NORTHERN CLIMATE EXCHANGE, *Yukon Research Centre*

PROJECTED FUTURE CHANGES IN GLACIERS AND THEIR CONTRIBUTION TO DISCHARGE OF THE YUKON RIVER AT WHITEHORSE

February 2014

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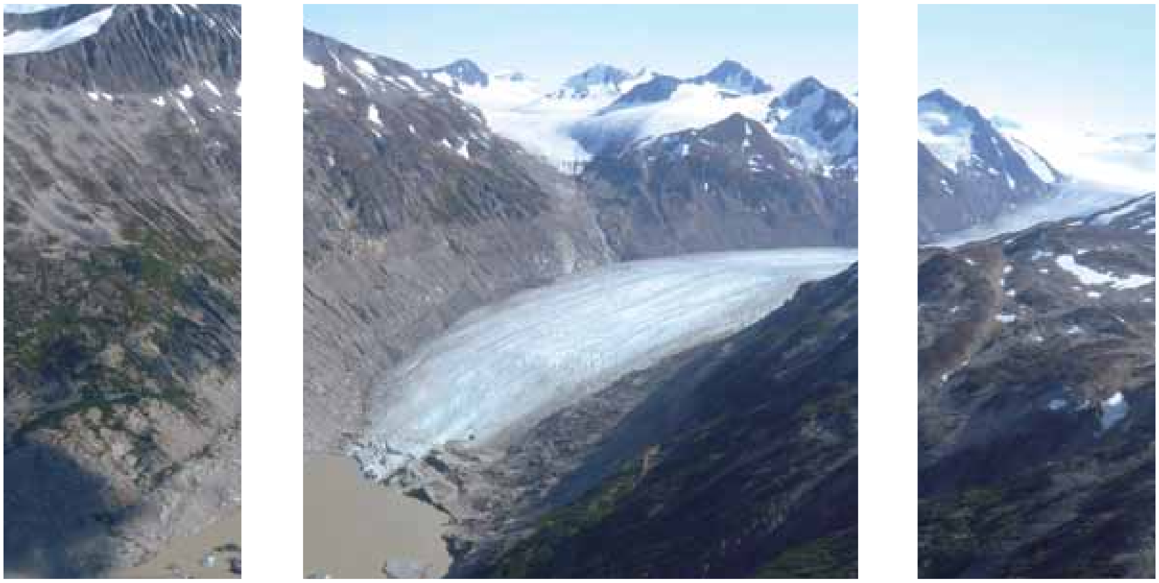

Projected Future Changes in Glaciers and their Contribution to Discharge of the Yukon River at Whitehorse

Prepared for Yukon Energy Corporation
February 2014

Yukon Geological Survey

University of Alberta

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Front cover photograph: Photo of the Fantail Glacier (referred in this report as "GL2") located in the Boundary Ranges of northern British Columbia; view is to the south. Photo courtesy of Chris DeBeer.

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EXECUTIVE SUMMARY

This study was carried out by the Northern Climate ExChange (NCE), Yukon Research Centre, Yukon College for the Yukon Energy Corporation (YEC) in order to understand the hydrological role of glaciers, and their future potential response to climate change, in the Upper Yukon River Basin above Whitehorse. There is presently uncertainty in both the contribution that glaciers provide to the flow volume of this river, as well as how future climate change will affect this contribution and alter the balance of runoff from glacial sources and non-glacial sources. To accomplish this research and attempt to resolve these issues, this study used a variety of approaches, including: 1) field-based, ice-penetrating radar measurements over a sample of glaciers within the basin to obtain information on their current thickness and volume; 2) compilation of a remotely sensed, image-based inventory of the present area and distribution of glaciers within the basin, together with an analysis of recent changes in glacier extent over the past several decades (and back to 1948 for some selected regions); 3) calibration and validation of a hydrological model (HBV-EC model within the Green Kenue™ platform) for the simulation of seasonal hydrographs and glacier contributions for two tributary rivers (Fantail and Wheaton rivers) of the Yukon River, as well as for the Yukon River at Whitehorse; 4) and the application of various climate scenarios within the model to evaluate the potential response of glacier area and mass balance, river discharge, and glacier contributions to runoff over the next 60 years.

The field work was carried out in August 2011, and involved a number of helicopter supported surveys consisting of transects across the aforementioned glacier surfaces to obtain along-glacier and cross-sectional profiles of glacier ice thickness. These were later converted into estimates of total glacier volume for the selected glaciers using interpolation procedures in ArcMap™ 9.3 GIS. The glacier inventory work showed that glaciers presently occupy an area of roughly 1002 km^2 within the Upper Yukon River Basin, and have been undergoing continual retreat and area loss since at least 1948, with acceleration in the rates of loss in recent decades. The largest glacier in the basin, the Llewellyn Glacier (433 km^2), comprises nearly half of the total present ice surface area. A volume-area scaling relationship was developed using the ice thickness data and volume estimates obtained in this study, and indicated that glaciers presently have an estimated total volume of ~187 km^3.

The model used to simulate seasonal hydrographs in each basin was setup using the Green Kenue™ software tool, which contains the HBV-EC hydrological model routines. Evaluation of the model performance focused on the Fantail, Wheaton, and Upper Yukon rivers, and demonstrated that the model was able to reliably simulate the magnitude and timing of river discharge. The model also properly simulated internal watershed and glacial processes such as snow accumulation, melt, and glacier mass balance. An important conceptual distinction between glacier melt and glacier wastage, developed originally by Comeau et al. (2009), was considered. In this, melt consists of the melt of snow and ice that is less than or equivalent to the volume of snow accumulated into a glacier system each year, and wastage represents the amount of melt that exceeds the volume of snow accumulation into a glacier system in a given year, resulting in a net mass loss from the glacier. With these definitions in place, the two components were quantified to allow a better assessment of the contribution that glaciers make to runoff and how this may change under a suite of climate projections. According to the simulation results of the contemporary period (i.e., 1981 - 2011), glaciers contribute 16% and 7% of the total annual flow volume of the Upper Yukon River through melt and wastage, respectively. Of each of these amounts, 46% and 39% is solely derived from the Llewellyn Glacier, which highlights its importance in terms of runoff contribution relative to other glaciers in this region. In comparison, seasonal snowmelt from non-glacier sources accounts for about

44% of the total annual flow of the Upper Yukon River according to this model, while rainfall and groundwater contributions comprise the remaining 33%.

Future climate scenarios were applied to the model to evaluate the response of glaciers and glacier runoff to various projections. Four different projections were applied:

1. a steady-state climate based on conditions over the past 30 years (called SC-1);
2. a scenario based on the Intergovernmental Panel on Climate Change (IPCC) Global A1B scenario in which there is modest warming and a slight increase in precipitation (SC-2);
3. a scenario based on the Scenarios Network for Alaska Planning (SNAP) downscaled A1B projection for the region, in which there is more extreme warming and precipitation increases (SC-3); and
4. a scenario that includes A1B temperature increases and a 25% reduction in precipitation (SC-4).

The model was applied, and glacier extents were adjusted every 20 years to simulate terminal retreat based on 3-dimensional representations of glaciers from the field data analysis. Simulations focused on the time periods of 2010 - 2030, 2030 - 2050, and 2050 - 2070. The results demonstrated that under the SC-1 and SC-4 scenarios, total runoff at Whitehorse gradually is predicted to decline due to either reduced glacier wastage contribution or reduction snowpack accumulation and glacier melt. Under the SC-2 and SC-3 scenarios, runoff likely increases due to the additional snow accumulation with faster and greater melt in spring, increased summer rainfall, and sustained mass loss from glaciers, where the magnitude of increase is greater for the SC-3 projection due to the large increases in precipitation in this scenario. Simulated seasonal variations in runoff showed different patterns, depending on the approach, and showed increases in runoff in all months under SC-2 and SC-3 scenarios, a declining summer runoff under SC-1, and predominant spring and summer decreases in runoff under the SC-4 approach. Finally, by simulation and by estimation of the present volume distribution glaciers, results showed that glacier wastage contributions to the flow of the Yukon River (which represent a 'surplus' flow derived from the loss of long-term stored glacier ice) will continue to enhance runoff for many decades into the future, even under sustained terminal retreat and areal shrinkage of glaciers in this basin. Taken together, it was inferred that the most likely future response of the flow of the Yukon River is for an average tendency towards increasing annual runoff with an extension of higher flows across the 'shoulder' seasons (i.e., early spring and late fall). These higher flows during the shoulder seasons will be of benefit to YEC since this will extend the period of viable hydro-power production.

Based on the findings of this study, this report provides several suggested initiatives that YEC might consider for future adaptation to climate change and runoff response. Four main areas for further research focus and monitoring were identified:

1. A further investigative study of the Llewellyn Glacier due to its vast size compared to the other glaciers in the region, and its potentially high sensitivity to climate change.
2. The installation of a network of meteorological observation stations in the alpine headwaters region to monitor hydro-meteorological conditions in these areas, from which the highest specific runoff amounts (i.e., mm per unit area) are derived.
3. An increased focus on snow processes and their sensitivity to changing climate conditions using physically based approaches, due to the importance and dominance of seasonal snowmelt as a contributor to runoff in this basin.

4. The future integration of physically based hydrological modelling tools with existing hydrograph routing techniques (e.g., US Army Corps of Engineers HEC-ResSim model), in order to properly represent runoff routing and the flow of water through the complex system of lakes within the basin, and ultimately improve simulations of hydrograph shape and timing at the basin outlet.

LIST OF ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiomet
BC-TRIM	British Columbia Terrain Resources Information Management Program
B_m	Model Bias
CDCD	Canadian Daily Climate Database
CDED	Canadian Digital Elevation Data
DEM	Digital Elevation Model
ELA	Equilibrium Line Elevation
ETM+	Enhanced Thematic Mapper
GIS	Geographic Information Systems
GRU	Grouped Response Unit
HYDAT	Environment Canada Hydrometric Database
IPCC	Intergovernmental Panel on Climate Change
MB	Glacier Mass Balance
MRG	HBV-EC Glacier Ice Melt Factor
NCE	Northern Climate ExChange
NHRC	National Hydrology Research Centre
NS	Nash-Sutcliffe model efficiency coefficient
NTDB	National Topographic Database
NTS	National Topographic System
RMSE	Root Mean Squared Error
SNAP	Scenarios Network for Alaska Planning
SPOT	Système Pour l'Observation de la Terre
SRTM	Shuttle Radar Topographic Mission
SWE	Snow Water Equivalent
TM	Thematic Mapper
UBC	University of British Columbia
USGS	United States Geological Survey
VA	Volume-Area
WSC	Water Survey of Canada
YEC	Yukon Energy Corporation

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1. INTRODUCTION AND PROJECT DESCRIPTION

Climate change in Arctic and sub-Arctic areas, including Yukon Territory, is having an impact on the hydrological cycle through changes in temperature and precipitation. Recent studies have documented considerable cryospheric changes and an intensifying hydrological cycle in the north, providing evidence of pronounced winter and spring warming, decreasing snow cover, earlier melting of snow, predominantly negative glacier mass balance, the retreat of glacier termini, and increasing streamflow variability (e.g., Serreze, et al., 2000; Whitfield and Cannon, 2000; Déry et al., 2009; Barrand and Sharp, 2010; Berthier et al., 2010). Future warming trends in northern regions are expected to occur at a relatively greater rate than most other parts of the world (Solomon et al., 2007), and this is a concern for future water resource management and planning. Within the southern Yukon Territory and the headwaters of the Yukon River, a particular concern is the ongoing and potential future loss of glaciers, and the effects this might have on river discharge timing, magnitude, and seasonality patterns. The hydrological role that glaciers play in this area is currently uncertain, but it is speculated that surface runoff from glacial sources is an important component of discharge that contributes to industrial activities such as hydroelectric power generation, especially during the summer months. Therefore, in order to begin to adapt to potential future climatically induced perturbations on the hydrologic regime of glacierized basins in the headwaters of the Yukon River, it is important to have a thorough understanding of the current and future state of the glaciers. Additionally, a more detailed understanding of glacial contributions to the flow of the Yukon River is required. This contribution also needs to be placed in context with other sources of runoff, such as seasonal snowmelt, for example.

A large portion of the Yukon's power demands are met through hydroelectric generation at the Yukon Energy Corporation's (YEC) Whitehorse facility, which must be augmented with diesel power generators during low-flow periods such as the winter months. To improve the understanding of the potential future hydrological responses to climate change in the Yukon River headwaters, this study was undertaken by the Northern Climate ExChange (NCE), of the Yukon Research Centre, Yukon College, in collaboration with the Yukon Geological Survey and the University of Alberta. Results will assist YEC in developing future management plans and potential mitigation strategies, as well as help to identify future research priorities, so that YEC can best adapt to the effects of climate change.

1.1 OBJECTIVES

The purpose of the study is to assess climate-induced changes to the contribution of glacially sourced waters to Yukon's hydroelectric power generation. The specific objectives of the project are to:

i. Generate an inventory of the glaciers and ice patches that currently contribute to YEC's hydroelectric generation facility at Whitehorse.

ii. Determine the likely impacts of different climate-change scenarios on the flow regime of glacierized basins with the Yukon River headwaters area and on discharge from the Yukon River at Whitehorse.

iii. Suggest recommendations to YEC for mitigation of likely flow regime changes, and highlight key areas for additional research and/or monitoring.

It is noted that the focus of this report is on the current and future runoff contributions from glaciers in high elevation parts of the Yukon River headwaters. An in-depth assessment of the potential changes in snow processes and hydrology over non-glaciated areas within the region was not included as part of this study, but the analysis presented in this report highlights some key changes to snowpack conditions that are likely to occur in the Upper Yukon River Basin, along with the implications for runoff.

1.2 OUTLINE OF THE REPORT

The following sections of this report describe the work that was undertaken as part of this project and presents the results and their interpretation in order to provide a better understanding of the hydrological role of glaciers in this region. Section 2 describes the focal areas for this research along with the field data collection campaign that was carried out on several glaciers within the Fantail and Wheaton River basins. The analysis of these data is also presented here, and estimates of the current volume of ice within these glaciers are derived. Section 3 focuses on the glacier inventory within the Upper Yukon River Basin and provides information on the current state (spatial distribution, area, and volume) of the glaciers, along with an analysis of recent observed changes in glacier area and volume. The hydrological model used in this research for examining glacier responses and changing flow regimes is described in Section 4. Here, the calibration and validation of the model are described, and the model is applied under historical as well as a variety of future climate-change scenarios to investigate the hydrological role of glaciers in the basin. Section 5 provides recommendations for mitigation strategies, additional research, and monitoring.

2. RESEARCH SITES AND FIELD DATA COLLECTION

2.1 PHYSIOGRAPHY AND CLIMATIC SETTING

This project focused on the glaciated headwater areas of the Upper Yukon River Basin above Whitehorse (Figure 1). This region includes the rugged Boundary Ranges that rise above lower plains and the more gently rolling mountains to the north and east. Elevations reach just over 2700 m on some of the highest peaks, and broad upland areas along the southwest boundary of the basin contain large icefields with numerous outlet valley glaciers extending in all directions. The largest of these is the Juneau Icefield at the far southern end of the basin, from which the 433 km^2 Llewellyn Glacier flows northward. Higher mountains up to 20 - 30 km to the east of the southwestern basin margin also contain numerous cirque glaciers, and smaller hanging glaciers and glacierets. The total ice-covered area within the basin as of summer 2010 was roughly 1002 km^2.

Climatic conditions vary strongly over the basin, with a large southwest to northeast gradient in total annual precipitation and a transition from wet maritime to drier continental conditions. Annual precipitation amounts along the southwest marginal areas of the basin are greater than 1250 mm, with large uncertainty, and decrease sharply to 250 - 375 mm over a distance of less than 50 km (Brabets et al., 2000). This pattern is directly evidenced by the presence of large glaciers and icefields in the southwestern part of the basin, and the lack of glaciers anywhere else, and suggests that the greatest specific runoff (i.e., mm per unit area) is generated here in the high-elevation, southern headwaters. Temperature patterns are characterized by short, warm summers, and long, cold winters (14.1°C average July temperature, -17.7°C average January temperature at Whitehorse). High in the headwater areas, it is less clear what the annual and diurnal temperature patterns are, but these are likely to be more moderated by the influence of maritime air masses.

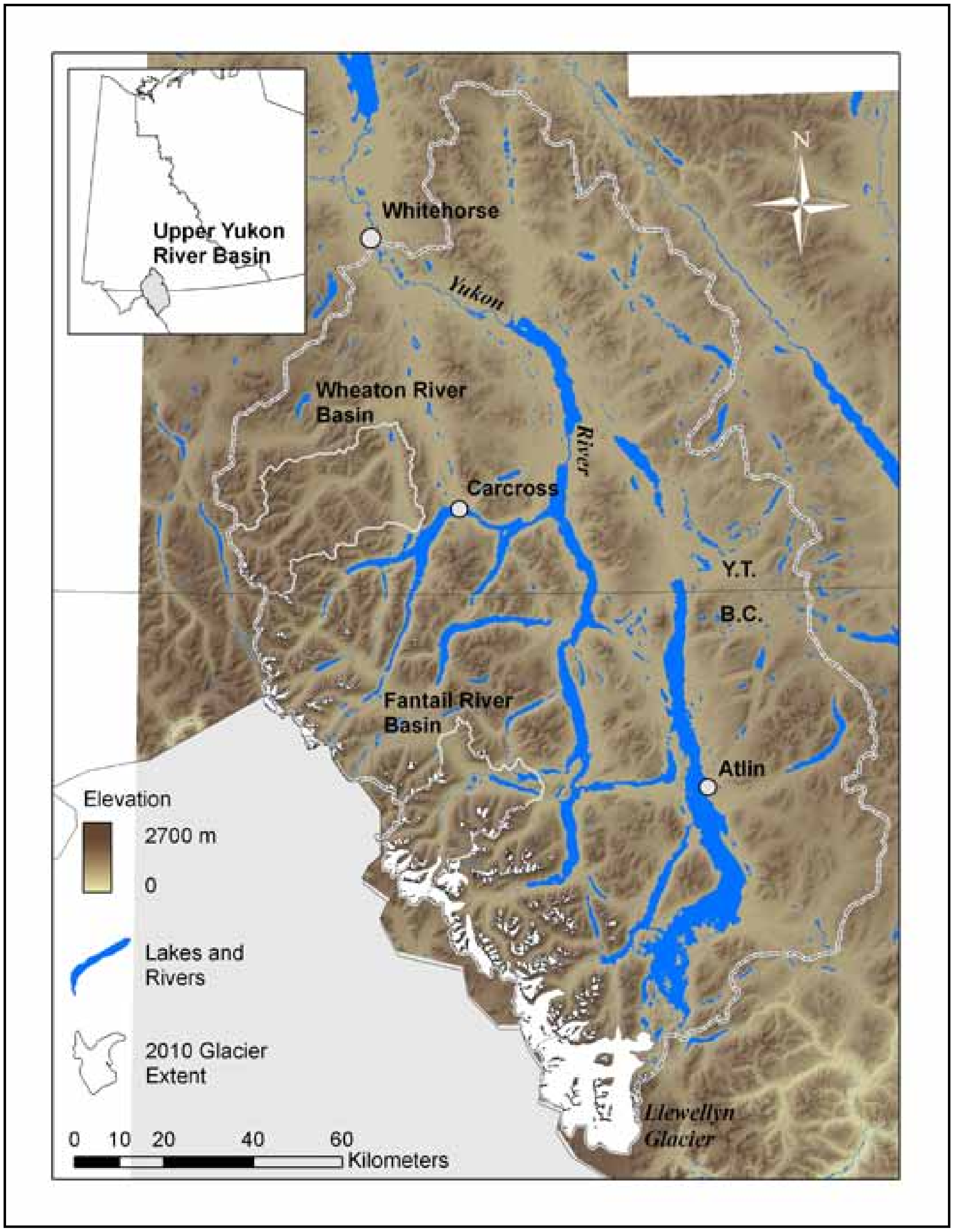

Figure 1. *Map of the Upper Yukon River Basin above Whitehorse (denoted by dashed line), showing location of the Fantail and Wheaton River basins, and the location and extent of glaciers within the basin in 2010. Gross drainage area of the basin is 19 600 km^2 according to the Water Survey of Canada (WSC). (Glaciers outside of the basin are not shown).*

2.2 FOCAL RESEARCH SITES

For the purposes of this project, two smaller tributary rivers and their drainage basins were selected for more in-depth study and field survey measurement. These include the Wheaton and Fantail River basins (Figures 1, 2 and 3), which are situated within different climatic settings

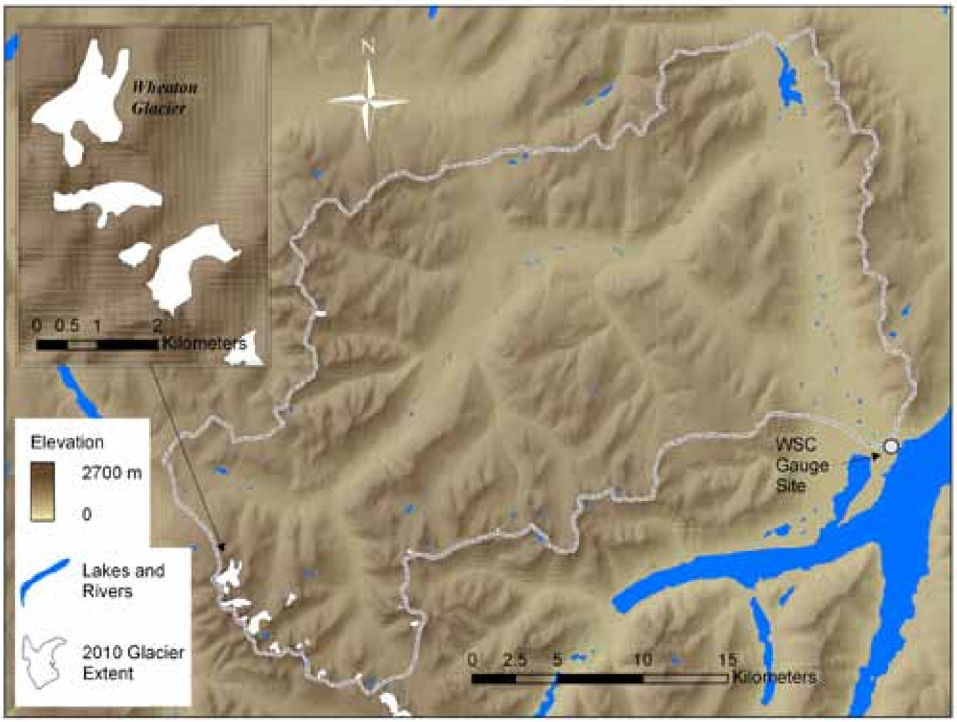

Figure 2. *Map of the Wheaton River Basin in southern Yukon Territory. Inset map shows a more detailed depiction of the extent of the Wheaton Glacier and other nearby small glaciers. Gross drainage area of the basin is 864 km^2 according to WSC.*

and have different amounts of glacier coverage. These focal basins and the glaciers within them were selected based on several different criteria, including: 1) the glaciers of Fantail Basin are representative of those in surrounding areas, and the basin includes a wide range of individual glacier sizes; 2) Wheaton Glacier has a history of previous research, which increases the knowledge value of the collected data; and 3) both watersheds have either historical or ongoing hydrometric flow records. These criteria were chosen for the purpose of measuring a representative sample of glaciers over their size class distribution in order to determine parameters for a volume-area (VA) scaling relationship (see Section 2.4), and to later be able to use collected information as part of the calibration and validation process of a hydrological model. Initial field plans for this project included focusing on the Llewellyn Glacier in addition to these other sites, but logistical and cost constraints limited this option. It was instead decided to focus on the other areas to best optimize our efforts for a single season.

Discharge measurements of the Wheaton River have been carried out by the Water Survey of Canada (WSC) since 1955 and are currently ongoing. The basin as a whole presently contains ~5 km^2 of glacier ice (less than 1% of total basin area), with the 1.4 km^2 Wheaton Glacier accounting for over 30% of glacier area. Despite the low fractional ice coverage in this basin, it remains valuable as a research site for examining glacial contributions in sparsely glaciated parts of the Yukon River headwaters, because the runoff from this basin can be used toward hydrological model calibration and evaluation. The Fantail River Basin contains roughly 107 km^2 of glaciated area (~15% of total basin area), and includes a number of individual glaciers spanning a wide range in area that are representative of most glaciers in the southern Yukon

River Basin. WSC river discharge measurements are only available for Fantail River for the period 1956 - 1993, but this historical data still allows for hydrological model development and testing to be carried out.

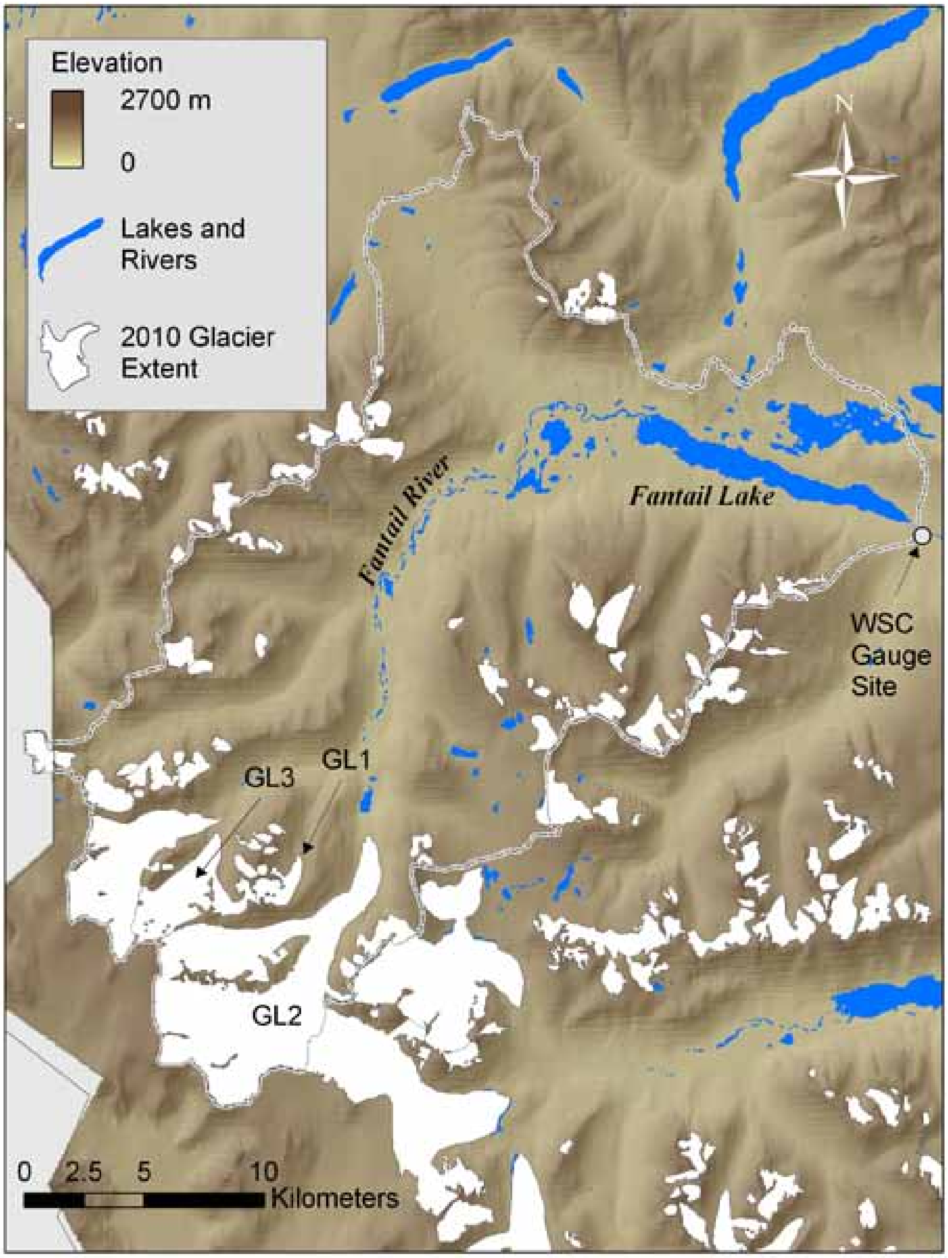

Figure 3. *Map of the Fantail River Basin in northern British Columbia. Topographic ice-flow divides are indicated to distinguish individual glaciers based on their flow drainage. GL1, GL2 and GL3 refer to specific glaciers selected for field surveys. Gross drainage area of the basin is 717 km² according to WSC.*

2.3 FIELD DATA COLLECTION AND ANALYSIS

In August 2011, field-based surveys of ice thickness and glacier margin position were carried out to estimate current glacier volume and quantification of errors associated with ice-margin delineation. The glaciers selected for these surveys included the Wheaton Glacier and several glaciers within the Fantail River Basin (referred to as GL1, GL2 and GL3), which are indicated in Figures 2 and 3. These glaciers were selected for accessibility and representativeness over the range of glacier sizes observed in the region, while specific survey transects across the glacier surfaces were selected to best represent their longitudinal and/or cross-sectional profiles given constraints on glacier travel due to ice surface conditions (e.g., crevasses, steep slopes), weather and time. Figure 4 illustrates the location of the transects that were surveyed by the field research team. Ice-margin positions were also surveyed using hand-held GPS units wherever possible near the locations of survey start and end points. The field team was supported by helicopter and flown from either Atlin, BC, or Whitehorse, YT, in order to reach the various locations across each of these glaciers and transport the survey equipment and other gear needed for this work (see Figures 1 - 5).

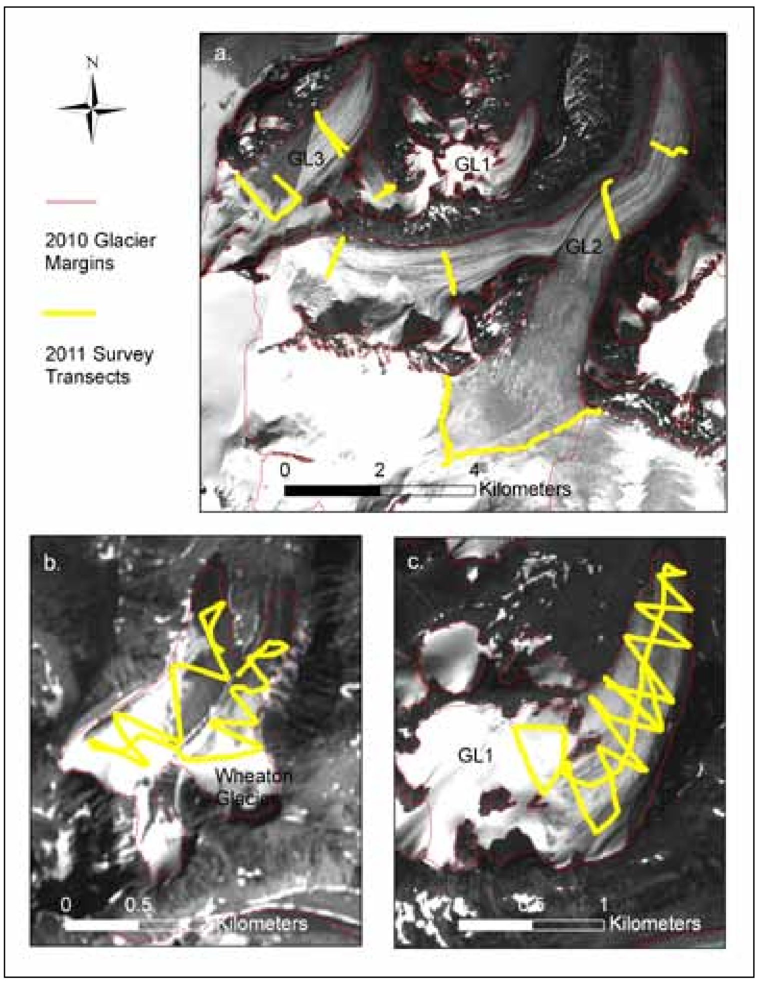

Figure 4. *Locations of radar profile surveys across the selected glaciers in this study: a) large glaciers (GL2, GL3) within the Fantail Basin; b) Wheaton Glacier; and c) smaller glacier (GL1) within the Fantail Basin. Basemaps are SPOT 5 panchromatic images acquired in 2006 and 2010.*

Figure 5. *The system and its associated hardware components were mounted on skis with flexible plastic tubing protecting the antennae, and the entire system was pulled on foot and guided over the glacier surface by the field research team. The photos show the setup and deployment of the radar system on glaciers within Fantail Basin: a) connecting plastic tubing to stabilize and secure antennae for travel over the complex ice surface; b) towing the radar unit over the glacier surface.*

Ice thickness values were determined using a Blue Systems Integration 5 MHz radar system (see Mingo and Flowers, 2010). The system uses a Narod and Clarke (1994) impulse radar transmitter built by Icefield Tools, Whitehorse, YT (Specifications: 1-200 Mhz bandwidth; 24 kW peak power; 1.6 kV into 50 Ohms; rise time <2 ns; repetition rate 512 Hz). The transmitting antenna was a tuned-impedance dipole of length 20 m. A half-dipole (10 m) receiving antenna was connected to a Pico Model 4227 12-bit Analog-to-Digital Converter (sampling rate: 250MS/s), which sent digitized waveforms to an Intel Atom-based 1.6 GHz embedded processing controller for storage. Each recoded trace waveform is a 'stacked' average of 100 individual returns; this stacking improved the signal-to-noise ratio by a factor of 10. The location and corresponding ice-surface elevation of each stacked waveform was recorded using a Garmin GPS 18x receiver. Accuracy for these receivers is typically better than 3 m using WAAS (Wide Area Augmentation System) and better than 15 m otherwise (95% probability). These accuracies are absolute; relative positional accuracies (e.g., between ice thickness measurements along a survey transect) are better still.

Ice thickness values were determined using BSI's IceRadarAnalyzer software (Versions 3.1 and 4.0) from the time difference $\Delta t = t_{2\text{-}way} + t_{air}$ between (1) the arrival of the direct airwave t_{air} and (2) the two-way travel time $t_{2\text{-}way}$ of the wave reflected off of the bed. Assuming that the reflection is located at a point midway between the two antennae's centres, the ice thickness d is related to the time difference as:

$$d = \left\{ \left[\frac{v_{ice}}{2} \left(\Delta t + \frac{a}{v_{air}} \right) \right]^2 - a^2 \right\}^{\frac{1}{2}} \tag{2.1}$$

Here a = 30 m is the centre-to-centre antenna distance, v_{air} = 300 m/µs is the wave propagation speed in air, and v_{ice} = 168 m/µs is the wave propagation speed in ice. The airwave has a characteristic positive- negative-positive signature in the radar waveform; t_{air} is selected as the rising limb of the first positive excursion. The bed reflection has a similar positive-negative-positive signature; correspondingly, the two-way travel time $t_{2\text{-}way}$ is selected as the rising limb of the first positive excursion of this feature in the waveform (e.g., see Hubbard and Glasser, 2005). Although the bed reflection is clear and distinct in many of the radar waveforms, in others it is weak and/or obscured by noise. In these cases, the bed waveform was band-pass filtered (to eliminate noise) and an exponential gain was applied (to counteract the attenuation of the signal with increasing bed depth). In determining ice thickness values, only those traces for which (1) a distinct bed return could be identified and (2) a good GPS location was obtained were used.

Processed radar waveform data were imported into ESRI® ArcMap™ 9.3 geographic information systems (GIS) software as 3-dimensional point data (easting, northing, ice thickness) for further analysis and estimation of total glacier volume (Figure 6). Total volume estimates were made by creating ice thickness contours using manual on-screen digitization techniques based on the imported ice thickness data. All glacier margins were assigned a thickness of 0 m. For steep, inaccessible areas, or parts of the upper glacier accumulation zones that could not be reached for measurement during the field campaign, the shallow ice approximation was used to derive local estimates of ice thickness. This was accomplished by employing a raster representation of the local ice surface slope derived from a digital elevation model (DEM) and using the following equation to estimate local ice thickness:

$$H = \frac{\tau}{\rho g \sin\alpha} \tag{2.2}$$

Here, H is ice thickness, τ is the basal shear stress, ρ is the density of ice (900 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), and α is the local surface slope. A constant shear stress of 1 bar (10^5 Pa) was assumed. Once the ice thickness contours were created, an inverse distance weighting interpolation procedure was applied to generate a raster representation of the local ice thickness across each of the individual glaciers. Figure 7 depicts an example of this interpolation for GL2, which helps to illustrate the variation in glacier depth over different parts of the glacier, and the immense thickness in some areas (e.g., where the two tributary arms of the glacier merge, and in the relatively flat upper plateau area). There is high confidence in the ice thickness estimates in locations where survey measurements were obtained, but the local thickness values in the upper accumulation zone and over steep, crevassed, and inaccessible parts of the glacier, is less certain. However, this is not likely to have a major effect on the overall error of total volume estimates as the surveys did capture a large and representative area of each glacier. Furthermore, the condition of glacier thickness equal to 0 m at the margins constrained local thickness estimates, and the shallow ice approximation produced values that corresponded reasonably well with measurements in locations where they were available. Future work will help verify the thickness estimates in the upper accumulation zone of each glacier.

Estimates of the total volume within each of the surveyed glaciers were made by calculating the average value of the ice thickness raster grid over the areal extent of each glacier using ArcMap™ 9.3. In this way, areas outside of the glacier 'polygon', and parts of other glaciers flowing outward from central icefield flow divides were excluded. The total volume was then determined as the product of the glacier surface area and the average thickness. Table 1 presents the summary results that were obtained from this analysis.

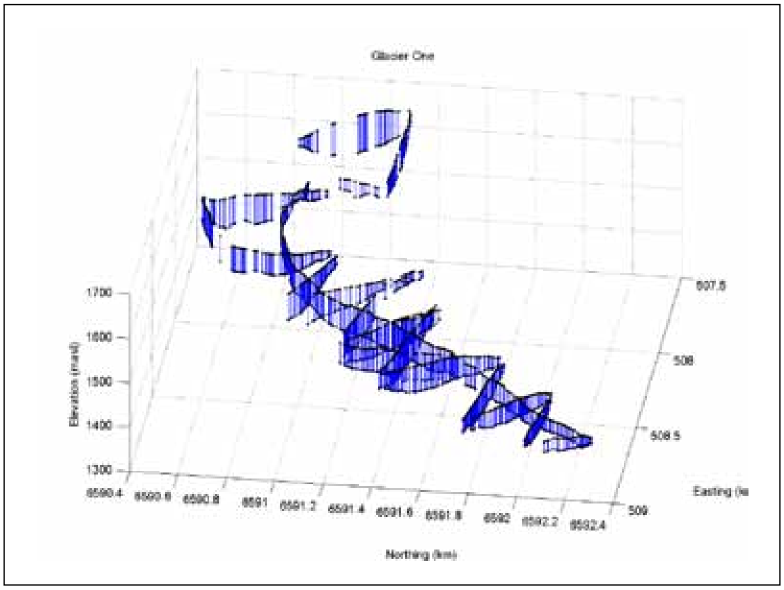

Figure 6. 3-Dimensional representation of processed radar waveform data, showing glacier surface elevation, bed elevation and ice thickness along survey transects for GL1 in Fantail Basin.

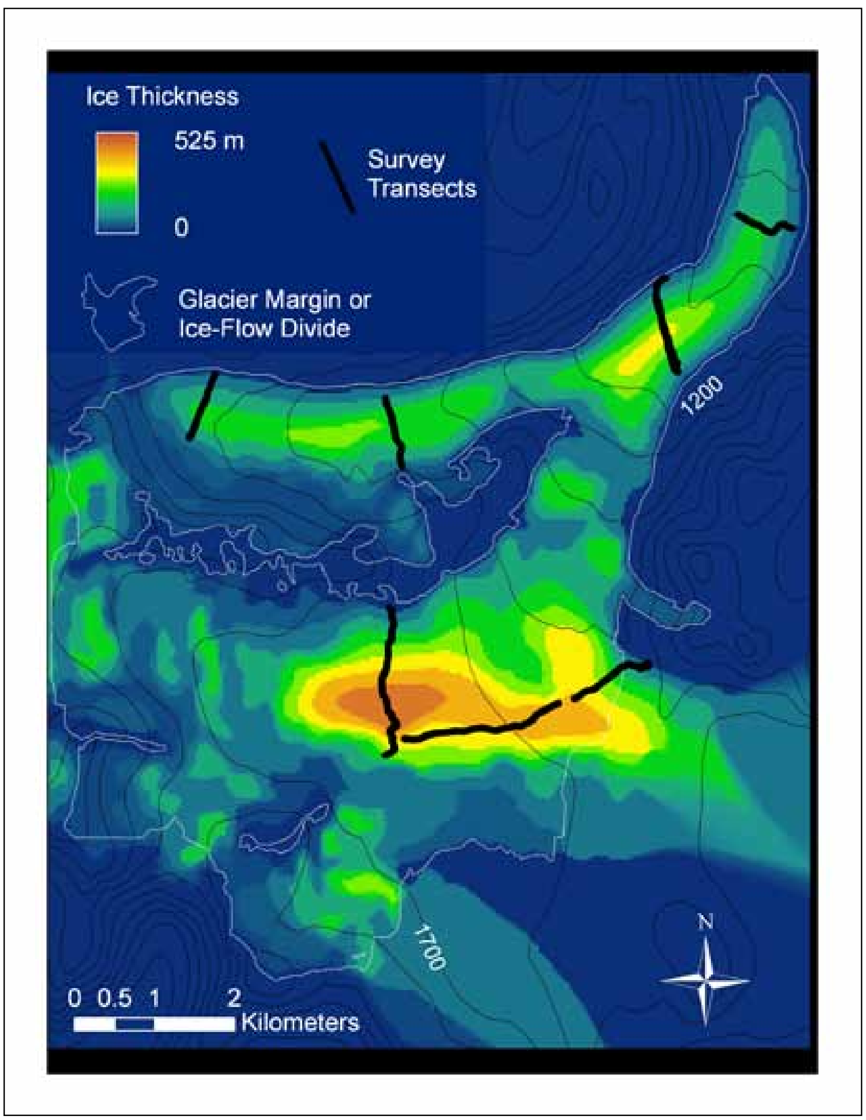

Figure 7. *Ice thickness interpolation of GL2 within the Fantail Basin. Surface elevation contour lines are shown at a 100 m interval.*

Table 1. Summary results of glacier thickness and volume based on field measurements and GIS interpolation analysis.

Glacier	Surface Area (km^2)	Average Estimated Thickness (m)	Maximum Measured Thickness (m)	Estimated Ice Volume (10^6 m^3)
GL1	2.38	33.5	84.4	79.7
GL2	45.6	135.9	515.2	6191
GL3	9.49	83.1	252.2	789
Wheaton	1.45	44.4	156.4	64.4

2.4 GLACIER VOLUME-AREA SCALING ANALYSIS

Part of the rationale for selecting these particular glaciers for field surveys was to obtain volume estimates over a range of glacier sizes that are representative of the glaciers in this region. Many studies have shown, both through empirical results and based on physical considerations (Chen and Ohmura, 1990; Bahr et al., 1997), that glacier volume can be related to surface area through a power law as follows:

$$V = c_0 A^{c_1} \tag{2.3}$$

where V is glacier volume (units: 10^6 m^3), A is glacier surface area (units: 10^6 m^2 or equivalently, km^2), and c_0 and c_1 are scaling coefficients. Based on a sample of glaciers from across the globe, Chen and Ohmura (1990) found values of these coefficients of c_0 = 28.5 and c_1 = 1.36, while Bahr et al., (1997) derived similar values for these coefficients based on physical principles of glacier flow dynamics. Therefore, the purpose of the volume estimates obtained in this study was to determine if measured glacier volume and area could fit such a relationship, and if so, what the values of the scaling parameters should be. The relationship could then be more reliably used to scale up the results from the sample of glaciers studied in Fantail and Wheaton River basins, to the entire Upper Yukon River Basin to make an estimate of the current total volume of glacier ice storage.

Figure 8 shows a plot of the volume vs. surface area of the glaciers studied as part of this project, and includes the scaling relationship based on c_0 = 28.5 and c_1 = 1.36 for reference. The results conform well to a power scaling law and appear to fit reasonably well to the global scaling relationship. A best fit line to these points in the log-scale plot of volume vs. area gives parameters of c_0 = 31.9 and c_1 = 1.38 for the sample of glaciers analyzed here. The parameters obtained here give slightly greater volume estimates than those of the global relationship, which may be due to regional bedrock geology, particular climatic and glaciological conditions, among other factors. It also may be that there is some error in the obtained values from the analysis (described in the previous section), or due to the limited size of the area studied for this investigation. In the future, it would be beneficial to include measurements from a larger glacier such as the Llewellyn Glacier (433 km^2) in order to extend the dataset over a greater range of glacier sizes.

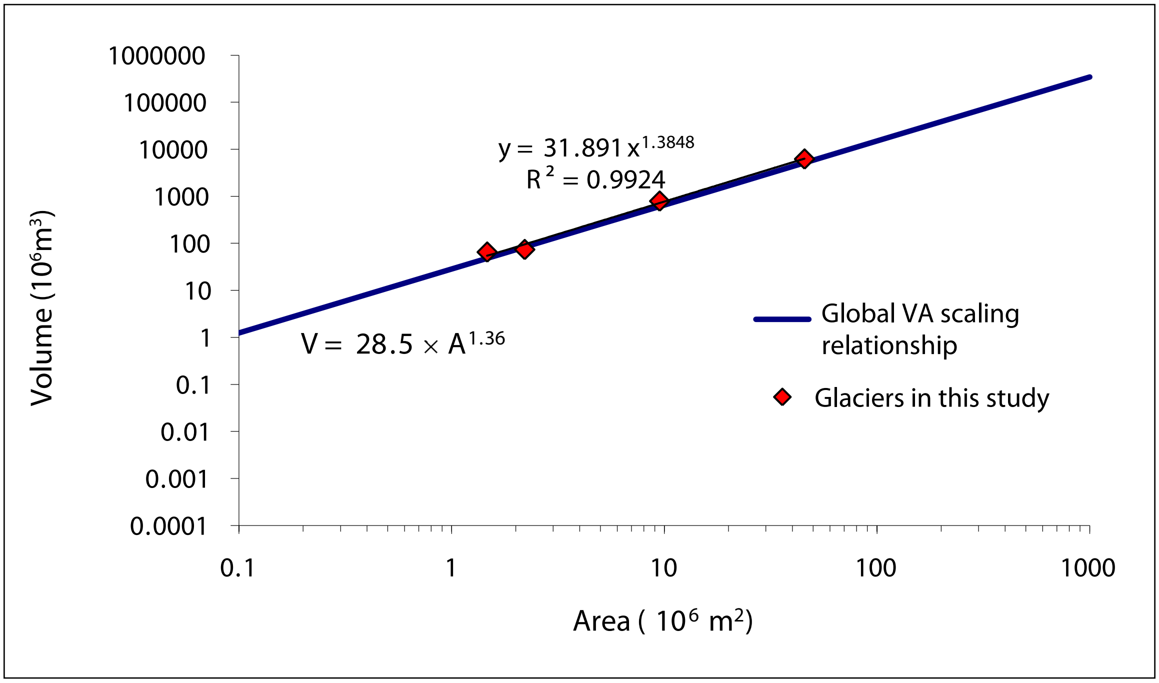

Figure 8. *Comparison of glacier area and volume measurements, along with a plot of the VA scaling relationship derived from a global set of glaciers from the study of Chen and Ohmura (1990).*

3. GLACIER INVENTORY AND RECENT GLACIER CHANGES

One of the objectives of this study is to generate a current inventory of the areal extent and distribution of glaciers within the Upper Yukon River Basin, along with the amount of ice presently stored in these glaciers. This was done based on an analysis of remotely sensed imagery using GIS (geographic information systems) software, where satellite images and aerial photography from different time periods were used to define the glacier margins and quantify recent changes in terminus position and glacier area. The present volume of ice was estimated by applying the volume-area scaling relationship and parameters derived from our field measurements.

3.1 METHODS

3.1.1 Sources of Data

Remotely sensed imagery from several different time periods was used to generate the glacier inventory and assess recent historical changes in glacier extent. Glacier extent in 2010 was based on an analysis of SPOT 4/5 orthorectified imagery that was obtained through the Geobase website (http://www.geobase.ca/geobase/en/). Both panchromatic (10 m resolution) and multispectral (20 m resolution) SPOT imagery over this region were obtained to be able to clearly identify and distinguish snow and ice surfaces from adjacent terrain. The data were obtained in the Universal Transverse Mercator projection in reference to the North American Datum 1983. The positional accuracy of this product is stated to be 30 m or better with a 90% confidence level for more than 98% of the orthoimages. More information about this product is available on the Geobase website.

Several Landsat 7 ETM+ (Enhanced Thematic Mapper) scenes acquired in 1999 and 2000 were used to define the glacier extent at these times. These data were also obtained through the Geobase website as Landsat 7 Orthorectified Imagery over Canada, which is derived from Landsat-7 raw image level L1G (i.e., radiometrically and systematically corrected) processed data. The planimetric error associated with this imagery is reported to be ±30 metres or less with a 90% level of confidence (DeBeer and Sharp, 2007; 2009).

Several Landsat 5 Thematic Mapper (TM) scenes over the study region from ca. 1990 were obtained through the Data Library Services of the University of Saskatchewan as part of the Global Data Bundles compiled by Land Info (http://www.landinfo.com). This is part of the Landsat 4/5 TM GeoCover 1990 (1988 - 1992) near-worldwide satellite imagery archive. This imagery is a false-colour composite of TM bands 7-4-2 with a spatial resolution of 30 m, and is projected in UTM coordinates in the WGS84 datum. No information could be obtained on the exact date of acquisition of this image or the correction procedures used for orthorectification, but comparison of features in the imagery with the same features in the SPOT 5 and Landsat 7 ETM+ Orthorectified Imagery revealed a very close spatial correspondence.

Digital glacier outlines were obtained from E. Berthier from the study by Berthier et al., (2010) for comparison. A thorough overview and close inspection of the glacier margins from this dataset revealed that the outlines corresponded to the ca. 1990 time period, as seen from the Landsat 5 TM data, and so these glacier polygons were used to represent glacier extent at that time.

One further time period was considered in this study in order to extend the analysis of glacier changes back to 1948. Glacier margins at this time were based on federal government aerial photography (flight lines A11379, 382, 385, 390, 392, 521 and 524). These photos were obtained between June and September of 1948. This provides coverage over the glaciers within the Fantail and Wheaton River basins, as well as over the Llewellyn Glacier. Original air photo prints are archived at the National Hydrology Research Centre (NHRC) in Saskatoon, Saskatchewan as part of the Canadian Glacier Inventory, and were digitally scanned at high resolution. The digital photos were then spatially referenced to the SPOT 4/5 orthorectified imagery using the georeferencing tool and the spline transformation in ArcMap™ 9.3 to fit control points exactly. For each digital photo, a minimum of 10 points (but generally between 15 and 20 points) were defined based on clearly identifiable features in both the photo and the SPOT image, such as moraines, vegetation, rock outcrops, etc., that were located close to the ice margins. Thus, the positional error of the spatially referenced aerial photographs was minimized in areas very near to the control points, and was estimated to be within ±30 m on average in locations along the lower margins of each glacier.

Several digital elevation models (DEMs) representing different time periods were obtained for use in this study. The Canadian Digital Elevation Data (CDED) 1:50 000 and 1:250 000-scale products were obtained for this region through the Geobase website. Elevation data are relative to mean sea level, and coordinates are based on the North American Datum of 1983. The source of these data is provincial datasets and the National Topographic Database (NTDB), with each CDED file covering one half of a National Topographic System (NTS) map sheet. The grid resolution varies from 8 to 23 m for the 1:50 000 tiles, and from 32 to 93 m for the 1:250 000 tiles based on geographic coordinates. For most of the glaciated areas in this study, the data are from the British Columbia Terrain Resources Information Management Program (BC-TRIM) dataset, which is stated to have a horizontal accuracy to within 10 m for 90% of all well-defined planimetric features, and to within 5 m of the true elevation for 90% of all discrete spot elevations and DEM points. The elevation data contained within the CDED files over this region correspond to August 1987.

Two further DEM products were obtained through the United States Geological Survey (USGS) EarthExplorer website (http://earthexplorer.usgs.gov/) to compare glacier surface elevations at different time periods. The first is the Shuttle Radar Topographic Mission (SRTM) DEM, which was obtained in February 2000 and has a horizontal resolution of 1 arc second (i.e., roughly 16 × 30 m for this region). The absolute vertical accuracy of the elevation data is stated to be 16 m at 90% confidence. The second is the ASTER Global DEM, which corresponds to October 2011 over the study area, and has a spatial resolution of 1 arc-second (~16 × 30 m). The vertical (root-mean-squared-error) accuracy is stated to be generally between 10 and 25 m.

3.1.2 Ice Margin Delineation

Ice margin delineation followed the same approach as was used by DeBeer and Sharp (2007; 2009). Ice margins and interior bedrock outcrops were delineated onscreen using ArcMap™ GIS version 9.3 based on the various imagery datasets. The glacier margins were defined manually by the operator by digitizing a series of points and constructing polygon shapefiles, which were clipped based on polygons representing rock outcrops to create an 'ice surface only' polygon. Where icefields diverge into separate outlet glaciers, the polygon was "cut" by manually delineating the ice flow divides, which were identified based on the DEM topography and by using the "Basin" utility in the Spatial Analyst extension of AcrMap™. This allowed measurements and analysis of change to be associated with individual ice drainage catchments.

The ice margins in the upper parts and accumulation zone of most glaciers were primarily based on the glacier shapefiles provided by E. Berthier (Berthier et al., 2010), and were only adjusted or corrected in situations where obvious change had occurred based on the satellite imagery or aerial photography for each time period. This minimizes errors associated with differences in snow conditions between the various image products, as this has the potential to cause significant errors in the estimates of glacier changes.

3.1.3 Error Estimation

An analysis was carried out in order to derive an estimate of the total uncertainty associated with the glacier area measurements for the 2010 inventory. This analysis was similar to that carried out by DeBeer and Sharp (2007) for a glacier change assessment in the southern Canadian Cordillera. Potential error associated with the delineation of glacier margins (and ultimately glacier area) depends upon the accuracy with which these can be identified and digitized. (Errors potentially arising from positional error in the satellite imagery were not considered because these are likely to be consistent across the image). The accuracy of the digitization process depends upon the image resolution, the snow conditions, and the contrast between the ice and adjacent terrain. For unobscured sections of ice margin, representing ~85% of the total perimeter of the glaciers studied, the measurement error was estimated to be ±15 m, which is slightly greater than the resolution of the SPOT 4/5 panchromatic imagery. Where extensive debris-cover or shadows obscure glacier margins (roughly 10% of the total perimeter), the error was estimated as ±45 m. For debris-covered sections of glacier termini, a comparison of field GPS measurements of the actual ice margin of GL1 (see previous) with the delineated margin based on the SPOT 4/5 imagery indicated this error is a reasonable estimate. Where there were shadows, a contrast stretch of the SPOT 4/5 imagery was sometimes used to improve the ability to detect the ice-rock boundary, although this was generally not a problem as other imagery could be relied upon for verification. Maximum uncertainty occurs where extensive snow obscures the ice margins (estimated to be 5% of the total perimeter), and for some very small glaciers this makes it difficult to interpret whether the snow is a perennial patch or is obscuring a permanent glacier. Some of the approaches to avoid misclassification in these situations included making judgements based on multiple imagery sources and looking for features such as crevasses or emerging bare ice surfaces (e.g. DeBeer and Sharp, 2009). For this 5% of the ice margin length, error was estimated to be ±90 m.

The overall uncertainty in glacier area was quantified by multiplying the fraction of the total length of all glacier perimeters affected by various identification and digitization errors by the respective line placement uncertainty mentioned above. The overall uncertainty could then be defined as:

$$\delta Q = \sqrt{(\delta q_1)^2 + (\delta q_2)^2 + (\delta q_3)^2} \tag{3.1}$$

where δQ is the total uncertainty (units: km^2) and δq_1, δq_2, and δq_3 are the overall uncertainties in areas of unobscured margins, debris-covered margins, and snow-covered margins respectively. The actual error may be overestimated in this way as this assumes the maximum digitizing offset over all the glacier margins, while it is likely that errors would tend to be more random and cancel out on average.

3.2 RESULTS

3.2.1 PRESENT GLACIER AREA AND VOLUME

Figure 1 provides a regional overview of the location and distribution of glaciers within the Upper Yukon River Basin as determined through the analysis described in Section 3.1. A summary of the area and volume inventory is given in Table 2, which shows the variation in the number, area and volume of glaciers over the size class distribution. In 2010, the most recent period for which satellite imagery was available, there were a total of 367 individual glaciers with a combined area of roughly 1002 km^2 and an estimated total volume of 187 km^3 of ice. The Llewellyn Glacier alone comprises nearly half of the total surface area of all the glaciers in the basin, and an estimated 74% of the total ice volume. Although there are relatively few other larger glaciers (i.e., glaciers with surface areas greater than 10 km^2), these glaciers account for an additional 29% of the total glacier area and 20% of the total glacier volume. Additionally, the intermediate-sized glaciers (i.e., those 1 to 10 km^2 in area) account for a considerable fraction of the total glacier area (18%) due to their high numbers, but make up only a very small fraction of the total volume of stored ice (4.5%). The smallest glaciers (i.e., those less than 1 km^2) make up nearly 10% of total glacier surface area but only just over 1% of the total ice volume in the basin. This inventory provides a clear perspective on the relative importance (in terms of area and volume of stored ice) of the different glaciers over the size categories in the region.

3.2.2 RECENT CHANGES IN GLACIER AREA AND VOLUME

Glacier areas and extent were compared for the different time periods of each satellite image to quantify the net amount of retreat and glacier surface area change over the past several decades, and to characterize any trends in the rates of change. Glacier extents were compared for 1948, 1990, 1999 and 2010 for all glaciers within the Fantail and Wheaton River basins, and for two time periods (1990 and 2010) for all glaciers within the study region. In addition, the ice margin position was delineated for the Llewellyn Glacier for the 1948 time period. Some of the results are shown in Figure 9 to illustrate the spatial pattern of terminal retreat of a number of glaciers, which are representative of the pattern observed across the entire southern Yukon River headwater area. Table 3 provides summary glacier area measurements and net changes in area between observation periods for the glaciers studied in this project, while Figure 10 and Table 4 provide information on the observed net rates of change of glacier area based on comparison of the outlines from different dates.

Table 2. Summary results of glacier inventory for the Upper Yukon River Basin in 2010. Size class represents the maximum glacier size within each class, count is the total number of individual glaciers within each class, and volume is the total estimated ice volume of all glaciers in each class.

Glacier Size Class (km^2)	Count	Area (km^2)	Volume (km^3)
0.1	26	1.8	0.0
0.5	177	48.4	1.0
1	70	49.8	1.4
5	81	161.6	7.0
10	3	20.1	1.4
20	4	64.1	5.9
100	5	222.7	31.5
500	1	433.5	138.9
Total	367	1022 ± 31	187.1

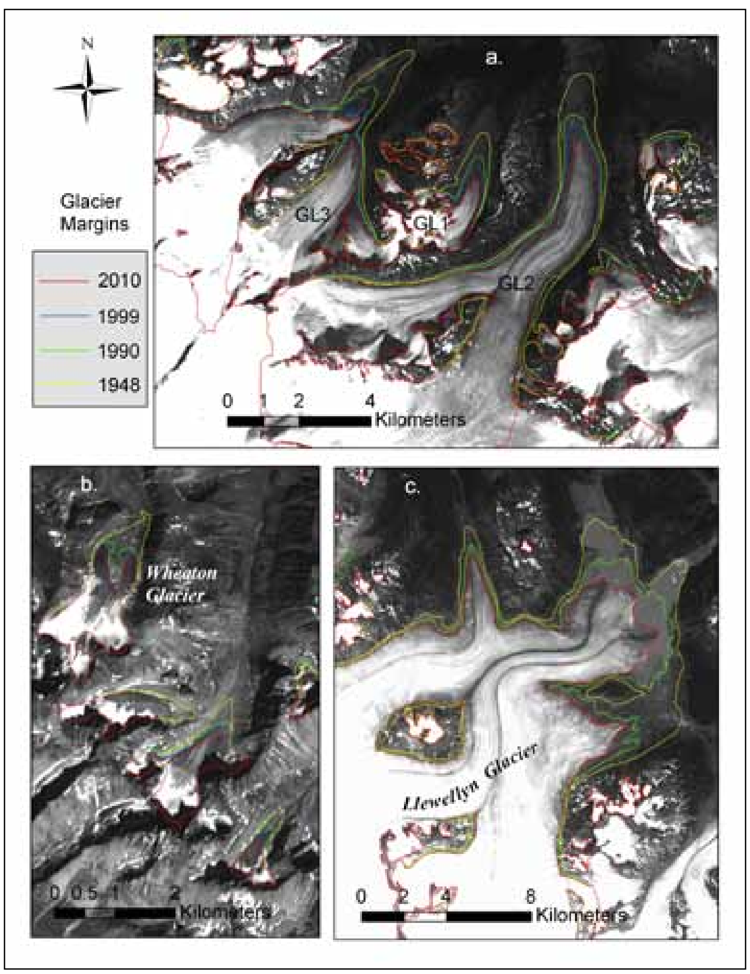

Figure 9. *Historical changes in lower glacier margins and termini position over the past several decades for: a) largest glaciers in the Fantail River Basin; b) largest glaciers in the Wheaton River Basin; and c) the Llewellyn Glacier.*

Table 3. Recent net changes in area of glaciers in the Fantail and Wheaton River Basins, the Llewellyn Glacier, and all glaciers within the study region. Percentage changes in glacier area are based on the amount of change in comparison to initial surface area for the period of change considered. *GL3 in this table includes both tributary glaciers, which became detached just after 1999 (see Figure 9a).

Glacier	1948 Area (km^2)	1990 Area (km^2)	1999 Area (km^2)	2010 Area (km^2)	Area Change 1948-2010 (km^2/%)	Area Change 1990-2010 (km^2/%)
GL1	3.9	3.2	2.8	2.4	-1.5 / -38.7	-0.82 / -25.5
GL2	51.0	48.2	47.4	45.6	-5.1 / -9.9	-2.2 / -4.6
GL3*	29.2	27.3	26.6	25.6	-3.6 / -12.4	-1.7 / -6.2
All Fantail Basin Glaciers	127.3	115.1	111.8	106.8	-20.5 / -16.1	-8.3 / -7.2
Wheaton Glacier	2.0	1.7	1.5	1.4	-0.54 / -27.2	-0.22 / -13.3
All Wheaton Basin Glaciers	6.5	5.6	5.0	4.7	-1.80 / -27.8	-0.95 / -16.8
Llewellyn Glacier	472.9	449.1	-	433.5	-39.5 / -8.3	-15.6 / -3.5
All Upper Yukon River Basin Glaciers	-	1065.0	-	1002.0	-	-62.9 / -5.9

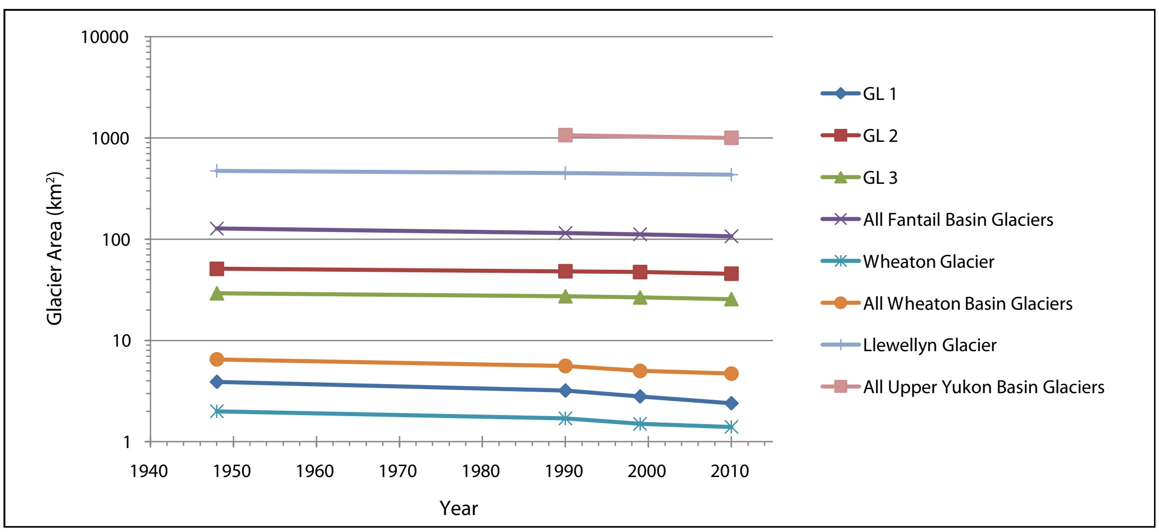

Figure 10. *Plot of glacier area over time for the same glaciers as in Table 3, showing net rates of change over the period of study.*

Table 4. Net rates of glacier area change over the study period for the same glaciers as in Table 3 and Figure 10 above.

Glacier	1948 - 1990 km^2 per year	1990 - 1999 km^2 per year	1999 - 2010 km^2 per year	1990 - 2010 km^2 per year
GL1	-0.02	-0.04	-0.04	-0.04
GL2	-0.07	-0.09	-0.16	-0.13
GL3*	-0.05	-0.08	-0.09	-0.09
All Fantail Basin Glaciers	-0.29	-0.37	-0.45	-0.42
Wheaton Glacier	-0.01	-0.02	-0.01	-0.02
All Wheaton Basin Glaciers	-0.02	-0.07	-0.03	-0.05
Llewellyn Glacier	-0.57	-	-	-0.78
All Upper Yukon River Basin Glaciers	-	-	-	-3.15

The result of this analysis show that the glaciers in this region have been undergoing sustained terminal retreat and area loss over the last 60 years. A large portion of the overall net change in area had occurred during the period 1948 - 1990, but this is partly due to the longer intervening period between successive observations. Assuming that no major change in glacier behaviour (such as a short-lived period of terminal advance followed by continued glacier recession) occurred during that period, the data show that rates of glacier retreat and area loss have significantly accelerated in the past several decades. On average, the rates of glacier area loss have nearly doubled in the past two decades, relative to the net rates observed between 1948 and 1990. It is likely that this has been accompanied by similar trends in the rate of ice volume (and thus mass) loss, which is of more importance for the hydrological regime of glacierized basins in the Yukon River headwaters.

To investigate the changes in volume of ice within the glaciers, two separate approaches were taken. The first was to apply the established volume-area scaling relationship to derive estimates of the net loss of glacier volume based on the observed changes in glacier surface area. The second involved a comparison of the various DEMs that were obtained for this study mentioned in Section 3.1.1, in order to quantify the surface elevation change and thereby derive volume loss estimates.

Figure 11 shows net surface elevation changes over the period 1987 - 2000 derived from a comparison of the SRTM DEM and the CDED DEM using ArcMap™ 9.3. Surface lowering of up to nearly 100 m was observed over the lower parts of large glaciers in the region, as well as in some upper parts of the Llewellyn Glacier and various other locations. The spatial pattern of surface elevation change is clearly evident and involved mostly downwasting and ice loss in the lower ablation zone of most glaciers, especially in the area near the terminus. Other zones of the glaciers underwent more limited changes, and in some cases a possible increase in surface elevation in the upper accumulation zones was indicated. However, there is a clear bias between the two separate DEM products, which is evident from a difference in elevation over non-glaciated parts of the landscape that would have undergone no significant change over the relevant timescales. On average, there is a slight positive bias for these non-glaciated areas, with surface elevation values tending to increase by roughly 5 - 10 m overall. Thus, the glacier surface downwasting may be slightly underestimated by this approach. The accuracy of DEMs is likely to be best over parts of the glaciers with clearly distinguishable features (e.g., bare ice, debris, rocks, etc.) that facilitate stereogrammetry in the DEM generation process (CDED and ASTER products), while it will be poorest over featureless and broad snow-covered areas such as the upper accumulation zones. This may be responsible for some of the large changes observed in the upper parts of the Llewellyn Glacier.

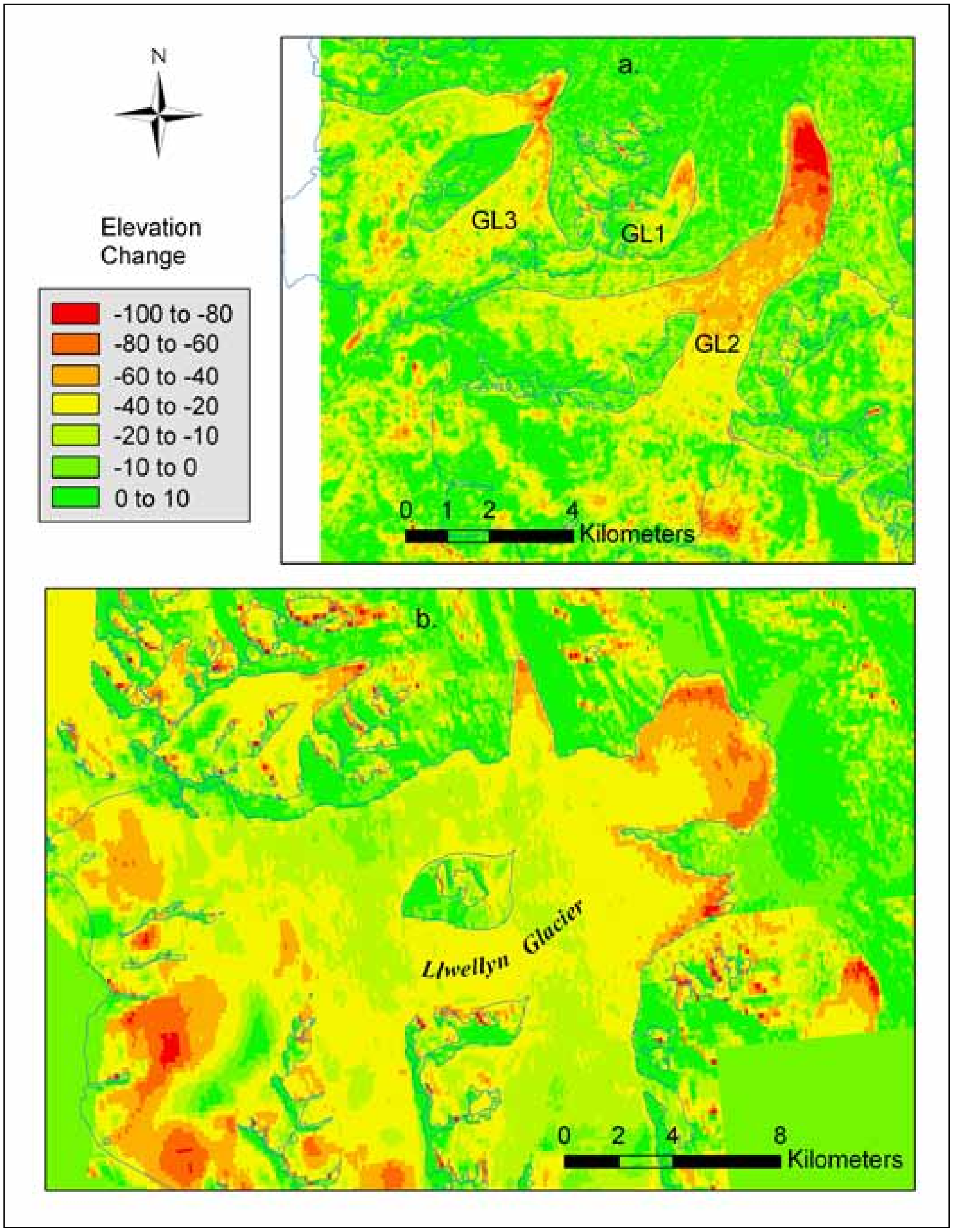

Figure 11. *Spatial patterns of surface elevation change over glaciers within the Fantail River Basin and the Llewellyn Glacier over the period 1987 – 2000 from comparison of CDED DEM and ASTER Global DEM. The 1990 glacier margins are shown for reference.*

Table 5. Comparison of glacier volume changes based on estimates derived from multi-temporal DEM comparison and from the volume-area scaling approach. Percentage difference is the absolute difference relative to the estimates based on DEM comparison. *The 1999 volume of Llewellyn Glacier was estimated from VA scaling based on the average surface area between 1990 and 2010.

Glacier	1990 Area (km^2)	1987 - 2000 DEM Mean Elevation	1987 - 2000 DEM Volume Change (10^6 m^3)	1990 - 1999 VA Scaling Volume Change (10^6 m^3)	Difference (10^6 m^3/%)
GL1	3.2	-30.0	-96.0	-26.8	69.2 / 72
GL2	48.2	-19.3	-930.3	-141.8	788.5 / 85
GL3*	27.3	-18.5	-505.0	-113.4	391.6 / 78
Llewellyn Glacier	449.1	-27.5	-12 350	-3457*	8893 / 72

Notwithstanding potential errors in the DEM comparison approach, total volume loss was estimated by taking the average surface elevation change over the 1990 glacier area, and multiplying this change by the total area at the time. The results are given in Table 5 for several glaciers in the Fantail Basin and for the Llewellyn Glacier, and are compared with those obtained using volume-area scaling. Glacier volume losses were found to be quite high for some of the large glaciers, exceeding over 0.9 km^3 from GL2 in the Fantail Basin and over 12 km^3 of ice from the Llewellyn Glacier. Comparison with the volume-area approach showed that this method yielded only a small fraction of the overall ice loss as estimated from multi-temporal DEMs. This may be to some extent attributable to the difference in specific time periods compared by the different approaches, but more likely indicates a problem with the use of volume-area scaling over different times, possibly due to glacier tributaries becoming detached or glaciers not being in a steady-state condition, for example. This is an important finding as this suggests that the volume-area scaling approach does not provide a reliable tool for estimating net glacier wastage contributions to regional runoff; furthermore, it may not necessarily work well for model simulations aimed at predicting future glacier extent (i.e., by simulating future volume loss and using the inverse of this relationship). This is considered further, along with the hydrological implications of these changes and of projected future glacier changes, in the next section of this report.

4. HYDROLOGICAL MODEL APPLICATION AND CLIMATE SCENARIO ANALYSIS

4.1 HYDROLOGICAL MODEL DESCRIPTION

4.1.1 GREEN KENUE™ AND HBV-EC MODEL

To achieve the second objective of this project, the Green Kenue™ software tool was used together with the HBV-EC hydrological model, available through the National Research Council of Canada (NRC) website (http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html). As described on this webpage: *"The Green Kenue™ platform is an advanced data preparation, analysis, and visualization tool for hydrologic modelers, and provides a state-of-the-art interface for integrating environmental databases and geospatial data with model input and results data. Green Kenue™ provides complete pre- and post-processing for the WATFLOOD* *and HBV-EC hydrological models… Green Kenue™ provides an interface to Environment Canada's hydrometric station database (HYDAT) as well as the Canadian Daily Climate Database (CDCD). Stations are queried interactively and available time series data can be extracted, re-sampled, analyzed, and processed with various editors and calculators"*. Further information about the Green Kenue™ software tool is available through the NRC website at the link above, where an in-depth user guide and manual can be obtained.

Green Kenue™ provides the functions of the HBV-EC model, which is a conceptual watershed model originally developed by the Swedish Meteorological and Hydrological Institute (Lindström et al., 1997), and later adapted by Environment Canada and the University of British Columbia (UBC) to simulate watershed response in mountainous terrain, as well as other environments (NRC, 2010). The Canadian version of the model has been further upgraded by D. Moore at UBC to include a glacier routine in the 1990s, and this model has been widely applied for the study of glacierized basins and investigation of the glacier contributions to total flow (Moore, 1993; Stahl et al., 2008; Jost et al., 2012). Lindström et al. (1997), Moore (1993), and the National Research Council (2010) provide detailed descriptions of the model routines.

The model makes water balance computations at a specified time-step defined by the frequency of input observational meteorological data (typically daily). These are made over distinct spatial units, called grouped response units (GRU), which are defined based on characteristics of the surface topography (elevation, slope, aspect) and the landcover (lake, glacier, forest, open). The Green Kenue™ tool is used to import and process DEM and landcover data to generate an operational HBV-EC model. In addition, the model considers different climate zones in order to represent the spatial variation and gradients in climate that may occur across a basin. As described by the National Reasearch Council (2010): *"Each climate zone is associated with a single climate station and unique parameter values for specifying the distribution of climate within the zone, such as temperature and precipitation lapse rates. Runoff from a climate zone is lumped through a series of fast and slow response reservoirs of similar configuration to those in the traditional HBV model (Lindström et al., 1997)"*.

The model uses a temperature index approach for simulating the melt of snow and glacier ice. Jost et al. (2012) provide a detailed overview of the melt routine of HBV-EC, and the following excerpt is based on their description:

Daily snowmelt (*M*) (mm day^{-1}) is calculated as:

$$M(t) = B_0 \times MRF \times (1 - AM \times \sin(s) \times \cos(a)) \times T_{air} \quad (4.1)$$

where B_0 is a base melt factor (mm day^{-1} C^{-1}) that varies sinusoidally between a minimum value (B_{min}) at the winter solstice, to a maximum value at the summer solstice (B_{min} + *DC*) to account for seasonal variations in solar radiation, and *DC* is the increase in melt factor between winter and summer solstices. The melt ratio for forests, *MRF*, ranges between 0 and 1 and reduces melt rates under forests compared to melt at open sites. The coefficient *AM* controls the sensitivity of melt rates to slope and aspect. For glacier GRUs, melt is computed as for an open site (*MRF* = 1) until the previous winter's snow accumulation has ablated. At that point, glacier melt is computed by multiplying open-site melt by the coefficient *MRG*, which typically ranges between 1 and 2, to reflect the reduction in surface albedo.

Storage and drainage of meltwater and rain for each glacier GRU are modelled using linear reservoirs. The outflow coefficient for each GRU depends on snow depth, ranging from a low value (KG_{min}) when the GRU has deep snow cover, to a maximum value (KG_{min} + *dKG*) when the

GRU is snow-free (Stahl et al., 2008). This representation conceptually accounts for seasonal changes in the efficiency of the glacier drainage system. Glacier mass balance can be computed by post-processing HBV-EC model output for the glacier GRUs. Glaciers in HBV-EC cannot vary in area or volume during a model run without stopping and restarting the simulation.

4.1.2 MODEL SETUP AND PARAMETERIZATION

The modelling strategy used in this project was to first develop, calibrate and validate the model with a specific spatial structure and model parameter set for the Fantail and Wheaton basins in the Yukon River headwaters (Figures 1, 2 and 3). This would allow for more reliable parameter value selection to ensure that the model properly simulates snow accumulation and melt, glacier mass balance, and river discharge. Following the initial setup and testing for the headwater basins, the model was applied over the much larger Upper Yukon River Basin. This approach is necessary because runoff routing through the complex system of lakes and reservoirs in the basin above Whitehorse makes it difficult or impossible to properly calibrate parameters, such as melt factors and precipitation gradients, based on measured hydrographs at Whitehorse.

A particular challenge involved extracting simulated glacier mass balance (for individual glaciers) from the results of the model. Green Kenue™ and the HBV-EC model will output a table file that contains all the results in a hierarchical format (first for the entire basin, then for individual climate zones, then for individual slope, aspect, and elevation bands, and landcover classes within each climate zone). Therefore, the model had to be set up spatially so as to define separate climate zones for any particular individual glacier, thereby facilitating the analysis of the results specific to each glacier (defined as its own climate zone). The same model parameters for snow and glacier melt, and the same meteorological forcing data could be used, but in this way the overall (as well as elevation band specific) model results corresponding to an individual glacier or collective group of glaciers could be analyzed.

To determine the mass balance of individual glaciers, collective groups of glaciers, and specific elevation zones (i.e., bands) of glaciers, time series values of simulated snow water equivalent (SWE) and glacier ice melt were extracted from the model output file. Stahl et al. (2008) provide a concise summary of the approach to calculate glacier mass balance using the HBV-EC model, and the following excerpt is from their description:

By analogy with the stratigraphic method for mass balance computation (Østrem and Brugman, 1991), the winter balance of an individual glacier, glacier elevation zone, or group of glaciers for a given year, b_w, was determined as the maximum daily value of SWE for that year. The summer balance, b_s, depends on whether all of the snow melts off the glacier, and was determined as:

$$b_s = \min[\mathrm{SWE}] - \max[\mathrm{SWE}]$$

$$\text{if } \min[\mathrm{SWE}] > 0 \qquad (4.2)$$

and

$$b_s = -[\max[\mathrm{SWE}] + \textstyle\sum M_{ice}]$$

$$\text{if } \min[\mathrm{SWE}] = 0, \qquad (4.3)$$

where is the cumulative ice melt for the year, up to the date of the onset of continuous snow cover over the glacier. The net mass balance, b_n, is then:

$$b_n = b_w + b_s, \qquad (4.4)$$

and the total mass balance (*MB*) (as a water equivalent volume) for the glacier, or glaciers, in a given year can be computed as:

$$MB = \sum(A \cdot b_n), \tag{4.5}$$

where *A* is the area over which the specific balance computations apply.

The model was first set up for Fantail and Wheaton River basins using processing routines within Green Kenue™ as well as the glacier inventory shapefiles that were generated in ArcMap™ 9.3. Landcover representation was based on the *Land Cover, Circa 2000 – Vector* product obtained from the Geobase website (http://www.geobase.ca), which was reclassified into either open alpine, forest, lake, or glacier surface classes. Glacier polygons generated as part of the glacier inventory in this project were used for 1990 and 2010 time periods, as it was observed that there are significant errors in the classification of many glaciers in the Geobase landcover product. The reclassified landcover data were then converted into a raster file using ArcMap™ 9.3 for import into Green Kenue™. Similarly, different climate zones were delineated to isolate various individual glaciers and glacier groups, and were then converted to raster files, imported into Green Kenue™, and used together with the CDED surface elevation DEM to generate the watershed representation for the HBV-EC model. Figure 12 shows an example of the watershed delineation and different model landcover and surface topographic criteria used to define computational elements for the Fantail River Basin. Here, 5 separate climate zones were defined: zone 1 (all non-glaciated parts of the basin), zone 2 (GL2), zone 3 (GL1), zone 4 (GL3), and zone 5 (all other smaller glaciers in the basin).

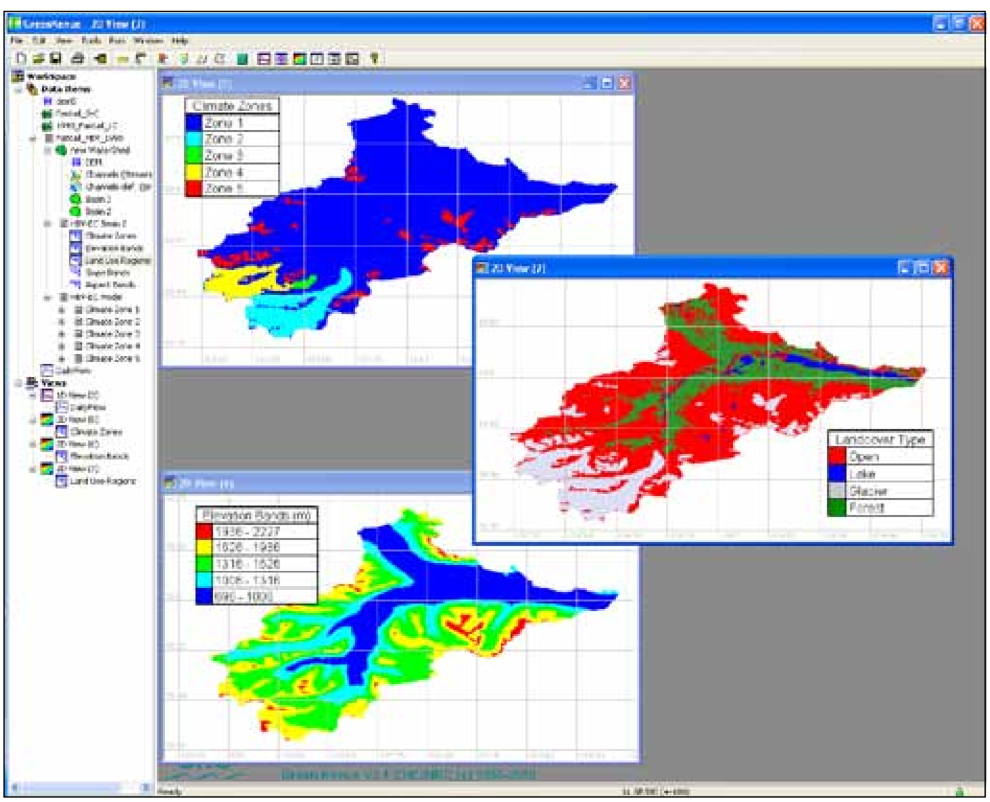

Figure 12. *Screen image of the Green Kenue™ interface showing watershed model of Fantail River Basin (climate zones, elevation bands, landcover type) for the 1990 time period. Spatial coordinate system is an unprojected latitude and longitude grid.*

The model was also set up spatially in a similar manner for the Wheaton River Basin, and for the Upper Yukon River Basin. In the latter case, The Llewellyn Glacier was defined as its own climate zone in the model, as were the other glaciers in the basin, and the wetter southwestern part of the basin was distinguished from the drier eastern and northern parts of the basin by including two separate non-glacier climate zones across the basin.

Model forcing data included historical meteorological data (i.e., temperature, rainfall, snowfall) from Whitehorse, YT and Atlin, BC (see Figure 1) obtained through the National Climate and Information Archive of the Meteorological Service of Canada (http://www.climate.weatheroffice.gc.ca). The observational data from these stations was extrapolated across the region and to the smaller headwater basins based on temperature and precipitation lapse rates, and calibrated precipitation correction factors (i.e., a multiplier to account for differences location of the measuring station and location of the simulated area) in the HBV-EC model. The air temperature lapse rate was set at a constant 6.5°C per 1000 m, while precipitation lapse rates were set between 100% and 175% per 1000 m, and precipitation correction factors were between 1.2 and 4.0. These values were necessary in order for the model to produce adequate snowfall amounts over the alpine glaciated regions, and attest to the much greater precipitation amounts received in these areas compared to low elevation eastern parts of the basin. The threshold (minimum) temperature for snowmelt onset was set as 1.0°C, while the temperature index base melt factor, B_0, ranged from a minimum of 2.0 to a maximum of 4.0 mm °C^{-1} day^{-1}. The glacier ice melt factor, *MRG*, which is the ratio of melt of glacier ice to melt of seasonal snow, was set at 1.5 for all glaciers except Llewellyn Glacier, which was set at 1.7 to represent the greater melting of the large expanse of this glacier's lower terminal region. These values correspond very well to the parameter values used in other HBV-EC glacier hydrology modelling applications (e.g., Stahl et al., 2008). All snow and ice melt parameters were set uniformly across the basin, while precipitation factors were adjusted for different glacier and non-glacier climate zones to best match observed snow accumulation amounts. These amounts were estimated based on Environment Yukon snow survey data in the Yukon River Southern Lakes and Whitehorse Regions (www.env.gov.yk.ca/monitoringenvironment/snow_survey.php), from observed snowline elevation at the end of summer on glacier surfaces, and based on the condition that high alpine non-glacier surfaces should generally be snow-free by the end of summer and not develop long-term persistent snowpacks.

Runoff routing is computed separately for glacierized and non-glacierized GRUs in the HBV-EC model (Stahl et al., 2008). For non-glacierized units, soil reservoir drainage enters a common set of lumped reservoirs that represent both 'fast' and 'slow' drainage. Each glacier GRU, in contrast, has a separate reservoir for runoff routing, where outflow is parameterized according to a time-varying outflow coefficient that is related to SWE, and effectively represents the temporal evolution of the sub-, en-, and supra-glacial drainage systems over the spring and summer. At the basin outlet, the streamflow is comprised of outflow from each of the fast, the slow, and the glacier reservoirs.

4.2 MODEL APPLICATION AND EVALUATION

The model was set up and run for the time period of 1981 - 2011, with surface landcover (i.e., glacier extent) defined for both the 1990 and 2010 dates of remotely sensed image acquisition. The evaluation of the model focused on its ability to properly simulate not only the hydrograph characteristics at the outlet of the basin being modelled, but also to ensure that it reasonably represented the important processes within the basin, including glacier mass balance (i.e., the overall balance, and the mass balance gradient with elevation) and snowcover. The period 1985 - 1993 was chosen for model testing and evaluation. This period was chosen because it is short enough to assume that the ca. 1990 glacier extent is held constant without causing significant errors, but still provides a series of years for model hydrograph evaluation. Note that the Fantail River only has discharge records from the Water Survey of Canada (WSC) up until December 1993, and therefore, evaluation of the hydrograph could only be completed based on the 1990 glacier extent. For the other basins, the evaluation period was extended up to 1995 (i.e., 1985 - 1995), while for the Yukon River at Whitehorse, an additional evaluation period of 2005 - 2010 was considered, based on the 2010 glacier extent.

Figure 13 illustrates both the simulated and measured hydrographs for the Fantail River over this evaluation period. The calibrated model captured the basic characteristics of the measured hydrographs, such as the magnitude and peak flow rates in most (but not all) years, the timing of hydrograph rise and the snowmelt freshet in spring, the decline to low flow conditions in fall and winter, and the total volume of discharge. There are a number of short-term errors in the high frequency variability of the simulation results, with the model producing discharge that is too peaked or 'flashy' during individual snowmelt and rainfall events. This is likely not observed in reality due to the attenuation of flood waves in Fantail Lake. Generally, however, the model performed very well and provides a reliable tool for simulating runoff from this glaciated headwater basin.

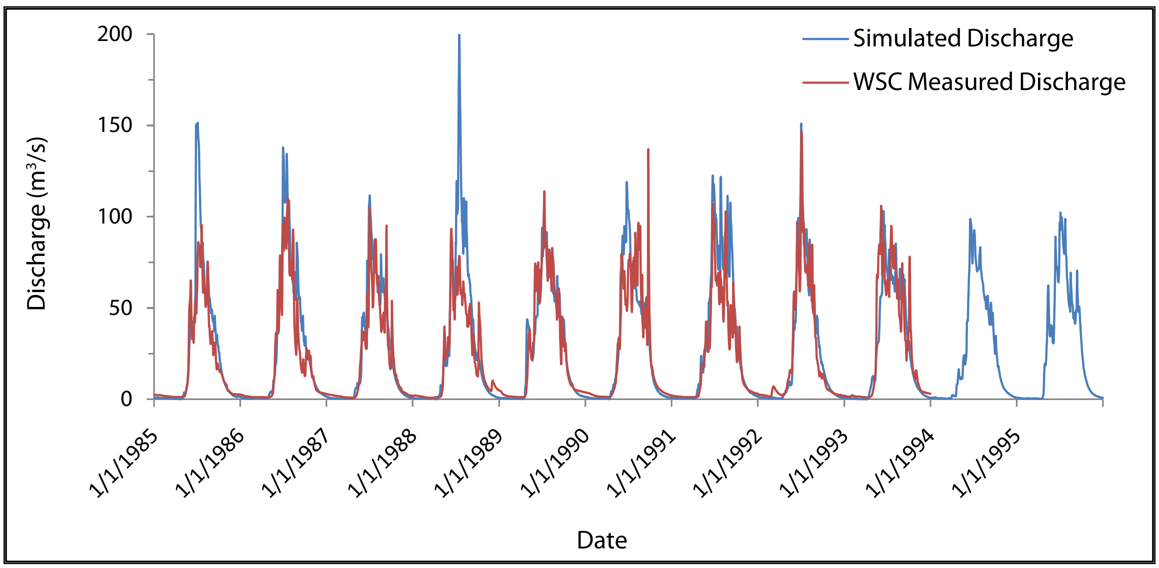

Figure 13. *Simulated and measured hydrograph of Fantail River for ca. 1990 model evaluation period.*

Figure 14 provides the hydrographs for the Wheaton River for the period 1985 - 1995, and Figure 15 presents the hydrographs of the Yukon River at Whitehorse for the same evaluation period. The model produced somewhat reasonable hydrographs for the Wheaton River, but with notable errors such as overestimation of the flow magnitude during spring and summer, and in many years, an underestimation of the baseflow contribution during the winter. This is likely due to improperly calibrated model hydrograph recession parameters and storage-outflow parameters (which control model response to both fast and slow reservoir water releases). It is noted that there was some difficulty in setting the proper trade-off between fast and slow reservoir parameters to achieve the correct discharge magnitude for this river. Simulated discharge of the Yukon River at Whitehorse (Figure 15) corresponded reasonably well with the measured hydrograph, although the actual magnitude of error is considerably greater than the other, smaller headwater basins. To reproduce flows for the Yukon River, the fast reservoir parameter in HBV-EC had to be set to 0, such that it released no water, while the slow reservoir parameter was set very low (i.e., 0.0001 compared to the model default of 0.05), so that only a small fraction of the stored water was released each day. This effectively represents the attenuation of flood waves and the routing of runoff through the large and complex system of lakes in the Southern Lakes area of the Upper Yukon River Basin.

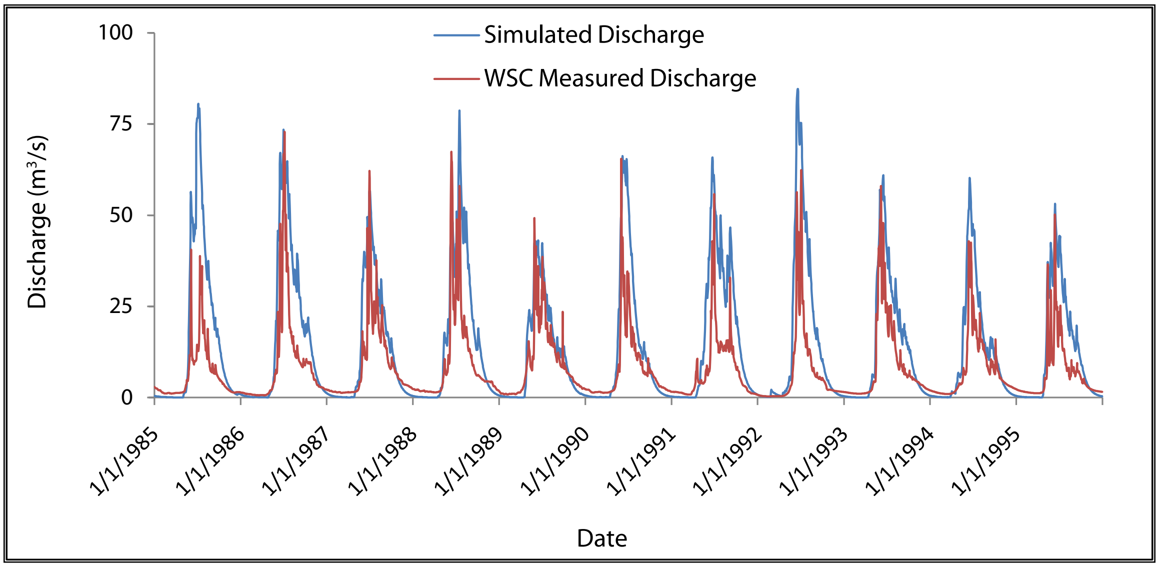

Figure 14. *Simulated and measured hydrograph of Wheaton River for ca. 1990 model evaluation period.*

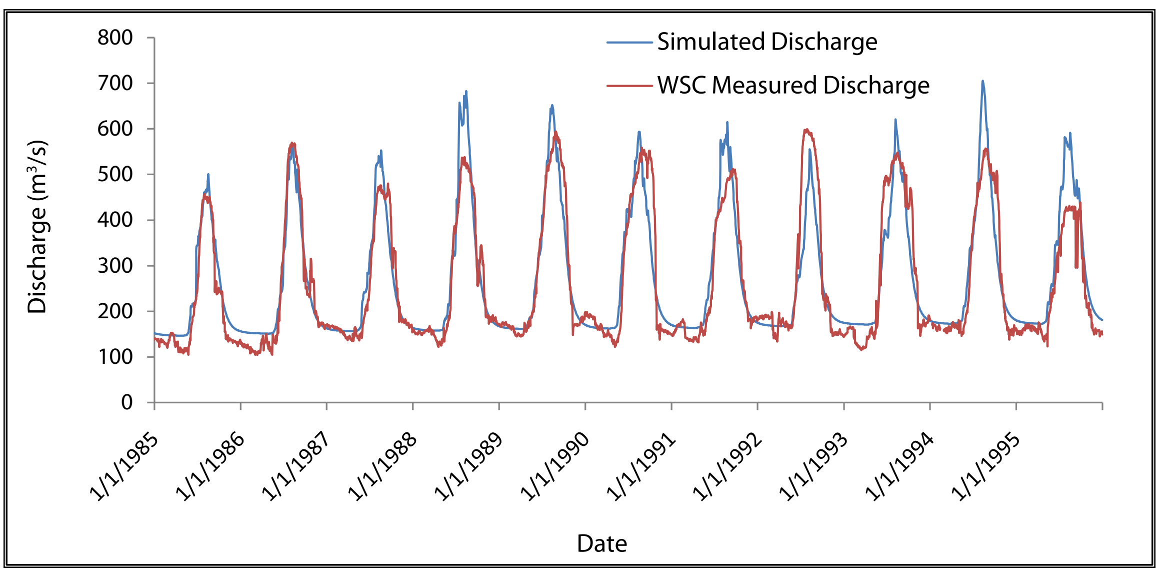

Figure 15. *Simulated and measured hydrograph of Upper Yukon River above Whitehorse for ca. 1990 model evaluation period.*

A quantitative assessment of the model performance was made using criteria including the Nash–Sutcliffe model efficiency coefficient, *NS* (Nash and Sutcliffe, 1970), the root mean squared error, RMSE, and the Model Bias, B_m. *NS* values were calculated as:

$$NS = 1 - \frac{\sum_{i=1}^{n}(d_{m,i} - d_{s,i})^2}{\sum_{i=1}^{n}(d_{m,i} - \overline{d_m})^2}, \qquad (4.6)$$

where d_m is measured river discharge, d_s is simulated river discharge, is the mean measured discharge, *i* is an index for the measurement/simulation pair, and *n* is the total number of pairs. *NS* values range from –∞ to 1.0, where an efficiency of 1.0 indicates the model is a perfect match to the measured data, and a value of 0 indicates the model captures none of the observed variability and the predictions are as accurate as the average of the measured discharge rates. Negative *NS* values occur when the measured average is a better predictor than the model. *RMSE* was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(d_{m,i} - d_{s,i})^2}{n}}, \qquad (4.7)$$

where again d_m is measured river discharge, d_s is simulated river discharge. The *RMSE* gives a weighted measure of the residuals between simulated and measured discharge values. Finally, the Model Bias, B_m, was determined as:

$$B_m = \frac{\sum_{i=1}^{n} d_{s,i}}{\sum_{i=1}^{n} d_{m,i}} - 1 \qquad (4.8)$$

Positive and negative B_m values indicate the fraction by which discharge is either overestimated or underestimated throughout the simulation, and thereby describes the reproduction of total runoff.

Table 6 presents the results for the quantitative model performance evaluation for each of the rivers examined in this study. The *NS* values are all very high (i.e., close to 1). However, as has been noted in other modelling studies of seasonal hydrographs (Stahl et al., 2008), this should not be immediately interpreted as the model performing exceptionally well. Values for *RMSE* and B_m provide more insight into the performance of the model and magnitude of errors associated with the hydrograph simulation. The *RMSE* values show that the absolute magnitude (as a weighted average) of simulation errors is 15 and 12 m^3/s for the Fantail and Wheaton rivers, respectively, which is equivalent to about 20% and 30% of their typical peak flow rates. The magnitude is greater for the Upper Yukon River, from 53 to 56 m^3/s, but in this case the error is only equivalent to about 10% of the normal peak flow rate. The B_m values indicate a systematic overestimation of flows, which is relatively low for the Fantail and Upper Yukon rivers, and relatively high for the Wheaton River. The errors are relatively large during the spring and summer periods, when discharge magnitudes are at a maximum. In comparison to other modelling studies in glaciated basins (e.g., Stahl et al., 2008; Jost et al., 2011), these errors are slightly greater in magnitude, but this is due to the lack of reliable observational data for model forcing and calibration in this region.

During the model calibration and parameter selection process, careful consideration was given to making sure the model realistically simulated the overall mass balance of selected glaciers within the Fantail River Basin, as well as for the Llewellyn Glacier. Average annual net mass balance for glaciers in the Fantail Basin ranged from -0.6 to -0.9 m water equivalent for the simulation based on 1990 glacier extent, and was -0.4 m for the Llewellyn Glacier. These values agreed reasonably well with estimates of the long-term average rate of glacier surface downwasting when compared to the multi-temporal DEMs. For the Llewellyn Glacier, it was assumed that the overall ice loss was not as great in magnitude as that indicated in Figure 11 and Table 5 because of the potentially large DEM errors in the vast upper accumulation zone.

Table 6. Summary of model evaluation criteria for hydrograph simulations of Fantail, Wheaton and Upper Yukon rivers.

Evaluation Parameter	Fantail River (1985 - 1993)	Wheaton River (1985 - 1995)	Yukon River (1985 - 1995)	Yukon River (2005 - 2010)
NS	0.99	0.99	0.99	0.99
RMSE (m^3/s)	15.20	12.30	53.30	55.90
Bm	0.11	0.75	0.04	0.06

A focus was also placed on obtaining realistic elevational gradients in glacier mass balance over the studied glaciers, which was achieved by analyzing the results from specific elevation bands that were output from the model. Net annual specific mass losses (per unit area) in the lower terminal parts of the larger glaciers, such as GL2, GL3, and Llewellyn Glacier were up to several metres per year, and were 1 - 2 m per year for smaller glaciers such as GL1. These rates of change over the long term fit well with the surface lowering observed by multi-temporal DEM analysis, and there is a higher confidence level in the results over the lower parts of the glaciers because of the better DEM accuracy. It was ensured that the model produced long-term conditions of zero net annual mass balance at locations coinciding with the observed late summer snowline (i.e., a good approximation of the glacier equilibrium line elevation (ELA)) in the available imagery and from our field observations in late August 2011. Thus, realistic mass balance gradients were achieved in the model for at least the lower ablation zone of these glaciers. Upper parts of the glacier accumulation zone had positive net annual mass balances, on average, that ranged from 1 - 2 m, to up to more than 9 m water equivalent in limited areas at the highest elevations. These values are assumed to be realistic since overall glacier mass balances were still predominantly negative; very high rates of accumulation are likely to occur in isolated areas where redistribution of snow by avalanches and blowing snow are transported onto the glacier surface (although these processes are not explicitly simulated by the model).

End-of-winter snow accumulation amounts for non-glaciated parts of these basins were also considered, to ensure that the model was properly representing the magnitude of runoff contributions from snowmelt in these areas. Simulated average pre-melt SWE amounts ranged from ~150 mm across much of the drier eastern and northern parts of the Upper Yukon River Basin (which is consistent with observational snowcourse data from Environment Yukon; http://www.env.gov.yk.ca/monitoringenvironment/snow_survey.php), up to as much as 400 - 500 mm or more in the upper parts of headwater basins in the southwestern part of the basin. Model simulations were run in such a way as to ensure that most or all snowpacks in non-glacier areas had melted out by the end of the summer, except during high snowfall years.

By taking the approach described above for the model setup, calibration, and testing, a much higher confidence can be achieved not only with simulated runoff, but also with snow and glacier melt and long-term glacier mass loss contributions to flow. Based on the successful performance of the model in the region, it was subsequently applied to gain insight on the current and future hydrological role of glaciers in the Upper Yukon River Basin. This first involved analyzing the results for the contemporary period to characterize present glacier contributions, and then involved the application of various future climate scenarios in the modelling framework in order to predict how glaciers and glacier runoff may respond over the next several decades. These initiatives are described in the following two sections of this report.

4.3 CONTEMPORARY GLACIER CONTRIBUTIONS TO RUNOFF

To begin the analysis and discussion of how glaciers in the Upper Yukon River Basin presently contribute to the flow of this river, it is important to distinguish some key concepts and definitions. Many studies in a variety of regions have previously examined the hydrological role of glaciers in regional-scale drainage basins (e.g., Comeau et al., 2009; Huss, 2011; Jost et al., 2012). The study of Comeau et al., (2009) made an important distinction between glacier 'wastage' and glacier 'melt'. They noted that wastage is the volume of ice melt that exceeds that due to snow accumulation into a glacier system in a given hydrological year, whereas melt is restricted to the portion of snow and ice melt volume that is less than or equal to that year's volume of accumulated snow . By these definitions, glacier melt can be considered as the release of water from short-term storage (as its magnitude is, by definition, limited to the amount of snow that accumulates during that hydrological year), and does not increase total annual streamflow. In contrast, wastage is the release of water from a longer-term storage reservoir, and results in an increase in water volume flowing from the glacier over and above that accumulated during the hydrological year. This is an important piece in understanding how glaciers influence and contribute to runoff in a basin, as there is currently a misconception that glaciers inherently provide a source of runoff that would no longer exist if the glaciers were to disappear. Rather, the contribution from glacier melt would diminish as the glaciers became smaller (especially affecting later summer runoff), but at the same time, snowmelt from previously glaciated surfaces would still contribute to runoff. If glaciers were in a state of equilibrium, or zero net mass balance, then there would be no additional wastage contribution to enhance runoff on an annual basis. However, the presence of glaciers in a basin does provide a 'buffer' that can help to augment otherwise low streamflow, in years with unusually warm and dry conditions. If glaciers in a basin were to undergo sustained mass loss and terminal retreat, glacier wastage contributions would continue, at some rate, until the glaciers disappeared. Additionally, as glaciers retreat, the buffering effect they have on streamflow would diminish over time, and eventually become negligible. These theoretical concepts will help to place the current and projected future states of glaciers in the Upper Yukon River Basin, and their hydrological influences, into better context.

Glacier melt and wastage components were determined on an annual basis for individual glaciers, and groups of glaciers, that were defined separately as distinct climate zones within the model framework. This was achieved by analyzing the model output file with conditional statements, such that:

$$\text{If } [b_n < 0, \text{then Melt} = b_w, \text{otherwise Melt} = b_s]\ , \tag{4.9a}$$

and

$$\text{If } [b_n < 0, \text{then Wastage} = b_n, \text{otherwise Wastage} = 0] \tag{4.9b}$$

where b_n, b_s, and b_w are the net annual, summer, and winter mass balances, respectively, as calculated by Equations 4.2 - 4.4. By these definitions, glacier melt ranges in magnitude from the summer balance at a minimum (in years with positive net mass balance), to the total amount of the winter accumulation at a maximum (in years with negative net mass balance). Wastage is equivalent to the net mass balance in years with a negative balance, and is zero otherwise. Theoretically, a negative wastage contribution is possible, because in years having a positive mass balance, water that would otherwise contribute to runoff is instead stored as an amount of mass added to the glacier system; however, this was not considered in this study. Furthermore, the definition of glacier melt applied here does not consider the additional contributions that may result from snowfall events and their subsequent melt that occur after the time of maximum snow accumulation on the glacier (i.e., summer snowfall events). This was assumed to not be a significant component of total glacier contribution to runoff. The total volumes of glacier wastage and melt were computed by taking the product of the water equivalent depths of melt or wastage and the respective area of the landcover class (or specified climate zone in the model).

4.3.1 Fantail River

Table 7 provides the results for the Fantail River Basin over the previous several decades and demonstrates how the various individual glaciers within the basin contribute to runoff on average. According to the simulations, glacier melt provides roughly 19% of the total annual flow volume of this river, while wastage has contributed an additional 10% of the flow. Thus, taken together, nearly 30% of the runoff in this headwater basin is ultimately derived from glacial sources (including snowmelt on glacier surfaces), yet glaciers only occupy ~15% of the overall basin area (i.e., in 2010). This demonstrates the much higher specific runoff yield (i.e., mm per unit area) of glacier surfaces, which is to be expected since these areas clearly accumulate greater winter snowpacks than non-glacierized areas. Areas of the landscape without glaciers, however, occupy a much larger proportion of the total basin, and therefore seasonal snowmelt in these areas contributes more to annual runoff volumes (i.e., ~36%) than glacier melt and wastage combined.

Table 7. Average annual and summer (July, August and September) contribution of glacier wastage and melt within the Fantail River Basin during the period 1981 – 2011. Quantities in parentheses are the maximum simulated contributions to total annual and summer discharge.

Model Zone	Annual				Jul, Aug, Sep
	Melt		Wastage		Wastage (% total dis.)
	(10^6 m^3)	(% total dis.)	(10^6 m^3)	(% total dis.)	
GL1	4.0	0.5	1.6	0.2	0.3
GL2	69.6	8.7	37.6	4.7	7.3
GL3	40.6	5.1	18.5	2.3	3.6
Other Small Glaciers	39.6	4.9	19.3	2.4	3.7
All Fantail Basin Glaciers	154 (216.3)	19.2 (24.4)	77.0 (176)	9.6 (22.7)	14.9 (36.2)
Non-Glaciated Terrain	287.0	35.8	-	-	-

The results also reveal that nearly 10% of the total annual flow volume over the past few decades (and likely at least the past 60 years) has been derived from the loss of glacier mass and long-term ice storage, representing a surplus of water above that due to snow and glacier melt alone. The hydrological buffering influence of glaciers in this basin is clearly evident based on the maximum wastage contributions, which showed that this component provided nearly 23% of total annual runoff and just over 36% of summer runoff in one year (i.e., 2004 according to the model).

In addition, the results demonstrate that an overwhelming proportion of the total glacier contributions in the Fantail Basin (both melt and wastage) are derived from the two largest glaciers (GL2 and GL3). This underscores the relative importance of such glaciers, as they tend to have larger ablation zones and longer tongues, which extend to lower elevations and are thus subject to melting over longer periods during the year. Many of the smaller glaciers are restricted to high-elevation sites, where the summer ablation season is generally shorter. Furthermore, these smaller glaciers do not contain nearly as much stored ice volume compared to the larger glaciers and icefields, despite having a total collective area similar to that of a single large glacier. Thus the larger glaciers have the potential to act as a hydrological buffer for a much longer time into the future under conditions of ongoing glacier decline.

4.3.2 UPPER YUKON RIVER

The same analysis (described above) was carried out for the simulations over the entire Upper Yukon River Basin in order to understand how glaciers contribute to runoff at Whitehorse. The results are provided in Table 8. For this analysis, several different groups of glaciers were considered separately: small glaciers (generally corresponding to those less than 10 km^2; see Table 2), intermediate glaciers (generally between 10 and 20 km^2), and large glaciers (generally between 20 and 100 km^2); the Llewellyn Glacier was considered independently from the other groups of glaciers. These categories broadly classify glaciers in order to best represent the spatial differences in precipitation gradients over the glaciers; the criteria used to distinguish them as separate climate zones included their location relative to the southwest basin margin along the central divide of the upland icefields. The analysis of glacier contribution to discharge at the scale of the Yukon River above Whitehorse shows that, overall over the past several decades, glacier melt represents roughly 16%, and glacier wastage a further 7%, of the total annual flow. Thus, nearly 23% of the annual runoff volume is derived from glacial sources in the headwaters, while the area occupied by glaciers in 2010 is only about 5% of the total basin area. This is indeed a significant amount of runoff generated from this relatively small area, and shows that on average, glacier-covered areas have a specific runoff yield (mm per unit area) of more than four times that of other parts of the basin.

Table 8. Average annual and summer (July, August and September) contribution of glacier wastage and melt within the Upper Yukon River Basin above Whitehorse during the period 1981 – 2011. Quantities in parentheses are the maximum simulated contributions to total annual and summer discharge.

Model Zone	Annual				Jul, Aug, Sep
	Melt		Wastage		Wastage (% total dis.)
	(10^6 m^3)	(% total dis.)	(10^6 m^3)	(% total dis.)	
Small Glaciers	0.24	2.8	0.11	1.3	2.9
Intermediate Glaciers	0.13	1.5	0.07	0.9	2.0
Large Glaciers	0.37	4.3	0.18	2.1	4.7
Llewellyn Glacier	0.62	7.3	0.23	2.7	6.0
All Yukon Basin Glaciers	1.35 (1.78)	16.0 (23.6)	0.58 (1.40)	6.9 (15.4)	15.6 (33.4)
Non-Glaciated Terrain	3.74	44.1	-	-	-

Flow contributions derived from the loss of long-term storage of ice (by sustained negative net mass balance) has averaged roughly 7% on an annual basis, and nearly 16% of summer (i.e., July, August and September) discharge. It is difficult to precisely quantify the amount of water flowing in the river during the summer that is ultimately generated from glacier sources, due to the routing of water through the Southern Lakes system and the time it takes for the water to reach the gauging stations. An attempt was not made in this study to determine that, but rather the purpose was only to put into perspective the relative amounts produced from glacier mass loss in comparison to flow volume. These results showed that wastage contributions have, in recent decades, been as high as 33% of the total flow in the months of July through September, which clearly indicates the magnitude of the buffering capacity that glaciers can have.

As was observed for the Fantail River, the most significant contributions (in terms of both glacier melt and wastage) to flow in the Upper Yukon River came from the small number of large glaciers (i.e., glaciers such as GL2, GL3, the Llewellyn Glacier, and several outlet glaciers from the icefields along the southwest basin margin). By far, the greatest single contributor over the last several decades has been the Llewellyn Glacier, which has contributed nearly the same amount of melt as all other glaciers combined, and nearly 40% of all the wastage within the basin during this time frame. This glacier very likely contains more than half of the total volume (and possibly up to 80% or more, by the volume-area scaling estimate) of ice in the entire basin, and thus its current state and potential future evolution will largely dominate the glacier hydrological patterns and responses in the years to come.

A final point to be noted from this analysis, which should not be overlooked, is the relative importance of seasonal snowmelt from non-glaciated parts of the basin (and from snowmelt on glacier surfaces as well). The relative amount of annual runoff from this source in the contemporary period (i.e., 1981 - 2011) is 44%, and when including melt from glaciers, it is 60%. Thus, the hydrology of the Upper Yukon River basin is largely dominated by seasonal snowmelt processes, which provide a source of runoff in spring and early summer before glacier ice in the headwater areas begins to melt in significant quantities. These are therefore the processes that control the timing and magnitude of runoff in the transition from baseflow period of April and May. It is therefore important, from the perspective of hydro-power generation at Whitehorse, to understand snowpack variability over time-scales ranging from annual to decadal and longer, which represents a key component of future hydrological response of the Yukon River.

4.4 FUTURE CLIMATE SCENARIO ANALYSIS

4.4.1 DESCRIPTION OF SIMULATION APPROACH AND PROCEDURES

With this clearer understanding of the contemporary role of glaciers for the hydrology of the Upper Yukon River Basin, it is possible to investigate the potential future response of glaciers in this region to climate change. The general approach in this study was to (1) run the calibrated glacier-hydrological model under a suite of climate change scenarios, starting from the 2010 glacier extent; (2) analyze the results for a period of two decades and take accumulated values of net mass balance; (3) generate a new set of glacier margins based on the net loss of glacier volume; (4) re-incorporate the new glacier surface extent into the model; and (5) repeat the procedure for the next model simulation period. Figure 16 is a flow chart that illustrates the steps involved in this procedure. The results were examined for the time periods 2010 - 2030, 2030 - 2050, and 2050 - 2070, and the glacier margins were updated in the model for the years 2030 and 2050. At these times, a new model structure (defined within an HBV parameter set) was generated using updated landcover and climate zone grids corresponding to the new glacier extents, while holding all model parameter values constant for each of the climate zones and GRUs. This is a novel way of applying the HBV-EC model, which allows the unique responses of individual glaciers, or glacier types, to be identified and represented by the model.

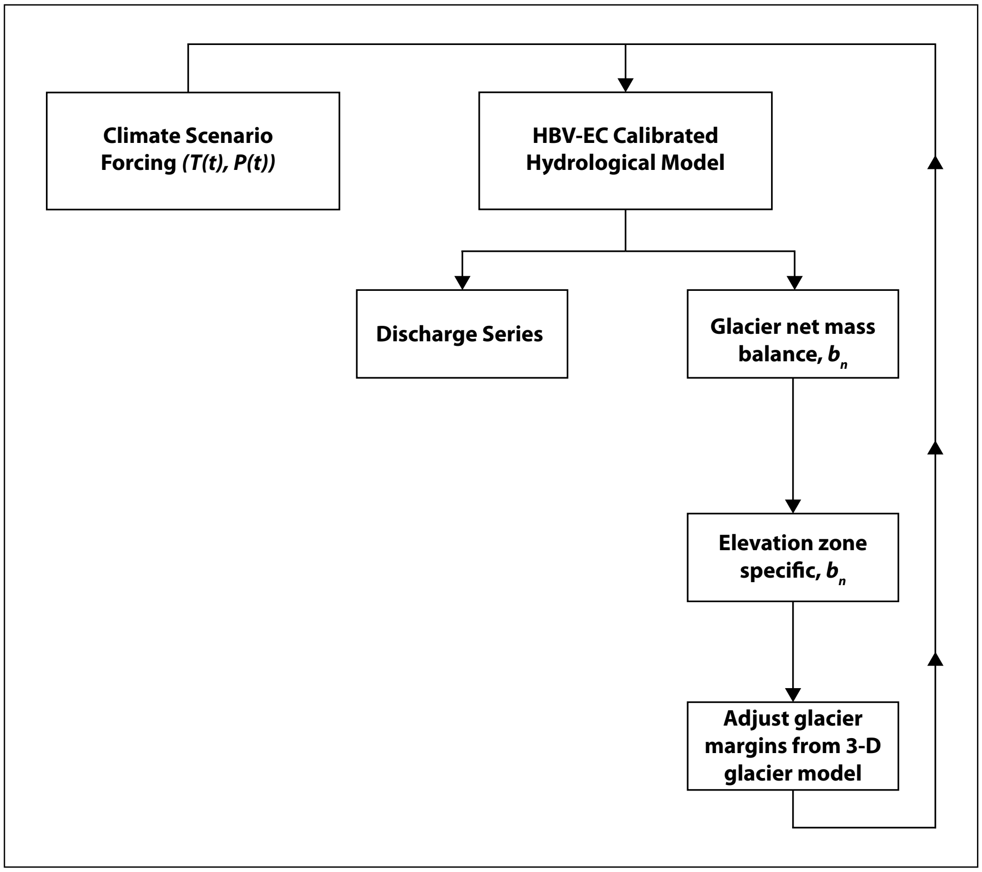

Figure 16. *Flow chart depicting procedures for climate scenario analysis by the model, and adjustment of glacier margins to be input for future subsequent landcover conditions.*

To investigate the range of potential future hydrological conditions associated with a range of likely to extreme climate projections, a set of four different idealized scenarios were considered. Table 9 provides the changes in temperature and precipitation imposed in each of the scenarios for each model evaluation period up to 2070. In all cases, the future scenario was implemented to the model by adjusting all records in the historical 1981 - 2011 meteorological observation data according to the values set out in this table, and importing it into the HBV-EC simulation with the updated landcover and climate zone grids. The first of the scenarios (SC-1) assumed no change in the climate of the last 30 years, and applied the same observations in each period. (As in the other climate scenarios, glacier extents were updated after each simulation interval). The second scenario (SC-2) was based on the Global A1B scenario of the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al., 2007), which indicates a modest rise in annual average temperature of up to several degrees Celsius by 2070, and a slight increase in precipitation (~15% annual average for the Upper Yukon River Basin region). The changes in air temperature were applied incrementally over the three time periods, without accounting for seasonal variations in the rates of change, while precipitation was assumed to increase by a constant 15% in all seasons for the entire 2010 - 2070 time period. The third scenario was adapted 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 under this scenario are based on raster values surrounding Carcross, Yukon, and changes were projected for 2030 and 2050 using the A1B scenario based on the IPCC Special Report on Emissions Scenarios (Nebojša et al., 2000). The A1B scenario anticipates medium to high degrees of climate change. This scenario was used because it provides a high-end range in possible shifts in temperature and precipitation by 2030 and 2050, thereby encapsulating the most significant potential changes in headwater glacial conditions. Seasonal changes in temperature and precipitation were estimated for the three time periods investigated in this study by interpolating between 2030 and 2050 downscaled A1B projections, and extrapolating the 2050 projection forward for the time period 2050 - 2070 represented here. Of the modelled climate scenarios, these had the greatest overall magnitude of temperature and precipitation increases. The final scenario considered (SC-4) was a hypothetical projection with IPCC Global A1B annual temperature trends applied, but with a fixed 25% decrease in precipitation. This is an unlikely scenario, but was included to characterize the effects of any sustained decrease in precipitation together with gradual warming trends.

Table 9. Summary changes in temperature and precipitation for different climate scenarios over the period 2010 - 2070. Subscripts su, fa, wi and sp denote summer, fall, winter and spring respectively.

Climate Scenario	2010 - 2030 Temperature Changes (°C)				2030 - 2050 Temperature Changes (°C)				2050 - 2070 Temperature Changes (°C)			
	T_{su}	T_{fa}	T_{wi}	T_{sp}	T_{su}	T_{fa}	T_{wi}	T_{sp}	T_{su}	T_{fa}	T_{wi}	T_{sp}
SC-1	0	0	0	0	0	0	0	0	0	0	0	0
SC-2	0.75	0.75	0.75	0.75	1.5	1.5	1.5	1.5	2.25	2.25	2.25	2.25
SC-3	0.15	1.2	1.80	0.9	1.0	3.1	4.95	2.0	2.2	6.9	8.1	3.1
SC-4	0.75	0.75	0.75	0.75	1.5	1.5	1.5	1.5	2.25	2.25	2.25	2.25
Climate Scenario	**2010 - 2030 Precipitation Changes (%)**				**2030 - 2050 Precipitation Changes (%)**				**2050 - 2070 Precipitation Changes (%)**			
	P_{su}	P_{fa}	P_{wi}	P_{sp}	P_{su}	P_{fa}	P_{wi}	P_{sp}	P_{su}	P_{fa}	P_{wi}	P_{sp}
SC-1	0	0	0	0	0	0	0	0	0	0	0	0
SC-2	15	15	15	15	15	15	15	15	15	15	15	15
SC-3	20	15	24	17	27	30	51	36	15	30	55	40
SC-4	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25

Finally, a key component of the future climate simulation analysis was the incorporation of updated glacier margins at 20-year intervals. This allowed estimation of both the amount of retreat to be expected over time and the associated hydrological implications of this retreat. It was originally envisioned that by refining the parameters in a volume-area scaling relationship for the region through our field measurements, this would provide a technique to rescale future glacier area based on simulated wastage and volume loss. However, comparison of this technique with estimates of ice loss by repeat DEMs (discussed in Section 3.2.2) showed that this may not provide a reliable approach, and so an alternative method was used. For this method, the 3-dimensional glacier representations generated from the field data and the GIS interpolation procedure (described in Section 2.3), were used to redefine glacier margins after a prolonged period of simulated wastage. Figure 17 illustrates an example of this approach for GL2 in the Fantail River Basin under the SC-4 scenario. The general approach was to adjust the terminal position, lateral margins, and ice-surface elevations enough to represent the total amount of wastage over the period in the lower elevation bands, scaled by the overall glacier net mass balance. This takes into account the fact that a glacier is not simply a static system in which the ice surface elevation is simply reduced by an amount equal to the net depth of ablation at a particular point in space; in reality, some of the ice loss in lower parts of the glacier is compensated by ice flux down the glacier from higher elevations. By this approach, if the overall net mass balance of a glacier is more strongly negative (compared to other scenarios for the same time period), then a greater fraction of the total simulated ice surface lowering (specific to a given elevation band) is applied. However, if overall net balance is less strongly negative, then a smaller fraction of this surface lowering was applied. Ice margins above the glacier equilibrium line (ELA) are not adjusted unless the ELA moved up significantly in elevation according to simulation results. This provides a realistic representation of the true changes in glacier margins and areal extent likely to occur in the future, as observations over the previous 60 years have shown that changes in ice margin position have largely occurred in the lower ablation zones of individual glaciers, while changes above the ELA have been largely undetectable.

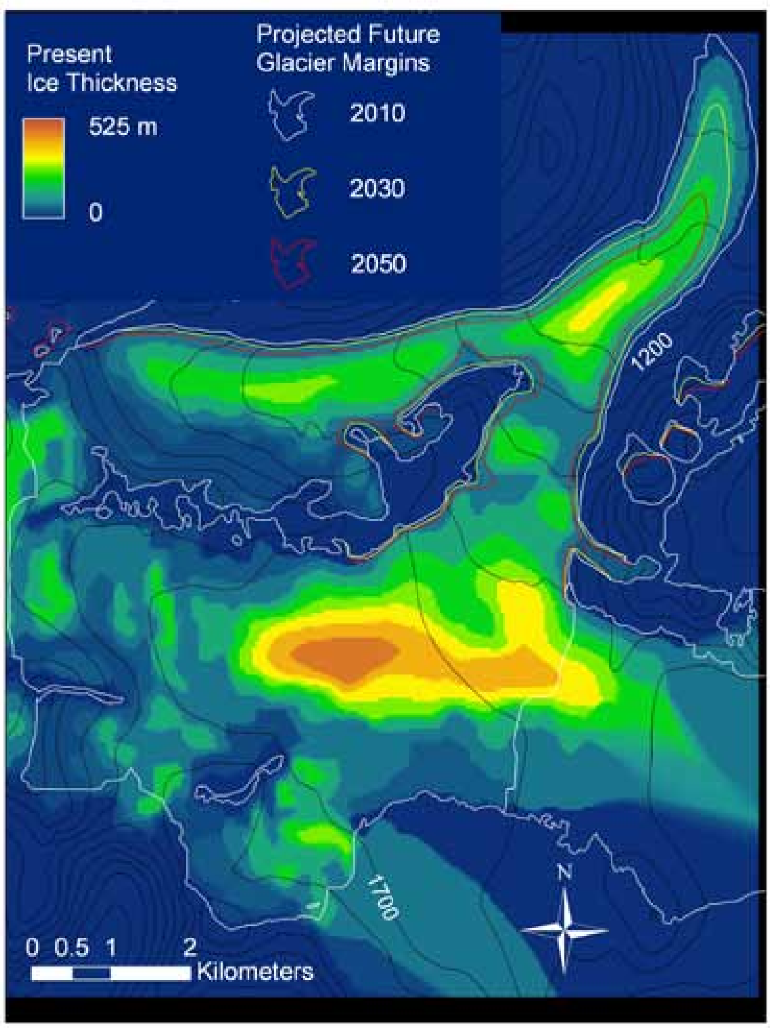

Figure 17. *Example of glacier margin and surface area rescaling based on 3-dimensional ice thickness model of GL2 in Fantail River Basin. Projections based on climate SC-4 scenario.*

This strategy was applied for the glaciers over which we had obtained radar ice thickness measurements. For other glaciers in the region, a comparative approach had to be taken to adjust the glacier margins, which was based on previous changes in response to mass balance perturbations observed from the remotely sensed imagery and from the projected changes for this control group of glaciers. For glaciers of similar form and approximate size, the relative amounts of terminal retreat and lateral margin contraction were taken from the projections of these initial glaciers and applied similarly to the others. This is somewhat subjective and prone to uncertainty for individual glaciers, but the overall loss of glacier area should be reasonably well represented by this approach.

The climate scenario analysis was carried out for both the Fantail River Basin (~700 km^2) and for the Upper Yukon River Basin (~20 000 km^2) in order to examine the hydrograph responses across a range of spatial scales. The results for the Fantail River are discussed first, as this basin provides a useful test case for providing insight on the patterns of projected hydrological changes in a typical glaciated headwater basin. Here, the changes in hydrograph characteristics can be more easily interpreted due to less extensive lake and groundwater storage, smaller basin area and range of climatic conditions, and fewer complicating effects due to long travel times through the river and stream network. Following interpretation of the hydrological response to climate change in the headwaters, the results for the Yukon River are presented and compared with those for the Fantail River. Although the prediction of the likely changes to hydrograph timing and magnitude at Whitehorse is a primary objective of this study, this is a more difficult task given the presence of numerous large lakes along the river network. Thus, it is worthwhile to compare and contrast the results to determine how the effects of changing headwater processes may be translated to the flow downstream at the larger scale. Specific features that were examined and characterized in both cases include glacier melt and wastage contributions, glacier area, snowmelt from non-glaciated parts of the landscape, total discharge volume, and seasonal patterns of runoff.

4.4.2 FANTAIL RIVER DISCHARGE PROJECTIONS

Figure 18 shows the simulated monthly average discharge values for the Fantail River with reference to a baseline period of 1981 - 2011 (Simulated discharge values were used in order to avoid biasing the interpretation of any changes that could be due to inconsistencies between the model and reality). Each scenario produces unique responses and trends in seasonal runoff that differ considerably from one another. A key difference is that the SC-1 and SC-4 scenarios produce declining runoff in nearly all months, and for the total annual flow, while the SC-2 and SC-3 scenarios have the opposite effect. In the case of the SC-1 scenario, under a steady climate, the decline is primarily due to the fact that the glaciers continue to lose mass, but at a declining rate, nearly approaching a new equilibrium condition (with reduced glacier surface area) by the 2050 - 2070 time period. Thus the surplus water contribution derived from glacier wastage (presently equivalent to about 10% of total flow volume) in this basin gradually declines, with the effect of mostly reducing the July, August and September discharge.

For the SC-4 scenario, the cause of the considerable reduction in runoff volume is for different reasons. The immediate streamflow reduction from the ‘sudden’ and sustained 25% reduction in precipitation occurs mostly in June and July, which are the peak months for snowmelt runoff from both glacier and non-glacier sources; this indicates that reduced winter snowpacks are the likely cause of this pattern. However, there are other notable characteristics in the trends and seasonality here. For example, runoff continues to decline through the months of June, July and August, even after the step-change in precipitation imposed in the model. This is likely due to continually diminishing snowpacks in each of the successive simulation time frames, as a greater fraction of precipitation falls as rain with warming temperatures. The same process would have an impact on all climate scenarios with warming trends, and is likely to occur in the future (even though uncertainties in the rate of magnitude of future warming remain). Earlier melt of snow in the spring by up to several weeks produces a slight rise in April and May runoff, despite the reduction in overall snowpack volume. Also, despite the fact that glacier mass loss and terminal retreat is substantial under this scenario (due to a reduction in snow accumulation and increase in ice melt), the additional contributions from glacier wastage are not sufficient to offset the reductions in runoff caused by the other processes (except partially in the late fall).

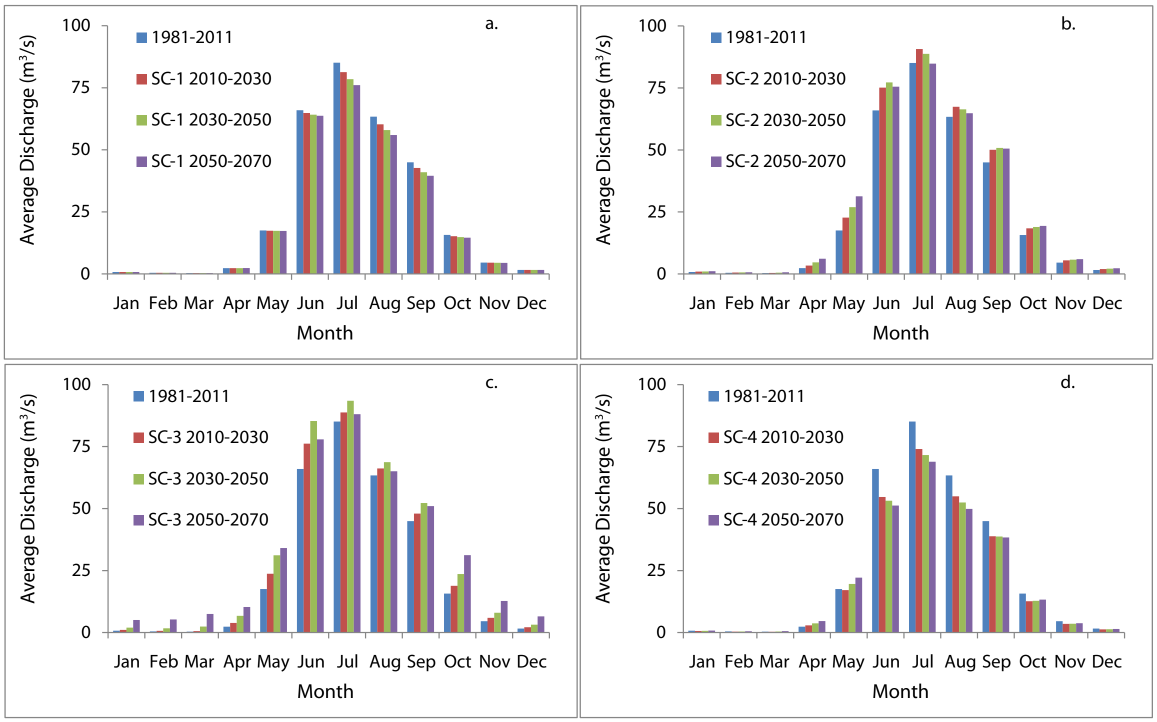

Figure 18. *Monthly average discharge rate projections of Fantail River under various climate scenarios. The 1981 – 2011 simulation results are shown for comparison with contemporary hydrograph magnitude and seasonality patterns.*

The SC-2 and SC-3 scenarios show relatively similar relative patterns in seasonal runoff response to climate and glacier change, but with differing magnitudes. Both scenarios include an increase in precipitation, as well as an increase in temperature. As in other scenarios, the net effect in both cases is a continual reduction in glacier mass and retreat, and neither simulation produces conditions that allow a new equilibrium glacier state to be reached. However, the additional accumulation of winter snowpack, especially within the SC-3 scenario (which includes extraordinarily high increases in winter precipitation), partly compensates the overall net mass balance of the glaciers relative to what would occur under increased temperature alone. The overall effect in both scenarios is increased snowpack accumulation with greater runoff from snowmelt, earlier timing of hydrograph rise due to earlier melt onset, greater glacier ice melt with an important glacier wastage component, and in the case of the SC-3 scenario, increased winter baseflow, which is likely due to the occurrence of mid-winter snowmelt and rainfall events.

4.4.3 YUKON RIVER DISCHARGE PROJECTIONS

Model projections for future Yukon River discharge are given (1) in Table 10, which presents a summary of the results for the average annual contributions to Yukon River flow under the different scenarios; (2) in Figure 19, which illustrates the predicted seasonal variation in average monthly discharge of the river at Whitehorse; and (3) in Table 11, which gives the associated values of the relative changes compared to the baseline simulation for the contemporary period. Many of the same general principles apply as was noted in the Fantail headwater basin, and can be attributed to similar shifts in snow and glacier hydrological processes.

Table 10. Summary of overall projected changes in annual runoff volume, contributions from glacier melt and wastage, total glacier area, and non-glacier snowmelt contribution under various climate scenarios for the Upper Yukon River Basin. Relative changes are shown as percent relative to the 1981 – 2011 baseline conditions.

Climate Scenario and Associated Variables	1981-2011 baseline period	2010-2030 model period	2030-2050 model period	2050-2070 model period	2010-2030 relative change (%)	2030-2050 relative change (%)	2050-2070 relative change (%)
SC-1							
Total Discharge (10^9 m^3)	8.49	8.21	8.08	7.98	-3.23	-4.82	-6.0
Glacier Melt (10^9 m^3)	1.35	1.27	1.22	1.18	-6.59	-10.2	-13.2
Glacier Wastage (10^9 m^3)	0.58	0.46	0.39	0.35	-21.6	-32.5	-40.4
Glacier Area (km^2)	1002	-	960	931	-	-4.19	-7.04
Non-Glacier Snowmelt (10^9 m^3)	3.74	3.77	3.79	3.80	0.71	1.20	1.57
SC-2							
Total Discharge (10^9 m^3)	8.49	9.11	9.34	9.53	7.30	10.1	12.3
Glacier Melt (10^9 m^3)	1.35	1.45	1.43	1.34	6.83	5.83	-0.90
Glacier Wastage (10^9 m^3)	0.58	0.60	0.99	1.40	3.25	69.83	140
Glacier Area (km^2)	1002	-	957	914	-	-4.52	-8.83
Non-Glacier Snowmelt (10^9 m^3)	3.74	4.20	4.01	3.83	12.2	7.27	2.33
SC-3							
Total Discharge (10^9 m^3)	8.49	9.05	9.94	10.6	6.59	17.1	25.4
Glacier Melt (10^9 m^3)	1.35	1.41	1.59	1.43	4.29	17.6	5.38
Glacier Wastage (10^9 m^3)	0.58	0.38	0.59	1.67	-34.7	1.34	186
Glacier Area (km^2)	1002	-	962	925	-	-3.96	-7.73
Non-Glacier Snowmelt (10^9 m^3)	3.74	4.21	3.77	2.86	12.7	0.71	-23.6
SC-4							
Total Discharge (10^9 m^3)	8.49	7.82	7.88	7.98	-7.87	-7.12	-6.03
Glacier Melt (10^9 m^3)	1.35	0.99	0.94	0.84	-27.1	-30.7	-37.8
Glacier Wastage (10^9 m^3)	0.58	1.52	1.37	2.07	160.7	134	255
Glacier Area (km^2)	1002	-	938	886	-	-6.39	-11.5
Non-Glacier Snowmelt (10^9 m^3)	3.74	3.77	3.77	2.40	0.71	0.71	-36

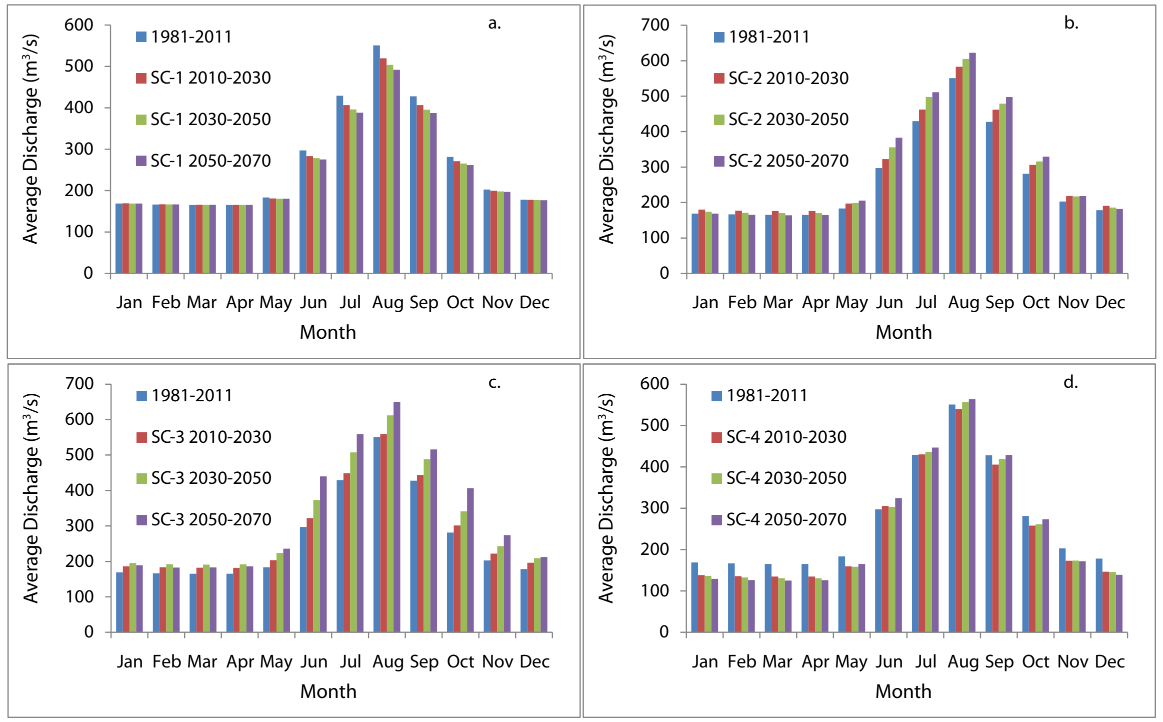

Figure 19. *Monthly average discharge rate projections of Upper Yukon River at Whitehorse under various climate scenarios. The 1981 – 2011 simulation results are shown for comparison with contemporary hydrograph magnitude and seasonality patterns.*

The SC-1 scenario produces a decline in flow for all months, as glaciers gradually approach an equilibrium state with the current climate. It is noted, however, that the slight reduction shown in May (and part of the reduction shown in June) is not realistic and is attributed to the model structure and setup used in this study. For example, because glaciers were defined in the model as distinct climate zones with separate, higher parameter values for precipitation lapse rate and adjustment factor, they inherently received greater snow accumulation amounts than non-glacier areas at equivalent elevations. This is a realistic assumption for a glacier system as a whole, and has been suggested previously (Moore, 1993). By this model approach, however, bedrock and/or moraine exposed by glacier retreat following ice wastage are redefined as non-glacier terrain, and thus receive less snowfall, whereas in reality, these areas would continue to receive the same average snowfall (neglecting climatic-induced changes) and would thus provide the same specific snowmelt runoff in spring.

As discussed above in Section 4.3, as glaciers retreat and approach an equilibrium state under a steady climate, glacier *ice* melt and wastage volumes would tend to decrease over time. The basin-wide effect (other factors held constant) would be a reduction in the total volume of annual runoff that results purely from the diminishing wastage (i.e., 'surplus' water) contributions, which primarily occurs during the summer and early fall months. This is indeed apparent in the results for the Yukon River under the SC-1 climate scenario.

As was noted in the results for the Fantail River, the SC-2 and SC-3 scenarios produced a clear increasing trend in runoff for the months of May through October (and into December for the SC-3 projection). These scenarios lead to greater total annual runoff and a widening of the period of high flows, which encompasses more of the 'shoulder' seasons (i.e., spring and fall). This is due to the increase in snowpack accumulation, as well as the increase in air temperature and specific melt rates (i.e., mm per unit area) over both snow-covered and glacier ice surfaces. This in turn leads to earlier, faster, and more abundant spring snowmelt runoff generation, and greater volumes of glacier meltwater production, despite the reduction in glacier surface area. This is clearly a favourable projection from the perspective of hydro-power generation at Whitehorse, as this may increase the period of viability for operation of power generators and reduce the dependence on supplementary diesel power generation. However, there is uncertainty in the precise timing of these flows, and it is less clear what the winter response to changing hydrological regimes in the headwaters may be. This is due the considerable effects of storage and transmission of runoff through the Southern Lakes system within the Upper Yukon River Basin.

Table 11. Relative predicted changes in seasonal discharge compared to 1981 – 2011 baseline model conditions for the Upper Yukon River.

Scenario and Time-Frame	Monthly and Annual Differences (% relative to 1981 - 2011)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
SC-1 2010-2030	0.2	0.3	0.4	0.3	-1.2	-4.7	-5.3	-5.6	-5.0	-3.7	-1.4	-0.2	-3.2
SC-1 2030-2050	0.0	0.2	0.3	0.2	-1.5	-6.3	-7.7	-8.5	-7.5	-5.6	-2.3	-0.6	-4.8
SC-1 2050-2070	-0.1	0.1	0.2	0.2	-1.6	-7.4	-9.6	-10.7	-9.5	-7.0	-2.9	-0.8	-6.0
SC-2 2010-2030	6.6	6.6	6.5	6.6	7.6	8.4	7.7	5.8	8.0	8.9	7.8	7.1	7.3
SC-2 2030-2050	3.2	2.8	2.8	3.0	8.3	19.7	15.9	9.8	11.9	12.3	7.2	4.3	10.0
SC-2 2050-2070	0.0	-0.7	-0.8	-0.2	12.0	28.9	19.1	13.0	16.3	17.2	7.5	2.0	12.3
SC-3 2010-2030	10.0	10.1	10.1	10.2	11.0	8.4	4.4	1.5	3.8	7.1	9.4	10.2	6.6
SC-3 2030-2050	15.6	15.3	15.5	16.1	22.0	25.6	18.2	11.1	14.2	21.3	19.9	17.2	17.1
SC-3 2050-2070	12.0	9.7	10.6	12.6	28.6	48.0	30.2	18.0	20.6	44.5	35.2	19.2	25.4
SC-4 2010-2030	-18.1	-18.4	-18.5	-18.4	-13.1	2.8	0.2	-2.1	-5.2	-8.3	-14.6	-17.8	-7.9
SC-4 2030-2050	-19.3	-20.4	-20.9	-20.9	-13.7	2.1	1.6	1.1	-2.0	-7.1	-14.5	-18.2	-7.2
SC-4 2050-2070	-23.4	-24.1	-24.3	-23.6	-10.0	9.2	4.1	2.3	0.3	-2.8	-15.3	-22.0	-6.1

An interesting finding from the SC-4 climate scenario is that although there was an overall reduction in the total annual volume of runoff by 6 - 7%, the buffering effect of glaciers in the basin helped considerably to offset the reduction, and this effect actually increased into the 2050 - 2070 time period. Spring and summer discharge rates were maintained, while winter baseflow declined. Thus, it appears that due to the considerable volume of ice stored in the basin (especially in larger glaciers such as the Llewellyn Glacier) and the relatively low elevation of many large expanses of ice, glaciers will likely have an important hydrological role through their wastage contribution for many decades to come, regardless of most anticipated trends in climate across the region. The only potential exception might be a situation in which an onset of sustained cooler conditions leads to new equilibrium, or even positive mass balance condition; this however, is not a likely scenario.

5. RECOMMENDATIONS

5.1 ADAPTATION TO FUTURE RUNOFF REGIMES

The results of this study show that there is no consistent trend in future seasonal, total annual, and inter-annual runoff patterns that can be expected with a high degree of certainty. Instead, the hydrological response of the region's glaciers to climate change depends very strongly on what scenario unfolds and how global and regional patterns of climate variability are manifested at smaller spatial scales within this region. However, some key insights into the hydrological response of glaciers to different climatic trends have been gained, and it is possible to use the modelling results to outline the general types of changes that are most likely to occur. These are briefly discussed here to summarize the findings from the various modelling scenarios and to frame the context for adaptive measures YEC might consider in the future.

The most likely climate projections for this region suggest an increase in annual and seasonal temperatures, which may be as high several degrees Celsius on average (Solomon et al., 2007; SNAP, 2010). According to the modelling work carried out in this study, this warming will have the tendency to increase snow and ice melt rates and to advance the onset of spring snowmelt by up to several weeks. In addition, warming of only several degrees during the winter and spring will very likely reduce the magnitude of snowpack accumulation that is available for melt and runoff in spring, because of a greater fraction of precipitation falling as rain. The model results also indicate that this will increase the rate of glacier ice melt and wastage and thereby enhance the summer and fall runoff volumes from more highly glaciated headwater basins, which will in turn increase flow in the Yukon River.

Results obtained from the modelling work in this study also highlight the potential responses to the likely expected future changes in precipitation. Most climate projections are in agreement that, on average, precipitation amounts (especially winter precipitation amounts) will increase by some extent in northwestern North America (Solomon et al., 2007; SNAP, 2010). These changes will further increase spring and summer runoff through enhanced snowmelt contributions and additional rainfall. However, year-to-year variability of winter snowfall amounts might also increase; this effect (which was not explicitly modelled in this study) could increase the risk of low flows during the spring and summer in some years due to the fact that snowmelt runoff in the Yukon River Basin (from both glacier and non-glacier areas) provides the most signification fraction of the total flow of the Yukon River (i.e., ~60% on average). The high relative contribution of seasonal snowmelt is an important finding, which emerged directly from the modelling work in this study. As far as the effects on glaciers, the model results here show that additional winter snowfall will increase the net mass balance of glaciers (i.e., to less negative values than would otherwise be the case for glaciers in this region). This occurs because of the higher winter accumulation, which also delays the onset of melting of glacial ice. Because ice has a lower albedo (reflectivity) than snow, it generally melts more rapidly (Moore, 1993). Coupled with an increase in annual and seasonal air temperatures, glaciers will likely remain in a state of disequilibrium and negative net mass balance in the foreseeable future, and will thus continue to retreat. Therefore, given the likelihood that both temperature and precipitation will increase with continued climate change, the anticipated response of flow of the Yukon River at Whitehorse is generally an increase in flow from early spring through to late fall, with the magnitude of discharge changes depending on the degree of climatic change. Modest increases in precipitation (i.e., 5 - 15%) are more realistic in the future, and so very large positive discharge trends are not likely to be expected.

Finally, according to the model results, continued glacier recession and mass loss over the following decades is to be expected with a high degree of certainty, providing an ongoing 'surplus' contribution to runoff from the wastage of the numerous large glaciers in the Upper Yukon River Basin. Before this study was conducted, it was unclear how much ice was stored in the headwaters of the Yukon River, the timescale over which it would be lost, and what the consequences of this melt on river discharge would be. This work has shown, with a relatively high degree of confidence, that glaciers in this region represent a considerable reservoir of ice storage (i.e., an estimated ~187 km^3), and that even under conditions of strongly negative sustained net mass balances, glaciers will continue to contribute to the flow of the Yukon River for many decades. The simulations demonstrated that by 2050, glacier extent will be reduced by only ~12% relative to 2010, even in the most extreme climate scenarios investigated (i.e., SC-4). Therefore, the glacier cover within the basin will continue to have the capability to augment, to some extent, otherwise lower discharge rates in years with low winter snowpack, especially under warm conditions. It is noted that the response of the numerous relatively small and isolated glaciers is less certain due to the highly localized set of climatic and morphological conditions each glacier occupies (as these details could not be accurately represented given the resolution of the current model). However, the study did show that on a regional basis, these smaller glaciers are collectively much less hydrologically significant than are the relatively fewer number of large glaciers - especially the Llewellyn Glacier.

Taken together, these modelling projections suggest that runoff will most likely exhibit an increasing trend during the spring and summer months in the coming decades. However, it is noted that this forecast is based on a relatively simple analysis using idealized conditions. Although the most likely future projection suggests gradually increasing runoff trends, the problem of uncertainty remains, especially for predicting the hydrological response on a short-term basis and dealing with the effects of high year-to-year variability in climatic conditions. Adaptation and risk mitigation strategies must therefore focus on developing tools and techniques for reducing the predictive uncertainty, rather than relying on simplified forecasts or procedures based on historical observations and empirical relationships. The work undertaken in this project has helped to identify several critical areas in which attention should be focused, so that these goals can ultimately be achieved. These are described in the following section of this report.

5.2 FUTURE RESEARCH AND MONITORING PRIORITIES

The third objective of this project was to suggest recommendations to YEC for mitigation of likely flow regime changes, and to highlight gaps in the understanding or monitoring initiatives where further work should be focused. The following recommendations result either from observations made during the course of the study or from the modelling results.

1) Detailed Investigation of the Llewellyn Glacier

The results showed that the Llewellyn Glacier is the region's single greatest contributor to runoff from melt and wastage components (i.e., 7.3 and 2.7% of total flow volume respectively), and this glacier presently contains at least half (and likely a greater fraction) of the total ice volume in the Upper Yukon River Basin. It has the largest ablation-zone surface area of any glacier in the basin, and its terminus extends to a relatively low elevation, which increases both the intensity and duration of melt there. The Llewellyn Glacier might also be particularly sensitive to climate change, as suggested by factors such as its significantly greater recent mass balance losses compared to other glaciers, and the fact that a significant portion of its lower margin terminates in a large proglacial lake. This remains unclear at this time, and as a result, its future response to continued climatic change is difficult to project. Whatever its response, it is likely to retain its dominant hydrological role in the region. For these reasons, it is important to further characterize both the glacier's current form, flow dynamics, and mass balance characteristics and its likely response to future climate scenarios through complementary field and modelling studies.

2) Permanent Meteorological and Snowpack Stations in Headwater Basins

Two major limitations in this study were the sparse nature of available meteorological data and the lack of high-elevation monitoring sites in the headwater regions of the Yukon River Basin (where a significant portion of runoff is generated). Modelling efforts depend critically on establishing accurate precipitation and temperature gradients and on having high-quality data available for basin simulations. Extrapolations over large distances and elevation ranges, and across sharp climatic gradients, can introduce significant errors into hydrological models. Furthermore, it is likely that projected changes in climate will not occur uniformly across the region, which will increase the unreliability of low elevation climatic stations for representing conditions in more remote and/or high elevation parts of the basin. By constructing a network of automated weather and snowpack monitoring stations across the Yukon River Basin, baseline hydrometeorological conditions can be established, to which future climate variations can be compared. This will better prepare YEC for future changes in river discharge and help to ensure that future energy needs of Yukoners are met. Such a network of sites would also provide valuable information for tracking seasonal and inter-annual variations in SWE in different parts of the basin, and thereby provide improvements to the runoff forecasts. Suggestions for possible site locations include high elevation areas in the headwaters near to active WSC hydrometric gauges, (i.e., to maximize the utility of the data in runoff modelling analyses), or regions near or adjacent to glaciers, such as within the Fantail River Basin, or near the Llewellyn Glacier. Ideally, multiple stations could be set up at different elevations in close proximity to be able to accurately define both vertical and horizontal gradients in temperature and precipitation.

3) Further Investigation of Snow Processes and Hydrology

The results from this study have helped to shed light on the relative contributions to runoff from both glacier components, as well as seasonal snowmelt over glacierized and non-glacierized parts of the basin. In total, snowmelt from non-glacier areas accounts for ~44% of the annual runoff; when including glacier melt, this increases to 60% of annual runoff. Snowmelt thus represents the single most important component for sustaining runoff in this river basin. For this reason, the development of an accurate snow hydrology model should be considered a top priority in future basin-scale hydrological models. It is important to note that a large part of the uncertainty in the simulated future climate scenarios and runoff projections of this study is due to the fact that the model did not consider any processes from a physically based perspective. In regions such as the Yukon Territory, for which surface hydrology is dominated by cold region processes (such as rain and snow precipitation; snow and ice melt and sublimation; blowing snow transport; both snow-shrub tundra and snow-boreal forest canopy interactions; and infiltration to frozen soils), what is needed for accurate forecasting of melt runoff are physically based models of surface processes and energy balance. It is especially important to understand these processes and their changing response in the glaciated and high-snow accumulation headwater parts of the basin, where the highest specific runoff rates (mm per unit area) are derived. It is also noted here that changes to snowmelt hydrological processes are likely of prime importance to YEC during early spring and the transition from winter baseflow to the spring freshet. Potentially earlier melt onset and/or greater frequency of mid-winter snowmelt events may have the potential to move this period forward by up to several weeks or more on average, but this remains to be better elucidated by further modelling studies.

The suggested network of meteorological observation stations would be ideal to support such an initiative, by providing measurements of the key parameters that govern snow hydrology. Furthermore, the Wolf Creek Research Basin located near Whitehorse (http://www.taiga.net/wolfcreek/) (Pomeroy and Granger, 1999) has a long and valuable history of research on sub-arctic hydrology, and is another focal area that could be invested in for continuation of studies on snow processes, and for model development and testing. Its legacy of data collected over the past two decades is invaluable for basing hydrological models of the southern Yukon, and maintaining long-term observations at established research basins such as this is important for characterizing continuing climate and landcover change, and their associated hydrological effects. The suggested additional meteorological stations would provide a valuable complement to this existing research basin, and extend these studies and observations to the glaciated headwater region of the Yukon River.

4) Incorporation of Models with Regional Routing Procedures

A final suggestion to help YEC develop better forecasts and runoff projections is to link the suggested research and monitoring activities with hydrograph routing approaches, in order to represent the lateral transfer of runoff through the system of lakes to the gauge at Whitehorse. The U.S. Army Corps of Engineers routing program, HEC-ResSim (http://www.hec.usace.army.mil/software/hec-ressim/), for example, provides a useful tool that can be used to model reservoir operations for various goals and constraints, and has been previously applied in the Southern Lakes region of the Upper Yukon River Basin (NHC, 2008). Future initiatives for simulating runoff processes from local sites in the headwaters of the Yukon River Basin can be used towards producing inputs for a calibrated HEC-ResSim model, and thus result in improved hydrograph simulations at Whitehorse. The modelling in this study depended on calibrated parameters that did not truly represent the attenuation and transfer of flood waves through the Southern Lakes system, yet this is an important component for proper hydrograph prediction. Therefore, future efforts should focus on integration of these approaches to ensure the most robust simulations possible, and thereby be able to plan water management decisions based on improved forecasts.

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