Network Model Development for the Mackenzie River Shipping Corridor in the Northwest Territories

by

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Abstract

The Mackenzie River shipping corridor is one of the most important transportation corridors in the Northwest Territories (NWT), an area of Canada that is rich in natural resources. The corridor is the main means of transporting goods to many communities in the NWT. It is also considered to be a potential shipping route for delivering heavy equipment to Alberta's oil sands, one of the largest hydrocarbon deposits in the world. The route, however, presents uncertainties and challenges in the delivery of goods due to shallow and variable water levels, and navigational hazards. Moreover, the route's capacity to move goods has not been realized due to low demand in the area. Better understanding of the route's capacity and reliability may enable greater utilization of this transportation corridor. The current study designs a network representation of the transportation corridor that can be used to understand route capacity and reliability issues. This research addresses two questions: i) what data are required to build a shipping network representation for the Mackenzie River corridor, and ii) how can the network representation be built using available data sources?

To answer the first question, datasets used in inland and maritime freight transportation literature were identified, and then the datasets relating to the Mackenzie River inland water transportation system were gathered and organized. The data were taken from different published and unpublished reports, as well as other data sources, such as Water Survey of Canada (WSC)'s water level data and GNWT Geomatics's shape files. The data include spatial features of the Mackenzie River freight transportation system, water level, freight operators and their operations, and freight demand. Spatial features of the freight transportation system consist of the Mackenzie River and its adjacent channels, landing locations at communities, danger zones,

navigational hazards, and other intermediate river locations. Shape files provided the locations of spatial features. Other attributes of these features were obtained from documents and other data sources such as river miles from Canadian Coast Guard (CCG)'s danger zone information and Mackenzie River's distance chart, and hydrometric station IDs from WSC's hydrometric database. Abstract information about freight operation (i.e. speed, transit time, and loading/unloading times) and landing facilities could be obtained. However, available information satisfies the data requirements for a strategic-level freight problem.

The second part of this study describes building a network representation. This process involved identifying different node types (terminals, hazardous locations, and intermediate points), and link types representing freight operations on the Mackenzie River system (loading/unloading at communities, tug and barge operations on normal river segments, and tug and barge operations on hazardous river segments). Network nodes were prepared using shape files of the Mackenzie River spatial features in GIS, and other node attributes were also coded. Each node has six attributes: a unique ID, location (longitude and latitude), neighbouring (connected) node information, location type (i.e. node type), information on the nearby hydrometric station, and its river mile. Then, links were built from the node information by applying an algorithm that was written using simple logic to calculate link length and to assign link type, mean speed, and water level. Links have five attributes: start and end nodes, length, link type, mean speed, and water level. Furthermore, a path generation algorithm was written to find all the paths between any OD pair in the network. Other network data include tug and barge information and community cargo demand. All these data were stored conveniently in matrix form, in order to be used in computation software (e.g. MATLAB or OCTAVE) for application later. Network visualization was mostly performed in GIS. Nodes and links were checked manually, and the path generation test was conducted to verify that the network was coded correctly and that the path generation algorithm was working properly. Future work will involve formulating a mathematical model based on the network representation to estimate freight flow on the Mackenzie River system under different supply-demand and climate change scenarios.

Dedicated to my parents

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Table of Contents

List of Tables

List of Figures

CHAPTER 1. INTRODUCTION

1.1 Background

The Mackenzie River is the longest river in Canada and one of the longest rivers in the world (Environment Canada, 2013). It starts at the southeastern shore of Great Slave Lake, flows south to north through the Northwest Territories (NWT), connecting many communities, and ends at the Beaufort Sea (Figure 1-1). The Mackenzie River is the most important inland shipping corridor of the NWT, a region in Canada that is rich in natural resources. NWT's natural resources include significant oil and gas prospects in the Beaufort Sea, the Mackenzie River Delta, and the Sahtu region, as well as mines in the Slave Geological Province (Industry, Tourism and Investment Northwest Territories, 2014), and most of these resources are undeveloped. Resource development will require access to these areas. Road or railway construction in NWT is challenging due to permafrost (i.e. the ground that remains below 0^0C for two years or more), which makes the ground unstable as it melts at a high temperature (Environment and Natural Resources Northwest Territories, 2008). However, the Mackenzie River can provide access to the oil and gas prospects in the Sahtu and the Delta region, as well as the Beaufort Sea area. Moreover, many communities do not have all-weather road access: coastal communities (i.e. Tuktoyaktuk, Paulatuk, Ulukhaktok, and Sachs Harbour), Aklavik among the Delta communities, Sahtu region river communities (i.e. Tulita, Norman Wells, Fort Good Hope, Colville Lake, and Deline), and smaller communities in other regions (see Figure 1-1). These communities can be accessed via waterways, seasonal winter roads and/or air. Resupply of coastal, Delta, and Sahtu region communities in the NWT and Kitikmeot region communities in Nunavut (NU) depends on the Mackenzie River (Mariport Group Ltd., 2011a).

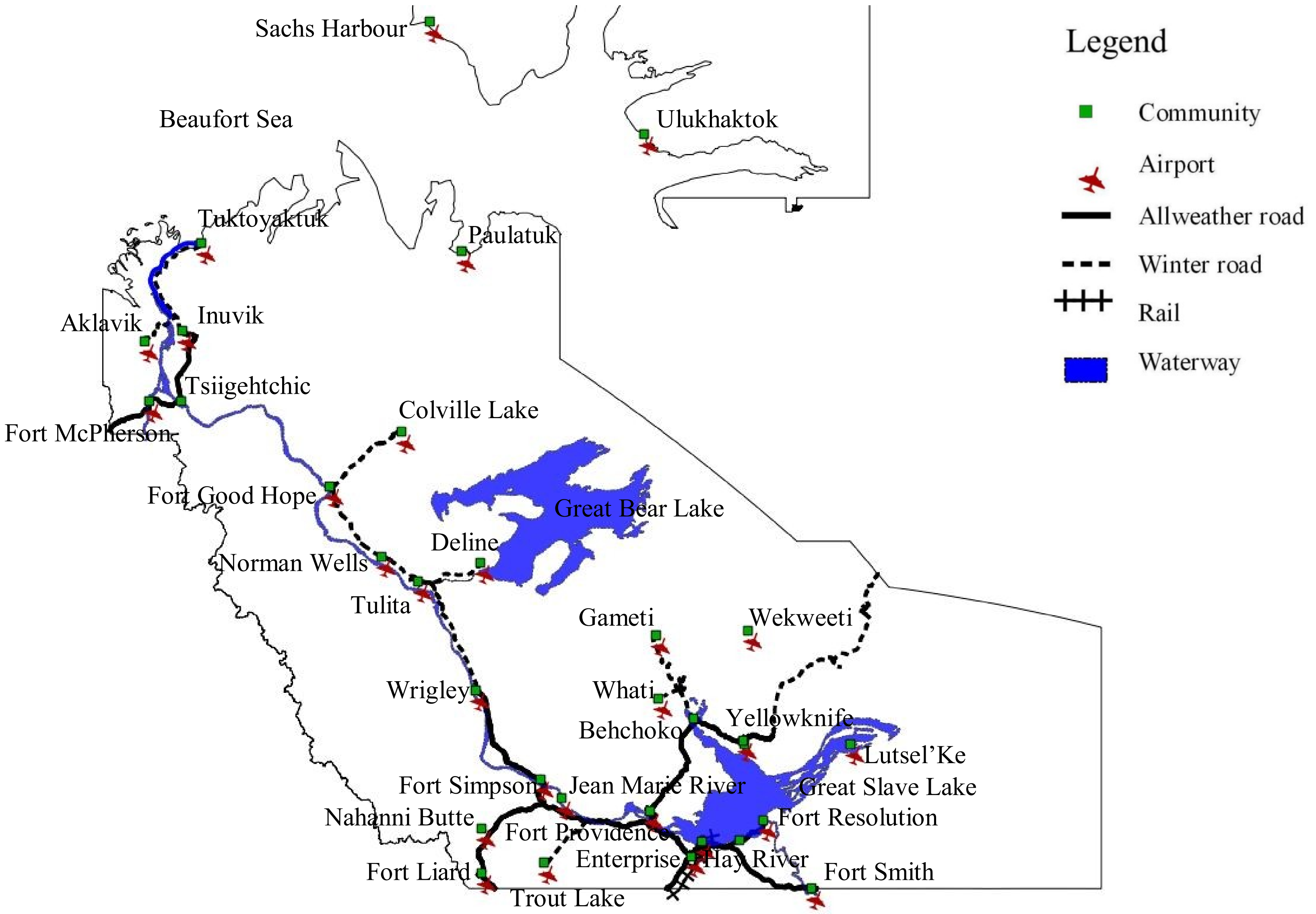

Figure 1-1 Communities and transportation modes in the Northwest Territories

Aside from its role in the NWT's resource development and community resupply, the Mackenzie River can serve as a route from Asia and Europe to the oil sands in Northern Alberta, which is one of the largest hydrocarbon deposits in the world (Oil Sands Discovery Centre, n.d.). In the proposed "northern delivery route" via the Mackenzie River, heavy equipment can be transported to the oil sands in Fort McMurray at a lower cost and in less time than the existing delivery route (Mariport Group Ltd., 2007a).

Unlike many other important waterways, navigating the Mackenzie River is difficult due to its shallow depths and constantly changing geomorphology:

> Navigation on the Mackenzie system is notoriously difficult, and as development along the basin area grew, it became difficult to find qualified river pilots. …. South of Fort Smith, navigation is made challenging by many meanders and a minimal depth on the order of 5 feet. Each new season presented an entirely new lay out of channels and sand bars, with the result that river pilots had to learn the river anew each year (van Wyck, 2010, p. 32).

The Mackenzie River has "a short shipping season", low water levels at the end of the shipping season, and a number of rapids on its course, which make navigation troublesome (CMHC-SCHL, n.d.). Low water levels have caused problems in freight transportation on the river. The Northern Transportation Company Limited (NTCL), a major shipping carrier on the Mackenzie River, had to cancel scheduled voyages for community resupply due to extremely low water levels towards the end of the 2014 shipping season (CBC, 2014). A recent study identified possible climate change issues affecting the Mackenzie River transportation system through discussion with local stakeholders.

> There is much anecdotal evidence of changes along the river in recent years, including less water in general, increased severity of breakup, more variability in the timing of freeze-up, increased erosion and associated sedimentation, as well as changes in wind and weather patterns. (Hicks & Andrishak, 2014, p. iv)

Thus, it is known that freight transportation on the Mackenzie River is affected by its characteristics (i.e. navigational hazards, water level issues, and seasonal window) and climatic conditions (e.g. precipitation, wind, and temperature). However, no study has quantified the effects of these factors on freight transportation on the Mackenzie River.

Shipping potentials (i.e. freight volume that can be moved under different shipping scenarios) and uncertainties due to environmental and climatic conditions of the Mackenzie River route can be evaluated quantitatively and more precisely using a network model. There has been no such study for the Mackenzie River corridor to date. A network representation abstracts the corridor as a prototype that can be modeled via simulation (e.g. Almaz & Altiok (2012)) or a mathematical model (e.g. Righini (2014)). Network models can be used to design aspects of marine transportation services, such as service network design, fleet size, mix, schedule determination, route selection etc. (Christiansen, Fagerholt, Nygreen, & Ronen, 2007), as well as scenario, policy and risk analyses (for example, to evaluate waterway dredging impacts) (Almaz & Altiok, 2012; Merrick, et al., 2003). This research aims to gather relevant data in order to build a network representation of the Mackenzie River shipping corridor. The resulting representation will be the foundation for investigating different future shipping scenarios, with the end goal of providing a policy- and decision-making support tool that both federal and territorial governments (i.e. Transport Canada and the Northwest Territories) can use. It may also be informative to operators for high-level operational planning.

1.2 Research Objectives

This research aims to build a network representation for the Mackenzie River shipping corridor which can be used in network modelling. There are two primary objectives of this research:

- To gather and organize data related to the Mackenzie River shipping corridor
- To build a network representation of the Mackenzie River shipping corridor, using available data gathered during the study

This research offers two major contributions. Data and its sources gathered during this study may assist other researchers and practitioners in future studies on the Mackenzie River freight transportation system. The second contribution will be the construction of a network representation for the Mackenzie River shipping corridor. The representation can be used to help ascertain network freight movement patterns under different supply-and-demand scenarios through modelling. To the best of our knowledge, no such representation or model exists for this corridor. In addition, description of the network representation process may help other researchers and practitioners in building future models for similar Northern region contexts.

1.3 Organization of the Thesis

The thesis is organized into five chapters. The background and objectives of this research have been discussed in the current chapter, Chapter 1. The remaining contents of the thesis are briefly described below.

Chapter 2 consists of a literature review of the network representation of transportation systems and studies relating to inland water and marine transportation.

Chapter 3 presents the gathered data related to Mackenzie River freight transportation. The data have been organized into two sections: Mackenzie River transportation system, and freight demand. The Mackenzie River transportation system section contains the supply side information of the system[1], such as spatial features (i.e. the river and adjacent channels, communities, danger zones and navigation hazards, and other intermediate river locations), water level, and information about freight operators and their operations. The river system and communities' dry cargo and fuel demands are discussed in the freight demand section.

Chapter 4 describes the building and testing of the network representation. The procedure starts with node and link classification. Then, network node and link preparation are discussed, and a summary of the network is provided. Network model testing is also presented in this chapter.

Finally, Chapter 5 summarizes the research results, contributions, and applications in future work.

[1] Many physical systems in the world, including a transportation network, can be studied as a system that follows supply-demand mechanism. The elements or components of the system can be classified as either supply or demand side of the system.

CHAPTER 2. LITERATURE REVIEW

Section 2.1 of this chapter briefly discusses the network representation of transportation systems. Then, a brief review of inland and marine freight transportation studies is presented in Section 2.2. Model data and structures are discussed in the section.

2.1 Network Representation of Transportation Systems

Modelling of a transportation system requires expressing its “infrastructures and services”, “operating and control policies”, and demand in mathematical form (Sheffi, 1984). A transportation system can be represented as physical and/or conceptual components arranged in a structured way. The network representation of the structure facilitates forming mathematical equations and performing computations on the system (Sheffi, 1984; Ahuja, 1993).

A network consists of a set of nodes and links (Sheffi, 1984). Generally, physical elements of a transportation system are expressed as nodes, and connections between these elements as links. Each link is usually associated with some constraints to flow (e.g. passengers, vehicles, or freights) between its connecting nodes. The measure of impedance can be time, cost, utility, and other measures depending on “the nature of the network and the link flows” (Sheffi, 1984).

A transportation network may be expressed in multiple ways depending on its characteristics (Sheffi, 1984). For example, a four-legged intersection can be represented by a node and eight directed links, each link representing one movement in or out the node. However, this representation cannot distinguish different turning movements at the intersection. At some intersections, left turns may have more impedance to flow (in terms of travel time) than right turns, or left turns may be restricted. To consider turning movements, the intersection has to be represented by four nodes instead of one node. These nodes can be connected by links in order to represent the available turning movements.

Transportation network representation may vary depending on the transportation mode (i.e. road, rail, water, or air). Road and rail networks have very well-defined locations that can be considered as nodes (i.e. intersections), while waterway or air network nodes may have to be chosen subjectively. For example, navigation buoy locations in a waterway may or may not be considered as nodes. However, some intermediate river locations are considered as nodes, such as locks on a waterway (Thiers & Janssens, 1998; Almaz & Altiok, 2012). Often waterway and air transportation links are conceptual rather than physical. In other words, a link in a conceptual represenation means a connection or relation between two nodes while a link in a physical represenation indicates absolute distance and orientation of two nodes as well as connection. Whether a conceptual or physical representation will be chosen may depend on the suitability of the representation for a particular network (e.g. physical representation for a road network). It may also depend on the tool used in model building, e.g. a discrete event simulation tool may require conceptual representation of the network to be modeled.

In a multi-modal transportation system, each mode is represented as a separate network (or sub-network), connected by transfer links with other modes. Different processes within the transportation system, such as loading/unloading, storage, and transfer activities inside a terminal, can also be represented by virtual links (Jourquin & Beuthe, 1996; Southworth & Peterson, 2000). Modes are assigned different IDs (Jourquin & Beuthe, 1996), which allow them to be identified during the mathematical model building process. Graphical representation does not have much significance other than to provide a visual impression of the system and show model outputs. Thus, each component or process (e.g. movement of different shippers on the same mode) considered in the mathamatical model may or may not be graphically shown using multiple links (i.e. virtual links).

The node and link structure or network topology, and relevant data such as link cost and capacity are stored in network representation (Ahuja, 1993). Network representation affects performance (i.e. how fast it works and memory requires) of a network algorithm on the network, such as label correction algorithm for a shortest path problem. Storage space, suitability to the network in problem, ease of implementation and manipulation can be deciding criteria for choosing a network topology. Ahuja (1993) illustrated four common types of network topology and data storage systems: i) Node-Arc Incidence Matrix, ii) Node-Node Adjacency Matrix, iii) Adjacency List, and iv) Forward Star and Reverse Star. Node-Arc Incidence Matrix "stores a network as an n x m matrix", where n and m are the number of nodes and links; each column has two non-zero elements (i.e. +1 in node i and -1 in node j). Node-Node Adjacency Matrix is an $n\,x\,n$ matrix that stores network topography. The matrix has one column and one row for each node in the network. The adjacency list stores the node adjacency information (i.e. connected nodes) of "each node as a singly linked list" (i.e. a collection of cells). Each cell in the list corresponds to an arc. Forward star and Reverse star systems store node adjacency lists "in a single array". Keeping both Forward Star and Reverse Star systems is not efficient, since both lists have some information in common. Among these four common network representations, Adjaceny List, Forward and Reverse Star systems are "space efficient", "efficient to manipulate", and suitable for both sparse and dense networks. Node-Node Adjacency list is easy to implement and suitable for dense networks but inefficient to manipulate. Node-Link Incidence Matrix is "space inefficient" and "expensive to manipulate" but useful in the minimum cost flow problem as "it represents the constraint matrix". Network can also be represented in other ways which have similarities with these common systems. For example, the Adjacency List can be stored as a matrix. When Adjacency List is stored as a matrix, it becomes less efficient than the Adjacency List but more efficient than the Node-Arc Incidence Martix and the Node-Node Adjacency Matrix. Matrix is the convenient data structure or form for widely used computational softwares such as Matlab and Octave. Type of network topology may not be much important for small networks.

Network representation of freight models dates back to the 1970s when Kresge & Roberts (1971) built the Harvard model to predict multimodal intercity freight flow. The model used a simple network representation; for instance, links were used to represent entire routes connecting cities or regions instead of individual roadway segments. Later, other freight network models, such as Bronzini (1980) and McGinnis, Sharp, & Yu (1981), used detailed representations of transportation networks. Friesz, Gottfried, & and Morlok (1986) utilized separate networks for shippers and carriers to model their interactions. Guelat, Florian, & Crainic (1990) proposed a modelling framework for a multi-modal network consisting of nodes, links, intermodal transfers, and modes. Different modes between the two adjacent nodes were represented by parallel links. Links had different cost and delay functions for different modes.

Geographic Information Systems (GIS) have been used to build large-scale real-world multi-modal freight transportation network models. Southworth & Peterson (2000) built an integrated multi-modal inter-continental and trans-oceanic network model for the freight flow simulation of the United States, using GIS shape files of different modes and Commodity Flow Survey (CFS)'s origin-destination (OD) information. This work was facilated with pre-processed shape files of different modes by other entities for different purposes. The integrated model building still required significant shape file editing. The study proposed a nearest distance and least cost-based method to determine the likely access or egress links to freight origin or destination nodes. Undoubtedly, GIS enables cost-effective integration of a large network. However, it may still require much additional work to build a working model using GIS files of network elements or features. Prior to the study, Jourquin & Beuthe (1996) used a GIS-based software called NODUS to model wood transportation in a Trans-European multi-modal network.

In summary, network representation of a transportation system is useful in analyzing a system using mathematical models. The type of representation used for a network depends on its characteristics of the network and purpose of the study. Computation tools such as Matlab or Octave will be used in the project which favours matrix data structure. The Adjacency List network topology of the Mackenzie River will be stored in matrix form since it is more efficient than the Node-Arc Adjacency Matrix and the Node-Node Incident Martix. The same network can be represented in different ways. Finally, GIS may be quite helpful in network model building, particularly for large networks. This study will also use GIS to make the best use of available digitized information of the Macknezie River freight transportation system.

2.2 Studies on Marine and Inland Water Transportation Systems

Inland water and maritime freight transportation literatures can be classified into two major groups: i) simulation model, and ii) optimization model. Simulation models or studies have investigated port operation and logistics, scenario and policy analysis for waterways, and risk analysis (Almaz & Altiok, 2012). Most optimization models in marine and inland water transportation have been applied to solve different freight operators' problems, for example, network design, fleet size and mix determination, etc. (Christiansen, Fagerholt, Nygreen, & Ronen, 2007).

A number of simulation studies have evaluated scenario and policy decisions on inland waterway transportation in recent years. Almaz & Altiok (2012) developed a discrete event simulation model of the Delaware River and Bay waterway system to study the dredging impact on the system's efficiency. Smith, Sweeney II, & Campbell (2009) investigated congestion on the Upper Mississippi River by simulating and testing operating conditions. Ozbas & Or (2007) investigated navigation rules and regulations, vessel and cargo characteristics, meteorological and geographical conditions, pilotage and tugboat services in the Istanbul Channel using a simulation model. Merrick, et al. (2003) analyzed traffic density to assess the risks associated with ferry service expansion in the San Francisco Bay area. Thiers & Janssens (1998) developed a mathematical traffic simulation model for maritime access to the port of Antwerp, Belgium. Golkar, Shekhar, & Buddhavarapu (1998) built a simulation model for the Panama Canal, "…. to be used in assessing pilot working conditions, and … in evaluating canal capacity under different operating conditions (p. 1229)."

As mentioned, numerous studies have optimized mathematical models to solve "strategic, tactical, and operational" problems of maritime transportation (Christiansen, Fagerholt, Nygreen, & Ronen, 2007). Maritime transportation problems can be classified into one of these three classes. Examples of these problems and discussions may be found in Christiansen, Fagerholt, Nygreen, & Ronen (2007).

- Strategic problems primarily include ship design, network and transportation system design, fleet size and mix design, as well as port/terminal location, size, and design.

- Tactical problems include adjustments to fleet size and mix, fleet deployment, ship routing and scheduling, berth/crane scheduling, container yard planning management, container stowage planning, and distribution of empty containers.
- Operational problems are related to cruising speed selection, ship loading, and environmental routing.

Some examples of mathematical model optimization are mentioned here. Jaikumar & Solomon (1987) proposed an algorithm to determine the minimum number of "tugs required to transport a given number of barges between different ports in a river system". Sambracos, Paravantis, Tarantilis, & Kiranoudis (2004) evaluated the applicability of small containers in the Aegean Sea in Greece by determining homogeneous fleet size for known supply-demand at first, and then solving a vehicle route problem for periodic needs. Fagerholt & Lindstad (2000) determined a cost-effective fleet size and schedule as well as routing for servicing from an onshore depot to offshore oil installations in the Norwegian Sea. An algorithm was developed to calculate the routes for pre-determined scenarios with a certain number of service hours and services.

Both simulation model and optimization model of a waterway or maritime transportation system require different data related to the waterway network, meteorological conditions, vessels, operations in the system, and freight demand. These data are briefly described here.

- Waterway network data would consist of cargo loading/unloading locations (e.g. terminals, quays, and wharfs), anchor or mooring locations, locations where a waterway splits into branches (i.e. bifurcations), and other natural or man-made features on the waterway such as locks, rapids, and other hazards. These locations are demarcated by nodes in a network model. Location (i.e. longitude and latitude) and other neighbour or connected locations (i.e. network topology or adjacency information) are relevant data used in a waterway freight system model. In this study, network topology or adjacency have been referred as neighbour or connected nodes.

- Then, different meteorological data such as wind, visibility, and precipitation data may also be required in a network model if these parameters significantly affect freight movement. These weather parameters may have noticeable impacts on model outputs (e.g. terminal utilization, average delay etc.) on a daily basis. However, these impacts may not be significant over a year compared to the overall model output values. For example, Almaz & Altiok (2012) excluded weather parameters from their model since these parameters did not have significant impacts on model outputs.
- Vessel characteristics, such as dimensions, drafts, and load capacity, are used in a model to determine vessel operability and freight volumes in any waterway freight system model.
- Operations in a waterway or maritime freight system primarily include cargo loading and unloading, sailing, anchoring, and lightering. There are specific operational data related to a waterway or maritime freight system: loading and unloading times, transit times and/ or speeds between destinations, delays at waterway features, such as terminals, locks, hazards, and anchors, time required to transfer cargo from one vessel to another during lighterage. These operational data characterize different features of a waterway freight network. For example, loading/unloading time, and delays at a terminal determines how many vessels or

freight volumes can be processed at the terminal over a period of time. Whether historical operational data are available or not available, some indicative values (e.g. average transit times or speeds) would be required in a freight network model. Tidal and navigational rules also affect freight operations on a waterway (Ozbas & Or, 2007). Low tides may restrict deep draft vessel operation. There might be navigational rules imposed by the local authority managing a waterway, such as if visibility is below certain threshold two way operations may be stopped.

- Freight demand in a waterway system determines the vessel activities. Necessity of freight volume information depends on the model's purpose. Most studies required freight demand information. Accurate freight volume information may or may not be available.

Both simulation and mathematical models of river or marine systems consider geographically important locations (such as locks on a waterway, if exist) as well as terminals or ports as nodes (e.g. Righini (2014), Almaz & Altiok (2012), Smith, Sweeney II, & Campbell (2009), Ozbas & Or (2007), Sambracos, Paravantis, Tarantilis, & Kiranoudis (2004), Merrick, et al. (2003), Fagerholt & Lindstad (2000), Jaikumar & Solomon (1987) etc.). Danger zone or navigation hazard in a waterway may be analogous to locks, which cause more uncertainty in freight delivery due to more difficult operating conditions. Other locations such as anchor or mooring locations and bifurcations pertain to a specific waterway. These other locations may or may not be considered in a model, depending on their effects on freight transportation. Additional nodes may be required for the model. Almaz & Altiok (2012) divided the study section of the river into six zones to implement vessel movement rules and regulations in the model. Virtual references or nodes were considered at the entrance and exit of these zones[2]. Thiers & Janssens (1998) coded the waterway into nodes, such that each link length is equal to the minimum safe distance between vessels. Vessel safety distances varied at different river locations, depending on the allowable speed. Righini (2014) considered river terminals, locks, and locations where the river splits into two or more streams as nodes. In many mathematical models, only terminals and anchor locations are represented by nodes. Although graphical representation of links may not show the actual path, real travel distances and transit times between nodes are considered in calculation.

Often, model testing is not reported in the literature. However, model testing is an important part of model building. Golkar, Shekhar, & Buddhavarapu (1998) tested a pilot rotation module of their model by comparing model data and actual outputs for three randomly selected days. The module was adjusted based on the test results. Almaz & Altiok (2012) tested each sub-model to verify the correctness of its output. Tracing (verifying model outputs manually) and animation techniques were also used to test the model. Discussion on model testing could not be found in literatures on inland waterway or marine network analyses using optimization techniques. The elements (i.e. node and links) of a network and accuracy of the mathematical model formulation (i.e. forming the objective function using network elements) can be checked prior to solving the (mathematical) model.

Data used in most studies include physical or spatial features of the waterway or marine system (e.g. terminal, anchorage, and lock), distances between these features, speed, transit time, delay, and loading/unloading times. Additionally, fleet size and capacity as well as navigation rules and regulations (if present) are necessary in a model.

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[2] Virtual references or nodes do not have any physical existence like a port or a terminal, a lock, and or other important features of a waterway system. These nodes are considered for convenience in analyzing the waterway system.

CHAPTER 3. DATA GATHERING AND ORGANIZATION

This chapter presents the data and information gathered for the purpose of network representation of the Mackenzie River freight transportation corridor. The data gathering process is introduced in the first section of this chapter. Section 3.2 discusses important features affecting freight transportation on the Mackenzie River, including danger zones on the river, water levels, and operators. In Section 3.3, freight transportation demand on the Mackenzie River corridor is briefly described. Finally, a summary of the chapter is provided in Section 3.4. An earlier version of this chapter was documented in S A, Kim, & Zheng (2015), a project progress report prepared for Transport Canada.

3.1 Overview of Data Gathering

Data were gathered from published and unpublished documents, as well as online resources. Unpublished documents and information were obtained through meetings with the Department of Transportation (DOT) of the Government of the Northwest Territories (GNWT), and the Northern Transportation Company Limited (NTCL). Meetings were held with DOT and NTCL. General information and some data about the Mackenzie River freight transportation were gathered through these meetings. DOT meetings primarily provided information on existing data sources including different reports e.g. Mariport reports. NTCL meetings helped to understand its operation on the Mackenzie River. Meeting minutes are attached in Appendix A. Much of information for this study was drawn from Mariport Group Ltd.'s reports on Western Arctic communities' resupply (e.g. Mariport Group Ltd. (2011a)) and PROLOG & EBA's study on the northern transportation system (i.e. PROLOG & EBA (2010)). Online resources include documents and data available on federal and territorial government websites, such as the Water Survey of Canada (WSC) (Water Survey of Canada, 2014b) and GNWT's geospatial data warehouse (GNWT Centre for Geomatics, 2014).

Gathered data were organized into two sections: i) the Mackenzie River transportation system, and ii) freight movement demand. The Mackenzie River transportation system section presents supply side information on the freight transportation system.

3.2 The Mackenzie River Transportation System

The Mackenzie River transportation system consists of the Mackenzie River, its adjacent channels, communities along the river, and freight operators. Freight deliveries on the Mackenzie River predominantly originate upstream (i.e. Hay River and Fort Simpson) and are destined for communities downstream, flowing to the Beaufort Sea (Mariport Group Ltd., 2011a). There are navigational hazards, such as rocks, shoals, and other obstacles, on the Mackenzie River (Canadian Coast Guard, 2013). River, channels, communities, and navigational hazards are spatial features of the system. Aside from these spatial features, water levels on the river impact freight transportation by affecting the navigability of tugs and barges and their load carrying capacities. Furthermore, information on freight delivery companies (operators) and their operations are also important in understanding freight transport on this river system.

3.2.1 Spatial Features of the System

The locations of important spatial features can be collected from relevant GIS shape files. These spatial features will be coded as nodes and connected by links to represent the network. Network representation will be discussed in Chapter 4. Collection of the data is discussed below.

3.2.1.1 Mackenzie River and adjacent channels

Information related to the Mackenzie River and its channels was collected to determine relative positions and distances of important features (e.g. communities, hazards, and other intermediate locations) on and/or along the river. Adjacent channels include those used to access communities not located directly on the banks of the Mackenzie River (such as Aklavik, which is accessed through the Aklavik Channel). There are shape files of rivers and channels at several map scales (i.e. 1:1 to 1:60000, 1:3000000 to 1:5000000, 1:5000000 to 1:10000000, 1:60000 to 1:300000 and 1:300000 to 1:3000000) in the NWT geospatial data warehouse (GNWT Centre for Geomatics, 2014). The layer at 1:300000 to 1:3000000 scales was used to extract shape files because it contains fewer undesired water bodies than other shape file layers, and is convenient for further processing. These shape files do not contain river and channel width, depth, and location of other important river features, such as docks and anchors. Navigation charts would be a useful source for such information. However, Mackenzie River navigation charts are not available in electronic format (Canadian Hydrographic Service (CHS), n.d.). All query results concerning the Mackenzie River and channels connecting adjacent communities (i.e. Aklavik Channel, Oniak Channel, East Channel, Schooner Channel and Napoiak Channel) were first imported to the Geographic Information System (GIS) software, processed to keep desired waterways in the shape files, and then merged together. The merged shape file was used to build a network representation of the Mackenzie River transportation system (see Section 4.1).

3.2.1.2 Communities

Locations of the NWT communities were collected from the "NWT Communities – 2m – scale" layer in the NWT geospatial data warehouse (GNWT Centre for Geomatics, 2014). NWT communities and regions are shown in Figure 3-1.

Figure 3-1 Mackenzie River, communities, and administrative regions in the Northwest Territories

Both permanent and temporary barge landing sites exist in the communities along the Mackenzie River and its adjacent rivers and channels. A permanent landing facility may be a dock, a wharf, or a beach (Imperial Oil Resources Ventures Limited, 2004b), while temporary landing sites are built using barges anchored on the river shore (Imperial Oil Resources Ventures Limited, 2004a). "At barge landing sites, the towed barges will be moored to a buoy. A tug will then take each barge to the barge landing site for unloading" (Imperial Oil Resources Ventures Limited, 2004a, pp. 8-3). NWT communities are small and mostly connected by gravel roads to landing sites about a kilometre or a few kilometres away. Although detailed information of community access could not be obtained, it was checked in the satellite images of communities on Google Earth and the GNWT Geomatics Website. Transporting goods from the river to communities may not include significant costs and is unlikely to vary much among communities. Communities can be considered centroids, where freight flows originate or end. Loading/unloading activities were also assumed to occur at community locations.

Table 3-1 summarizes available information about community marine facilities in the NWT. Available information includes access hours per day, availability of mooring facility, heavy equipment, and cargo assembling and storage site, annual marine cargo volume, facility ownership, and communities' access by alternative modes.

Table 3-1 Summary of Marine Facilities in Communities Connected via Mackenzie River in the Northwest Territories

Community	Access (hours/day) during navigation season	Secure moorage for loading and unloading	Access for heavy equipment	Secure marshalling and storage site	Annual marine cargo (tonne)	Federal (F)/ Private(P)/ Charter (C)	Other modes: All-weather road (AW), Winter road (W), Rail (R), and Air (A)
Tuktoyaktuk	24	Y	Y	Y	>10000	F, P	W, A
Ulukhaktok	4	Y	Y	Y	2000-10000	P	A
Paulatuk	4	N	Y	Y	<2000	P	A
Sachs Harbour	4	N	Y	Y	<2000	P	A
Aklavik	4	Y	Y	Y	2000-10000	P	W, A
Inuvik	24	Y	Y	Y	>10000	F, P	AW, A
Fort McPherson	4	N	Y	Y	<2000	P	AW, A
Tsiigehtchic	4	N	Y	Y	<2000	F	AW
Fort Good Hope	4	Y	Y	Y	2000-10000	F	W, A
Norman Wells	24	Y	Y	Y	>10000	2F,P	W, A
Deline	N/A	N/A	N/A	N/A	N/A	N/A	W, A
Tulita	4	N	Y	Y	<2000	F	W, A
Colville Lake	N/A	N/A	N/A	N/A	N/A	N/A	W, A
Fort Simpson	4	N	Y	Y	<2000	F	AW, A
Fort Providence	N/A	N/A	N/A	N/A	N/A	N/A	AW, A
Wrigley	4	N	Y	Y	<2000	C	AW, A
Jean Marie River	4	N	Y	Y	<2000	C	AW, A
Hay River Reserve	N/A	N/A	N/A	N/A	N/A	N/A	AW, R

Source: Imperial Oil Resources Ventures Limited (2004b).
Y= Yes, N= No, and N/A= Not applicable

Information on the daily hours of access to community landings would be particularly useful in the model. Communities with only four hours of access per day may only be able to load/unload one or two barges in a day, depending on the cargo type and quantity. Historical data for loading/unloading times could not be obtained. The annual marine cargo quantity provides an indication of marine freight activities at NWT communities. Communities with low annual marine cargo may have low population or alternative delivery modes. Marine facility ownership may restrict marine operations at a community; federal facilities may be used by any entity, while private or charter facilities' access may be limited to a specific carrier. Federally owned facilities are located at Tuktoyaktuk, Inuvik, Tsiigehtchic, Fort Good Hope, Tulita and Fort Simpson. Fisheries and Oceans Canada own these federal facilities. Other attributes, including secure moorage, marshalling and storage site, and heavy equipment access, may be used in the model if further information is available, such as mooring capacity, storage capacity, waiting time and cost of accessing marine facilities at the communities.

3.2.1.3 Navigational hazards and other locations

The locations of navigational hazards such as rocks, bends, ramparts, rapids, and shoals on the river were collected from the "Geonames – 0 – 60k scale" layer in the NWT geospatial data warehouse (GNWT Centre for Geomatics, 2014). These locations were identified by querying geolocation types (e.g. rock) on the shape file layer. Any location can be searched in the shape file layer by its name (i.e. geoname). Other locations include danger zone start and end locations and intermediate river locations. Danger zones are further discussed in Sub-Section 3.2.2. Intermediate river locations are additional points on the river that were placed mainly to abstract the geometry of the river. Tugs and barges may take a turn to stay on course in these intermediate locations.

3.2.2 Danger Zones

Danger zones are river sections that are difficult to navigate due to the presence of obstacles or navigational hazards. Danger zones affect tug and barge movement on the river, imposing operational limitations (e.g. lower operating speeds, reduced drafts, and moving barges through hazardous sections one at a time) as a response to the risks posed by hazards such as running aground. The Canadian Coast Guard (CCG) has designated some of the Mackenzie River sections and its adjacent rivers and channels as danger zones (Canadian Coast Guard, 2013), shown in Figure 3-2. Each danger zone has an identification number, and the river miles of its start and end locations. A tug and barge entering or exiting a danger zone needs to communicate with, and obtain clearance from, the Iqaluit Marine Communications and Traffic Services centre (MCTS) (Canadian Coast Guard, 2013).

There are 10 danger zones on the Mackenzie River. Danger zone 10 contains narrow and shallow channels in the Mackenzie Delta (Canadian Coast Guard, 2013). An enlarged image of the Delta region is also provided in Figure 3-2. Lengths of these danger zones range from 11 miles to 80 miles (Canadian Coast Guard, 2013). As shown in Figure 3-2, there is no danger zone on the main shipping channel in between the north end of zone 6 and Tununuk Point. Other danger zones in this area are on the adjacent channels of the Mackenzie River. One of these channels is the Oniak Channel, which connects the Mackenzie River to the East Channel. The lower part of the East Channel continues to Inuvik, and the upper part ends at the Beaufort Sea. Aside from their geographic locations, no information could be obtained about tug and barge operations in these danger zones, such as the anchor locations, operating speeds, and transit times. This information could not be found in the available documents. A knowledgeable person on these matters such as a tug captain could not be reached during this thesis work.

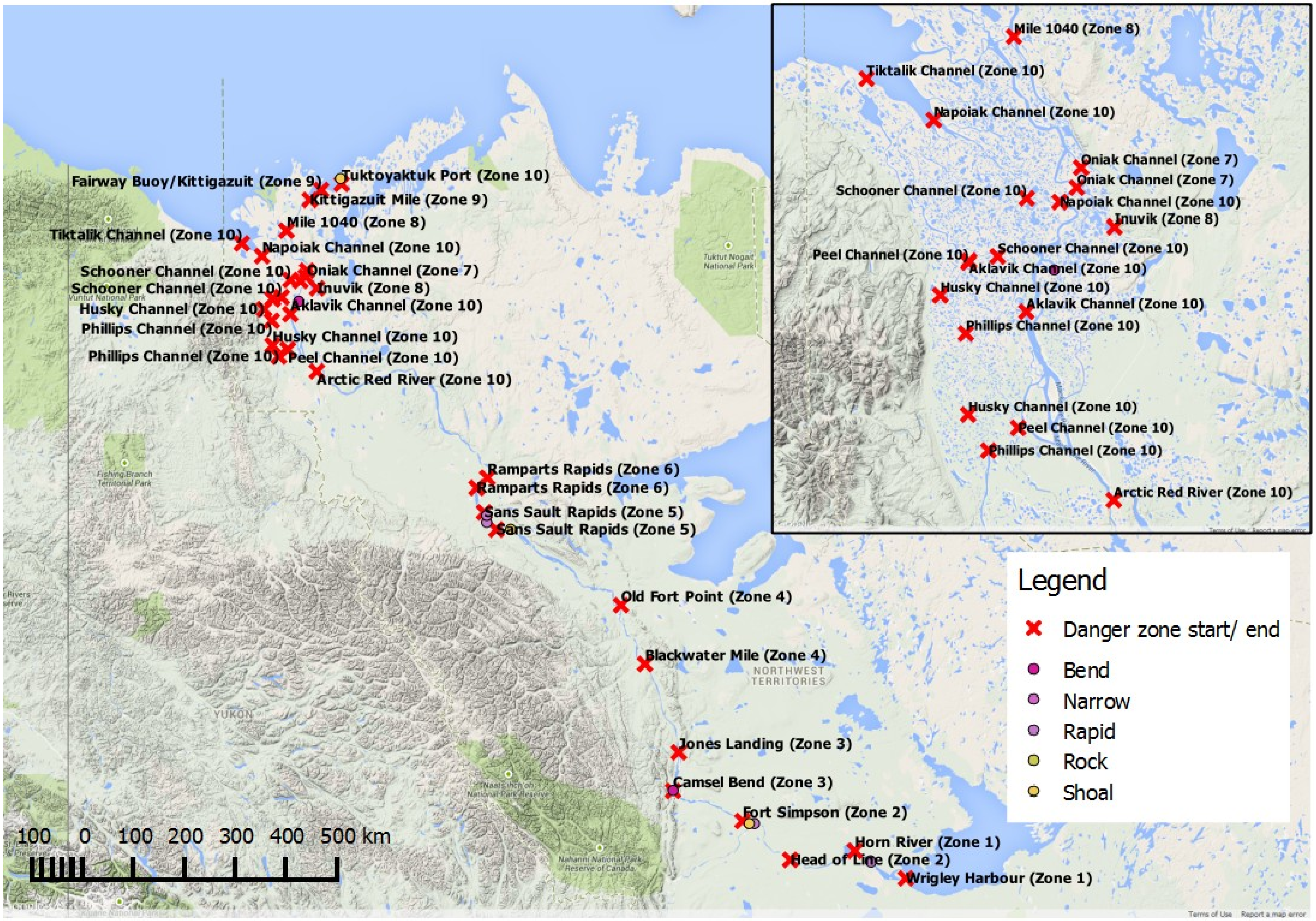

Figure 3-2 Danger zones and navigational hazards on the Mackenzie River.

3.2.3 Water Levels

Water levels have a critical impact on freight movement on any inland waterway, including the Mackenzie River. The available draft—the depth that a ship can sink into the water under a load—depends on the water level, and therefore is directly related to the goods carrying capacity of a tug and barge system. The tug and barge draft will be larger for a heavier load and vice-versa. Water depths change along the river and over time. Climate changes are also likely to affect water levels and freight movement on the Mackenzie River (Sung, Burn, & Soulis, 2006). The impact of climate on freight movement can be assessed by evaluating freight volume on the waterway for different water level scenarios.

Historical and real-time water flows and water levels are available from the Water Survey of Canada's (WSC) website. WSC collects water level and flow data in almost real time (i.e. within 3 to 4 hours of measurement) from over 1700 hydrometric stations, and historical data are available from more than 7600 active and inactive stations "on rivers, streams and lakes across Canada" (Water Survey of Canada, 2014c). Historical data availability varies from station to station. Five types of water level and discharge data may be available at a station. These include daily, monthly, annual extreme, peak, and real-time data (hourly) (Water Survey of Canada, 2014a).

Figure 3-3 shows all the active and discontinued hydrometric stations on the Mackenzie River. Active stations have up-to-date water level and/or flow data, while discontinued stations have historical data for their operational time period. All hydrometric stations have a location (i.e. longitude and latitude), the start and end years of operation, drainage area, and status on real-time data availability. The water level of any section or location on a river can be assumed to be equal to that of its adjacent hydrometric station.

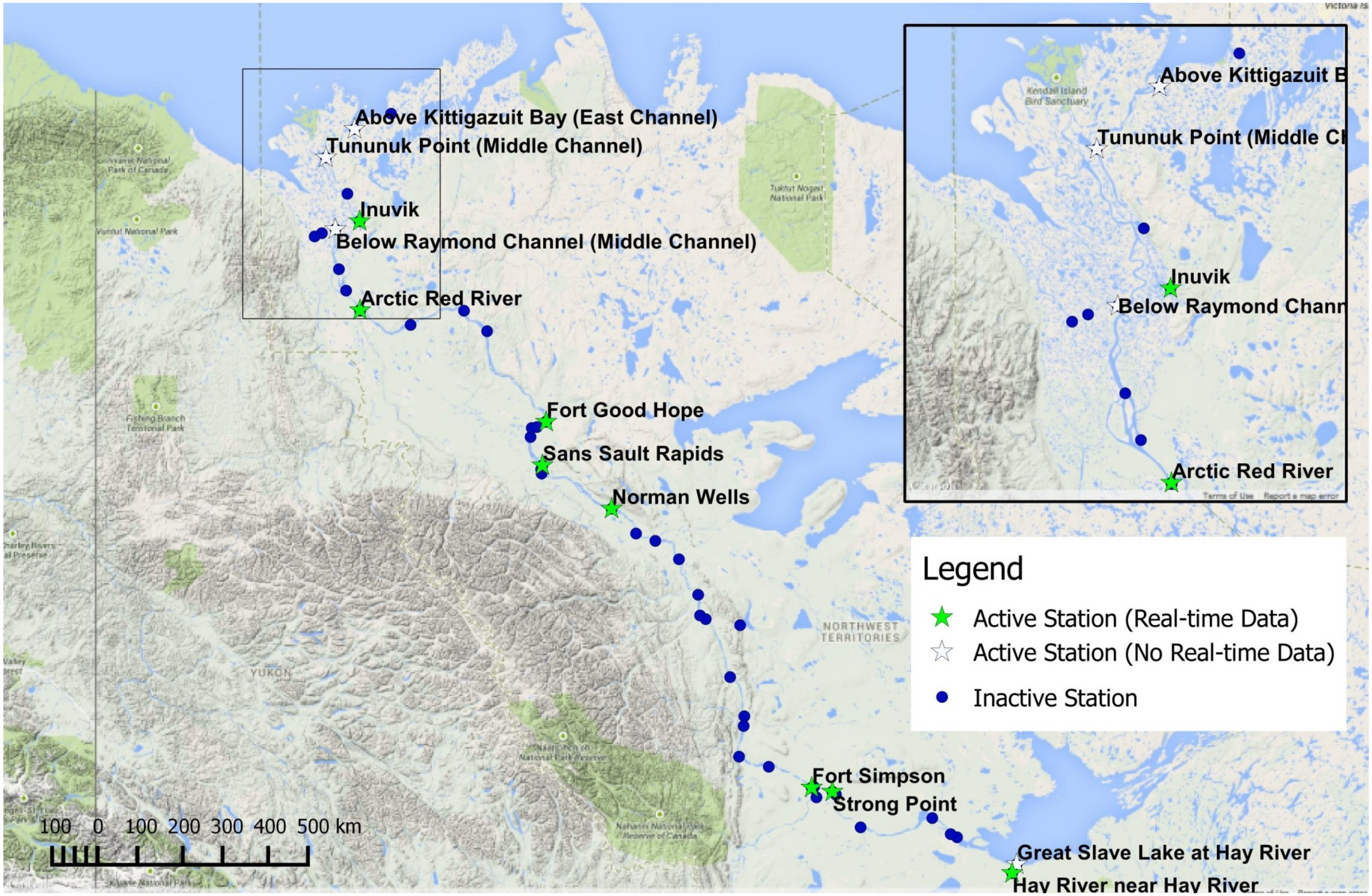

Figure 3-3 Hydrometric stations on the Mackenzie River in the Northwest Territories.

In this study, some basic analyses have been done using the water level data pertaining to understanding barge movement on the river.

3.2.3.1 Water levels over the short term

Figure 3-4 shows monthly mean water levels at the Fort Good Hope hydrometric station (see station location in Figure 3-3) on the Mackenzie River between 2002 and 2012. This period was chosen to explore the change in water levels at an arbitrary location on the Mackenzie River in recent years.

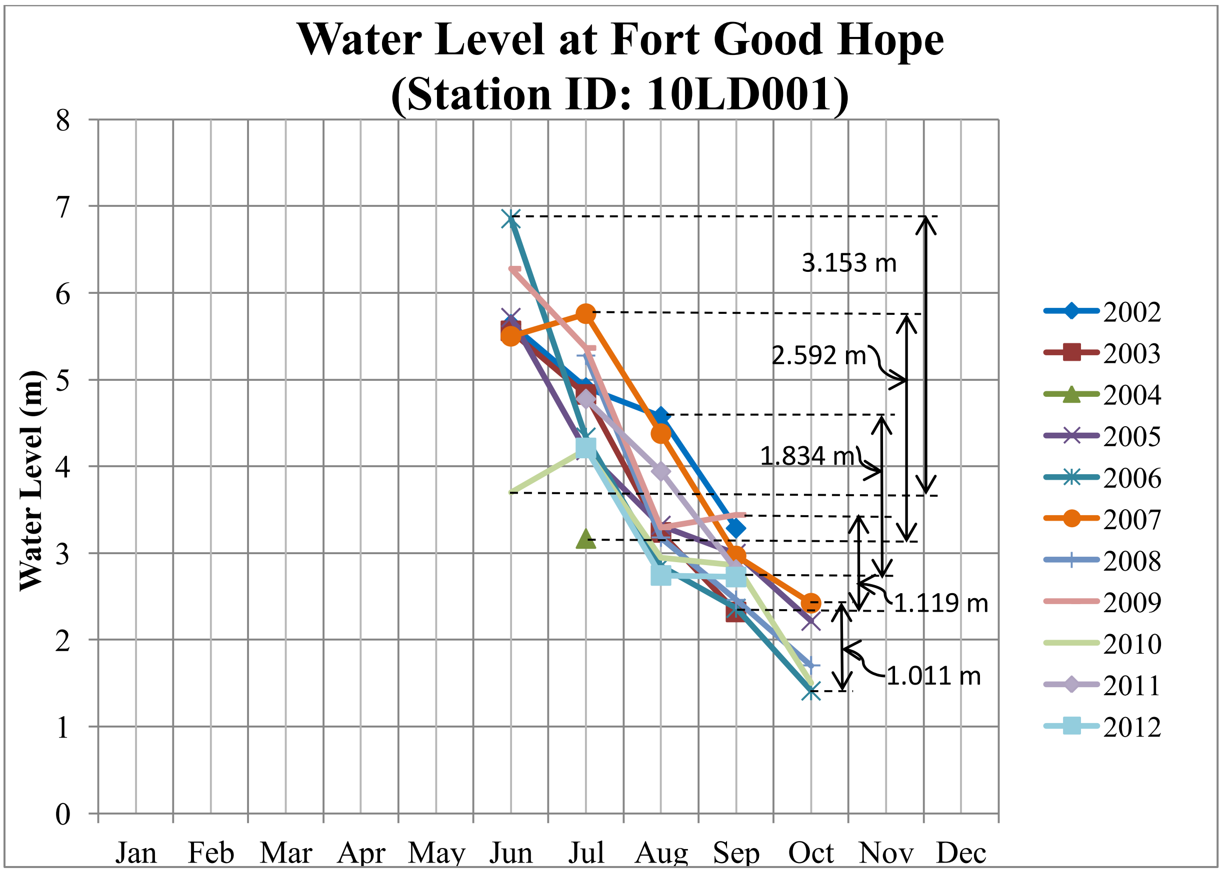

Figure 3-4 Monthly mean water levels at the Fort Good Hope hydrometric station, 2002-2012

Figure 3-4 shows that monthly mean water levels at Fort Good Hope have been quite variable from 2002 to 2012. This implies a high level of uncertainty in freight movement on the river from one year to another year. For example, highest and lowest monthly mean water levels for June at Fort Good Hope during 2002-2012 were 6.9 metres (in 2006) and 3.7 metres (in 2010) respectively. The mean water level in June 2010 may be an outlier. Excluding this value from mean water level values in June results in a range of 1.356 metres and average of 5.923 metres (for 2002-2012). Again, mean water levels were higher and more variable in the earlier months than in later months of the shipping season (i.e. June-October). In some late seasons, mean water levels decreased to values less than 1.5 m. Mean water levels decreased during 2003-2004, 2008, 2010, and 2012, but increased in 2007 and 2009 from previous years.

Exploration of water levels at the active hydrometric stations on the Mackenzie River suggests that water levels typically peak in May or June due to the spring snowmelt (Woo & Thorne, 2003). Water levels reach their lowest levels in October or November. The shipping season on the Mackenzie River typically starts in mid-June and ends in mid-October (PROLOG & EBA, 2010). During the early season, water levels are typically highest, and barges can be loaded with more freight (i.e. at higher draft). Barges are able to carry less freight later in the season due to shallower drafts than in the early season.

3.2.3.2 Water level scenarios in recent years

Figure 3-5 provides further information on available water depths along the Mackenzie River from May through October, for 2002 to 2012. These years were chosen since water levels are available at all the active hydrometric stations (locations can be found in Figure 3-3) from 2002 to 2012. The figure suggests which locations have the lowest water levels and greater uncertainty (i.e. difference between the high and low water levels). The minimums of the low, mean, and high water levels at the different locations are marked by lines of red, blue, and green dots.

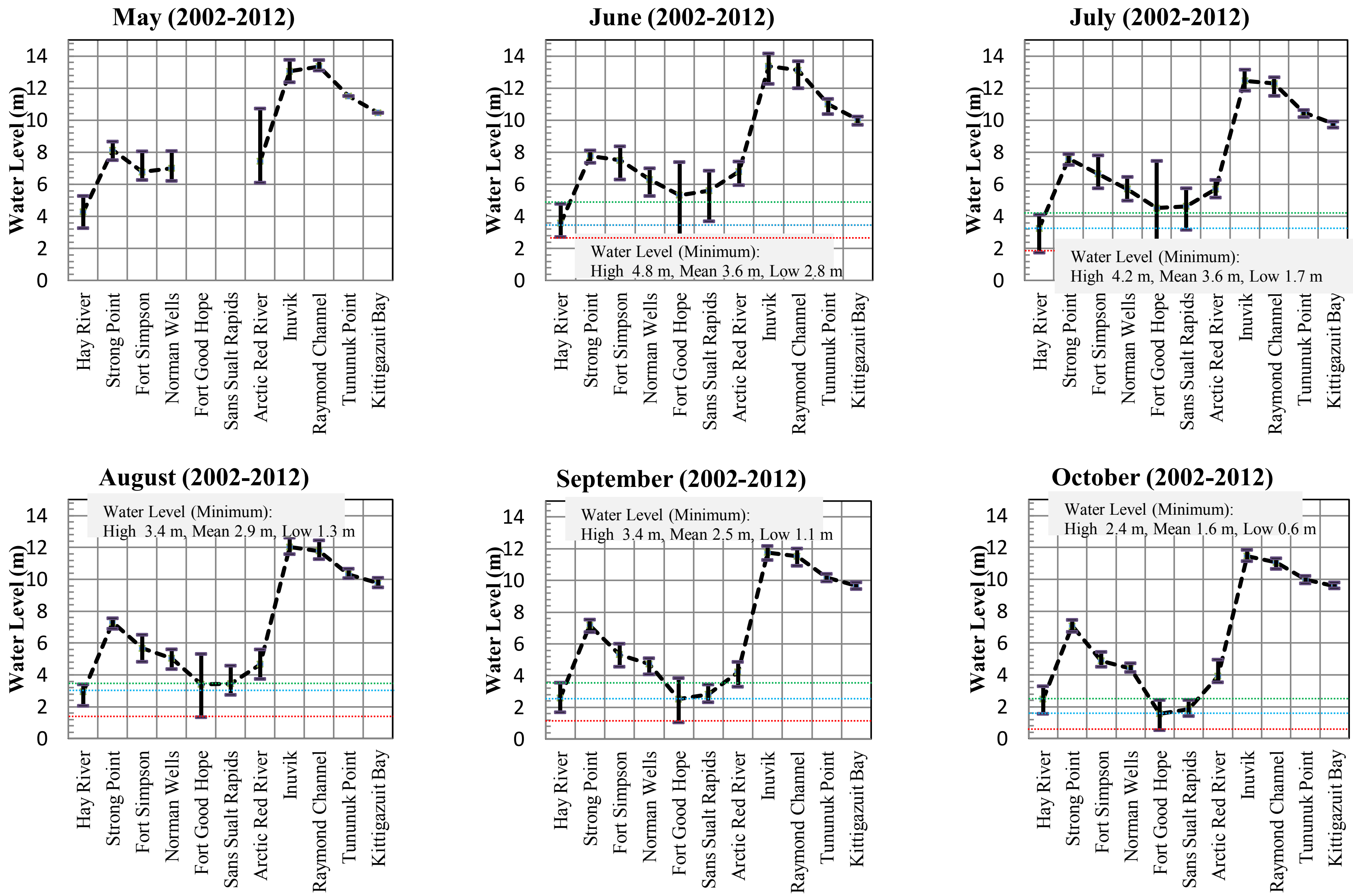

Figure 3-5 Water levels (high-mean-low) on the Mackenzie River (based on 2002-2012 water level data)

As shown in Figure 3-5, water levels on the Mackenzie River in June, for example, indicate that the lowest water levels were between 2.8 metres (red line) and 4.8 metres (blue line) during the 2002-2012 shipping season. Assuming one-fifth of the water level as a clearance distance between the vessel's bottom and the river bed, the available draft will be between about 2.2 and 3.8 metres. This would be the low water level shipping scenario on the Mackenzie River during the peak flow month of June. Similarly, the available draft will be between approximately 0.4 to 1.9 metres (1'4" to 6'4") in October. To estimate or assume a lowest water level scenario on the river, any water level between the green and red lines can reasonably be considered a low water level scenario for October. The water level information is summarized in Table 3-2.

Table 3-2 Water Level Scenario on the Mackenzie River in Different Months

Month	Minimum of water Levels (m)		
	Low	Mean	High
May	-	-	-
June	2.8	3.6	4.8
July	1.7	3.6	4.2
August	1.3	2.9	3.4
September	1.1	2.5	3.4
October	0.5	1.6	2.4

In Table 3-2, the low, mean, and high water levels decrease from June to October (except mean values in June and July, and high values in August and September). The lowest water level (i.e. minimum of the low water levels) was recorded at Fort Good Hope. The information presented in the table could be used to assume available vessel drafts on the Mackenzie River during different months of a shipping season. It should be noted that the above discussion is entirely based on the analyses of available water level data, and there may be other critical locations on the river that could not be identified.

3.2.3.3 Water levels over the long term

Figure 3-6 shows the long-term trend of monthly mean water levels at Fort Good Hope over several decades. Each line in this figure represents the monthly mean water levels for a decade during 1961-2010.

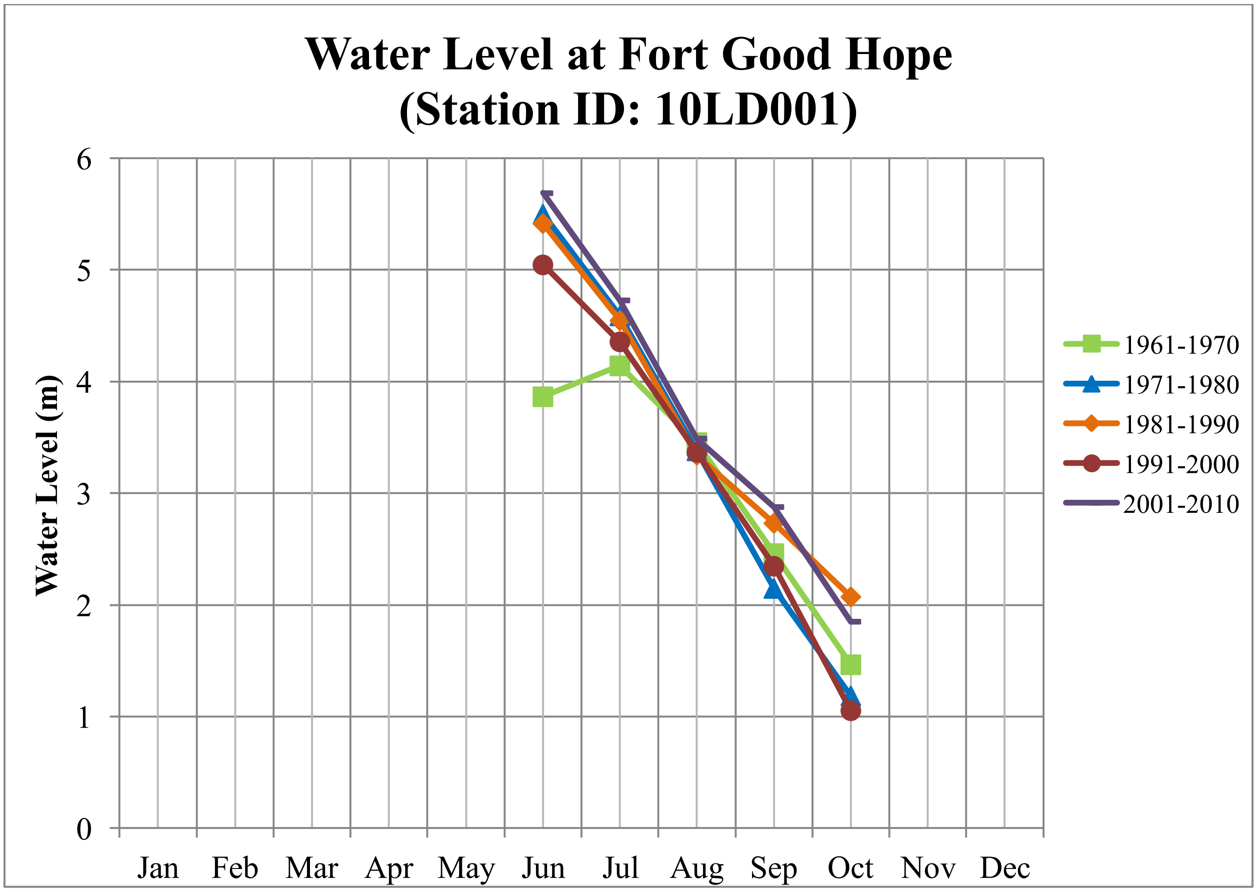

Figure 3-6 Decennial mean water levels at Fort Good Hope in the Mackenzie River

Mean water levels in June and July increased from the 1961-1970 decade to the 1971-1980 decade; then slightly decreased in the 1981-1990 decade; further decreased in the 1991-2000 decade; and finally increased to the highest of all five decades in the 2001-2010 decade. Mean water levels in August have changed the least compared to other months in these five decades. Mean water levels in September decreased from the 1961-1970 decade to the 1971-1980 decade; increased in 1981-1990; again decreased in 1991-2000; and finally increased in 2001-2010.

October's mean water level decreased in 1971-1980 from the mean water level in 1961-1970; then increased in 1981-1990; again decreased in 1991-2000; and finally increased in 2001-2000. Over the long term, the water level changing patterns have been similar for the June and July months of the shipping season. Other months have had different water level changing patterns in different decades. This figure suggests that the water level increased in earlier months of the shipping season over the long term. This could be due to increasing snow melt as the temperature rises. Mean water levels have been higher in the recent decade than in earlier decades.

High-mean-low monthly mean water level values at Fort Good Hope for each decade between 1960 and 2010 are shown in Figure 3-7. Water level variations (i.e. difference between high and low water levels) can be observed from this figure.

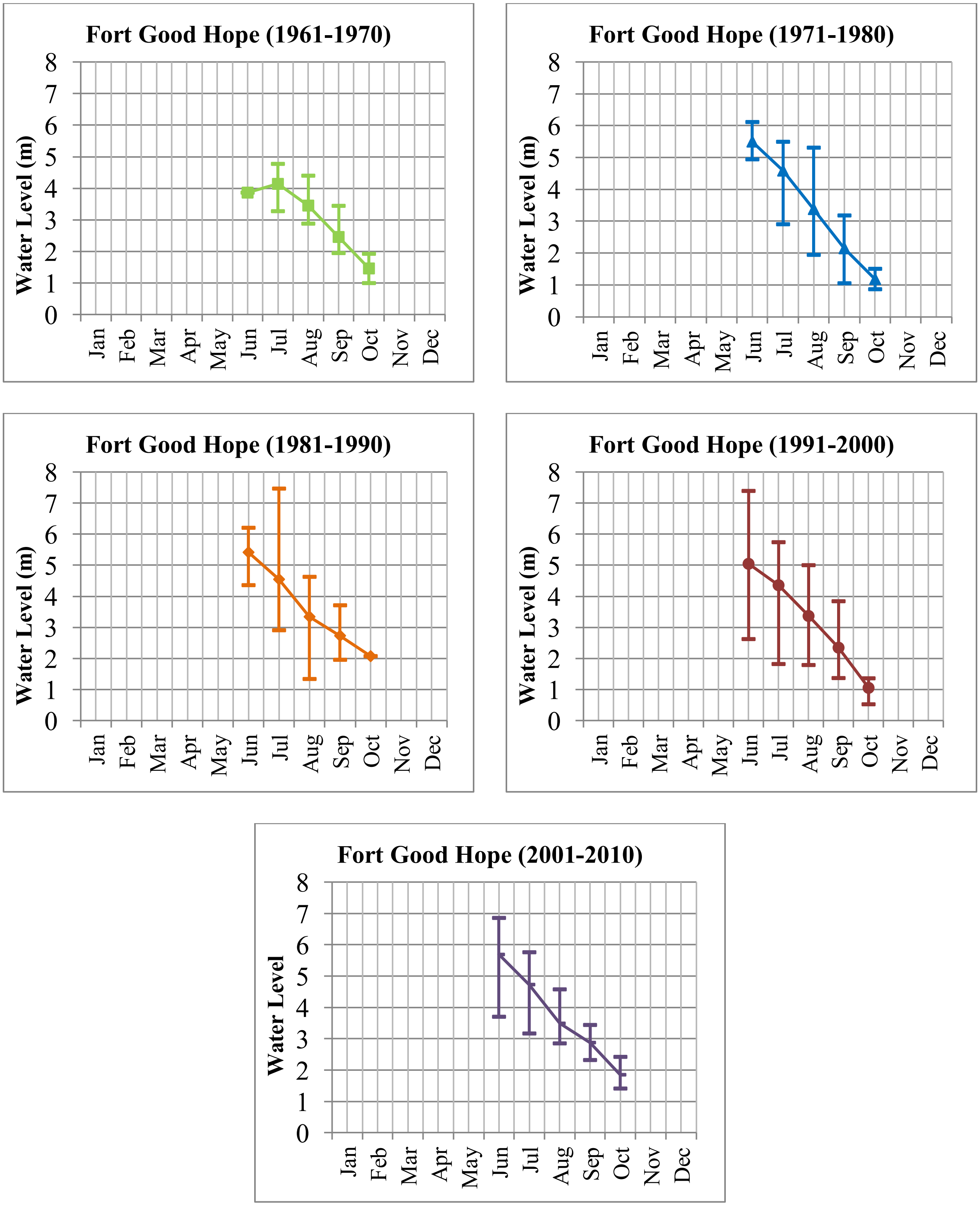

Figure 3-7 Variation of decennial mean water levels at Fort Good Hope in the Mackenzie River

Figure 3-7 shows that monthly mean water levels have become more uncertain (i.e. large difference between high and low water levels) in later decades, despite increasing mean water levels. Monthly mean water levels have gradually decreased from June to October except in the 1960s when the water level reached peak in July instead of June. The long-term water level trend at other hydrometric station locations may be more or less different than that at Fort Good Hope. Increasing uncertainty (i.e. a large change in water level over subsequent years), increasing mean water levels particularly at the beginning of the shipping season, and gradually decreasing water levels during a season are common water level characteristics of any location on the Mackenzie River.

3.2.4 Mackenzie River Freight Operators

Freight is shipped on shallow draft barges towed or pushed by tugs owned and operated by private companies on the Mackenzie River. The quantity of goods that can be shipped depends on the capacity and quantity of those tugs and barges. The three private operators that provide freight transportation services on the Mackenzie River are Northern Transportation Company Limited (NTCL), Cooper Barging Service Ltd., and Horizon North Logistics Inc. NTCL and Cooper Barging Service Ltd. operate charter freight services as well as scheduled deliveries during each shipping season. Horizon North Logistics Inc. provides charter services to oil and gas exploration activities (Horizon North Logistics Inc., 2009).

NTCL is the largest operator on the Mackenzie River, with a fleet of 12 tugs and 69 barges (NTCL, 2014a; NTCL, 2014b). NTCL's services are based in Hay River, where it has a large terminal and a shipyard. Other NTCL terminals are in Norman Wells, Inuvik and Tuktoyaktuk (NTCL, 2014c). NTCL has a gravel lay-down area at Norman Wells where cargos are dropped off and picked up, and temporarily stored (NTCL, 2014c). NTCL facilities at Inuvik and Tuktoyaktuk include a gravel lay-down area, warehouse, and finger piers (NTCL, 2014c). Two to three barges can be handled at the same time at these finger piers (NTCL, 2014c). NTCL's Tuktoyaktuk terminal may be used as the transshipment point for coastal communities' (e.g. Kitikmeot communities) cargos originating at the Mackenzie Delta, and accepts priority cargos for the Government of Nunavut (GN). Most of the other communities along the river can be accessed through beach landings or federal wharfs (Imperial Oil Resources Ventures Limited, 2004b). NTCL completed 14 resupply voyages to different NWT and Nunavut (NU) communities in 2013, with the first and last voyage starting on June 17 and October 7 respectively.

Another Mackenzie River freight operator, Cooper Barging Service Ltd., has 3 tugs and 9 barges (Cooper Barging Service Limited, 2014a), and delivers freight to communities between Fort Simpson and Norman Wells. It has a major staging and landing facility at Fort Simpson (Cooper Barging Service Limited, 2014a). Cooper Barging Service Limited advised that cargo should reach Fort Simpson at least 48 hours prior to the scheduled departure (Cooper Barging Service Limited, 2014b). In 2014, the operator completed six out of seven scheduled voyages between Fort Simpson, Tulita, and Norman Wells (Cooper Barging Service Limited, 2014b). Its first voyage started on June 16, and the last voyage ended on September 29 (Cooper Barging Service Limited, 2014b). Each voyage had two legs: the first leg was from Fort Simpson to Tulita, which takes two days, and the second leg was from Tulita to Norman Wells, which takes one day (Cooper Barging Service Limited, 2014b).

The third operator, Horizon North Logistics Inc. serves oil and gas exploration activities by transporting camps, matting, modular structures, equipment, and oilfield and mining related supplies to exploration sites in the Mackenzie Delta and Beaufort Sea (Horizon North Logistics Inc., 2009).

3.2.4.1 Tugs and barges operating on the Mackenzie River

Tugs are characterized by vessel class, dimension, horsepower (hp), speed, loaded draft, and fuel consumption rate. Tugs are assigned a vessel class based on their operational capabilities on different water bodies (e.g., sea, lake, and river). A tug's dimensions may restrict its operations on narrow sections or sharp bends of a river. Horsepower indicates the maximum load hauling capability of a tug. Loaded draft is the depth that a tug sinks into the water at its load capacity. There should be an observed safety margin beyond the loaded draft for safe and efficient operation of a tug. A tug's fuel consumption rate is used to estimate voyage cost. NTCL has tugs capable of operating in the Arctic and on the Mackenzie River (NTCL, 2014a), while Cooper Barging Service Ltd.'s tugs operate only on the Mackenzie River. Dimensions of the tugs are roughly 160' x 50' x 10' (NTCL, 2014a). Most NTCL tugs operating on the river have capacities ranging between 4000 and 6000 hp. Cooper Barging Service Limited's tugs are of smaller capacity compared to NTCL tugs. A tug of 2500-3000 hp can haul about 6000 deadweight tonnage (dwt) (Mariport Group Ltd., 2011c). The minimum draft of these tugs may vary from 3'9" to 4'6" (NTCL, 2014a; PROLOG & EBA, 2010). A normal tug operating speed is between 10 and 14 knots (NTCL, 2014a; PROLOG & EBA, 2010). However, these speeds are only achievable under ideal operating conditions (i.e. no hazards, draft restrictions, or other restrictions). Further details of tug specification can be found in NTCL (2014a), PROLOG Canada & EBA Engineering Consultants Ltd. (2010), and the Government of Canada's vessel search website (n.d.).

The quantity of goods that can be shipped in a voyage depends on barge size and capacity. Barge specification details include barge series number, type, length, breadth, depth, load area, light draft, load line draft, and deck and bulk capacity (NTCL, 2014b; PROLOG & EBA, 2010). Similar to tugs, the length and breadth of a barge indicate how much space would be required to maneuver the barge on a river or a channel. The number of barges that can be towed or pushed together is dependent on river and channel restrictions at the bends or the narrow passages. Load area limits the size and quantity of cargo that can be loaded onto a barge. Light and load line drafts are the depths to which a barge sinks at minimum and maximum load, respectively. Each barge has a maximum load capacity. NTCL has one NT 12000, four 1800, twenty-eight 1500a/1500b, twenty-four 1000, and eleven 800 series barges (NTCL, 2014b). Cooper Barging Service Limited has three 800, five 400, and one 200 series barges (Government of Canada, n.d.; PROLOG & EBA, 2010). The dimensions (Length x Breadth x Depth) of 1500 (i.e.1500a/1500b), 1000, and 800 series barges are 250' x 56' x 9'6", 200' x 50' x 7'6", and 160' x 48' x 9'8" respectively (NTCL, 2014b). Light drafts of 1500, 1000, and 800 series barges are 1'9", 1'6", and 1'3" respectively (NTCL, 2014b). Load line drafts of 1500, 1000, and 800 series barges are 6'9", 5'0", and 6'11" respectively (NTCL, 2014b). The total capacities of 1500, 1000, and 800 series barges are 2190, 1005, and 930 tonnes respectively (NTCL, 2014b).

3.2.4.2 Barge capacity and operation on the Mackenzie River

The following factors affect the load capacity of a barge on the Mackenzie River:

- Water level/draft: On the Mackenzie River, a barge at 5'0" draft can handle more than 1.5 times the load at 3'6" draft (Mariport Group Ltd., 2011d).
- Barge and load size: "The standard tow operated on the Slave/Peace/Athabasca route was six 600 series barges at a target draft of 3'6" " (Mariport Group Ltd., 2007a, p.

19). Although the tow of four 1000 series barges is shorter in length than the tow of six 600 series barges, 1000 series barges are almost one and a half times wider than 600 series barges (Mariport Group Ltd., 2007a, p. 19). Thus, the 1000 series barges may have difficulty in narrow channels.

Moreover, barge capacity may be reduced depending on the size and shape of the load. A large load straddling several barges (e.g. a heavy oil sands module) may have greater difficulty in maneuvering on a narrow river and channel (Mariport Group Ltd., 2007a, p. 19).

- Goods type: The quantity of cargo carried by a barge depends on the composition of the load (i.e. dry cargo or bulk fuel, or both dry cargo and bulk fuel). In a deck cargo and bulk fuel combination, the equivalent weight of bulk fuel can be calculated using appropriate load conversion factors (Mariport Group Ltd., 2011d).

The relationships between available water depth and barge capacity have been discussed in several Mariport Group reports (2007a), (2011c) and (2011d). Typical deck loads are between 600 and 800 tons with no bulk (Mariport Group Ltd., 2011d). Figure 3-8 shows the capacity of barges at different drafts.

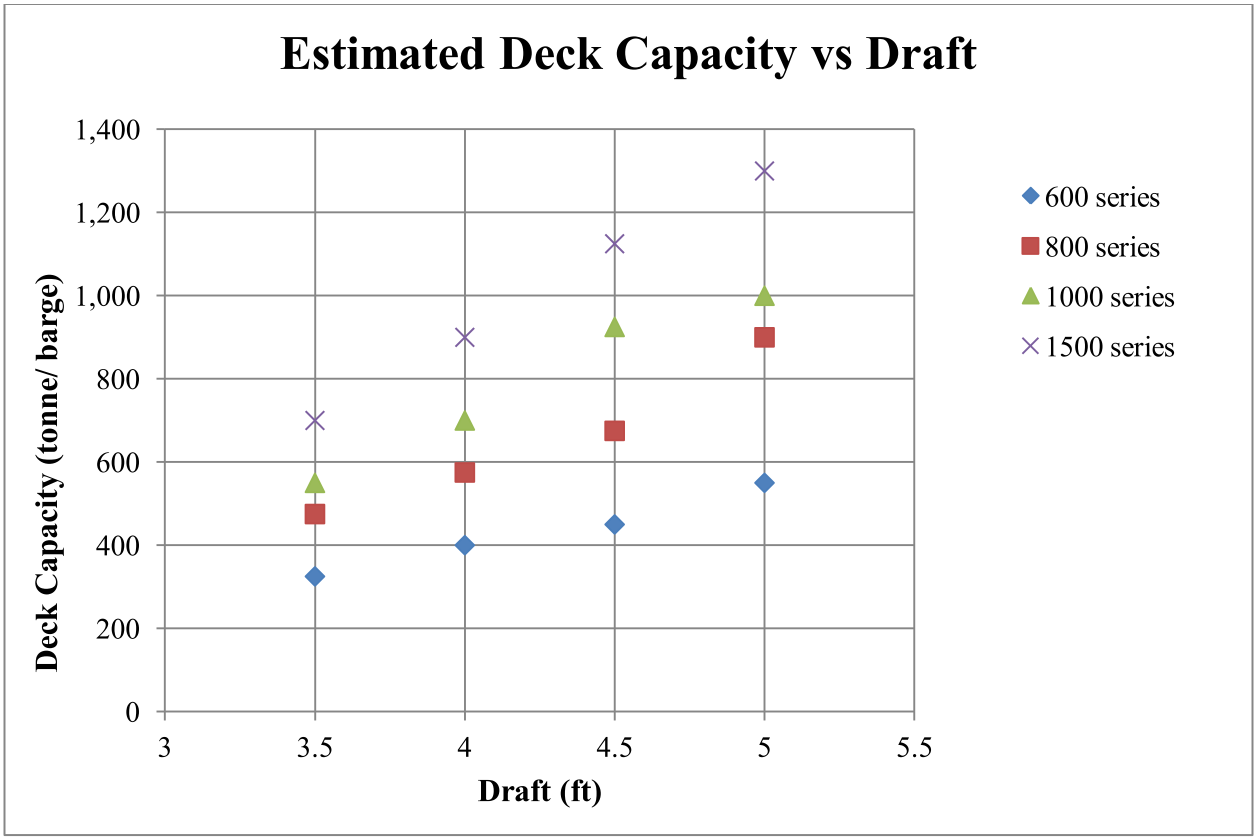

Figure 3-8 Deck capacity of barges at different drafts, Source: Mariport Group Ltd. (2007a, p. 19)

As shown in Figure 3-8, barge capacities can be said to increase linearly as draft increases, and higher series barges have more cargo capacity than lower series barges. Maximum cargo capacity on a tow can be determined by multiplying the number of barges with the deck capacity at a specific draft.

Tug and barge operating speeds on the river are between 1 and 12 knots depending on water levels, upstream or downstream sailing direction, and proximity to navigation hazards. Barges are typically pushed downstream and towed upstream. Barges are better controlled in a push operation than a tow while sailing downstream (Smith, 2014). As a result, they typically travel at higher speeds in a push operation. For example, speed of an Arctic Type B barge ranges between 10-12 and 6-7 knots at push and tow operations respectively (Mariport Group Ltd., 2011c).

Transit times between different locations on the river primarily depend on the tug speed. Operating speed is normally limited by navigational hazards on the river. NTCL provided indication of transit times between several locations on the river. These transit times are given in Table 3-3.

Table 3-3 Typical Transit Times from Hay River on the Mackenzie River

Destination	Transit Time (in day)
Tulita	3.5
Norman Wells	4.5
Fort Good Hope	5.5
Inuvik	7
Tuktoyaktuk	8

Source: Smith (2014)

The time it takes to load/unload freight at the communities must be included as part of the total tug and barge transit times. Some estimates on bulk fuel delivery time in the Eastern Arctic were obtained from a report by the Mariport Group Ltd. (2011c). The report estimated six hours for equipment setup at each community, with additional delays estimated at five hours per community. For example, a delivery of 850 m^3 of diesel to a community may take between 16 and 21 hours (i.e. 6 hours of setup, 0 to 5 hours of delay, and 10 hours of pumping time at 85 m^3/hr pumping rate).

3.3 Freight Movement Demand

The Mackenzie River is used to transport community supplies, resource development cargo, and bulk fuel (PROLOG & EBA, 2010). Community resupply primarily consists of two major types of cargo: dry cargo and petroleum products. Dry cargo includes all types of general cargo used by communities, including cargo related to development works (i.e. building materials). Petroleum products are different fuels used by the communities (e.g. diesel, gasoline, and jet fuel). Power supply in many communities is dependent on diesel generators (Mariport Group Ltd., 2011a). As a result, bulk diesel is one of the major commodities delivered to the communities.

The main source of dry cargo for the Western Arctic and the Mackenzie River communities is Edmonton. Dry cargo reaches the communities via truck transport from Edmonton to Hay River, and then by NTCL's tugs and barges from Hay River (Mariport Group Ltd., 2011d). River communities in the Sahtu region are also served by Cooper Barging Service Ltd. via Fort Simpson (Mariport Group Ltd., 2011d).

Petroleum, Oil and Lubricants (POL) can be delivered from refineries in Canada, the United States, and other offshore sources in Europe or Asia (Mariport Group Ltd., 2011c). The Strathcona refineries near Edmonton are the most traditional POL source for the NWT. However, depending on the availability of cheaper fuel from refineries in the US or Europe and shorter sailing distances to certain communities in the Arctic, other sources may be used.

The following section provides background information on freight demand in the NWT.

3.3.1 River and Marine System Demand

The Mackenzie River serves as the main transportation connection for a number of communities without all-weather road connectivity (PROLOG & EBA, 2010, pp. 26, 34). For example, there is no all-weather road connection from Wrigley to Fort Good Hope, and then from Fort Good Hope to the Delta region (PROLOG Canada Inc., 2011, p. 18). Figure 3-9 shows the freight volumes in tonnes per year for the two operators on the Mackenzie River.

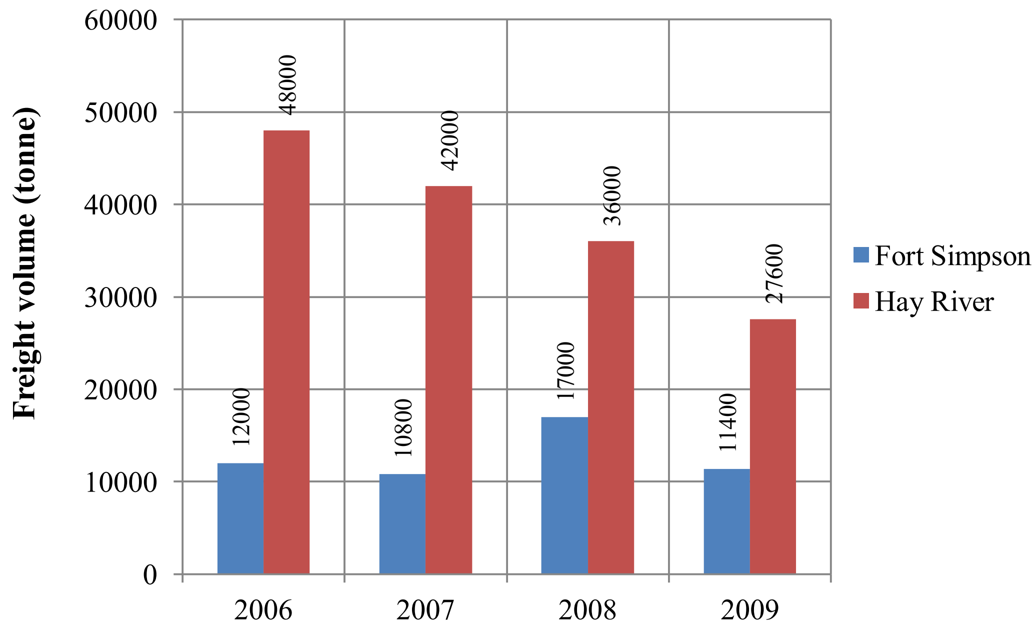

Figure 3-9 Freight demand on the Mackenzie River, Data source: PROLOG Canada (2010)

In general, freight volumes have decreased in recent years throughout the NWT, primarily due to the decline in oil and gas resources development activities (PROLOG & EBA, 2010; Schlenker Consulting Ltd., 2012). Hay River freight volumes have decreased significantly while Fort Simpson's volumes remained stable. Since resource development activities near the Mackenzie River are near Norman Wells and further north (Schlenker Consulting Ltd., 2012; Imperial Oil Resources Ventures Limited, 2004), Hay River cargo volumes may have decreased due to reduced freight demand for destinations near and beyond Norman Wells. As mentioned previously, there is no all-weather road between Wrigley and Fort Good Hope, and as a result, the river provides the main freight access for communities located in between. This may explain why Fort Simpson freight volumes have not experienced declines similar to those at Hay River.

Figure 3-10 provides further information on marine and river freight by commodity group from 2006 to 2009.

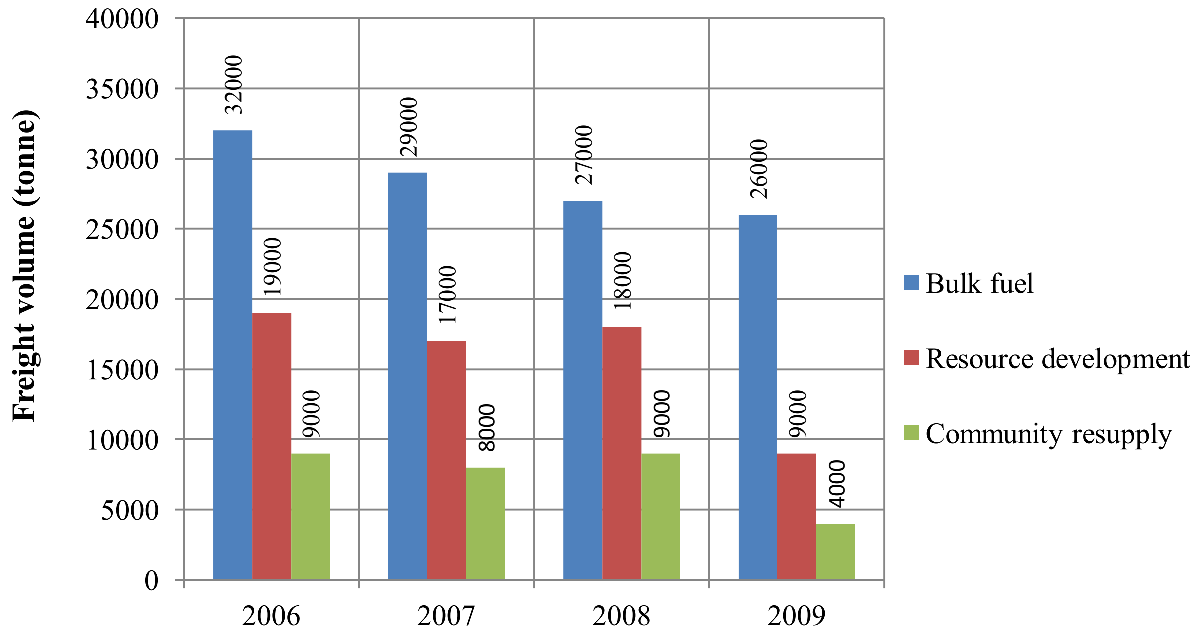

Figure 3-10 Freight Movement Demand by Commodity Group on the Mackenzie River, Data source: PROLOG Canada (2010)

Bulk fuel constitutes almost half the marine and river freight. Resource development and community resupply cargo declined in 2009 from previous years. Increased resource development activities may also lead to some population growth within the region temporarily, and thus community resupply demands could also increase with more cargo related to resource development. Decrease in bulk fuel resupply was less compared to other cargo types. This might be due to increasing demand for fuel in the communities.

3.3.2 Community Cargo Demands

The Mariport Group Ltd. estimated community dry cargo demand based on some assumptions and previous years' freight demand data (Mariport Group Ltd., 2011d). Figure 3-11 presents dry cargo demand by regions in the NWT. Nunavut Kitikmeot Region and mines have also been added to the figure since Kitikmeot Region is served out of Hay River.

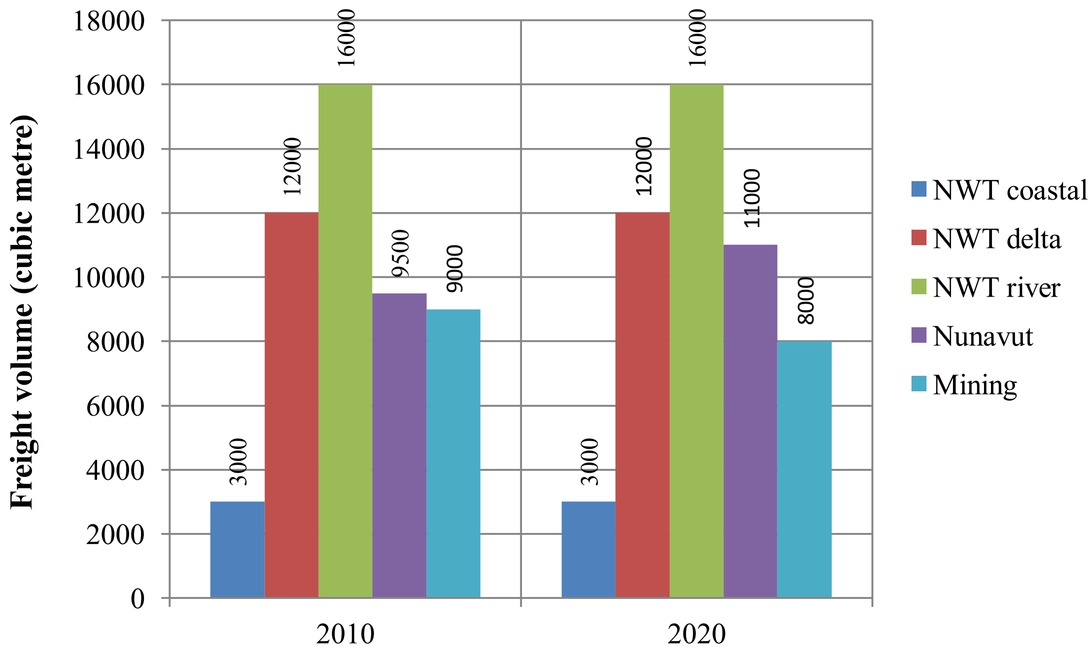

Figure 3-11 Estimated dry cargo in 2010 and 2020, Data source: Mariport (2011b)

As shown in Figure 3-11, it is estimated that there will not be significant changes in dry cargo volume in 2020 compared to 2010. The population is projected to remain steady in 2020. Thus, dry cargo volume is also estimated to remain unchanged (Mariport Group Ltd., 2011d).

The Mariport Group Ltd. also estimated the demand of petroleum products (POL) for communities in the NWT in one of their studies (Mariport Group Ltd., 2011c). Mariport Group Ltd. estimated POL demand using a trend analysis of historical data available from the NWT Petroleum Products Division (PPD) and other available sources (Mariport Group Ltd., 2011c). Figure 3-12 shows regional POL demand as determined by the Mariport Group Ltd. The Delta and Kitikmeot regions have the largest POL demand. These demands are projected to increase over the years.

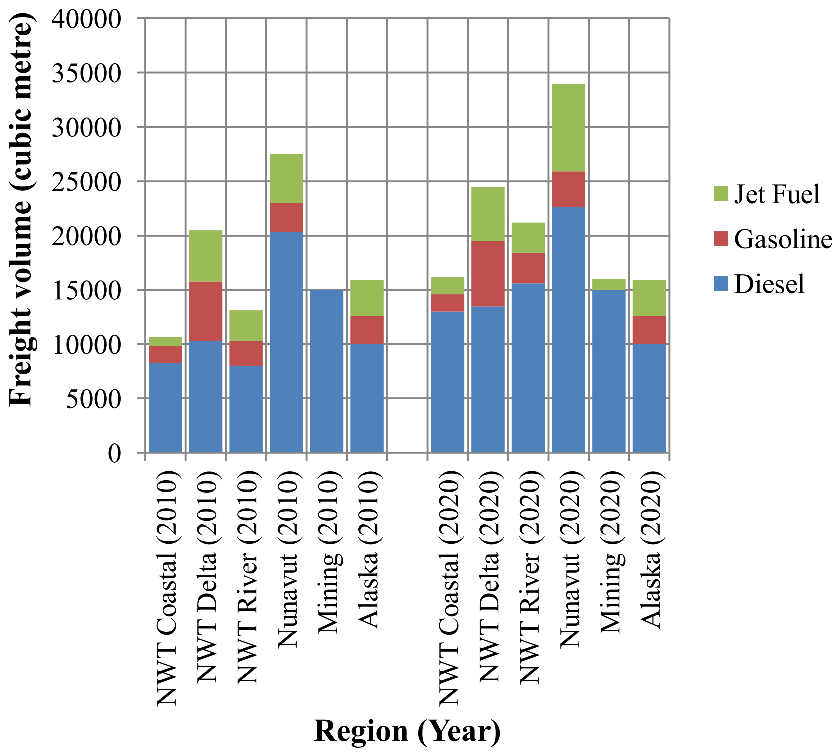

Figure 3-12 Estimated Petroleum Product Volumes in 2010 and 2020, Data source: Mariport Group Ltd. (2011b)

Total bulk fuel demand is estimated to increase in 2020 compared to 2010. Since population is projected to remain steady (Mariport Group Ltd., 2011b), the increase in fuel demand would be due to increases in fuel consumption in the communities and resource development activities. Unit fuel delivery costs can be lowered by delivering fuel in a medium or large tanker (Mariport Group Ltd., 2011c). Existing low demand and scattered delivery locations (i.e. communities) are obstacles to achieving large volumes that can be delivered using medium or large tankers. Tug and barge service will also be required to deliver fuel to communities transhipped from ocean tankers. Fuel storage is another issue affecting delivery options. Some NWT communities do not have the infrastructure to store large volumes of fuel (Mariport Group Ltd., 2011c). Different parties involved in POL sourcing and specification issues may also cause difficulty in sourcing fuel using large or handy size tankers.

3.3.3 Heavy Modules for Northern Alberta Oil Sands

Alberta's oil sands industry requires heavy equipment at extraction sites and process plants (Mariport Group Ltd., 2007a). Estimates of (heavy module) unit numbers could not be found. Mariport Group Ltd. mentioned that it had discussions with two logistics companies and four oil companies about the potential of the northern route (Mariport Group Ltd., 2007a). Synenco, the Northern Light oil sands project operator, wanted to move about 60 pieces of equipment using the route (Mariport Group Ltd., 2007a). The route can be used to move oil sands modules as heavy as 2000 metric tonnes and with dimensions of 164'x85'x82' approximately (Arctic Module Inland Transportation, 2009).

3.4 Summary

This chapter presented available data on the Mackenzie River, gathered from different sources and organized here to be used in the network representation described in Chapter 4. The data include information related to spatial features of the Mackenzie River transportation system (i.e. river and channels, communities, danger zones, and navigational hazards), water levels, tugs and barges, facilities, and operations of freight operators. Available freight movement data for the river system have also been gathered and included in this chapter.

Spatial features of the Mackenzie River transportation system will be coded as nodes, and connected by links in the network representation. The locations of these features were obtained from relevant shape files in the geospatial data warehouse of the GNWT. These shape files do not contain all the required attributes (e.g. tug speed on the river, loading/unloading time at communities, water level of river segments) of these features. Tug speeds on the river and cargo loading/unloading times at communities were obtained from reports and information provided by the GNWT and the NTCL. Most communities do not have a wharf or dock to load/unload goods on/off barges. Information on loading/unloading locations, facilities, and the maximum number of barges that can be loaded and/or unloaded at any instance could not be obtained from the available documents.

Danger zones are important spatial features of the Mackenzie River transportation system that are likely to have an adverse impact on tug and barge operation. A major limitation of this study is the lack of operational information (e.g. speed) for tugs and barges on the river in the danger zones. Another important attribute of the river transportation system is water level. Water level determines the amount of goods that can be shipped on the river. Locations with available water level information and some analyses of water level at these locations have been provided along with their implications on shipping. Increasing uncertainty (i.e. a large change in water level over subsequent years), increasing mean water level particularly at the beginning of the shipping season, and gradually decreasing water levels during a season are common water level characteristics of any location on the Mackenzie River. Water level information is available for a limited number of locations along the river. In addition, the specifications of available tugs and barges in the Mackenzie River system have been provided in this chapter. Specifications include the size, speed, and cargo capacity of these vessels.

Finally, freight demand information for the Mackenzie River system provides an idea of how much goods have been shipped in recent years using the river system. Although more freight is shipped from Hay River compared to Fort Simpson, freight volumes decreased significantly at Hay River in recent years. The freight demands of Mackenzie River–dependent regions were also gathered. Data shows that dry cargo demands in most of these regions will remain the same in 2020 while fuel demands will increase. Demands and information on other restrictions on the river (i.e. water depth and seasonal restrictions) would be required in the model to predict freight movement in the corridor.

CHAPTER 4. TRANSPORTATION NETWORK MODEL BUILDING AND TESTING

This chapter discusses the network model building process for the Mackenzie River shipping corridor. The purpose of building this representation of the network is to use it in solving different freight problems related to the Mackenzie River. Spatial features of the Mackenzie River (i.e. river, communities, danger zones, navigation hazards, and other locations) along with relevant information were coded as nodes. Then, links were formed using the node information, which would be used in modelling. River nodes and links have been discussed in Section 4.1. Section 4.2 discusses the network model testing, which primarily involved verifying whether paths can be generated using the node information. The chapter closes with a summary in Section 4.3. An earlier version of this chapter was included in S A, Kim, & Zheng (2015), a project progress report prepared for the Transport Canada.

4.1 Network Model Building

The Mackenzie River was abstracted in a node-link representation. Nodes represent points on the river where tug and barge operating conditions or operations (i.e. changing speed and/or direction) may change because of the river's physical characteristics (e.g. bend, rapid), and transhipment and warehousing points. Different types of nodes and links required for this representation were first identified, and then divided into classes to consider their effects on the network. For example, links connecting a river location to a community will have loading/unloading times, while other river links will have different operating speeds depending on their navigability. Then, nodes were prepared using shape files representing different elements (i.e. Mackenzie River and adjacent channels, communities, danger zones, and other locations) and other available information as discussed in Chapter 3. Node attributes considered in the network representation were also discussed. After that, network links were prepared using the node file. Finally, other data related to the network such as tugs and barges, and community cargo demands were stored to be used in modelling application for different freight problems (e.g. optimum fleet size determination).

4.1.1 Node and Link Classification

A general node and link classification of the Mackenzie River representation is presented in Figure 4-1. Nodes are classified into three types depending on what they represent—a community landing or terminal, the start or end of a danger zone, or an intermediate river location. Each type of node has different characteristics. Tug and barges anchor at a landing site to load and unload goods. Landing locations are at communities along the river. These locations are origins and destinations of goods, and assigned node type 1 in the representation. Node type 1 is connected to a source and a sink in the network representation[3]. The start and end of a danger zone or a navigational hazard marks the location on the river where tug and barges will travel cautiously at a lower speed. Tug and barge operation on the river also depends on the water level and/or physical characteristics (i.e. available turn radius) of the hazardous location. For example, barges may have to anchor ahead of a hazard and then be towed one at a time to pass the location (Smith, 2014). Hazardous locations on the river include bends, narrows, rapids, rock, and shoal etc. Node type 2 is assigned to these river locations. The third type of location is an intermediate point on the river that is not an origin, a destination, or a navigational hazard; intermediate river points are designated node type 3. Depending on data availability (e.g. speed,

[3] A source is a node where all goods flows are generated (in a freight network model), and a sink is a node where all goods flows are terminated. Source and sink are considered for the sake of mathematical model formulation.

spacing between tug and barges, passing or overtaking) for these locations, node type 3 can be used to capture tug and barge operations at locations other than those designated node type 1 and 2, such as at a river bend that is not hazardous enough to be considered a node type 2. Tugs and barges must still turn at such locations to remain on course. While preparing the Mackenzie River network representation, node type was assigned before merging different node layers in GIS. Shape files containing three different types of spatial features were merged into one using the "Merge shape files to one" tool in the "Data Management Tools" in QGIS (QGIS development team, 2014).

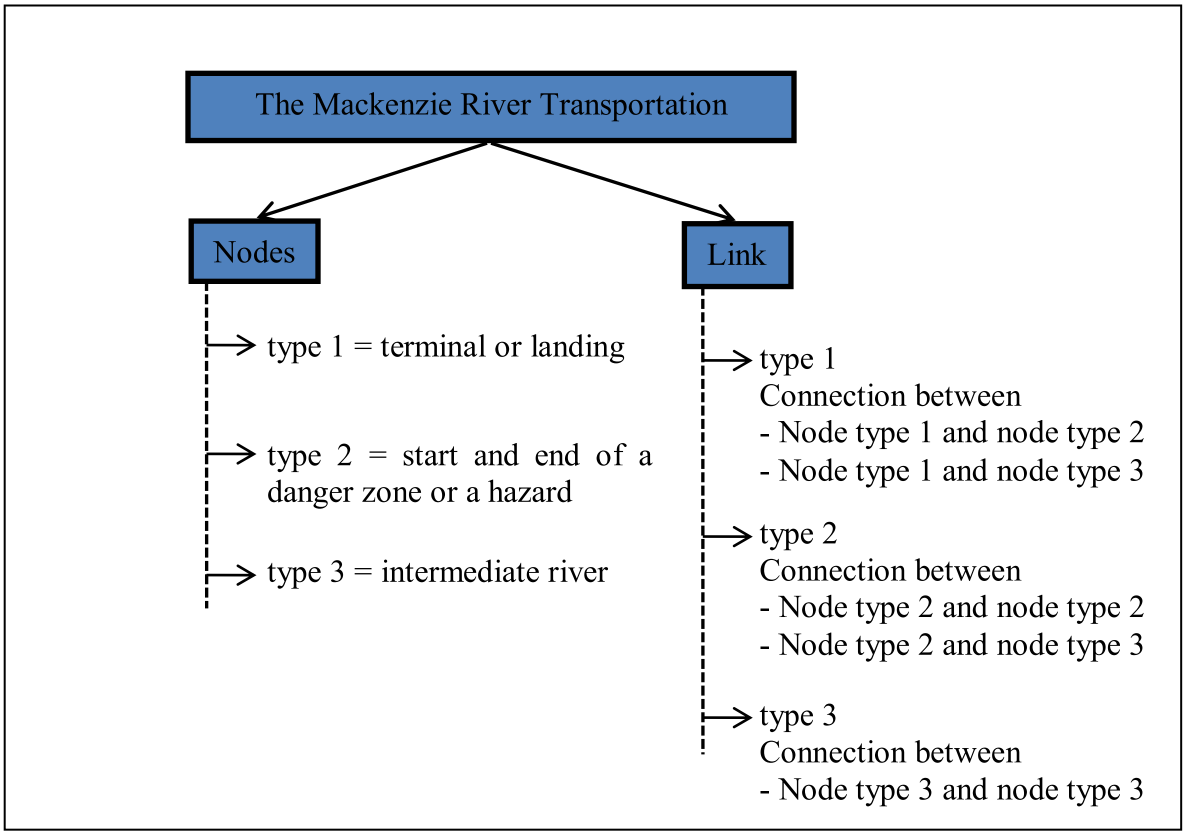

Figure 4-1 Node and link classification of the Mackenzie River network representation

Links are also classified into three types depending on their nodes. The link between a type 2 or 3 node and a type 1 node is the connection of a river location to a terminal (e.g. Hay River or

Inuvik) or a landing. This type of link involves cargo loading and unloading activities. The link between a type 2 or 3 node and a type 2 node connects a hazardous location to another hazardous location or intermediate point of the river. This link is less likely to have normal operating conditions. Normal operating conditions allow for travelling at average tug operating speeds on the Mackenzie River, while extreme conditions result in below-average operating speeds. The link between a node type 3 and a node type 3 is considered to have normal operating conditions (also referred to as a normal segment later on). In the Mackenzie River network representation, link type is determined based on the start and end node types retrieved from the node file. Link type affects transit time and the maximum number of tugs and barges that can be present on the link at any time. Link speeds in the network representation are assigned based on link type. Figure 4-2 shows a sample river segment abstracted into a node-link system.

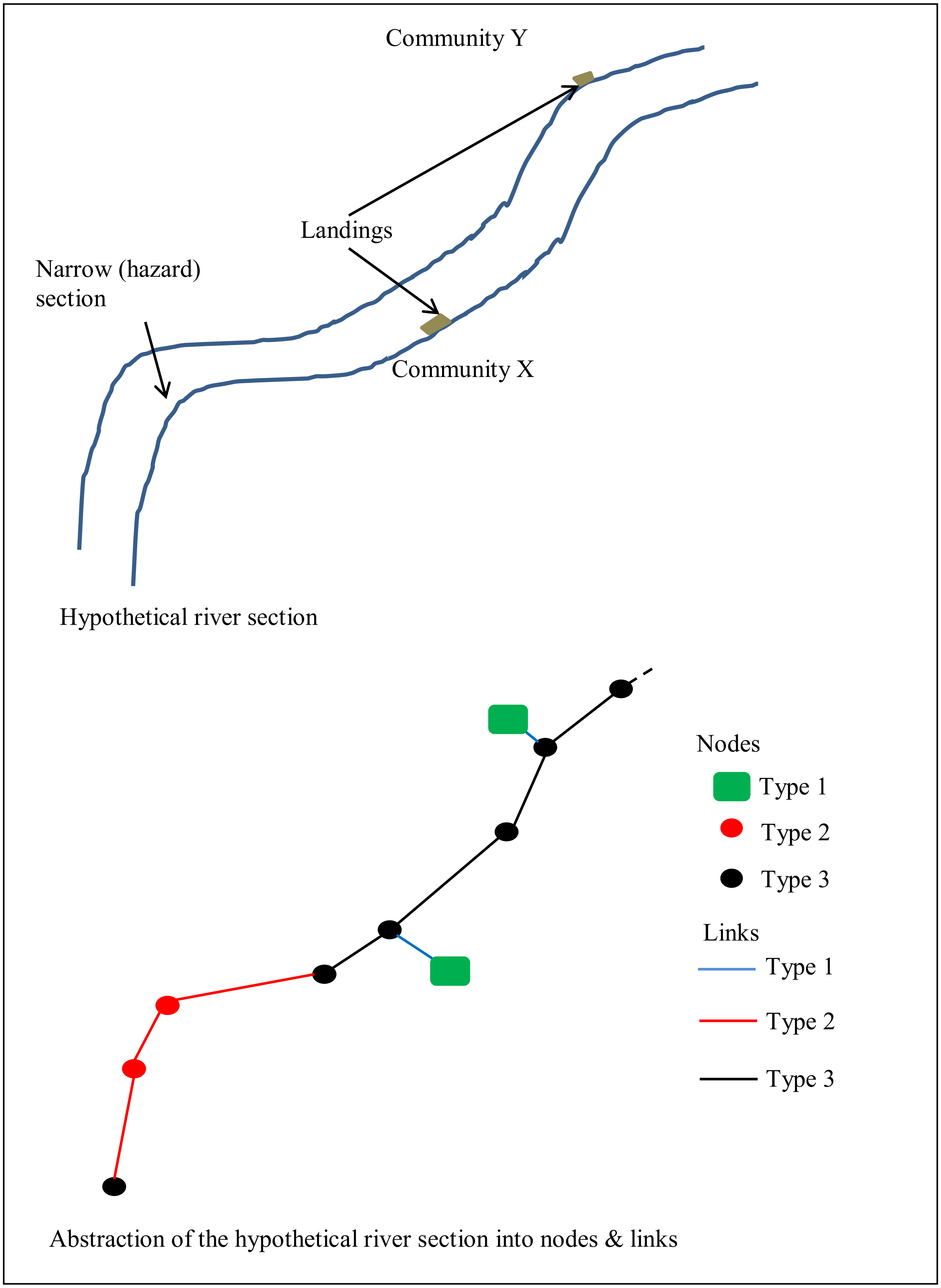

Figure 4-2 Sample river segment network representation

In Figure 4-2, three types of nodes and links are shown. Links shown in red will have a lower operating speed than those shown in black. Tugs and barges traversing red links will have higher travel costs (than normal links) mainly due to higher operational risk factors. Undirected links have been used in the above figure only for the purpose of illustration. Links are often coded as directed for convenience in mathematical model formulation.

4.1.2 Nodes

Communities, danger zones, navigational hazards, and some additional intermediate points are nodes in the network representation. Intermediate points were used to approximately capture the shape of the river. These locations were identified on the "Mackenzie River and its adjacent channels" shape file (described in Section 3.2.1.1) using QGIS 2.0.1, a free and open source Geographic Information System (QGIS development team, 2009) software. Initially, an absolute criterion was set for identifying the intermediate locations. For example, locations at a mile or a minimum safe distance apart on the Mackenzie River shape file could be chosen as the intermediate locations. Alternatively, locations on the Mackenzie River shape file which has a sharp angle could be chosen as the intermediate locations. Any of these criteria would result a large number of nodes with not any known operational significance such as tug speed change or interruption. Thus, a few locations on the Mackenzie River shape file were chosen manually to graphically represent the river. Spatial features of the Mackenzie River system (described in Section 3.2.1) were available as point shape files. The retrieved communities' shape file was edited in the GIS software to keep selected communities (also described in Section 3.2.1.2) as the network nodes. Features in shape files were edited using tools in the "Digitizing" and "Advanced Digitizing" toolbars in QGIS. To edit a feature on a shape file layer, first the feature was selected. Then, "Toggle editing" was turned on and required edit such as add, delete and move etc. were done. Danger zone starts and ends as well as other navigational hazard locations were obtained through querying the “geoname” shape file layer by name and type respectively. To identify the navigational hazards on the “Mackenzie River and its adjacent channels” shape file, the navigational hazards shape file was overlaid on the line shape file layer of the Mackenzie River. Navigational hazards outside the Mackenzie River and its adjacent channels were then selected and deleted. All these point shape file layers were merged together in GIS to build a shape file of nodes. Each node in the network representation has the following attributes.

4.1.2.1 Unique node number (i.e. ID)

Each node in the network representation was assigned an ID for convenience in identifying the node or location in an application. River nodes were assigned IDs starting at 201 in Tuktoyaktuk. Generally, upstream nodes have IDs greater than their downstream nodes. Communities were assigned arbitrary IDs less than 100. Node ID has no other significance in the representation.

4.1.2.2 Longitude and latitude

Latitudes and longitudes can be obtained from the spatial features’ shape files. This information may be useful to transfer the results to other software for analysis or visualization purposes.

4.1.2.3 Connecting nodes

Links are formed using information on connecting nodes (i.e. network topology (Ahuja, 1993)). Once the nodes are merged and assigned IDs, neighbour nodes (i.e. connected nodes) were identified using GIS. Merged nodes were overlaid on the “Mackenzie River and its adjacent channels” shape file and the Google physical layer available through the “OpenLayers plugin” in QGIS to identify which nodes are connected. Consecutive nodes on the Mackenzie River shape file are connected nodes. Google physical layer confirmed that these shape files are overlaid on the right locations. Connected nodes can be identified using either the Mackenzie River shape file or the Google physical layer. Connected nodes were stored in a matrix form. Provisions for five connected nodes were kept after a preliminary scan of the network. Most nodes have two or three connected nodes. More connected nodes can be easily accommodated by adding additional columns to the matrix. Similarly, the matrix size can be reduced if a column is completely unused.

4.1.2.4 Node type

Node type was discussed in 4.1.1.

4.1.2.5 Hydrometric station ID

If a node on the Mackenzie River has a hydrometric station within five miles, then the node is assigned a station ID. Otherwise the ID is set as zero. The hydrometric stations' locations were collected from the WSC website (described in 3.1.3). The concept of incorporating water level information in the network illustration is illustrated in Figure 4-3.

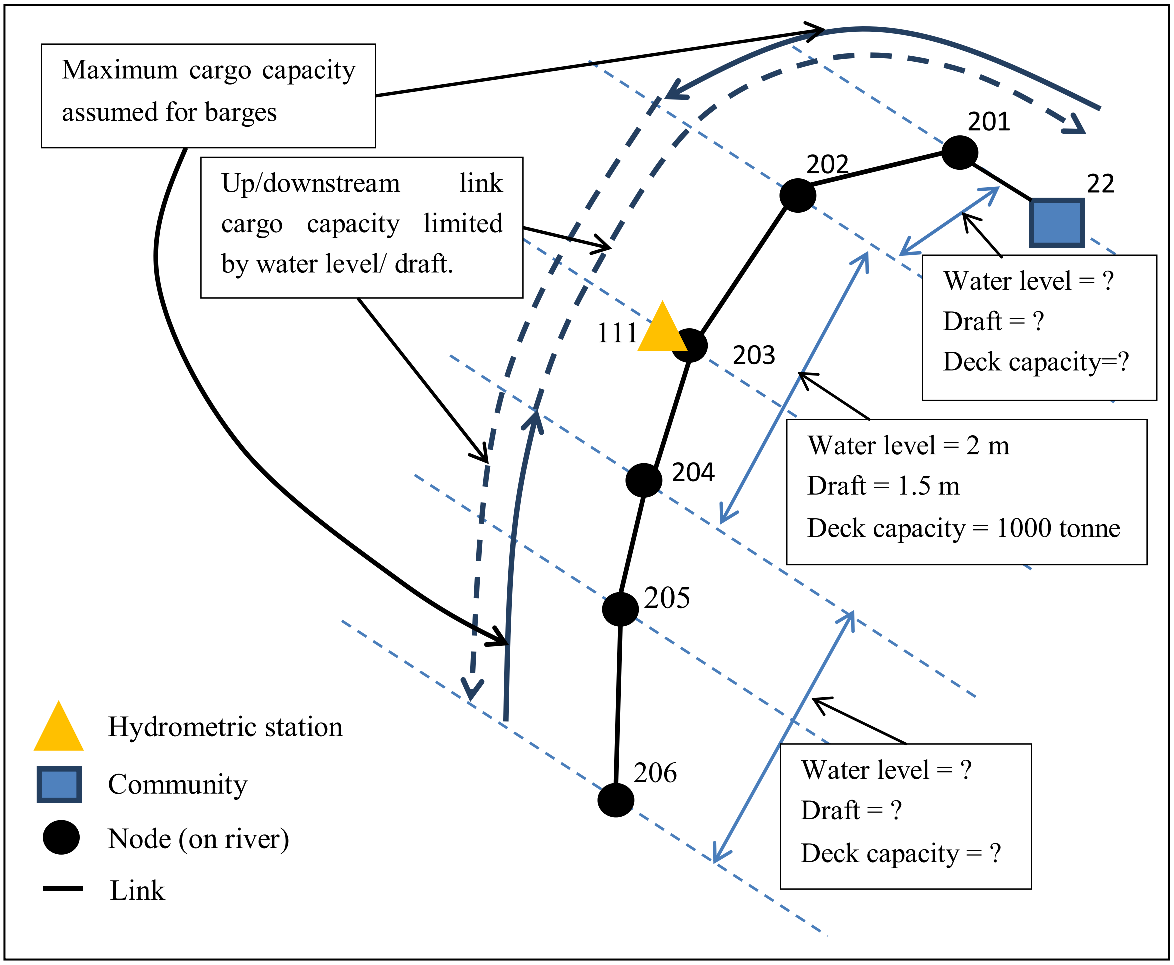

Figure 4-3 Incorporating water level in the Mackenzie River network representation

In Figure 4-3, there is a hydrometric station at node 203, but other nodes do not have any hydrometric station. Assume that the mean water level at station 111 is 2 m, available draft at this water level is 1.5 m or 5 ft, and deck cargo capacity of a 1000 series barge at 5 ft draft is 1000 tonnes. Then, water levels on the links (202, 203) and (203, 204) are assumed to be equal to the water level at hydrometric station 111. Thus, the maximum deck cargo capacity of these two links would be equal to 1000 tonnes. Any freight delivery by tug and barge traversing links (202, 203) and/or (203, 204) cannot carry deck cargo over 1000 tonnes on each barge. Other links are assumed to have no cargo load restrictions imposed by water levels since no water level information is available. Rather cargo load limits on these links (without water level information) would be the maximum cargo capacity of a barge which could be more than 1000 tonnes in the present example. That means upstream delivery from node 22 to 202 can carry the maximum barge load, and any node beyond 202 will be limited by 1000 tonnes per deck. In downstream delivery, deck cargo capacity can be assumed maximum up to node 204 while 1000 tonnes beyond node 204.

The cargo capacities of links can be utilized as constraints in the mathematical model formulated using the node and link information. There would also be other factors associated in the problem such as the number of available tugs and barges, transit times, and loading/unloading times, fuel consumption, fuel cost etc.

4.1.2.6 River mile

River miles measure the distance of the node on a river from a reference point (i.e. Wrigley Harbour at the southeastern shore of Great Slave Lake). Link length is calculated based on river miles. River miles of some of the nodes are known from different sources (i.e. danger zone and distance table). River miles of other nodes were calculated using the shape file of the Mackenzie River and river miles of known locations (i.e. distances of points along the line shape of the river).

The processed node information was stored both in GIS shape file, and *.csv file format. The *.dbf extension of the shape file contains network data required in computation. The *.csv file can be manipulated as required for computation software (e.g. MATLAB) in order to implement a mathematical model using the network data. Table 4-1 shows a sample of the node file, which stores node attribute data of the network.

Table 4-1 Node List File Sample

Node	Longitude	Latitude	Connected Node 1	Connected Node 2	Connected Node 3	Connected Node 4	Connected Node 5	Node Type	Nearby Hydrometric Station ID	River Mile
22	-133.03605	69.44997	202	0	0	0	0	1	0	1086
201	-133.03059	69.45109	22	202	0	0	0	2	0	1086
202	-133.61664	69.388629	201	203	0	0	0	2	0	1081
203	-133.95459	69.28615	202	204	0	0	0	2	111	1070
204	-134.24914	69.217342	203	205	0	0	0	3	0	1060
205	-134.38264	69.09291	204	206	0	0	0	3	0	1050
206	-134.65489	68.999668	205	207	213	0	0	3	110	1043
207	-134.63275	68.967178	206	208	0	0	0	2	0	1040
208	-134.14065	68.688738	207	209	0	0	0	3	0	1012
209	-133.98109	68.562705	208	210	211	0	0	3	0	1001
210	-133.73749	68.356035	28	209	0	0	0	2	108	977
28	-133.72501	68.358	209	0	0	0	0	1	0	977

In Table 4-1, node 22 represents a landing site at a community (type 1) and it is connected only to node 201. Terminals and community landing sites in the network are assumed to have the same river miles as its connecting node on the river. The connection between node 22 and node 201 represents loading/unloading operations. Furthermore, node 203 is a hazard point (type 2) at river mile 1070. The water level at node 203 is represented by the water level at hydrometric station 111.

4.1.3 Links

Connected nodes' information (see Table 4-1) is used to define links. Each link in the network representation has the following attributes.

4.1.3.1 Start and end nodes

Each link in the network representation is identified by its start and end nodes. Links were not provided any unique ID. In the node file, the first column contains all the nodes in the network, and the fourth to eighth columns contain neighbour (connected) nodes. For example, in Table 4-1, node 201 is connected to node 22 and node 202. Thus, there are two links (201, 22) and (201, 202) containing start node 201. Links were formed by pairing up nodes in the first column to its connected nodes in the fourth to eighth columns. There is no node labelled zero in the network. Since data were saved in a matrix structure for convenience in using available computation software like "MATLAB" or "OCTAVE", unused cells in the connected nodes were filled with zero.

4.1.3.2 Length

Once the links are formed, link lengths can be calculated as the difference between river miles of start and end nodes. The river mile of each node is stored in the node file, and can be retrieved by searching the file.

4.1.3.3 Link type

Link type was discussed in 4.1.1.

4.1.3.4 Water levels

The water level data inclusion process was explained in 4.1.2.5.

4.1.3.5 River transit speeds

Tug speed on a link is used to determine transit time and the maximum number of tugs and barges that can be present on the link at any time. Because tug speeds will vary with environmental and operating conditions, they are considered to be random variables. Most waterway simulation studies have obtained tug speed from historical data. Almaz & Altiok (2012) calculated vessel speed between stops from travel times that were beta distributed. Ozbas & Or (2007) calculated speed from uniformly distributed travel times. There is no unique travel time or speed distribution for vessels. Again, in a mathematical modelling study, Righini (2014) assumed constant barge speed. Historical travel time and speed data were not available in this study. However, indicative transit times for a few destinations from Hay River could be obtained from NTCL. Tug speed on a link is assumed to be equal to the sum of mean speed and a normally distributed error term with zero mean for convenience. Tug speed on a link depends on whether the link belongs to a normal river segment or a hazardous segment. The mean speed of a hazardous segment is less than that of a normal segment. Speed on a link should be greater than zero and less than the maximum tug speed.

$$v_k = \mu_k + \varepsilon, \quad \varepsilon \sim N(0, \sigma) \tag{4.1}$$

Where,

v_k is the tug speed on k type link (in knots),

μ_k is the mean tug speed of link type k (in knots), and

ε is an independent and identically distributed Normal error term with zero mean and σ standard deviation.

Preparing speed information for network links has two steps: i) mean speed calculation for river segments from transit time data, and ii) assigning calculated speeds to the links in the network. Mean speeds for different types of links were estimated using known transit time data and link lengths. Transit times between Hay River and several other terminals and communities (i.e. Tulita, Norman Wells, Fort Good Hope, Inuvik, and Tuktoyaktuk) were obtained from NTCL (Smith, 2014). The mean speed on a hazard link/segment is assumed to be half of the normal link/segment's mean speed. The distances between the origins and destinations, and normal and hazard segment lengths can be calculated using the node file. Total normal and hazard segment lengths on a given route are the sum of all normal (type 3) and hazard (type 2) links on the route, respectively. Assuming no intermediate stop between origin and destination (OD), transit times, waterway segment lengths, and speeds can be expressed by a set of equations:

$$t_{ij} = \frac{d_{ij,k=2}}{\mu_{k=2}} + \frac{d_{ij,k=3}}{\mu_{k=3}} \tag{4.2}$$

$$\mu_{k=2} = \frac{\mu_{k=3}}{2} \tag{4.3}$$

$$d_{ij} = d_{ij,k=2} + d_{ij,k=3} \tag{4.4}$$

Where

t_{ij} is the transit time between start location i and end location j (hour),

$d_{ij,k=2}$ is the total hazard segment length between i and j (sum of type 2 link lengths, miles),

$d_{ij,k=3}$ is the total normal segment length between i and j (sum of type 3 link lengths, miles),

d_{ij} is the total distance between i and j (mile),

$\mu_{k=2}$ is the mean tug speed on hazard (type 2) links (mile/hour), and

$\mu_{k=3}$ is the mean tug speed on normal (type 3) links (mile/hour).

Limited and approximate transit time information was available from NTCL as mentioned earlier. Since it is assumed that there is no intermediate stop on an OD trip, transit times for non-overlapping river segments can be easily calculated from the given transit times for consecutive overlapping segments. For example, transit times for Hay River to Tulita and Hay River to Norman Wells are provided. The transit time between Tulita to Norman Wells can be calculated as the difference between these two given transit times. Hence, the mean speed for different river segments can be calculated from transit time data using eq. 4.2-4.4. Table 4-2 shows the calculated mean speeds.

Table 4-2 Calculated Mean Tug Speeds

Start	End	Distance (mile)	Hazard Segment (mile)	Normal Segment (mile)	Transit Time (days)	Mean Speed (knots)	
						Hazard Segment	Normal Segment
Hay River	Tulita	545.4	307	238.4	3.5	4.4	8.8
Tulita	Norman Wells	51	0	51	1	0.9	1.8
Norman Wells	Fort Good Hope	121	102	19	1	4	8.1
Fort Good Hope	Inuvik	330	11	330	1.5	4.2	8.5
Inuvik	Tuktoyaktuk	109	57	52	1	3	6

All the normal and hazardous OD links are assigned the mean values of corresponding river segments. For example, if one freight delivery starts at Hay River and ends at Fort Good Hope (with or without intermediate stops), links from Hay River to Tulita will be assigned mean speeds of 4.4 and 8.8 knots on type 2 and type 3 links respectively. Then, links between Tulita to Norman Wells will be assigned mean speeds 1 and 0.9 knots on type 2 and type 3 links respectively. Finally, links between Norman Wells and Fort Good Hopes will be assigned mean speeds 4 and 8.1 knots on type 2 and type 3 links respectively. In Table 4-2, an anomaly is the calculated mean speeds between Tulita and Norman Wells. Although there is no danger zone or hazardous segment between these two locations, mean speeds are very low. The transit time might not be for a non-stop journey. As a result, mean speeds were underdetermined. Mean speeds between Tulita and Norman Wells were assumed to be the same as its preceding segment.

Finally, to assign speeds to the links between the start and end locations of river segments in Table 4-2, the links were first identified by applying a path generation algorithm. The algorithm can identify all links on a path between two nodes based on the connected nodes' information. Then, mean speeds were assigned to these links depending on their type (i.e. 1, 2, or 3 identified in an earlier step).

Table 4-3 shows a sample of a link file prepared as in the above-mentioned procedure.

Table 4-3 Link List File Sample

Node 1	Node 2	Length	Link Type	Water Level	Speed
22	201	0	1	0	0
201	202	5	2	10.039	3
202	203	11	2	10.039	3
203	204	10	2	0	3
204	205	10	3	0	6
205	206	7	3	11.011	6
206	207	3	2	11.011	4.2
207	208	28	2	0	4.2
208	209	11	3	0	8.5
209	210	24	2	13.374	8.5

An Octave code (Octave community, 2014) was written to prepare the link file from the node file, and the link file is assigned the above attributes from the node file. At first, the Octave code prepares network links by pairing up each connected node (end node of a link) to its corresponding node (start node) in the node list. Then, river miles and node types for each node of these links are assigned from the node list to calculate link length and link type. Link types are determined based on the link classification discussed in 4.1.1. After that, water level data is assigned to the link if there exists a hydrometric station on the start or end node. Hydrometric station at a node is looked up in the node list, and water level is assigned from the water level data of the hydrometric station. Finally, speed was assigned to each link depending on its location on the river segment and link type (speed assignment to links explained in 4.1.3.5). The links within a river segment were identified by applying a path generation algorithm. The link generation technique is applicable to any network with nodes coded as described earlier.

The path generation algorithm was written based on the Breadth First Search (BFS), a common network shortest path search algorithm. The BFS algorithm was modified to find all possible paths in the network. Knowing all paths between an origins and destinations may be useful to apply routing strategies in case the shortest or most used path is closed due to an incident except on the Mackenzie River main channel where there is only one path. In the BFS technique, the first node is added to a list, then "admissible arcs" are found for the node (Orlin, 2010). An "admissible arc" contains a node that has not been visited (i.e. unmarked). The algorithm runs till it finds an "admissible arc" or the list is empty. However, all the paths from an origin to a destination can be found by visiting each neighbouring node (i.e. both visited and unvisited) as long as the node is not in the path. This algorithm may become NP-hard in a complex large network. Because the Mackenzie River network representation is simple insofar as there are very few route alternatives for an OD pair, this technique can easily find all possible paths. An alternative would be to apply a shortest path algorithm such as Dijkstra's method (Ahuja, 1993).

The pseudo codes of link and path generation programs are given in Appendix B.

4.1.4 Other Components in the Network Model

There are other data presented in Chapter 3 that are not directly coded as attributes of nodes and links, such as tugs and barges and freight demands.

4.1.4.1 Tugs and Barges

Different classes of tugs and barges operating on the river were introduced in Section 3.1.3. Each tug has nine attributes: name, operator, operator ID, assigned ID, maximum speed, operating speed, tow speed, load line draft, and fuel consumption. General tug attributes (i.e. horsepower, speed, load line draft, and fuel consumption) have been briefly described in Chapter 3. Three different speeds have been coded due to variability in data availability (see Table 4-4). Name, owner, and assigned ID were used for the purpose of identification in the network representation.

There are a fixed number of tugs operated by the Mackenzie River freight operators. Each tug was assigned a numerical ID for convenience in problem formulation. Imagine, tug #1 is assigned six barges to deliver goods to several locations on the river system, and it will take three weeks to complete the delivery and return to its origin port. Once assigned a delivery, the tug will not be available for a particular time period. Thus, it would require an ID to keep track of it while forming a mathematical problem. Tugs owned by one operator are not likely to assign other operators' barges. Hay River origin freight deliveries are towed by NTCL tugs, and Fort Simpson origin freight by Cooper Barging Service Ltd.

Barges have eleven attributes: series number, operator, operator ID, quantity, length, breadth, depth, light draft, load line draft, capacity, and fuel capacity. Barge attributes were discussed in Chapter 3. Additional attributes such as series number and operator ID are used to identify available or assigned barges with different operators.

Tug and barge attributes are stored separately in two *.csv files. Tables 4-4 and 4-5 show the tug and barge files respectively.

Table 4-4 Tug File Sample

Tug Name	Operator	Operator ID	Assigned ID	Horse - power	Maximum Speed (knot)	Operating Speed (knot)	Tow Speed (Knot)	Load line Draft	Fuel Consumption
M.V. Alex Gordon	NTCL	1	1	7200	14	11.5		14.17	417
M.V. Jim Kilabuk	NTCL	1	2	7200	14	11.5		14.17	417
M.V. Nunakput	NTCL	1	3	4300	12		7	6	525
M.V. Pisurayak Kootook	NTCL	1	4	4300	12		7	6.5	525
M.V. Pat Lyall	NTCL	1	5	4300	12		7	6.5	525
M.V. Vic Ingraham	NTCL	1	6	4500		12		3.75	550
M.V. Edgar Kotokak	NTCL	1	7	5600		14		3.75	550

Table 4-5 Barge File

Series	Operator	Operator ID	Quantity	Length (ft)	Breadth (ft)	Depth (ft)	Light Draft (ft)	Load Line Draft (ft)	Capacity (tonne)	Fuel Capacity ('000 litres)
12000	NTCL	1	1	404	105	23	0	16	15000	0
1800	NTCL	1	4	210	56	13	2.5	10	2590	0
1500	NTCL	1	28	250	56	9.5	1.75	6.75	2190	1800
1000	NTCL	1	24	200	50	7.5	1.5	5	1005	1300
800	NTCL	1	11	160	48	9.67	1.25	6.92	930	800
800	Cooper	2	3	165	45					
400	Cooper	2	5	127	32	0	0	0	900	0
200	Cooper	2	1						275	

* Unavailable data left blank.

4.1.4.2 *Community freight demand*

Community freight demands are stored in *.csv files as well. The community freight demand file has six attributes: name, ID, dry cargo, diesel, gasoline, and jet fuel. Table 4-6 shows a sample of the community freight demand file.

Table 4-6 Community Cargo Demand File Sample

Community Name	Node	Dry Cargo (tonne)	Diesel (cubic metre)	Gasoline (cubic metre)	Jet Fuel (cubic metre)
Fort Good Hope	5	1000	2107	647	
Fort McPherson	7		2250	670	
Tulita	8	1000	1880	472	
Fort Simpson	11				
Hay River	13				
Norman Wells	17	2000	3700	1100	2800
Tuktoyaktuk	22	2000	4350	1000	
Aklavik	27		2500	580	
Inuvik	28		4485	3000	4725
Tsiigehtchic	29	2000	1053	146	

* Unavailable data left blank.

4.1.5 Network Summary

The complete network is presented in Figure 4-4.

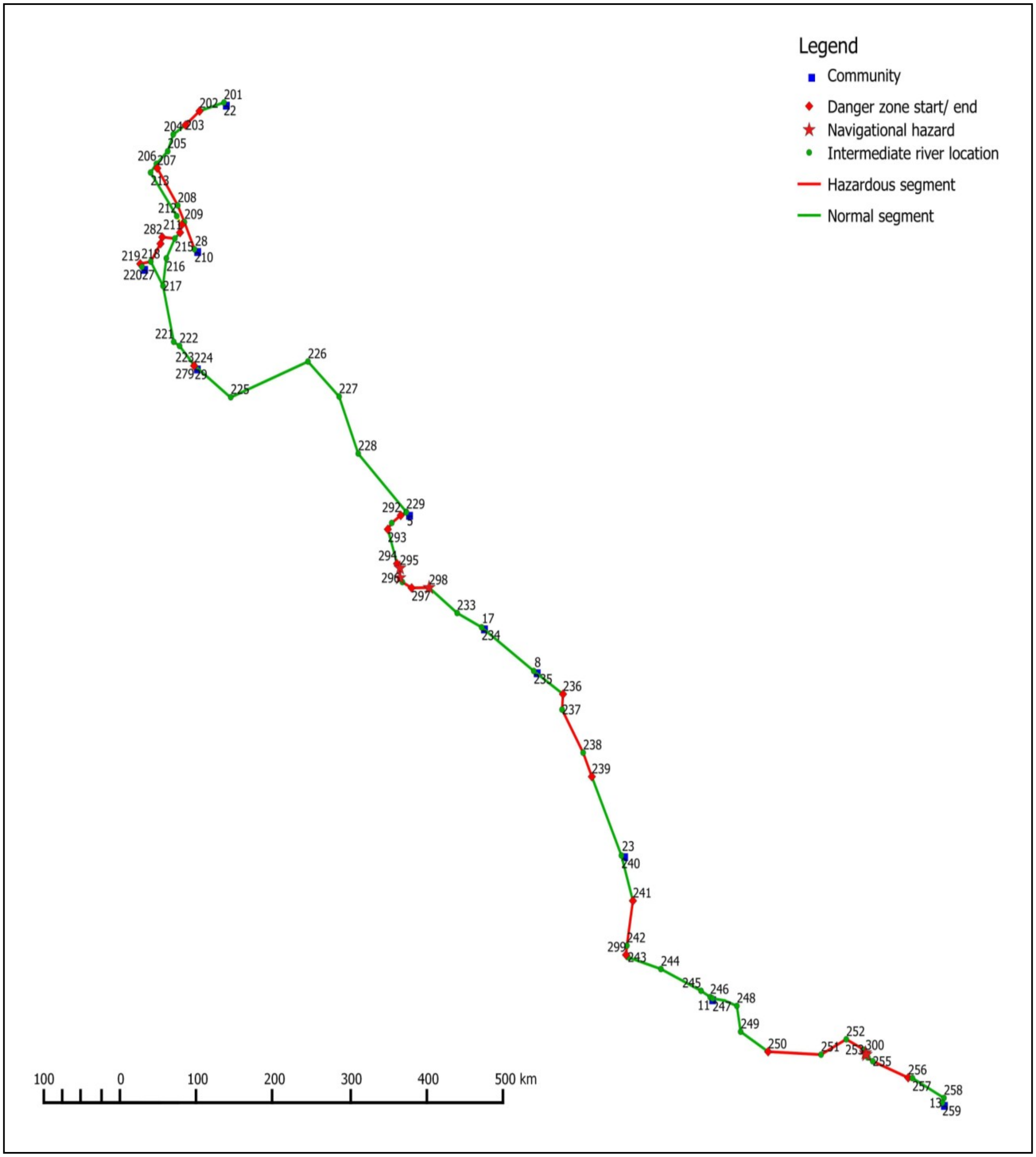

Figure 4-4 Nodes and links in the Mackenzie River shipping corridor network representation

There are 85 nodes in the network representation. The communities to which freight deliveries are made include Hay River (Node 13), Fort Simpson (Node 11), Wrigley (Node 23), Tulita (Node 8), Norman Wells (Node 17), Fort Good Hope (Node 5), Tsiigehtchic (Node 29), Inuvik (Node 28), Aklavik (Node 27) and Tuktoyaktuk (Node 22). There are 25 danger zone demarcation nodes in the representation. An odd number of nodes resulted because of the node representing the mouth of the Arctic Red River at the Mackenzie River; its downstream node was not included in the representation as it is located outside of the shipping channel. Three channels in danger zone 10, the Aklavik, Schooner and Tuktoyaktuk Entrance Channels, were included in the representation, resulting in additional danger zone demarcation nodes. Five navigational hazards are identified along the river: one location containing shoal and rock, and four rapids. Four of them are located within danger zones: Fort Providence Rapids, Green Island Rapids, North Rapids and San Sault Rapids. Other points are intermediate points on the river that primarily indicate a change in river course (i.e. direction). Some intermediate points are known locations on the river. However, these locations are neither hazardous locations nor an origin/destination.

There are 169 links in the network representation. The links that have normal operating conditions are marked in green (Figure 4-4). Of the 169 links, 66 are between danger zone ends and/or contain navigational hazards that are marked in red.

4.2 Network Model Testing

Although some discussion on model validation can be found in the freight network model literature, there is little or no discussion on model testing. Both nodes and links of the network representation were tested in this study.

Network nodes were prepared from shape files in GIS. Whether the nodes were placed on the right places (e.g. communities, danger zones, navigation hazards, and other intermediate points) was checked manually in GIS by overlaying the node shape file layer on the Google map layer. Connected nodes and river miles have been checked at random locations on the network to reduce the amount of work. Node type and hydrometric station ID have been checked for all nodes. There were a few errors in the connected node information of the node file, which were corrected during this check.

Network links were prepared from the node file. Whether link types, speeds, and water levels were assigned correctly was also checked manually for random links. Required information for checking these link attributes can be obtained from the node file. To check a link type, its start and end node types were first obtained from the node file. Then, link type was determined according to the link classification described in Section 4.1.1, and compared to the assigned link type in the link file. Whether the link mean speed was assigned properly was checked by determining the river segment of the link; then the river segment's speed at the corresponding link type (i.e. normal or hazardous) was compared to the assigned link speed. All the checks yielded correct results, which may imply the nodes and links were coded correctly.

Additionally, a path generation test was done on the network. In the path generation test, whether the node sequences or paths can be generated correctly between a given set of OD pairs was verified. This test can ensure node and links have been coded properly (i.e. a missing node or link can be checked), and also confirms the path generation code has been working. The path generation algorithm has been discussed in the preceding segment. In the test, paths were generated for a couple of randomly chosen origin and destination pairs. Then, the paths were checked in the visual representation of the network (see Figure 4-4). The representation provided correct results in each test.

4.3 Summary

This chapter has discussed the building of the Mackenzie River shipping corridor's network representation. Nodes and links of the network were classified into several groups to facilitate identification and the inclusion of their impacts on freight transportation in the network representation. Nodes were classified into three types: terminals or landings, navigational hazards, and intermediate river locations. Then, links were classified into three types based on their start and end node types or conditions. These links are related to one of the three tug and barge operations on the Mackenzie River: community loading/unloading, operation on a normal river segment, and operation on a hazardous river segment.

Nodes were processed from the shape file layers of the Mackenzie River, NWT communities, and other river locations in GIS software. Each node has six attributes: a unique ID, location (longitude and latitude), neighbour (connected) node information, location type (i.e. node type), information on the nearby hydrometric station, and its river mile. Links were built from the node information by applying an algorithm that was written based on simple logic to calculate link length and to assign link type, mean speed, and water level. Moreover, a path generation algorithm was implemented to find the links between any OD pairs in the network. Links have five attributes: start and end nodes, length, type (e.g. indicates nature of tug and barge operation on the link), mean speed, and mean water level. Tug and barge information, as well as community cargo demands, were also stored to be used in model application. Numbers of different tugs and barges with different operators, tug speed, tug and barge drafts, and barge load capacities were stored in the relevant files. Dry cargo and fuel demands were stored at corresponding community nodes. All these types of information were stored in matrix form for convenience to be used in computation software (e.g. MATLAB or OCTAVE) for model application later. Network visualization was done primarily in GIS. It involved importing the shape files to QGIS, editing symbol and/ or colour of different shape file objects to represent different node and link types.

Nodes and links of the network were checked manually in GIS to ensure they were coded correctly. Then, a path generation test was performed, which verified that paths could be generated for any OD pair in the network. Generated paths were verified in the visual representation of the network. The test was successful at each attempt. Application of a mathematical model or a simulation model, or both, on the Mackenzie River network would require these nodes, links, and paths in the model formulation. A common application of a network model is predicting freight flows on the network. Model application will be examined in the future.

CHAPTER 5. CONCLUSION

5.1 Summary of Work Completed

This research aimed to build a network representation of the Mackenzie River shipping corridor in the Northwest Territories (NWT). Two research questions were answered: 1) what data would be required to build a network representation of the Mackenzie River shipping corridor, and 2) how can the network representation be built using available data sources? To answer these questions, two research objectives were identified. The first objective was to gather and organize data related to the Mackenzie River shipping corridor, and the second objective was to represent the network using the available data.

The outcomes of data gathering and organization have been documented in Chapter 3 of this thesis. Data related to the Mackenzie River inland water transportation system were gathered from different published and unpublished reports, particularly by the Government of Northwest Territories (GNWT) and Transport Canada, and other data sources, such as Water Survey of Canada's (WSC) water level data and GNWT Geomatics' Geographic Information System (GIS) shape files. The data include spatial features of the Mackenzie River freight transportation system, water level, freight operators and their operations, and freight demand. Spatial features of the freight transportation system consist of the Mackenzie River and its adjacent channels, landing locations at the communities, danger zones, navigational hazards, and other intermediate river locations. The locations of these features were identified from relevant shape files using GIS. Although exact landing locations, loading/unloading capacity at the communities, and cost could not be obtained, the available information satisfies the data requirements for a strategic-level model (e.g. estimating freight flows on a network under different scenarios over a long planning horizon). Another important feature of the network, Mackenzie River danger zones (i.e. hazardous river segments) designated by the Canadian Coast Guard (CCG) as well as navigation hazards (e.g. rapids, shoals, and rocks) were identified using the GNWT Geomatics' geospatial data warehouse. In these danger zones, tug speeds can be as low as one knot, and barges may need to be anchored and towed one or two at a time to pass some critical locations. Historical operational data, such as operating speed and transit times on these danger zones were not available. Water level data, which determines how many goods can be transported on a waterway, were available at some specific locations on the river. Increasing uncertainty (i.e. a large change in water level over subsequent years), increasing mean water level in recent years particularly at the beginning of the shipping season, and gradually decreasing water levels during a season are common water level characteristics of any location on the Mackenzie River. Information on freight operators' operations was obtained from documents and through meetings with NTCL. However, historical operational data could not be obtained, particularly more accurate transit times, loading/unloading times, and costs. Some indication of freight transport demands could be obtained from an earlier study. Data indicate that community dry cargo demand would remain almost the same in the near future, while fuel demand may increase. Resource development activities have declined in recent years; had they not declined, earlier data show that freight volume would likely increase on the Mackenzie River.

Chapter 4 documented the tasks carried out to address the second objective, which is to represent the network. A node and link classification system was proposed to identify distinct locations and operations on the Mackenzie River freight transportation system. Three types of nodes were identified: terminal or landing location in a community, hazardous location on the river, and other intermediate river locations. Similarly, three types of links were defined, which indicate three different operations on the Mackenzie River system: community loading/unloading, operation on a normal river segment, and operation on a hazardous river segment. Nodes were prepared from the shape files collected in the data gathering step. The shape files were processed (edited and merged) in GIS. Each node has six attributes: a unique ID, location (longitude and latitude), neighbour (connected) node information, location type (i.e. node type), information on the nearby hydrometric station, and its river mile. These attributes were coded from other data sources as well as relevant shape files. Then, links were built from the node information by applying an algorithm written based on simple logic to calculate link length and to assign link type, mean speed, and water level. Links have five attributes: start and end nodes, length, link type, mean speed, and water level. Furthermore, a path generation algorithm based on Breadth First Search was written to find all the paths between any OD pair in the network. Other network data include tug and barge information (contains draft, load capacity, and quantity—the most important attributes) and community cargo demands. All these data were stored in matrix form for convenience and to be used in computation software (e.g. MATLAB or OCTAVE) for application later. Network visualization was done in GIS. Nodes and links were tested manually in GIS to verify the correctness of network coding. A test, path generation, was performed on the network. In the test, paths were generated for randomly chosen OD pairs, and output links were checked in the visual representation of the network. The test yielded correct results each time.

Application of the network representation has not been conducted in this study. It would require an optimization or a simulation model formulation using the coded network to solve a problem. The network representation can be used to solve different freight-related problems on the network.

5.2 Research Contributions

This study identified, gathered, and organized required data to build a network representation of the Mackenzie River shipping corridor. Then, a network representation of the shipping corridor was built using the gathered data. The network representation process largely depends on the context, and there has not been any such study on the Mackenzie River inland water transportation system, as found during the data identification, gathering, and organization process. Although network representation is an important step in solving freight transportation problems, the literature does not seem to contain much discussion on network building. This study strives to understand this pre-application stage of freight network representation, particularly in the case of an inland water transportation network. The network representation built in this study can be used to study freight transportation system on the Mackenzie River.

5.3 Recommendation for Future Work

Three areas are recommended for future research: further network data gathering or possibly collection, improving the network representation and its building process, and prospective applications.

Firstly, there are opportunities to use more data in the representation. Data deficiencies have already been discussed in Chapter 3. Landing facilities and loading/unloading data can be collected. These data may include different information related to a terminal or landing: the number of tugs and barges that can access a community landing and can wait to access the landing at any time, historical loading/unloading times (including setup and delays), costs associated with loading/unloading at the landing or terminals and possibly intermodal transfer times and costs data. Although available data can be used to make assumptions and apply the network representation for problem solving, the above-mentioned information would contribute to a better representation of the system. These data are neither publicly available nor easily obtainable from the operators. Then, further information can be collected about tug and barge operation on the river. Danger zone locations on the Mackenzie River are known. Tug speed may be as low as one knot in some locations of these danger zones, and the danger zone average speed is likely to be lower than that of other river locations. However, there is no absolute information about speed in the danger zones and navigational hazard locations. Some critical locations require barges to be anchored and towed one or two at a time to cross that location. Again, no information could be obtained about these locations, context (i.e. when this situation may arise), and their effect on transit time or delivery cost. Unlike some other studied waterways in the United States (e.g. Almaz & Altiok (2012)) and overseas (e.g. Thiers & Janssens (1998)) in which lock location, operations, vessel statistics, accurate terminal and landing operation, and navigation route data were available, it is likely that this information is neither documented nor publicly available. However, an experienced Mackenzie River boat captain can provide educated information on the above queries.

Secondly, there is scope to improve the network representation. Depending on the availability of further information, additional node and link classes can be created, for example, unhazardous river bends that cause a change in tug and barge operation. These locations can be investigated if detailed tug and barge operation data become available. It should be noted that more network detail may not be essential for representations addressing long-term strategic problems. The impact of this type of location may not be significant over a long analysis period. The network representation process can also be improved. The entire GIS file processing to prepare node and links could be automated, which would require much additional time.

Identifying the neighbour (connected) links was the most onerous task in node file preparation. Automation of this process would definitely facilitate network representation, particularly for a larger network. The difficulty in automating the task also depends on the quality of the shape file. In a road network, node and links are usually predefined as intersections and connecting roads respectively. However, river nodes are to be chosen depending on requirements of the model. Some river nodes, such as terminal and lock or navigational hazard locations, can be easily identified.

Thirdly, the network representation can be used in numerous ways to solve freight-related problems. However, determining the utilization of the system's present capacity would be a really useful application of the representation. System utilization may be expressed as a ratio of how much cargo has been shipped to the maximum cargo shipment capacity. Then, the impacts of different network elements or factors on the system utilization can be tested. For example, what would be the utilization of different landing facilities at an increased demand scenario? Freight operators' problems, such as network design, fleet size and mix determination, and scheduling, can also be solved with the network representation by formulating appropriate optimization or simulation models.

The representation is built only for the Mackenzie River shipping corridor. It can be extended as a multi-modal system by including other modes into the network and their functions into the representation. Climate change impacts on the Mackenzie River can also be investigated in future studies.

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Appendix A Meeting minutes

General information about the Mackenzie River freight transportation was gathered from meetings with the Department of Transportation of the Government of the Northwest Territories (GNWT) and Northern Transportation Company Limited (NTCL). These meeting minutes were documented in S A, Kim, & Zheng (2015).

NEXTAW Project Meeting 1

July 15, 2014
10:30 am to 15:30 pm
DOT Headquarters, 2nd Floor, Lahm Ridge Tower, 4501 Franklin Avenue, Yellowknife, NT

Participants: (U of A) Dr. Amy Kim, Rokib S A
(DOT GNWT) Pietro de Bastiani, Greg Whitlock, Darren Locke, Rob Thom, Matt Fournier
(Industry, Tourism & Investment) Kevin Todd
(Petroleum Product Division) Derrick Briggs
(Canadian Coast Guard) Francois Lamy
(NT Energy) Andrew Stewart, Geraldine Byrne

Agenda

Introductions – Describe Area of Marine or Transportation Interest/Expertise
Pietro started the meeting with an introduction to the NEXTAW project and its context to transportation in the NWT
Meeting attendees introduced themselves and expressed their expertise and interests

Project Overview

Amy presented the NEXTAW project overview. In the presentation, project background and approach were briefly explained. Previous studies related to the shipping routes, intermodal freight modelling issues and climate change impacts on transportation were mentioned. Domestic transportation needs/ issues should be emphasized as well as inbound/outbound transportation issues related to the shipping route in the study. It was pointed out that fuel for communities and industrial use is the source of the majority of transportation demands. NT Energy has interests in this regard. There was also a short discussion on open water season on the Mackenzie River and issues during the early and late season. A critical issue in navigation safety is displaced buoys by river debris and/ ice. Variability in water levels and flows in the Mackenzie River system are seen as implications of climate change and have impacts on river navigation. During discussion on the risks and challenges, some points were clarified by the NWT DOT. DOT has information on goods movements by road and air transportation. However, exact information on marine goods movements may not be available since private operators (e.g. NTCL and Cooper) are not required to report to the government.

Presentation on Arctic Marine Issues (Pietro)

History of the northern routes, and NTCL, Marine resupply in NWT was discussed. Ten communities in NWT are served by marine. Northern road network map was presented which included all weather roads, winter roads, bridges and ferries etc. Arctic shipping issues were also discussed (e.g. related to Northwest Passage and Over the Pop gateway). Shipping window is very small and highly variable. A major problem is lack of enhancement of charts for navigation and absence of heavy capability ice-breakers in Canadian arctic. Better charts can reduce shippers' risks. In the inland river system, water level has become more uncertain due to climate change. Finally, oil and gas resources in Central Mackenzie and Beaufort Sea were discussed. Transportation connectivity will be required to develop both on and off shore natural resources.

General Discussion & Focused Questions

Some major points in the discussion are as follows:

- Mackenzie River corridor is not included in the corridors that Canada has given attention to regarding infrastructure investments and support services.
- Fuel delivery to communities is critical. Derrick mentioned that 16/32 communities have fuel delivered by GNWT as there is no commercial market.

- Edmonton is the stepping point for northern shipping, Strathcona refineries. Trucks will move product as far north as possible, when it is transshipped to air.
- Beaufort Sea oil and gas development leases may improve transportation facilities in the future.
- NWT's multi-modal transportation strategy appeared in discussion in context to the project. Last 25-year strategy was done in 1990. Next update is to be released in February 2015. This strategy will address challenges and opportunities in Northern Transportation systems. The NEXTAW research project can complement the marine transportation of NWT transportation strategy.
- "Over the Top": Chinese clients opted to take the Columbia/Snake River route through Idaho. Presented some major issues but obviously client deemed that they would rather deal with those issues over the ones that could potentially present themselves using an arctic route.
- Data availability (e.g. statistical data of demands, available base layer/GIS files) was discussed. Darren Locke of NWT DOT will be the contact person for NWT about data or other information needs from UofA. Data includes:
- Highway System/ Road Structure: volume, historical open/close dates, bridges, traffic report (available on website), collision statistics/ fact (available on website)
- Marine Statistics (not certain about what would be available)
- Some freight Volume (mostly fuel)
- Some air transportation data would be available

Other general information

- Some data and information is available on the GNWT's website.
- GNWT's motivations and interest in the NEXTAW project. Some points came out of the discussion, which included promoting sea route, ensuring Canada's support for northern transportation, and emphasizing the idea that any benefit to the territories will also bring benefit to Canada.
- Environmental impacts of shipping. It is not expected that shipping will present further environmental impacts beyond current conditions. However, assessment studies are performed before taking any new initiatives.

- Possibility of new goods transportation along the route. The Mackenzie River shipping route is a historic route which has demonstrated capability for goods movement. However, difficulty in handling of export and import goods can be overcome by dredging, and use of an ice breaking ship at Point Barrow.
- There are some other corridors available in addition to the Mackenzie River corridor. Shipping in Mackenzie River can be compared to these corridors.
- There was also discussion about search and rescue operation in marine transportation in Arctic.
- Any research output/ information will be disseminated with consent from NWT and Transport Canada.

Action Items

U of A: Will be in contact with GNWT DOT, particularly Darren, for information and data

GNWT DOT: Main contacts are Darren and Pietro for this project

- Will provide data and information about the transportation network and volumes on marine, roads, and air (note that general high level volumes are typically what's available and this should be fine for our purposes)
- More specifically:
    - Darren: GIS files of the transportation network and information layers; aviation statistics (possibly detailed aircraft, cargo, and passenger volumes from IATA?); 2007 Airport Runways Report
    - Rob: all roadway (all-season and winter) volumes and collisions report; 2012 Highway Traffic Report available online?
    - Pietro: can speak with Tom Maher about available high-level, aggregate marine cargo/pax volumes; also may possibly be able to provide Mariport study (east-west access, freight volumes)
    - Francois (Canadian Coast Guard): we will contact him with any questions about river charts, etc.
    - ??: private and public marine infrastructure – locations of ports, etc.

Next meeting: To be decided

NEXTAW Project Meeting - 2

August 29, 2014

2:00 pm to 3:00 pm

Room 3-105, NREF, University of Alberta, Edmonton, AB

Participants: (U of A) Rokib S A

(DOT GNWT) Pietro de Bastiani and Matt Fournier

Agenda

1) Rokib provided an update of the project which mainly discussed data collection effort. Data included GIS data of the Mackenzie River and road networks, water level data, and goods movement data gathered from Mariport Group reports provided by the Department of Transportation, Government of Northwest Territories (GNWT). An initial idea on node and link coding was also provided in the meeting.
2) Pietro discussed about some characteristics of the Mackenzie River route which included river freeze up and break up, community fuel demand, navigation restriction imposed by the Deh Cho Bridge, navigation hazards near Fort Providence and Fort Good Hope.
3) Pietro and Matt provided some contacts for assistance in data collection.

Action Items

U of A: Will be in contact with GNWT for further information and data

NTCL: Pietro will inform contacts for assistance in data collection.

Next meeting: To be decided

Meeting with NTCL - 1

September 12, 2014

11:00 am to 12:00 pm

Suite 1209, 10104 103RD Ave., Edmonton, AB

Participants: (U of A) Amy Kim and Rokib S A

(NTCL) William Smith

Agenda

1) Amy briefly described the NEXTAW project background and objectives to Bill.
2) Bill was asked about freight operation system on the Mackenzie River. Bill briefly described about cargo receipt and shipping on the river. The description also included shipping season, NTCL facilities, and shipping operation. Mackenzie River shipping season typically starts in mid-June and ends in mid-October. Transit from Hay River to Tuktoyaktuk typically takes 9 to 12 days with stops at communities. Hay River terminal has road, rail, air and water mode accesses. Most goods go down the river, and some repair equipment come up the river. Operational speed of tugs on the river may be 1 to 2 knots in hazard areas, and up to 10 to 11 knots in other river sections. Barges may have to anchor and towed one at a time on hazard locations on the Mackenzie River.
3) Then, Bill was asked about specific questions on NTCL freight delivery system. These questions included location of cargo transshipment points, NTCL and other terminals on the Mackenzie River, facilities and activities at terminals, access to terminals, incident during operation, and number of tug and barges on operation. NTCL has a large terminal and a shipyard at Hay River. It also has terminal or landing facilities at Norman Wells, Inuvik, and Tuktoyaktuk. At any given time, 5-6 NTCL tugs and 30-40 barges could be in operation on the Mackenzie River. NTCL has staff and facilities to repair any broken tug or barge while on operation.

4) On a question about voyage plan for a season, Bill replied that NTCL obtains some idea on volume of mining and community resupply cargo from its clients at the beginning of each season. Cargo related to mining, oil, and gas is variable. The system is being utilized at 50-60% of its capacity mainly due to variable demand for mining, oil and gas cargos.
5) Questions were also asked about other shippers and charter services on the Mackenzie River. Beside NTCL service, Cooper Barging Service Ltd carries cargo between Fort Simpson and Norman Wells. NTCL provides charter service to mining, and oil and gas projects as required.
6) Bill also briefly explained the 'Northern Module Route' during the meeting. The route has not been chosen mainly due to uncertainties.

Action Items

U of A: Will be in contact with Bill for further information and data

Next meeting: May be held after the shipping season ends in October

Meeting with NTCL (teleconference) - 2

November 21, 2014

11:00 am to 12:00 pm

Participants: (U of A) Amy Kim and Rokib S A

(NTCL) William Smith

Agenda

1) Terminals/ landing on the Mackenzie River
2) Amy asked Bill about specific locations for landing at communities on the Mackenzie River. Bill provided information on available landing facilities at communities. Few communities have good landing facilities.
3) On a question about loading-unloading time at communities, Bill suggested to consult Mackenzie River tug captain for information. He also wanted to provide contact of a tug captain.
4) Danger zones/ hazards
5) Questions were asked about location of danger zones or hazard locations on river, and operation of vessels (i.e. what happens when vessels are in close proximity or in a danger zone, and vessel operating speed). Bill provided some general information about vessel (i.e. tug and barges) operation on the Mackenzie River. However, he again referred to a NTCL captain for more specific information.
6) Other questions
7) Bill was asked about which channel vessel use to go to Aklavik, and also asked about distances of some location along the river. Aklavik Channel is used to go to Aklavik. Information on other channel may be obtained from captains. Bill also wanted to provide a distance metric of the Mackenzie River.
8) NTCL was asked to provide historical voyage schedule and freight volume information.

9) Finally, Bill was also asked about water level information on the Mackenzie River for determining barge draft. Tug captains and Canadian Coast Guard have better information on water level. There are gauges on the river to provide water level information. Bill referred to a water level report published by Angus Pippy of Canadian Coast Guard.

Action Items

U of A: will be in contact with Bill for further information and data

NTCL: Bill will provide: contact information for David Day, NTCL tug captain, distance metric, sample water level information, some freight information (restricted to dissemination)

Next meeting: January 2015

Appendix B Pseudo code for the link file generation

The pseudo code of the node to link generation algorithm is provided here:

Input: Node list (A); A contains nodes in A(:,1), longitude and latitudes in A(:,2:3), neighbour (connected) nodes in A(:,4:8), node type in A(:,9), nearby hydrometric station id in A(:,10), and river mile in A(:,11).
Segment speeds (S); S contains start nodes of river segments in S(:,1), end nodes of the river segments in S(:,2), normal segment speed in S(:,3), and hazardous segment speed in S(:,4).
Water level at stations (W); W contains assigned hydrometric station ID in W(:,1), water level scenario identifier in W(:,2), and water levels from June to October in W(:,3:8).
Output: Link list (L); L contains start node of links in L(:,1), end node of links in L(:,2),length of links in L(:,3), link types in L(:,4), Water level in L(:,5), and Speed in L(:,6).

```
% create a link list (to determine start and end nodes) from the node list
for each node in the node list do
    for each element in connected nodes do
        if the connected node is not equal to zero then
            first node of a link is set as the node in the list, and
            second node of the link is set as the connected node;
        end
    end
end

% determining and assigning link length and link type
for each element of the links in the link list do
    for each element in the node list do
        if first node of the link is equal to the node then
            river mile of the start of the link is equal to the river mile of the node, and
            type of the start of the link is equal to the type of the node;
            break;
        end
    end

    for each element in the node list do
        if second node of the link is equal to the node then
            river mile of the start of the link is equal to the river mile of the node, and
            type of the start of the link is equal to the type of the node;
```

```
                break;
            end
        end

        link length is equal to the absolute difference between the river miles of start and end
            nodes of the link

        if type of start or end node of a link is equal to 1 then
            link type is 1;
        elseif type of start or end node of a link is equal to 3 then
            link type is 3;
        else
            link type is 2;
        end
end

% assigning mean speed to links
for each element in the set of origins do
        generate path between a origin and destinations using the "FindPath_" function;
        if path is not empty then
            store start and end node of links on the path, origin and destination nodes in a
                matrix (say, 'Path-Matrix'), and
            assign corresponding hazardous and normal segment speeds to each link in the
                'Path-Matrix' (origin and destination within segments with known speed);
        end
end

for each element in the link list do
        for each element in the 'Path-Matrix' do
            if link type is 3 and first node of the link is equal to the first or second node of the
                link in 'Path-Matrix' then
                    speed of the link is the normal segment speed of the 'Path-Matrix' link;
                    break;
            end
            if link type is 2 and first node of the link is equal to the first or second node of the
                link in 'Path-Matrix' then
                    speed of the link is the hazardous segment speed of the 'Path-Matrix' link;
                    break;
            end
        end
```

```
end

% assigning water level to links
for each element in the link list do
    for each element in the node list do
        if assigned hydrometric station ID in the node list is not zero and first or second
            node of the link is equal to the node in the node list then
            for each element in the water level file do
                if month (in the water level file) is equal to the given month then
                    for each element in the hydrometric station ID column do
                        if hydrometric station is equal to the assigned
                            hydrometric station ID and water level
                            scenario is equal to the given water level
                            scenario then
                                water level on the link is equal to the
                                water level of the assigned
                                hydrometric station ID on the given
                                month and scenario;
                        end
                    end
                end
            end
        end
    end
end
```

The pseudo code of the path generation algorithm is provided below:

Input: Neighbour (connected) nodes in A(:,4:8), start node/ origin a_0, and end node/ destination b_0.
Output: Paths (path2); path2 contains origin node in path2(:,1), destination node in path2(:,2), path number in path2(:,3), start node of a link in a path in path2(:,4), and end node of a link in a path in path2(:,5).

set current node equal to the start/ origin node;
set next node equal to the current node;
create a path;
set first element of the path equal to the next node;

```
set path row index equal to 1;

for each element in the neighbour (connected) node matrix do
    if the element in the first column of the neighbour (connected) node matrix is equal to the
        start/ origin node  then
            index of the current node is the row index of the element of the neighbour
                (connected) node matrix;
        break;
    end
end

while (1)
    if the number of rows in the path matrix is greater than the number of node in a path then
        break;
    end


    while the path index is less than or equal to the number of paths in the path matrix then
        if the last node of a path is not the destination node then
        current node of the path is the last node;
            if the last node of a path is equal to zero then
                next node of the path is equal to zero ;
            else
                set index of current node equal to zero;
                for each element in the neighbour (connected) node matrix do
                    if the element in the first column of the neighbour
                    (connected) node matrix is equal to the start/ origin node
                    then
                        index of the current node is the row index of the
                        element of the neighbour (connected) node matrix;
                    break;
                end
            end

        if the last node of a path is equal to zero then
            current node of the path is equal to zero ;
        else
            set node's neighbour (connected) node vector equal to the row of the
            current node in the neighbour (connected) node matrix;
            set path's node vector equal to the column of the current path;
```

```
                next node= up_node (node's neighbour (connected) node vector, path's
                node vector);
            end
        end

            if index of the current is not equal to zero then
                if there are more than one next node then
                    create new paths equal to (the number of next node -1) by coping
                    the current path;
                end

                for each of current path and/ or newly created paths do
                    add the current next node to the end of the path;
                    update next node index and current path index;
                end

            update path index;

            else
                add the next node to the end of the path;
            end
        end

        end

        for each path in the path matrix do
            if current node of the path is equal to zero then
                number of paths completed is incremented by 1;
            end
        end

        if number of paths completed is equal to number of paths in the path matrix then
            break;
        end

    end

    for each path in the path matrix do
        if end or destination node is reached in a path then
            keep the path as a valid path;
```

```
        end
end

if there is more than one path then
        for each path in the valid path matrix do
                for each element in the valid path matrix do
                        if the element in not zero then
                                set first element of the row in Path2 matrix as origin node;
                                set second element of the row in Path2 matrix as destination node;
                                set third element of the row in Path2 matrix as path index;
                                set fourth element of the row in Path2 matrix as the current node;

                                update path index;
                                update row index in Path2 matrix;
                        else
                                set first element of the row in Path2 matrix as origin node;
                                set second element of the row in Path2 matrix as destination node;
                                set third element of the row in Path2 matrix as zero;
                                set fourth element of the row in Path2 matrix as zero;
                        end
                end
        end
end

for each path in the Path2 matrix do
        for each element in the Path do
                if the element in the path is not zero then
                        set fifth element of the row in Path2 matrix as the next node;
                end
        end

        update path index;
        update row index in Path2 matrix;
end
```

The algorithm for the up_node function is provided as below:

```
for each element in node's neighbour (connected) node vector do
        for each element in the path's node vector do
```

if the element in node's neighbour (connected) node vector is non-zero and not equal to the element of the of the path's node vector **then;**

increment count by 1**;**

end

end

if count is equal to zero and neighbour (connected) node is not zero **then;**

keep the element in node's neighbour (connected) node vector as next node in the next node vector;

end

end