Sensitivity of Dempster Highway Hydrological Response to Climate Warming

Final Report

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Executive Summary

Observations confirm that the climate of northern regions has become warmer and wetter over the last three decades resulting in degrading permafrost and changing vegetation. Studies have shown that climate change has already produced alterations to the hydrological cycle and hydrologic response with greater flooding and a general negative impact on transportation and community infrastructure. The project components include a detailed sensitivity assessment of hydrological response to climate warming and associated permafrost thawing using the Cold Regions Hydrological Model (CRHM) along the Dempster Highway corridor. CRHM is a modular numerical modelling system created from recent process based research, including state of the art work carried out in Yukon's Wolf Creek Research Basin. The model contains a full suite of cold regions hydrological modules including, snow, frozen soils, permafrost thaw and runoff and is capable of assessing not only climate change but vegetation change and permafrost thaw impacts. CRHM has already been widely used for climate and land-use change studies in Yukon, NWT, Canadian Rockies, US Rockies, Prairies, Tibetan Plateau, Patagonia, the Pyrenees and the Alps. Using a range of climate change scenarios, assessments were carried out within the eight ecoregions which the Dempster Highway traverses. Since representative Dempster Highway climatological data is sparse, two comprehensive meteorological/precipitation stations were designed, built and placed along the Dempster corridor to supplement existing data. In addition the project took advantage of numerical weather model reanalysis and climate model output datasets made available through participation in the NSERC Changing Cold Regions Network (CCRN). Study objectives include a better quantification of the magnitude, timing and interaction of water balance components (precipitation, evapotranspiration, runoff and storage). Projected changes to hydrological response of extreme events have been summarized and flood frequency curves based on annual peak flows have been developed for Dempster Highway stream crossings. These products will allow for the development of adaptation strategies and options which may include infrastructure design modification.

The multi-year study commenced November 1, 2013 and ended March 31, 2016. This report is the final report for the project. Research results from activities carried out during this period are summarized below.

INTRODUCTION

The Dempster Highways traverses 736 kilometres and crosses 231 streams between the Dempster corner at the Klondike Highway junction, Yukon and Inuvik, NWT. The project components include a detailed sensitivity assessment of hydrological response to climate warming and associated permafrost thawing using the Cold Regions Hydrological Model (CRHM) along the Dempster Highway corridor. CRHM is a numerical modelling system created from recent process based research, including state of the art work carried out in Yukon's Wolf Creek Research Basin. The model contains a full suite of cold regions hydrological modules including, snow, frozen soils, permafrost thaw and runoff and is capable of assessing not only climate change but vegetation change and permafrost thaw impacts. CRHM has already been widely used for climate and land-use change studies in Yukon, NWT, Canadian Rockies, US Rockies, Prairies, Tibetan Plateau, Patagonia, the Pyrenees and the Alps. Using a range of climate change scenarios, assessments were carried out within the ten ecoregions which the Dempster Highway traverses. Since representative Dempster Highway climatological data is sparse, two meteorological stations were established to supplement existing data.

In addition the project took advantage of numerical weather model reanalysis and climate model output datasets made available through participation in the NSERC Changing Cold Regions Network (CCRN). Study objectives include a better quantification of the magnitude, timing and interaction of water balance components (precipitation, evapotranspiration, runoff and storage). Projected changes to hydrological response of extreme events have been summarized and flood frequency curves based on annual peak flows have been developed for Dempster Highway stream crossings. These products will allow for the development of adaptation strategies and options which may include infrastructure design modification.

METHODOLOGY

Ecoregion Descriptions

The Dempster Highway passes through ten ecoregions: Klondike Plateau, Yukon Plateau – North, Mackenzie Mountains, North Ogilvie Mountains, Eagle Plains, British-Richardson Mountains, Peel River Plateau, Fort McPherson Plain, Great Bear Lake Plain, and Tuktoyaktuk Coastal Plain between the Dempster Corner and Inuvik (Figure 1). A summary of the main characteristics of each ecoregion according to the description presented in Smith et al. (2004) for the Yukon Territory and the Ecosystem Classification Group (2007) for the Northwest Territories is presented.

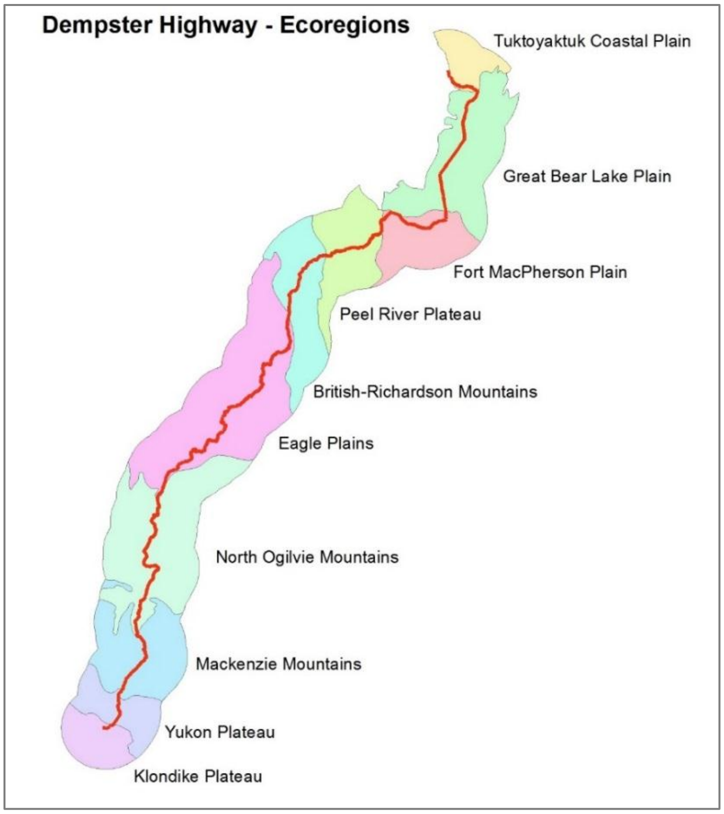

Figure 1: Dempster Highway ecoregions

Klondike Plateau (KP): Land cover consists of boreal coniferous forest (60%), mixed forest (15%), alpine tundra (20%), lakes and wetlands (5%). This ecoregion marks the northern limit of lodgepole pine in North America. The climate is strongly continental with mean annual temperatures around -5°C. Precipitation is lightest from February to April with annual mean precipitation ranging from 300 to 500 mm. Elevation ranges from 290 to 2000 m asl with an average of 850 meters on the plateau. Permafrost is discontinuous but extensive throughout the ecoregion.

Yukon Plateau-North (YPN): The largest ecoregion entirely within the Yukon at 57,091 km^2 is composed of boreal/subalpine coniferous forest (75%) and alpine tundra (20%) with some lakes and wetlands (5%). Mean annual temperatures in the YPN ecoregion are near -5°C with strong seasonal variability accentuated by differences in elevation. Annual precipitation ranges from 300 to 600 mm, with the wettest period during July and August. Winds are generally low. Permafrost is discontinuous in the YPN, primarily controlled by microclimatic factors (e.g. ground surface moisture and organic-layer thickness).

Mackenzie Mountains (MM): Land cover is dominated by subarctic coniferous forest (50%), followed by rocklands (30%) and arctic/alpine tundra (20%). The topography of this ecoregion is generally between 750 and 1,500 meters above sea level (m asl) with the Ogilvie Mountains reaching above 2,100 meters. The mountains produce a barrier effect to the air masses moving inland from the Gulf of Alaska, resulting in an intense wet belt along the southern slopes. Mean annual temperatures are around -6°C. Mean annual precipitation is highly variable, ranging from

450 to greater than 600 mm. Precipitation peaks are typically in July and August with 50 to 70 mm in a month. Summer precipitation can fall as snow, particularly at higher elevations. Permafrost is found throughout the ecoregion at higher elevations and is continuous in most of the Yukon portion of the ecoregion.

North Ogilvie Mountains (NOM): Land cover is made up of subarctic coniferous forest (50%), arctic/alpine tundra (25%), rocklands (20%), lakes and wetlands (5%). NOM elevations are typically between 900 and 1,350 m asl and the terrain is mostly flat-topped hills with a few higher mountain summits. Mean annual temperatures range from -7 to -10°C and mean annual precipitation ranges from 300 to 450 mm, with considerable variation in both variables based on elevation. This ecoregion is completely underlain by permafrost, with the exception of southern portions of the region close to watercourses, including areas along the Dempster Highway.

Eagle Plains (EP): Land cover in this ecoregion is subarctic coniferous forest (90%) with some mixed forest (5%) and arctic/alpine tundra (5%). Most of the elevations are between 300 and 600 m asl. Mean annual temperatures are near -7.5°C with a strong seasonality; summer means around 13°C and winter means around -25°C. Mean annual precipitation is near 400 mm with most precipitation falling in summer during showers and thunderstorms. EP ecoregion is underlain by continuous permafrost.

British-Richardson (BR): Land cover consists of alpine/subarctic tundra (65%), subarctic coniferous forest (20%) and rocklands (15%) and is strongly influenced by aspect and elevation. Elevation ranges from 40 to 1,610 m asl with relief in the mountain ranges between 450 and 900 meters. Mean annual temperatures are around -7.5°C and the mean annual precipitation ranges from 250 to 400 mm with the heaviest precipitation occurring between June and August. There are frequent occurrences of strong to gale-force winds through depressions in the ecoregion. Permafrost is continuous.

Peel River Plateau (PRP): Land cover is made up of subarctic coniferous and mixed forest (75%) with transition zones between forest and tundra (10%), alpine tundra (10%), and numerous small lakes and wetlands scattered over the plateau (5%). Elevations vary between 45 and 1470 m asl with ridges and hills commonly around 750 meters and mountain peaks between 1000 and 1400 meters. Mean annual temperatures are near -8°C and mean annual precipitation is around 300 mm. Permafrost is continuous throughout the ecoregion.

Fort McPherson Plain (FMP): Land cover is dominated by subarctic coniferous and mixed forest (85%), followed by small lakes and non-treed wetlands (15%). It is a low elevation ecoregion generally sloping northeast with an elevation of just over 440 m asl in the south to approximately 35 m in the north. Mean annual temperatures are near -8°C and mean annual precipitation is around 300 mm. The FMP ecoregion is in the continuous permafrost zone.

Great Bear Lake Plain (GBLP): The GBLP ecoregion of Northwest Territories is located within the Campbell Hills High Subarctic (HS) ecoregion according to the Ecosystem Classification Group Report (2007). Land cover is variable between coniferous and mixed forest and tundra with lakes, bogs and fens. Topography in the ecoregion ranges from 25 to 350 m asl. Mean annual temperatures are around -9°C and mean annual precipitation ranges from 200 to 300 mm. Permafrost is extensive and discontinuous.

Tuktoyaktuk Coastal Plain (TCP): The TCP ecoregion covers the Mackenzie River delta and is located within the Sitidgi Plain HS of Northwest Territories according to the Ecosystem Classification Group. Land cover consists of sparsely treed coniferous forest and tundra with lakes, bogs and fens. Elevation ranges from 0 to 200 m asl with an average of 50 meters. Mean annual temperature is around -11°C with a summer mean of 5°C and a winter mean of -26°C. Permafrost is continuous in the ecoregion.

Ecoregion Physical Characteristics and Hydrometeorological Station Metadata

Since an ecosystem approach was used for the project, a database of physical, meteorological and hydrological characteristics of the ten Dempster Highway ecoregions was developed. Existing digital elevation data was used to extract physical landscape parameters which included sub-catchment area, aspect, slope, and vegetation classification. A database of all existing climatological data within the study area, including data from the existing and historical meteorological stations was also developed. Similarly, a hydrological database of all active and historical hydrometric stations within the study area was also developed.

Table 1 provides a summary of the land cover characteristics and meteorological station elevation and metadata parameters for the ten study ecoregions. There are a number of historical and active meteorological stations within the study region; however, the majority of these have very short periods of record.

Table 1: Ecoregion land cover characteristics and meteorological station and metadata

Ecozone	km Post	Station Name	EOSD Land Cover	Elevation	Data Source	Active?	Period of Record	Air Temp	Relative Humidity	Wind Speed	Incoming SW Rad	Snow Depth	Precip
Klondike Plateau	-	Dawson A	Low Shrub	370	MSC	yes	76-	H 76-13	H 76-13	H 76-13		D 76-13	D 76-07 TyB&Nph, D 08-13
		Dawson	Tall Shrub		MSC	yes	95-	H 95-14	H 95-14	H 95-14		D 06-14, H 13-14	D 99-06, D 06-14 Gnr, H 13-14 Gnr
Yukon Plateau -North	yt 8	Antimony Creek	Herb	apx 537	WFM	yes	05-	H 05-13	H 05-13	H 05-13			H 05-13 TBRG
Mackenzie Mountains	yt 65	Klondike	Conif. Sparse	973	MSC	no	66-10	D 66-07				D 80-07	D 66-07
					Highways	yes	08-	D 08-14					D 08-14 (snow.cm)
	yt 71	Tombstone Interpretive Centre	Low Shrub/Herb	1034	Parks	yes	12-	H 12-14		H 12-14	H 12-14		H 12-14 PLUV
	yt 72	Tombstone Pass		1378	YCCIC-NWtel	yes	13-	H 13-14	H 13-14	H 13-14	H 13-14		
	yt ~77	North Fork Mountain	Herb/Exposed	1494	Parks	yes	12-	H 12-14		H 12-14	H 12-14		H 12-14 TBRG
North Ogilvie Mountains	yt 99	North Fork Pass	Low Shrub/Herb	1202	YCCIC-NWtel	yes	13-	H 13-14	H 13-14	H 13-14	H 13-14		
	yt 123	Chapman Lake	Low Shrub	apx 946	YTG	no	06-10	H 06-11		H 06-11			H 06-11 Rain Only
	yt 124	Permafrost Site 1	Low Shrub			yes	13-	Air temperature, Permafrost, Wind speed and direction (not in hand)					
	yt 168	Red Creek			Univ. Ott.	yes	07-	Permafrost, Lapse Studies, Basic Met (not in hand)					
	yt ~192	Engineer Creek	Exposed	1289	YCCIC-NWtel	yes	13-	H 13-14	H 13-14	H 13-14	H 13-14		
	yt 198	Ogilvie River	Variable	597	MSC	no	71-08	D 71-07				D 80-07	D 71-07
					Highways	yes	08-	D 08-14					D 08-14 (snow.cm)
Eagle Plains	yt 259	Dempster 164	Herb	apx 854	MSC	no	77-88	Fisher-Porter Precip but data has not been found in MSC archives					
	yt 282	Dempster 177	Conif. Sparse	apx 715	MSC	no	73-74	D 73-74					D 73-74
	yt 286	Dempster 179	Conif. Open	apx 683	MSC	no	77-78	D 77-78					D 77-78
	yt 324	Dempster 203	Conif. Sparse	apx 618	MSC	no	74-75	D 74-75					D 74-75
	yt 348	Ehnjuu Choo	Conif. Sparse	817	YCCIC-NWtel	yes	12-	H 12-14	H 12-14	H 12-14	H 12-14		
	yt 361	Eagle Plains	Conif. Sparse	721	WFM	yes	10-	H 10-13	H 10-13	H 10-13			H 10-13 TBRG
	yt 369	Eagle Plains	Conif. Sparse	620	MSC	no	79-08	D 79-07				D 81-07	D 79-07
					Highways	yes	08-	D 08-14					D 08-14 (snow.cm)
	yt 421	Permafrost Site 2	Low Shrub	640		yes	13-	Air temperature, Permafrost, Wind speed and direction (not in hand)					
British-Richardson Mountains	yt 456	Rock River	Herb	731	MSC	yes	74-	H 94-14	H 94-14	H 94-14			
	nt 1	North Vittrekwa	Bryoids	882	YCCIC-NWtel	yes	12-	H 12-14	H 12-14	H 12-14	H 12-14		
	nt 9	Permafrost Site 3	Herb	661		yes		Air temperature, Permafrost, Wind speed and direction (not in hand)					
Peel Plateau	nt 51	Permafrost Site 4	Herb	459		yes		Air temperature, Permafrost, Wind speed and direction (not in hand)					
Fort MacPherson Plain	nt 83	Fort McPherson	Conif. Sparse	35	MSC	no	50-77	D 50-77					D 50-77
		Fort McPherson A				yes	1892-	D 81-88, H 88-14	H 88-14	H 88-14		D 81-07	D 81-07
	nt 107	Deep Water	Conif. Open	107	YCCIC-NWtel	yes	12-	H 12-14	H 12-14	H 12-14	H 12-14		
	-	Satah River	Low Shrub	86	MSC	no	95-01	H 95-01	H 95-01	H 95-01			
Great Bear Lake Plain	nt 184	Rengleng			YCCIC-NWtel	yes	09-	Soil temperature to 10 m					
Tuktoyaktuk Coastal Plain	nt 258	Inuvik A	Conif. Sparse	68	MSC	yes	58-	H 58-13	H 58-13	H 58-13	H 60-72	D 58-05	D 57-06
	nt 260	Inuvik Climate	Tall Shrub		MSC	yes	03-	H 03-14	H 03-14	H 03-14			D 03-13 Gnr&TBRG, H13-14 Gnr&TBRG
	nt 260	Inuvik UA	Tall Shrub		MSC	no	95-07	D 95-05			H 73-04	D 95-07	D 95-07
	-	Trail Valley	Bryoids		IP3	yes	96-	H 96-06	H 96-06	H 96-06	H 96-06		H 96-06 TBRG
Mackenzie Delta	-	Aklavik A		6	MSC	yes	53-	H 53-14	H 53-14	H 53-14	H 57-60	D 55-07	D 50-07

Table 2 provides a summary of Dempster Highway and representative hydrometric stations. While there are a number of historical stations and active intermediate station in the study area, there are very few representative streams with small drainage areas typical of Dempster Highway stream crossings.

Table 2 Dempster Highway and representative hydrometric stations

Km Post	Ecoregion	Station Name	Drainage Area (km^2)	Data Source	Active?	Period of Record
yt 29	Yukon Plateau-North	Benson Creek	93	WRB	no	75-76
-	Klondike Plateau	Klondike River above Bonanza	7810	WSC	yes	65-11
-	Klondike Plateau	Hunker Creek	200	WRB	no	81-82
yt 52		Wolf Creek	175	WRB	no	75-82
yt 57		Grizzly Creek	34	WRB	no	75-82
yt 115	North Ogilvie Mountains	Blackstone River @ km 120	637	WRB	no	75-82
yt 124	North Ogilvie Mountains	Blackstone River near Chapman	1180	WSC	yes	84-11
yt 132	North Ogilvie Mountains	Cache Creek (Skinny-dip Creek)	240	WRB	no	77-82
-	Eagle Plains	Dalglish Creek	634	WRB	yes	13-
-	Eagle Plains	Peel River		WSC		
-	Eagle Plains	McParlon Creek	603	WRB	yes	13-
-	Eagle Plains	Whitestone River	6730	WSC	no	79-96
nt 178	Great Bear Lake Plain	Rengleng River	1300	WSC	yes	73-12
nt 220	Great Bear Lake Plain	Caribou Creek	590	WSC	yes	75-11
nt 244	Great Bear Lake Plain	Cabin Creek	140	WSC	no	84-96
nt 245	Great Bear Lake Plain	Campbell Creek		WSC	no	73-74
nt 260	Tuktoyaktuk Coastal Plain	Havikpak Creek	15	WSC	yes	95-11
nt 268	Tuktoyaktuk Coastal Plain	Boot Creek	28	WSC	no	81-90
-	Tuktoyaktuk Coastal Plain	Trail Valley Creek	68	WSC	yes	77-11

Table 3 provides a summary of snow survey sites along the Dempster Highway and representative ecoregion locations.

Table 3: Dempster Highway snow survey courses

Km Post	Ecoregion	Station Name	EOSD Land Cover	Elevation	Data Source	Active?	Period of Record	Data In-hand
-	Klondike Plateau	King Solomon Dome	Low Shrub	1080	WRB	yes	75-13	monthly snow depth, SWE
-	Klondike Plateau	Midnight Dome	Conif. Sparse	855	WRB	yes	75-13	monthly snow depth, SWE
yt 61		Grizzly Creek	Tall Shrub	975	WRB	yes	75-13	monthly snow depth, SWE
yt 130	North Ogilvie Mountains	Blackstone River	Conif. Sparse	920	WRB	yes	76-13	monthly snow depth, SWE
yt 193	North Ogilvie Mountains	Ogilvie River	Variable	595	WRB	yes	76-13	monthly snow depth, SWE
yt 298	Eagle Plains	Riff's Ridge	Conif. Open	650	WRB	yes	87-13	monthly snow depth, SWE
yt 368	Eagle Plains	Eagle Plains	Conif. Sparse	710	WRB	yes	83-13	monthly snow depth, SWE
yt 378	Eagle Plains	Eagle River	Tall Shrub	340	WRB	yes	83-13	monthly snow depth, SWE
nt 163	Great Bear Lake Plain	Rengleng River	Conif. Open	84	AAND	yes	83-13	monthly snow depth, SWE
nt 216	Great Bear Lake Plain	Caribou Creek	Conif. Open	76	AAND	yes	83-13	monthly snow depth, SWE

Dempster Highway Climate

The climate of the Dempster Highway is classified as subarctic continental (southern) and arctic (northern) which is characterized with relatively warm summers and cold winters (Wahl et al., 1987). Mean annual temperatures are near -5 and -11°C in the southern and northern Dempster Highway corridor respectively. In the southern corridor mean summer air temperatures range from 10 to 15°C with extremes to 30+°C. Mean winter air temperatures range from -25 to -35°C with extremes to -55°C. In the northern corridor mean summer air temperatures range from 8 to 10°C with extremes to 30°C. Mean winter air temperatures range from -24 to -32°C with extremes to -50°C only due to some heat transfer from the Arctic Ocean (Wahl, 2004). Precipitation along the corridor is variable as the mountain ranges act as barriers to air masses moving from both the Gulf of Alaska and Beaufort Sea. Annual precipitation amounts in the southern corridor range from 450 to 600 mm with approximately 65% as summer precipitation. Annual precipitation in the northern corridor is light, ranging from 125 to 200 mm with approximately 80% as summer precipitation.

Meteorological Stations

Existing Dempster Highway meteorological stations are shown (green dots) in Figure 4 with those also measuring precipitation noted in blue. Two comprehensive meteorological/precipitation stations (red dots) were established in regions where insufficient meteorological data were available. Two field tours were carried out to establish the stations. During the first tour in June, 2014 two stations were installed; one at km 152 (Windy Pass) and one at km 436 (Rio Roca) (Figure 4). Station characteristics are listed in Table 4 and illustrated in Photographs 1 and 2. Instrumentation for these stations is detailed in Table 5. Campbell Scientific CR1000 data loggers record measurements every 30 minutes except for soil moisture and temperature, which are recorded every 6 hours.

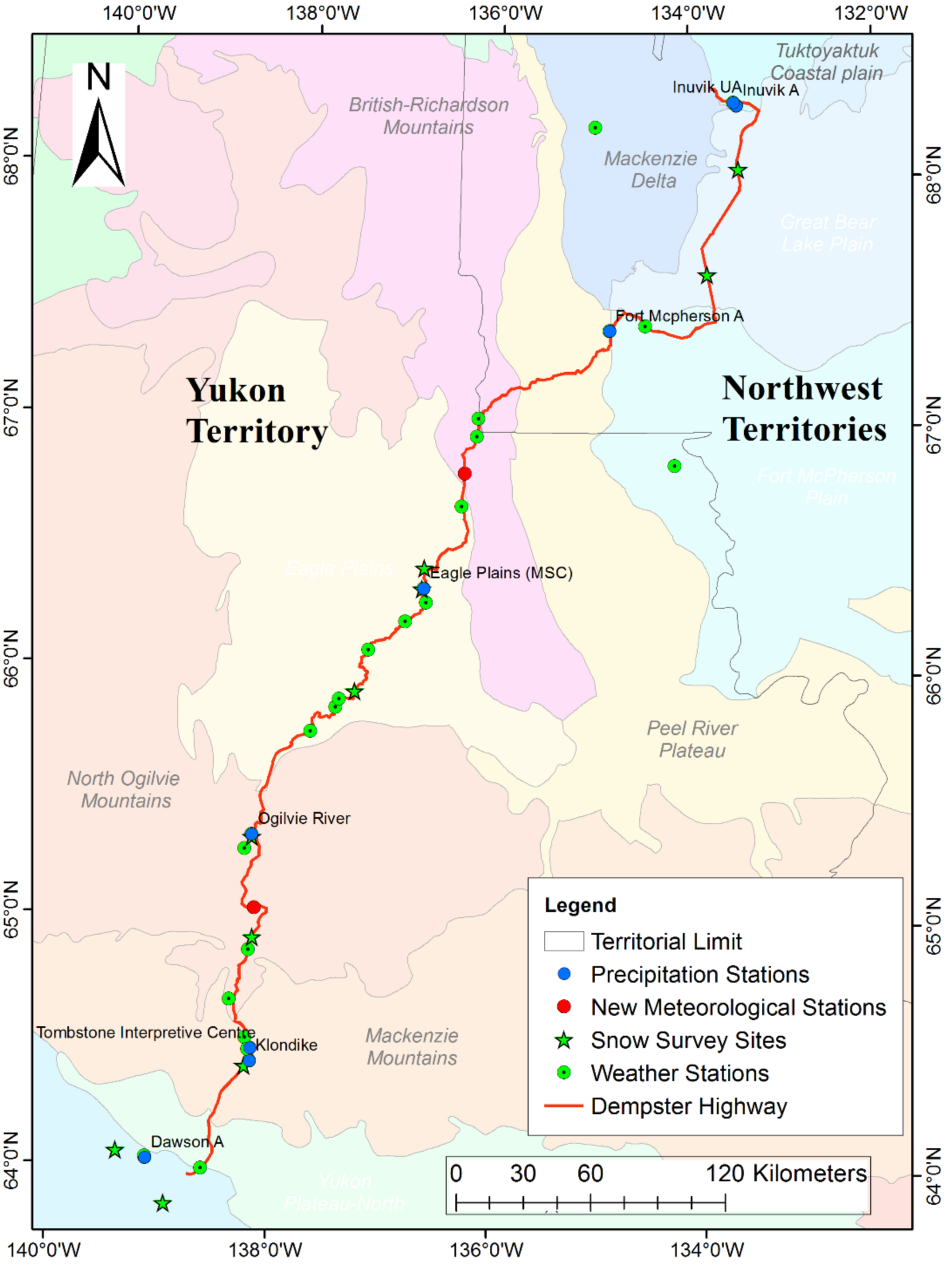

Figure 2: Hydrometeorological station locations

Table 4: Meteorological station location and landscape characteristics

Station	Geographic Coordinates	Elevation [m asl]	Slope	Vegetation
Windy Pass	65° 4’ 0.8’’ N 138° 14’ 46.1’’ W	1030	5°	Shrubs, moss and scattered spruce
Rio Roca	66° 50’ 1.0’’ N 136° 20’ 0.0’’ W	660	4°	Grasses, moss, lichen and scattered spruce and shrub

Photograph 1: Windy Pass Meteorological Station

Photograph 2: Rio Roca meteorological station

Table 5: Meteorological station instrumentation

Measurement	Manufacturer	Model	Quantity	Sensor Height [m]	
				Windy Pass	Rio Roca
Precipitation	Ott	Pluvio2	1	2	2
Air Temperature and Relative Humidity	Rotronic	HC-S3-XT	1	2.1	2.9
Outgoing and Incoming Shortwave Radiation	Apogee	SP-230	1 (each)	2.0 and 2.4, respectively	4.1 and 4.3, respectively
Wind Speed and Direction	RM Young	05108-10-L	1	4.3	5
Snow Depth	Campbell	CSI SR50A	1	2.2	2.5
Soil Heat Flux	Hukseflux	HFP01-L	1	-0.03	-0.03
Soil Moisture and Temperature	Campbell	CS655-L	4	-0.1, -0.23, -0.51, -0.91	-0.10, -0.30, -0.50, -0.76
Ground Surface Temperature	Omega	Type E Thermocouple	1	-0.01	-0.01
Snow Temperature	Omega	Type R Thermocouple	2	0.25, 0.40	0.10, 0.40

During the second field tour in early September, 2014 the stations were inspected and adjusted as necessary. Two soil pits were dug (one per station) to install the soil moisture and temperature sensors. Snow temperature thermocouples at two heights were also installed at each station. Qualitative analysis of the soil profiles from each soil pit is presented in Table 6.

Table 6: Meteorological station soil profile characteristics

Windy Pass		Rio Roca	
Depth [m]	Description	Depth [m]	Description
0 – 0.23	Organic Layer (with roots)	0 – 0.18	Organic Layer (with roots)
0.23 – 0.38	Black Soil	0.18 – 0.81	Black Soil (permafrost was likely reached)
0.38 – 1.07	Grey Mineral Soil (permafrost not reached)	-	-

Stream Crossings

Table 7 provides a summary of Dempster Highway stream crossings by ecoregion and drainage area. There are 231 stream crossings with the majority between 1 and 10 km^2, while there are only 27 with drainage areas greater than 100 km^2.

Table 7: Dempster Highway Stream Crossings

Ecoregion	Drainage Area (km^2)						
	1-10	10-25	25-50	50-100	100-200	200-500	>500
Klondike Plateau	2	0	0	0	0	0	1
Yukon Plateau	11	1	1	1	0	0	0
Mackenzie Mountains	20	4	1	1	2	0	0
North Ogilvie Mountains	38	8	5	1	2	1	3
Eagle Plains	13	3	0	1	0	1	1
British-Richardson Mountains	22	6	3	1	2	0	0
Peel River Plateau	6	0	0	0	0	0	0
Fort McPherson Plain	3	1	0	0	0	1	0
Great Bear Lake Plain	29	7	6	3	1	1	1
Tuktoyuktuk Coastal Plain	5	3	1	0	0	1	0
Fort McPherson Plain/Peel River Plateau	4	1	0	0	0	1	0
Total	**153**	**34**	**17**	**8**	**7**	**6**	**6**

Dempster Highway Streamflow Response

Hydrological response along the Dempster Highway is largely snowmelt driven with secondary summer rainfall influences. Similar to all cold regions, spring streamflow response is characterized by a rapid rise in discharge as a result of snowmelt contributions. Secondary peak flows occur during the summer months as a result of rainfall inputs, while smaller streams experience their annual peak flow as a result of intense summer.

Permafrost has a dominant control over hydrologic response in northern regions by producing short pathways to the stream channel, with little interaction with subsurface processes (Hinzman et al., 2013). A thicker active layer increases residence time and promotes a longer, slower pathway to the stream channel as compared to a more rapid response of near surface flow. Dempster Highway hydrologic response follows this principle, and is closely tied to the underlying permafrost (Janowicz, 2008). While precipitation decreases in higher latitudes, the ratio of runoff to precipitation generally increases (Kane and Yang, 2004) due to the increasing dominance of the underlying permafrost. The opposite trend generally applies to minimum winter flows, which decrease in more northerly watersheds as a result of lesser groundwater contributions due to the increasing control exerted by the underlying permafrost. In Arctic regions, only large rivers have any appreciable winter flows, while in discontinuous permafrost regions, even small streams may display extended streamflow throughout the winter due to continued groundwater contributions (Hinzman et al., 2003).

Dempster Highway Climate Change Projection

Annual, winter and summer air temperatures have increased in the Dempster Highway regions of Yukon and NWT. Precipitation trends are not consistent. Winter precipitation has generally decreased within the Dempster Highway corridor, while summer precipitation has generally increased slightly (Janowicz, 2010).

Higher winter and spring air temperatures are producing an earlier onset of spring runoff, and more rapid snowmelt events, resulting in a compressed snowmelt runoff period with higher peak flows in some regions.

The warming climate also appears to be resulting in a change in the permafrost distributions of the Dempster Highway. Permafrost warming and the associated thaw results in a thicker active layer and permafrost loss in favourable areas. In the near-term, permafrost degradation is expected to be greatest within the discontinuous permafrost zone since this permafrost class is warmer than the continuous class; therefore, more susceptible to thawing (Hinzman et al., 2005).

As permafrost properties change with climate warming, hydrologic response appears to be changing as well. Degrading permafrost increases the thickness of the active layer, decreases the overall thickness of the permafrost and in certain areas eliminates the presence of underlying permafrost entirely. These actions place a greater importance on the interaction between surface and subsurface processes. Observations of the last few decades indicate that annual mean flows have increased within continuous and discontinuous permafrost zones (Janowicz, 2008). Annual peak flows have decreased within some continuous permafrost regions, and lesser so within discontinuous regions. Winter low flows have experienced significant increases within continuous and discontinuous permafrost regions over the last three decades (Walvoord and Striegl, 2007).

Study Stream Basins

Since it is not possible to carry out hydrologic modelling for all stream crossings, select watersheds representative of the Dempster Highway ecoregions were selected for intensive analyses. Seven basins were selected for this research; these are (from north to south) Havikpak Creek, Cabin Creek, Rock River, Km 245 Creek, Cache Creek, Black Shale Creek and Morrison Creek. All basins are located in different biophysical and climate regions (ecoregions).

The location of these basins is presented in Figure 5 and physical characteristics summarized in Table 8. As can be seen from this figure, the southern five basins are located in the Yukon Territory, whereas the northernmost two are in the Northwest Territories. Latitude ranges from roughly 64 °N for Morrison Creek to 68 °N for Havikpak Creek. Digital Elevation Models (DEMs) from the ASTER-GDEM satellite (20 km resolution) for each basin are presented in Figure 6.

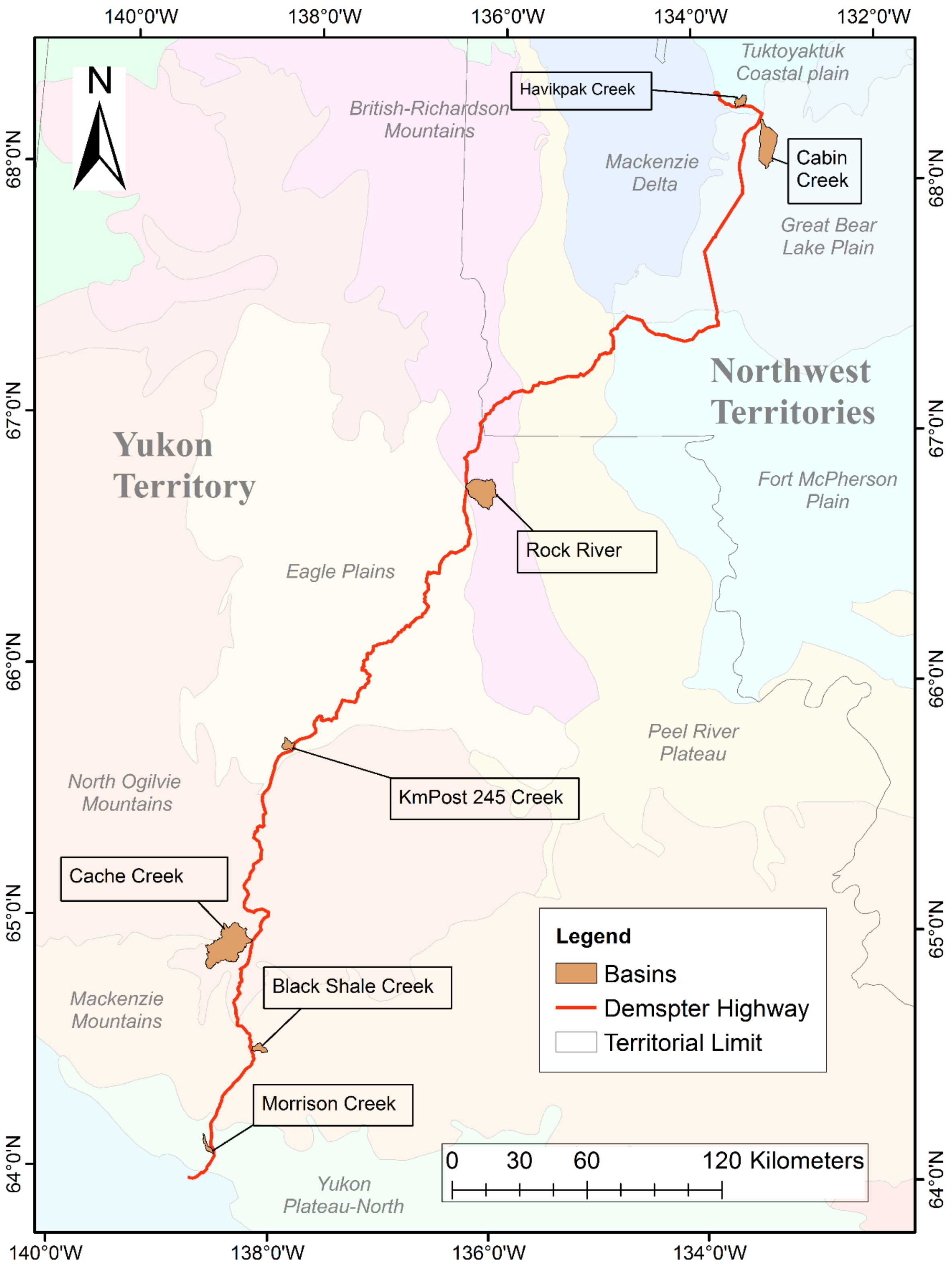

Figure 5: Basins locations. Background labels are associated with different ecoregions.

Table 8: Selected Basins

Basin	Ecoregion	Area [Km^2]	Elevation Range [m asl]	Streamflow Records	Pp Records
Morrison Creek	Yukon Plateau-North	10.5	606 – 998	-	Hourly Dawson (05-)
Black Shale Creek	Mackenzie Mountains	15.9	1,039 – 2,120	-	Hourly Tombstone (09-14) Klondike (66-07)
Cache Creek	North Ogilvie Mountains	213	890 – 1,734	Annual peak 77-82	Hourly Windy Pass (14-)
Km 245 Creek	Eagle Plains	17.3	463 - 922	-	Daily Eagle Plains (79-07)
Rock River	British-Richardson	115.5	507 – 1,169	-	Hourly Rio Roca (14-)
Cabin Creek	Great Bear Lake Plain	105.4	15 - 203	Daily 84-96	Hourly Inuvik (57-13)
Havikpak Creek	Tuktoyaktuk Coastal Plain	16.9	29 - 228	Daily 02-11	Hourly Inuvik (57-13)

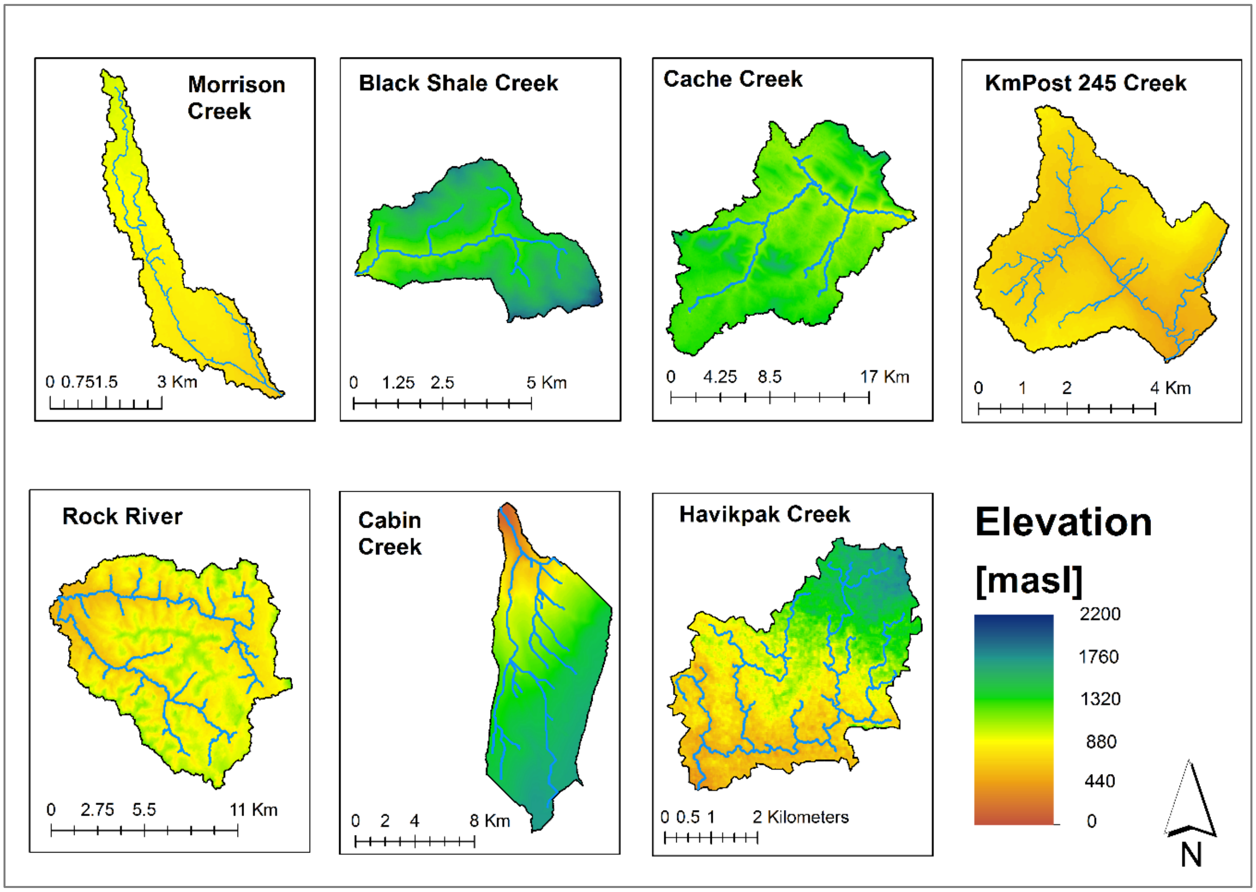

Figure 6: Basins Digital Elevation Model

Hydrological Modelling

Project components included a detailed assessment of hydrological response to climate warming and associated permafrost thawing. The Cold Regions Hydrological Model (CRHM) (Pomeroy et al., 2007) was selected as the modelling platform for this study. CRHM is a physically based hydrological model that contains a full suite of cold regions hydrological modules including, snow, frozen soils, permafrost thaw and runoff and is capable of assessing not only climate change but vegetation change and permafrost thaw. The specific modules selected for use in this project are presented in Table 9.

Table 9: Hydrological Processes simulated by CRHM

Physical Process	Method
Global Radiation	Calculates theoretical direct and diffuse global radiation, and maximum sunshine hours (Garnier and Ohmura, 1970)
Shortwave Radiation	The model presented by Annandale et al. (2002)
Longwave Radiation	The model presented by Sicart et al. (2006)
Albedo	An albedo model developed by Gray and Landine (1987)
Net Radiation	A model developed by Brunt (1932) to estimate all-wave radiation to snow-free surfaces
Blowing Snow Transport and Sublimation	The Prairie Blowing Snow Model (PBSM; Pomeroy and Li, 2000)
Evapotranspiration	Penman Monteith (Monteith, 1981) and Priestley & Taylor (1972)
Runoff Routing	Muskingum (Chow et al., 1994, p. 312)
Soil Moisture	A Three-Layers Soil Model with depression and detention storage (Pomeroy et al., 2007)
Canopy Interception	The Rutter Interception Model (Valente et al., 1997) for the summer. A Canopy Interception model for the winter (Hedstrom and Pomeroy, 1998; Parviainen and Pomeroy, 2000; Pomeroy et al., 1998)
	A Canopy Interception model for the winter (Hedstrom and Pomeroy, 1998; Parviainen and Pomeroy, 2000; Pomeroy et al., 1998)
Frost Table Thaw	The XG-algorithm (Changwei and Gough, 2013)
Snow Accumulation and Melt	A Two-Layer Energy Balance Model (SNOBAL; Marks et al., 1998)
Soil Infiltration	The Ayers model for unfrozen soils (Ayers, 1959). Infiltration into frozen soils using the method described in Gray et al. (2001)

These processes represent the most relevant hydrological processes controlling the streamflow regime of Arctic and subarctic basins. The interaction between these processes is presented in Figure 7. As CRHM has a strong physical basis, most physical parameters can be obtained from the study basin physiographic characteristics (slope, aspect and elevation), landcover class (tundra, shrubland, forest and wetland) and previous studies from two research basins in the region: Wolf Creek near Whitehorse (Pomeroy and Granger, 1998) and Trail Valley Creek near Inuvik (Marsh et al., 2004). With the exception of Havikpak Creek, the other study basins do not have any streamflow records; therefore, Havikpak Creek data was used to estimate the hydrological parameters for the other study basins.

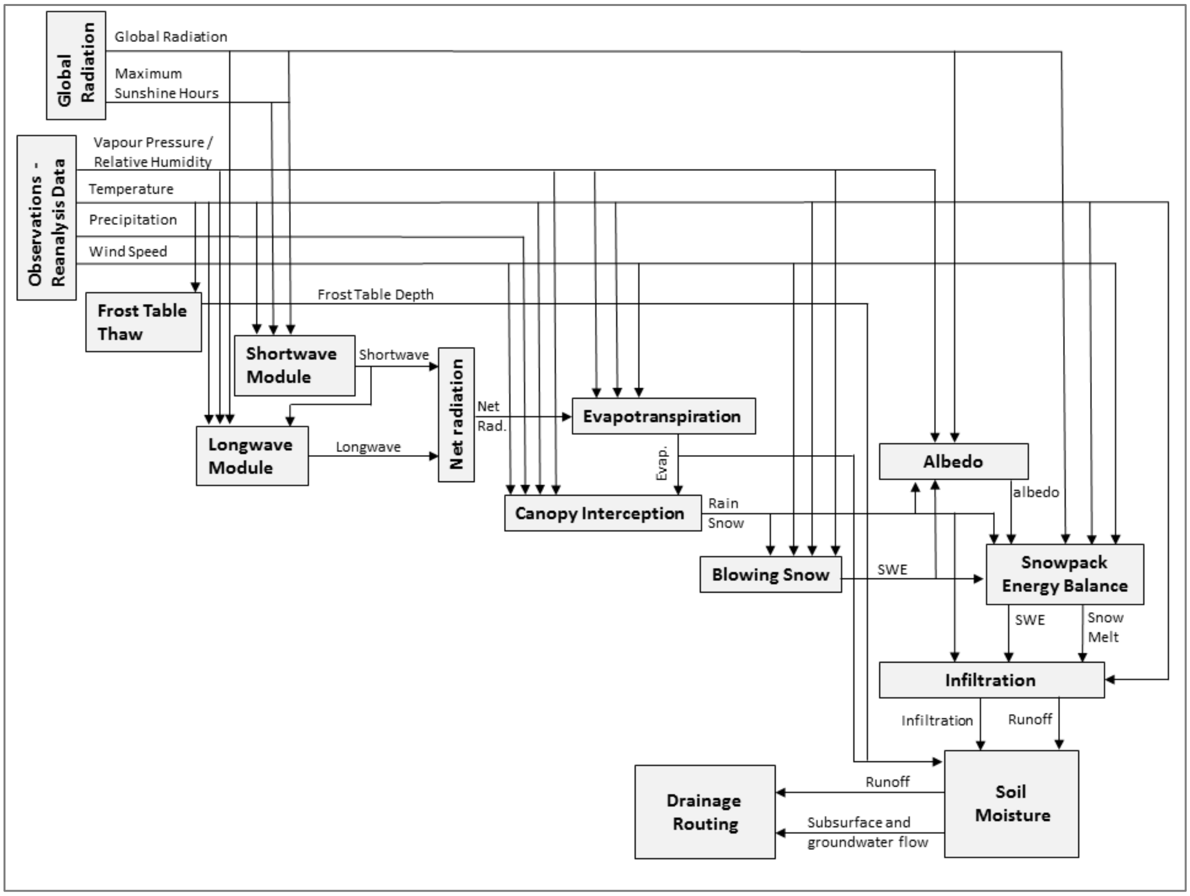

Figure 7: Physical processes flowchart within CRHM

The basic control volume used in CRHM to compute the mass and energy balance is the Hydrological Response Unit (HRU). HRU definition is based on basin physiographic characteristics and land cover type (Wulder et al., 2008a, 2008b). The number of sub-basins and HRUs defined for each study basin is summarized in Table 10.

Table 10: Number of HRUs and Sub-basins for each basin

Basin	# Sub-basins	# HRUs
Morrison Creek	1	9
Black Shale Creek	1	24
Cache Creek	2	39
Km 245 Creek	1	25
Rock River	2	66
Cabin Creek	1	21
Havikpak Creek	1	13

An example of HRU and sub-basin delineation for the Rock River study basin is presented in Figure 8. Different colors are associated with the different HRUs as defined in the CRHM model.

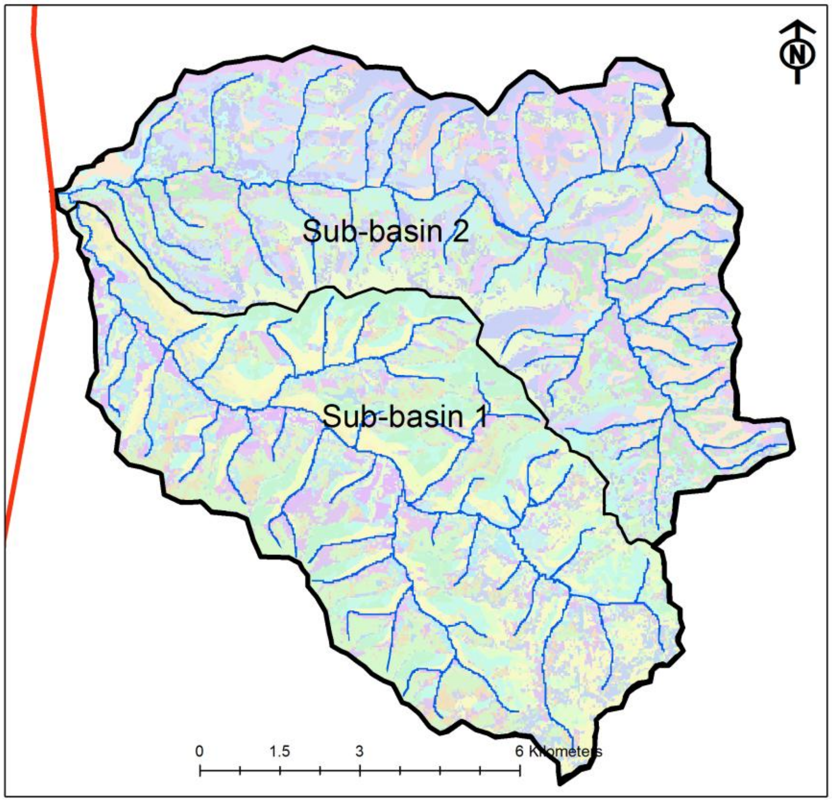

Figure 8: Rock River HRU and Sub-basin delineation

Reanalysis Data

As long term records for the main weather variables namely, relative humidity, wind speed, temperature and precipitation is not available, data from atmospheric reanalysis is used. In this study we use the ERA-Interim (Dee et al., 2011) reanalysis that covers our study domain. ERA-Interim covers the period between 1979 until present with a spatial resolution of 0.75 degrees and a temporal resolution of 3 hours (http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/). Given the relatively coarse spatial resolution of ERA-Interim for hydrological studies, a bias correction is performed. The bias correction method used in this study uses the records from the stations along the Dempster highway, including the two stations installed for the specific purpose of this study: Windy Pass and Rio Roca station. The location of each basins and the ERA-I grid is presented in Figure 9. Bias correction is applied as follows:

$$VAR_{corr,i}^{ERAI} = \frac{\overline{VAR}^{Obs}}{\overline{VAR}_{raw}^{ERAI}} * VAR_{raw,i}^{ERAI}$$

where VAR_{corr}^{ERAI} is the corrected variable from ERAI for the hour “i”, $\overline{VAR}_{raw}^{ERAI}$ is the mean raw variable from ERAI, $\overline{VAR}^{Obs}$ is the mean variable from observations and VAR_{raw}^{ERAI} is the raw variable from ERAI for the hour “i”. Corrected variables are relative humidity, wind speed, temperature and precipitation.

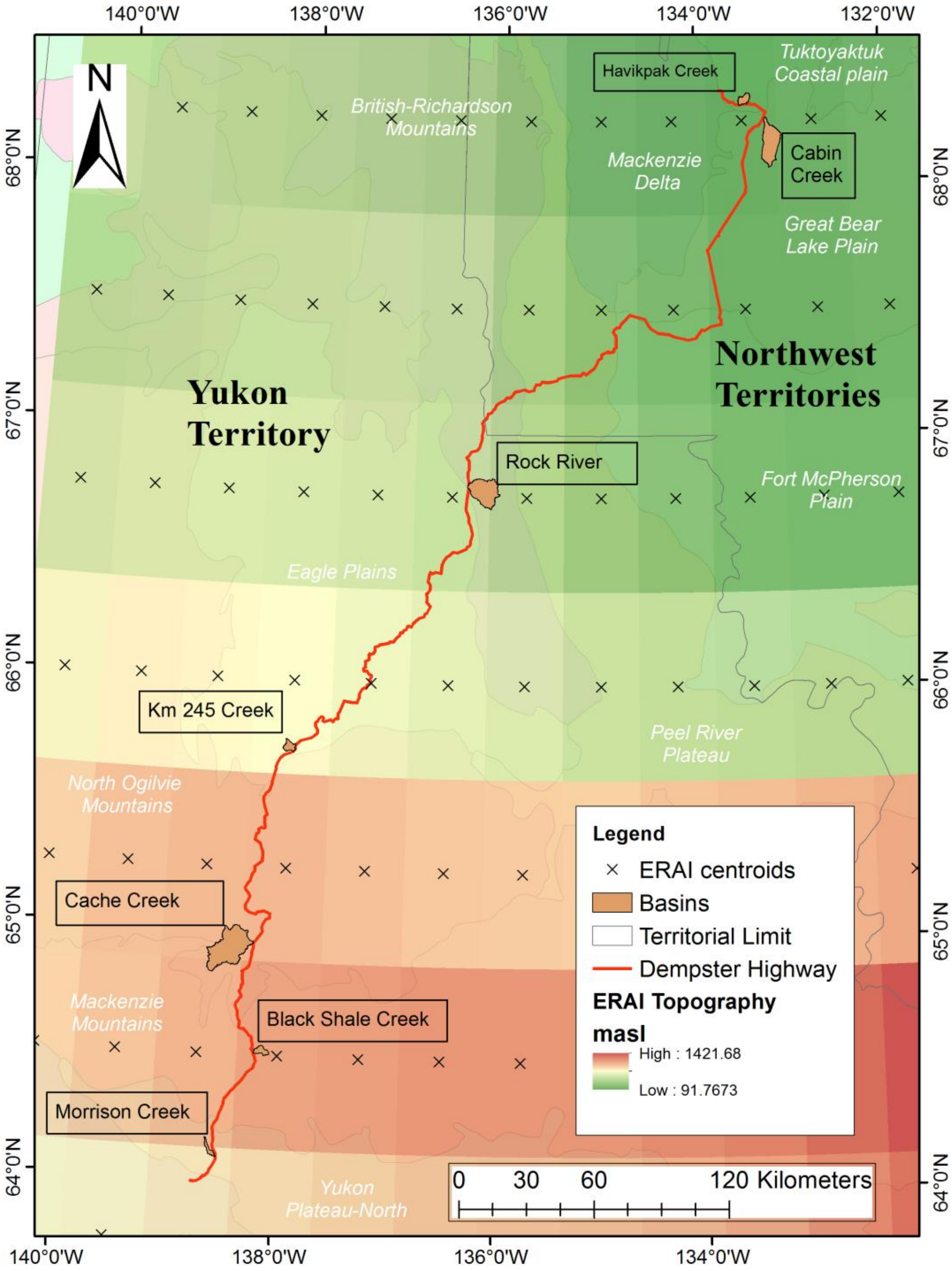

Figure 9: Basins and ERA-Interim reanalysis grid

Climate Change Scenarios

To estimate the potential changes in streamflow regime along the Dempster highway, 41 climate change scenarios were assessed. These scenarios are defined as the increase in historical mean annual temperature in 1°C steps up to 5°C (six scenarios) and precipitation changes for summer (5% of mean precipitation increase up to 30%) and winter (10% of mean precipitation up to 60%) (seven scenarios). The result is 41 scenarios plus the control run associated with no change in historical precipitation and temperature (Table 11). These scenarios represent potential changes in future climate for this region and are based on projected changes in temperature and precipitation developed by various global circulation models to the year 2080. For the purpose of this climate sensitivity analysis, relative humidity and wind speed are held constant.

Table 11: Climate Change Scenarios

Scenario ID#	Temperature Change (°C)	Precipitation Change (%)	Scenario ID#	Temperature Change(°C)	Precipitation Change (%)
1	0	0 (S) and 0 (W)	22	3	0 (S) and 0 (W)
2	0	5 (S) and 10 (W)	23	3	5 (S) and 10 (W)
3	0	10 (S) and 20 (W)	24	3	10 (S) and 20 (W)
4	0	15 (S) and 30 (W)	25	3	15 (S) and 30 (W)
5	0	20 (S) and 40 (W)	26	3	20 (S) and 40 (W)
6	0	25 (S) and 50 (W)	27	3	25 (S) and 50 (W)
7	0	30 (S) and 60 (W)	28	3	30 (S) and 60 (W)
8	1	0 (S) and 0 (W)	29	4	0 (S) and 0 (W)
9	1	5 (S) and 10 (W)	30	4	5 (S) and 10 (W)
10	1	10 (S) and 20 (W)	31	4	10 (S) and 20 (W)
11	1	15 (S) and 30 (W)	32	4	15 (S) and 30 (W)
12	1	20 (S) and 40 (W)	33	4	20 (S) and 40 (W)
13	1	25 (S) and 50 (W)	34	4	25 (S) and 50 (W)
14	1	30 (S) and 60 (W)	35	4	30 (S) and 60 (W)
15	2	0 (S) and 0 (W)	36	5	0 (S) and 0 (W)
16	2	5 (S) and 10 (W)	37	5	5 (S) and 10 (W)
17	2	10 (S) and 20 (W)	38	5	10 (S) and 20 (W)
18	2	15 (S) and 30 (W)	39	5	15 (S) and 30 (W)
19	2	20 (S) and 40 (W)	40	5	20 (S) and 40 (W)
20	2	25 (S) and 50 (W)	41	5	25 (S) and 50 (W)
21	2	30 (S) and 60 (W)	42	5	30 (S) and 60 (W)

*S and W represent Summer and Winter

Peak Flow Frequency Distribution Function

Annual hourly peak streamflow from the CRHM model runs for each study basin and climate scenario is extracted to analyze the changes in the frequency distribution function (FDF) with respect to the “control run”. The Generalized Extreme Value (GEV) distribution is used as it has shown to adequately represent the distribution of peak flows (Ramachandra and Hamed, 2000). Parameters of the GEV distribution are estimated using the method of maximum likelihood.

Significant variability in projected changes of the annual peak flow is observed, depending on the climate scenario and the return period of interest. Greater return periods are usually associated with a greater increase in the annual peak flow; however, these events are also the ones with the largest uncertainty. Some study basins appear to exhibit feedback associated with both increasing temperature and precipitation, limiting the potential impact of climate change on annual peak flows. This compensation effect may be possibly explained by the effect of increased temperatures on the spring snowpack, which is at the primary control peak flows in this region. Higher temperatures decrease the proportion of snowfall over total precipitation, producing relatively smaller snowpacks; also, greater evaporation losses are expected due to increasing temperature.

DISCUSSION AND ANALYSIS

Changes in Annual Peak flow Frequency Distribution Function for different Ecoregions

Yukon Plateau-North

Morrison Creek basin is assumed to be representative of the changes expected in the Yukon Plateau-North Ecoregion. Figure 10 presents the potential changes in the frequency distribution function (FDF) for Morrison Creek against the historical simulations (control run). Each subplots show the change in the FDF for a constant increase in the mean annual temperature and different changes in the summer (S) and winter (W) precipitation. A zero increase in the mean annual temperature and a progressive increase in the annual precipitation show an increase in the annual peak flows for any given return period. For example, the 200 years return period flood for the control run has an associated peak flow of roughly 2 [m^3/s], whereas for the scenario with the largest increase in precipitation (30% in summer and 60% in winter) the annual peak flow increases to 3 [m^3/s], representing an increase of 50%. As the increase in the mean annual temperature rises, the effect of an increasing precipitation decays, as the warmer temperatures reduce snow accumulation by changing snow contribution to precipitation and evaporation. In this case (+5°C increase), the annual peak flow of a 200 years return period flood increases only approximately 25% for the higher increase in precipitation; moreover, it decreases about 40% for a small increase in precipitation.

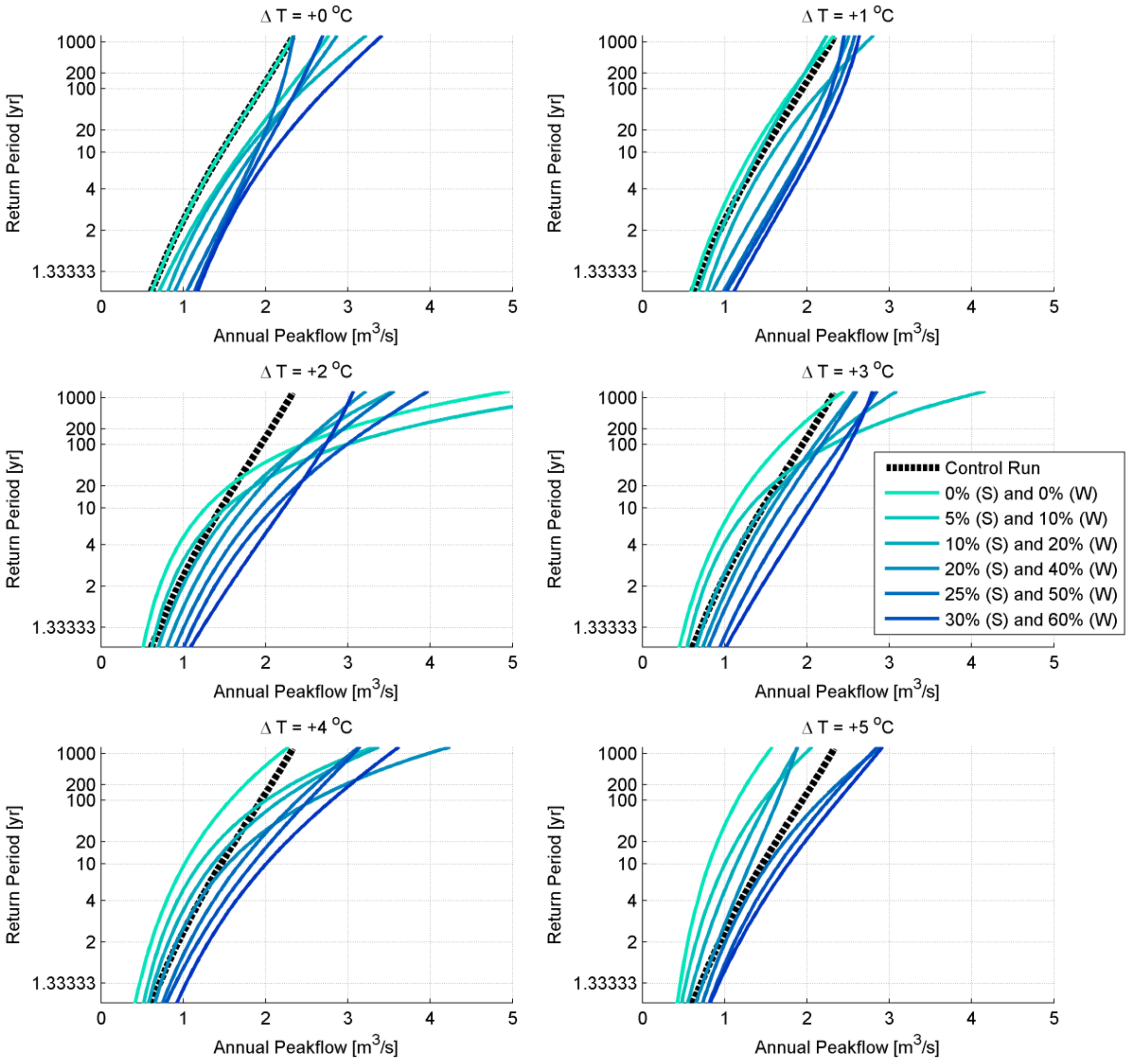

Figure 10: Morrison Creek annual peak flow FDF for the control run (historical simulations) and climate scenarios. "S" and "W" refers to increases in summer and winter precipitation, respectively.

Mackenzie Mountains

Black Shale Creek is the representative basin for this ecoregion. Figure 11 presents the changes in the annual peak flow FDF for the control run and the climate change scenarios. Overall, a consistent increase in the annual peak for any given return period and climate scenario is observed. As opposed to the behaviour observed for the Yukon Plateau-North, the Mackenzie Mountain ecoregion does not show the compensation effect of increasing mean annual temperatures to increasing precipitation over the FDF. It can be concluded that rivers in this ecoregion might potentially increase its annual peak flow for almost any of the climate change scenario combination here assessed. The greater increase in the annual peak flow is, as expected, associates with the largest increase in precipitation, and also with the scenario with greater increase in mean annual temperature (5 °C). For example, the annual peak flow with 200 years return period increases from roughly 6 [m^3/s] to 10 [m^3/s], representing an increase of 67%.

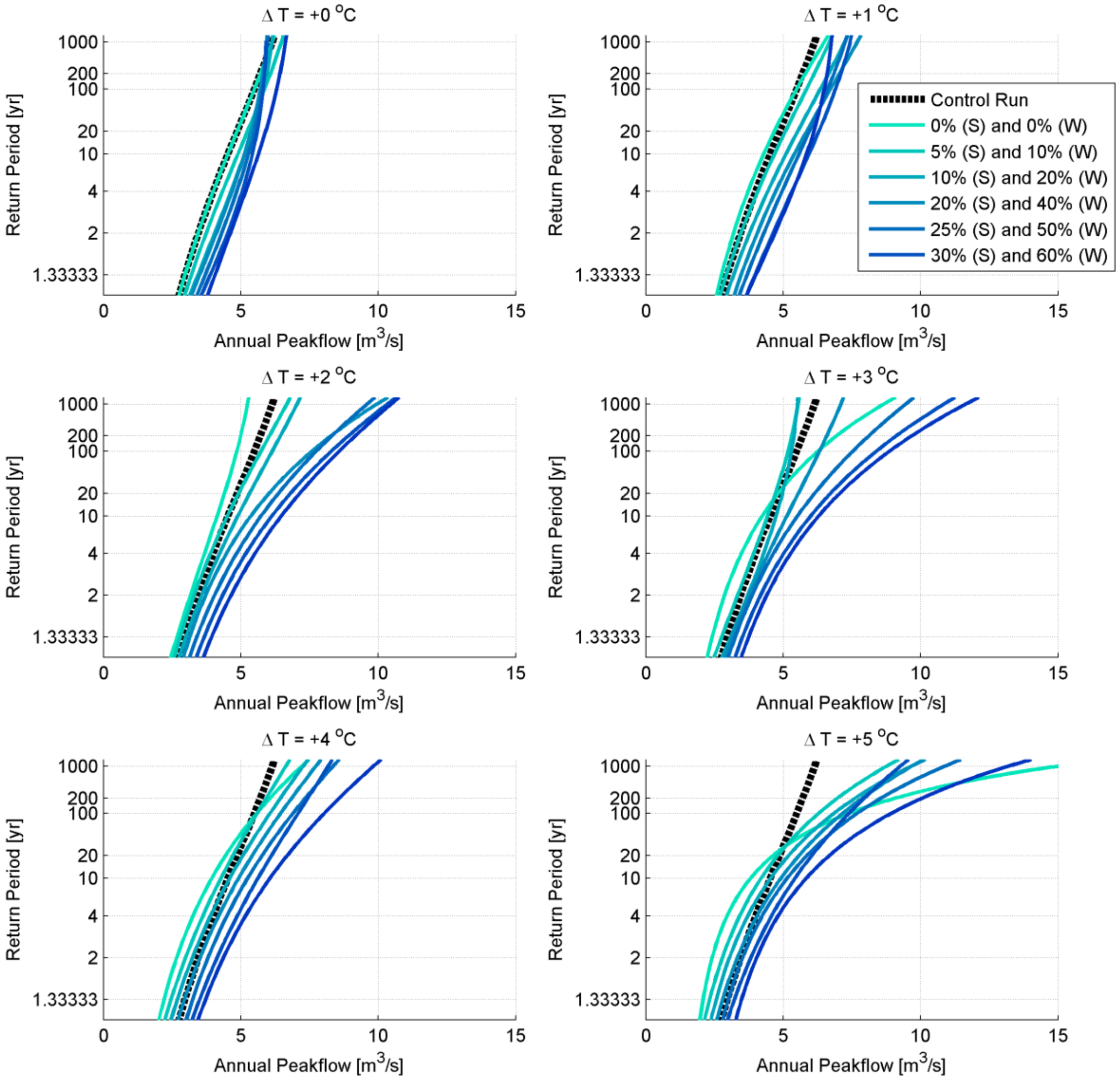

Figure 11: Black Shale Creek annual peak flow FDF for the control run (historical simulations) and climate scenarios. "S" and "W" refers to increases in summer and winter precipitation, respectively.

<u>North Ogilvie Mountains</u>

Cache Creek is the representative basin of the North Ogilvie Mountains. Figure 12 presents the changes in the annual peak flow FDF for the control run and the climate change scenarios. Similar to Black Shale Creek in the Mackenzie Mountains ecoregion, climate change in Cache Creek shows a consistent increase in the annual peak flow for all the scenarios here assessed. No compensation between increasing temperature and precipitation is observed. The maximum increase in annual peak flow is observed for an intermediate increase in temperature of 4 °C, as opposed to the Mackenzie Mountains that occurs at the +5°C scenario. Expected changes in annual peak flow FDF are much more intense than for previous ecoregions. For example, the 200 years return period flood is expected to increase from roughly 90 [m^3/s] to as much as 170 [m^3/s], representing an increase of around 90%. Here, even small changes in annual precipitation and temperature might produce significant changes in the annual peak flow FDF, as can be observed for the scenarios with +1°C and +2°C increase in mean annual temperature.

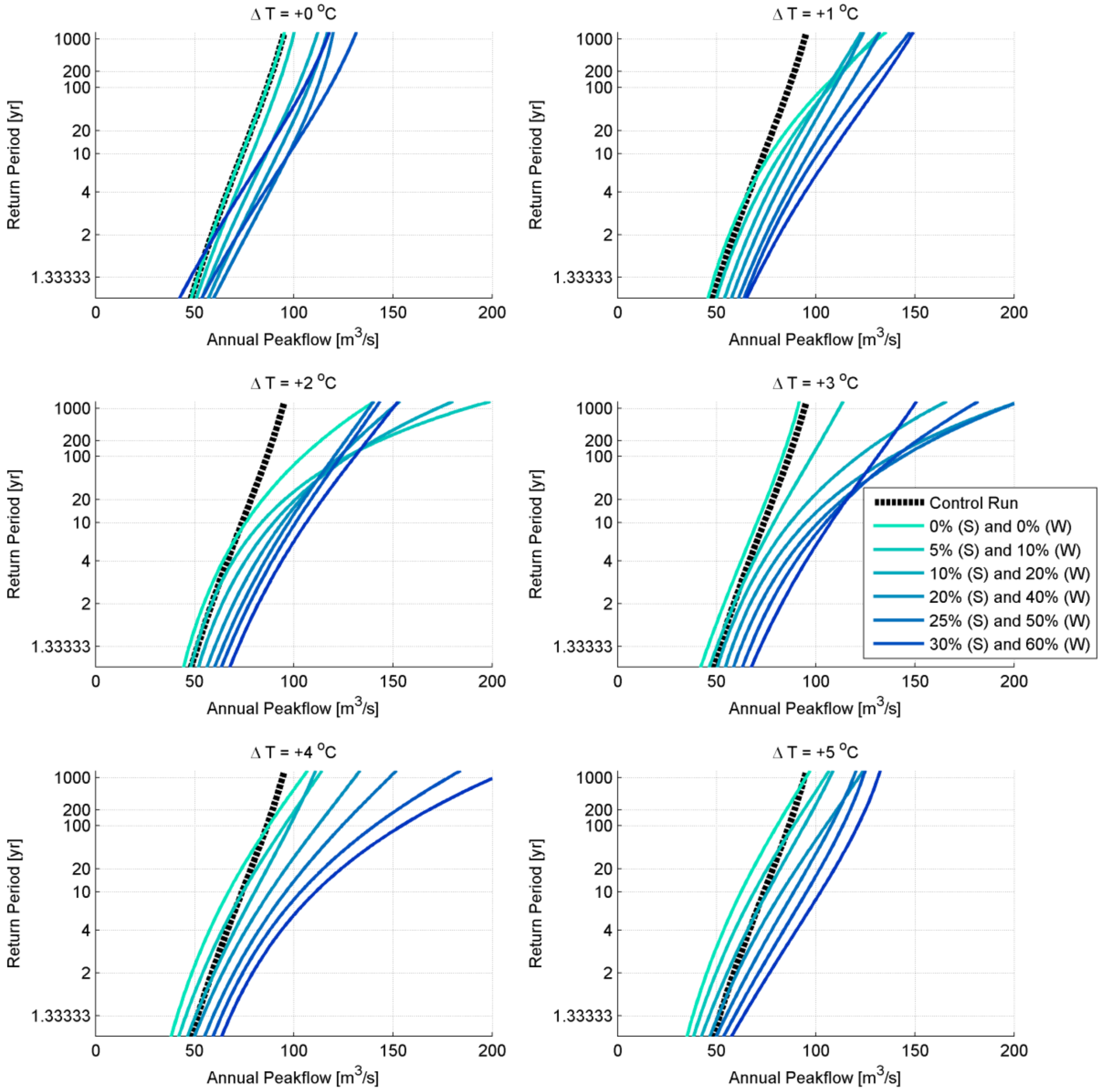

Figure 12: Cache Creek annual peak flow FDF for the control run (historical simulations) and climate scenarios. "S" and "W" refers to increases in summer and winter precipitation, respectively.

Eagles Plains

Km 245 Creek is the representative basin for the Eagle Plains ecoregion. Figure 13 presents the changes in the FDF of annual peak flow for the control run and the climate change scenarios. This basin shows more moderate changes in the annual peak flow FDF for intermediate changes in temperature and precipitation, as opposed to previous ecoregions. However, larger changes are simulated for an increase in +5°C in the mean annual temperature. For example, the 200 years return period flood increases form roughly 4.5 [m^3/s] to 7 [m^3/s], representing an increase of 55%. In this scenario, the difference between the control run and future simulation increase with the return period. A compensatory effect between increasing temperature and precipitation is observed for the scenarios with greater increase in temperature (>3°C).

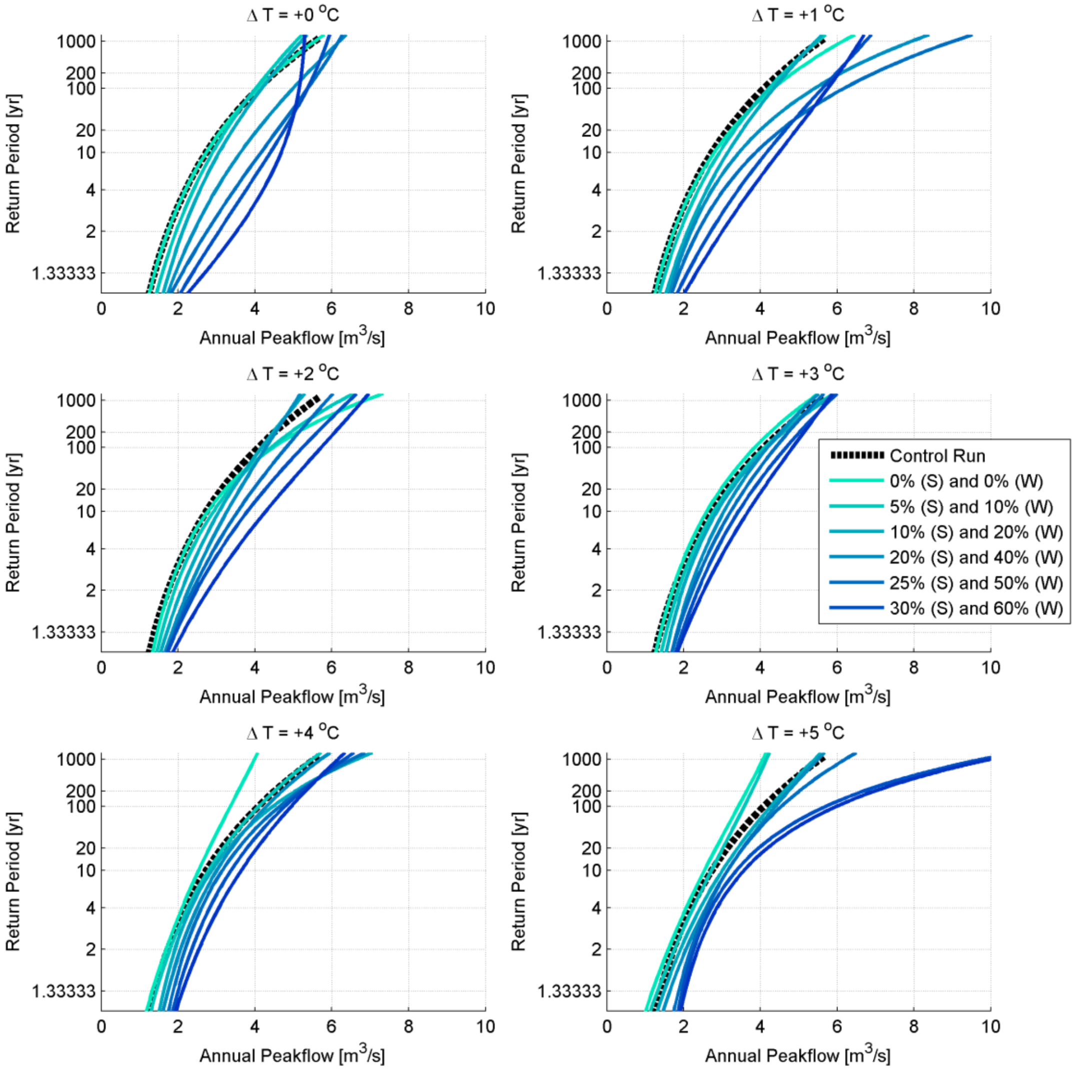

Figure 13: Km 245 Creek annual peak flow FDF for the control run (historical simulations) and climate scenarios. “S” and “W” refers to increases in summer and winter precipitation, respectively.

British-Richardson Mountains

Rock River basin is the representative basin for the British-Richardson Mountains ecoregion. Figure 14 presents the changes in the FDF of annual peak flow for the climate change scenario and the historical simulation. Changes in the FDF associated with a large increase in temperature (>4°C) and relatively small changes in precipitation (10 and 20% increase in summer and winter precipitation, respectively) show a decrease in the annual peak flow. For example, the 200 years return period flood in the +5°C scenarios decreases from roughly 18 [m^3/s] in the control run to 15 [m^3/s], representing a 17% decrease. However, moderate increases in temperature (i.e. +2°C and +3°C) and large increases in precipitation show a substantial increase in the annual peak flow, up to roughly 25 [m^3/s] (40% increase).

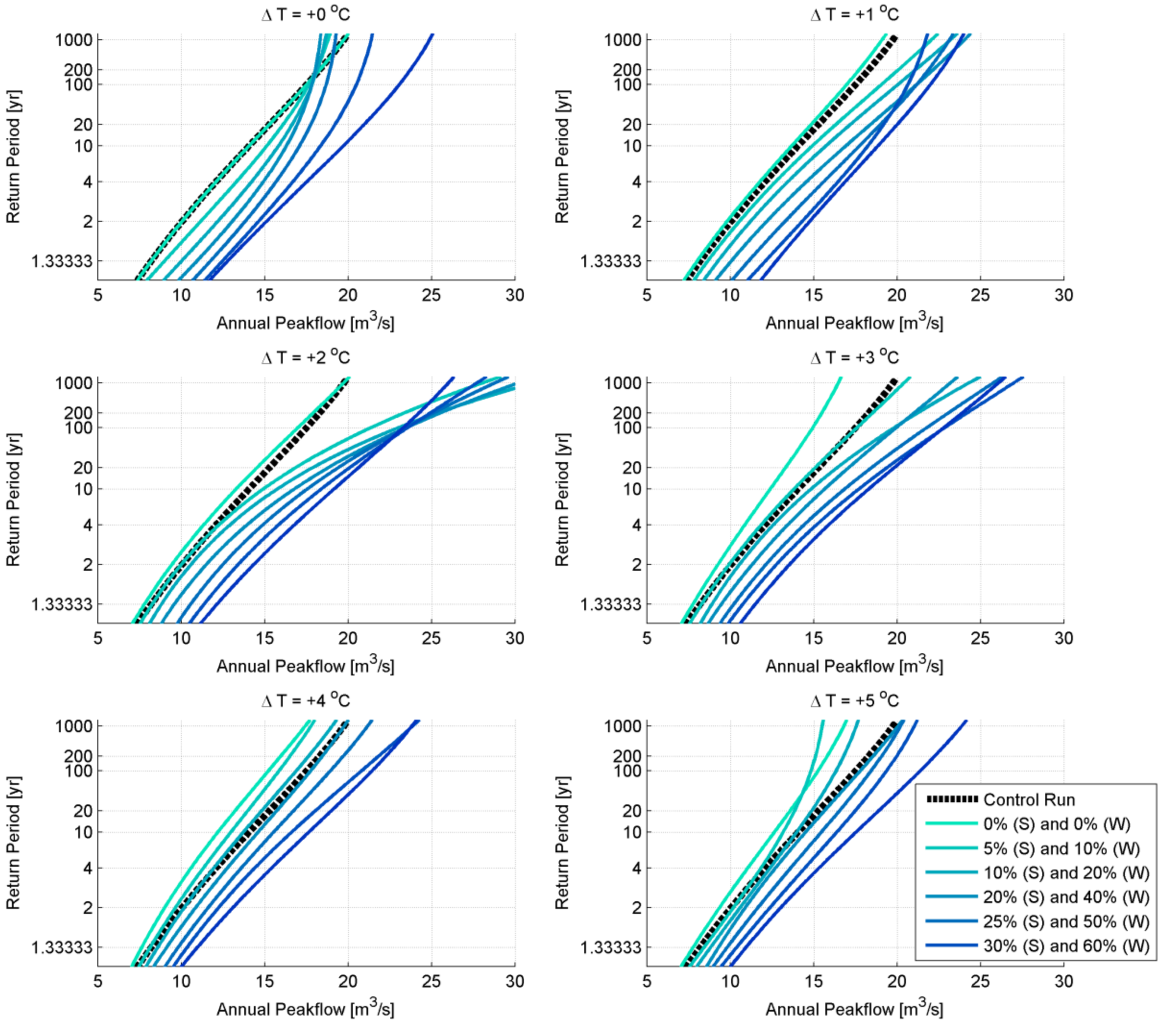

Figure 14: Rock River basin annual peak flow FDF for the control run (historical simulations) and climate scenarios. “S” and “W” refers to increases in summer and winter precipitation, respectively.

Great Bear Lake Plain

Cabin Creek is the representative basin for the Great Bear Lake Plain ecoregion. Figure 15 presents the changes in the FDF of annual peak flow for the climate change scenario and the historical simulation. A zero increase in the mean annual temperature and an increasing precipitation show an intensification of annual peak flow for low return periods (<200 years); however, for greater return periods, the associated annual peak flow decreases. A similar phenomenon is observed for a +5°C increase in the mean annual temperature. However, moderate changes in temperature (0°C < and <4°C) present a more consistent increase in the FDF for an increasing annual precipitation. For example, a +3°C increase in temperature show an increase from roughly 27 [m^3/s] for the control run to 40 [m^3/s] (40% increase) for the largest increase in precipitation, for the 200 years flood.

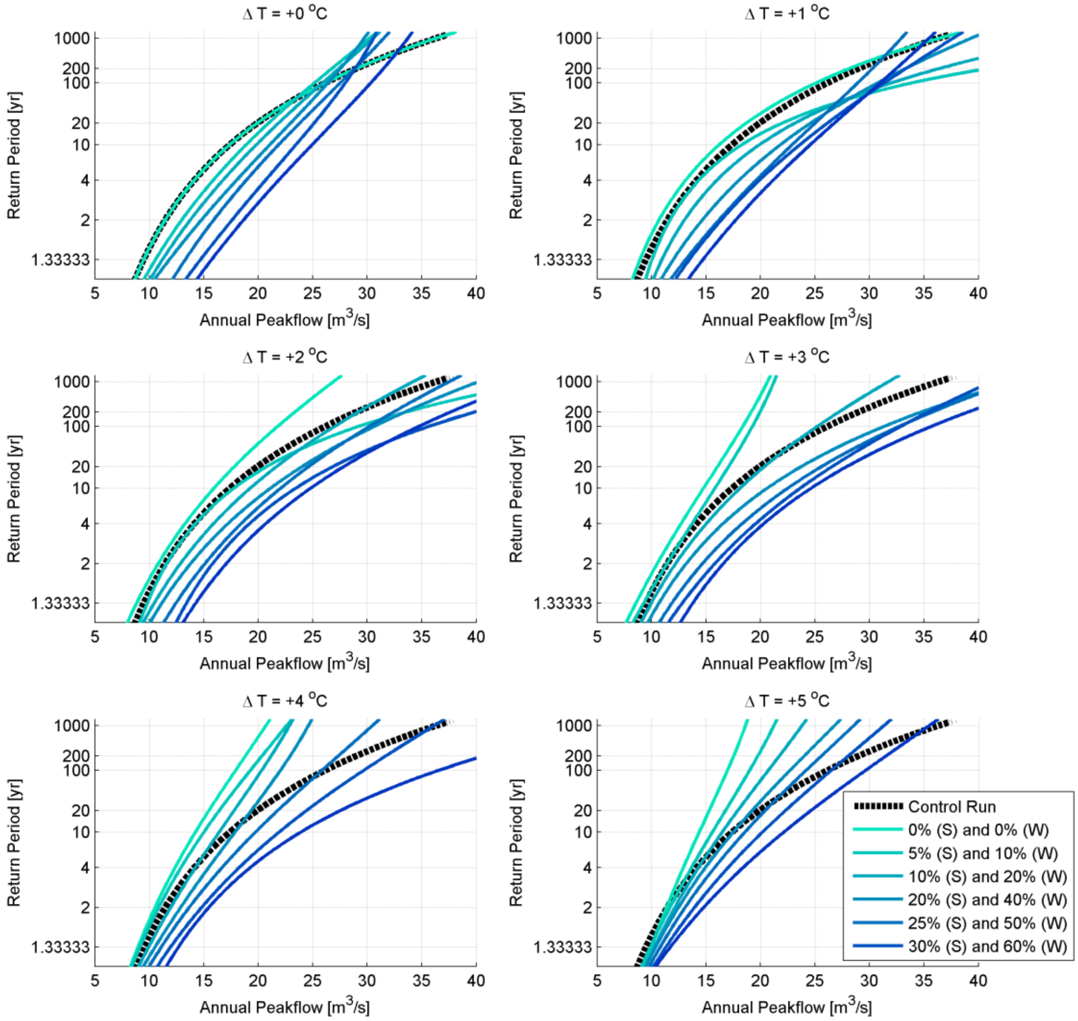

Figure 15: Cabin Creek basin annual peak flow FDF for the control run (historical simulations) and climate scenarios. "S" and "W" refers to increases in summer and winter precipitation, respectively.

Tuktoyaktuk Coastal plain

Havikpak Creek basin is the representative basin for the Great Bear Lake Plain ecoregion. Figure 16 presents the changes in the FDF of annual peak flow for the climate change scenario and the historical simulation. An overall consistent increase in the annual peak flow FDF is observed for most of the climate scenarios assessed. Annual peak flows with low return period (<20 years) exhibit a consistent increase; however, for some climate scenarios, annual peak flow with a greater return period show a decreasing trend. For example, in the +3°C scenario, the 4 years return period flood increases from roughly 2 [m^3/s] up to 4 [m^3/s] (100% increase), whereas for a return period of 200 years, the annual flow decreases from roughly 6 [m^3/s] down to 4 [m^3/s] (33% decrease).

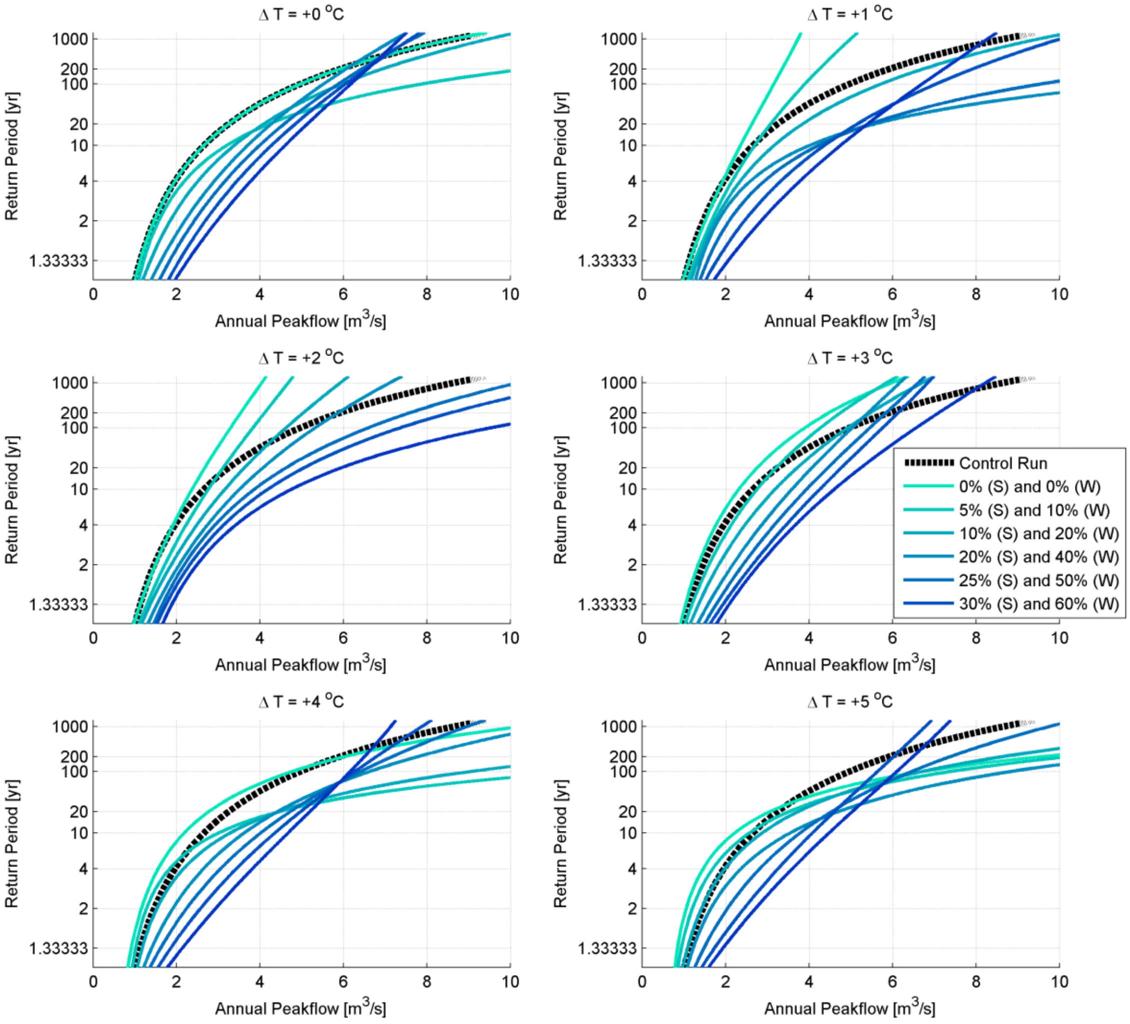

Figure 16: Havikpak Creek basin annual peak flow FDF for the control run (historical simulation) and climate scenarios. "S" and "W" refers to increases in summer and winter precipitation, respectively.

General Analysis

Overall, great variability in the expected changes in the annual peak flow is observed, depending on the climate scenario and the return period of interest. Greater return periods are usually associated with a greater increase in the annual peak flow; however, these events are also the ones with the largest uncertainty. Some ecoregions show compensation between the increasing temperature and the increasing precipitation, limiting the potential impact of climate change over annual peak flows. This compensation effect is explained by the impact of warmer temperature over the end-of-the-winter snowpack, which is control peak flows in this region. Warmer temperatures decrease the proportion of snowfall over total precipitation, producing relatively smaller snowpacks; also, greater evaporation losses are expected due to increasing temperature.

Transfer of Annual Peak flow Frequency Distribution Function to Individual Ecoregion Streams

Table 12 provides a summary of peak flow design estimates for the control case (present flow) and select climate change scenarios for the six study basins. Only Havikpak Creek has an active hydrometric station with a period of operation from 1995 to present. A single station flood frequency analysis was carried out with the 18 year data set (there are two years of missing data). A reasonable comparison was achieved between the single station analyses and the control record. As a further check a comparison was made with a flow estimate that was developed by Yukon Highways and Public Works staff member for Km 245.2 stream crossing for a heavy runoff event that took place on June 29, 2013 (Ross, 2014). The estimate, developed using the culvert method, yielded a value of 2.30 m^3/s which corresponds to an approximate five year return period event based on the control flow for the Km 245 Creek study basin. As a further check peak flow estimates developed using regional analyses provide similarly reasonable comparisons with the control flow estimates.

Table 13 provides a summary of all stream crossing on the Dempster Highway with corresponding streamflow factors to transfer peak flow design estimates within individual ecoregions.

Table 12: peak flow estimates for select climate change scenarios

Basin	Return Period	Scenarios				
		Control	+2°C		+5°C	
			5% S, 10% W	30% S, 60% W	5% S, 10% W	30% S, 60% W
Rock River	2 yr	10	10	14.3	10.1	13
	10 yr	14	14.8	19.2	13.2	17.5
	50 yr	16.2	18.4	21.6	14.2	19.8
	100 yr	17.4	23.4	22.3	15.2	21.3
Morrison	2 yr	0.96	0.86	1.56	0.52	1.16
	10 yr	1.44	1.5	2.2	1	1.76
	50 yr	1.74	2.18	2.56	1.22	2.1
	100 yr	1.92	3	2.72	1.46	2.38
Havikpak	2 yr	1.48	1.52	2.48	1.2	2.72
	10 yr	2.64	2.76	4.72	2.52	4.44
	50 yr	3.76	3.4	7.04	4.48	5.92
	100 yr	4.92	3.84	9.52	7.36	8.8
Km 245	2 yr	1.6	1.92	2.76	1.76	2.36
	10 yr	2.64	2.88	4.24	2.68	3.48
	50 yr	3.36	3.6	5.04	3.12	4.64
	100 yr	4	4.24	5.6	3.48	5.96
Black Shale	2 yr	3.48	3.24	4.68	2.76	4.08
	10 yr	4.56	4.56	6.5	4.2	5.84
	50 yr	5.12	5.24	7.7	5.36	7.4
	100 yr	5.48	5.72	8.6	6.8	8.96
Cache	2 yr	51.6	50.8	80.4	50	74.8
	10 yr	72.4	82	105.6	67.6	102.4
	50 yr	79.6	104.8	119.2	78	113.6
	100 yr	85.2	125.6	128.8	86.8	120
Cabin	2 yr	11.3	11.6	16.9	11.7	14.6
	10 yr	17	17.6	24.6	15.4	22
	50 yr	21.7	23.2	30	17.5	26.3
	100 yr	26.2	29.1	34.7	18.9	29.6

Table 13: Dempster Highway stream crossings with corresponding streamflow factor for transferring peak flow design estimates to ecoregion streams

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
6.5	YT		7.0	Klondike Plateau		0.59
7.5	YT		1.9	Klondike Plateau		0.16
9	YT	Linta Ck	27.3	Yukon Plateau		2.31
12.5	YT		2.5	Yukon Plateau		0.21
15.5	YT		1.4	Yukon Plateau		0.12
17	YT		1.5	Yukon Plateau		0.13
18	YT	Morrison Ck	11.8	Yukon Plateau		1.00
18.5	YT		1.6	Yukon Plateau		0.14
21	YT		1.4	Yukon Plateau		0.12
23	YT		3.3	Yukon Plateau		0.28
24	YT	Glacier Ck	5.2	Yukon Plateau	50024	0.44
26.5	YT	Nordling Ck	6.7	Yukon Plateau		0.57
28.5	YT	Benson Ck	90.9	Yukon Plateau	50028	7.70
30	YT		2.4	Yukon Plateau		0.20
33	YT		3.9	Yukon Plateau		0.33
34	YT		3.5	Yukon Plateau		0.30
35	YT		1.1	Mackenzie Mountains		0.06
36.5	YT		3.8	Mackenzie Mountains		0.22
38	YT		6.0	Mackenzie Mountains		0.35
40.5	YT	Peasoup Ck	9.4	Mackenzie Mountains		0.54
42	YT		1.2	Mackenzie Mountains		0.07
43	YT		4.4	Mackenzie Mountains		0.25
44	YT	Yin Yang Ck	5.4	Mackenzie Mountains		0.31
45	YT		1.0	Mackenzie Mountains		0.06
45.5	YT		1.7	Mackenzie Mountains		0.10
46	YT		2.6	Mackenzie Mountains		0.15
47	YT	Scout Car Ck	22.5	Mackenzie Mountains	50047	1.30
48.5	YT		3.3	Mackenzie Mountains		0.19
50	YT	Wolf Ck	67.5	Mackenzie Mountains	50050	3.90
56	YT		1.8	Mackenzie Mountains		0.10
58	YT	Grizzly Ck	33.7	Mackenzie Mountains	50058	1.95
60	YT		1.0	Mackenzie Mountains		0.06
62.5	YT	Black Mike Ck	7.3	Mackenzie Mountains		0.42
66	YT		2.6	Mackenzie Mountains		0.15
67	YT	North Fork Klondike R	189.2	Mackenzie Mountains	50066	10.94
69.5	YT		5.0	Mackenzie Mountains		0.29
72	YT	Black Shale Creek	17.3	Mackenzie Mountains		1.00

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
75	YT		1.4	Mackenzie Mountains		0.08
77	YT	Boulder Ck	24.8	Mackenzie Mountains	50076	1.43
79.5	YT		4.0	Mackenzie Mountains		0.23
82.5	YT		1.6	Mackenzie Mountains		0.09
86	YT	East Blackstone R	104.5	Mackenzie Mountains	50086	6.04
87	YT		2.4	Mackenzie Mountains		0.14
88.5	YT		22.4	Mackenzie Mountains		1.29
91	YT	Foxy Ck	42.4	North Ogilvie Mountains	50090	0.20
92	YT		3.0	North Ogilvie Mountains		0.01
94	YT	Wildhorse Ck	17.9	North Ogilvie Mountains		0.08
95	YT		1.1	North Ogilvie Mountains		0.01
97	YT		1.0	North Ogilvie Mountains		0.00
97.5	YT		1.1	North Ogilvie Mountains		0.01
98.5	YT	Slavin Ck	11.9	North Ogilvie Mountains		0.06
100	YT		2.0	North Ogilvie Mountains		0.01
104	YT	Treadgold Ck	2.3	North Ogilvie Mountains		0.01
105.5	YT		2.4	North Ogilvie Mountains		0.01
106.5	YT	Henry Ck	23.8	North Ogilvie Mountains		0.11
108	YT		5.9	North Ogilvie Mountains		0.03
111	YT		2.8	North Ogilvie Mountains		0.01
120	YT		14.7	North Ogilvie Mountains		0.07
122.5	YT		2.6	North Ogilvie Mountains		0.01
124.5	YT		12.4	North Ogilvie Mountains		0.06
125	YT		4.1	North Ogilvie Mountains		0.02
126.5	YT		1.3	North Ogilvie Mountains		0.01
128	YT		1.3	North Ogilvie Mountains		0.01
129	YT	Cache Ck	216.3	North Ogilvie Mountains	50129	1.00
130.5	YT		6.8	North Ogilvie Mountains		0.03
132	YT		7.8	North Ogilvie Mountains		0.04
135	YT		7.3	North Ogilvie Mountains		0.03
137.5	YT		2.4	North Ogilvie Mountains		0.01
138	YT		1.6	North Ogilvie Mountains		0.01
139.5	YT		1.0	North Ogilvie Mountains		0.00
146	YT		6.4	North Ogilvie Mountains		0.03
147	YT		27.4	North Ogilvie Mountains		0.13
149	YT		6.8	North Ogilvie Mountains		0.03
152	YT		3.3	North Ogilvie Mountains		0.02
160	YT	Engineer Ck	144.8	North Ogilvie Mountains	50160	0.67
164.5	YT		1.5	North Ogilvie Mountains		0.01

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
166	YT		1.0	North Ogilvie Mountains		0.00
168	YT	Red Ck	103.1	North Ogilvie Mountains	50168	0.48
170.5	YT		32.8	North Ogilvie Mountains		0.15
172	YT		1.0	North Ogilvie Mountains		0.00
175	YT		35.2	North Ogilvie Mountains		0.16
176	YT		6.8	North Ogilvie Mountains		0.03
179.5	YT		15.3	North Ogilvie Mountains		0.07
180	YT		1.2	North Ogilvie Mountains		0.01
182	YT		1.5	North Ogilvie Mountains		0.01
185	YT		14.4	North Ogilvie Mountains		0.07
188	YT		9.5	North Ogilvie Mountains		0.04
190	YT		2.6	North Ogilvie Mountains		0.01
192	YT		1.6	North Ogilvie Mountains		0.01
198	YT		7.6	North Ogilvie Mountains		0.04
200.5	YT		3.3	North Ogilvie Mountains		0.02
206.5	YT		1.2	North Ogilvie Mountains		0.01
208	YT		56.5	North Ogilvie Mountains		0.26
209.5	YT		1.8	North Ogilvie Mountains		0.01
210	YT		1.0	North Ogilvie Mountains		0.00
215	YT		1.9	North Ogilvie Mountains		0.01
216.5	YT		2.6	North Ogilvie Mountains		0.01
218	YT		14.5	North Ogilvie Mountains		0.07
221.5	YT	Davies Crk	325.0	Eagle Plains	50221	18.68
222.5	YT		1.3	Eagle Plains		0.07
223	YT		5.9	Eagle Plains		0.34
226.5	YT		2.6	Eagle Plains		0.15
228	YT		62.9	Eagle Plains		3.61
231.5	YT		3.6	Eagle Plains		0.21
233	YT		3.1	Eagle Plains		0.18
234	YT		6.6	Eagle Plains		0.38
234.5	YT		20.7	Eagle Plains		1.19
236	YT		2.9	Eagle Plains		0.17
236.5	YT		2.1	Eagle Plains		0.12
237	YT		16.4	Eagle Plains		0.94
238	YT		1.4	Eagle Plains		0.08
239	YT		4.6	Eagle Plains		0.26
241	YT		3.7	Eagle Plains		0.21
245	YT	Km 245 Creek	17.4	Eagle Plains		1.00
350	YT	Fly camp Ck	7.4	Eagle Plains	50350	0.43

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
381	YT		4.1	Eagle Plains		0.24
410.5	YT		3.8	Eagle Plains*	50410	0.22
411	YT		2.6	Eagle Plains*	50411	0.15
412	YT		1.9	Eagle Plains*		0.11
415	YT	Glacier Ck	18.7	Eagle Plains*	50414	1.07
416	YT		41.4	Eagle Plains*		2.38
418	YT		1.4	Eagle Plains*		0.08
421	YT		2.0	Eagle Plains*		0.11
422	YT	Vadzaih Kan Ck	27.4	Eagle Plains*	50421	1.57
423	YT		1.1	Eagle Plains*		0.06
426	YT	Sister Ck	14.0	Eagle Plains*	50426	0.80
428	YT		1.7	Eagle Plains*	50428	0.10
433	YT		2.1	British-Richardson Mountains	50433	0.02
433	YT	Rock River	121.2	British-Richardson Mountains	50432	1.00
434.5	YT		1.4	British-Richardson Mountains	50434	0.01
436	YT		1.1	British-Richardson Mountains		0.01
445	YT	White Fox Ck	64.4	British-Richardson Mountains	50445	0.53
446	YT		119.3	British-Richardson Mountains	50446	0.98
453	YT		2.3	British-Richardson Mountains	50452	0.02
453.5	YT		2.7	British-Richardson Mountains	50453	0.02
454	YT		4.3	British-Richardson Mountains	50454	0.04
456	YT		2.1	British-Richardson Mountains	50456	0.02
458.5	YT		2.0	British-Richardson Mountains	50459	0.02
460	YT		2.0	British-Richardson Mountains	50460	0.02
463	YT		0.6	British-Richardson Mountains	50462	0.00
14	NT		1.4	British-Richardson Mountains		0.01
13	NT		1.4	British-Richardson Mountains		0.01
12.5	NT		1.8	British-Richardson Mountains		0.01
10	NT		2.0	British-Richardson Mountains		0.02
19	NT		4.1	British-Richardson Mountains		0.03
10.5	NT		11.9	British-Richardson Mountains		0.10
18	NT		13.5	British-Richardson Mountains		0.11
20.5	NT		13.9	British-Richardson Mountains		0.11
8.5	NT	North Vittrekwa R	23.9	British-Richardson Mountains		0.20
14.5	NT		43.0	British-Richardson Mountains		0.35
87	NT		1.3	Fort McPherson Plain		0.01
85	NT		2.4	Peel River Plateau		0.02
27.5	NT		7.9	Peel River Plateau		0.07
147	NT		8.5	Fort McPherson Plain		0.07

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
91.5	NT		13.8	Fort McPherson Plain		0.11
122.5	NT	Frog Ck	311.4	Fort McPherson Plain		2.57
201	NT		1.0	Great Bear Lake Plain		0.01
235.5	NT		1.0	Great Bear Lake Plain		0.01
216	NT		1.2	Great Bear Lake Plain		0.01
227	NT		1.3	Great Bear Lake Plain		0.01
218	NT		1.8	Great Bear Lake Plain		0.01
211	NT		2.0	Great Bear Lake Plain		0.02
222.5	NT		2.0	Great Bear Lake Plain		0.02
238	NT		2.2	Great Bear Lake Plain		0.02
198	NT		2.2	Great Bear Lake Plain		0.02
168.5	NT		2.3	Great Bear Lake Plain		0.02
246	NT		2.3	Great Bear Lake Plain		0.02
228	NT		2.4	Great Bear Lake Plain		0.02
209	NT		2.6	Great Bear Lake Plain		0.02
205	NT		2.7	Great Bear Lake Plain		0.02
242	NT		2.7	Great Bear Lake Plain		0.02
173.5	NT		2.8	Great Bear Lake Plain		0.02
151	NT		3.0	Great Bear Lake Plain		0.02
163	NT		3.0	Great Bear Lake Plain		0.02
226.5	NT		3.3	Great Bear Lake Plain		0.03
234	NT		3.5	Great Bear Lake Plain		0.03
155.5	NT		3.6	Great Bear Lake Plain		0.03
199.5	NT		3.6	Great Bear Lake Plain		0.03
226	NT		3.6	Great Bear Lake Plain		0.03
213	NT		4.4	Great Bear Lake Plain		0.04
240.5	NT		4.6	Great Bear Lake Plain		0.04
176	NT		7.2	Great Bear Lake Plain		0.06
208.5	NT		9.0	Great Bear Lake Plain		0.07
239.5	NT		9.4	Great Bear Lake Plain		0.08
157.5	NT		9.6	Great Bear Lake Plain		0.08
223	NT		12.1	Great Bear Lake Plain		0.10
160	NT		12.4	Great Bear Lake Plain		0.10
170	NT		13.5	Great Bear Lake Plain		0.11
200	NT		14.3	Great Bear Lake Plain		0.12
197	NT		16.8	Great Bear Lake Plain		0.14
152.5	NT		19.3	Great Bear Lake Plain		0.16
204	NT		19.3	Great Bear Lake Plain		0.16
191	NT		26.6	Great Bear Lake Plain		0.22

Km Post	Territory	Name	Drainage Area (km2)	Ecoregion	Culvert ID	Streamflow Factor
162	NT		28.3	Great Bear Lake Plain		0.23
229.5	NT		28.9	Great Bear Lake Plain		0.24
195.5	NT		30.5	Great Bear Lake Plain		0.25
192	NT		35.4	Great Bear Lake Plain		0.29
153.5	NT		49.7	Great Bear Lake Plain		0.41
208	NT		51.8	Great Bear Lake Plain		0.43
194.5	NT		52.2	Great Bear Lake Plain		0.43
190	NT		55.1	Great Bear Lake Plain		0.45
244	NT	Cabin Ck	121.2	Great Bear Lake Plain		1.00
220.5	NT	Caribou Ck	321.4	Great Bear Lake Plain		2.65
178	NT	Rengleng R	1494.8	Great Bear Lake Plain		12.33
31.5	NT		1.3	Peel River Plateau		0.01
31	NT		1.6	Peel River Plateau		0.01
61	NT		2.6	Peel River Plateau		0.02
29	NT		3.1	Peel River Plateau		0.03
40.5	NT		5.6	Peel River Plateau		0.05
252	NT		1.9	Tuktoyuktuk Coastal Plain		0.13
262	NT		2.0	Tuktoyuktuk Coastal Plain		0.14
272	NT		2.1	Tuktoyuktuk Coastal Plain		0.14
266	NT		2.3	Tuktoyuktuk Coastal Plain		0.16
254	NT		3.7	Tuktoyuktuk Coastal Plain		0.25
248	NT		10.0	Tuktoyuktuk Coastal Plain		0.68
259	NT	Havikpak Ck	14.6	Tuktoyuktuk Coastal Plain		1.00
265	NT		17.4	Tuktoyuktuk Coastal Plain		1.19
269	NT	Boot Ck	31.0	Tuktoyuktuk Coastal Plain		2.12
247	NT		366.8	Tuktoyuktuk Coastal Plain		25.12

CONCLUSIONS

A comprehensive climate change hydrologic response sensitivity assessment of Dempster Highway stream crossings has been carried out. The project components include a detailed sensitivity assessment of hydrological response to climate warming and associated permafrost thawing using the Cold Regions Hydrological Model (CRHM) along the Dempster Highway corridor. The project took advantage of numerical weather model reanalysis and climate model output datasets made available through participation in the NSERC Changing Cold Regions Network (CCRN). Forty one climate change scenarios, plus the control case, were assessed based on the increase in historical mean annual temperature in 1°C steps up to 5°C. Precipitation scenarios included changes for the summer period in 5 percent increments of mean precipitation to 30 percent, and winter precipitation in 10 percent increments up to 60 percent. These scenarios represent potential changes in future climate based on projected changes in temperature and precipitation developed by various global circulation models to the year 2080.

Study objectives included a quantification of the magnitude, timing and interaction of water balance components (precipitation, evapotranspiration, runoff and storage). Projected changes to hydrological response of extreme events have been summarized and flood frequency curves based on annual peak flows have been developed for Dempster Highway stream crossings. Independent assessments of the study basin flood frequency relationships suggest that the developed results provide reasonable peak flow design estimates for Dempster Highway ecosystem stream crossings for a range of climate change scenarios.

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