A Freshwater Classification of the Mackenzie River Basin

Mike Palmer, Jonathan Higgins and Evelyn Gah

Abstract

The NWT Protected Areas Strategy (NWT-PAS) aims to protect special natural and cultural areas and core representative areas within each ecoregion of the NWT to help protect the NWT's biodiversity and cultural landscapes. To date the NWT-PAS has focused its efforts primarily on terrestrial biodiversity, and has identified areas, which capture only limited aspects of freshwater biodiversity and the ecological processes necessary to sustain it. However, freshwater is a critical ecological component and physical force in the NWT. To evaluate to what extent freshwater biodiversity is represented within protected areas, the NWT-PAS Science Team completed a spatially comprehensive freshwater classification to represent broad ecological and environmental patterns. In conservation science, the underlying idea of using ecosystems, often referred to as the coarse-filter, is that by protecting the environmental features and patterns that are representative of a region, most species and natural communities, and the ecological processes that support them, will also be protected. In areas such as the NWT where species data are sparse, the coarse-filter approach is the primary tool for representing biodiversity in regional conservation planning.

The classification includes the Mackenzie River Basin and several watersheds in the adjacent Queen Elizabeth drainage basin so as to cover the ecoregions identified in the NWT-PAS Mackenzie Valley Five-Year Action Plan (NWT PAS Secretariat 2003). The approach taken is a simplified version of the hierarchical classification methods outlined by Higgins and others (2005) by using abiotic attributes to characterize the dominant regional environmental patterns that influence freshwater ecosystem characteristics, and their ecological patterns and processes.

The challenges to classify the study area included obtaining datasets that contained attributes meaningful for describing and differentiating freshwater ecosystems, that cover the entire basin under study and that provide an adequate level of detail for analysis. Datasets fitting these criteria were: surficial geology, permafrost, sources of water (groundwater potential), glacial coverage, eskers and lakes. The base data used to generate hydrologic units and eventually ecosystems to classify was the 1:1 million Atlas of Canada National Scale Frameworks hydrology vector data (stream network and modeled catchments) (Government of Canada 2008). The modeled catchments were used as the base units for classification. Calculations on the input datasets were completed twice on a catchment basis – once for local values (those within the boundaries of local catchments) and once for accumulated values (those contributing areas upstream of catchments).

The resulting classification defined over 800 unique types. Twenty seven of these types are described in Appendix IV. The described types cover 48% of the Basin and include the 10 most common types and 5 of the least frequently occurring types.

The classification describes broad scale patterns of geophysical and climatic patterns that influence the creation and maintenance of freshwater habitats and the biological communities that reside within them. The NWT-PAS will use the classification as a

foundation to evaluate whether the diversity of freshwater habitats within the NWT is well represented in protected areas. The classification can also be used to inform land use planning and regulatory processes across the NWT to illustrate potential impacts or avoidance of impacts to freshwater ecosystem diversity and key processes from different development and protection scenarios.

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Contributors and Reviewers

Rick Tingey (Round River Conservation Studies)
Evie Witten (TNC)
Michele DePhillip (The Nature Conservancy (TNC))
Cathy Flannigan (US Fish & Wildlife Service – Alaska)
Paula Gagnon (TNC)
Kristy Ciruna (Nature Conservancy of Canada (NCC))
Bruce Friesen-Pankratz (Indian and Northern Affairs Canada (INAC))
Evie Witten (TNC)
Joanna Wilson (GNWT)
Alicia Korpach (DUC)
Lillith Brook (INAC)
Kerry Pippy (Environment Canada)
Dick Mahoney (Nacho Nyak Dun First Nation , Yukon)
Jesse Carrie (U. Manitoba)
Steve Grasby (Geologic Survey of Canada)
Steve Kokelj (Environment Canada Water Resources)

Fortune Ogbebo (Environment Canada)
Marlene Evans (Environment Canada)
Daniel Peters (Environment Canada)

Introduction

The goal of the Northwest Territories Protected Areas Strategy (NWT-PAS) is to protect special natural and cultural areas of the NWT and core representative areas within each ecoregion of the NWT. In June 2005 a team was established by partner organizations involved in the PAS to develop options for terrestrial core representative areas in the NWT. The team (known as the NWT-PAS Science Team) is led by the Government of the Northwest Territories Department of Environment and Natural Resources and over the years has included representatives from Ducks Unlimited Canada, The Nature Conservancy, Indian and Northern Affairs Canada, World Wildlife Fund Canada, and the Canadian Parks and Wilderness Society. To date this work has been completed and been mainly focused on identifying terrestrial areas for protection using core representative areas. A technical report describing the work is available online at http://www.nwtpas.ca/documents/document-2008-ENR179.pdf

To ensure that freshwater biodiversity and the processes necessary to sustain it are also represented within protected areas, the NWT-PAS Science Team, led by freshwater experts from The Nature Conservancy, has developed a freshwater classification for the Mackenzie River Basin and a portion of the Queen drainage basin. Since almost half of the Mackenzie River Basin lies outside the NWT, but drains into the NWT on its way to the Arctic Ocean, thus potentially affecting downstream aquatic systems in the NWT, the entire Mackenzie River Basin was included in this classification. In addition, several watersheds in the adjacent Queen Elisabeth drainage basin were included because they overlap with priority areas set out in the Mackenzie Valley Five Year Action Plan (Northwest Territories Protected Areas Strategy Secretariat 2003). This plan was developed to enhance protected areas planning in 16 terrestrial ecoregions potentially affected by a proposed gas pipeline development and was the driving force behind building the freshwater classification. It is important to note that we have included the adjacent Queen Elizabeth Basin (Figure 1) in our analysis as it overlays part of the study area relevant to the Protected Areas Strategy. It is much smaller in size and contributes most of its flow to the Arctic Ocean. Different processing steps were also used on this section because of its simpler flow characteristics. All references to the Mackenzie River Basin throughout this paper also refer to the Queen Basin unless noted otherwise.

Given the huge size of the study area and the limited amount of data that covers the entire study area, this classification is based on the dominant geomorphic patterns across the study area. It is not intended to predict species distribution or specific habitats but instead will serve as a foundation for a freshwater coarse-filter to help ensure that the diversity of freshwater habitats, the processes that maintain them and the freshwater biodiversity that use those habitats within the NWT is well represented in protected areas. This foundation

can lead to more detailed watershed planning and have ongoing uses for freshwater and fisheries planning and management throughout the NWT and the Mackenzie River Basin.

Figure 1: The study area – Mackenzie River Basin and part of the Queen Elizabeth Basin

Objective and Scope of Work

Our objective is to produce a freshwater classification for the Mackenzie River Basin and adjacent drainage basins in the Queen Elisabeth watershed on a catchment scale. The classification can be used to develop a freshwater "coarse-filter" (Higgins et al 2005) and conduct a representation analysis (Noss 1996; Gah et. al 2008) for the study area to identify gaps in protection and to help guide protected area planning in the Northwest Territories in accordance with the NWT Mackenzie Valley Action Plan.

Background of the Study Area

Covering about 1.8 million square kilometers, or roughly 20% of the Canadian landmass, the Mackenzie River Basin is composed primarily of 3 physiographic regions; Precambrian Shield, Interior Plains, and the Cordillera, with some Arctic Coastal Plains to the far north and eastern portion of the drainage. The region's climate and vegetation have been used to distinguish patterns within and among these regions as Montane, Boreal, Tundra, and Taiga. There are distinct climatic gradients from the south (cold temperate) to the north (sub-arctic to arctic), and from the west (mountain) to the east (sub-arctic). There is a significant annual precipitation gradient from the west to northeast, ranging from more than 1,000 mm in the southwest, to 500 mm in the northwest, to 200 mm on the Arctic coast.

Climate interacting with the physiography of the region results in distinct patterns of river valley morphology and hydrology. The width, depth, meander patterns and valley characteristics of rivers differ among these regions based on the sources of water, the energy of the systems, and the geology and soils they are on. The seasonal flows of the rivers in the Mackenzie Basin tend to exhibit essentially a subarctic nival regime: high flows that occur during the snowmelt and river ice breakup period are followed by a steady decline, sometimes raised by summer and autumn rain events, until the winter, when low flow prevails. This flow regime is modified in areas with other sources of water (glaciers, groundwater), and storage capacity (lakes, wetlands). Glaciers contribute to extended summer flows, described as a proglacial regime. Groundwater sources contribute to more stable low flows. Large lakes tend to reduce high flows and extend low flows, described as a prolacustrine regime.

Hydrology

The Mackenzie River system flows 4,241 kilometres from the Columbia ice-field in Jasper National Park in Alberta and the snowfields of the upper Peace River headlands in northeastern British Columbia to its final destination at the north coast of the Northwest Territories. It is large by North American standards, second only to the Mississippi River system. Some of the major features of the Basin include the Athabasca River, with its start in the Rocky Mountains of central Alberta and joins the Peace River eventually ending into Lake Athabasca, which lies in northeastern Alberta and northwestern

Saskatchewan. The Peace-Athabasca delta is located here, one of the largest inland freshwater deltas in the world. Lake Athabasca drains into the Riviere des Rochers, which joins the Peace River just North of Ft. Chipewyan to form the Slave River. The Slave River continues north into the NWT and drains into Great Slave Lake at Fort Resolution. Many rivers and streams empty into Great Slave Lake, including the Yellowknife, Snare, Emile, Beaulieu, Snowdrift, Taltson, and Hay Rivers. Great Slave Lake drains into the Mackenzie River from its west arm and at Ft. Simpson the Liard River joins from the south bank. Near the North Nahanni River it deflects north past an escarpment of the Mackenzie Mountains lying parallel to the river. The Redstone and Keele rivers are two larger tributaries that flow from the mountains entering the Mackenzie from deep canyons. Along the same area the Mackenzie gains water from tributaries to the east including the Hare Indian, Blackwater and Willowlake rivers (The Canadian Encyclopedia 2009).

The Great Bear River begins on the southwest shore of Great Bear Lake at the community of Deline and eventually joins the Mackenzie from the east at Tulita, adding cold, clear water. Further north to Norman Wells the Mackenzie continues through relatively flat, weedy channels and beneath ribbed cliffs, widening to 5 km and becoming braided with numerous channels and islands. A few kilometres above Fort Good Hope the river runs between high, limestone cliffs called The Ramparts to again resume a meandering path to the northwest encountering sandbars and islands. The Arctic Red River enters 270 km from the Beaufort Sea and the Arctic coast. At Point Separation the Mackenzie delta begins, which reaches 80 kilometres in width and is a maze of channels and countless islands (The Canadian Encyclopedia 2009).

The Mackenzie River empties a volume of 9,910 cubic metres per second into the Beaufort Sea of the Arctic Ocean at the Mackenzie River delta making it the tenth largest river basin in the world and accounting for 60% of the freshwater that flows into the Arctic Ocean from Canada and about 9% of the freshwater discharged to all the oceans by all Canadian watersheds (MRBB 2003). The freshwater and energy (heat) discharged from the river into the Beaufort Sea play a significant role in regulating the circulation of the world's oceans and variability of climate systems (Mackenzie GEWEX Study 2004).

The Queen Elizabeth drainage basin is the western part of the Central Arctic Coastal Basin. All drainage in this basin flows north into the Arctic Ocean through various rivers and streams, most notably the Back and Coppermine rivers. The western extent of the basin is bound by Great Bear Lake which is covered by ice 8 months out of the year. The Queen basin straddles the divide between boreal forest in the south and treeless tundra in the north making vegetation transition from stands of black spruce, tamarack and white spruce in the south to dwarf and sparse shrubs in the north due to harsh climate and shallow soils (Burridge and Mandrak 2008).

Geography

In the upper Mackenzie River Basin the foothills of western Alberta and eastern British Columbia rise above the plains, mainly as linear ridges, rolling plateau remnants, and broad valleys. Moving east into the central part of the Basin near the Peace River the area is underlain by Cretaceous shale with undulating glacial till above. Moving still further east to the Slave River lowlands of northeastern Alberta and northwestern Saskatchewan the Basin is underlain by nearly flat Palaeozoic carbonates forming sandy plains, or limestone bedrock overlain with silts, clays and extensive peat deposits (Burridge and Mandrak 2008).

Great Bear Lake, the largest lake in Canada and Great Slave Lake, the deepest lake in Canada are within the NWT part of the Mackenzie River Basin (Natural Resources Canada 2009). Permafrost underlies roughly 75% of the Basin. Pingos and patterned ground features, both associated with continuous permafrost, are found along the north coast (MRBB 2003).

The Mackenzie River flows through eight ecozones: the Boreal Plains, Boreal Shield, Boreal Cordillera, Taiga Plains, Taiga Shield, Taiga Cordillera, Montane Cordillera and Arctic. In general, the vegetation changes from boreal forest in the south to alpine in the mountains and arctic tundra in the north and east.

The entire Basin contains about 400,000 people with the highest population density being south of the 60th Parallel. The Basin north of the 60th parallel consists mostly of sparsely populated communities comprised largely of aboriginal peoples; the one exception being the capital of the NWT, Yellowknife. The population density of the Basin is less than one-tenth of that in the rest of the country (Statistics Canada 2006).

Economic Activities

Mining, agriculture, forestry, hydroelectric projects and fossil energy deposits all contribute to the resource based economy in the Basin. The development and extraction of these resources has varying impacts on freshwater systems from water extraction to altered flow regimes to point and non-point source pollutants (MRBB 2003).

North of the 60th parallel there are limited impacts from agriculture and forestry with home heating being the main use of wood in the NWT. There are eleven hydroelectric generating stations in the Great Slave sub-Basin which power Yellowknife and multiple surrounding communities on both sides of Great Slave Lake. Other smaller power stations are spread across the Basin. These projects affect both water flow and amount along with in-stream travel of species (NWT Power Corporation 2002).

Gold, zinc and diamond mines, among many others, are located in the basin north of the 60th parallel. Oil and gas extraction and exploration is also occurring, mainly around Norman Wells with a facility generating 6-7 million barrels of oil a year, moved through a pipeline south to Alberta. A proposal, to develop a pipeline to access to the natural gas reserves of the Mackenzie Delta, is currently being reviewed that would extend a pipeline

corridor from Norman Wells north to Inuvik, on the Arctic coast (Mackenzie Gas Project 2003).

South of the 60th parallel, agriculture and forestry becoming increasingly important economic activities coupled with oil and gas activity, most notably Alberta's oil sands. The oil sand deposits in northern Alberta are the largest deposits of recoverable fossil energy in the world – estimated at 300 billion barrels. Existing and proposed oil sands projects, on the shores of the Athabasca River, are causing known impacts to wetlands, groundwater, soils and habitats (Griffiths and Dyer 2008).

Conservation Planning Approach

For decades terrestrial features have been classified through the use of satellite imagery and aerial photos, each year focusing on finer spatial resolution and ever splitting into more refined classes. Many areas of the earth have been studied to this extent by identifying places of forests, prairies, urban features and water. Exploring the dataset released by J. Cihlar and J. Beaubien in 1998 titled "*Land cover of Canada Version 1.1*", one can find over 31 classes describing the natural landscape for Canada with forest classes as exact as "Evergreen Needleleaf Forest Medium Density Southern Forest" or "Mixed Intermediate Heterogeneous Forest" and "Crop Land Medium Biomass". However, less detail is available for aquatic components, with these datasets generally having only one class simply entitled "Water". To address this gap in freshwater information the PAS Science Team employed the fundamental concepts of a coarse-filter analysis, as suggest by regional contemporary systematic conservation planning efforts (Groves et al 2002, Groves and contributors 2003). The premise of the coarse filter is that conserving representative ecosystem units conserves many common species and natural communities, the ecological processes that sustain them, and the environments in which they evolve (Hunter 1991). The coarse-filter analysis is one of four products typically used to inform the creation of robust, representative protected areas networks:

- Coarse-filter: ecosystems or other mapped and classified units that differentiate patterns of habitats and the processes that create and maintain them. These are commonly classified using data on geomorphic attributes, such as landform, geology, climate, vegetation types, and other attributes that strongly influence the patterns, dynamics, and biotic composition of landscapes.
- Fine-filter: the diversity and number of special features that are unique, rare or sensitive areas or species
- Focal species analysis: inclusion of key wildlife or fish habitat areas
- Consideration of how species genetics and demographics and ecosystem processes are connected across the landscape (Noss et al., 1999, Dobson et al., 1999; Hoctor et al., 2000, Taylor et al., 1993).

In both the terrestrial and freshwater realm, biotic patterns are greatly influenced by environmental factors such as climate, soil, and lake characteristics. Furthermore, vegetation communities and other species assemblages respond to environmental

gradients across the landscape. Therefore, protecting examples of broad landscape and habitat patterns in each ecoregion of the NWT or within watersheds in the NWT should result in protecting the majority of species that occur within the region without having to consider those taxa individually (Noss and Cooperrider 1994). Most species are poorly sampled, many are still unknown, and the vast number of species makes it intractable to follow each one independently. Using this approach moves beyond a focus on species and begins the proactive process of protecting ecosystems and habitats on a systematic basis (Moyle and Yoshyiama 1994; Angermeyer and Scholsser 1995; Higgins et al 2005). Coarse-filters are generally used in conjunction with available information on species and natural communities that are often not captured by just using the coarse-filter, such as special, rare, and endangered habitats and species that are defined as the fine-filter (e.g. Hunter, 1991;Noss and Cooperrider, 1994; Noss, 1996a; Kirkpatrick and Brown, 1994; Kintsch and Urban, 2002; Groves, 2003).

The PAS Science Team has developed a method for generating the terrestrial component of the coarse-filter and conducting a representation analysis for the NWT which is based on best practices in systematic conservation planning, adapted to the context of the NWT. Three coarse-scale geophysical and biological conservation feature datasets (soil/surficial geology units, physiographic units and land cover classes within terrestrial ecoregions) thought to be good surrogates for biodiversity were used to identify potential options for terrestrial ecological representation that is not represented in the current network of existing and proposed protected areas (Gah et al 2008).

Building on these terrestrial concepts of classification and representation of landscape features, a coarse-filter freshwater classification provides the basis for understanding distinct types of freshwater systems in an area. By picking datasets that influence aquatic systems the PAS Science Team is able to map the location of unique combinations of these influences and help guide planning efforts around those key areas. See Appendix I for examples of freshwater classifications in other parts of the world.

A Hierarchical Freshwater Classification Approach

Freshwater biodiversity, habitats and ecological processes are shaped by a hierarchy of spatial and temporal processes (Frissel et al 1986; Tonn 1990; Maxwell et al 1995; Poff 1997; Mathews 1998; Jensen et al 2001). Also, landscape patterns and processes tend to be hierarchical, where large-scale patterns and processes constrain those at finer scales (Allen and Starr 1982; O'Neill et al 1986).

An example of a terrestrial hierarchichal classification is "A National Ecological Framework for Canada" that divides Canada into ecozones, ecoprovinces, ecoregions and ecodistricts (Ecological Stratification Working Group 1996). The information used to classify each level is based on those attributes that drive patterns and processes at that level.
 Hierarchical classification for freshwater ecosystems has been widely adopted conceptually and in practice. Some of the important concepts and structures developed for this approach are documented in Warren (1979), Frissell *et al.* (1986), Cupp (1989),

Pflieger(1989), Moyle and Ellison(1991), Hudson *et al*. (1992), Leach and Herron (1992), Naiman *et al*.(1992), Townsend and Hildrew (1994), Ward and Palmer (1994), Angermeier and Schlosser (1995), Maxwell *et al*. (1995), Rosgen (1994), Seelbach *et al*. (1997), Pahl-Wostl (1998), Haberack(2000), and Higgins *et al*. (2005).

Overview of the NWT Hierarchical Approach

Terms used throughout this section:

Attributes - input datasets to the freshwater classification (surficial geology, permafrost, etc)
Classes – a distinct kind of attribute (till veneer surficial geology, extensive discontinuous permafrost)
Type – a unique combination of the classes of attributes in a local or accumulated catchment define a freshwater type. The classification is made up over 800 types in the Mackenzie River Basin.

The PAS Science Team decided to follow the approach set forth by Higgins et al. 2005 where 4 hierarchical levels are described: an aquatic zoogeographic unit; ecological drainage units (EDUs); aquatic ecological systems (AES); and macrohabitats. Higgins uses 4 levels as the "minimum set to describe key scales of ecological patterns" but does note that the finest level, macrohabitats, can be omitted if input data is not of adequate scale or quality. Zoogeographic units define the species pool that is available. The next level (EDUs) represent patterns of interactions between landscape features (e.g. geology and landform), and climatic that influence broad-patterns of freshwater ecosystems such as channel morphology, hydrologic, temperature and nutrient regimes (Lotspeich 1980; Jensen et al 2001). Aquatic ecosystems are stream and lake networks representing a range of areas with distinct finer-scale geomorphic patterns tied together by similar environmental processes. Macrohabitats define distinct segments of aquatic ecosystems, and are derived when sufficient data are available, and they are meaningful units for conservation planning. Given the size of the study area, these were not deemed practical, and are generally not used in regional conservation planning.

Figure 2 depicts the hierarchical levels that were used in the study area: the basin, EDUs and catchments.

Figure 2: An illustration of the hierarchical units within the Mackenzie River Basin

Ecological Drainage Units (EDUs)

EDUs (Figure 3) were created and classified using existing sub-sub drainage basins as spatial units to maintain or aggregate them into EDUs, from the Atlas of Canada National Frameworks Hydrology Data sub-sub drainage basins (Figure 4). The EUDs were classified using descriptions of climate, elevation, landform, geology, dominant vegetation, stream morphology, temperature, hydrologic regime,and other information when available, from the terrestrial ecozones of Canada (Ecological Stratification Working Group 1996) (Figure 5). The terrestrial ecozones of Canada data were revised by the PAS Science Team to include recent revisions by the Government of the Northwest Territories' Department of Environment and Natural Resources to the NWT part of the Taiga Plains (Ecosystem Classification Working Group 2007) and Taiga Shield (Ecosystem Classification Working Group 2008) ecozone boundaries. In total, 21 distinct EDUs were delineated and classified within the study area. Descriptions of the EDUs can be found in Appendix II.

Sources and download links for datasets used to delineate EDUs

Major river basins and sub-sub drainage basins (Figure 3)

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Source: Atlas of Canada 1,000,000 National Frameworks Data, Hydrology – Drainage Areas, Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2006-07
Online linkage: http://geogratis.cgdi.gc.ca/geogratis/en/option/select.do?id=27730

Terrestrial Ecozones of Canada (Figure 4)
Source: Ecological Stratification Working Group. 1996. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of Environment Directorate, Ottawa/Hull.
Online linkage: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/intro.html

Revised NWT Taiga Plains ecozone boundaries (Figure 4)
Source: Ecosystem Classification Working Group 2007 (rev. 2009): Ecological Regions of the Northwest Territories – Taiga Plains, Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada
Online linkage: http://www.enr.gov.nt.ca/_live/pages/wpPages/Taiga_Plains.aspx

Revised Taiga Shield ecozone boundaries (Figure 4)
Source: Ecosystem Classification Working Group 2008: Ecological Regions of the Northwest Territories – Taiga Shield, Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada
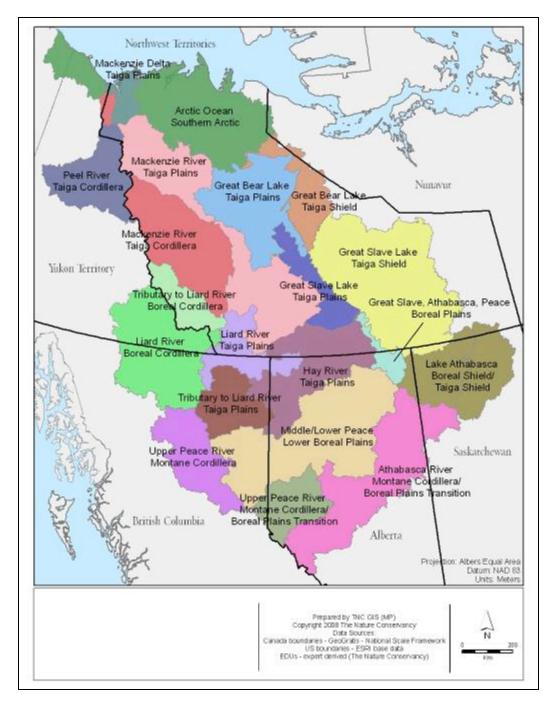Online linkage: http://www.enr.gov.nt.ca/_live/pages/wpPages/Taiga_Shield.aspx

Figure 3: Ecological Drainage Units (EDUs) of the Mackenzie River Basin and part of the adjacent Queen Elizabeth drainage Basin.
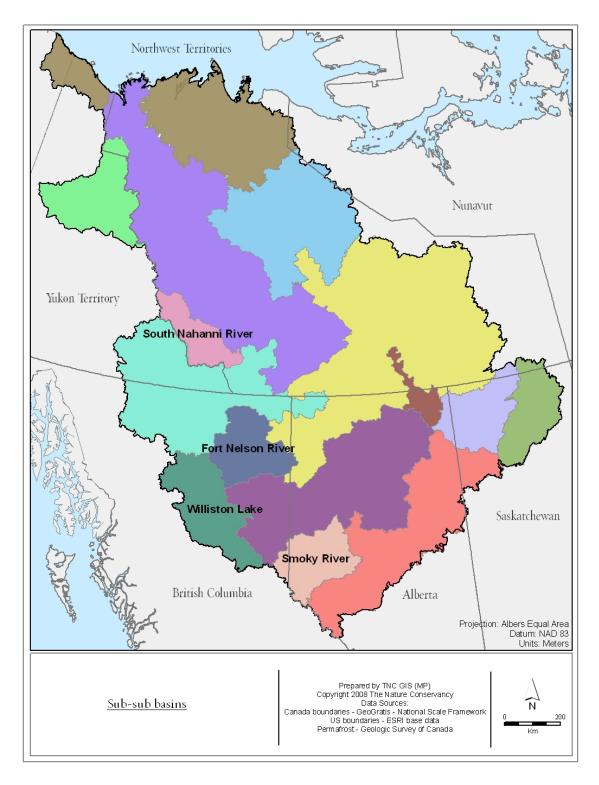
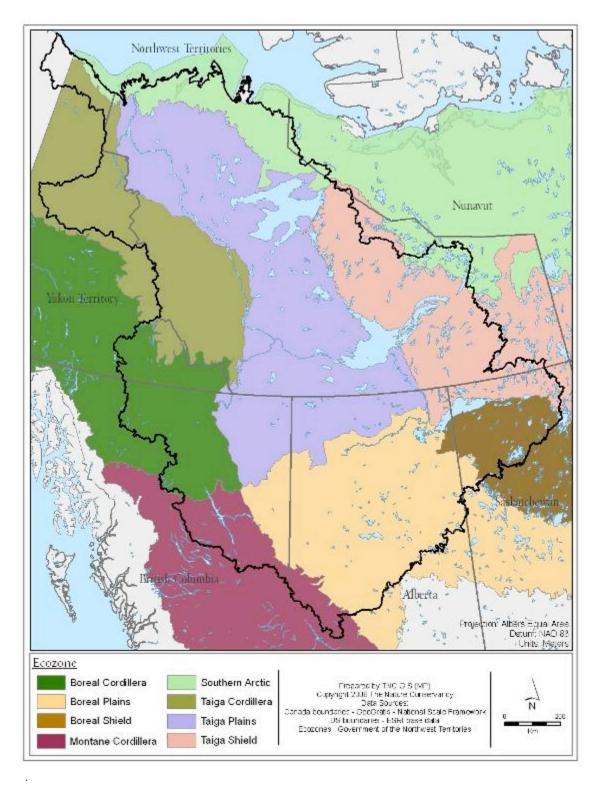Figure 4: Sub-sub basins of the study area (labels missing due to lack of information in the source file).

Figure 5: Terrestrial Ecozones of Canada that intersect the study area.

Catchments

Catchments are the smallest drainage units within the Atlas of Canada 1,000,000 National Frameworks Data, Hydrology drainage area datasets and nest within the sub-sub drainage basins and the major river basins of the study area. They were used as the spatial units to define aquatic ecosystems in the classification hierarchy.

The catchments do not describe strict watershed divides, but instead, define areas of landscape relative to streams in the drainage network based on proximity and are thus approximate watershed areas or stream catchments (GeoAccess Div, CCRS 2003). The drainage network data used to model the catchments is the Atlas of Canada 1,000,000 National Frameworks Hydrology analytical drainage network vector data. Each catchment is linked to its corresponding stream or flow line segment in the drainage network through a unique identifier in the respective data table.

This relationship between streams segments and corresponding catchments allows the use of a Geographic Information System (GIS) to perform upstream tracing to calculate the total land area drained at any given point in the drainage network. Once the area drained is known it is possible to calculate the upstream patterns of any attribute within that area at any given point in the drainage network. This process is also referred to as 'flow accumulation analysis.'

The Mackenzie Basin and adjacent drainages in the Queen Elizabeth Basin have a total of about 63,000 catchment polygons.

Sources and download links for catchment and drainage area data:

Catchment data
Source: Atlas of Canada 1,000,000 National Scale Frameworks Data, Hydrology – Drainage Areas, Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2006-07
Online linkage: http://geogratis.cgdi.gc.ca/download/frameworkdata/drainage_areas

Drainage Network – Analytical Network
Source: Atlas of Canada 1,000,000 National Scale Frameworks Data, Hydrology – Drainage Network, Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2006-07
Online linkage:
http://geogratis.gc.ca/download/frameworkdata/hydrology/analytical/drainage_network

Creating a Classification

Spatial Data Analysis - Methods for evaluating patterns of freshwater classification attributes

Work on a freshwater classification for the extended Mackenzie River Basin began in 2006 and was funded and led by The Nature Conservancy (TNC) to support the NWT-PAS. TNC contracted Round River Conservation Studies (RRCS) to provide GIS analysis and modeling for the project. The RRCS GIS analyst performed all data preparation, quality control checks and data analysis and modeling for the first draft of the classification. The RRCS GIS analyst also provided scripts and code to automate the flow accumulation analyses. A TNC GIS analyst with support from the Government of the NWT (GNWT), Department of Environment and Natural Resources (ENR) PAS GIS analyst completed the additional work required for the classification. GNWT ENR also contracted the RRCS GIS analyst to provide support with re-running flow accumulation analyses for subsequent drafts.

Initially the GIS analyst contracted to perform GIS analysis for the first draft of the freshwater classification (Rick Tingey, Round River Conservation Studies – in the following referred to as 'the GIS contractor') attempted to use GIS software tools (ESRI ArcHydro data model) to construct a drainage network and drainage areas for use in creating flow accumulation and direction for the classification. However, the best DEM data available for the entire study area is at a grid resolution of roughly 70 meters (meaning there is only one elevation value mapped for each 70m x 70m square of land). This level of detail is not suitable for modeling hydrography in a relatively flat landscape that has very complex drainage patterns typical of the NWT portion of the Mackenzie River Basin. For this reason, it was decided to employ the existing Atlas of Canada 1,000,000 National Frameworks catchment and analytical drainage network data as the base spatial data framework for this freshwater classification effort.

The GIS contractor performed quality control checks, and where necessary edited the spatial catchment and/or drainage network data to ensure that there was a consistent unique identifier between streams and associated catchments, that all streams were digitized in the direction of flow and that there were no breaks in the stream network that would interrupt flow. This initial step required significant time and effort, but was necessary to ensure that that flow accumulations ran smoothly and produced reliable results.

Other points noted during inspection of the catchment data included the following:
- about 2.5% of all catchments are smaller than 1 hectare. These appear to be slivers resulting from the process used to model the catchments. Most of these catchments have no stream arcs associated with them and may therefore have erroneously been defined as headwater catchments.

- The catchment data for the Mackenzie River Basin includes catchments extending in Alaska. Datasets for this area were not included in the classification so these catchments are not attributed in the final classification.

Following cleanup of the catchment and analytical stream network data, both ESRI ArcGIS and ArcInfo Workstation software were utilized to facilitate the data management and flow accumulation analyses in the GIS. General patterns that were calculated for each catchment are as follows and serve as the basis for the freshwater classification:

1. local catchment analysis:
    a. area of each classification attribute within each local (individual) catchment;
    b. percent of each classification attribute within each local catchment.
2. accumulated catchment analysis:
    a. total upstream accumulated area of selected classification attributes and;
    b. percent of total upstream drainage area of selected classification attributes.

Local catchment analysis:

The quantification of 1a and 1b above are referred to as local catchment analysis because the classification attributes were analyzed within each individual catchment only. First, the total area of each individual catchment was calculated, and then the area of each of the 12 surficial geology classes, 8 permafrost classes and 3 classes of dominant sources of water to streams and lakes, the area of glacial coverage, the total area of waterbodies and the total length of eskers within each individual catchment were calculated. Next, the percent coverage of each classification attribute was calculated. For eskers, the esker length to catchment area ratio was calculated for each catchment. The results from this analysis were a GIS attribute table for each attribute, containing a field with the catchment unique identifier, a field with the total area of the attribute within each catchment and a field with the proportion of the attribute within each catchment. All tables were joined into one local catchment table that could be linked back to the catchment data for further analysis.

Accumulated catchment analysis:

The analyses of 2a and 2b are referred to as accumulated catchment analyses as here the accumulated patterns of attributes upstream to any given catchment was calculated to determine the potential accumulated influence of those patterns on the hydrology and aquatic habitats within any given catchment. Attributes that were calculated were drainage area, 12 surficial geology classes, 8 permafrost classes, 3 classes of sources of water, and glacier coverage.

First the total upstream accumulated drainage area was calculated for each catchment by using tracing tools in the ESRI ArcGIS and ArcInfo GIS software to trace upstream from any given catchment in the study area to identify the uptream area that contributes flow and materials to that local catchment and summarizing the total area that is upstream and contributing to the local catchments. This type of analysis is also referred to as flow

accumulation analysis. Similarly, flow accumulation analyses were performed for each surficial geology, permafrost and groundwater potential class and for glaciers to summarize the total upstream accumulated area for these classification attributes for any given catchment in the study area. Catchments with no associated stream link were treated as headwater catchments where total accumulated area equals the local catchment area. Following the accumulated upstream area calculations for all attributes, the percent of total upstream drainage area that is contributed by each selected attribute was calculated.

The results from this analysis were a GIS attribute table for each attribute, containing a field with the catchment unique identifier, a field with the total upstream accumulated area of each attribute for each catchment and a field with the percent of total upstream drainage area that is contributed by the attribute. All tables were joined into one master accumulated catchment table that could be linked back to the local catchment data for further analysis.

Initially the intent was to use ESRI ArcInfo workstation trace tools to perform flow accumulation analyses within both the Mackenzie River Basin and the several drainage areas within the Queen Elizabeth Basin as these tools required less processing time than the ArcGIS network analysis tools and are generally easier to set-up and execute. However, braided mountain streams and complex delta stream systems in the Mackenzie River Basin, in which streams split and flow back together again, resulting in 'looped' stream flows, caused the trace tools to "error out" and freeze because they were not able to determine the flow direction of the streams. Therefore, ESRI ArcInfo workstation trace tools could only be used to perform flow accumulation analyses within the Queen Elizabeth Basin where the drainage network was less complex. To facilitate the process of performing flow accumulation analyses for 25 classes of attributes in the Queen Elizabeth Basin, the GIS contractor provided an aml (Arc Macro Language) script to automate the necessary processing steps.

For the more complex Mackenzie River Basin stream network, ArcGIS Network Analyst tools were used to perform flow accumulation analyses. A number of processing steps were required to account for looped flows to ensure accurate and reliable results. The GIS contractor was able to use Visual Basic code available for download at the ESRI Support Center website (http://arcscripts.esri.com/details.asp?dbid=14481) to modify the code to meet the needs of this classification.

Dominance:

In most cases more than one attribute class occurs in a local or accumulated catchment. To simplify the process of creating types, one attribute class needs to represent the entire catchment. In order to select this single class, rules of dominance were created. Dominance was defined as a single class covering more than 50% of a local catchment or more than 50% of the upstream accumulated catchment area. If no class exceeded 50% coverage within a local catchment or the upstream accumulated catchment area, then those catchments were considered to have 'mixed coverage.'

Next, a decision was made for each attribute on whether to use the dominance on a local or accumulated basis to develop types, based on how each attribute influences freshwater systems.

Surficial geology: local
Permafrost: local
Sources of water: accumulated
Glaciers: accumulated

Surficial geology and permafrost were used as local dominance because of their direct influences to streams including channel morphology and substrate texture of catchments which in turn influence in-stream habitats. It should be noted that surficial geology and permafrost can also have downstream impacts but these were not deemed as useful by the NWT-PAS Science Team; however, both local and accumulated values for each variable in each catchment were calculated and stored in the files.

Sources of water and glaciers were chosen as accumulated attributes because of their influence on hydrologic, sediment, and temperature regimes.

Illustrated example analysis steps required to construct the classification

The classification is constructed using ESRI GIS software and using a variety of analysis steps based on the catchments, stream network and stream junctions (nodes) and the classification attribute datasets. In Figure 7A the streams are represented as blue lines, the junctions of the streams, or nodes, as blue dots and the local catchments for each stream segment as red outlines. Each stream segment, a line between two nodes, has a unique identification number. This unique identifier is the same as the identification number for the catchment associated with the stream segment, allowing stream reaches and catchments data to be linked. It is this relationship between stream reaches and catchments that allows the GIS software to trace upstream (or downstream) from node to node and calculate the total land area drained at any given node in the drainage network and the amount of any variable of interest present in the area drained.

A.   B.

Figure 7: Simplified steps in calculating dominant local and accumulated measures to serve as the foundation of a freshwater classification.

A) Shows a portion of the contributing (upstream) catchments that drain into the stream network at the red colored node in catchment 11. Each blue line is a stream reach, each blue point is a node (junction) on the stream network and each catchment is the approximate area of land that drains into a stream reach.

B) The same catchments overlain on the surficial geology data (note the surficial geology classes and colors in the legend). This map shows the amount of each surficial geology class within each individual (local) catchment. C) Shows the catchments color coded by the dominant surficial geology class within each local catchment. D) Shows the catchments color coded by dominant surficial geology class within the upstream accumulated catchment area for each catchment.

Figure 7B depicts the same catchments overlain on the surficial geology dataset as an example. The first step is to compute how much area of each surficial geology class is present within each individual (local) catchment. These values are referred to as the

"local values" for each catchment. Where more than one surficial geology class occurs within a catchment the dominant class is determined.

Figure 7C shows catchments colour-coded to show the dominant local surficial geology class within each local catchment. Dominance is defined as a single class covering more than 50% of the local catchment. If no class exceeds 50%, then the dominance is considered "mixed". The threshold of 50% was decided upon after thorough analysis of the distribution of classes from each dataset (12 surficial geology classes, 8 permafrost classes and 3 sources of water classes) in the catchments. For most dataset classes more than 75% of the catchments were found to have a single class cover more than 50% of the local catchment.

Figure 7D shows the dominant surficial geology class in all upstream catchments contributing to any given local catchment. Headwater catchments, those without flow entering from upstream, are still defined by their local dominance. GIS software tools were used to trace upstream from any given catchment in the study area to identify those upstream catchments that contribute flow and to summarize the total upstream accumulated area for each surficial geology class using the local catchment values shown in Figure 7B. This type of analysis is referred to as flow accumulation analysis.

Notice how the dominant accumulated surficial geology class has changed from the dominant local classes in Figure 7C for catchments 7, 8, 10 and 11. The reason for this change is that a surficial geology class in all the upstream catchments, which differed from the locally dominant surficial geology class, added up to be over 50% of the upstream catchment area.

For example, In Figure 7C the dominant local surficial geology class in catchment 8 is Gp+Gx – Glaciofluvial Plain. Catchments 4 and 5 flow into catchment 8 and the dominant accumulated surficial geology class in those two upstream catchments is Tb – Till Blanket. Therefore, Tb is assigned to catchment 8 as the dominant accumulated contributing surficial geology class for catchment 8 because catchments 4 and 5 contribute more than 50% of the upstream area (Figure 7D). A similar "class switch" can be seen for catchment 7, 10 and catchment 11 which are all assigned a mixed dominant surficial geology class because the upstream contributing catchments have a diversity of classes, none of which add up to more than 50% coverage of the total upstream catchment area.

Classification Datasets and Variables

The following section describes the individual classification attributes used for the classification, their relevance for the classification and the processing steps required to prepare the datasets for input into the local and accumulated catchment analyses.

Accumulated Catchment Size

Figure 6: Accumulated size of catchments of the Mackenzie River Basin and parts of the adjacent Queen Elizabeth Basin based on the total upstream area of land drained at any given stream reach.

Relevance for the freshwater classification

Catchment area is correlated with channel morphology, types and ratios of habitats, habitat stability, and flow volume (Vannote et al 1980, Mathews 1998). For instance, small catchments tend to have small streams that are often shallow and intermittent, lack extensive floodplains, and have pool, riffle, and run habitats distributed throughout. Large catchments generally result in larger river systems that are permanent, have larger homogeneous sections of habitats, often with extensive floodplains. Catchment area was calculated for every aquatic ecosystem polygon and were defined as 4 classes of catchment size: $< 100 \text{ km}^2$, 101-10,000 km^2, 10,001 – 1,000,000 km^2 and >1,000,000 km^2. The characteristics of small rivers and streams are tied closely with the characteristics of their local catchments. The impact of entire contributing catchments on

larger rivers is often less influential on local channel morphology and lateral habitats such as floodplains than nearby landscape features. The spatial distribution of the size classes of catchments is shown in Figure 6 above.

Description of datasets used and pre-processing steps

Total upstream accumulated drainage area for each catchment was calculated using the Atlas of Canada, 1,000,000 National Frameworks Hydrology catchment and analytical stream network data described in section "Catchments" (page 17). Necessary pre-processing and methods used to calculate local and accumulated catchment areas is described in the section 'Creating the classification' (page 19).

Data Sources:

Catchment data:
Source: Atlas of Canada 1,000,000 National Frameworks Data, Hydrology – Drainage Areas, Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2008-07

Online linkage: http://geogratis.cgdi.gc.ca/download/frameworkdata/drainage_areas

Drainage Network – Analytical Network:
Source: Atlas of Canada 1,000,000 National Scale Frameworks Data, Hydrology – Drainage Network, Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2008-07

Online linkage:
http://geogratis.gc.ca/download/frameworkdata/hydrology/analytical/drainage_network

Sources of Water

Figure 8: Sources of water in the Mackenzie River Basin and several drainages in the adjacent Queen Elizabeth Basin..

Relevance for the classification:
Climate determines the types, temporal patterns and amount of precipitation, and hence, is a dominant controlling factor of hydrologic regime. Climate is incorporated at the EDU level. Variability of hydrologic regimes within climatic regions is determined by the dynamics and sources of water to aquatic habitats from the landscape. The seasonal flows

of the rivers in the Mackenzie River Basin tend to exhibit essentially a subarctic nival regime: high flows that occur during the snowmelt and river ice breakup period, followed by a steady decline, sometimes raised by summer and autumn rain events, until the winter, when low flow prevails. The amount and timing of precipitation, snow cover, and temperature regimes strongly influences the variability within this regime. This flow regime is modified in areas with other sources of water (glaciers, groundwater), and storage capacity (lakes and wetlands). Glaciers contribute to extended summer flows, described as a proglacial regime, and have distinct sediment and temperature regimes. Groundwater contributes to more stable low flows and temperatures, and often influences chemistry and productivity. Large lakes tend to reduce high flows and extend low flows, described as a prolacustrine regime (Woo and Thorne 2003).

The sources of water dataset provides a description of the estimated dominant proportion of water to streams and lakes resulting from sub-surface sources such as aquifers, interstitial areas in coarse surficial geology, surface run off or a mixture of sources. The source of water not only influences hydrologic regimes, it also influences the temperature regime and chemistry of streams and lakes (Winter 1977, 2001, Jensen et al 2001). For this classification, sources of water were estimated based on the relative proportions of surficial geology classes and other features, such as glaciers and eskers, and classified into three major source of water classes:

Groundwater
Surface water and
Groundwater/surface water

Description of dataset used and pre-processing steps:
The sources of water dataset was provided by Dr. Steve Grasby (Research Scientist, with the Geological Survey of Canada (GSC) and currently leading GSC's Groundwater Program) and Paul Wozniak (Geospatial Data Specialist, GSC)). The dataset was produced by Grasby using his expert knowledge to group surficial geology classes based on their propensity to contribute groundwater to a hydrologic system.

Data source:
Surficial Materials of Canada, Map 1880A: Government of Canada, Natural Resources Canada, Geological Survey of Canada, Terrain Sciences Division
Scale 1:5 million

Online linkage: http://gsc.nrcan.gc.ca/map/1880a/index_e.php
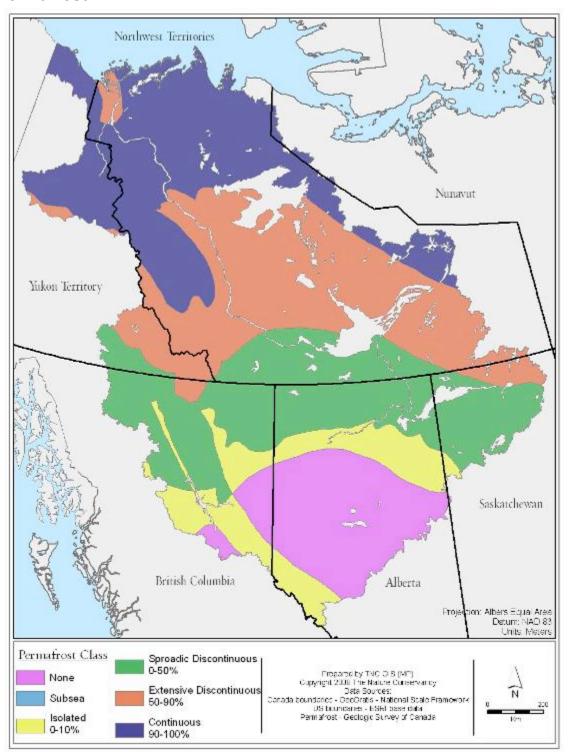
Permafrost

Figure 9: Permafrost classes of the study area

Relevance for the classification*:

Permafrost, originally termed as permanently frozen materials (Muller 1943), is now commonly defined as bedrock, organic or earth materials that are at or below 0° C for at least two consecutive years (Woo 2000). Permafrost inhibits infiltration of water and promotes surface flow (Williams and Smith 1989), leading to lakes and wetlands above the impermeable frost table.

Permafrost characteristics strongly influence the morphology and hydrologic characteristics of lotic systems. Large rivers on permafrost tend to be shallow, and can be braided, aggrading or anastomosing (braided), single channel, degrading or stable, with gravel or silt substrate, depending on permafrost and vegetation conditions (Church 1977). Small streams can be single, well developed channels with gravel on uplands with sufficient hydrologic force, beaded (thermokarstic) (sequence of narrow and deep areas between shallow connections), tundra seepage areas with little to no channel definition, and/or narrow and deep muskeg channels (Church 1977).

Water storage capacity of the subsurface is also limited in permafrost rich areas (Rouse et al 1997). The permafrost thickness, ice content, thickness of the active layer, and the presence of taliks determine surface and subsurface water dynamics. Taliks are sub-surface non-frozen materials that often convey groundwater (Rouse et al 1997). Streams and rivers on permafrost tend to have high spring flows from snow and active permafrost layer melt waters. Flows respond quickly to rain events, as the active layer of permafrost is either frozen or saturated resulting in poor capacity to absorb and store water. The active permafrost layer can provide local subsurface flows when melted during the summer (McNamara et al 1998; Woo 2000).

Description of dataset used and pre-processing steps:

The permafrost dataset used for the first draft of the classification was UNEP/GRID-Arendal circum-arctic Map of Permafrost and Ground-Ice Conditions, ver. 1.0 (1998) and included areas of permafrost combined with landform information , e.g. thick overburden, thin overburden, ground ice content, etc. Advice from permafrost experts Steve Kokelj (Environmental Scientist, Indian and Northern Affairs Canada, Yellowknife, NT) and Dr. Caroline Duchesne (Physical Scientist, Natural Resources Canada, Ottawa, ON) suggested that the landform information added a degree of complexity that was not necessary for this classification, considering that landforms were already included to a degree in the surficial geology data. Following the advice of these permafrost experts, Canada Permafrost as part of The National Atlas of Canada 5th Edition (Heginbottom, 1995) was used, which contained the following classes in the study area:
None
Subsea – under or near water in coastal zones
Isolated – 0-10% of area in this zone contains permafrost
Sporadic discontinous – 0 -50% of area in this zone contains permafrost
Extensive discontinous – 50 - 90% of area in this zone contains permafrost
Continuous - 0 -100% of area in this zone contains permafrost

Data source:
Received Heginbottom, J.A., 1995, Canada Permafrost, The National Atlas of Canada 5th Edition, Natural Resources Canada, Geological Survey of Canada, Map MCR 4177F, from Dr. Caroline Duchesne.

Scale 1:7,500,000

Glaciers/Ice Fields

Figure 10: Location of glaciers or ice fields in Western Canada and the Mackenzie River Basin

Relevance for the classification:

Even with minimal catchment coverage, glaciers significantly affect hydrologic, sediment and temperature regimes. A glacier is in continual mass balance flux meaning, dependent on environmental conditions, its extent and mass is constantly changing (Hock et al. 2007). Glaciers provide cold melt water and high amounts of sediments and suspended solids to rivers and lakes. Glacial ice contains an abundance of microbes including bacteria, rotifers, fungi and viruses that enter streams during times of negative mass balance, generally during spring melting events (Hodson 2008). Proglacial hydrologic regimes have a predictable annual hydrograph, with peak flows in June /July and sustained extended flows throughout the summer.

Catchments with > 5% glacier coverage of their accumulated upstream catchment area were defined as being *glacially influenced.* The 5% threshold was suggested by Dr. Chris Spence (Northern Hydrologist, Environment Canada, Saskatoon, SK) based on work by Strahl and Moore (2007) on mountain watersheds in British Columbia. Glacially influenced catchments are uncommon in the Mackenzie River Basin, occurring in the mountainous western and southern areas of the basin.

Description of dataset used and pre-processing steps:
The glacier/ice field dataset used for this classification is the VMAP0 Revision 4 Atlas of Canada 1:1 M, Snow/ice fields, 2000, a Canada-wide dataset that contains the extent of snow fields and icefields in 2000. See Figure 10.

Data source:
Snow field/ice field, current extent, VMAP0 Revision 4 (Atlas of Canada vectors)

Online linkage: http://geogratis.cgdi.gc.ca/geogratis/en/option/select.do?id=5340

Density of Lakes within Catchments

Figure 11: Lakes in the study area

Relevance for freshwater classification:

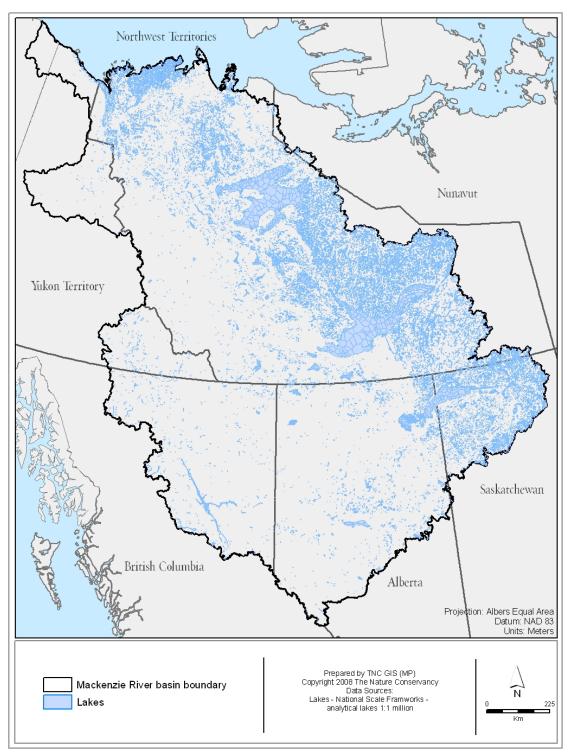Lakes are important habitats for many aquatic and freshwater-dependent species. In cold regions they are affected by long frozen periods, which in turn impact gaseous exchange and nutrient cycling (Rouse et al 1997). Lakes that constitute part of a river system, especially large and/or deep lakes, generally act as sinks for sediment and increase deposition by slowing water flow. Large lakes add water storage capacity, and tend to reduce high flows and extend low flows in rivers (Woo and Thorne 2003). Due to these impacts on freshwater systems, Marlene Evans (Research Scientist, Environment Canada, Burlington, ON) and Daniel Peters (Hydrologic Researcher, Environment Canada, Saskatoon, SK) suggested a lake dominance component be added to the classification at a workshop held in Yellowknife, NT, in November 2007 to solicit feedback on the first draft of the freshwater classification.

Description of dataset used and necessary pre-processing steps:

The source dataset for this attribute was the Atlas of Canada, 1,000,000 National Scale Frameworks Hydrology – analytical lakes. A catchment was considered dominated by lakes if 30% or more of the catchment area consisted of lakes. This threshold was proposed by Dr. Dirk De Boer, Professor at the University of Saskatchewan, Centre for Hydrology, after careful consideration of maps created by the PAS Science Team depicting varying percentages of catchment coverage by lakes across the Basin. Thirty percent appeared to give the most accurate picture of the patterns expected for lake dominance across the Basin in regards to Dr. De Boer's extensive experience of working in the Basin.

Data Source:
Atlas of Canada, 1,000,000 National Scale Frameworks, Hydrology – drainage network (analytical), Government of Canada, Natural Resources Canada, Canada Centre for Remote Sensing, The Atlas of Canada. 2006-07

Online linkage:
http://geogratis.gc.ca/download/frameworkdata/hydrology/analytical/drainage_network/
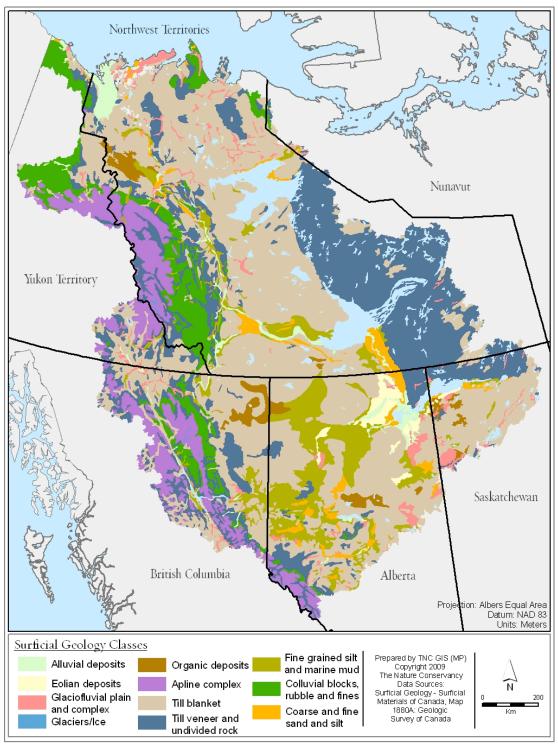
Surficial Geology

Figure 12: Surficial geology classes in the study area, grouped based on texture, to reduce the number of classes in the original dataset.

Relevance for the freshwater classification:

Surficial geology influences the sources of water (i.e. groundwater and/or surface water), water chemistry, water temperature, geomorphology, substrate and hydrologic regime characteristics of streams and lakes (Winter 1977; Lotspeich 1980; Cupp 1989; Montgomery and Buffington 1993; Reis 1994; Maxwell et al 1995; Seelbach et al 1997; Jensen et al 2001; Winter 2001).

Description of dataset used and data pre-processing:

The surficial geology dataset used for this classification was the 1:5 million scale Surficial Materials of Canada, Map 1880A, dataset. This dataset is based primarily on texture and morphology and includes 19 surficial geology classes. To simplify the dataset and reduce the number of classes for use in this freshwater classification, With expert advice from Steve Grasby (Research Scientist, Geological Survey of Canada (GSC), Calgary, AB), we grouped the original surficial geology classes into 10 classes based on permeability, texture and composition (i.e. all colluvial classes were grouped into one class, till veneer (associated with rock) was grouped with undivided rock). Classes that weren't surficial geology classes, such as water and ice, were coded 'not applicable' and were not used for analysis. Original and grouped classes are shown in Table 1.

Table 1: Original and grouped surficial geology classes.

Original Classes	Description	Grouped Classes
I	Glaciers--ice and minor morainal debris	N/A
water	Water	N/A
A	Alluvial Deposits--stratified silt-- sand-- clay-- and gravel; floodplain-- delta-- and fan deposits; in places overlies and includes glaciofluvial deposits	A
E	Eolian Deposits--sand and minor silt; dunes-- blowouts-- and undulating plains; in most places overlies deltaic sediments-- coarse lacustrine sediments-- or glaciofluvial deposits	E
Gp	Glaciofluvial Plain--sand and gravel; deposited as outwash sheets-- valley trains-- and terrace deposits	Gp+Gx
Gx	Glaciofluvial Complex--sand and gravel and locally diamicton; undifferentiated ice contact stratified drift-- and outwash; locally includes till and rock	Gp+Gx
Tb	Till Blanket--thick and continuous till	Tb
Tv	Till Veneer--thin and discontinuous till; may include extensive areas of rock outcrop	Tv+R
cL	Coarse grained (Glacio)Lacustrine--sand-- silt-- and gravel; deposited as deltas-- sheet sands-- and lag deposits	cL+sL
sL	Lacustrine Sand--sand and locally gravel; deposited as sheet sands-- lags-- and beaches	cL+sL
fL	Fine grained (Glacio)Lacustrine--silt-- and clay-- locally containing stones; deposited as quiet water sediments	fL+mM
mM	Marine Mud--fluid silty clay and clayey silt; deposited as quiet water sediments	fL+mM
O	Organic Deposits--peat-- muck and minor inorganic sediments; large bog-- fen-- and swamp areas where organic fill masks underlying surficial materials; geneally >2 m thick	O
bC	Colluvial Blocks--Blocks-- and rubble with sand and silt; derived from crystalline bedrock-- medium grade metamorphic substrate-- and cemented sandstone	rCfCbCsC
rC	Colluvial Rubble--rubble and silt; derived from carbonate and consolidated fine clastic sedimentary rock substrate	rCfCbCsC
fC	Colluvial Fines--silt-- clay-- and fine sand; derived from substrate weakly consolidated shale and siltstone substrate	rCfCbCsC
sC	Colluvial Sand--Sand and gravel; derived from poorly lithified sandstone and conglomerate substrate	rCfCbCsC
Ra	Alpine Complexes--rock-- colluvium-- and till; rock and Quaternary deposits complex in an area-- characterized by alpine and glacial landforms	Ra

R	Undivided--rock with minor Quaternary deposits	Tv+R

Data source:
Surficial Materials of Canada, Map 1880A: Government of Canada, Natural Resources
Canada, Geological Survey of Canada, Terrain Sciences Division. Scale 1:5,000,000

Online linkage: http://cgc.rncan.gc.ca/map/1880a/index_e.php
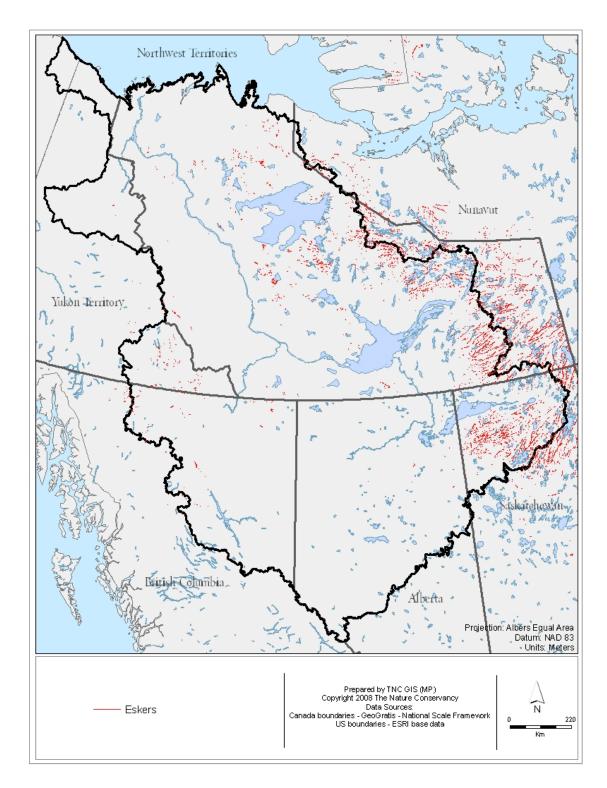
Eskers

Figure 13: Eskers in the study area.

Relevance for the freshwater classification:
Eskers are elevated sinuous mounds of debris formed in drainage channels within and under glaciers. When glaciers melt, debris such as sand and gravel, which collected in the drainage channels, is deposited on the landscape. On top of eskers the vegetation is highly reduced due to dryer, windswept conditions. Wind also blows away fine soils leaving a stone covered pavement (Traynor 2001). This pavement limits water infiltration, yet the composition of eskers (sand and gravel) are materials that have high water storage capacities. Many eskers also contain ice. The storage capacity and ice can alter seasonal flow regimes of water.

Esker relative density was calculated by dividing the length (in metres) by the local area of the catchment (in meters squared). A value over 0.75 of this dividend resulted in a catchment being labeled "esker dominant." The equation and threshold were needed to have a quantified approach to esker dominance and developed out of visual inspection of the esker and catchment datasets.

Description of dataset and pre-processing:

Esker data used for this classification was the esker layer of the 1:250,000 scale National Topographic Database (see source below). Merged mapsheets of individual NTDB layers, including eskers, for all of the NWT are available from the GNWT spatial data warehouse (see "Online Linkage" below). Mapsheets covering the Mackenzie Basin in British Columbia, Alberta and Saskatchewan and containing esker layers were downloaded and merged with the NWT-wide esker data to create one esker dataset that covered the entire study area.

Data Source:
1:250,000 scale National Topographic Database, Government of Canada, Natural Resources Canada, Centre for Topographic Information (Sherbrooke). Map dates range from 1944-2002.

Online linkage:
Individual 1:250 scale NTDB mapsheets:
http://ftp2.cits.rncan.gc.ca/pub/bndt/250k_shp_en
or http://geogratis.cgdi.gc.ca/geogratis/en/product/search.do?id=8147

Classification Results

Each classification attribute (i.e. catchment size, water sources, surficial geology classes, etc.) provide insights into the characteristics of catchments and the aquatic habitats within them. The classification attributes can be used individually for specific queries or analyses of specific patterns and processes or the attributes can be combined for each catchment to generate an overall classification. For the final classification, all classes for each attribute within each catchment were combined by concatenating them, resulting in

865 freshwater ecosystem types in the study area (Figure 14). These freshwater types give an overview of the regional patterns of environmental conditions within the study area that influence aquatic ecosystem characteristics. These classes are the finest level of distinctions that can be derived from the coarse-scale spatial data that were available for this classification.
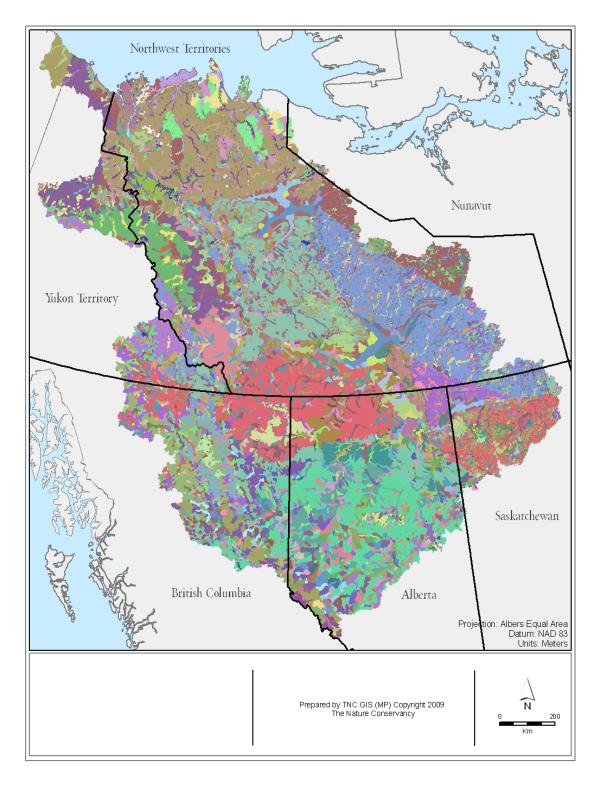
Figure 14: Final Mackenzie River Basin classification depicting all 865 classes created.

The catchments and resulting freshwater ecosystem types are nested spatially within the Ecological Drainage Units (EDUs). EDUs provide information about larger spatial scale patterns of climate, landform and vegetation. These patterns constrain the smaller-scale patterns and processes of the aquatic ecosystems. By determining which EDU a freshwater class is located within, the broader context and patterns and processes at different spatial scales can be analyzed. Aquatic ecosystem types with similar local physical characteristics can have a suite of different dominant characteristics if they are in different EDUs, and hence in different climate, landform and vegetation zones.

Potential Uses of the Freshwater Classification

The freshwater classification and maps describe the variety and depict the spatial distributions of geomorphic patterns and processes of freshwater systems. Similar classifications have been used as a component of regional systematic conservation planning in other parts of North America and other continent of the world (e.g. Higgins 2003; Higgins et al 2005; Thieme et al 2007; Nel et al 2009). More recently, they have also been used in conjunction with species data to inform sampling design, build predictive models for species distributions, and to assess gaps in the protection of freshwater ecosystems (Sowa et al 2007). Such classification frameworks are becoming an integral part of decision support systems for basin-wide management planning and evaluation, and are being used to inform the designation of new protected areas, as a component of impact assessments of infrastructure development projects to inform sustainable regional hydropower development, and as part of the scientific basis for water policies focused on allowable thresholds of flow alteration (Poff et al 2009).

The PAS Science Team will use this classification as a freshwater coarse-filter and analyze the extent to which freshwater ecosystems are represented within protected areas. This analysis will identify gaps in representation of aquatic ecosystems to inform protected area planning and management, and land use planning efforts in the future. The classification can also be used to evaluate the potential impacts to, and losses of, representative ecosystems resulting from development such as planned hydropower projects, roads and pipelines. Uses in the long-term might include using the classification as part of a systematic conservation plan for the basin, which would include evaluating the relative conditions and threats to each occurrence of the ecosystems in order to identify the best candidates of each type for conservation. Additionally, the classification can be an integral component of decision support systems for catchment and basin-wide management planning.

Known Limitations and Next Steps

The finest level spatial units used for this classification, the local catchments, are limiting for many reasons, but were the best available given the hydrography data available for the Mackenzie River Basin. In other classification efforts, catchments of different sizes

could be developed. The PAS Science Team was limited to using small local catchments, and then aggregating them up into larger units. The resolution and accuracy of the stream network and the catchment boundaries is limited by the data in the digital elevation model. These data do not provide accurate stream networks or catchment boundaries in flat areas due to the large resolution of the data.

Spatial data that were both meaningful for the classification and comprehensive for the study area were limited. The data were generally only available at coarse scale, which limits the resolution and accuracy of the attribution of small spatial units when they cross boundaries of classes of mapped attributes. Downscaling data was avoided, but there are no doubt inaccuracies that exist as a result of unintended downscaling that occurs when assessing any defined spatial unit.

To date the classification results have not been validated with on-the-ground observations.

Since almost half of the Mackenzie River Basin lies outside the NWT, but drains into and thus potentially affects downstream aquatic systems in the NWT, the entire Mackenzie River Basin was included in this classification. Datasets that cover the entire study area and are meaningful for the classification are limited. These datasets are often at various scales and most are course- ranging from 1:1 million to 1:10 million. Using data at different scales for analysis is generally not recommended and can provide misleading results. However, this classification didn't focus on exact areas of each attribute within a catchment as the basis for the classification, but rather on the dominance of attributes within the local or the upstream catchments. By using catchments as the finest scale to summarize variables, inconsistencies in the classification results due to differing input scales were reduced. Also, the classification does include an intermediary analysis unit of EDUs which can be useful for analysis at larger scales, thus reducing varying input scale inconsistencies further, and the PAS Science Team urges individuals interested in larger scale patterns to consider the EDU level of the classification.

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Appendix I – Freshwater classifications in other parts of the world.

The classification approach for the Mackenzie Basin is based on Higgins et al (2005) which The Nature Conservancy (TNC) has applied widely across North, Central and South America and China (Terneus et al 2004; Higgins and Duigan 2009; The Nature Conservancy 2009; Heiner et al *in press*). Similar approaches have been applied globally (see Nel et al 2008), with specific examples published by the World Wildlife Fund in

South America (Theime et al 2007), researchers in Australia (Stein 2008), and agencies in South Africa (Nel et al 2006).

Two examples of how classification products have been used in Basin-wide conservation planning by The Nature Conservancy include:

Priority Areas for Freshwater Conservation Action by Smith et al, 2002 available at http://conserveonline.org/docs/2003/08/se_biodiv_assess.pdf

In this effort "four highly significant regions of freshwater biodiversity" were examined by mapping distinct aquatic systems. The maps fed into a hierarchical classification of communities and ecosystems, and prioritized the area for conservation action. Patterns of diversity were also assessed from the maps and threats against integrity of species were analyzed by scientists. The intent of the output was to identify priority freshwater areas for conservation, facilitate strategies for multi-site projects and create a base-line for future assessments of conservation gains and status of freshwater biodiversity.

Conservation Priorities for Freshwater Biodiversity in the Upper Mississippi River Basin by Weitzell et al, 2003 available at http://www.natureserve.org/publications/upperMSriverBasin.jsp

The Upper Mississippi River Basin (UMRB) is a well studied region but still lacks a comprehensive assessment to guide efforts towards freshwater biodiversity across the Basin. To address this shortcoming The Nature Conservancy teamed with NatureServe and the US Environmental Protection Agency to compile data on distribution, variety and condition of freshwater species and ecosystems. Ecological system types were classified from this data an ecological integrity was assessed. The final product was a result of working with regional experts to identify 47 high priority combined freshwater and terrestrial conservation priorities. These areas will be used to guide conservation planning efforts, design sampling frameworks and provide reference conditions for stream monitoring.

Recent examples of applications by other agencies and organizations include using this approach as a basis for the Aquatic GAP program approach in Missouri (Sowa et al 2007), freshwater regional planning by the World Wildlife Fund (Theime et al 2007), and freshwater conservation assessments in South Africa (Nel et al 2007). TNC, lead by Cathy Flannigan, also recently applied this approach in the north slope of Alaska. The north slope landscape shares some similarities with the northern portions of the Mackenzie River Basin, and a hydrography data situation for assessing watersheds that is very similar to the situation presented in this report.

The classification approach described in Higgins et al (2005) is a hierarchical one, where river segments and individual lake types are nested spatially within ecosystem units of varying sizes. The site and ecosystem scales allow the ecosystems to be used as regional planning coarse-filter targets, and the finer-scale components to be used for site-level planning. These units are nested within Ecological Drainage Units (EDUs) which are

large catchments of distinct environmental and/or ecological patterns delineated according to regional-scale patterns of climate, landform and drainage density.

Appendix II – EDU Descriptions

The EDUs in the Mackenzie River Basin were generated by aggregating existing sub-sub watersheds (Water Survey of Canada 1980) based on spatial drainage patterns, and dominant patterns of landform and climate. The summaries below were derived primarily using the landscape, climate and vegetation descriptions from the Ecozones and Ecoregions of Canada (Environment Canada 2005), patterns of hydrologic regime (Woo and Thorne, 2003), and environmental characteristics (Brunskill 1986).

The Mackenzie River Basin is composed primarily of 3 physiographic regions; Precambrian Shield, Interior Plains, and the Cordillera, with some Arctic Coastal Plains to the far north and eastern portion of the drainage. The region's climate and vegetation have been used to distinguish patterns within and among these regions as Montane, Boreal, Tundra, and Taiga. There are distinct climatic gradients from the south (cold temperate) to the north (sub-arctic to arctic), and from the west (mountain) to the east (sub-arctic). There is a significant annual precipitation gradient from the west to northeast, ranging from more than 1,000 mm in the southwest, to 500 mm in the northwest, to 200 mm on the Arctic coast. These climatic patterns, interacting with the physiography, result in distinct patterns of river valley morphology and hydrology. The width, depth, meander patterns and valley characteristics of rivers differ among these regions based on the energy of the systems, and the geology and soils they are on. The seasonal flows of the rivers in the Mackenzie Basin tend to exhibit essentially a subarctic nival regime: high flows that occur during the snowmelt and river ice breakup period are followed by a steady decline, sometimes raised by summer and autumn rain events, until the winter, when low flow prevails. This flow regime is modified in areas with other sources of water (glaciers, groundwater), and storage capacity (lakes, wetlands). Glaciers contribute to extended summer flows, described as a proglacial regime. Groundwater sources contribute to more stable low flows. Large lakes tend to reduce high flows and extend low flows, described as a prolacustrine regime.

The Cordillera
The Cordillera in the western portion of the Basin is the northerly extension of the Rocky Mountains, mostly at elevations of 2,000-2,500 m. Stream runoff in this region is relatively high compared to the rest of the Basin and rivers originating in the Cordillera provide the highest proportional contributions of flow to the Mackenzie River because of high precipitation and limited water storage capacity. Rivers draining the Cordillera are subarctic rivers which have cut deeply into bedrock, and they transport significant amounts of suspended sediments and gravel from relatively soluble geology.

Upper Peace River - Montane Cordillera

Located in the southwest portion of the Basin, this drainage initiates in the Rocky Mountains in portions of the Cordillera in eastern British Columbia. The streams and rivers in this drainage area receive some of the highest precipitation in the Basin, contributing to the significant portion of water yield to the Peace River, which provides over 20% of the flow to the Mackenzie River. This region of the Cordillera receives between 500-800 mm of annual precipitation, with higher levels of precipitation occurring at higher elevations. Rocky outcrops are common and plant communities are complexes of alpine and sub-alpine vegetation. Isolated and discontinuous sporadic permafrost exists in this drainage at higher elevations. Waters are primarily surface drainage in origin with some small areas of mixed surface and groundwater sources.

Liard River - Boreal Cordillera
The Liard River headwaters originate in the steep Pelly Mountains in the Boreal Cordillera. Mean annual precipitation is 500-1000 mm, varying with elevation. This extensive precipitation and the large drainage area is why the Liard River is the largest contributor of flow to the Mackenzie River. Much of the Pelly Mountains are above the treeline, and the area is characterized by Alpine tundra communities at high elevations and Boreal forests cover the lower-elevation valley bottoms. Permafrost is sporadically distributed. Higher elevation areas contain coarse igneous rocks. Plateau areas often have sandy loam morainal parent materials. This drainage transitions from the Pelly Mountains to the Liard Plain, a broad, rolling, low-lying area mantled with glacial drift and outwash deposits in which the Liard River is entrenched. Annual precipitation in the plain is 350-450 mm. Vegetation is primarily Boreal forest. The plains area is underlain by Carboniferous Palaeozoic limestone and Cretaceous shale. There are areas of coarse-textured fluvioglacial deposits. Permafrost is scattered, confined mainly to lower north-facing slopes and sphagnum bogs. Sources of water are primarily surface runoff and mixed surface and groundwater, with local groundwater from fluvioglacial deposits along the mainstem river valley.

Tributary to the Liard River – Taiga Cordillera
The rivers and tributaries to the north of the Liard River, including the North Nahanni, Redstone, Root, Ravensthroat, Keele and the Moutain Rivers flow along and through the Selwyn Mountains in the Taiga Cordillera. This region is composed of rugged mountains reaching a height of 2,950m. The region has been extensively glaciated, with local glaciers still occurring in high elevation alpine areas and some valleys. Bare talus slopes, rock outcrops and rubble are common at higher elevations. The region has extensive intrusive granitics. Mean annual precipitation ranges from 600mm at lower elevations to 750 mm at higher elevations. Alpine vegetation at higher elevations and sub-alpine vegetations at lower elevations are characteristic of the region. Permafrost is extensive but discontinuous in the western part, and continuous with low ice content in the eastern part of the region. Alluvial, fluvioglacial, and morainal veneers and blankets dominate the surficial geology of the region. The generally thin surficial geology results in primarily surface-dominated sources of water, with some local areas of mixed surface and groundwater, and groundwater sources, along with local glacial sources of water.

Peel River - Taiga Cordillera

The Peel River originates in the heterogeneous landscape of the Wernecke and the North Olgilvie Mountains. Portions of this region in the Olgilvie Mountains contain high elevation peaks reaching a height of 2,134m, composed of sedimentary strata with intrusive granitic materials. The Wernecke Mountains are composed of metamorphic materials and carbonate rocks carved by glaciers. Bare talus slopes and rock outcrops are common at higher elevations. Mean annual precipitation is approximately 400mm. Alpine tundra vegetation is characteristic at higher elevations with subalpine open woodlands at lower elevations. Alluvium, fluvioglacial deposits, and morainal veneers and blankets are dominant in the drainage. The more northwesterly portion of the drainage originates in the same mountain ranges but unglaciated, and some areas are dominated by flat topped and rounded hills which are remnants of a former plain. This area contains some of the coldest valleys in Canada, reaching a temperature of -50° C. Bedrock is dominated by limestone and marine shales, and permafrost is continuous. Rivers in this area are often wide and flat bottomed. Permafrost is continuous and of low ice content for most portions of the drainage, with pockets of extensive but discontinuous permafrost to the west. Sources of water are surface, mixed surface and groundwater, and groundwater.

Mackenzie River – Taiga Cordillera
The Mackenzie River has many streams flowing into it from the west, initiating in the same region, but more southerly, than the Peel River. The mainstem of the Mackenzie is also on the eastern edge of the Taiga Cordillera in this EDU. The eastern ranges of the Mackenzie Mountains that lie in the rain shadow of the higher Selwyn Mountains to the west, providing mean annual precipitation greater than 600 mm. This results in significant contribution of the flow to the Mackenzie River despite the relatively small drainage area. There is localized alpine and valley glaciation. The region is characterized by alpine tundra at upper elevations and subalpine open woodland vegetation at lower elevations. Alluvium, fluvioglacial deposits, and morainal veneers and blankets are dominant in the region. Rock outcrops are common at higher elevation. Permafrost is primarily continuous, with variable ice content in the eastern portion of the drainage near the mainstem of the Mackenzie River. Sources of water are primarily surface run off with some mixed surface and groundwater along the Mackenzie River valley where there are extensive alluvium and fluvioglacial deposits.

Mackenzie River – Taiga Cordillera North
There is a small pocket of Taiga Cordillera to the west of the Mackenzie River delta. This area is marked by short, cool summers. Winters are generally extremely cold, although winters at higher elevations are more moderate during frequent periods of temperature inversion. Major mountain passes can be subject to strong outflow winds, causing severe wind chill conditions. Mean annual precipitation ranges between 300 mm and 400 mm. The characteristic vegetation is alpine tundra at upper elevations and subalpine open woodland vegetation at lower elevations. Permafrost is continuous. Source of water is primarily surface run off.

The Interior Plains

The Interior Plains extend from the Cordillera east to the Precambrian Shield, and from the southern portion of the Basin to the Arctic Coastal Plain. The landscape is flat or rolling terrain, interrupted by ranges of hills and small mountains, and is underlain by sandstones, shales, dolomites, limestones, evaporites, lignite coal, and glacial and alluvial deposits. Rivers meander and down cut tens of meters through alluvium and sedimentary bedrock. Deep soils of the northern Boreal forest and poorly drained muskeg meadows provide water storage, with extensive areas dominated by wetlands. The large rivers maintain low to near average flows during winter from wetland discharge.

Upper Peace River - Montane Cordillera/Boreal Plains transition
Located in the southwest portion of the Basin, this drainage initiates in the Montane Cordillera on the British Columbia/Alberta border, transitioning to the east into the Boreal Plains Ecozone. This area is a transition zone from mid-Cordillera to mid-Boreal vegetation. This transition results in changes from high gradient, constrained streams, 600-800 mm of annual precipitation and alpine and sub-alpine vegetation, to foothills that rise abruptly above the plains and are mainly linear ridges, rolling plateau remnants, and broad valleys. These strongly dissected uplands with local relief of 100-200 m are covered with thin, discontinuous, loamy glacial till, some peat blankets, and clayey lacustrine and sandy fluvioglacial deposits. This area receives 450-600 mm annual precipitation. There is some isolated permafrost in this drainage at higher elevations. Waters are primarily surface drainage in origin from the headwaters in the far south, with mostly mixed surface and groundwater areas and areas of high groundwater sources in the central and northern regions of the drainage.

Athabasca River - Boreal Plain with small transition from Montane Cordillera.
The Athabasca River is a major tributary to the Mackenzie River, flowing northeast from its origins in the Rocky Mountains in the Montane Cordillera. It experiences precipitation and landform characteristics and patterns of change similar to the Upper Peace River transition and the Middle/Lower Peace River EDUs. The headwaters of the Athabasca River are in areas with 500-800 mm precipitation annually, with higher levels of precipitation occurring at higher elevations. Glaciers occur in the higher elevation areas in this drainage. As a result of the precipitation and glacial sources of water, the Athabasca River contributes 17% of the flow to the Mackenzie River system. Rocky outcrops are common and plant communities are complexes of alpine vegetation in the headwaters, transitioning to the boreal plains composed of level, to gently undulating landscapes with wide river valleys. The surface materials are predominantly clayey lacustrine sediments with some sandy fluvioglacial deltas associated with its major river systems, and areas of poorly drained soils with 20% organic materials. The area is characterized by cool, short summers and cold winters, with 450-550 mm annual precipitation. Poorly drained fens and bogs are found in kettled to dissected, deep, loamy to clayey-textured glacial till, lacustrine deposits, and there are inclusions of coarse, fluvioglacial deposits in the northeastern portion of this drainage. Associated with rougher morainal deposits are a large number of small lakes, ponds, and sloughs occupying shallow depressions. Permafrost is very rare and found only in peatlands. The sources of water vary from glaciers and surface, mixed and groundwater throughout the drainage.

Liard River Mainstem -Taiga Plain
The Liard River flows through low relief areas that are flat or gently rolling topography on shale with surface deposits of peat-covered clayey lacustrine and glacial tills. The region is marked by short summers and long cold winters, with 350-450 mm of mean annual precipitation in this sub-humid high boreal ecoclimate. Permafrost is sporadic and discontinuous for the majority of this drainage, with some extensive discontinuous permafrost in the northern portion of the drainage. Sources of water are predominantly mixed surface and groundwater, and wetland storage.

Tributary Liard River – Taiga Plains
This tributary to the Liard River, the Fort Nelson River, is in the same region as the Liard River mainstem, and it flows through low relief areas that are flat or gently rolling topography on shale, with surface deposits of peat-covered clayey lacustrine and glacial tills. The region is marked by short summers and long cold winters, with 350-450 mm of mean annual precipitation in this sub-humid high boreal ecoclimate. Permafrost is sporadic and discontinuous. Sources of water are predominantly mixed surface and groundwater, and wetland storage.

Hay River – Taiga Plains
The Hay River drains the same landscape as the Liard River, low relief areas that are flat or gently rolling topography on flat Paleozoic strata and Cretaceous shale with surface deposits of peat-covered clayey lacustrine and glacial tills. The region is marked by short summers and long cold winters, with 350-450mm of mean annual precipitation in this sub-humid high boreal ecoclimate. Permafrost is sporadic and discontinuous. Sources of water are predominantly mixed surface and groundwater, and wetland storage. This region also includes the southern shore and drainage of Great Slave Lake.

Middle/Lower Peace River - Boreal Plains
The Peace River mainstem is in the Peace Lowlands, a distinct terrestrial ecoregion in the Boreal Plains ecozone characterized as a sub-humid low boreal ecoclimate. This ecoregion is composed primarily of gently undulating or sloping landscapes associated with the Peace River and its tributaries. Rivers are heavily incised down to 300m in the far southwestern portion of this drainage. It has warmer summers than surrounding areas, with 350-600mm precipitation annually. There are some open parklands that tend to have saline soils. Clayey lacustrine deposits are the predominant parent material, along with some fine-textured tills and significant areas of sandy fluvial deposits in river deltas. Other portions of this drainage include uplands that are transition zones from cordillera landscapes to the Boreal plains. These landscapes contain a mix of steep slopes, rolling plateau remnants, and broad, gently undulating valleys, with areas of extensive organic soils. The drainage has some isolated permafrost with sporadic permafrost occurring to the north. Waters are surface, mixed surface and groundwater, and groundwater sources.

Great Slave Lake, Peace River and Athabasca River Deltas – Boreal Plain
This drainage contains the lower portions and the delta of the Athabasca and Peace Rivers, and the Slave River between Lake Athabasca and Great Slave Lake on the Boreal

Plain. Underlain by relatively flat, low-relief Palaeozoic carbonates, except for the delta, the region is mainly an undulating sandy plain with some eolian features. The climate is characterized by short, cool summers and long, cold winters, with mean annual precipitation ranging from 300-400 mm. The region has a sub-humid mid-boreal ecoclimate with boreal vegetation. Cold and poorly drained fens and bogs are covered with tamarack, black spruce, ericaceous shrubs, and mosses. Up to 50% of the area is covered by peatlands. Some saline inclusions occur along the Slave River. Sporadic discontinuous permafrost with low ice content is prevalent, mainly in the organic deposits. There are extensive areas of groundwater sources because of the coarse sandy materials and large river deltas.

Great Slave Lake - Taiga Plains
The Great Slave Lake-Taiga Plains EDU includes the north arm of Great Slave Lake, and is composed of low relief Paleozoic carbonate rocks and numerous lakes. This area is a sub-arctic ecoclimate dominated by black spruce with an understory of dwarf birch, Labrador tea, lichen and moss. Wetlands cover half of this area, and have fen/bog vegetation. Permafrost is discontinuous throughout the area. Waters are from surface sources.

Great Bear Lake – Taiga Plains
The Great Bear Lake -Taiga Plains EDU comprises most of the lake, with the exception of the eastern shore and drainage. It is characterized by undulating glacial drift and outwash deposits on Cretaceous shale and Devonian limestone. This region has a high sub-arctic ecoclimate, with the latitudinal limit of tree growth along its northern edge. The predominant vegetation is open, very stunted stands of black spruce and tamarack, as well as low-shrub tundra. As elevation increases to the south, entrenched river valleys are 60-150 m below the surface of the surrounding landscapes. Permafrost is deep, extensive and discontinuous. Sources of water are primarily surface run-off.

Mackenzie River – Taiga Plains
The Mackenzie River mainstem and many of its small tributaries extend from Great Slave Lake to the Beaufort Sea. The vast majority of this EDU is in the Taiga Plains. Although there is commonality among the ecoregions within this vast ecozone, there are three sections that provide some distinction in terms of climate, geology and landforms. These have been simplified below as Upper (southern), Middle, and Lower (northern).

Upper (southern)
The most southerly portion of the Mackenzie River mainstem and associated lateral drainage initiate at the outlet of Great Slave Lake. The mainstem portion of the drainage is in lowlands, lying between the Northern Alberta Uplands and Sibbeston Lake Plain ecoregions to the west, and the Horn Plateau ecoregion to the east. All of these stated areas provide drainage to the Mackenzie River as well. The region that contains the mainstem portion of the Mackenzie River has a sub-humid mid-boreal ecoclimate, and the landscape is composed of broad, level lowland plain with a mean annual precipitation ranging from 350-450 mm. Poorly drained fens and bogs are common and cover about one third of the region. The drainage is composed of low-relief, flat-lying Palaeozoic

strata near Great Slave Lake, and Cretaceous shale in its western section. Surface deposits are predominantly peat-covered clayey lacustrine and glacial till on nearly level to gently rolling topography. There is extensive discontinuous permafrost in this portion of the drainage. The sources of water are predominantly mixed surface and groundwater, groundwater, wetland and lake storage. The surrounding drainages are heterogeneous. To the west, annual precipitation ranges from 200-500 mm, and the landscape has significant coverage of wetlands on generally flat to rolling terrain. The permafrost ranges from sporadic discontinuous in the southern portions, to extensive discontinuous to the north. Sources of water are mixed surface and groundwater, groundwater, and wetland storage. To the East, the Horn Plateau rises from the lowlands, providing drainage to the Mackenzie River. The landscape is level to undulating with loamy glacial till and organic deposits. This region receives 250-400 mm mean annual precipitation. Approximately 50% of this region is covered by wetlands, which are predominantly peat plateau bogs, fens and palsas. There is extensive discontinuous permafrost. Sources of water are surface and mixed surface and groundwater, and wetland storage.

Middle
The central portion of the Mackenzie River mainstem lies between the Peel River Plateau to the west, (just east of the Cordillera), and the Norman Range and Franklin Mountains to the east, extending from north of Fort Good Hope to Wrigley. This region is broad, rolling, drift-covered plain, with a sub-humid, high-boreal ecoclimate with mean annual precipitation ranging from 300-400 mm. Wetlands cover up to 50% of this region, dominated by peat plateau bogs and ribbed and horizontal fens. Permafrost is extensive discontinuous. Sources of water are surface, mixed surface and groundwater, groundwater along large alluvial deposits, and wetland storage. The Mackenzie River is entrenched for a portion of this region. The Peel River Plateau to the west is terraces and rounded plateaus covered by thin discontinuous glacial drift and organic deposits, with wetlands covering 25% of the region. The ecoclimate is high subarctic, with 200-275 mm of annual mean precipitation. Permafrost is continuous. Sources of water are primarily surface runoff and some wetland storage. To the east, the Franklin Mountains and the Norman Range form thin parallel bands of north/south low mountains and ridges with steep sloping glacial drift, colluvium and organic deposits. Permafrost is extensive discontinuous with low to medium ice content. Sources of water are surface and mixed surface and groundwater.

Lower (northern)
The lower Mackenzie River is within a landscape with the Fort McPherson Plains to the west and the Great Bear Lake Plain to the east. The Fort McPherson Plains are heterogeneous, with a broad shallow basin to the south, and isolated hills composed of carbonate rocks to the north. Some parts of the EDU have numerous lakes while others have none. The ecoclimate is high subarctic with 250-350 mm of annual precipitation. The permafrost is continuous with medium to high ice content. Sources of water are predominantly surface and mixed surface and groundwater. The Arctic Red and Ontaratue rivers are in deeply incised valleys and flow into the Mackenzie from this region. To the east, the northern portion of the Great Bear Lake Plain is composed of flat lying Cretacious shale and Devonian limestone covered by undulating glacial drift and

outwash deposits. This region receives from 200-300 mm of mean annual precipitation. Permafrost is extensive and discontinuous. Sources of water are generally mixed surface and groundwater.

The Precambrian Shield

The Precambrian Shield lies east of Great Bear and Great Slave Lakes. Bedrock is on or near the surface, with thin glacial and alluvial deposits in low areas. Elevation ranges less than 100 m with numerous lakes, swamps and bogs. Permafrost varies in thickness from 10 m in the south near Lake Athabasca, to 90-375 m in the area between Great Bear and Great Slave Lakes. The terrain is hummocky with polygonally patterned ground and ice-sorted materials. Soils range from ice-free boulder and gravel deposits to high ice-content silty clay and organic acidic soils. Most rivers in this region are chains of lakes linked by channels, with shallow meandering streams only occurring in small areas of organic materials. Sources of deep groundwater are rare. Winter flows of large rivers are maintained where there is adequate lake storage, but most small streams freeze during the winter.

Lake Athabasca - Boreal Shield and Taiga Shield
This area drains the Taiga Shield from the north, and the Boreal Shield from the south. The Boreal Shield ecozone gently slopes to the northwest, with numerous small and medium sized lakes in the northeast portion, and extensive wetlands in the western third of the Boreal Shield. The climate is characterized by short, cool summers and cold winters. Annual precipitation is 350-450 mm. This region has a subhumid mid-boreal ecoclimate, dominated by boreal vegetation. The landscape is covered with undulating to ridged fluvioglacial deposits and sands, and acidic till. Permafrost occurs sporadically. There are extensive esker fields to the east. Sources of water are from mostly mixed surface and groundwater sources in a complex matrix. The Taiga Shield area to the north is characterized as upland elevations dominated by bedrock exposures with discontinuous veneers of sandy till, and lowlands covered by level to gently undulating organic deposits. The drainage in this region contains numerous small lakes, often linked by fast-flowing streams. The mean annual precipitation ranges from 200-375 mm in this region of the drainage. Vegetation is characterized by medium to tall, closed stands of trembling aspen and balsam poplar with white spruce, balsam fir, and black spruce occurring in late successional stages. Poorly drained fens and bogs are covered with low, open stands of tamarack and black spruce and have localized permafrost. Strongly glaciated rock outcrops are common. Permafrost is sporadic and discontinuous. The source of water is primarily surface run off.

Great Slave Lake – Taiga Shield
The East Arm of Great Slave Lake and the eastern drainage into that lake are in the Taiga Shield ecozone. The area is marked by cool summers and very cold winters, and has a subhumid, high boreal ecoclimate. The mean annual precipitation ranges from 200-375 mm. Vegetation is characterized by medium to tall, closed stands of trembling aspen and balsam poplar with white spruce, balsam fir, and black spruce occurring in late successional stages. Poorly drained fens and bogs are covered with low, open stands of tamarack and black spruce, and have localized permafrost. North of the East Arm Hills,

ridged to hummocky crystalline bedrock forms broad, steeply sloping terrain. The East Arm Hills, formed of down-faulted and folded, differentially eroded sediments and gabbro sills, dip southerly, forming broad cuestas as much as 275 m above Great Slave Lake, the surface of which is about 150 m above sea level in elevation. The intervening valleys are flooded by arms of Great Slave Lake and other lakes. Upland elevations are dominated by bedrock exposures with discontinuous veneers of sandy till, whereas the lowlands are covered by level to gently undulating organic deposits. The area contains numerous small lakes, often linked by fast-flowing streams that eventually drain into Great Slave Lake. Strongly glaciated rock outcrops are common. There are numerous esker fields to the east. Permafrost is extensive and discontinuous with low ice content and sparse ice wedges throughout most of the area. Sources of water are surface drainage and lake and wetland storage.

Great Bear Lake – Taiga Shield
The McTavis Arm of Great Bear Lake and surrounding drainage is in the Taiga Shield ecozone. This region has a high subarctic ecoclimate, and is part of the Boreal forest/tundra transition and the northern limits of tree growth. The mean annual precipitation ranges from 200-300 mm. The surface is typical of the bare rock parts of the Shield. Numerous lakes fill the lowlands, and rounded rocky hills reach 490 m in elevation. The soils have formed on discontinuous veneers and blankets of hummocky to rolling, sandy morainal, fluvioglacial, and organic deposits. Permafrost is extensive discontinuous with low to moderate ice content and sparse ice wedges. Sources of water are surface runoff and wetland and lake storage.

Mackenzie River Delta
The Mackenzie River and the Peel River join to make the largest river delta in Canada, with an active area of over 12,000 km^2, making this one of the largest river deltas in the world. The delta is a complex area of peat-covered deltas and fluvial marine deposits, with a remarkable number of lakes and channels dispersed among three major channels. The delta lies within a high subarctic ecoclimate. Wetlands extend over 50% of the delta and are characteristically polygonal peat plateau bogs with ribbed fens. The upper 30 m of sediment are younger than 5,000 years old due to the 120 million tons of sediment that are deposited annually. There are many "perched" lakes which are not directly connected to the river, but are connected during high flows or through groundwater. Extensive discontinuous permafrost with low to medium ice content is prevalent throughout most of the delta characterized by sparse ice wedges. The most northern and eastern portions of the delta are in the Southern Arctic ecozone. This portion of the outer delta is underlain with continuous permafrost with high ice content in the forms of ice wedges and pingos, which are unique characteristics of this landscape. There are extensive areas of mixed surface and groundwater and groundwater sources.

Appendix III – Review process of first draft of the freshwater classification

In November of 2007, a 2-day workshop was held in Yellowknife to convene experts to assess the work that had been undertaken by the PAS Science Team and contractors Round River over the course of the previous year to create a first draft of a freshwater classification for the Mackenzie River Basin and adjacent drainages of the Queen Elizabeth Basin. Discussions focused on whether or not appropriate variables had been chosen and appropriate measures had been calculated and if not, what changes needed to be made, how to simplify datasets, for which variables local versus accumulated processing should be applied and which thresholds should be used for dominance of variables.

Comprehensive notes were recorded at the workshop and expert advice to improve the classification was considered. Some suggestions could not be incorporated due to data limitations. However, where available data allowed, expert advice was incorporated into the revision of the classification.

Individual reviews

In order to accommodate all those who wished to provide feedback but could not attend the workshop, the PAS Science Team conducted many one on one conference calls, email sessions and provided a "Reviewer's Guide" full of maps, methods and questions as a framework to structure feedback. Nearly 75 people from across Canada, from non-government organizations, universities and government agencies provided comments. We are thankful to those below for providing their expert input.

Al Von Fister
Chris Spence
Peter Brunette
Alejandra Duk-Rodkin
Dirk De Boir
Richard Fernandez – EC
Carol Ann Duschene
Barrie Bonsal – EC
Dave Downing
Paul Wozniak – GSC
Mike Heiner - TNC
Kristy Ciruna - NCC
Dr. Feiyue Wang – U of Manitoba
Rick Tingey

Freshwater expert input

Key experts were also brought in at various points of the project to inject their expertise. The individuals doing most of the technical work for the PAS Science Team on the project did not have the background in freshwater science and classifications necessary to make the product as useful as possible.

Kristy Ciruna dedicated her time and knowledge early in the project to help get the project started. She received a new position and was not able to stay as engaged but her input was crucial in getting the classification started.

Jonathan Higgins was instrumental in providing feedback and direction in completing the classification by bringing his experience of creating and using classifications in various instances and geographies.
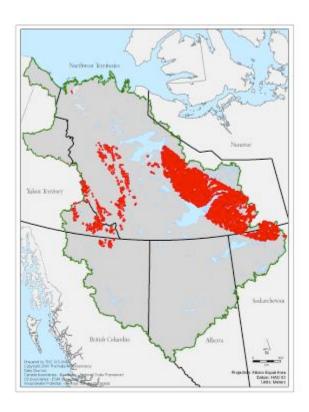
Appendix IV – Freshwater Class Descriptions

Ten most common classes

1.

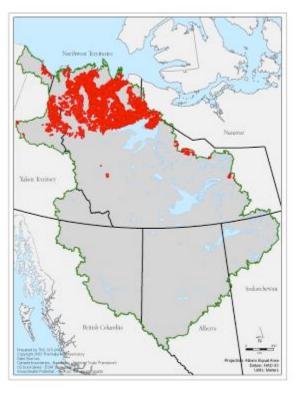| Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Extensive Discontinuous 50-90%	Surface	No	No	No	A

5889 catchments in the Basin, 5242 in NWT

These ecosystems are generally in the central portion of the basin on shield bedrock or other bedrock with thin glacial deposits or developed soils, and hence have little to no opportunity for groundwater inputs. Streams are not part of a well defined river network. With the extensive permafrost, thin till, and no down-cut stream valleys, streams tend to be shallow on exposed bedrock or on permafrost with little sand or gravel in the channel on bedrock. They can have flashy hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of muskegs. These streams tend to freeze in winter.

2.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Continuous 90-100%	Surface and Ground	No	No	No	A

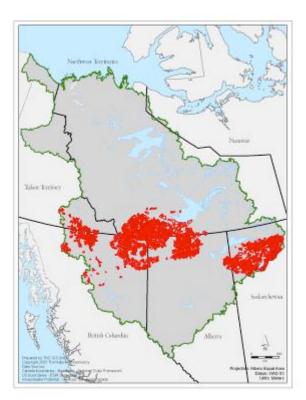5630 catchments in the Basin, 5406 in NWT

These ecosystems are found in the northern portion of the Mackenzie River Basin. Stream channels can be well defined in higher gradient areas, but the local extent and degree of ice content of the permafrost will affect the degree of down-cutting locally. The thick till provides sources of sand and gravel substrates and opportunities for local sources of groundwater. Continuous permafrost limits groundwater dynamics, but can contribute to spring flows as the active layer of permafrost melts in the spring, and can provide "groundwater" seepage to streams from the saturated active permafrost layer. Local extensive groundwater discharge can provide year round flow, but these small systems tend to freeze during the winter. Spring melt waters tend to flood extensive areas since the streams are shallow and permafrost limits the absorption and retention of water. The channel morphology ranges from defined channels to beaded channels, to not well defined channels depending on local permafrost and vegetation conditions.

3.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Sproadic Discontinuous 0-50%	Surface and Ground	No	No	No	A

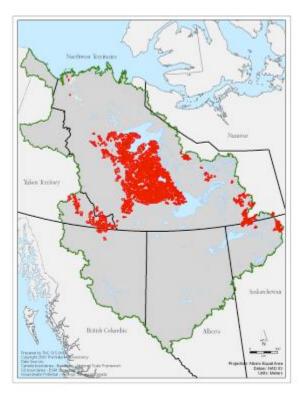4085 catchments in the Basin, 1017 in NWT

These ecosystems are in regions with thick glacial deposits and developed soils. Stream channels can be well defined, but the local extent and degree of ice content of the permafrost will affect the degree of down-cutting locally. The thick till provides opportunities for local sources of groundwater, resulting in a more stable hydrologic regime than surface dominated systems without lakes. However, the extent of permafrost affects this dynamic as well. Thick till provides sources of gravel and sand for stream channel beds. Local extensive groundwater discharge can provide year round flow during the winter, but these small systems tend to freeze during the winter. The channel morphology ranges from defined channels to beaded channels, to not well defined channel depending on local permafrost and vegetation conditions.

4.

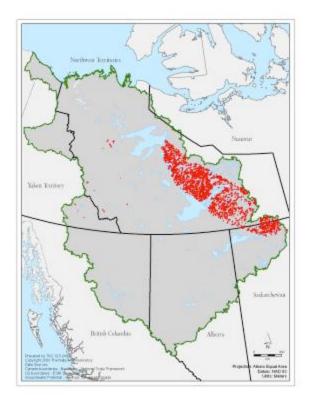| Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Extensive Discontinuous 50-90%	Surface and Ground	No	No	No	A

3783 catchments in the Basin, 3487 in NWT

These ecosystems are in regions with thick glacial deposits and developed soils. Drainage networks are well defined and there can be down-cut stream valleys, but permafrost will affect the degree of down-cutting. The thick till provides opportunities for local sources of groundwater, resulting in a more stable hydrologic regime than surface dominated systems without lakes. Thick till also provides sources of gravel and sand for stream channel beds. These ecosystems can flow throughout the year in places where permafrost is not well developed depending on the proportion of flow from groundwater sources. During summer melt, the saturated active layer of permafrost provides "groundwater" seepage. The channel morphology ranges from defined channels to beaded channels, to not well defined channel depending on local permafrost and vegetation conditions.

5.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Extensive Discontinuous 50-90%	Surface	Yes	No	No	A

3561 catchments in the Basin, 3176 in NWT

These ecosystems are mostly in the eastern portion of the basin with thin glacial deposits or exposed bedrock and hence have little to no opportunity for groundwater inputs. Streams are often primarily connections among lakes and are not part of a well defined river network. With the extensive permafrost, thin till, and no down-cut stream valleys, streams tend to be shallow on exposed bedrock or on permafrost. They have flashy hydrologic regimes that respond quickly to precipitation event, but peak flows can be dampened and low flows can be maintained at higher levels compared to non-lake dominated catchments because of potential water storage functions of lakes. These streams and shallow lakes tend to freeze in winter.

6.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Mixed	Mixed	Mixed	No	No	No	A

1946 catchments in the Basin, 999 in NWT

These ecosystems have no dominant geology, sources of water or type of permafrost, and can be quite heterogeneous. They may have local areas of well defined river channels, groundwater sources, and sand and gravel substrates, while being surface dominated, on bedrock and poorly defined channels in other portions of the same catchment. They can be catchments on physiographic and climatic transition zones, representing gradients of landform, geology and climate. The channel morphology ranges from defined channels to beaded channels, to not well defined channel depending on local permafrost and vegetation conditions.

7.

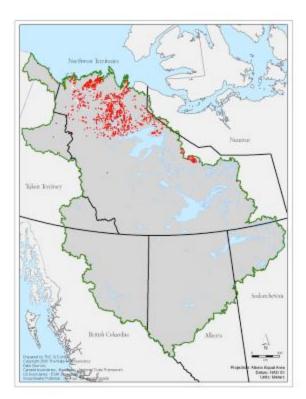| Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Continuous 90-100%	Surface and Ground	Yes	No	No	A

1488 catchments in the Basin, 1471 in NWT

These ecosystems are in the northern portion of the basin on thick glacial deposits in permafrost. Streams are often primarily connections among lakes and are not part of a well defined river network. Continuous permafrost limits stream channel down-cutting, and streams tend to be shallow with sand and gravel substrates from till materials, but can be deep below the outlets of lakes that provide sufficient flow. They have flashy hydrologic regimes that respond quickly to precipitation event and spring melt of the active permafrost layer, but peak flows can be dampened and low flows can be maintained at higher levels compared to non-lake dominated catchments because of the wat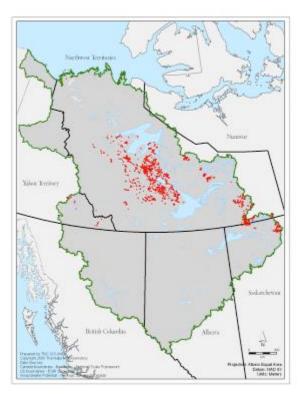er storage functions of lakes. These streams and shallow lakes tend to freeze in winter. Spring melt waters tend to flood extensive areas since the streams and lakes are shallow and permafrost limits the absorption and retention of water. The saturated active permafrost layer provides "groundwater" seepage during the summer. The channel morphology ranges from defined channels to beaded channels,

to not well defined channel depending on local permafrost and vegetation conditions, and the contribution of flow from lakes.

8.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Extensive Discontinuous 50-90%	Surface and Ground	Yes	No	No	A

1313 catchments in the Basin, 1214 in NWT

These ecosystems are mainly in the central portion of the Basin on thick glacial deposits and discontinuous permafrost. Streams are often primarily connections among lakes and are not part of a well defined river network. Locally extensive permafrost limits stream channel down-cutting, although streams with sufficient flow from lake outlets can be deeper. Streams tend to be shallow with sand and gravel substrates from till materials. They have flashy hydrologic regimes that respond quickly to precipitation event and spring melt of the active permafrost layer, but peak flows can be dampened and low flows can be maintained at higher levels compared to non-lake dominated catchments because of the water storage functions of lakes. Local extensive groundwater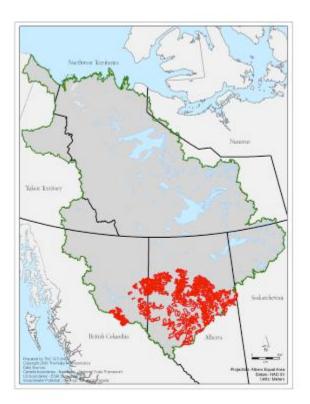 discharge can provide year round flow and the generation of aufice during the winter, but these small streams and lakes tend to freeze during the winter. Spring melt waters tend to flood extensive areas since the streams and lakes are shallow and permafrost limits the absorption and retention of water. The

channel morphology ranges from defined channels to beaded channels, to not well defined channel depending on local permafrost and vegetation conditions and the contribution of flow from lakes.

9.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	No permafrost	Surface and Ground	No	No	No	A

1280 catchments in the Basin, 0 in NWT

These ecosystems are in the southern portion of the basin on thick glacial deposits and well developed soils. Stream channels tend to be well defined with sand and gravel substrates. Local groundwater inputs vary in their contribution to flow and can provide stability to base flow and temperatures during the summer. Base flow levels depend on the degree of groundwater contributions which determine whether the smaller creaks flow year round.

10.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Sproadic Discontinuous 0-50%	Surface	No	No	No	A

1223 catchments in the Basin, 181 in NWT

These ecosystems occur in the southern portion of the Basin on thin glacial deposits. Streams can down-cut into till and contain sand and gravel substrates, but often reach bedrock and have wide channels with shallow habitats. These systems are flashy, driven by spring snow melt, and summer and fall precipitation events. They tend to freeze during the winter and can stop flowing during the summer depending on the degree of snow pack and precipitation events.

Top 8 classes remaining in the NWT

1.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Continuous 90-100%	Surface	No	No	No	A

1504 catchments in the Basin, 1427 in NWT

These ecosystems are located in the central/northeastern and in the central/northwestern portions of the basin where there are thin glacial deposits and poorly developed soils. Streams tend to not be part of a well defined river network unless down cut into the permafrost. Streams tend to be shallow on exposed bedrock or on permafrost with defined channel morphology dependent on local permafrost and vegetation conditions. They can have flashy hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of muskegs. These streams tend to freeze in winter.

2.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Continuous 90-100%	Surface	Yes	No	No	A

1025 catchments in the Basin, 1015 in NWT

These ecosystems are located in the central/northeastern and to a lesser extent in the northwestern portions of the basin where there is thin glacial deposits and poorly developed soils. Streams tend to not be part of a well defined river network and provide linkages to numerous lakes, with more defined river networks where they flow from lakes to larger river systems. Streams tend to be shallow on exposed bedrock or on permafrost with defined channel morphology dependent on local permafrost and vegetation conditions. Deep portions of streams can be found in beaded systems and below lake outlets where sufficient hydrologic energy can scour the stream channel. They can have flashy hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of muskegs and have tempered high flow peaks and sustained low flow conditions from lake influenced water storage. These streams tend to freeze in winter with exceptions of those below deep lakes that provide continuous flow and hence provide local winter refugia for aquatic biodiversity.

3.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Extensive Discontinuous 50-90%	Surface	No	No	No	B

698 catchments in the Basin, 641 in NWT

These ecosystems are located in the central/eastern and central/western portions of the basin where there is thin glacial deposits and poorly developed soils. Streams tend to be more down cut into permafrost than small catchments with channel morphology dependent on local permafrost and vegetation conditions. They have flashy hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of muskegs. They tend to have significant seepage from permafrost during the summer which provides base flow. These streams tend to freeze in winter.

4.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv + R)	Continuous 90-100%	Mixed	No	No	No	A

614 catchments in the Basin, 601 in NWT

These ecosystems are located predominantly and irregularly, mostly in the far northeastern portion of the basin where there are predominantly thin glacial deposits and poorly developed soils but also sporadic local groundwater potential. Streams tend to be shallow on exposed bedrock or on permafrost with defined channel morphology dependent on local permafrost, vegetation and groundwater conditions. They have a variety of hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of summer melt of permafrost and from muskegs, and groundwater contributions which provide relatively elevated base flows during the summer and local flows during the winter. They tend to have significant seepage from permafrost during the summer which provides base flow. These streams tend to freeze in winter where there is no groundwater recharge, but provide winter refugia for aquatic biodiversity where there is sufficient ground water.

5.

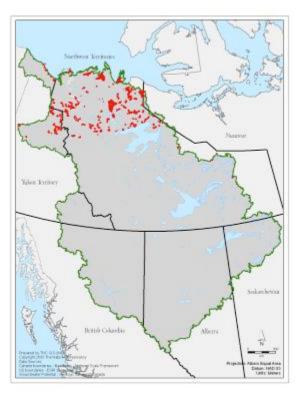| Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Continuous 90-100%	Mixed	No	No	No	A

551 catchments in the Basin, 514 in NWT

These ecosystems are located the far northern portion of the basin where there are thick glacial deposits and sporadic local groundwater potential. Streams tend to be shallow on permafrost with channel morphology dependent on local permafrost, vegetation and groundwater conditions. The thick till provides opportunities for deeper, well defined channels and ground water contributions. They have a variety of hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of summer melt of permafrost and from muskegs, and groundwater contributions which provide relatively elevated base flows during the summer and local flows during the winter. They tend to have significant seepage from permafrost during the summer which provides base flow. These streams tend to freeze in winter where there is no groundwater recharge, but provide winter refugia for aquatic biodiversity where there is sufficient ground water.

6.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Veneer (Tv +R)	Extensive Discontinuous 50-90%	Surface	Yes	No	No	B

494 catchments in the Basin, 467 in NWT

These ecosystems are located in the northeastern portion of the basin where there is thin glacial deposits and poorly developed soils. Streams tend to be shallow on exposed bedrock and permafrost with channel morphology dependent on local permafrost and vegetation conditions. They have flashy hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of muskegs. They tend to have significant seepage from permafrost during the summer which provides base flow but peak flows can be dampened and low flows can be maintained at higher levels compared to non-lake dominated catchments because of the water storage functions of lakes. These streams tend to freeze in winter.

7.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Mixed	Mixed	Surface	Yes	No	No	A

510 catchments in the Basin, 389 in NWT

These ecosystems are located mostly in the northeastern portion of the basin. Their catchments are heterogeneous, representing transition zones for geology, sources of water and permafrost. Such heterogeneity results in a variety of local stream morphology, hydrologic characteristics, and connectivity patterns to lakes and other streams.

8.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Glaciofluvial Plain (Gp + Gx)	Continuous 90-100%	Mixed	No	No	No	A

400 catchments in the Basin, 387 in NWT

These ecosystems are located in the northern portion of the basin on coarse sand and gravel outwash plains, valley trains, and terraces generated by rivers that drained glaciers that existed in this region in the past. Streams tend to be shallow on permafrost with channel morphology dependent on local permafrost, vegetation and groundwater conditions, with coarse gravels and sand substrates. They have a variety of hydrologic regimes that respond quickly to precipitation events, but can also be controlled by seepage of summer melt of permafrost and groundwater contributions through extensive coarse surficial deposits, which provide relatively elevated base flows during the summer and potential for local flows during the winter. These streams tend to freeze in winter where there is no groundwater recharge, but provide winter refugia for aquatic biodiversity where there is sufficient ground water.

Larger Size Classes

Focusing only on the most common classes is not a valid way to describe the variety of classes that were created in the classification. One large sector missed is larger size classes as these are less common in the basin but still play a vital role in the system. The Mackenzie River itself falls in a large size class due to the large accumulation of flow into that stream. Below are descriptions that include larger size classes, with a focus on those occurring in the NWT since this is the area of interest to the PAS.

1.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Alluvial Deposits (A)	Extensive Discontinuous 50-90%	Surface	No	No	No	D

349 catchments in the Basin, 349 in NWT

This is the Mackenzie River delta ecosystem located at the northern portion and outlet of the river. This is a constantly changing diverse landscape of migrating mainstem, tributary and distributary braided river channels, floodplains, numerous shallow small ponds and lakes (> 49,000), and islands determined by patterns of sediment deposition (120 million tons annually), ice and water scouring, and permafrost melting from hydrologic forces. The surficial geology is predominantly deposited silts, sands, clays and gravel, often on top of glacio-fluvial materials. The storage capacity of lakes and floodplains after flooding is approximately 47% of the high flow discharge of the Mackenzie River after ice break-up (Emmerton et al. 2006). The arctic nival hydrologic regime of the mainstem river at this point is determined by the precipitation patterns of the entire catchment. There is a great variety of local elevation, geology, permafrost and vegetation

conditions resulting in lakes, ponds, streams and wetlands in close proximity with distinct hydrologic, water quality and habitat characteristics. The mainstem river is shallow and sinuous with a high slit load, and is free-flowing and navigable 5 months of the year. This dynamic, large river delta is critical breeding, rearing and migratory habitat for numerous aquatic, avian and near shore marine species.

2.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Fine grained (Glacio)Lacustrine (fL + mM)	Mixed	Surface	No	No	No	D

26 catchments in the Basin, 26 in NWT

These ecosystems are associated with the mainstem Mackenzie River and occur on fine-grained silt and mud deposited at the bottom of still water lakes and lateral riverine habitats formed by glacial melt waters and by current sediment deposition. They are very low gradient, shallow, turbid ecosystems with soft substrates that are flashy in response to precipitation events. These ecosystems freeze during the winter.

3.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Continuous 90-100%	Surface and Ground	No	No	No	C

87 catchments in the Basin, 87 in NWT

These ecosystems are predominantly the mainstems of the major tributaries that join the Mackenzie River near its northern terminus. The hydrologic regimes of these rivers are determined by the conditions in their catchments. These rivers have sporadic sources of groundwater determined by local glacial till and permafrost conditions, which can provide winter refugia for aquatic biodiversity and generate aufice if groundwater is sufficient. These rivers tend to be shallow and sinuous, but local surficial geology, permafrost and vegetation conditions influence channel and valley morphology.

4.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Alpine Complexes (Ra)	Continuous 90-100%	Surface	No	No	No	C

16 catchments in the Basin, 16 in NWT

This ecosystem type is the portion of the Keele River mainstem flowing through the Taiga Cordillera. This landscape is dominated by alpine complex of rock, colluvium, and glacial till in alpine and glacial landforms. This region receives over 600mm of precipitation annually, resulting in significant flows and hydrologic energy that can down cut through till and permafrost resulting in a well defined river valley. The overall hydrologic regime of the river is determined by its catchment at this point.

Rare and Unique Classes

It is important to examine classes that occur less frequently in the classification as well. The PAS Science Team identified areas within the Basin that were unique due to a small number of catchments being in the class.

1.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Till Blanket (Tb)	Sproadic Discontinuous 0-50%	Surface	No	Yes	No	A

4 catchments in the Basin, 0 in NWT

These catchments are in mountainous region to the west. Their hydrologic regimes are proglacial: a very predictable annual hydrograph with high spring flows and extended, elevated summer flows, with cold water temperatures and high concentrations of sediments and suspended solids. They start as high gradient systems that are down cut into the thick glacial till, with sand and gravel substrates. These systems are unusual, with only four catchments occurring in the basin. Climate change is having a significant impact on glacier morphology and dynamics, and these ecosystems are changing rapidly and could become just surface dominated systems with no glacial influence in the future. Such changes could result in local extirpation of species and natural communities found only or primarily in these ecosystems.

2.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Glaciofluvial Plain (Gp + Gx)	Extensive Discontinuous 50-90%	Surface	No	No	Yes	B

3 catchments in the Basin, 3 in NWT

These ecosystems occur in the eastern portion of the basin in landscapes that were formed by materials deposited by rivers draining glaciers, and by eskers which are elevated sinuous mounds of debris formed in drainage channels within and under glaciers. When glaciers melt, debris such as sand and gravel which collected in the drainage channels is deposited on the landscape. Eskers are often local sources of groundwater, and they result in unique landscape characteristics. These ecosystems are composed predominantly of cobble and coarse sand substrates often with complex and extensive hyporheic zones with numerous benthic biota. While the catchments are dominated by surface sources of water and tend to have flashy hydrologic regimes, eskers and sub-surface coarse deposits provide local sources of groundwater and potential winter refugia for aquatic biodiversity, depending on the depth and volume of groundwater inputs.

3.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Coarse grained (Glacio)Lacustrine (sL + cL)	Mixed	Groundwater	No	No	Yes	A

16 catchments in the Basin, 14 in NWT

These ecosystems are on silt, coarse sands and gravel deposited as deltas and sheet sands from glacial outwash. These systems are low gradient with coarse substrates often with complex and extensive hyporheic zones with numerous benthic biota. They are groundwater dominated due to the permeability of the surficial deposits in their catchments. Their hydrologic regimes are relatively stable and can provide winter refugia for aquatic biodiversity depending on the depth amount of groundwater contributions to flow.

4.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Organic Deposits (O)	Continuous 90-100%	Surface	No	No	No	A

73 catchments in the Basin, 69 in NWT

These ecosystems are located in the northwestern portion of the basin on organic materials and permafrost in the Cordillera/Taiga plains landscapes. Organic deposits are generally expressed aquatically as peatlands and muskegs – wetland with high organic content that is broken down over long periods of time and can extend down to 100 feet, has high acidity, and can be stained from tannins. Streams associated with these areas can be narrow and deep, with gravel, sand or cobble substrates depending on local geology, permafrost and vegetation conditions. While sources of water are surface dominated, seepage from muskegs can provide significant base flows during the summer. These ecosystems represent catchments with the highest proportion of area of muskegs in the Mackenzie River Basin. These systems freeze during the winter.

5.

Dominant Surficial Geology	Dominant Permafrost	Dominant Source of water	Dominated by Lakes?	Glacially Influenced?	Dominated by Eskers?	Size Class
Colluvial Blocks (rCfCbCsC)	Extensive Discontinuous 50-90%	Surface	No	No	Yes	C

11 catchments in the Basin, 10 in NWT

These ecosystems are mostly associated with the North and South Nahanni Rivers located in the eastern edge of the Cordillera in the west/central portion of the Mackenzie River basin. Colluvial blocks are chunks of solid or consolidated aggregates that fall into a river channel from mass wasting erosion at the edge of slopes. They can determine the local river channel direction and morphology depending on their scope. These ecosystems are flashy because of their surface dominated catchment. Large rivers with extensive colluvial blocks are uncommon in the Mackenzie River Basin, and represent a physical landscape that is uncommon.