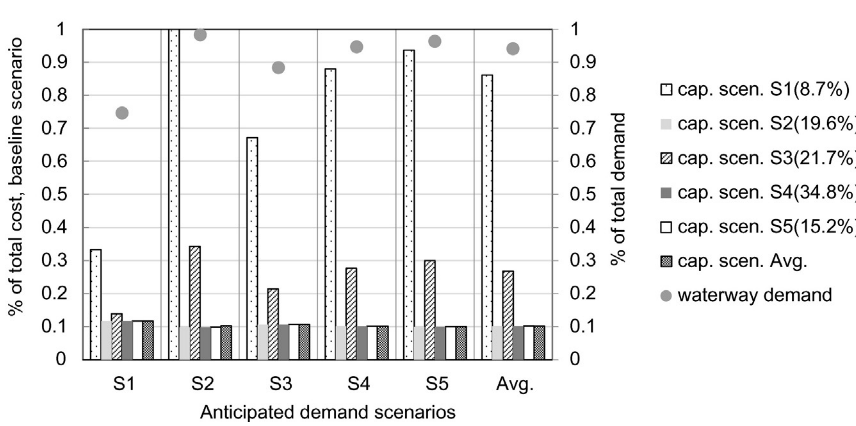


**Fig. 10.** Total generalized costs and waterway demand.

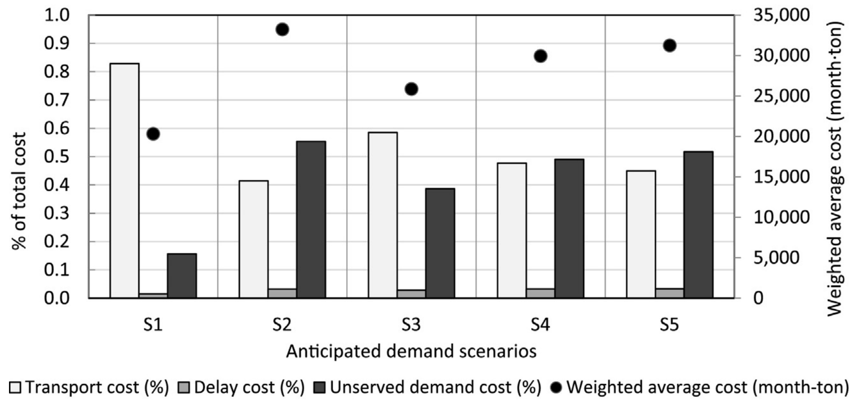


**Fig. 11.** Total weighted transport and delay costs.

variables driving mode shift from marine to truck transport, and the relative impacts of these variables on mode shift (i.e. parameter values). Secondly, another key assumption was that the water level scenarios reflect possible future conditions. Thirdly, freight network modeling simplifications and assumptions (regarding the sequence of visited destinations, and equipment quantities owned by freight transport operators) were made for model tractability. These assumptions will have a considerable impact on the volumes of freight that may experience modal shift, which in turn have implications for investment decisions. It is recommended that sensitivity analyses and further data collection be conducted in future work, which we discuss further in the conclusions.

## 7. Concluding remarks

The purpose of this paper is to explore the impacts of changing river water conditions, and resulting freight planning uncertainties, on the Mackenzie River Corridor freight transportation system in Canada's Northwest Territories, particularly for infrastructure investment decisions. Due to the increasing variability of water conditions on the Mackenzie River, shippers begin to consider alternative routes and modes for times when traditional river transport is perceived as unreliable (due to anticipated low water levels). We assess the impacts of water level variation on shippers' route choice decisions, waterway transport capacity, and the overall performance of the Northwest Territories freight transport system through a supply-and-demand cost model.

Water level scenarios on the Mackenzie River are identified through data clustering, and a route choice model is constructed to represent the choices that customers make when considering transportation costs and delivery schedule uncertainty. The model is set up such that customers that have typically used waterway transport will switch to alternative routes/modes as uncertainty regarding water conditions increases. Waterway route capacities are determined based on river water levels, and fleet (tug and barge) availability. Waterway capacity generally decreases with decreasing water levels, as both barge load capacities and travel speeds over hazard sections decrease. It was found that waterway capacity is restricted by equipment availability in June and July, when water levels are typically high, but by water levels in September and October.

There are several key results and implications from this research. The largest delays and total costs occur when there is a mismatch between anticipated water levels (which determine demand) and realized water levels (capacity) – a mismatch exacerbated by climate change impacts. For instance, if shippers anticipate good water conditions, thereby planning much freight shipment by barge, and water levels are low, then the system will see much delay, non-delivery by end of shipping season, and high costs due to both delays as well as mode shift to trucks. The results also suggest that if low water levels are anticipated but good water levels result, costs will rise but not as significantly due to the fact that there are not large volumes of delayed and undelivered freight, notwithstanding the high cost of truck transport. This suggests that customers and shippers anticipate lower and more variable water conditions, and no additions to shipping company fleets, it may be advisable to shift some freight to truck to hedge against higher likelihoods of delays and non-deliveries (and therefore, overall cost). To this end, trucks may gain more freight market share in the Mackenzie Corridor as a result of customers attempting to reduce their overall expected costs of shipping. This in turn suggests that it may be advisable for federal and territorial governments to improve roadway infrastructures (all-weather and winter) such as the Mackenzie Valley Highway, to

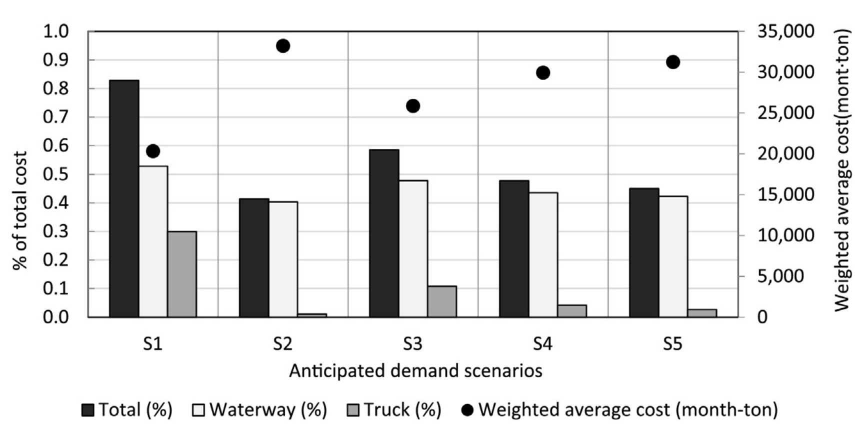


**Fig. 12.** Transport costs in the demand scenarios.

accommodate freight mode shifts prompted by the impacts of changing climate conditions. However, another implication of these modeling results is that shipping companies may consider adding more logistics capacity during months when water levels are more stable and higher (i.e. June and July), such that some deliveries that were historically made in late-season months (August, September and October) may be moved earlier <redacted reference>. Overall, a model such as the one presented in this paper can provide insight into how the multimodal transportation network may be utilized by shippers to better serve northern communities. The Government of the Northwest Territories can also use this work to help facilitate decisions about where and what types of transportation infrastructure investments are most needed, and help provide business cases for these investments, in order to maintain an active and competitive transportation network. This in turn would be instrumental in reducing and/or stabilizing the high cost of living in northern communities, and promote economic growth in the face of inevitable climate change.

There are many ways this work can be improved upon in the future. Assumptions were made to demonstrate the modeling procedure proposed – most considerably, assumptions were made regarding the variables driving mode shift from marine to truck transport, and the relative impacts of these variables on mode shift (i.e. parameter values). To continue this work, a full sensitivity analysis of these parameters should be conducted, and most importantly, more data should be collected and utilized. For instance, a survey of freight transport customers can be used to determine how sensitive their shipping decisions are to varying and uncertain climate conditions, and therefore, provide parameter estimates to the mode choice model. Another key assumption involved the water level scenarios generated. Mathematical models of Mackenzie River hydrologic conditions can be built to obtain future water levels estimates based on simulated water flow forecasts; if researchers pursue this work in the future, the results of these hydrologic models should be incorporated into this transportation model. In addition, freight network modeling simplifications and assumptions may be relaxed to build models that more realistically reflect logistics operations, and therefore, are more applicable for use by operators on the Mackenzie. Finally, as an alternative to generalized (total logistics) cost, use of the freight fluidity index to measure and improve supply-chain performance may be considered.

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