Northern Climate ExChange

independent information, shared understanding, action on climate change

COMMUNITY ADAPTATION PROJECT

PELLY CROSSING LANDSCAPE HAZARDS: GEOLOGICAL MAPPING FOR CLIMATE CHANGE ADAPTATION PLANNING

MARCH, 2011

Canada

Indian and Northern Affairs Canada
Affaires indiennes et du Nord Canada

Yukon College

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Energy, Mines and Resources

Yukon Geological Survey

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Production by Leyla Weston, Whitehorse, Yukon.

Front cover photograph: View to the northwest over the Pelly River, near Pelly Crossing, Yukon.

PREFACE

This report is part of a series of adaptation projects launched and produced by the Northern Climate ExChange, Yukon Research Centre, Yukon College. The scope of the report has been defined through a collaboration between the Northern Climate ExChange, Yukon Geological Survey, (Government of Yukon) and EBA Engineering Consultants Ltd. The project was funded by Indian and Northern Affairs Canada's Impact and Adaptations Program. The project began April 2010 and was completed in March 2011.

The objective of this project was to identify landscape hazards in Pelly Crossing and nearby surroundings by compiling geoscience data from various field studies and scientific reviews (*i.e.*, surficial geology and hydrology). This data was used to create a map of landscape hazards that delineate low, moderate and high-risk areas in the Pelly Crossing region. Potential impacts of a changing climate were incorporated in the identification of these three hazard zones.

This report is prepared as a guide, and not as a document upon which to base planning decisions. It is not intended for use as a basis for site selection for development, but rather as a guide in identifying areas that would require additional engineering studies, should development be desired.

The Northern Climate ExChange would like to continue doing Hazard Mapping Assessments for adaptation planning in other Yukon communities. We welcome any input or suggestions that you may have to improve future projects. Please contact me at (867) 668-8862, or by email at lkinnear@yukoncollege.yk.ca.

Lacia Kinnear

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Rick Janowicz is acknowledged for providing insight into the project. We are especially grateful to Leyla Weston who provided the technical editing and layout.

We would especially like to thank the Selkirk First Nation for supporting this project and welcoming us on their lands and within their Traditional Territory.

This project would not have been possible without the various summer field assistants whose commitment was unfailing. We would also like to acknowledge our Local Coordinator, Charlene Baker of Pelly Crossing, for the commitment that she has given throughout this project.

Funding for this project was provided by Indian and Northern Affairs Canada and the Government of Canada. Administrative support has been provided through Yukon College and the Yukon Research Centre.

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INTRODUCTION AND PROJECT DESCRIPTION

As outlined in the 2005 Arctic Climate Impact Assessment (Huntington and Weller, 2005), climate change is identified as a significant challenge for northern communities, where the impacts of a warming climate are already having a considerable effect. Many people living in small, isolated communities in northern Yukon are concerned about climate-related risks in their local area. Because adverse impacts are a reality, we must implement measures to reduce or moderate the negative effects of climate change. This is known as climate change adaptation. The first step in adaptation planning is the identification and characterization of vulnerabilities. Only then can we identify adaptation needs, which will result in the development of new policies and programs, as well as provide opportunities to reduce the negative impacts of current and future climate change.

There are two important terms to define when discussing climate change adaptation:

- vulnerability - refers to the susceptibility to harm in a system in response to a stimulus or stimuli; and
- adaptive capacity - reflects a community's potential or ability to address, plan for, or adapt to risk.

Vulnerability, at a local level, is conditioned by social, economic, cultural, political and biophysical conditions and processes operating at multiple temporal and spatial scales and in turn affects community exposure and adaptive capacity. To understand vulnerabilities within the landscape, we must assess the environmental conditions that may be affected by climate change and may therefore pose hazards to safe and sustainable development. Factors to be considered include permafrost and ground ice, surface water drainage, groundwater dynamics, surficial geology and slope stability. These factors combine to create landscape hazards that can pose risks to infrastructure, and may be exacerbated in a changing climate. Insights related to these hazards can be used to direct investigations that will support future adaptation and town planning processes.

The objective of this project is to identify landscape hazards in the Village of Pelly Crossing and nearby surroundings (Figure 1) by gathering and mapping geoscience data (surficial geology and hydrology). This data is used to create a map of landscape hazards based on geotechnical properties that suggest low, moderate and high-risk areas in the Pelly Crossing region. Potential impacts of a changing climate are incorporated in the identification of these three hazard zones. This report is prepared as a guide and not as a document upon which to base planning decisions. It should not be used for site selection for development, but rather treated as a guide in identifying areas that would require additional engineering studies, should development be desired.

This project is a partnership between the Northern Climate ExChange, Yukon Research Centre, Yukon College; Yukon Geological Survey; and EBA Engineering Consultants Ltd.

APPROACH AND METHODS

The goal of hazards mapping in the Pelly Crossing region is to identify landforms, sediments and landscape processes that may pose a threat to ongoing and future development under current and changing climate conditions. Surficial mapping studies were undertaken in order to determine the stability of surface sediments; detailed studies of hydrological processes were also carried out. Mapping and describing existing landforms and sediments was completed through

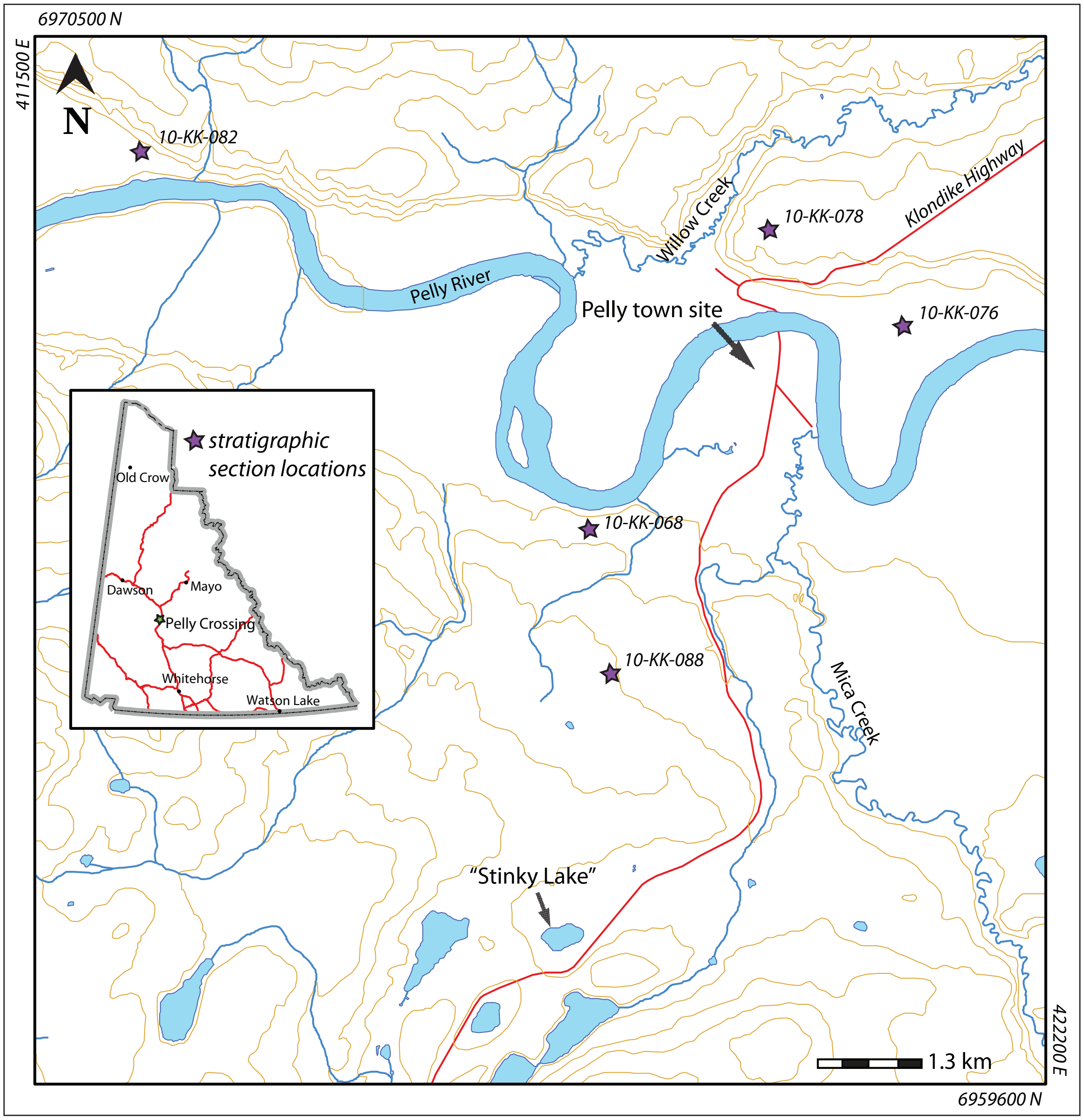

***Figure 1.** Location of study area. Locations of stratigraphic sections are shown.*

surficial geological mapping at a scale of 1:10 000 during the summer of 2010. Earlier mapping by Jackson (1997), as well as initial reviews of existing data (*i.e.,* borehole logs, geological maps and reports) demonstrated that hydrological processes have the greatest impact on community sustainability and safety.

To address the need for additional information related to the geology and hydrology of Pelly Crossing, detailed investigations were initiated to assess the current hydrological conditions in the community. Final hazard identification was completed by combining the results of the hydrological studies with surficial geological mapping to create a ranking of potential landscape hazards for distinct geological units within, and surrounding, the community of Pelly Crossing. Hazard rankings also include projected changes in climate variables such as temperature, precipitation and seasonality.

REGIONAL SETTING

The Village of Pelly Crossing (62°50′ N, 136°35′ W; see Figure 1) is located in central Yukon, on the floodplain of the Pelly River. Pelly Crossing is located within the Traditional Territory of the Selkirk First Nation. The community was settled after the Klondike Highway was built near the traditional First Nation community of Fort Selkirk. Pelly Crossing is now the administrative and social centre of the Selkirk First Nation.

SOCIAL SETTING

Population

The population of Pelly Crossing was 346 in June 2010. Population density per square mile was 9. The population grew by 6.4% between June 2009 and June 2010 – the second highest proportional shift in population in the Yukon Territory during that period. This rate of mobility is relatively common in Yukon communities that have less than 400 people (Yukon Bureau of Statistics (YBS), 2010). At the time the 2006 population census was conducted, there were 115 men for every 100 women in Pelly Crossing (YBS, 2007). The proportion of the population declaring aboriginal identity in 2006 was 85% (YBS, 2008).

Economy

At the time of the 2006 census, 20% of Pelly Crossing residents reported being employed in the service industry. Selkirk First Nation is the major employer in the community (Selkirk First Nation (SFN), 2007); the public sector employed 17% of the population in 2006. The remainder of local occupations constituted trades (17%), management occupations (11%), business, finance and administration (11%), primary industry (9%), arts/culture/recreation (9%) and processing/manufacturing (6%).

Infrastructure

The Selkirk First Nation operates a recreation centre, gas station, curling rink, seasonal swimming pool, and baseball diamond. The community also has a fire hall, a school (Eliza Van Bibber School), a nursing station, an RCMP detachment, a solid waste disposal facility and a sewage lagoon, which are provided by the territorial government (SFN, 2007). In 2006, there were 115 private dwellings occupied in Pelly Crossing. The bulk of these buildings (~74%) were built between 1986 and 2006. This correlates to the proportion of housing in the community considered to be substandard (~81%) (SFN, 2007). The community has also recently constructed a low-flow water system under the Pelly River to supply water to the Willow Creek and John Ra subdivisions on the opposite side of the river to the main village. The construction of 31 new homes has also been proposed (SFN, 2007).

PHYSICAL SETTING

Physiography

Pelly Crossing is located on the banks of the Pelly River in the broad Pelly River valley in the Central Yukon Plateau ecoregion. The physiography of the area is characterized by rounded and rolling hills, plateaus, and broad valleys surrounded by higher mountain ranges. Broad glaciofluvial terraces occur in the Pelly River valley and step down to the river's current elevation of ~500 m above sea level (a.s.l.).

VEGETATION

Vegetation in the Pelly region is dominated by northern mixed deciduous and coniferous forest (boreal forest), consisting predominantly of white spruce (*Picea glauca*) and minor amounts of black spruce (*Picea mariana*), as well as paper birch (*Betula papyrifera*). Due to frequent forest fires, aspen (*Populus tremuloides*) and lodgepole pine (*Picea contorta*) are prevalent at low elevations. South-facing slopes commonly have artemesia grasslands or steppe vegetation. The understory consists of feathermoss, willows, sagewort and ericaceous shrubs; sphagnum mosses are more common in wetter terrain.

CONTEMPORARY CLIMATE

The Pelly Crossing region is located in the Central Yukon Basin climate zone, and has a subarctic continental climate (Smith *et al.*, 2004) due to the topographic effects of the St Elias and Coast mountains (Wahl *et al.*, 1987). This climate zone is characterized by short, warm summers and long, cold winters. Pelly Crossing has major diurnal and seasonal temperature ranges and strong altitudinal temperature effects that vary with the seasons. Mean January temperature in Pelly Crossing is -27.9°C, while mean July temperature is 15.1°C, based on 30-year (1961-1990) climate normals measured at the Pelly Ranch meteorological station (62°49'N, 137°22'W; Environment Canada, 2010). The Pacific Ocean is the main source of moisture for the region (Smith *et al.*, 2004). The 30-year average precipitation at the Pelly Ranch meteorological station is 298.8 mm, and approximately 38% or ~1/3 of this precipitation falls as snow during the winter season (Environment Canada, 2010). Month-by-month climate normal data are summarized in Figure 2.

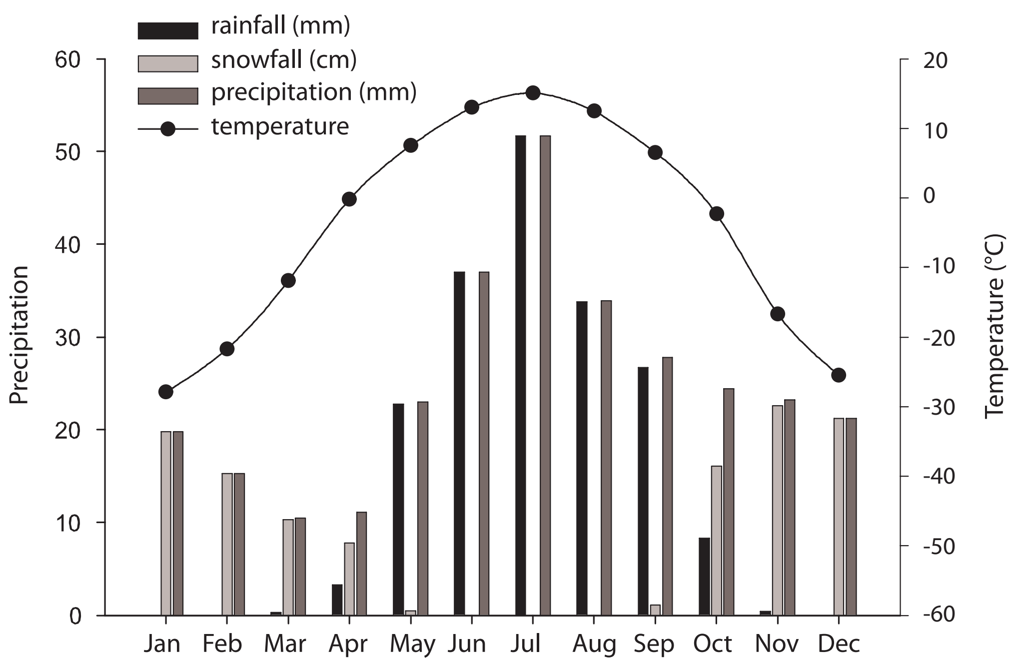

Figure 2. *Climate normal (1961-1990) temperature and precipitation for the Pelly Ranch meteorological monitoring station (Environment Canada, 2010). To calculate total precipitation in millimetres, snowfall was converted to snow water equivalent (SWE) and summed with rainfall.*

PAST CLIMATE TRENDS

To examine past trends in climate at several sites in the Yukon Territory, Purves (2010) examined monthly, daily and hourly climate archives using the Climate Manager program. Data were acquired by Environment Canada and the Yukon Forest Service (Purves, 2010; Environment Canada, 2010). Trends in collected data were examined using linear regression analysis from data plots developed in Microsoft Excel. In some cases, climatic trends have been extended beyond the period of record to project potential future change. While adequate data was not available to conduct such analysis for the Pelly Crossing region, an analysis for the Mayo region (~100 km northeast of Pelly Crossing) was conducted. Results from this analysis are included here, because they provide context within which to frame contemporary observations of change in the region. The subsections below describe trends in several climate parameters described by Purves (2010).

Mean Daily Winter Minimum Temperature

Data is available for every year between 1925 and 2009 inclusive, with the exception of 1926. There was a period of strong cooling in the middle of the last century, between 1943 and 1975, at a rate of ~1.6°C/10 yrs. Over the past thirty years, there has been a strong warming trend, at a rate of ~0.7°C/10 yrs. The mean daily minimum winter temperature for Mayo over the entire period of record increased by ~0.2°C/10 yrs. The mean minimum winter temperature between 1966 and 1977 was –29.3°C, while the mean minimum between 2000 and 2009 was -23.3°C.

Mean Daily Maximum Summer Temperature

Mayo experienced a period of declining mean daily maximum summer temperatures between 1941 and 1964, at a rate of ~5°C/10 yrs. Mean daily maximum summer temperatures increased over the last 30 years by ~0.4°C/10 yrs. Overall, for the full period of record, temperature increases are inferred to be ~0.1°C/10 yrs.

Mean Annual Temperature

Mean annual temperature data is available between 1929 and 2009 inclusive. There was a period of declining mean annual temperature, spanning 1947-1977. Mean annual temperature has increased over the last thirty years by ~0.3°C/10 yrs. Overall, for the full period of record, mean annual temperature is inferred to have increased by ~0.3°C/10 yrs.

Total Winter Precipitation

The period of record for this parameter encompasses the winters of 1925-2009, with the exception of 1926, 1946, 1994 and 1995. Mayo shows a very significant increase (~56%/10 yrs) in winter precipitation from 1933 to 1966, amounting to a nearly three-fold increase. There was a large decline in total winter precipitation between 1966 and 1968, and then an increase of ~7%/10 yrs for the thirty years between 1980 and 2009. However, when the period of analysis is limited to 1966-2005, the increase in winter precipitation is ~2%/10 yrs, demonstrating the effects of strong annual variability in this dataset. Over the entire period of record for Mayo, there is only a slight decline in total winter precipitation.

Total Summer Precipitation

Mayo has records of summer precipitation from 1926 to 2009, with the exception of 1995. There do appear to be some alternating periods of wetter and drier summers, but the overall trend shows an increase in summer precipitation of ~3%/10 yrs (*i.e.*, ~4 mm/10 yrs). Over the past thirty years, summer precipitation has increased ~6 mm/10 yrs, or 44%.

Total Annual Precipitation

The period of record for Mayo for total annual precipitation spans from 1927 to 2009. There is a trend towards increasing precipitation by ~2%/10 yrs (~6 mm/10 yrs) over the entire period of record. Over the past thirty years, annual precipitation has increased 67% (19 mm/10 yrs).

Snow on Ground for February 28

Data is available from 1955 to 2010, with the exception of 1995. This record shows a strong and steady decrease, amounting to ~11%/10 yrs (~7 cm/10 yrs). Over the past thirty years, there is a very slight increase in snow on ground as of February 28 by 7%.

Days Below –40°C

Data for Mayo indicates long-term cycles in the number of days below -40°C, but over the eighty years of available data, spanning 1929-2009, there is an indication of ~1 fewer day below -40°C per decade. Over the past thirty years, the rate has increased, and there are ~3 fewer days per decade below -40°C. If this trend were to continue, there would be no days below –40°C by 2047.

Frost-Free Days

Data for Mayo indicates long-term cycles in the number of frost-free days. However, when the entire period of record (1924-2009) is examined, there is a trend towards an increasing number of frost-free days at a rate of ~5 days/10 yrs (*i.e.*, an 84% increase). Over the past thirty years, this value has declined slightly, to an increase of ~4 frost-free days per century, or a 32% increase.

ENVIRONMENTAL SETTING OF THE PELLY CROSSING REGION

HYDROLOGY

Surface hydrology

The subwatershed of the Pelly Crossing region forms part of the Yukon River watershed, which covers 260 000 km^2 or 54% of Yukon Territory (Smith *et al.*, 2004). The area is situated in the Interior Hydrologic Region of the Territory, where drainage from the southern foothills of the Selwyn Mountains flows west to the Yukon River. The first and second-order streams descending from the foothills are generally steep and relatively short, producing rapid, flashy streamflow responses during the spring melt and some of the highest peak flows in Yukon. Mean annual runoff in the region is moderately high compared with other regions of the Territory, at 236-385 mm (Smith *et al.*, 2004). Peak river flows in the Interior Hydrologic Region generally occur in May and June in response to snowmelt inputs during the spring freshet, while secondary discharge peaks in response to late summer and autumn rainfall are also possible. Lowest flows are typically exhibited in this region in March and April, when groundwater contributions to streamflow, the only inputs to river discharge at this time, are minimal (Janowicz, 2008).

The Pelly River, which flows through the town of Pelly Crossing and is one of the principal tributaries of the Yukon River, drains a watershed of 49 000 km^2 (Water Survey of Canada, 2010). Its main tributaries are the Ross and MacMillan rivers. (Note: when referring to the Pelly River system or Pelly River watershed, both the Ross and MacMillan rivers are herein always included.) To monitor water levels in the Pelly River watershed, the Water Survey of Canada (WSC) has maintained gauging stations spanning the headwater tributaries of the Pelly River (including the Ross and MacMillan rivers) to its mouth, some of which provide real-time hydrometric data.

(See Table 1 for a summary of station information and Figure 3 for a map of their locations.) The WSC reports daily average, monthly average, and peak yearly discharge for each station (Water Survey of Canada, 2010). A hydrograph of monthly average discharge for the Pelly River at its mouth (the longest available record in the region, spanning 1953-2009) demonstrates the typical seasonal pattern of a river in Yukon's Interior Hydrologic Region, *i.e.*, having rapid increases in discharge in May and June, followed by a recession through summer and autumn (Figure 4). Average monthly discharge is low through the winter months, when groundwater is the only input to the river, and the lowest flows occur in March, prior to the spring freshet. Figure 4 also illustrates monthly average discharge for 1964, a year in which peak June discharge greatly exceeded the 1964-2009 average discharges, and for 2002, a year in which average June discharge was much below the 1964-2009 averages. The 2002 hydrograph also demonstrates the effects late-season precipitation can have on Pelly River discharge, as is exhibited by the above-average flows between August and October.

Table 1. Summary of Water Survey of Canada stations in the Pelly Crossing region (Water Survey of Canada, 2010). Stations are listed roughly in the order they appear from the headwaters of the Pelly River to its mouth at the Yukon River.

Station Name	Station ID	Latitude	Longitude	Gross Drainage Area (km2)	Parameter	Period of Record
South MacMillan River at Canol Rd	09BB001	62°55′30″N	130°32′30″W	997	discharge	1974-1998
Pelly River below Fontin Creek	09BA002	62°1′50″N	130°36′10″W	5020	discharge	1986-1994
Pelly River at Ross River	09BC002	61°59′12″N	132°26′54″W	18400	discharge	1951-1977
Pelly River below Vangorda Creek	09BC004	62°13′20″N	133°22′40″W	22100	discharge	1970-2010
MacMillan River near the mouth	09BB002	62°53′36″N	135°30′36″W	13800	discharge	1984-1998
Pelly River at Pelly Crossing	09BC001	62°49′47″N	136°34′50″W	49000	discharge	1951-2010

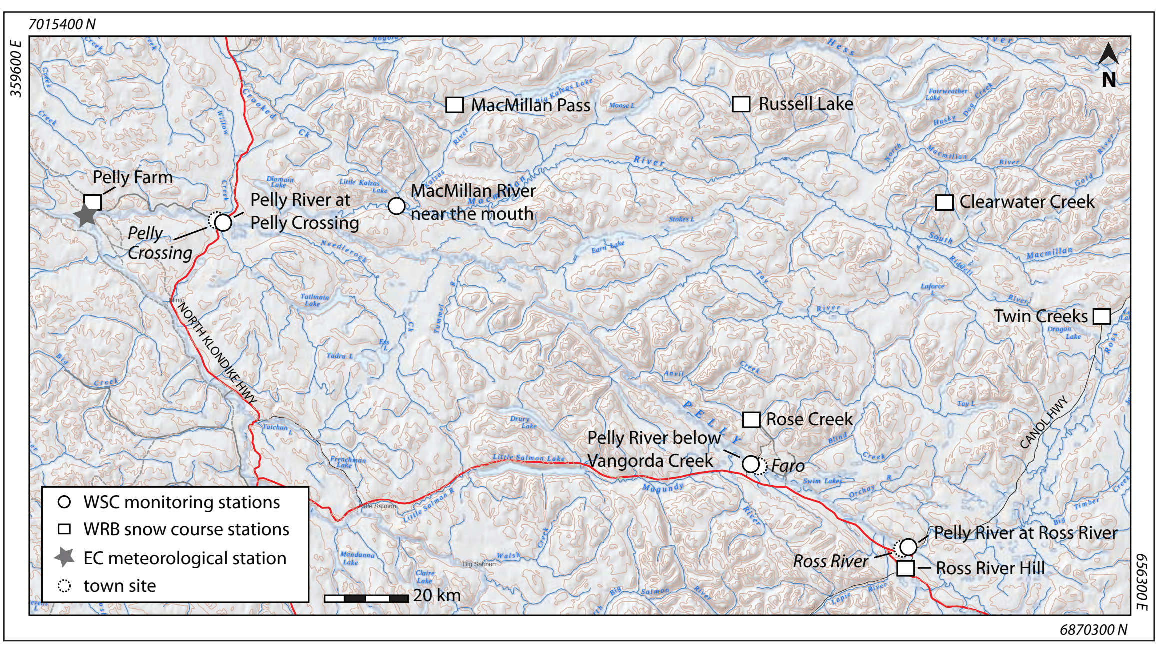

Figure 3. *Overview map of the Pelly Crossing study area, illustrating meteorological, river discharge and snow course monitoring stations referenced in this report. Only stations proximal to Pelly Crossing are shown. WSC – Water Survey of Canada; WRB – Water Resources Branch, Yukon government; EC – Environment Canada.*

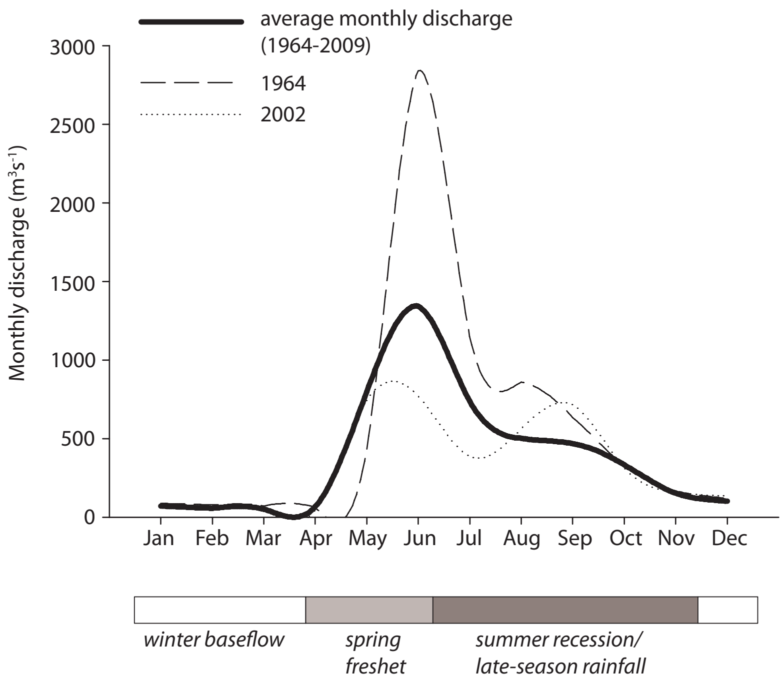

Figure 4. *Hydrograph depicting average monthly discharge for the Pelly River at Pelly Crossing (heavy solid line). Also shown are hydrographs for the years 1964 (long-dashed line) and 2002 (dotted line), demonstrating high and low June discharge, respectively. The 2002 hydrograph also exhibits a secondary peak in late summer/autumn in response to late-season rainfall (Water Survey of Canada, 2010).*

Peak yearly discharge also provides a basis for assessing the dynamics of surface water hydrology of the Pelly River and its tributaries. Figure 5 presents peak spring discharge for all WSC stations along the Pelly River and for its tributaries (see Table 1 for details of WSC station locations). Figure 5 clearly demonstrates that peak discharge events measured at headwater stations are mirrored in the discharge records of downstream stations, highlighting the importance of headwater snowmelt inputs to the Pelly River system. It is also possible that in the years in which headwater snowpacks are deep (producing high volumes of snowmelt and high, peak spring discharge events), downstream snowpacks are also deep. Thus, snowmelt contributions may continue to be significant along all reaches of the Pelly River and act as a key input to discharge along the river system.

Groundwater

As described, the Village of Pelly Crossing is built in the Pelly River valley, on the natural floodplain of the Pelly River. Water levels in several private and commercial wells around Pelly Crossing are recorded in a database maintained by the Government of Yukon, Water Resources Branch (Water Resources Branch, 2010a). These data generally show that water levels are ~5-10 m below ground surface in the town site of Pelly Crossing and in the vicinity of the RCMP station, Eliza Van Bibber School, community hall, store and nursing station, and up to ~23 m below ground surface in the Jon Ra Subdivision. While it is inappropriate to use these data to interpret groundwater depths around the town of Pelly Crossing (because they lack georeference information and only represent conditions at a single point in time), it cannot be disputed that the groundwater table is relatively shallow in the town of Pelly Crossing.

Winter snowpacks

The Government of Yukon, Water Resources Branch maintains several snow courses in the Pelly River watershed during the latter part of the winter season. The locations and elevations of these snow courses, as well as their periods of record, are summarized in Table 2 (see Figure 3 for locations; Water Resources Branch, 2010b). Generally, snow depth was measured at each snow course on February 1st, March 1st, April 1st, May 1st and May 15th until the early 1980s, when the February 1st measurement was no longer recorded. The May 15th snow depth is not always measured at all stations in all sampling years. Snow water equivalent (SWE) is also reported for all sampling points.

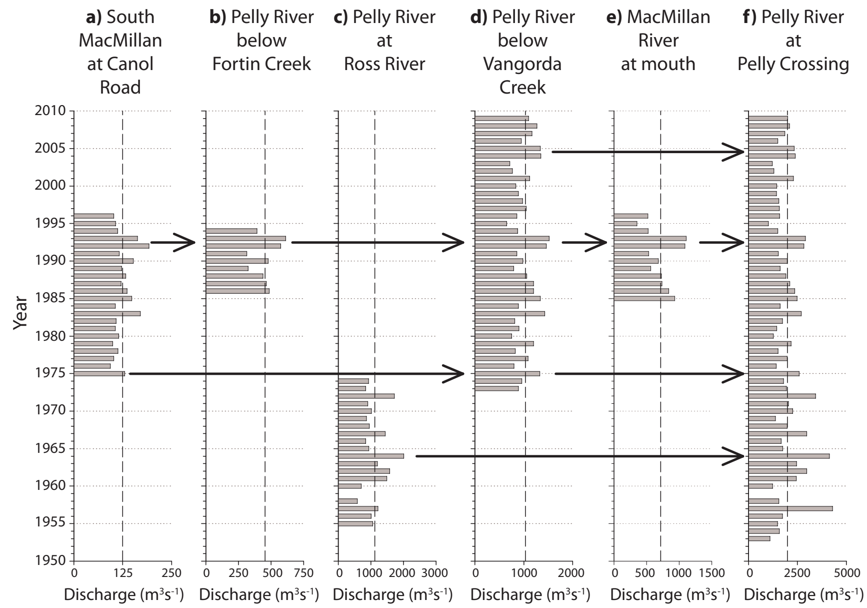

Figure 5. *Peak discharge (in m^3s^{-1}) at WSC stations located at the headwaters of the Pelly River (plot a) to its mouth at the Yukon River (plot f; Water Survey of Canada, 2010). Note: plot d shows level in "metres a.s.l." rather than discharge. Vertical, long-dashed lines indicate average peak discharge (or level, e.g., plot d) for each station for its period of record. Arrows highlight events that are equal to, or are above-average peak discharge (or level, e.g. plot d), demonstrating how peaks in headwater discharge propagate downstream.*

Table 2. Pelly Crossing region snow course locations, elevations and periods of record (Water Resources Branch, 2010b). Stations are listed roughly in the order they appear from the headwaters of the Pelly River to its mouth at the Yukon River. Location information is given with as much precision as has been reported by Water Resources Branch, Yukon government. Stations marked with an asterisk have been excluded from the analysis presented in this report because of their short periods of record.

Station Name	Station ID	Latitude	Longitude	Period of Record	Elevation (m)
MacMillan Pass*	09BB-SC02	63°11′N	135°11′W	1981-1982	1495
Fuller Lake	09BB-SC03	62°58′25″N	130°12′0″W	1986-2010	1126
Burns Lake	09BA-SC04	62°17′21″N	129°56′41″W	1986-2010	1112
Finlayson Airstrip	09BA-SC05	61°41′26″N	130°46′36″W	1987-2010	988
Twin Creeks	09BA-SC02	62°37′11″N	131°16′41″W	1977-2010	900
Hoole River	09BA-SC03	61°32′3″N	131°35′28″W	1977-2010	1036
Ross River Hill	09BA-SC01	61°56′N	132°28′W	1975-1985	975
Clearwater Creek*	09BB-SC01	62°56′N	132°14′W	1977, 1982	1465
Rose Creek	09BC-SC01	62°20′13″N	133°22′50″W	1975-1985, 2005-2009	1000
Russell Lake	09BB-SC04	63°11′59″N	133°28′45″W	1987-2010	1060
Pelly Farm	09CD-SC03	62°50′N	137°20′W	1986-2010	472

To facilitate comparison between SWE at each snow course station, SWE values have been converted to z-scores, using the following formula for each value in a snow course dataset.

$$z\text{ - }score = \frac{value\text{ - }mean}{stdev}$$

Z-scores provide an indication of the variation of a particular data point around the mean, while preserving the patterns inherent in the dataset. Importantly, because they are a unitless parameter, z-scores are readily comparable between data from different sites.

Figure 6 presents compiled SWE z-score values for all snow courses. The dotted line, tracing a z-score of 0, provides a point of reference against which to evaluate potential changes in SWE over the periods of record. Based on a visual assessment, three potential periods of variability can be identified in this record, although the length of record for each snow course varies (see Table 2 for details on periods of record for each snow course). Period A, which spans 1977-1985, represents a period in which SWE values appear to fluctuate around 0. Period B, which spans 1986-1995, appears to exhibit SWE values generally above average, while Period C (1996-2009) appears to exhibit variable SWE values, with low values until ~2003 followed by large fluctuations on a 2-3 year basis until present.

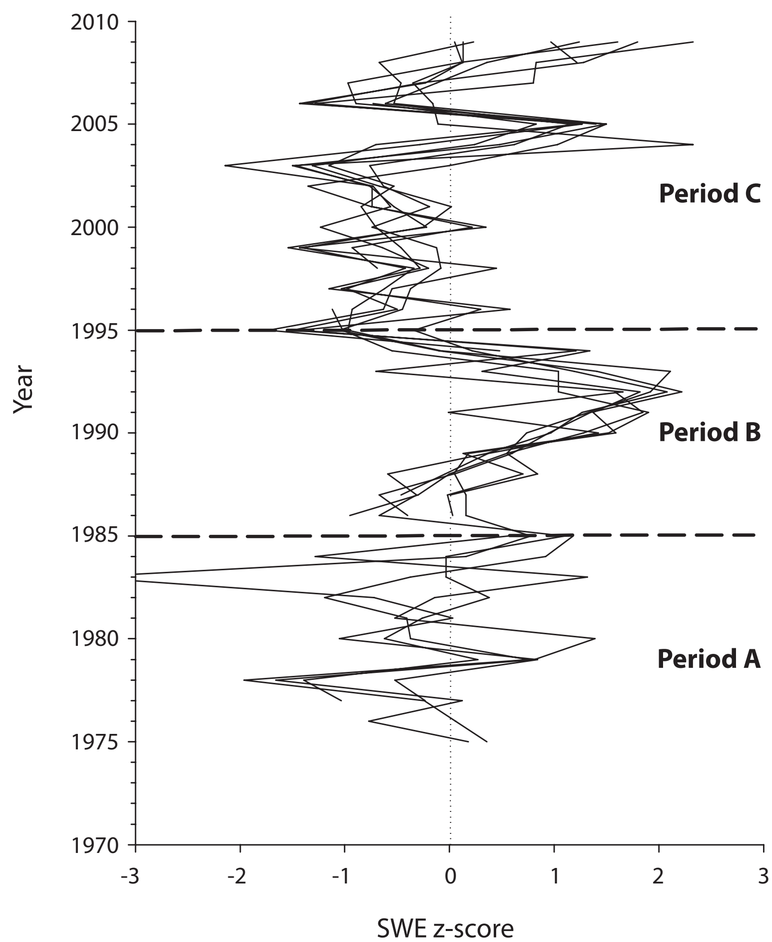

***Figure 6.** Z-scores of snow water equivalent (SWE) for snow courses in the Pelly Crossing region (see Table 2 for details about each snow course; Water Resources Branch, 2010b). Data from each snow course have been superimposed on this figure. The vertical dotted line represents a z-score of 0 and acts as a reference point, while the horizontal heavy-dashed lines indicate interpreted periods of decadal-scale shifts in SWE.*

To further examine the relationship between spring discharge on the Pelly River and winter snowpack, March 1st SWE is compared with peak spring discharge on the Pelly River at Pelly

Crossing (Figure 7). This Water Survey of Canada (WSC) station was chosen as the comparison site because it has the longest record of river discharge measured along the Pelly River and its tributaries (1953-2009), and because variations in peak discharge at this station reflect those of upstream stations (see Figure 5). Snow course data from March 1st were chosen for comparison because this measurement was consistently taken throughout the periods of record at all snow course stations (*i.e.*, both before and after the early 1980s). Furthermore, April 1st snow depths sometimes exhibit declines from March 1st values, indicating that melting may have begun by April 1st in some years. Hence, March 1st values represent a more reliable indication of the depth of the winter snowpack available to augment river discharge during the spring melt. SWE is presented in Figure 7, rather than snow depth, because SWE represents the amount of water contained in the snowpack and hence is a good indicator of available runoff during the snowmelt period. In fact, SWE is the most hydrologically important characteristic of snowcover (Walsh, 2005). Both SWE and Pelly River discharge are presented as z-scores, as this facilitates comparison between these two different parameters.

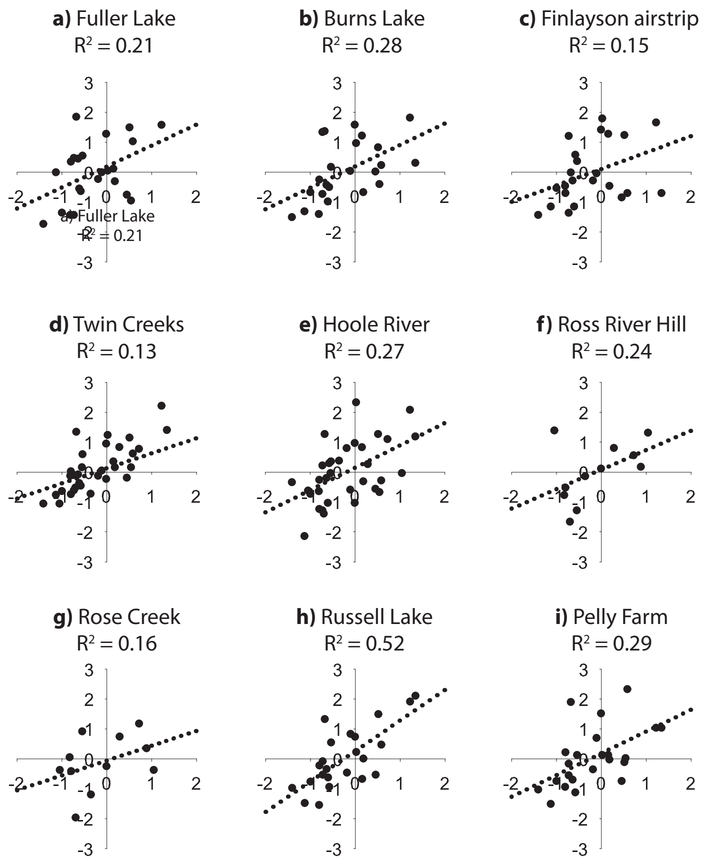

Figure 7. *Crossplots of z-scores illustrating peak spring discharge on the Pelly River at Pelly Crossing (plotted on the x-axis; Water Survey of Canada, 2010) versus March 1st SWE at Pelly River watershed snow course stations (plotted on the y-axis; see Table 2 for station information; Water Resources Branch, 2010b) over their corresponding periods of record. Stations are listed roughly in the order they appear from the headwaters of the Pelly River (plot a, Fuller Lake) to its mouth at the Yukon River (plot i, Pelly Farm). Linear regression lines have been calculated based on each dataset, and are shown as diagonal dotted lines. R^2 values, indicating the strength of the correlation between discharge and SWE (developed based on the linear regression for each plot), are given for each snow course station.*

First, to examine the correlation between March 1st SWE and spring peak discharge on the Pelly River, z-scores for each snow course are plotted against Pelly River discharge z-scores and the intersection of the two creates a point, as is shown on the crossplots in Figure 7. The strength of the correlation between peak spring discharge and March 1st SWE is defined by the R^2 value, which in this case is being used to describe the strength of the relationship between variables in a dataset. An R^2 of 0 indicates no correlation between the parameters being examined, while the highest possible correlation has an R^2 value of 1. In this dataset, the weakest correlation is with the Twin Creeks snow course station ($R^2 = 0.13$). The strongest correlation between discharge and SWE is with the Russell Lake snow course station ($R^2 = 0.52$).

Secondly, March 1st SWE values for Russell Lake (the record with the highest correlation; $R^2 = 0.52$) and Hoole River (the longest snow course record with good correlation; $R^2 = 0.27$) are plotted alongside Pelly River spring peak discharge (Figure 8). Again, it is evident that those years that have high March 1st SWE values produce above-average peaks in downstream discharge. This figure also highlights the three periods of potential SWE variability that was identified in Figure 6. As described, Period A (1974-1985) appears to exhibit March 1st SWE values that fluctuate around average conditions (see Figure 6). Peak spring discharge on the Pelly River during this 8-year period exceeds average peak spring discharge on 3 occasions, equivalent to once every 2.6 years (Figure 8). During Period B (1986-1995), when SWE appears to have been generally above-average, there were 4 above-average spring peak discharge events, equivalent to once every 2.25 years (Figure 8). Finally, during Period C (1996-2009), when SWE was initially low and then fluctuated widely around average, peak spring discharge exceeded the average on 5 occasions, equivalent to once every 2.8 years (Figure 8).

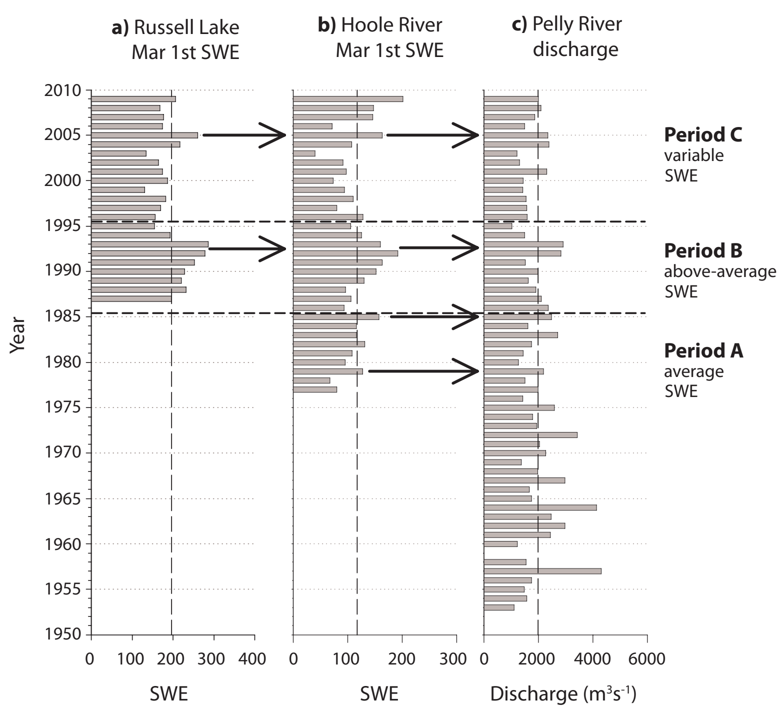

Figure 8. *March 1st SWEs for snow courses at Russell Lake and Hoole River (plots a and b respectively; Water Resources Branch, 2010b), and peak spring discharge on the Pelly River at its mouth (plot c; Water Survey of Canada, 2010). Vertical dashed lines indicate average conditions for each parameter respectively. Heavy horizontal dashed lines border potential periods of SWE variability identified in Figure 6, which are labeled along the right margin of this figure. Arrows identify examples of high SWE values present in both snow course records and corresponding downstream spring discharge peaks.*

While the comparisons between SWE and peak spring discharge presented here and in the above paragraphs are rudimentary and likely reflect variability inherent in the system, they will serve as useful points for discussion when examining the effects of on-going climate change and variability on the hydrology of the Pelly Crossing region, discussed further in the sections below.

SURFICIAL GEOLOGY

Surficial geology in the Pelly region is dominated by glacial and deglacial sediments deposited over the past ~2.6 million years. The community of Pelly Crossing is located on a broad gravel terrace of the Pelly River that was likely deposited near the end of the last glaciation. The modern Pelly River continues to dominate the erosion, transportation and deposition of surficial materials in the Pelly River valley today.

GLACIAL HISTORY

Glacial limits in the Pelly region were originally noted by Bostock (1966) while the surficial geology was later mapped by Jackson (1997). Bostock (1966) recognized four advances of the Cordilleran Ice Sheet: Nansen, Klaza, Reid and McConnell (from oldest to youngest respectively). However, subsequent authors have rarely distinguished between events that are older than the Reid advance, and collectively refer to these older glacial episodes as the 'Pre-Reid' glacial event, which represents up to seven glacial advances (Figure 9). Only the penultimate glacial advance (Reid advance) is easily distinguishable near Pelly Crossing. The Reid advance was more extensive than the most recent (McConnell) advance, and reached its westward limit in the Pelly River valley some 40 km west of Pelly Crossing near Fort Selkirk (Figure 10). This advance likely took place ~130 000 years before present and inundated all but the highest peaks in central Yukon (Ward *et al.*, 2008; Stroeven *et al.*, 2010).

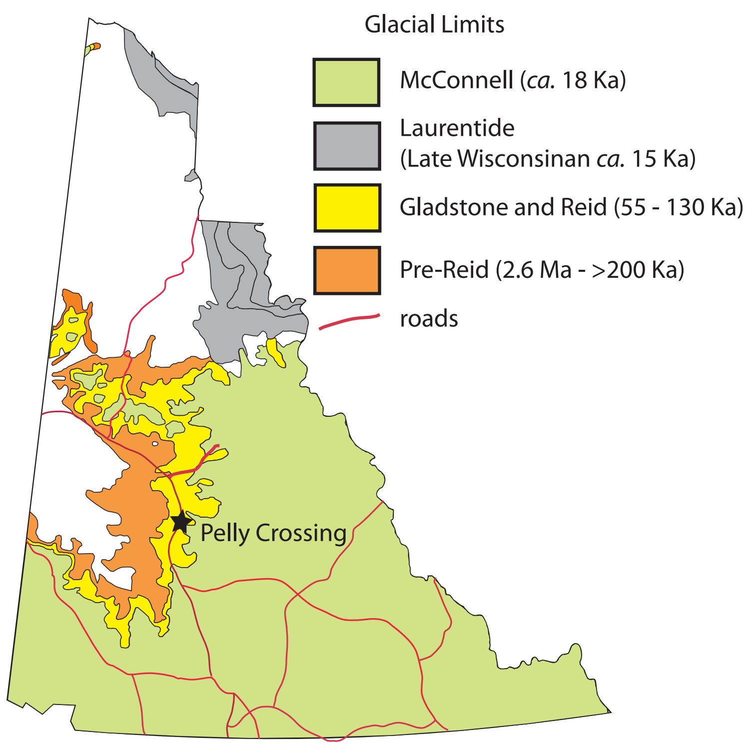

***Figure 9.** Simplified glacial limits map of the Yukon (modified from Duk-Rodkin, 1999).*

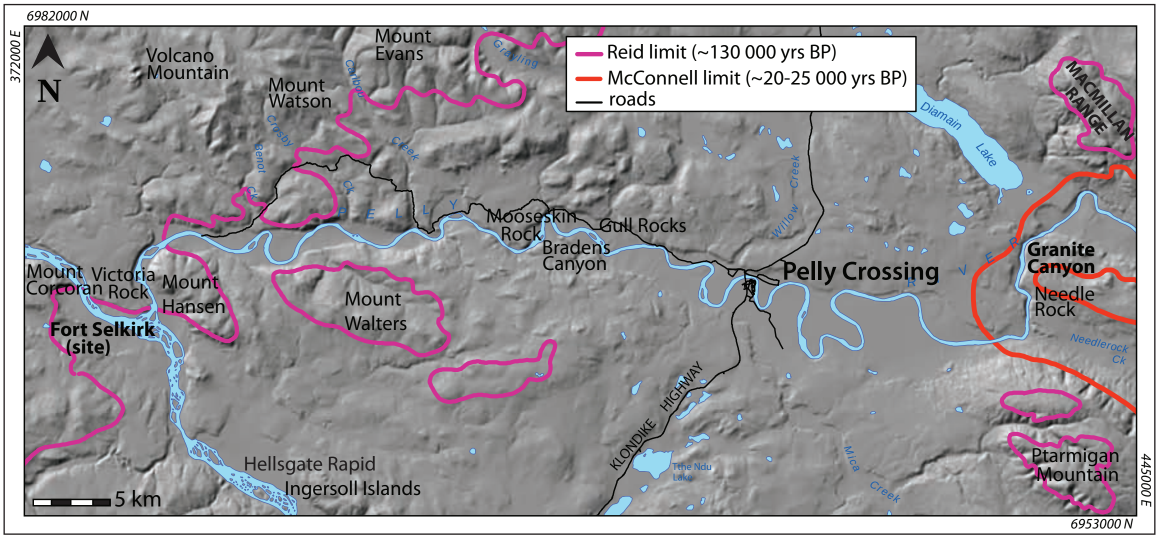

Figure 10. *Reid and McConnell glacial limits near Pelly Crossing (modified from Duk-Rodkin, 1999).*

Ice from the Reid glacial advance filled the Pelly River valley and deposited moraine on valley sides and upland surfaces around the community of Pelly Crossing. As the ice sheet receded from the region, it drew back toward the east and continued to discharge meltwater through the Pelly River valley. Some of this meltwater was likely impounded near the margins of the retreating ice and formed small glacial lakes in the Pelly River valley. Proglacial discharge during Reid deglaciation is responsible for the highest terrace surfaces on both sides of the Pelly River valley above the community of Pelly Crossing. As deglaciation progressed, the highest terraces would have been incised as the Pelly River attained a lower, non-glacial base-level.

The last glacial advance in Yukon, known as the McConnell Glaciation (~20-25 000 years before present) advanced westward from the Selwyn Mountains but was not extensive enough to reach the study area. The McConnell glacial advance reached its westward limit only 15 km east of Pelly Crossing near Granite Canyon (Figure 10). During this advance, glacial meltwater flowed through the Pelly River valley and contributed to additional glaciofluvial terraces on either side of the Pelly River near the community of Pelly Crossing. These McConnell terraces are lower in elevation than the older Reid terraces, but still occur above the modern floodplain of the Pelly River. It is likely that the terrace on which the community is built was deposited near the end of the last glaciation as the Pelly River began to achieve its post-glacial base-level.

After ice retreated and the remaining lakes drained, a large volume of fine-grained glaciolacustrine and glacially scoured material was available to be transported and reworked by eolian (wind) processes. Fine sand and silt was deposited as loess veneers and blankets over much of the landscape and likely remained a dominant sedimentary process until moister conditions prevailed and vegetation became established ~9000 years ago (Wolfe *et al.*, 2011). Since that time, eolian deposition has been limited to cliff-top loess deposition above unvegetated sediment bluffs.

Permafrost growth in poorly drained, fine-grained materials in the Pelly Crossing region likely began during the Holocene (~10 000 years ago until present) and is responsible for some shifts in vegetation cover (Burn *et al.*, 1986). Ongoing incision of glacial sediments by the Pelly River continues to transport large volumes of sediment within the map area.

SURFICIAL MATERIALS

The surficial geology for Pelly Crossing (*see accompanying map "Surficial Geology of Pelly Crossing"*) has been mapped based on existing subsurface data, previous surficial geology mapping (Bostock, 1966; Jackson, 1997), air photo interpretation, and ground truthing. New data includes textural information for more than 20 landforms (Appendix A) and descriptions of riverbank and road cut exposures. Previously acquired subsurface geological data is available from boreholes, test pits, and water well logs provided by EBA Engineering Consultants Ltd. (R. Trimble, EBA Engineering, pers. comm., 2010).

Surficial materials in the Pelly Crossing area are derived from glacial, fluvial, colluvial, eolian and organic processes. Each process, or combination of processes, forms distinct materials that can be characterized based on the grain size, sorting, structure and general distribution. Detailed descriptions of the surficial materials found in the Pelly Crossing map area are located in the map legend (*see accompanying map "Surficial Geology of Pelly Crossing"*).

Moraine deposits include materials that have been deposited directly by a glacier or ice sheet without modification by any other agent of transportation. Moraine deposits in the Pelly Crossing region are characterized by poorly sorted, moderately compacted material lacking stratification and containing a heterogeneous mixture of particle sizes, usually in a matrix of sand, silt and clay (Figure 11). In general, moraine deposits in the map area are found on upland surfaces above the Pelly River valley. Moraine deposits on these surfaces are relatively uniform undulating plains and blankets that drape the underlying bedrock. Because moraine deposits contain fine silt and sand, they can be poorly drained and prone to the development of permafrost and thick organic deposits.

Figure 11. *Moraine deposits on hillslopes above the Pelly River valley are composed of a heterogeneous mixture of particle sizes.*

Glaciofluvial deposits include materials that have been deposited by glacial meltwater either directly in front of, or in contact with, glacier ice. Glaciofluvial materials typically range from non-sorted and non-bedded gravel made up of a wide range of particle sizes, associated with very rapid aggradation at an ice front, to moderately to well-sorted, stratified gravel. Glaciofluvial materials are abundant in the Pelly Crossing region. They typically form broad, flat terraces along both sides of the Pelly River valley. There are at least three sets of terraces around Pelly Crossing that represent various water levels on proglacial streams that were likely much larger than the modern Pelly River. These distal glaciofluvial deposits are characterized by well-stratified, moderately sorted, graded and bedded sediments (Figure 12). Glaciofluvial landforms in the map area are typically stable, well drained, and free of extensive permafrost. Almost all existing community infrastructure is located on glaciofluvial terraces.

Figure 12. *In the Pelly Crossing region, distal glaciofluvial deposits are typically moderately sorted, stratified and uniformly bedded.*

Fluvial deposits are materials that have been transported and deposited by modern streams and rivers. Fluvial sediments mapped in the Pelly Crossing area are predominantly those associated with floodplains, fluvial terraces and channels of Pelly River and Mica Creek. These deposits generally consist of stratified beds of gravel and/or sand with sand and/or silt and/or organic materials (Figure 13). Fluvial deposits typically have more organic material and generally smaller grain sizes than glaciofluvial deposits in the Pelly Crossing area. Backchannel deposits west of Mica Creek and at the south end of the community are organic rich and are likely fed by groundwater and high, spring discharge levels on Mica Creek.

Figure 13. *Mica Creek overbank deposits are visible in a cut bank along the creek. Beds alternate between silt/sand/organic overbank sediments and coarse, cobble-pebble gravel deposited in channel environments.*

Eolian deposits include materials transported and deposited by wind. These deposits generally consist of medium to fine sand and coarse silt that is well sorted, non-compacted, and may contain internal structures such as cross-bedding or ripple laminae, or may be massive (without bedding structures). Loess deposits are typically tan to buff in colour, massive, and anywhere from ~10 cm to more than 30 cm thick (Figure 14). Loess deposits form a surface veneer or blanket over most of the map area, but are especially prevalent on morainal and glaciofluvial landforms. The most recent period of eolian deposition in the Pelly Crossing region began shortly after the McConnell ice receded, and was ongoing until ~9 000 years ago when the landforms likely became stabilized by vegetation (Wolfe *et al.*, 2011). Modern eolian deposition is limited to localized pockets above bare sediment cliffs (such as above the steep banks of the Pelly River).

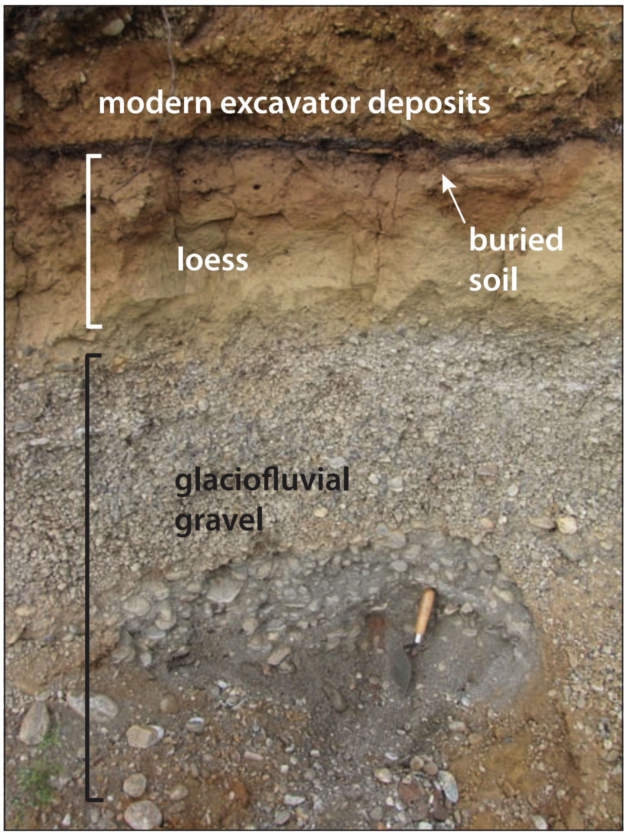

Figure 14. *A loess deposit on a high glaciofluvial terrace is overlain by artificial fill in a gravel pit. The loess unit is ~30 cm thick and overlies a glaciofluvial pebble-gravel. A buried soil horizon capping the loess unit is visible (arrow) below the artificial fill material.*

STRATIGRAPHY

The vertical layering of sediments can be a strong control on landscape stability. Simplified stratigraphy of the Pelly River valley is presented in Figure 15. The highest terraces on either side of the river have been inset by lower, younger terraces of Reid (R) and McConnell (M) ages, and finally the modern (last 10 000 years) fluvial system (light yellow terrace; Figure 15). Moraine deposits that are found on upland surfaces can also be seen in section below glaciofluvial materials on high terraces above the Pelly River (Figure 16); however, the stratigraphy visible in most valley sections and via previously acquired test pit and well logs (R. Trimble, EBA Engineering, pers. comm., 2010) predominantly record the vertical layering of fluvial and glaciofluvial deposits (Figures 17, 18, 19 and 20; see Figure 1 for section locations). While the most common sequence of stratigraphy is glaciofluvial gravel and sand overlain by eolian silt and sand (Figures 17 and 18), loess deposits can also be over-thickened by colluvial processes (Figure 19) or glaciofluvial sediments can be deposited directly on bedrock (Figure 20).

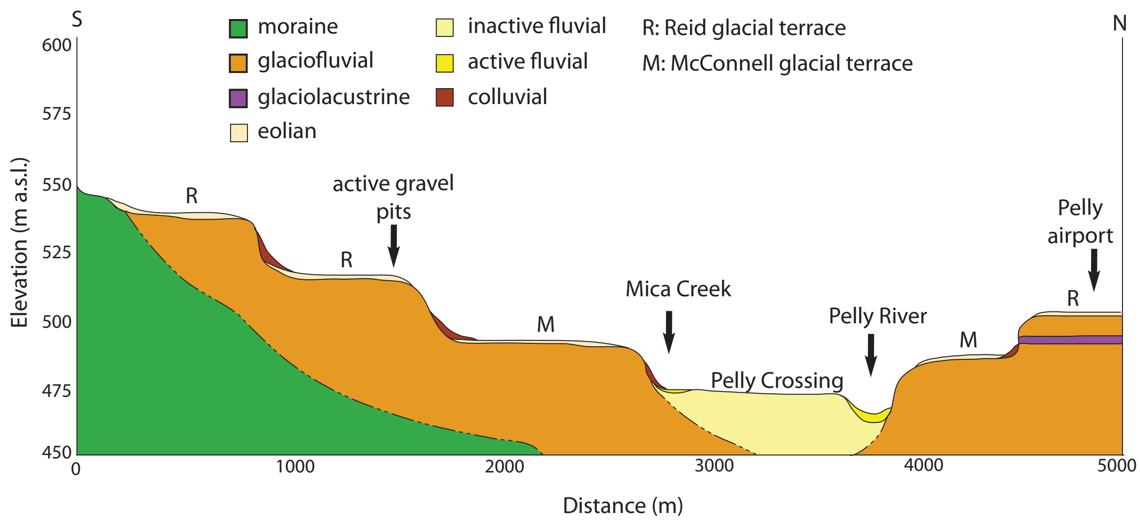

Figure 15. *A profile of the distribution of surficial sediments in the Pelly Crossing area illustrates multiple levels of glaciofluvial terraces and probable subsurface contacts.*

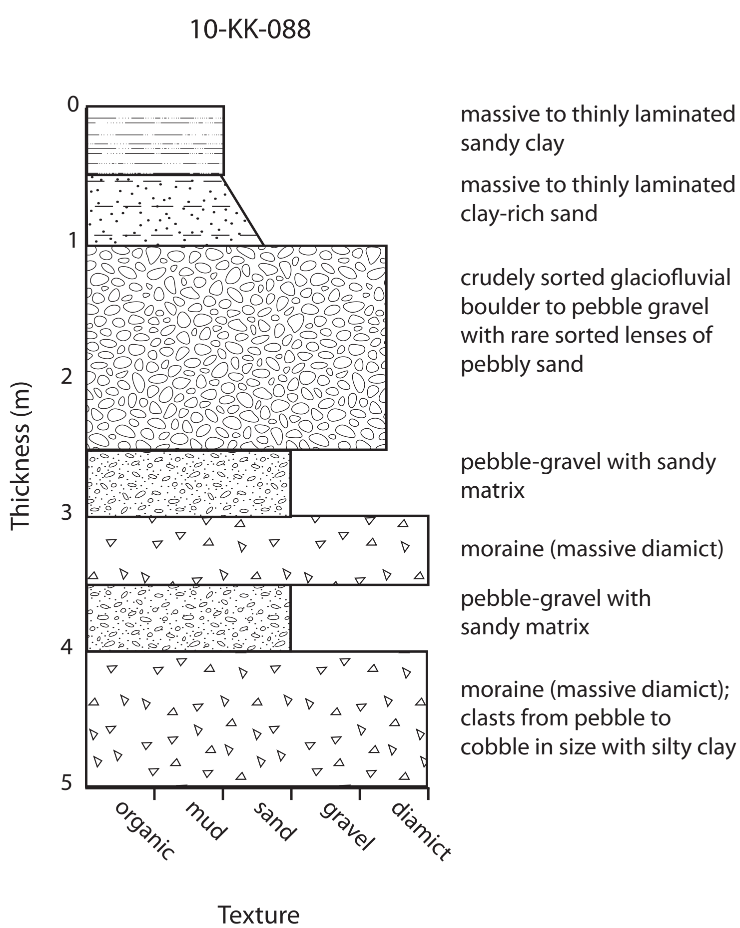

Figure 16. *Measured stratigraphic section 10-KK-088; see Figure 1 for section location.*

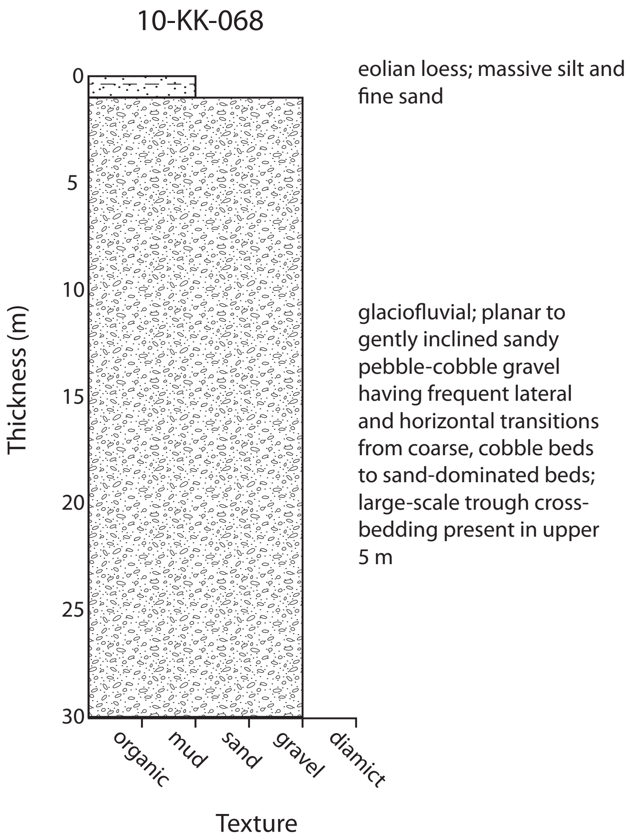

Figure 17. *Measured stratigraphic section 10-KK-068; see Figure 1 for section location.*

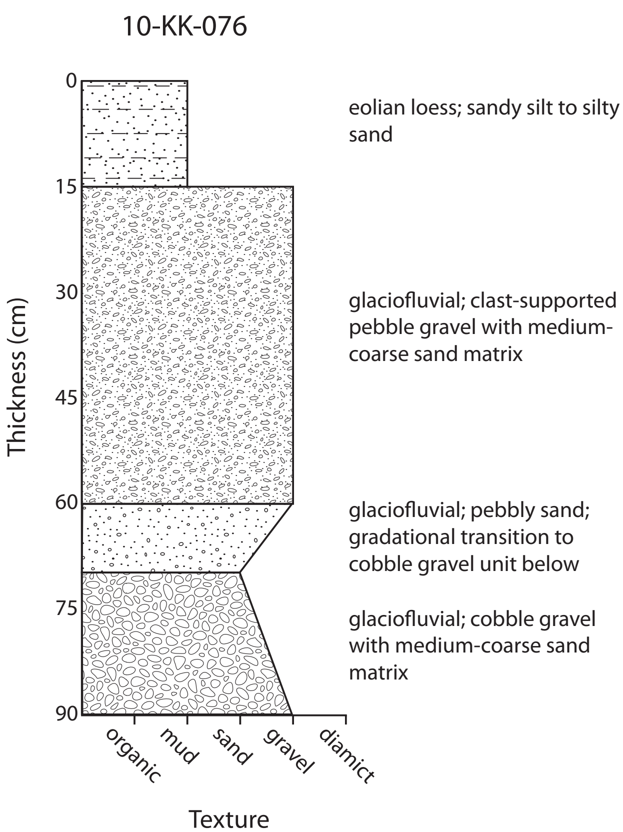

Figure 18. *Measured stratigraphic section 10-KK-076; see Figure 1 for section location.*

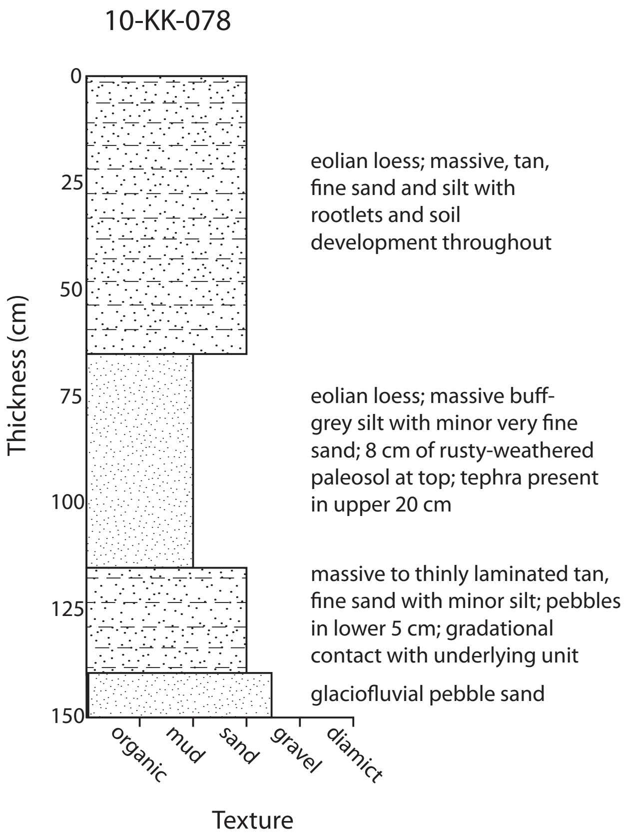

__Figure 19.__ Measured stratigraphic section 10-KK-078; see Figure 1 for section location.

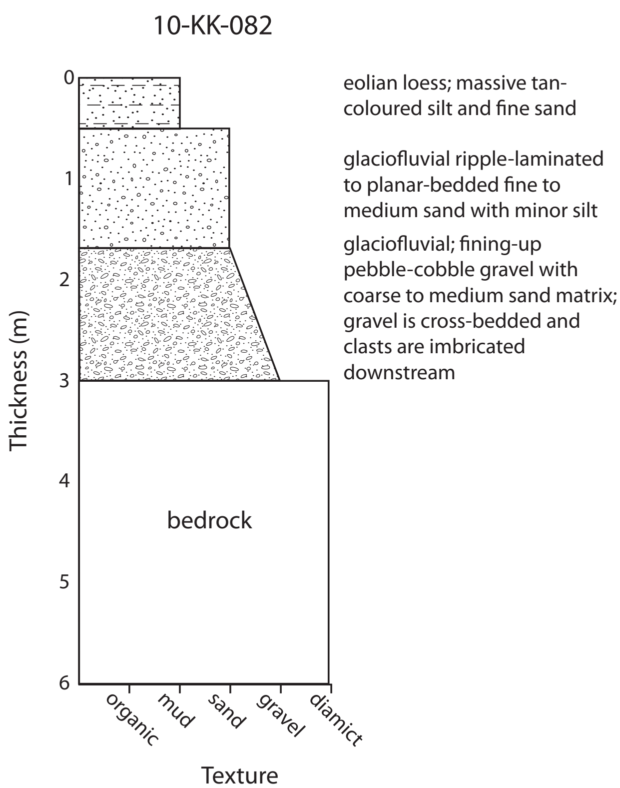

__Figure 20.__ Measured stratigraphic section 10-KK-082; see Figure 1 for section location.

PERMAFROST

Permafrost is defined as earth materials (surficial materials, bedrock and ice in the ground) that remain at temperatures below 0°C for more than one year. The surface layer that lies on top of permafrost and freezes and thaws annually is called the active layer. Pelly Crossing is located in the extensive discontinuous permafrost zone according to the Permafrost Map of Canada (Heginbottom *et al.*, 1995), meaning that more than half, but less than 90%, of the natural landscape is expected to be underlain by permafrost (Figure 21). The distribution of permafrost shown on this map is considerably generalized and predictions were made using climatic information at the scale of the entire country.

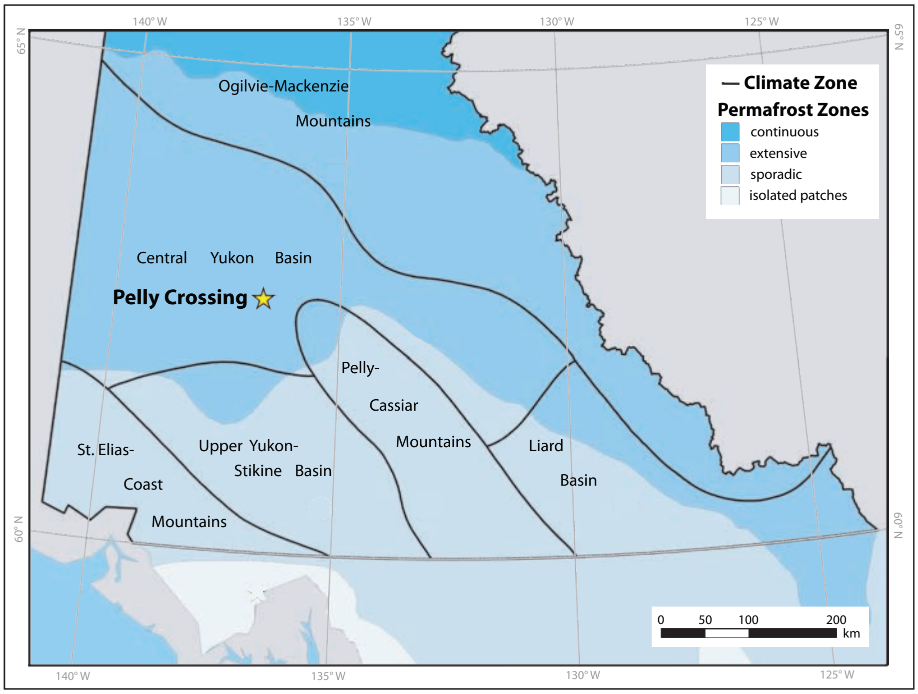

Figure 21. *Location of Pelly Crossing in relation to permafrost zones (after Heginbottom et al., 1995) and climatic regions in the Yukon (after Wahl et al., 1987).*

Permafrost in the extensive discontinuous zone tends to be more likely associated with fine-grained sediments or peat deposits where there are typically thick organic mats (mosses and other similar ground covers), and coniferous vegetation. Permafrost is commonly found in colder micro-climates (such as on north-facing slopes and in valley bottoms). However, predicting which sites are affected by permafrost and which are not, over an area of extensive discontinuous permafrost, is very challenging because of the number of factors that influence temperatures in the ground.

Figure 22 illustrates the results of recent permafrost probability modelling based on fieldwork carried out throughout the southern Yukon over the past five years (Lewkowicz and Bonnaventure, 2011; Bonnaventure *et al.*, *in press*). This map can be used to examine broad patterns of permafrost distribution across the landscape, but it is not a tool for site-level predictions because it does not take into account the effects of the local factors mentioned above (*i.e.*, surficial materials, vegetation and differential snow accumulation). The map shows probabilities ranging from 0.4 to 0.8, and values for the Pelly Crossing region range from 0.5 to

0.6. Probabilities are relatively high on north-facing slopes, and lower on south-facing slopes and exposed ridges. This map supports the classification of Heginbottom *et al.* (1995) and indicates that in the absence of disturbance (which warms the ground and thereby thaws permafrost), it is possible that permafrost could be found at any given site in the vicinity of Pelly Crossing (5 or 6 out of 10 chances), but is less likely to occur on south-facing slopes.

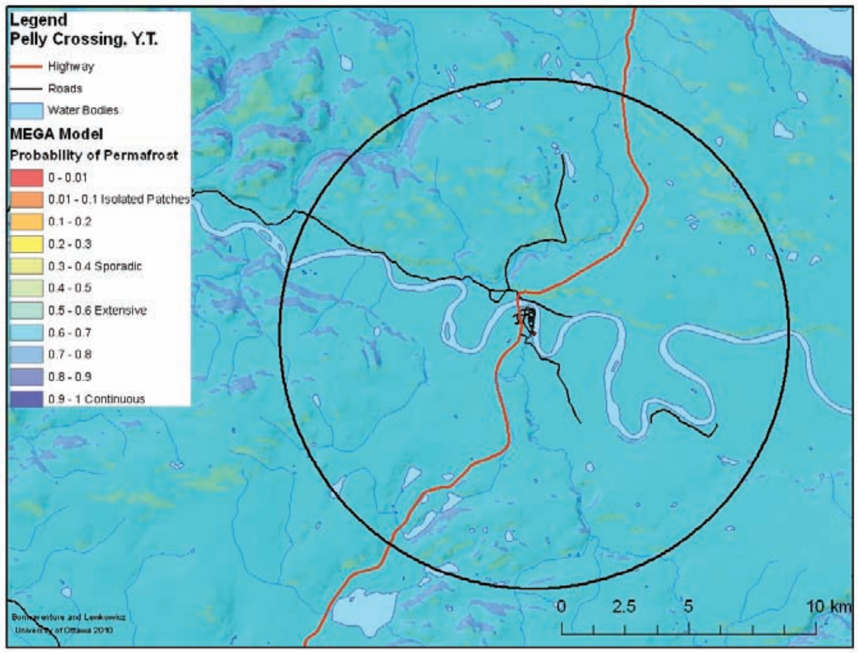

Figure 22. *Map of predicted permafrost probabilities under current climatic conditions, centred on Pelly Crossing, Yukon. The circle encloses terrain within 10 km of the community of Pelly Crossing. Note: these predictions do not include local variations related to surficial deposits or any other types of micro-variability, and therefore, are not designed for use at the site level. Predictions are based on methods described in Lewkowicz and Bonnaventure (2011) and Bonnaventure et al., (in press).*

By definition, in the extensive discontinuous permafrost zone, there must be some sites where ground temperatures average less than 0°C (permafrost sites) and others where temperatures are greater than 0°C (non-permafrost sites). The closer the temperatures of permafrost are to 0°C, the more likely it is that permafrost will thaw following disturbances such as vegetation clearance, construction, forest fire and climatic change. The impacts of this thaw will depend on how rapidly it occurs, and whether the permafrost contains a significant amount of ground ice, little ice, or no ice. It is critical to understand the characteristics and nature of permafrost prior to construction or infrastructure development, particularly in zones of extensive discontinuous permafrost.

No information is available regarding ground temperatures in the region around Pelly Crossing (R. Trimble, EBA Engineering, pers. comm., 2010) and very little permafrost was observed during field studies. It is likely that the well-drained glaciofluvial terraces around Pelly Crossing are not affected by permafrost. Fine-grained landforms such as active fluvial plains, moraine blankets and colluvial deposits are more likely to be affected by permafrost, particularly if the landforms have a north or east aspect.

Geologic hazards

The materials making up the surficial geology in and around Pelly Crossing are, for the most part, stable. However, geological, hydrological and climatological processes operating on these materials can pose a hazard to existing and future development. Pelly Crossing has abundant gravel and sand-rich landforms that are stable, well drained and ice free. Many of these landforms also occur above the floodplains of both the Pelly River and Mica Creek. These are ideal building sites for future infrastructure. Less stable landforms in and around Pelly Crossing include fluvial deposits within the active floodplains of the Pelly River, Mica Creek and Willow Creek; upland moraine deposits; and steep colluvial deposits along the edges of fluvial and glaciofluvial terraces. In particular, point bar deposits on the Pelly River floodplain are subject to upstream erosion, as well as periodic flooding. With the bulk of community infrastructure situated on gravel terraces along the Pelly River, permafrost is not a significant concern to community safety at this time.

Minor lacustrine deposits are present in the southern part of the map area. While these lakes and their sediments do not pose a specific hazard, they are of concern to the community because of the sulphurous odour frequently emitted from the lakes. One lake in particular, known as “Stinky Lake” by local residents (see Figure 1 for location), was the subject of a research study in the 1990s (Pienitz *et al.*, 2000). The lakes are naturally occurring saline lakes (salts are derived from underlying glacial moraine) with substantial growth of micro-organisms during summer months. The ultimate decomposition of lacustrine fauna, and in particular, algal mats, produces the smell often noted by local residents.

PROJECTED CLIMATE CHANGE AND POTENTIAL IMPACTS FOR THE PELLY CROSSING REGION

This section is intended to summarize projected changes in climate for the Pelly Crossing region, and to identify potential impacts of these changes on the region’s hydrology and surficial geology.

CLIMATE

Projected changes in temperature and precipitation for the Pelly Crossing region have been developed for this report. Projections are derived from the regionally downscaled climate data provided by the Scenarios Network for Alaska Planning (SNAP) at the University of Alaska Fairbanks (SNAP, 2010). Projected precipitation and temperature data were based on raster values surrounding the geographic centre of Pelly Crossing, as determined by SNAP. The range encapsulated was 625 km^2. Changes in climate for the Pelly Crossing region were projected for two time periods (2030 and 2050) using two standard scenarios (B1 and A1B). The B1 and A1B scenarios are based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (Nebojša *et al.*, 2000). The B1 scenario projects low to moderate degrees of climate change over the next century, while the A1B scenario anticipates medium to high degrees of climate change. These two scenarios were applied to this study because they provide a reasonable range in possible shifts in temperature and precipitation for Pelly Crossing by 2030 and 2050. Figures illustrating changes in mean annual, winter and summer temperatures and winter and summer precipitation, as well as additional parameters such as freeze and thaw dates, and growing season length are included in Appendix B.

Tables 3-5 outline projected annual and seasonal temperature changes, annual and seasonal precipitation changes, and annual and seasonal precipitation changes from baseline for the

B1 and A1B scenarios for 2030 and 2050 respectively; these projections were developed by SNAP (2010). For the sake of comparison, baseline data from 1961-1990 climate normal conditions are also included (see *Contemporary Climate* section above, and Figure 2). Generally, temperature projections indicate that warming will occur over both time slices (2030 and 2050), and regardless of whether one applies the B1, or A1B projections. The following ranges for temperature and precipitation demonstrate B1 and A1B projections respectively for the 2050 timeframe. Increases in mean annual temperature for the Pelly Crossing region are projected to be between 2.5°C and 3.7°C (Table 3). Warming is expected to be more significant in winter (5.0°C to 7.0°C) than in summer (0.7°C to 1.1°C) (Table 3). Precipitation is also projected to increase in the Pelly Crossing region over both time slices and regardless of projection (Tables 4 and 5). Annual precipitation may increase by between ~36.9% (B1 projection) and ~43.7% (A1B projection) by 2050 (Table 5). As with temperature, the projected increases in precipitation will vary seasonally, and the greatest proportional increases are generally predicted to occur in the spring and autumn (Tables 4 and 5).

Table 3. Projected yearly and seasonal temperature changes (expressed as °C) for the Pelly Crossing region based on the B1 and A1B IPCC scenarios for 2030 and 2050 respectively. Baseline climate normal values for 1961-1991 are also shown (Environment Canada, 2010). Values in brackets indicate direction and amount of projected change from baseline conditions.

Season	Baseline (1961-1990)	Modest climate change (B1)		Medium-high climate change (A1B)	
		2030	2050	2030	2050
Annual	-4.3	-2.2 (+2.1)	-1.8 (+2.5)	-2.4 (+1.9)	-0.6 (+3.7)
Spring	-1.5	-0.4 (+1.1)	-0.4 (+1.1)	-0.4 (+1.1)	1.6 (+3.1)
Summer	13.5	13.9 (+0.4)	14.2 (+0.7)	13.5 (0)	14.6 (+1.1)
Autumn	-4.2	-2.6 (+1.6)	-1.7 (+2.5)	-2.6 (+1.6)	-0.6 (+3.6)
Winter	-25.0	-20.6 (+4.4)	-20.0 (+5.0)	-20.1 (+4.9)	-18.0 (+7.0)

Table 4. Projected yearly and seasonal precipitation changes (expressed as mm total precipitation) for the Pelly Crossing region based on the B1 and A1B IPCC scenarios for 2030 and 2050 respectively. Baseline climate normal values for 1961-1991 are also shown (Environment Canada, 2010). Note: snowfall has been converted to snow water equivalent and is also expressed in mm.

Season	Baseline (1961-1990)	Modest climate change (B1)		Medium-high climate change (A1B)	
		2030	2050	2030	2050
Annual	299	399.31	409.31	420.19	429.77
Spring	45	59.49	64.45	66.45	68.25
Summer	123	164.72	164.72	166.31	172.14
Autumn	75	104.57	106.95	110.32	114.08
Winter	56	70.53	70.09	75.31	77.10

Table 5. Projected yearly and seasonal precipitation changes from baseline (1961-1990 climate normal) conditions (Environment Canada, 2010) for the Pelly Crossing region under the B1 and A1B IPCC scenarios for 2030 and 2050 respectively. See Table 4 for a summary of values for each time period and projection.

Season	Increase from 1961-1990 baseline							
	Modest climate change (B1)				Medium-high climate change (A1B)			
	2030		2050		2030		2050	
	mm	%	mm	%	mm	%	mm	%
Annual	100.31	33.50	110.31	36.90	121.19	40.50	130.77	43.70
Spring	14.49	32.20	19.45	43.20	21.45	47.70	23.25	51.70
Summer	41.72	33.90	41.72	33.90	43.31	35.20	49.14	40.00
Autumn	29.57	39.40	31.95	42.60	35.32	47.10	39.08	52.10
Winter	14.53	25.90	14.09	25.20	19.31	34.50	21.10	37.70

HYDROLOGY

Because hydrological data for the Pelly Crossing region is limited, examples and case studies from scientific literature are used to identify potential impacts of climate change on aspects of the Arctic hydrological system in general, and in the Pelly Crossing region specifically.

Temperature

Regionally downscaled climate data provided by the Scenarios Network for Alaska Planning (SNAP) at the University of Alaska Fairbanks suggests that by 2030, under a modest climate change scenario (*i.e.*, the IPCC B1 scenario; see Nebojša *et al*., 2000 for details), annual temperature in Pelly Crossing will increase by 2.1°C, while winter temperatures could increase by 4.4°C (Table 3). Many of the impacts of increasing temperature have the potential to affect the hydrology of the Pelly Crossing region. These include effects such as a shorter winter season, reduced snow accumulation, an increased potential for winter rain and mid-winter melts, earlier and more severe spring river break-ups, lower summer and fall river discharge, increased evaporation, and increased groundwater infiltration. As with many potential impacts of climate change, the interplay between these impacts can be difficult to assess. However, data suggesting that many of these changes are already taking place, including earlier spring break-ups and shorter winter seasons, provides a useful indication of what may be expected in the future.

The most significant impact of increasing temperatures will manifest in the autumn and winter, and will affect the duration of the snowcover season and the accumulation of winter snowpacks, hence affecting spring river discharge. The timing of freeze-up and break-up will also be affected. Warmer temperatures will reduce the length of the snowcover season (Lemmen *et al*., 2008; Wrona *et al*., 2005) and hence the amount of time available for snow accumulation. An increase in the proportion of rain to snow during the fall and winter also has the potential to reduce snowpack accumulation, while warmer temperatures may cause rain-on-snow events, promoting mid-winter melting (McBean, 2005; Wrona *et al*., 2005). The timing of break-up and freeze-up is also intimately linked with temperature, that is, ice freeze-up and break-up dates correlate most strongly with air temperatures in the preceding one or two months. In northern areas, freeze dates reflect the climate prevailing in October and November, while break-up dates reflect April and May temperatures (Magnuson *et al*., 2000). Higher temperatures could result in an earlier spring break-up, which is often associated with increased break-up severity. (However, warmer winter temperatures could counteract this effect, because reduced snowpack depths may mean thinner ice develops on rivers, hindering severe break-up conditions (Wrona *et al*., 2005)). Evidence of earlier spring break-ups is already being recorded in Yukon, whereby ice break-up on the Yukon River at Dawson and on Alaskan rivers have occurred earlier in the year, likely in response to higher spring temperatures (Brabets and Walvoord, 2009). An earlier spring break-up and a shorter snowcover season may subsequently affect the timing and magnitude of the spring meltwater pulse. Higher spring temperatures can cause a more rapid spring melt (Wrona *et al*., 2005), while an increased number of days with mid-winter or early spring thaws can result in a more protracted snowmelt, causing declines in runoff intensity and lower runoff peaks (McBean, 2005). Furthermore, an earlier spring runoff generally correlates with lower summer and fall flows (Barnett *et al.*, 2005).

Evaporation rates can also be affected by temperature increases. While temperature increases in summer are projected to be smaller than those in winter, summer temperature increases of 1-3°C will still have a significant effect on evaporative losses (Wrona *et al*., 2005). (Note: maximum summer temperature increases for the Pelly Region by 2050 are 1.1°C, based on the A1B scenario (Table 3)). Rising temperatures generally cause increased evaporation and evapotranspiration (Walsh, 2005), which, coupled with a longer snow-free season, can result in increased water loss from surface waters and potentially cause negative water balances. Increased evaporation can also reduce soil moisture (Barnett *et al*., 2005), which could in turn affect the vitality of the terrestrial ecosystem.

Increased temperatures also contribute to permafrost thawing, both directly (*e.g.*, through warming of the ground surface and subsequent deepening of the active layer) and indirectly (*e.g.*, through reductions in the ground-insulating capacity of the winter snowpack by declines in snow accumulation). Thaw of the permafrost table can have numerous effects on hydrology, including increased groundwater infiltration, lags between snowmelt and peak spring discharge, lower summer flows, and increased winter flows. In low-permafrost catchments, river flow varies most strongly with summer temperature, while in high-permafrost catchments, flow varies most strongly in response to changes in precipitation (Jones and Rinehart, 2010). This suggests a positive feedback cycle, in which warmer temperatures enhance permafrost thawing, which in turn affects the sensitivity of stream hydrology to temperature increases.

Precipitation and snowcover

For most cold regions, winter snowcover accumulation is the main contributor to spring runoff (Romolo *et al*., 2006). The seasonal storage of snow comprises a major portion of the freshwater budget, and its melt accounts for major runoff in downstream areas (Prowse, 2009). Hence, changes in the amount of snowfall or the proportion of precipitation comprised of snow will affect surface and groundwater hydrology. As mentioned above, data for the Mayo region are presented here because similar data for Pelly Crossing is not available; however, some conclusions can be drawn upon from the Mayo data. The International Panel on Climate Change has consistently reported increases in precipitation over the 20th century at northern high latitudes (Walsh, 2005) of ~0.5-1% per decade (McBean, 2005). Purves (2010) identified a trend towards increasing precipitation in Mayo by 2%/10 yrs (5.9 mm/10 yrs) between 1927 and 2009 This is consistent with other studies showing increases in precipitation over the Arctic between 1948 and 2005 (Lemmen *et al*., 2008), as well as increases in summer precipitation in the Yukon Territory, where the greatest increases have occurred in the southeast and central regions (Janowicz, 2010).

However, despite increases in precipitation, snowcover has largely declined across the Arctic. In the Northern Hemisphere, there has been a documented decline in snowcover of ~10% between 1972 and 2003 (Walsh, 2005; Lemmen, 2008). This change is important, because a large winter snowpack is critical for the development of ice-jam flood events (Romolo *et al*., 2006) and for producing high downstream discharge. In the Mayo region, Purves (2010) identified a decline in February 28th snow-on-ground of 11%/10 yrs between 1955 and 2010. It is evident that despite documented increases in precipitation, snowcover has declined; this apparent contradiction is likely related to increasing temperatures during the same time period, causing shorter snowcover seasons. It is important to be aware that such interplays between different climate parameters complicate projections of climate warming impacts on complex ecosystems. Implications of a shorter snowcover season are discussed further below, in the section *Freeze-up, break-up and river discharge*.

Climate models generally predict modest increases in global precipitation by the end of the 21st century, although there is considerable variability among model outputs. However, terrestrial North America is an area with one of the highest projected increases in precipitation, and the largest increases are projected for fall and winter (Wrona *et al*., 2005). Most models suggest annual precipitation will increase 15-30% by 2080 (Lemmen *et al*., 2008). SNAP climate projections for Pelly Crossing by the year 2030 and 2050 suggest increases in annual precipitation of ~34% and 37%, respectively; winter and summer precipitation is expected to increase by ~26% and 25%, and ~34% and 34%, respectively, under a moderate climate change scenario (*i.e.*, the IPCC B1 scenario; see Table 5 and Nebojša *et al*., 2000 for details). By 2050, under a medium-high climate change scenario (*i.e.*, the IPCC A1B scenario; see Table 5 and Nebojša *et al*., 2000 for details), annual precipitation is expected to increase by ~44%, whereby the increase in winter precipitation is predicted to be ~38%.

Projected changes in the ratio of precipitation to evaporation are generally positive, indicating that it is likely there will be more frequent and longer wet periods (Walsh, 2005). Climate change is also expected to cause major repartitioning of snow and rainfall (Prowse, 2009). In other words, if increases in precipitation coincide with increases in temperature, which is highly likely, the proportion of rainfall relative to snowfall could increase (Brabets and Walvoord, 2009), as could the number of rain-on-snow events, which are often conducive to the development of flash floods (McBean, 2005). This will have a significant effect in catchments with high amounts of permafrost, where stream flow exhibits a rapid response to rainfall due to increased surface runoff on frozen ground (Jones and Rinehart, 2010). In conjunction with these changes, projected declines in mean snowcover range between -9% and -18% by the 2071-2090 time period (Walsh, 2005).

It is apparent that while precipitation is projected to increase in the future, the decline in snowcover extent and duration will have negative effects on river discharge (discussed in more detail below). In the Pelly River watershed, this could mean earlier, potentially lower spring discharge peaks, with higher summer discharge in response to increases in rainfall. However, lower spring discharge peaks could be offset somewhat by projected increases in spring precipitation in the Pelly Crossing region. Regardless of their nature, these changes will affect the timing and shape of the seasonal hydrograph, and will have significant implications for both surface and groundwater dynamics.

Freeze-up, break-up and river discharge

Climate change has the potential to alter river discharge and the timing of events in the annual hydrograph (see Figure 4 for an example of a Pelly River hydrograph). Changes in the timing of river freeze-up and break-up, as well as the amount of winter precipitation and duration of the snowcover season, are the primary mechanisms that will be discussed in this section.

There is increasing evidence that river ice break-up is occurring earlier in spring, and freeze-up is occurring later in fall (Janowicz, 2010; Lemmen *et al*., 2008; Magnuson *et al*., 2000). Many factors affect the timing of break-up and freeze-up, but trends in both scenarios generally reflect changes in fall and spring air temperatures (Brabets and Walvoord, 2009; Lemmen *et al*., 2008). Projections indicate a 1-day advance per 0.2°C increase in air temperature for break-up, and vice versa for freeze-up (Walsh, 2005). SNAP's projections for the Pelly Crossing region indicate earlier thaw dates and later freeze-up dates, regardless of the time slice or scenario examined. For example, under a moderate climate change scenario (*i.e.*, IPCC B1 scenario), by the year 2030, thaw dates may occur up to 14 days earlier in Pelly Crossing. Likewise, freeze-up dates may occur up to 15 days later. In a study of historical trends in lake and river ice in the northern hemisphere, Magnuson *et al*. (2000) found that between 1846 and 1995, there have been shifts towards later freeze-up and earlier break-up dates. In their study, freeze-up dates occur later by 5.8 days per century, while break-up dates occur earlier by 6.5 days per century. Furthermore, they found that interannual variability in freeze-up and break-up dates has increased since the 1950s. Canadian data of break-up and freeze-up dates have documented that western Canadian sites have a predominant trend towards earlier break-ups (Lemmen *et al*., 2008). These long-term trends in river ice phenologies provide evidence that freshwater ecosystems are already responding to warming trends (Magnuson *et al*., 2000). In addition to altering freeze-up and break-up dates, increases in temperature have the potential to produce more frequent and sustained mid-winter thaws (Beltaos *et al*., 2006). In fact, the first mid-winter break-up in the Yukon was observed on the Klondike River at Dawson in the winter of 2002-03 as a result of rain and warm weather in December 2002 (Janowicz, 2010).

While temperature increases may affect the timing of freeze-up and break-up, the duration of the snow accumulation season and the amount of snowfall have an influence on the magnitude and timing of the spring discharge peak. Firstly, later fall freeze-up and earlier spring break-up reduce the length of the snowcover season, resulting in a shorter period in which snow can accumulate and hence potentially affecting the volume of the spring snowmelt pulse (Hay and McCabe, 2010; Walsh, 2005). Secondly, earlier snowmelt has the potential to reduce the seasonal regulatory effect of alpine snow storage (Prowse, 2009), especially if there are significant temperature increases at higher latitudes (for example, in the Pelly River headwaters). An earlier snowmelt season could also mean that the initiation of melt takes place during cooler spring temperatures, resulting in a more protracted melt and lower peak spring river discharge (Walsh, 2005). If the amount of winter snowfall declines, there is potential for two contrasting effects: 1) shallower snow depths could reduce the spring albedo, allowing more incoming solar radiation to be absorbed and the spring melt and river-ice break-up to occur earlier; and 2) shallower snow depths could mean a decline in the insulating effects of snowcover on river ice in winter and result in the development of thicker ice (Walsh, 2005). Both scenarios could alter the timing and severity of the spring break-up.

In terms of overall river discharge, future projections based on model scenarios show discharge increases of 20-30% on the Yukon River by 2050 compared with a 1961-1991 baseline (Lemmen *et al*., 2008; Arnell, 1999). Arora and Boer (2001) project a 10% increase in Yukon River discharge under a double-CO_2 scenario. Annual mean flows in permafrost regions of northwestern Canada show slight positive trends over the last three decades in both continuous and discontinuous permafrost zones, while annual peak flows have largely decreased in the sporadic permafrost region (although the decrease is not statistically significant) (Janowicz, 2008). Déry *et al*. (2009) suggest there is an intensifying hydrological cycle in northern Canada, manifested in a 15.5% increase in annual river flows due in part to many above-average flows recorded over the last decade. As SNAP's climate projections suggest, it is highly likely that the Pelly River and its tributaries will become ice-free earlier in the spring, shortening the on-ice travel season. The primary pulse of river discharge will also likely occur earlier in the spring (manifesting as an earlier discharge peak on the annual hydrograph). However, if the snow accumulation season is shorter, as SNAP's projections suggest, or the rate of melt protracted, there may be a decline in the magnitude of the spring pulse. The rate and timing of the spring melt are important factors in determining the occurrence of floods (Romolo *et al*., 2006) and river discharge later in the season.

Relevance for Pelly Crossing region hydrology

Based on the scientific literature discussed above, it is possible to speculate about potential impacts of climate change on the hydrology of the Pelly Crossing region. The following changes are based on projected increases in both temperature and precipitation:

- Shorter snowcover season, with reduced snowpack depth (especially during spring) and lower insulating capacity of the snowpack.
- Increased frequency of rain-on-snow events and increase in overall proportion of rain to snow.
- More frequent mid-winter and early spring thaws.
- Earlier break-up and later freeze-up of river ice.
- Thinner river ice cover (as a result of a shorter cold-weather season) or thicker river ice cover (as a result of lower snowpack insulation capacity).
- More rapid spring melt (if spring temperatures are significantly increased) or more protracted spring melt (if spring temperatures warm earlier in the season, but to a lesser degree).
- Increased or decreased break-up severity (depending on timing of melt, ambient air temperatures, amount of winter baseflow, thickness of river ice, etc.).
- Earlier and smaller spring snowmelt pulse and river discharge peaks.
- Lower summer and fall river discharge, as a result of lower spring discharge.
- Higher summer and fall river discharge, as a result of increased rainfall during the same period.
- Increased winter baseflow.
- Increased evaporation.
- Increased infiltration of the spring snowmelt pulse, reducing spring overland flow and delaying the spring discharge peak.
- Higher rates of groundwater recharge and increased groundwater storage, causing a hydrological transition towards an increasingly groundwater-dominated system.

In the Pelly Crossing region, the most significant areas of impact may be related to river discharge and changes in the depth of the groundwater table. Discharge in the headwaters of the Pelly River catchment is an important contributor to downstream river discharge, and there is a positive correlation between the snow water equivalent (SWE) of the winter snowpack (the most hydrologically important characteristic of snowcover (Walsh, 2005)) and spring streamflow downstream. This relationship is further supported by records of past SWE and river discharge, which demonstrate that during periods of above-average SWE, flooding was slightly more frequent. The relationship between SWE and river discharge highlights the importance of the winter snowpack on streamflow generation and regional hydrology. Hence, changes in snowpack depth, the duration of the snowcover season, or the timing of the spring melt, will all affect discharge in the Pelly River watershed and the Pelly Crossing region. In fact, because the spring discharge peak is the most hydrologically significant event of the year, it is highly susceptible to change, and the typical riverine hydrograph of the area may be altered (see Figure 4). It is possible that trends in river discharge may become more similar to that exhibited by the 2002 discharge record (dotted line on Figure 4), when spring discharge was exceptionally low. Interestingly, the 2002 hydrograph also shows the positive effect of late season rainfall on river discharge – a state that may also become more common with increases in summer and autumn rainfall.

SURFICIAL GEOLOGY

Projected changes in climate should not affect the stable landforms in the Pelly Crossing region in any significant manner. Changes in temperature and precipitation may, however, negatively influence landforms that are already exhibiting some forms of instability. Increased bank erosion caused by higher than normal discharge of the Pelly River could potentially accelerate undercutting of the river bank in town.

Increasing temperatures will have the greatest impact on surficial materials and landforms that are currently frozen. As these materials thaw, we can expect significant changes to the landscape. Hazards associated with permafrost are generally outside of the developed area of Pelly Crossing and should not be a major challenge for future development in the immediate vicinity of the community.

SYNTHESIS OF PELLY CROSSING ENVIRONMENTAL CHANGE

The potential environmental changes identified in the preceding sections of this report can be used to identify current and future landscape hazards in the Pelly Crossing region. The combined properties of surficial material type, landform shape and slope, hydrological regime, climate regime, and permafrost conditions have been used to arrive at a set of hazard ‘rankings’ that can be used to assess the potential stability of landscape units around the community of Pelly Crossing (*see accompanying map “Geological Hazard Rankings, Pelly Crossing, Yukon”*).

Based on processes acting on distinct geological units, a hazard ranking of low, medium, or high has been assigned to each geological unit in the hazard map area. Rankings are qualitatively assigned to reflect the following conditions:

1. **Low:** Stable landform. Unlikely to be affected by mass movement, thermokarst, subsidence, bank erosion, flooding or instability. These landforms typically consist of gravel or sand, are well drained, and have shallow to moderate slopes. Low hazard landforms may contain little to no permafrost and are above the floodplain of the Pelly River. Low hazard landforms are unlikely to become unstable under predicted changes in climate.

2. **Medium:** Unlikely to be affected by mass movement, thermokarst, subsidence, bank erosion, flooding or instability. These landforms typically consist of gravel, sand, glacial diamict or colluvial materials. They are well to moderately drained, and have shallow to steep slopes. Medium hazard landforms may have moderate amounts of permafrost and may occur within an area of shallow groundwater. Medium hazard landforms are likely to become either more or less stable under predicted changes in climate.
3. **High:** Unstable landform. Likely to be affected by mass movement, thermokarst, subsidence, bank erosion, flooding or instability. These landforms typically consist of glacial diamicts, colluvial materials, glaciolacustrine, lacustrine and fluvial deposits. They are generally moderately to poorly drained and have shallow to steep slopes. High hazard landforms may have a significant thickness of permafrost containing high ice contents, be prone to gravity-induced erosion, and occur within the floodplain of the Pelly River. High hazard landforms are likely to become either more or less stable under predicted changes in climate.

It is important to note that hazard rankings are based on general observations of surface materials, drainage, slope angle, vegetation and the presence of permafrost in landforms; limited subsurface information and textural analyses were also applied. This has resulted in a *projected* risk ranking that will require geotechnical and/or engineering analyses to quantify. While green (low risk) rankings do not ensure a landform is safe for development, we project that geotechnical studies on these landforms will result in significantly reduced site development and construction costs than on either yellow (medium risk) or red (high risk) landforms.

In classifying polygons, we have taken a precautionary approach and applied a category of higher risk where we are not confident in assigning a lower-risk category. However, every polygon will contain zones of lower and higher risk than the overall polygon classification. It is for this reason that this map should serve only as an initial guide for planning purposes. Any development will still require detailed site investigations.

Results of hazard classifications in the developed area of Pelly Crossing conclude that this region is at a low to medium risk of landscape instability (Figure 23; *see also accompanying map "Geological Hazard Rankings, Pelly Crossing, Yukon"*). Hazards in this area are largely related to flooding risk, slope instability, and the potential for permafrost thaw. Specifically, polygon numbers 54, 55, 68, 69, 70, 72, 76, 77, 105 and 136 are ranked at high (red) risk due to flooding potential on the Pelly River, Mica Creek and/or Willow Creek. Additionally, polygons 71, 72, 77 and 87 are at risk from riverbank erosion. Polygon numbers 86, 107 and 117 are ranked at high (red) risk due to slope instability along the steep edges of glaciofluvial terraces. Finally, polygon numbers 109 and 111 are ranked at high (red) risk due to the presence of thick organic mats and standing water that may be related to thermokarst processes. Abundant low risk (green) polygons are located on higher terraces on either side of the Pelly River (*i.e.* polygons 31, 33, 34, 36, 39, 42, 52, 53, 81, 90, 128 and 134). A breakdown of the risk related to each polygon is presented in Appendix C.

__Figure 23.__ Detailed view of hazard rankings in the developed area surrounding the community of Pelly Crossing. Polygon numbers are discussed in the text and summarized in Appendix C. High, medium and low hazard rankings are represented by red, yellow and green polygons, respectively.

FUTURE RESEARCH NEEDS AND NEXT STEPS

HYDROLOGY

This synthesis report identifies the significant lack of data with regards to groundwater characteristics in the Pelly Crossing region. In fact, groundwater data for the Pelly Crossing region are very sparse. While many boreholes, test pits and water wells have been excavated in the town of Pelly Crossing and all groundwater occurrences were recorded, no long-term monitoring records of any wells or test pits are available. Rather, data represent single site investigations and provide no context for investigating temporal variability. There is a lack of geo-referenced, spatially comparable groundwater data (*e.g.*, available data lacks reference to an elevation datum, thus making comparison between sites inappropriate). Additionally, records of wells and test pits excavated in the Pelly Crossing region span three decades, and were developed at different times of the year, further complicating comparison between sites and preventing robust evaluation of seasonal and long-term trends in groundwater levels. To address these concerns, a groundwater monitoring program should be developed for the Village of Pelly Crossing, focusing especially on flood-prone areas. Initial data could be used to develop a map of the water table in the area, including water table height, primary recharge areas, and direction and velocity of subsurface flows. Data collected over several seasons and consecutive years could be used to assess year-to-year changes in groundwater hydrology and, when compared with climate data for the region, may offer some indications of the variability in groundwater dynamics in response to climate variability.

PELLY CROSSING HAZARDS MAPS AND RESEARCH: GENERATING ACTION FROM SCIENCE

The knowledge and data generated by the Pelly Crossing Hazards project can be used in a number of ways to inform planning and policy developers and establish a baseline from which future science can be generated. In particular, the hazard map generated by this work will provide a key reference for future development. This study has identified numerous actions for the community of Pelly Crossing and includes the investigation of hydrological change in the landscape and adaptation planning.

This hazards project has contributed significantly to the assessment of climate change vulnerability for the community of Pelly Crossing. In particular, the hazards mapping project has increased the understanding of how landscape characteristics may change in Pelly Crossing as regional climate conditions change. This information can be utilized in the development of an adaptation plan to provide the basis for evaluating how community infrastructure, security and well-being may be influenced, and how the community might take action to respond.

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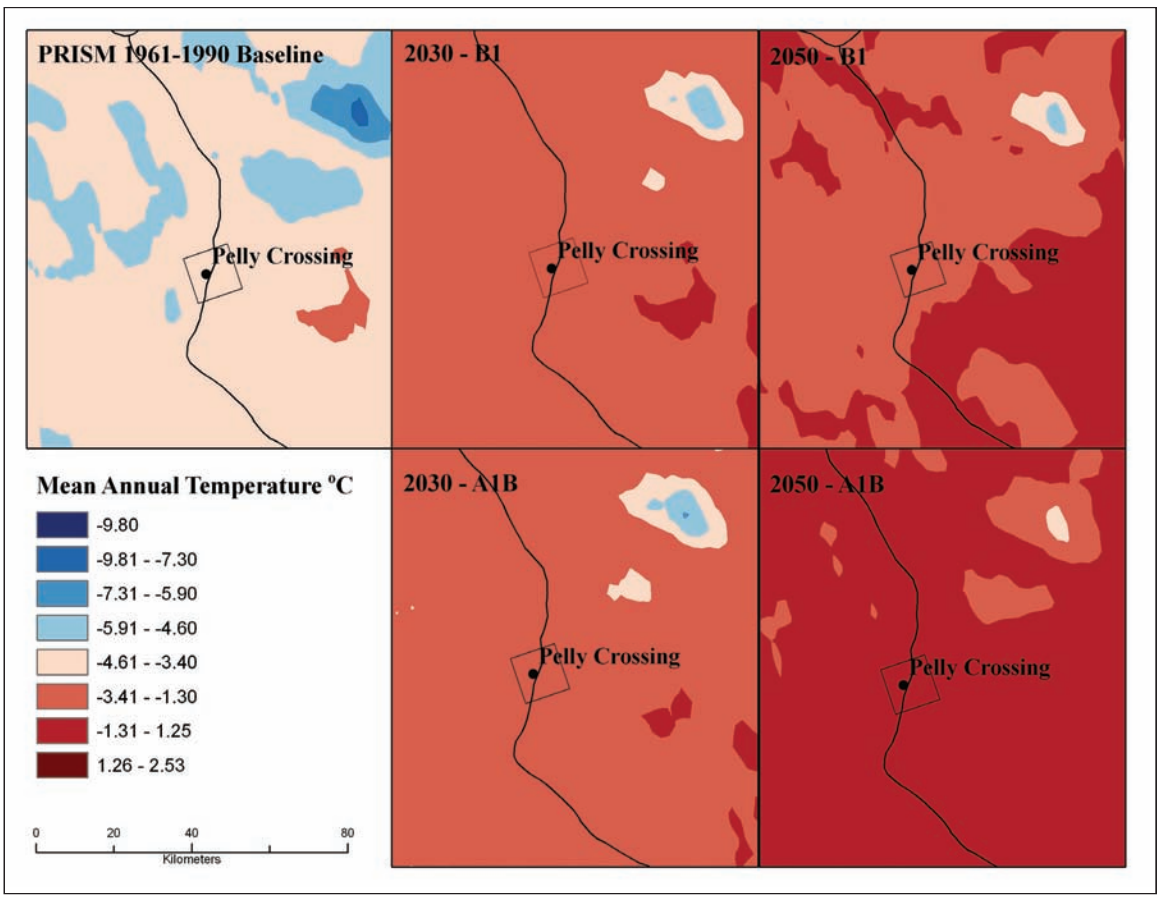
APPENDIX A - SURFICIAL GEOLOGY TEXTURES

Sample ID	Gravel content (%)	Sieve - #10 (>2.00 mm) % pebbles	Sieve - #35 (>0.50 mm) % coarse sand	Sieve - #230 (>0.063 mm) % fine sand	Sieve # 635 (>0.020 mm) % silt	Sieve - pan % mud	Texture	% Sand by hydrometer	% Silt by hydrometer	Clay content (%)
48	63	32	43	23	0.7	1.2	sand	98	0	0
50	97	41	29	14	3.1	13	loamy sand	81	10	9
51	0	1.1	1.2	7	37	54	silt loam	22	68	10
53	0	0	0	34	36	30	sandy loam	60	33	7
54	0	0	0	28	44	29	sandy loam	47	46	7
55	51	40	41	14	1	3.5	sand	93	4	3
56	59	6.2	46	27	3.3	18	sand	97	0	0
57	72	38	38	21	0.8	1.6	sand	99	0	0
58	62	52	36	9	1	1.9	sand	96	4	0
59	38	8.7	62	29	0.5	0.6	sand	99	0	0
60	62	13	44	37	2.1	4.6	sand	97	2	0
61	56	20	52	26	0.7	0.9	sand	100	0	0
62	35	7.9	63	25	1.9	1.8	sand	98	0	0
63	60	26	58	14	1.2	0	sand	100	0	0
64	0	0	0.7	73	13	13	loamy sand	84	14	3
65	0	0	1.6	75	16	7.7	sand	87	13	0
66	30	19	20	27	9.5	25	sandy loam	68	22	11
67	32	15	14	32	19	20	sandy loam	58	34	9
68	8	0.5	2.3	22	24	51	loam	38	42	21
69	56	22	22	35	9.6	12	loamy sand	82	16	3
70	52	16	24	33	8.8	19	sandy loam	77	17	7

APPENDIX B - SNAP PROJECTIONS

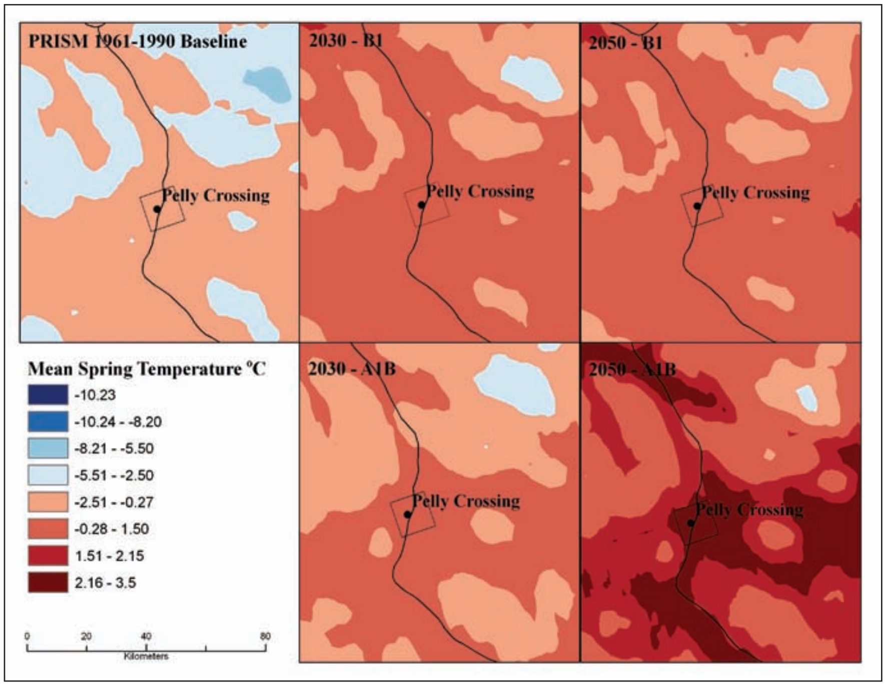
This section provides figures, focusing on the Pelly Crossing region, that illustrate projected changes in several climate parameters. Projections are derived from the regionally downscaled climate data provided by the Scenarios Network for Alaska Planning (SNAP, 2010) at the University of Alaska Fairbanks. Projected precipitation and temperature data were based on raster values surrounding the geographic centre of Pelly Crossing, as determined by SNAP. The range encapsulated was 625 km^2. Changes in climate for the Pelly Crossing region were projected for two time periods (2030 and 2050) using two standard scenarios (B1 and A1B) developed by the Intergovernmental Panel on Climate Change (IPCC). The B1 and A1B scenarios are based on the IPCC Special Report on Emissions Scenarios (Nebojša *et al.*, 2000). The B1 scenario projects low to moderate degrees of climate change over the next century, while the A1B scenario anticipates medium to high degrees of climate change. These two scenarios were applied in this study because they provide a reasonable range in possible shifts in temperature and precipitation for Mayo by 2030 and 2050.

Appendix B1 - Projected changes in mean annual temperature for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

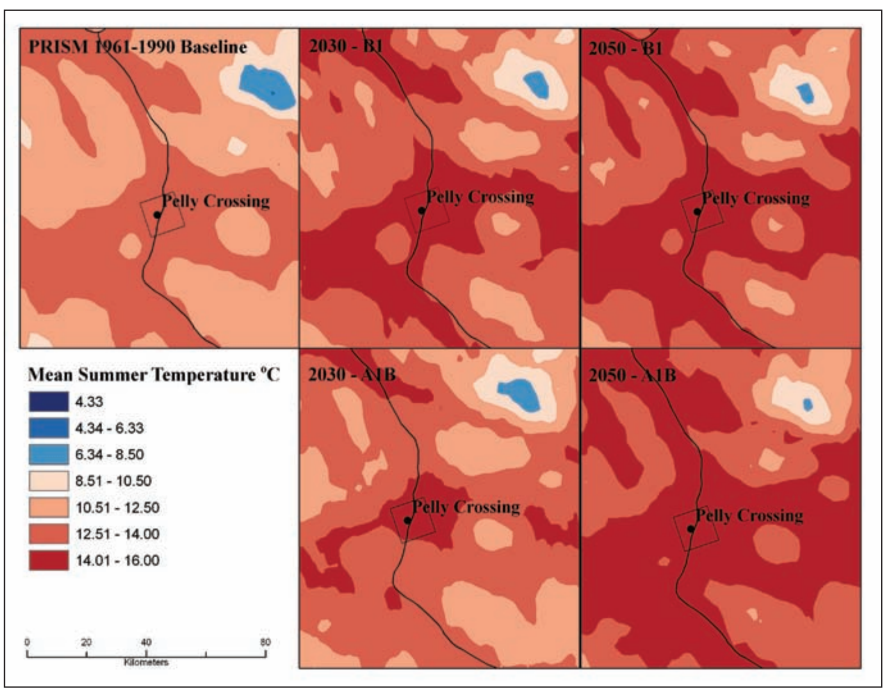


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B2 - Projected changes in mean spring temperature for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

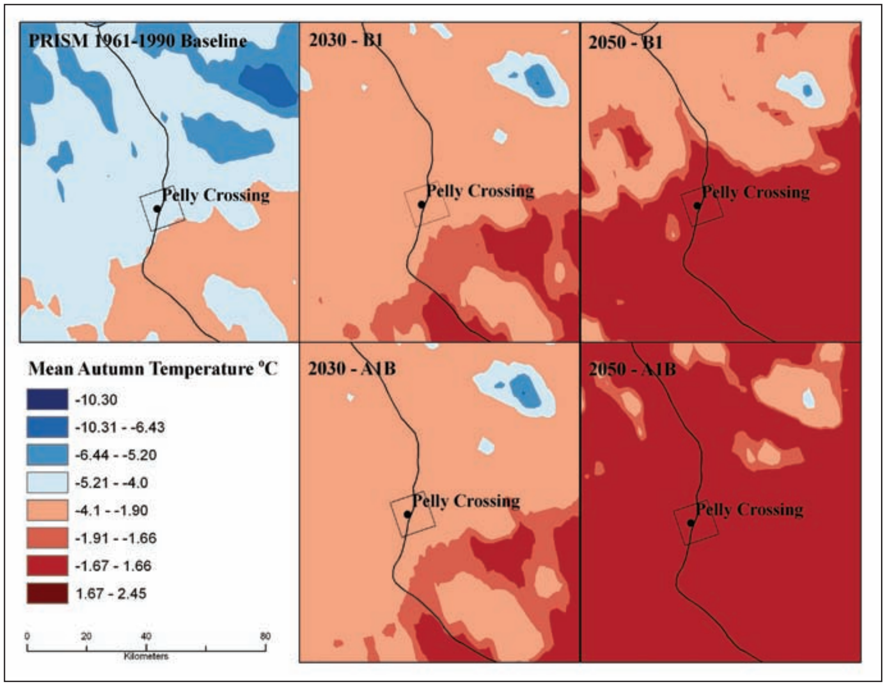


Appendix B3 - Projected changes in mean summer temperature for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

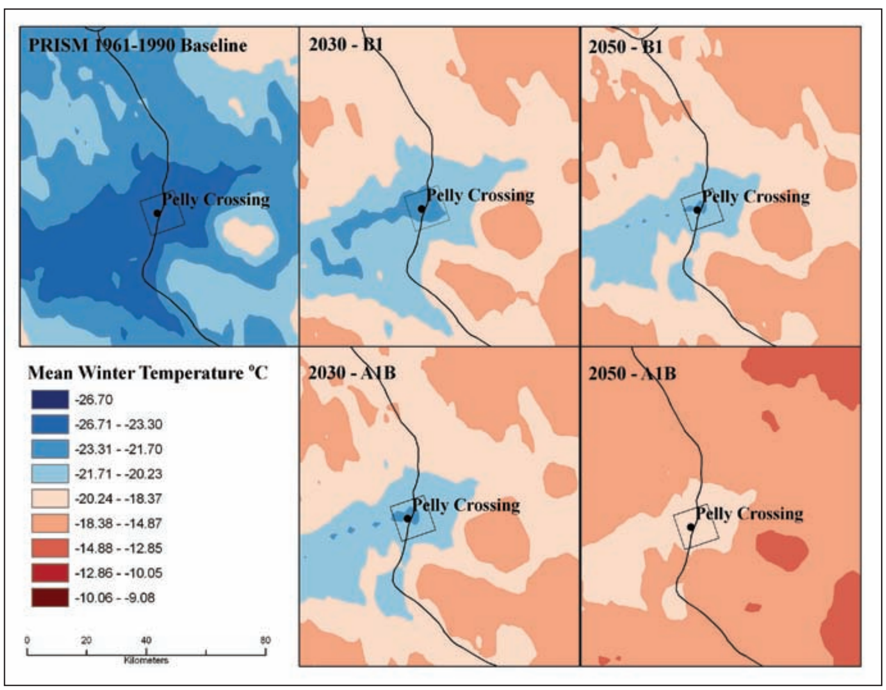


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B4 - Projected changes in mean autumn temperature for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

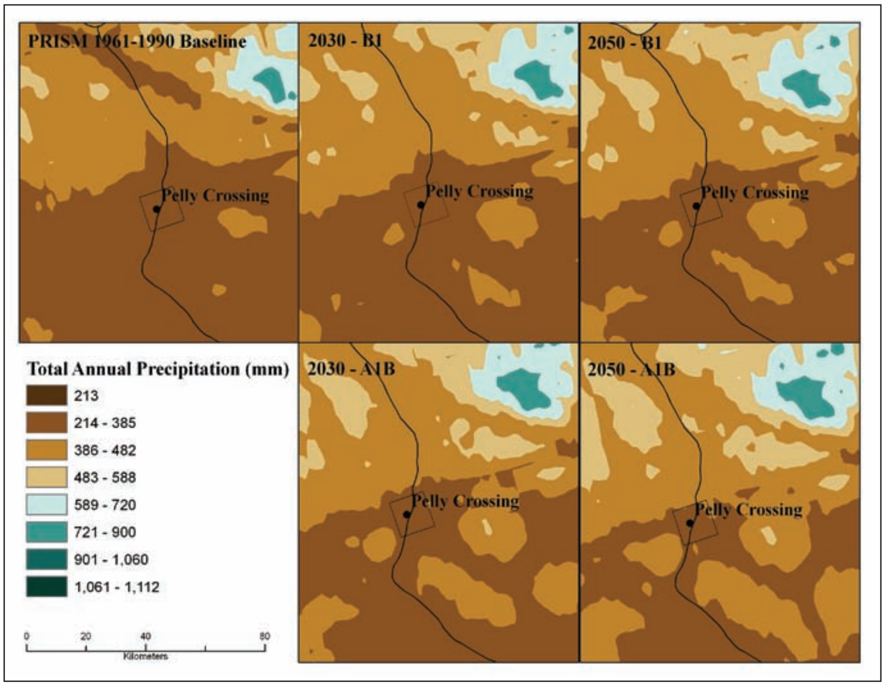


Appendix B5 - Projected changes in mean winter temperature for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

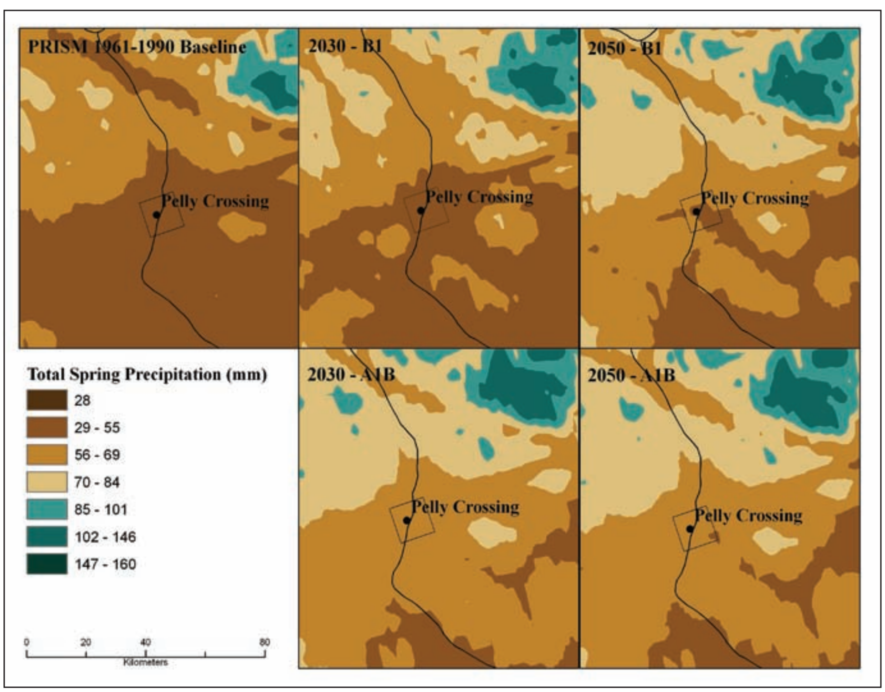


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B6 - Projected changes in total annual precipitation for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

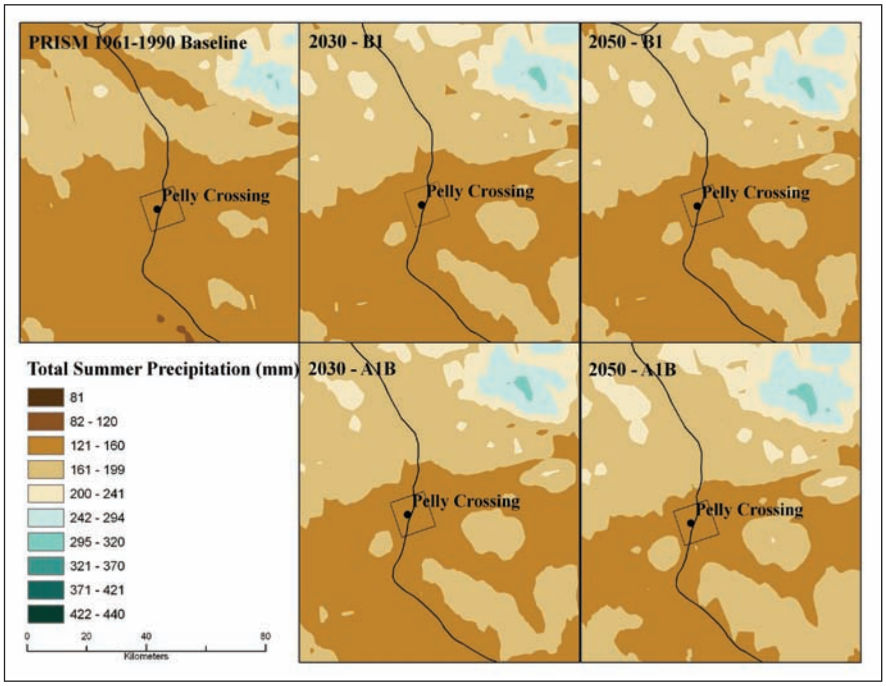


Appendix B7 - Projected changes in total spring precipitation for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

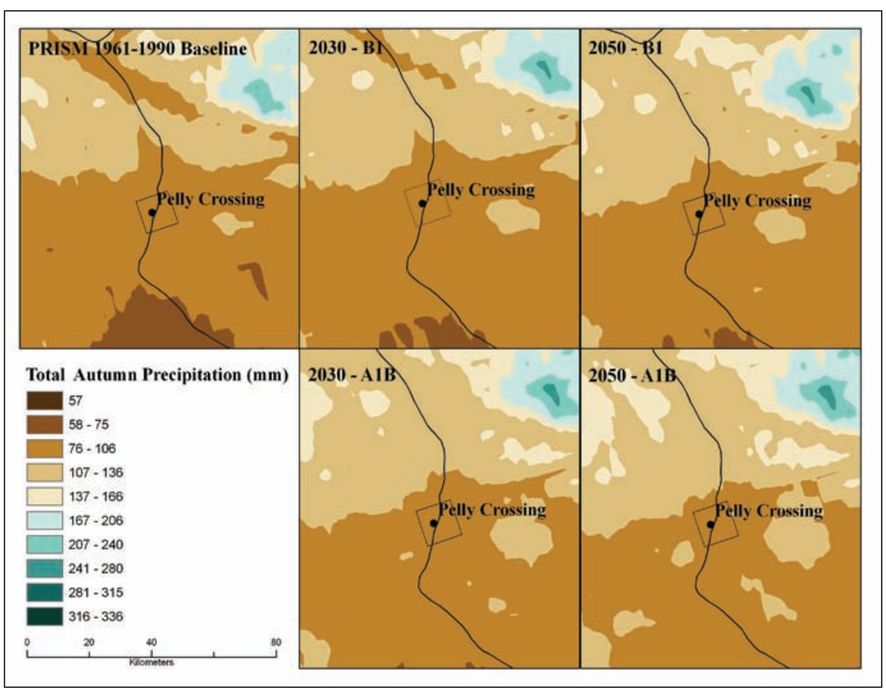


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B8 - Projected changes in total summer precipitation for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

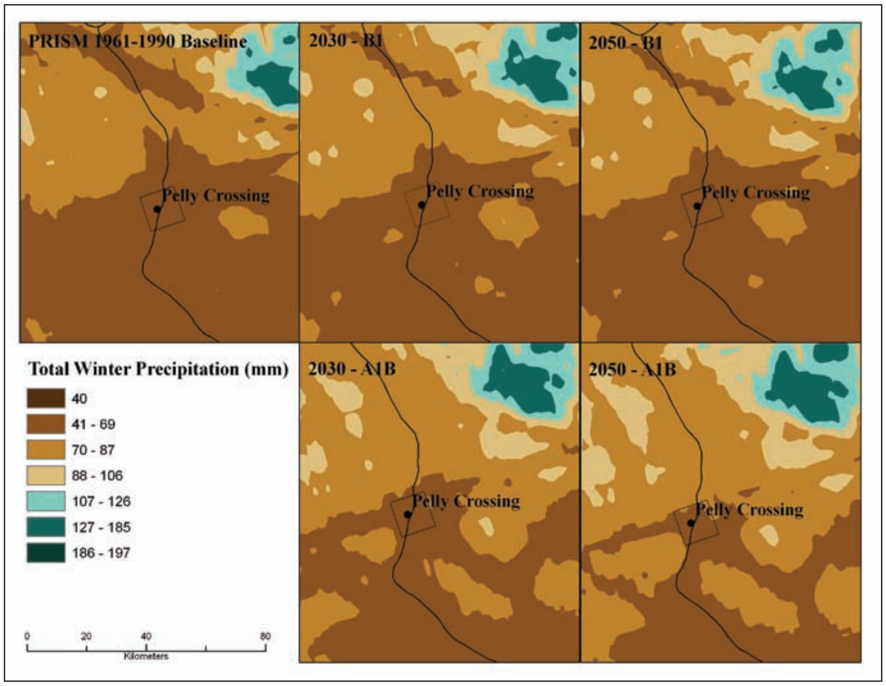


Appendix B9 - Projected changes in total autumn precipitation for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

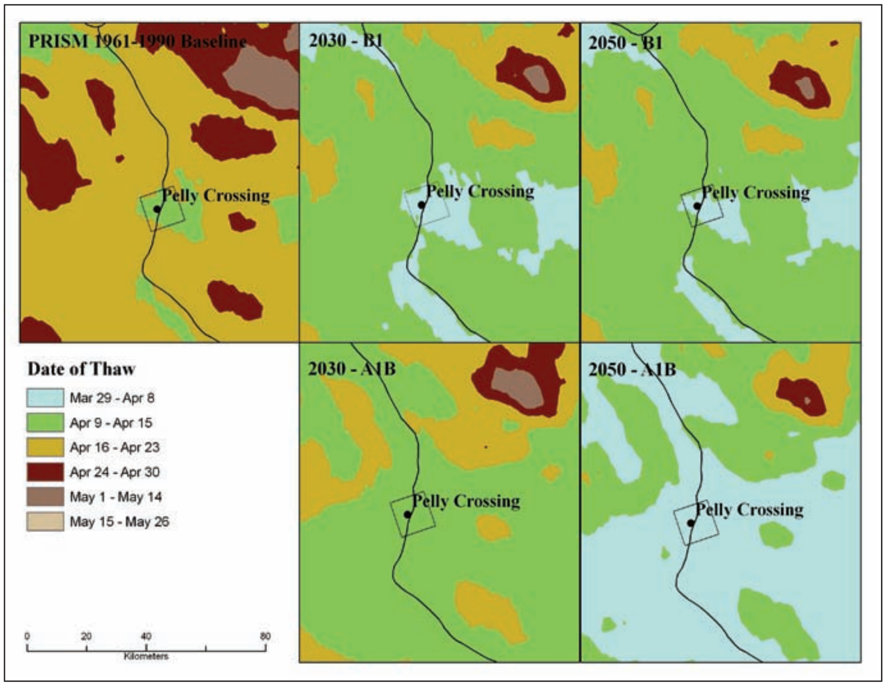


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B10 - Projected changes in total winter precipitation for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

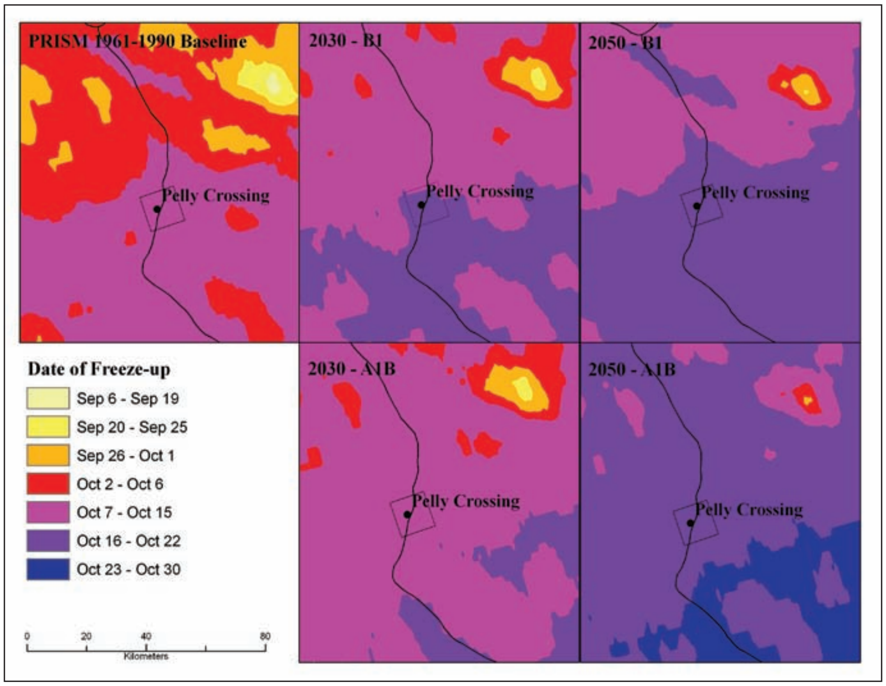


Appendix B11 - Projected changes in date of thaw for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.

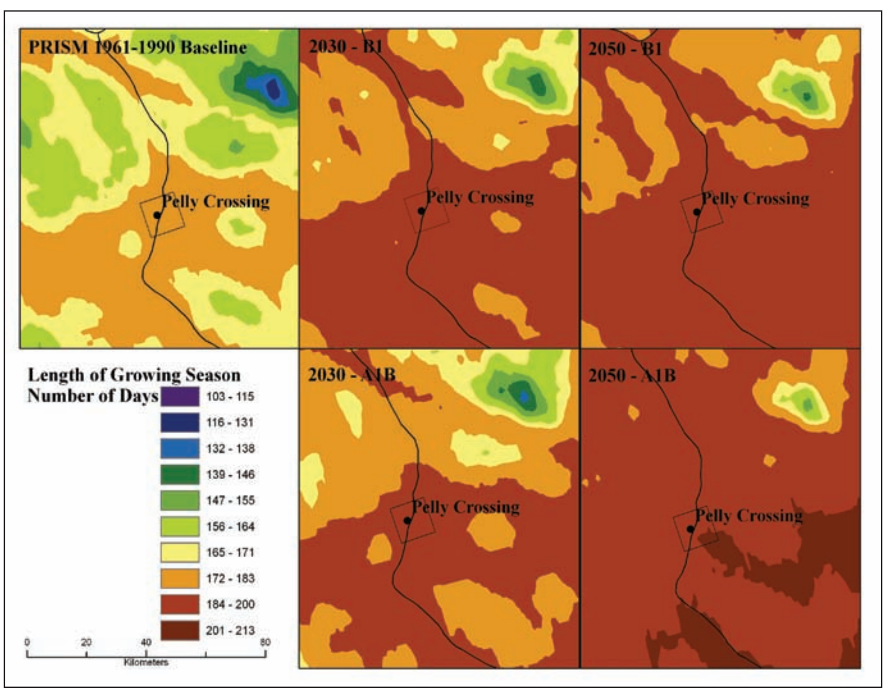


APPENDIX B - SNAP PROJECTIONS, *continued*.

Appendix B12 - Projected changes in date of freeze-up for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.



Appendix B13 - Projected changes in length of growing season for 2030 and 2050, based on the B1 and A1B scenarios, respectively. Baseline (1961-1990 climate normal) conditions are provided.



APPENDIX C - POLYGON HAZARD DESCRIPTION

Polygon number	Hazard rank	Map colour	Geologic label	Landscape hazards	Area (m^2)
1	2	Yellow	zsEv/sgFf	slope stability	74
2	1	Green	zsEv/sgFGp/kdMb	permafrost	206
3	2	Yellow	zsEb\pskMb	slope stability	48
4	2	Yellow	zsEv/kpsMb/sgFGf	slope stability	252
5	1	Green	dmkMv/Cv\R	permafrost	377
6	2	Yellow	spkCb/pksMb-X	permafrost, slope stability	371
7	3	Red	zsEb/zsLd//eOw	shallow groundwater	108
8	3	Red	zsEb/zsLd//eOw	shallow groundwater	536
9	1	Green	zsEv/pkzMvb	permafrost	2860
10	1	Green	dmkMv/Cv\R	permafrost	372
11	2	Yellow	zsEb\pkzMp-X	permafrost	4474
12	2	Yellow	zsEv/szgCa-X	permafrost, slope stability	233
13	2	Yellow	zsEb\Mb//zsdCv-X	permafrost, slope stability	2680
14	3	Red	zsEb/zsLd//eOw	shallow groundwater	394
15	3	Red	zsEb/zsLd//eOw	shallow groundwater	711
16	2	Yellow	zsEv/sgzCf-X	permafrost, slope stability	409
17	1	Green	zsEv/pksMr	permafrost	524
18	2	Yellow	zsEb\pksMb	slope stability	237
19	3	Red	zsEb/eOw-X	permafrost, shallow groundwater	158
20	3	Red	zsEb/eOw	shallow groundwater, slope stability	334
21	3	Red	gsFp	flooding risk	1111
22	1	Green	zsEb\sgFGtp//pkzMb	permafrost	1453
23	1	Green	gszFGt	negligible	54
24	1	Green	zsEv/sgFGt	negligible	1820
25	1	Green	gszFGt	negligible	37
26	1	Green	zsEv/pkzMb-X	permafrost	312
27	2	Yellow	zsEb\pkzMb-X	permafrost	1772
28	3	Red	eOw\szgCb-X	permafrost, shallow groundwater, slope stability	41
29	1	Green	zsEv/pkzMb-X	permafrost	9960
30	1	Green	zsEv/sgFGp	negligible	2274
31	2	Yellow	zsEb\sgFp-X	permafrost, slope stability	842
32	1	Green	zsEv/gskFGt-E	negligible	3764
33	1	Green	zsEb\gsFGt	negligible	745
34	1	Green	zsEb\sgFGtp//pkzMb	permafrost	3991
35	1	Green	zsEv/sgFGt	negligible	1528
36	2	Yellow	zCw\sgFp	slope stability	160
37	2	Yellow	szCv/gsFp	slope stability	156
38	1	Green	zsEb\gsFGt	negligible	626
39	2	Yellow	szCb\sgFGt	flooding risk	97
40	1	Green	zsEv/gsFGt//pkzMb	permafrost	112
41	1	Green	zsEb\gsFGt	negligible	404
42	3	Red	sgzFf	slope stability	44

APPENDIX C - POLYGON HAZARD DESCRIPTION, *continued.*

Polygon number	Hazard rank	Map colour	Geologic label	Landscape hazards	Area (m²)
43	2	Yellow	gsFp	flooding risk	480
44	2	Yellow	szdCb-X	permafrost, slope stability	1885
45	1	Green	zsEb\gsFGt	negligible	302
46	1	Green	zsEv/zpkMb-X	permafrost	1631
47	2	Yellow	zsgFt	flooding risk	861
48	1	Green	zsEv/sgFGt	negligible	324
49	2	Yellow	sgFt	flooding risk	174
50	1	Green	zsEv/sgFGt	negligible	203
51	1	Green	zsEv/sgFGt	negligible	1084
52	1	Green	zsEv/gskFGt-E	negligible	4974
53	1	Green	zsEv/sgFGt	negligible	5
54	3	Red	zcsFAp-Id	flooding risk	199
55	3	Red	gszFf	slope stability	99
56	1	Green	szCv\zEv\gsFGt	negligible	200
57	3	Red	gsFAp/eOw-I	flooding risk	1057
58	3	Red	eOw\szgCb-X	shallow groundwater, slope stability	249
59	3	Red	sgFp	flooding risk	85
60	3	Red	sgzFt	flooding risk	115
61	2	Yellow	zsEb\pkzMb-X	permafrost	9751
62	2	Yellow	gsFt	flooding rist	175
63	1	Green	zsCv\sgFGt	negligible	777
64	1	Green	zsEb\gsFGt	negligible	104
65	1	Green	zsEb\sgFGtp//pkzMb	permafrost	1321
66	3	Red	spkFt	flooding risk	1967
67	3	Red	sgzFt	flooding risk	685
68	3	Red	gsFt	flooding risk	139
69	2	Yellow	sgFt	flooding risk; riverbank erosion	1569
70	3	Red	spkFt	flooding risk; riverbank erosion	1255
71	3	Red	zsgCf	slope stability	244
72	1	Green	zsgCb\gsFGt	permafrost	89
73	1	Green	zsEb\gsFGt	negligible	42
74	3	Red	spkFp	flooding risk	343
75	3	Red	gsFt	flooding risk	156
76	2	Yellow	szCb\gsFGt	slope stability	83
77	3	Red	szgCf	slope stability	23
78	3	Red	szgCb	slope stability	15
79	1	Green	gsFGt-E	negligible	1904
80	1	Green	gsFGt	negligible	107
81	2	Yellow	zsCv\szgLGp	slope stability	179
82	2	Yellow	szCb\gsFGt	slope stability	418
83	3	Red	spkFt	flooding risk; riverbank erosion	988
84	3	Red	zsCv\szgLGp	slope stability	373

APPENDIX C - POLYGON HAZARD DESCRIPTION, *continued.*

Polygon number	Hazard rank	Map colour	Geologic label	Landscape hazards	Area (m^2)
85	2	Yellow	szgFt	flooding risk; riverbank erosion	1744
86	2	Yellow	zsgFt	flooding risk; permafrost	896
87	2	Yellow	szgCb	slope stability	79
88	1	Green	zsEb\gsFGt	negligible	776
89	1	Green	zsEvb\sgFGt-E	negligible	950
90	2	Yellow	gsFp	flooding risk	49
91	1	Green	zsEb\gsFGt	negligible	206
92	1	Green	gsFt	negligible	20
93	2	Yellow	gsFp	flooding risk	289
94	3	Red	sgFf	flooding risk	111
95	2	Yellow	szgFt	flooding risk	331
96	2	Yellow	sgFt	flooding risk	396
97	2	Yellow	xmCb\sgFGt	slope stability	33
98	2	Yellow	xmCv\sgFGt	slope stability	42
99	2	Yellow	zsEv/xmCv/sgFt	slope stability	170
100	3	Red	szgFt	flooding risk	628
101	2	Yellow	szgFp	flooding risk	164
102	1	Green	zsEw/gsFGt	negligible	2690
103	3	Red	gksFAp-M	flooding risk	4358
104	1	Green	sgFGt\R	negligible	79
105	3	Red	szdCvb\sgFGp/zscLGb	slope stability	333
106	1	Green	sgFGt\R	negligible	27
107	3	Red	eOd/zdcCb-X	permafrost, shallow groundwater, slope stability	38
108	3	Red	R/xmCv	slope stability	525
109	3	Red	eOd/zdcCb-X	permafrost, shallow groundwater, slope stability	68
110	3	Red	sgFAp	flooding risk	73
111	3	Red	zscCf-X	permafrost, slope stability	82
112	3	Red	euOd-X	permafrost, shallow groundwater	68
113	2	Yellow	zdCv\sgFp	flooding risk, slope stability	158
114	3	Red	szdCvb\sgFGp/zscLGb	slope stability	349
115	2	Yellow	szgFp	flooding risk	304
116	1	Green	zsEv/sgzFGt\sgFt	negligible	675
117	2	Yellow	zdCv\sgFp	flooding risk	12
118	3	Red	szdCv	slope stability	35
119	3	Red	szdCv\sgFGp/zscLGb	slope stability	112
120	1	Green	zsEv/zckMw\R	permafrost	253
121	3	Red	eOd/sdzCb-X	permafrost, slope stability	187
122	2	Yellow	zdCb	slope stability	16
123	2	Yellow	zsEb\zckMb/zspCb-X	permafrost, slope stability	927
124	1	Green	zsEv/sgFGp	negligible	5674
125	2	Yellow	zdCb	slope stability	66
126	1	Green	zsEv/zckMw\R	permafrost	3427

APPENDIX C - POLYGON HAZARD DESCRIPTION, *continued*.

Polygon number	Hazard rank	Map colour	Geologic label	Landscape hazards	Area (m^2)
127	2	Yellow	zCv/skpMb-X	permafrost, slope stability	347
128	1	Green	zsEb\spFGp//zpkMb	permafrost	4933
129	3	Red	szdCv	slope stability	208
130	3	Red	sgzFAp/eOp-I	flooding risk	1461
131	2	Yellow	szgCb-X	permafrost, slope stability	1435