APPENDIX 7E
GALORE CREEK PROJECT UBC WATERSHED MODELLING

Galore Creek Project

UBC Watershed Modelling

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Project #762-1

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1. INTRODUCTION

1. Introduction

This report outlines the set-up, calibration and application of UBC Watershed Models of Galore Creek and More Creek. The models were used to assist in the Hydrological Baseline Studies and the Environmental Impact Assessment for the Galore Creek Project.

The UBC Watershed Model (UBCWM) is a semi-distributed, deterministic hydrology model. The model was developed at the University of British Columbia by Prof. Michael Quick. Prof. Quick and his research team provided advice and input to all aspects of the model development for this study. The UBCWM was developed for the hydrological conditions found in British Columbia and compared to other common hydrological models it contains a more detailed and accurate representation of hydrology in mountainous and glaciated settings. The history of application of the model to mountainous regions within British Columbia and the inclusion of glacier processes made the UBCWM the most suitable model for use in the Galore Creek study area.

Galore Creek is located in north-western British Columbia within the coastal mountains. This region has complex hydrological processes, which are affected by regional precipitation gradients, influenced by topographic effects and impacted by the presence of large glaciers. Galore Creek and More Creek, the two watersheds considered in this study, both have almost 20% of their watershed areas covered by glaciers. The major challenge to the application of any hydrological model for watersheds in north-western British Columbia is the limited historical flow and meteorological data for this area of the Province. In order to try and overcome this limitation a comprehensive field monitoring program was undertaken for the Galore Creek Environmental Baseline Program (GCEBP) and this work provided an excellent data set to allow calibration of the models for the period 2004 – 2005. However, it should be noted that even with this data set a comprehensive calibration of the UBCWMs is not possible without additional data. This will limit the application of the models as forecasting tools, however, the level of calibration is sufficient to allow the models to be used to assist in understanding the hydrological processes in the study area and to undertake ‘what if’ scenario runs, assessing the impact of the development of the Galore Creek Project and the impact of climate change on the hydrology of the study area.

In detail this report will provide:

- brief description of the UBCWM;
- initial set-up of the UBCWMs of Galore Creek and More Creek;
- calibration of the UBCWMs; and
- scenario runs, including assessment of the impact of climate change and the Galore Creek development on the hydrological regime within the study area.

2. MODEL DESCRIPTION

2. Model Description

The UBCWM is a deterministic hydrologic model developed and maintained at the University of British Columbia (Quick, 1995). Using observed temperature and precipitation data, the program calculates watershed outflow resulting from rainfall, snowmelt and glacial melt. In addition to simulating stream discharge, the model also provides information on the accumulation and depletion of snowpack, soil moisture budget, soil and groundwater storage, contributions to runoff from various portions of the watershed, and surface and sub-surface components of runoff. The model has been used for watersheds ranging from a few square kilometers up to areas of several thousand square kilometers.

The model was initially designed for short term river flow forecasting at a daily or hourly resolution depending on the resolution of the meteorological input. However, if provided with continuous meteorological data the model can also be used for seasonal and/or multiple year simulations.

The UBCWM was primarily developed to describe and forecast streamflow in mountainous watersheds. Main features of the model incorporated specifically for use in mountainous areas include:

- characterization of the watershed based on up to 12 elevation bands. Each band is described by its area, mean elevation, amount and density of forest cover, imperviousness, and glaciated area;
- distribution of air temperature and precipitation data measured at one elevation to any other elevation;
- a snowmelt routine sensitive to the presence of vegetation and glaciers; and
- calculation of glacial melt from exposed portions (controlled by the depth and ablation rate of the snowpack) of any glaciers present in the watershed.

The division of a watershed into individual elevation bands allows runoff for each band to be calculated from precipitation and air temperature data unique to each band. This is extremely important in mountainous watersheds where orographic effects increase the amount of precipitation at higher elevations. The distribution of precipitation within the UBCWM is based on an exponential increase with elevation. Different gradients can be specified for low, middle, and high elevations within a watershed as the precipitation gradient generally decreases at higher elevations. For example, there is evidence that the most dramatic precipitation gradient occurs below an elevation corresponding to half the barrier height. Above this elevation, precipitation increases but at a lower rate until a level corresponding to two-thirds of the barrier height above which the precipitation gradient is dampened further.

Representing the temperature variation with elevation is also an important component of the UBCWM for use in mountainous watersheds as air temperature affects the precipitation gradient, the form of precipitation, as well as the timing and rate of snow and glacial melt. The use of temperature lapse rates (the rate that temperature decreases with increasing elevation) within the UBCWM allows for the consideration that a precipitation event may occur as rainfall at one elevation and snowfall at another.

The response of a watershed to rainfall, snowmelt or glacial melt inputs is controlled by a soil moisture deficit model. All inputs are separated into four runoff components dependant on the status of the soil moisture deficit of each elevation band. The four components can be considered as fast (overland flow), medium (interflow), slow (shallow groundwater), and very slow (deep groundwater) runoff.

Overland flow occurs only from the impervious fraction of each elevation band; however, the impervious fraction is a function of the soil moisture deficit such that the greatest imperviousness occurs when the soil is fully saturated. All inputs to the non-impervious fraction are applied to the soil moisture deficit of each band so that:

$$\text{Soil Moisture Deficit}_j = \text{Soil Moisture Deficit}_i - \text{Rainfall}_i - \text{Snowmelt}_i - \text{Glacial melt}_i + \text{Actual Evaporation}_i ,$$

where *i* and *j* represent consecutive time steps. Once the soil moisture deficit is satisfied, any excess inputs are applied first to the shallow and deep groundwater runoff components and finally to the interflow component. Although interflow is the final runoff component to receive inputs, it is generally the dominant component during large snowmelt and rainfall events. All runoff components end up being represented in the watershed outflow (including groundwater components), although after different delay periods.

A more detailed description of the UBCWM can be found in Quick, 1995.

3. MODEL SET-UP AND PARAMETERIZATION

3. Model Set-up and Parameterization

The description of a watershed and hydrologic processes in the UBCWM requires a number of input parameters and variables. Some of these parameters are physically measured in the field, others are based on previous model applications or taken from the literature, while others are calibrated to provide a best fit of the simulated to observed data.

Model set-up consisted of obtaining a complete set of measurable parameters and using these along with meteorological and hydrological data representative of the area to estimate initial values for parameters that would be adjusted during model calibration. Models were initially created of the entire Galore Creek and More Creek watersheds.

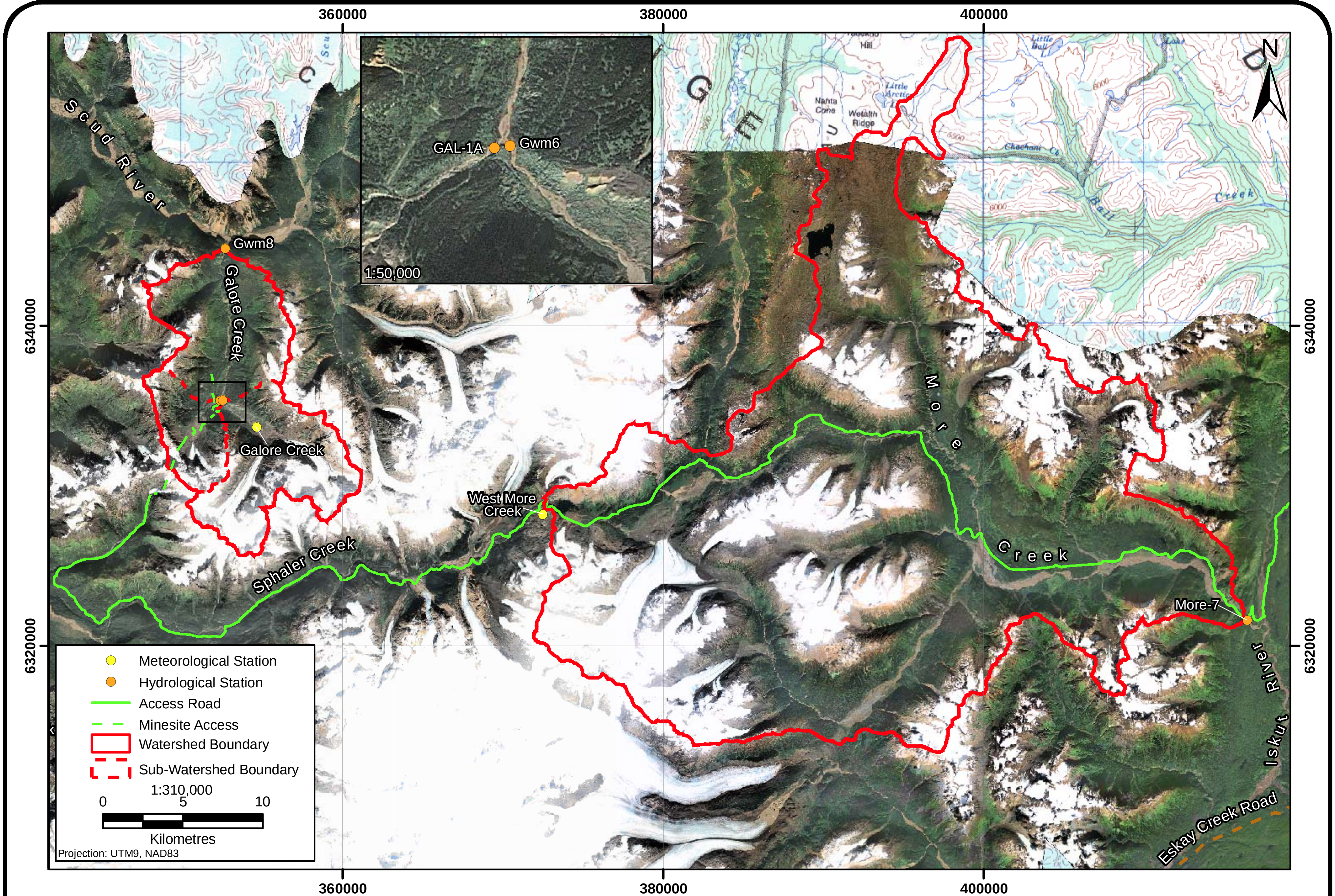
3.1 Hydrological Setting of Study Area

The Galore Creek Project is located within the coastal mountains of north-western British Columbia (Figure 3-1). The proposed mine site is situated at an elevation of 600 m within the Galore Creek watershed, a tributary of the Scud River. The majority of the proposed access road to the mine site follows the course of More Creek, a tributary of the Iskut River. Both the Iskut River and Scud River are tributaries of the Stikine River, one of the major river systems of British Columbia, which drains into the Pacific Ocean, near Wrangell, Alaska. The location of Galore Creek and More Creek are shown in Figure 3-1.

Plates 3-1 and 3-2 provide views of the watersheds and illustrate the physiography of the study area. Galore Creek and More Creek lie within steep mountainous watersheds. These are high energy environments, dominated by braided and gravel-bed rivers. A relatively large proportion of the watershed areas are covered by glaciers and permanent snow and ice patches. The watersheds are characterised by high runoff rates producing potentially high discharge rates and stream flow velocities.

A typical hydrological year for watersheds in the study area can be divided into three main flow periods:

- Winter (approx. November/December to April) – characterized by low to negligible stream flow, depending on the elevation of the stream and watershed area. Typically, flows are dominated by groundwater, but with higher flows occurring in response to snowmelt during warmer periods;
- Spring/Summer (approx. May to August) – characterized by high flows due to snowmelt. Flows rise in May at the onset of freshet. Peak flows can occur any time during June to August in response to snowmelt and/or rainfall events. Flows can begin to decrease in August as the remaining snow melts but during this period flows can be augmented by glacier melt water, producing diurnal variations in flow rates caused by the influence of daily air temperature fluctuations on glacier melting rates; and



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Watersheds and Sources of Hydrological and Meteorological Data for Galore Creek and More Creek UBCMW Models

FIGURE 3-1

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Plate 3-1 View of Galore Creek.

Plate 3-2 View of More Creek.

- Fall (approx. September to November/December) – characterized by generally moderate to low flows, but interrupted by rain-fed storm events. The most extreme flood events can occur during this period.

The study area lies in a transition zone between the very wet coastal region and the drier interior of British Columbia. The regional hydroclimate of north-western BC is dominated by weather systems generated from the Pacific Ocean, and is also strongly influenced by orographic effects caused by the local mountainous topography. This results in complex interactions between incoming weather systems and local topography that produce a high degree of spatial variability in snowfall and precipitation. Local topography also has an influence in controlling temperatures and the rate and timing of snowmelt. In addition, the presence of large glaciated areas can impact snowmelt rates and produce high runoff volumes during summer months.

3.2 Topographical Data

Digital 1:20 000 TRIM maps and 25 m DEMs available from the BC Integrated Land Management Bureau were used to supply the required topographical data of the study area. Based on this data, the watersheds were split into eight elevation bands as shown in Figures 3-2 and 3-3.

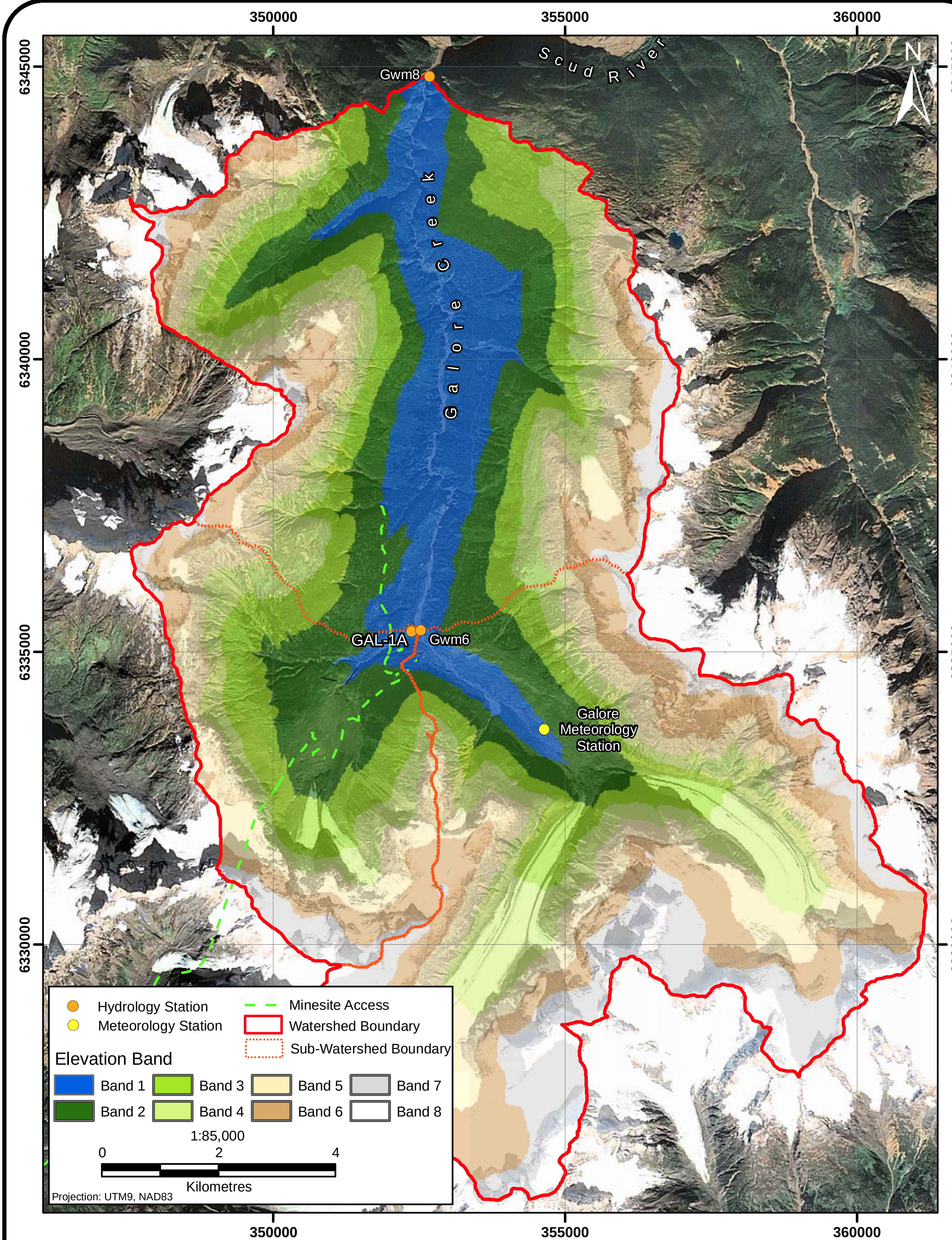
3.3 Land-use and Glacier Coverage

Along with topography, land-use data including vegetative and glacial coverage are also required to represent a watershed in the UBCWM. Vegetative cover data was obtained from the TRIM maps that had been ground-truthed during the GCEBP. Glacial cover data was obtained from delineations of high resolution IRS satellite imagery from the late 1990s. It is likely that there has been some glacial retreat from the time this data was originally produced. However, any glacial retreat that has occurred over the past 10 to 15 years is not expected to have a substantial impact on the model results.

3.4 Discharge Data

At the time of initial model set-up, hydrological data was available from a former Water Survey of Canada (WSC) station on More Creek but no data was available for Galore Creek. Therefore, the initial parameterization of parameters with uncertain values was based on the WSC More Creek hydrological data and regional meteorological data. More Creek and Galore Creek are hydrologically similar watersheds; consequently, the values obtained during initial parameterization of More Creek were also applied to Galore Creek.

Hydrologic data measured within the Galore Creek during 2004 and 2005 was used for model calibration.



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Elevation Bands within Galore Creek

FIGURE 3-2

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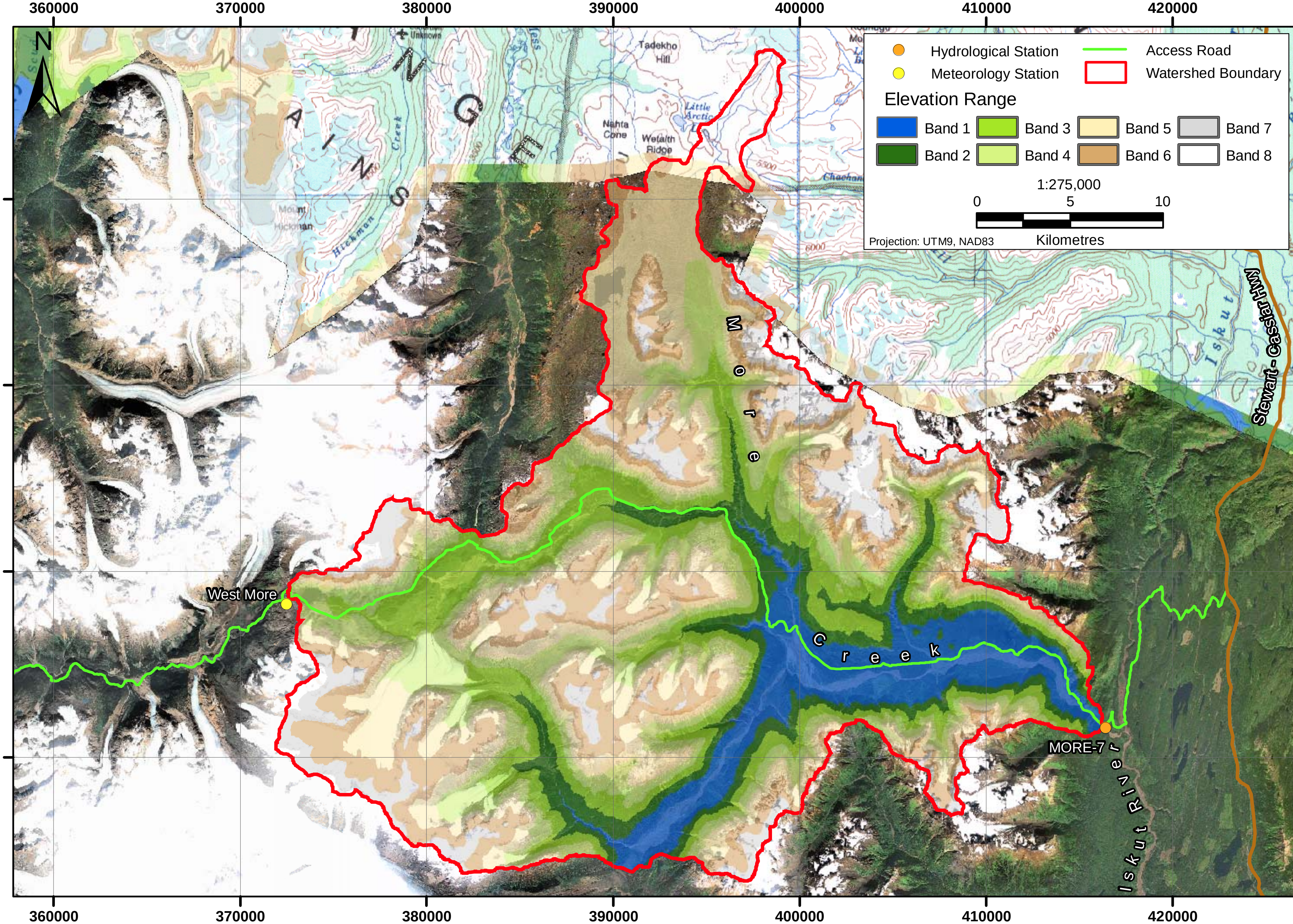

FIGURE 3-3

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Elevation Bands within More Creek

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3.5 Meteorological Data

In order to utilize the hydrological data available from the former WSC More Creek station, a meteorological time-series representative of the area and period of hydrological record was required. However, at the time of initial model set-up there was no on-site meteorological data available for either Galore Creek or More Creek. Therefore, data from the former Environment Canada – Meteorological Services of Canada (MSC) station at Bronson was used. The Bronson station was located approximately 56 km from Galore Creek.

Meteorological data measured at climate stations located within the Galore Creek and More Creek watersheds during 2004 and 2005 was used in model calibration.

3.6 Key Physical and Operational Parameters

Values of key physical parameters that measured in the field and used to characterize the watersheds are provided in Tables 3-1 and 3-2. A list of important operational parameters that were not measured in the field is summarized in Table 3-3.

Table 3-1
Key Physical Parameters of the Galore Creek UBCWM

Parameter	Elevation Band							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Elevation (m)	550 - 705	706 - 931	932 - 1148	1149 - 1367	1368 - 1587	1588 - 1798	1799 - 2020	2021 - 2240
Area (km^2)	12.0	21.2	20.8	22.2	25.1	22.6	14.3	3.3
Glaciated Area (km^2)	0	0.1	1.6	3.8	6.9	11.6	8.8	2.0
Forested Fraction (-)	0.26	0.35	0.25	0.07	0.01	0	0	0

Table 3-2
Key Physical Parameters of the More Creek UBCWM

Parameter	Elevation Band							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Elevation (m)	550 - 705	706 - 931	932 - 1148	1149 - 1367	1368 - 1587	1588 - 1798	1799 - 2020	2021 - 2240
Area (km^2)	43	70	134	161	198	159	77	12
Glaciated Area (km^2)	0	0	1.2	16.4	47.5	103.3	66.6	11.0
Forested Fraction (-)	0.64	0.64	0.55	0.23	0.02	0	0	0

Table 3-3
Important Operational Parameters

Parameter	Symbol	Reference/Source for Parameter Values
Impermeable fraction of elevation band	IMPF	Calibration / Prof. Quick
Albedo of very aged snowpack and glaciers	ALBD	Literature / Prof. Quick
Precipitation gradient factors for low, median, and high elevations	PPTG	Field measurements / Calibration
Elevations separating precipitation gradient zones	PPTZ	Literature / Prof. Quick
Groundwater percolation	GWPR	Calibration
Fraction of groundwater to deep storage	GWFD	Calibration
Rainfall and snowfall adjustment factors	PPTA	Calibration
Lag time for upper and deep groundwater discharge	GWLT	Calibration
Temperature lapse rates	TMPL	Literature / Prof. Quick

4. CALIBRATION

4. Calibration

Calibration of a distributed hydrological model can be a complex and difficult process. An important consideration during the calibration of a distributed or semi-distributed model is likelihood of equifinality, or the fact that given the number of parameters within the model different sets of calibrated parameters can result in equally acceptable model results (Beven, 2001). As a result the selection of the most appropriate set of model parameters is determined both by the quality of the fit of simulated flow against observed flow as well as an understanding of the actual processes within the study area.

The purpose of the models was to simulate the overall shape of flow hydrograph. Effort was put forth to reasonably simulate both high and low flow conditions. However, due to the fact that very limited data was available during low flow conditions, greater emphasis was placed on calibrating model performance during the open water season of May through September. Additionally, for the Galore Creek models, greater weight was put on calibration of Galore Creek as a whole than on the two headwater tributaries (Gwm6 and GAL-1A).

With limited observed data to compare to, it is difficult to quantitatively measure the goodness-of-fit of the models. Therefore, the goodness-of-fit during model calibration was based on visual comparison of the simulated and observed data. A main consideration was how well model results followed the observed shape of the annual hydrograph and monthly distribution of runoff. The models are not used to predict the absolute discharge from input precipitation data but rather to provide information on the change in flow regime resulting from “what if” scenarios. If future needs require the UBCWMs to be used in a forecasting manner, additional calibration will be required.

4.1 Sensitivity Analysis

Prior to performing the calibration a sensitivity analysis was done on key operational parameters of the Galore Creek UBCWM. Results from a sensitivity analysis can be useful in guiding the calibration process by indicating which parameters have the greatest influence on model output. It is expected that the UBCWMs of Galore Creek and More Creek would respond similarly to varying parameter values; therefore, results from the sensitivity analysis of the UBCWM of Galore Creek are assumed to represent the UBCWM of More Creek as well. Parameters listed in Table 3-3 were alternately increased and then decreased by 50% while keeping all other parameters constant. By comparing the resulting change in output from the initial model set-up, the relative influence of each parameter on the model can be seen. Results from the sensitivity analysis are presented in Figure 4-1.

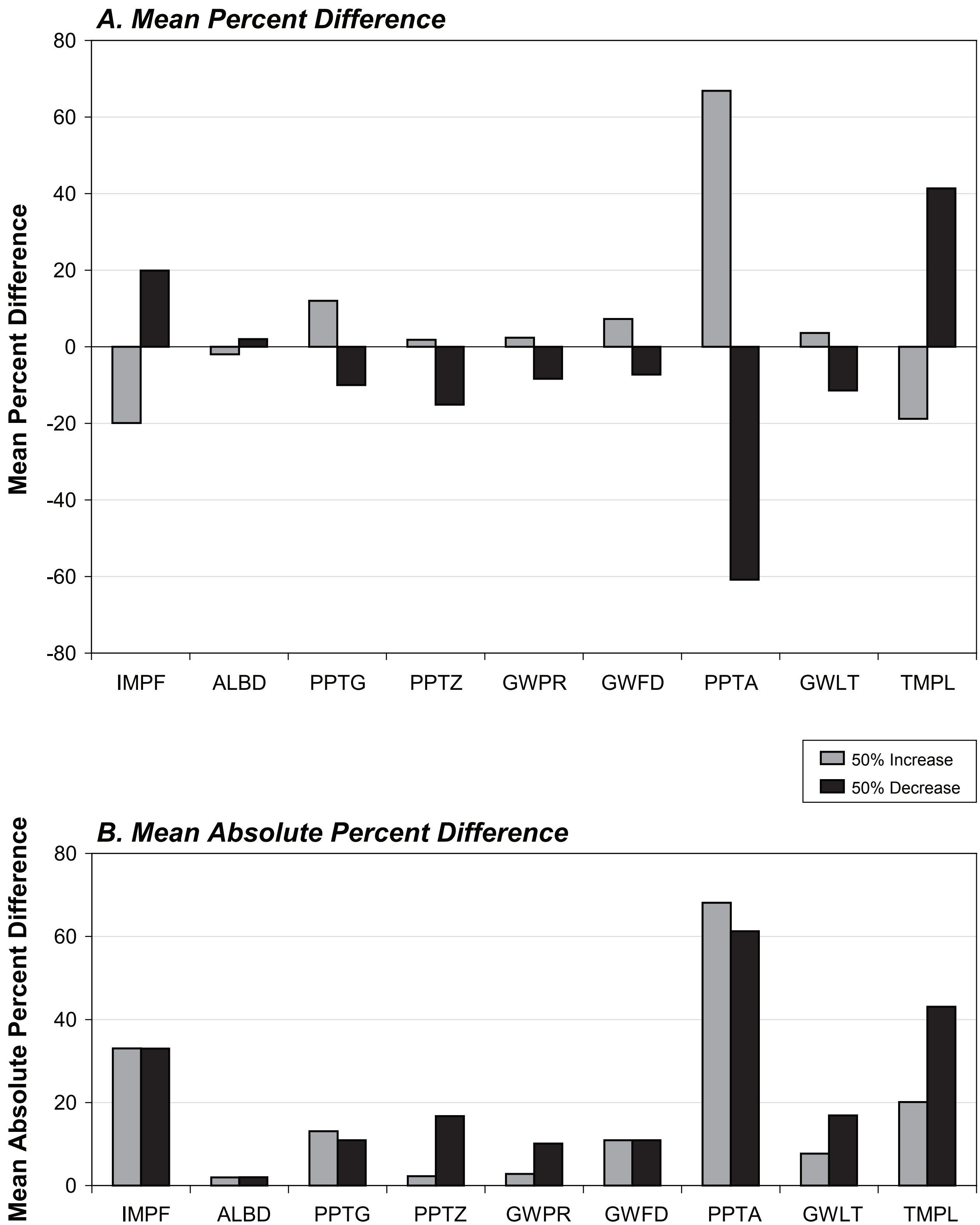

FIGURE 4-1

Results of the Sensitivity Analysis of the Galore Creek UBCWM

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The change in model output from the initial model set-up was calculated as the mean percent difference in daily discharge over the entire simulation period. These results are shown in Figure 4-1A. Because a change in some parameters, such as impermeable fraction of the elevation bands, resulted in relatively higher flows on some days and lower flows on other days, the mean percent difference underestimates the sensitivity of the model to such parameters. Therefore, the mean absolute percent difference was also calculated and presented in Figure 4-1B.

It can be seen that the model is most sensitive to the impermeable fraction of the elevation bands (IMPF), precipitation adjustment factors (PPTA), and temperature lapse rates (TMPL). The model output of total runoff is relatively less sensitive to groundwater parameters (GWPR, GWFD, and GWLT) as well as the albedo of very aged snowpack and glaciers (ALBD). Although the model is less sensitive to these parameters, they are important in controlling the contribution of the various runoff sources (rain, snowmelt, glacial melt, and groundwater) to total runoff, which is not necessarily reflected as change to total runoff.

4.2 Calibration Data

Hydrological and meteorological data from the GCEBP used to calibrate the models covered a 16 month period from the summer of 2004 through September, 2005. Hydrological data was collected at numerous locations in both watersheds, see Figure 3-1. Hydrological data could only be recorded during the open water period of May through September. Data considered in the calibration was taken from the hydrological stations that were of greatest interest and had the most reliable data sets; namely GAL-1A, Gwm6, and Gwm8. To take advantage of the fact that there were three locations within the Galore Creek watershed where hydrological data was available, models were created and calibrated for the two main headwater tributaries in addition to the model of the entire Galore Creek watershed. Meteorological data, including precipitation and maximum and minimum air temperature, was available from one station within the Galore Creek watershed and another within the More Creek watershed. This allowed for separate meteorological input to the More Creek UBCWM and the Galore Creek UBCWMs.

Although on-site data was available for the spring and summer of 2004, streamflow during this period is highly dependant on the snowpack accumulated during the previous fall and winter. Therefore it is necessary to have meteorological data for this period. To fill in this data gap, data was obtained from the MSC Unuk River - Eskay Creek climate station. This allowed the model to be initiated in 2004 which improved the performance of the model in the 2005 open-water season, but was not expected to greatly improve the model performance during the open-water season of 2004. Therefore, the calibration process focused on the open-water period from May through September of 2005.

4.3 Results

It was attempted to adjust as few parameters as possible from the initial set-up to arrive at the calibrated model. This is due to the fact that most parameters are either measurable, such as watershed area, or have default values that have been calibrated previously for hydrological conditions in British Columbia, see Section 3.6.

Final calibrated results are shown in Figures 4-2 and 4-3. A list of calibrated parameters is provided in Table 4-1.

Runoff simulated by the calibrated models of Galore Creek (Gwm8), the western headwater tributary of Galore Creek (GAL-1A) and More Creek compare well to the observed runoff data. The calibrated model of the eastern headwater tributary of Galore Creek (Gwm6) does not compare as well to the observed data as the other models. This may be due to unique features of the catchment that are not represented in the model or uncertainty in the observed data.

Data for calibration was only available for one complete year. The observed data is based on rating curves which were developed based on limited manual flow measurements due to the extreme environment of the study area. As a result, the rating curves and hence the observed discharge data has a degree of uncertainty ranging from 10 to 15%. Because of this, additional field data is required to facilitate improved calibration results.

Although the current UBCWM models will not be used to provide absolute stream flows for forecasting scenarios, the models do provide valuable insight into the hydrological process of the study area and can be used for “what if” scenarios. Therefore, the models should be used with caution but will be a useful tool for baseline and environmental impact assessment studies of the Galore Creek Project.

4.4 Summary

Hydrological watershed models were created for the entire Galore Creek and More Creek watersheds as well as two main headwater tributaries of Galore Creek using the UBCWM software. The models were initially set-up using observed hydrological data from the former More Creek WSC station along with regional climate data. A sensitivity analysis was conducted on the UBCWM of Galore Creek to aid in identification of key parameters to be involved in the calibration process. Hydrological and meteorological data collected during the GCEBP was used to calibrate the four UBCWMs. Runoff simulated by the calibrated models of Galore Creek as a whole, the western headwater tributary of Galore Creek and More Creek compared well to the observed runoff data. The calibrated model of the eastern headwater tributary of Galore Creek did not compare as well to the observed data as the other models. The current UCWMs should not be used for forecasting scenarios but will be a useful tool for baseline and environmental impact assessment studies of the Galore Creek Project.

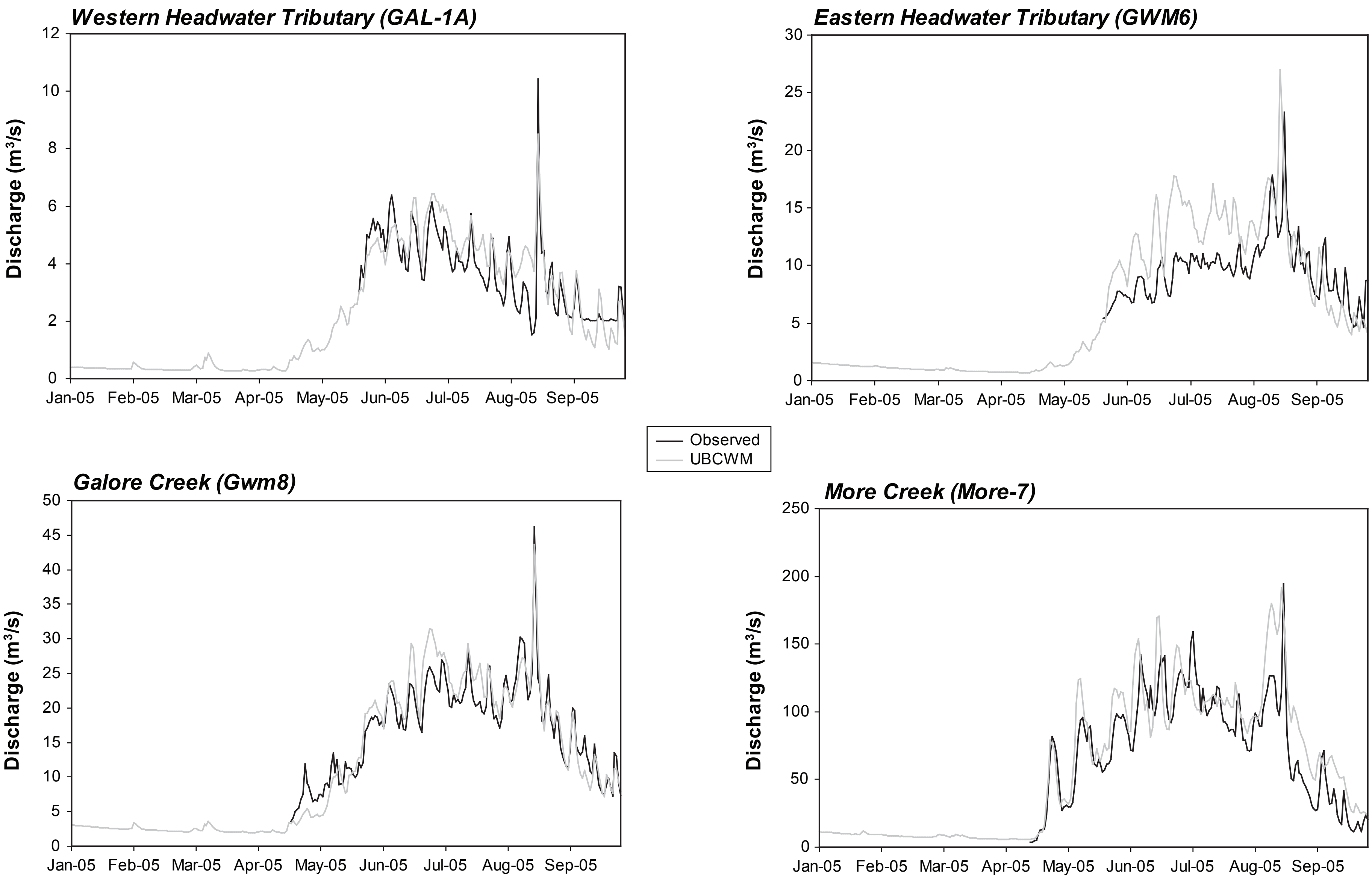

FIGURE 4-2

Simulated and Observed Hydrographs for Calibrated UBCWM Models of Galore Creek and More Creek

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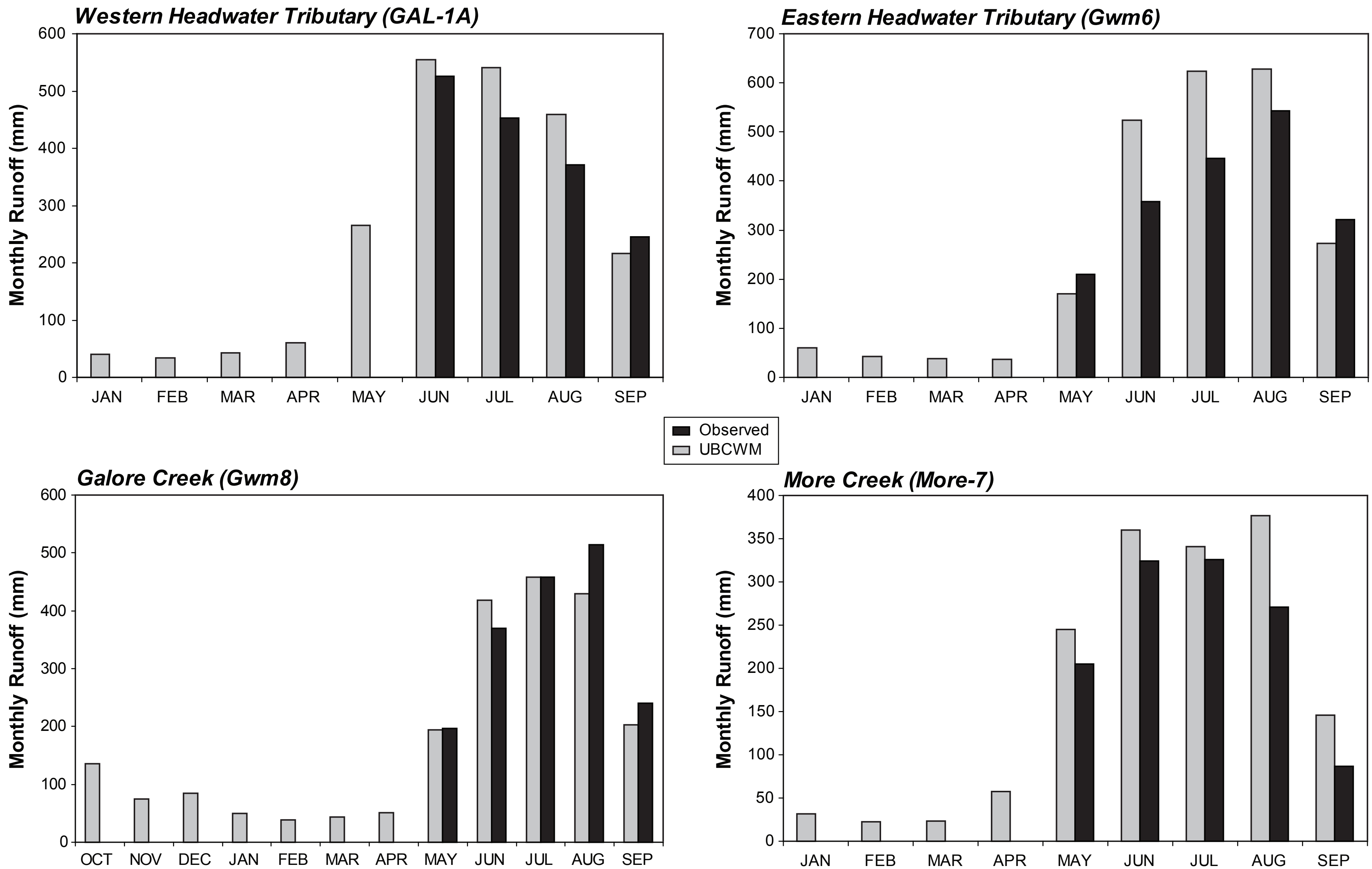

FIGURE 4-3

Simulated and Observed Monthly Runoff for Calibrated UBCWM Models of Galore Creek and More Creek

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Table 4-1
Calibrated Values for Important Operational Parameters

Parameter	Model			
	More Creek	**Gwm8**	**Gwm6**	**GAL-1A**
Impermeable fraction of elevation band	0.2 – 0.5	0.2 – 0.5	0.2 – 0.5	0.589 – 0.597
Albedo of very aged snowpack and glaciers	0.65	0.65	0.65	0.65
Precipitation gradient factors for low, median, and high elevations (% change per 100m)	7, 5, 3	7, 5, 3	7, 5, 3	7, 5, 3
Elevations separating precipitation gradient zones	1/2 maximum elevation of watershed, 2/3 maximum elevation of watershed	1/2 maximum elevation of watershed, 2/3 maximum elevation of watershed	1/2 maximum elevation of watershed, 2/3 maximum elevation of watershed	1/2 maximum elevation of watershed, 2/3 maximum elevation of watershed
Groundwater percolation (mm/day)	24.55	100	100	100
Fraction of groundwater to deep storage	0.646	0.546	0.1	0.546
Rainfall and snowfall adjustment factors	0, 0	0, -0.5	0, -0.5	0, 0
Lag time for upper and deep groundwater discharge (days)	46, 145	100, 1000	100, 1000	100, 1000
Temperature lapse rates[1] (^{o}C per 1000m)	0.0 – 11.0	0.0 – 11.0	0.0 – 11.0	0.0 – 11.0

1. The UBCWM uses different temperature lapse rates depending on elevation, occurrence of precipitation, and temperature metric (*i.e.* maximum or minimum temperature).

5. SCENARIO RUNS

5. Scenario Runs

The calibrated models were used for a number of investigations including:

- assessment of hydrological conditions in Galore Creek and More Creek;
- assessment of impact of climate change on hydrological response; and
- assessment of impact of mine development on hydrological response in Galore Creek and More Creek.

5.1 Breakdown of Annual Hydrograph Components

Output from the UBCWM includes the individual components that make-up the overall annual hydrograph such as rainfall runoff, snowmelt runoff, glacial melt runoff, and groundwater discharge. The comparison of the various components resulted in a much greater understanding of the key processes in the area than would have otherwise been attained. The breakdown of the annual hydrograph for each calibrated model is presented in Figure 5-1. Figure 5-2 presents each runoff component as a proportion of the simulated annual runoff and open-water season runoff for 2005.

As expected, snowmelt was the most dominant runoff component in both Galore Creek and More Creek during the 2005 open-water season as modeled by the UBCWM. Both watersheds receive high amounts of precipitation and due to relatively long winters, much of the annual precipitation is accumulated as snowpack until being released as snowmelt during the spring and summer.

Glacial melt becomes important towards the end of summer and early fall as glaciers within the watersheds become exposed from their snow cover. For 2005 in Galore Creek, simulated glacial melt remained relatively low as the snowpack was sufficient to last late into the summer. Between the two headwater tributaries, GAL-1A and Gwm6, glacial melt was proportionally less of the annual runoff in GAL-1A (2%) than Gwm6 (6%). This is consistent with the observations that Gwm6 is more glaciated than GAL-1A and that the sub-catchment of GAL-1A receives more snowfall, which would lead to glaciers remaining covered for longer periods of the summer and fall than in Gwm6.

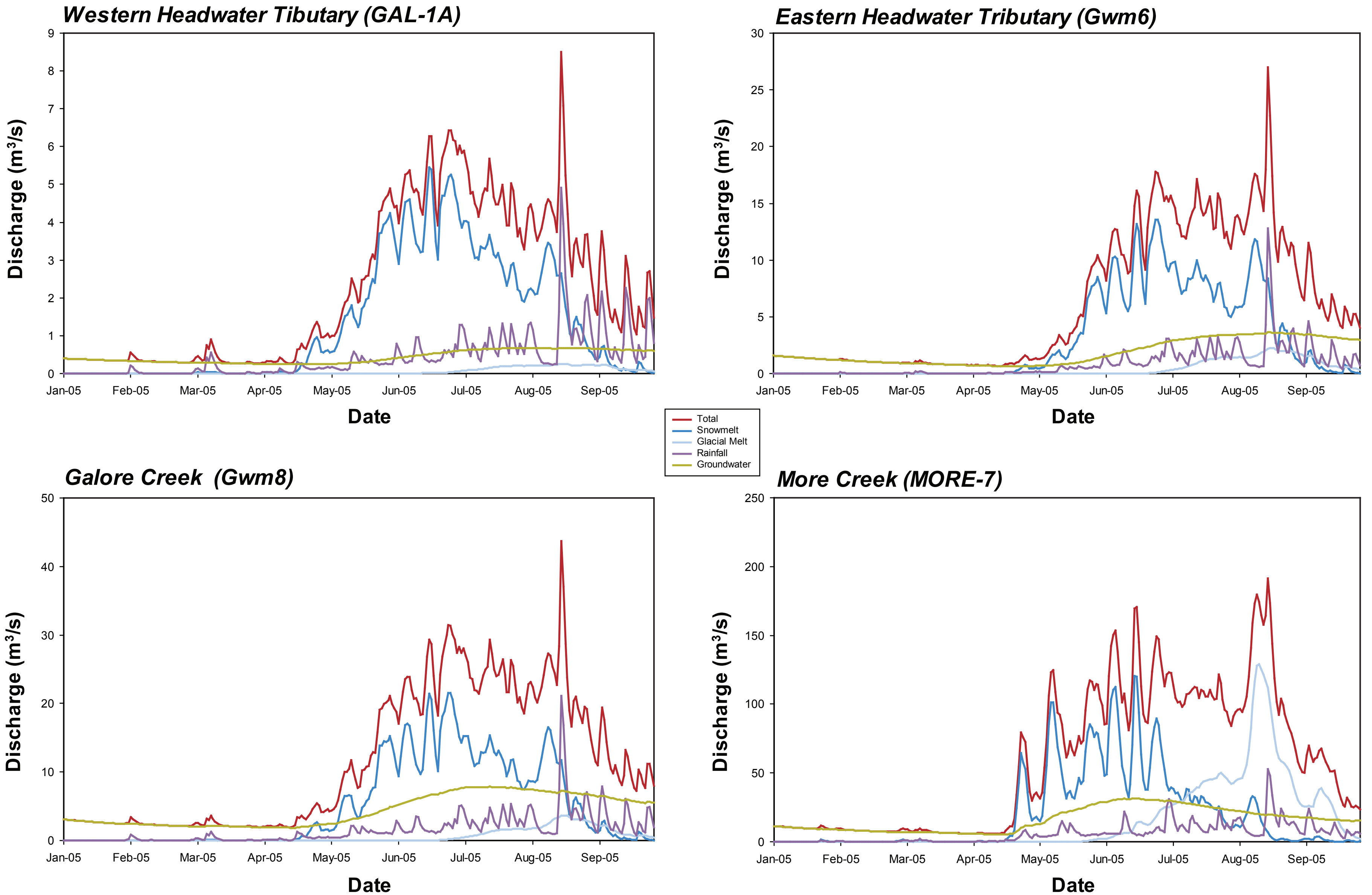

FIGURE 5-1

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Annual Hydrographs Simulated by the Calibrated UBCWM Models of Galore Creek and More Creek

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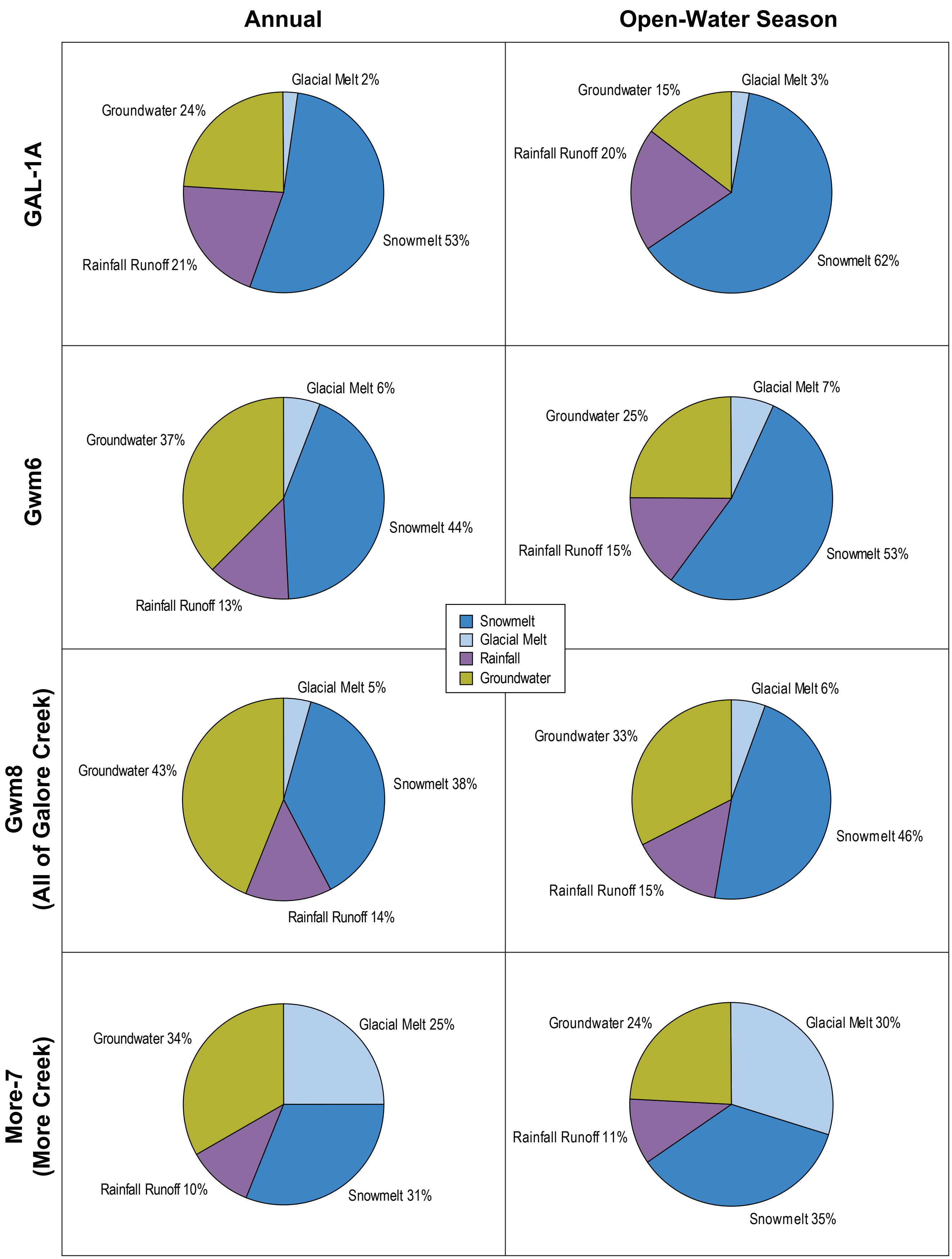

FIGURE 5-2

Proportional Contributions of Runoff Components

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For More Creek, the UBCWM simulated that glaciers within the watershed became exposed very early in the summer of 2005 and that glacial melt comprised 25% of the annual runoff. This is consistent with the fact that More Creek is more glaciated than Galore Creek, but may also be partially attributed to an artifact of the input data. The meteorological station used to provide input data for the More Creek UBCWM is located at an exposed, wind-swept site. This may have resulted in some undercatch in the precipitation measurements, which would have been greatest during snowfall events. A shallower simulated snowpack would result in earlier exposure of the glaciers and greater glacial melt. Nonetheless, whether the high amount of glacial melt is attributable to an under-estimate of the actual precipitation or not, the model results for More Creek illustrate the degree to which glacial melt can compensate for reduced snowmelt during dry years with little snowpack. This is an important conclusion, as it indicates that because Galore Creek and More Creek are substantially glaciated, annual runoff will not be affected as strongly by drier than normal precipitation years as non-glaciated watersheds..

The rainfall runoff component in both the Galore Creek and More Creek models remains relatively constant throughout the spring and summer of 2005 increasing in the late summer and early fall as a result of a few larger rainfall events.

Although snowmelt is the dominant modeled component during the open-water season, on an annual basis groundwater constituted substantial proportions of the annual runoff from GAL-1A and Gwm6 and comprised the greatest percentage of the total annual runoff at the mouth of Galore Creek and More Creek. This result must be viewed with caution though as the calibration procedure concentrated on the open-water season when the highest quality hydrological data was available. Calibration to improve model results during the open-water season may have been at the expense of poorer results during the winter baseflow season. This is difficult to asses as there is limited data on baseflow in Galore Creek. It is believed that in reality a portion of the total hydrological inputs to the Galore Creek surface hydrological system are lost to a deep groundwater system, which cannot be represented in the UBCWM models. It was attempted to represent a loss to the deep groundwater system during the open-water season by increasing the delay time groundwater experiences before appearing as watershed outflow. However, this resulted in greater groundwater discharge during the baseflow period than likely occurred in reality. This action was justified by the fact that it was more important to reasonably model the open-water season than the baseflow conditions.

5.2 Climate Change Scenarios

General circulation models (GCM) are the most commonly used tools to project climate trends and climate change into the future. GCMs simulate many climatologically significant processes as well as the interactions between the atmosphere, oceans, cryosphere, and land surface (Taylor and Barton, 2004). They model the change in climate parameters as a result of climate forcers such as changes in the atmospheric concentration of greenhouse gases and aerosols and calculate changes in the long-term average, or normal, of a given climate parameter (*i.e.* temperature and precipitation). However, GCMs cannot be used to directly predict effects on the hydrologic regime of an area resulting from the projected change in climate parameters, which may be an important consideration for any project or activity that is sensitive to changes in the hydrologic regime. Therefore, the UBCWM was linked to GCM output to investigate the impact that climate change may have on runoff from Galore Creek.

Climate change projections applied to the UBCWM of Galore Creek were taken from Appendix 2 of the *Surface Hydrology Assessment – Galore Creek Baseline Report* (Rescan, 2006). The data includes low, median, and high projections of the change in mean monthly maximum air temperature, minimum air temperature, and precipitation between the current baseline climate and the climate of the 2020s and 2050s. The range of projections applied to the Galore Creek UBCWM is shown in Table 5-1.

Table 5-1
Range of Climate Projections Applied to the UBCWM of Galore Creek

	2020s	2050s
Change in maximum temperature (^{o}C)	0 in January to 3.0 in May	-0.1 in March to 5.9 in December
Change in minimum temperature (^{o}C)	0.3 in February and March to 4.3 in January	0.1 in March to 6.5 in December
Change in precipitation (%)	-1.0 in June to 28.9 in February	0.4 in January to 35.4 in February

The projected changes in the climate variables were applied to the observed 2005 daily meteorological time-series using the delta method. The delta method involves applying the projected change of each climate parameter directly to the individual data points of the time-series. For example, the daily maximum temperature for every day of June in the original time-series was increased 3^{o}C to represent the high estimate climate change scenario for the 2020s. It should be noted that using the delta method to apply monthly GCM data to a daily time series results in a monthly percent increase in precipitation being applied uniformly to each day of that month. In reality it is more likely that the majority of the monthly increase would be accounted for in only a few events. This would result in an increase in the monthly total precipitation as well as an increase in the frequency of extreme precipitation events and high flood flows, which is not accounted for in the delta method.

In total, six climate change scenarios were applied to the UBCWM; low, median, and high scenarios for each of the 2020s and 2050s. The low scenario for each time period consisted of the low estimates for each of the climate parameters. The median and high scenarios for each time period were generated in the same manner.

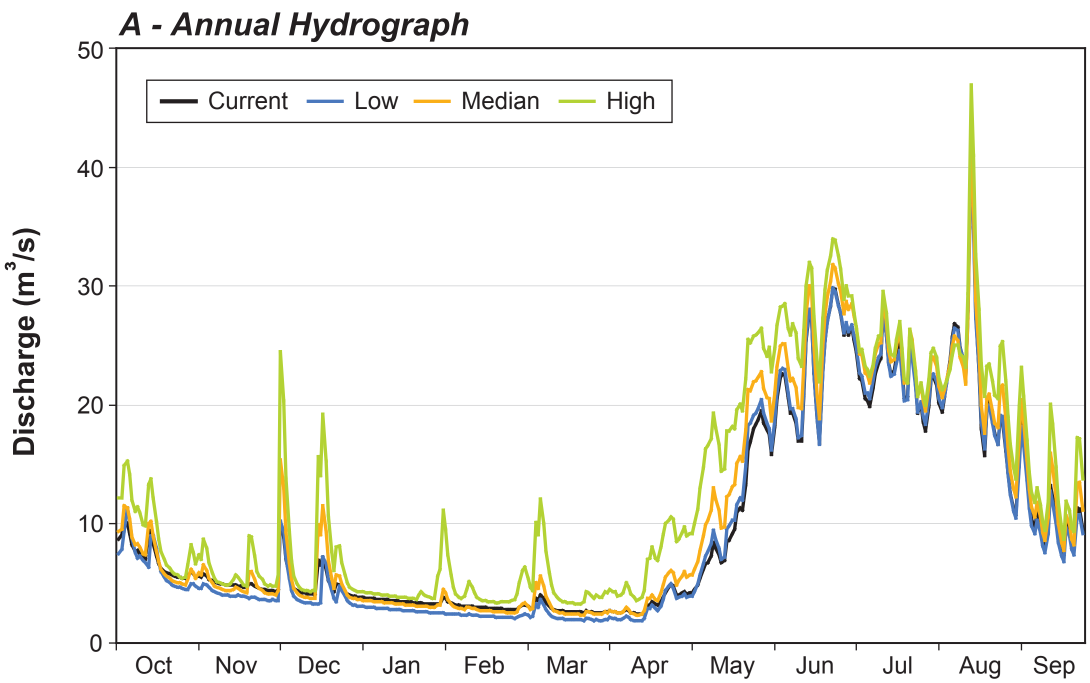
Issues relating to the climate change projections and their use in hydrologic models, such as climate projection uncertainty, output data resolution, and implications on hydrologically important watershed characteristics not considered in this modelling exercise are fully discussed in Appendix 2 of the *Surface Hydrology Assessment – Galore Creek Baseline Report* (Rescan, 2006).

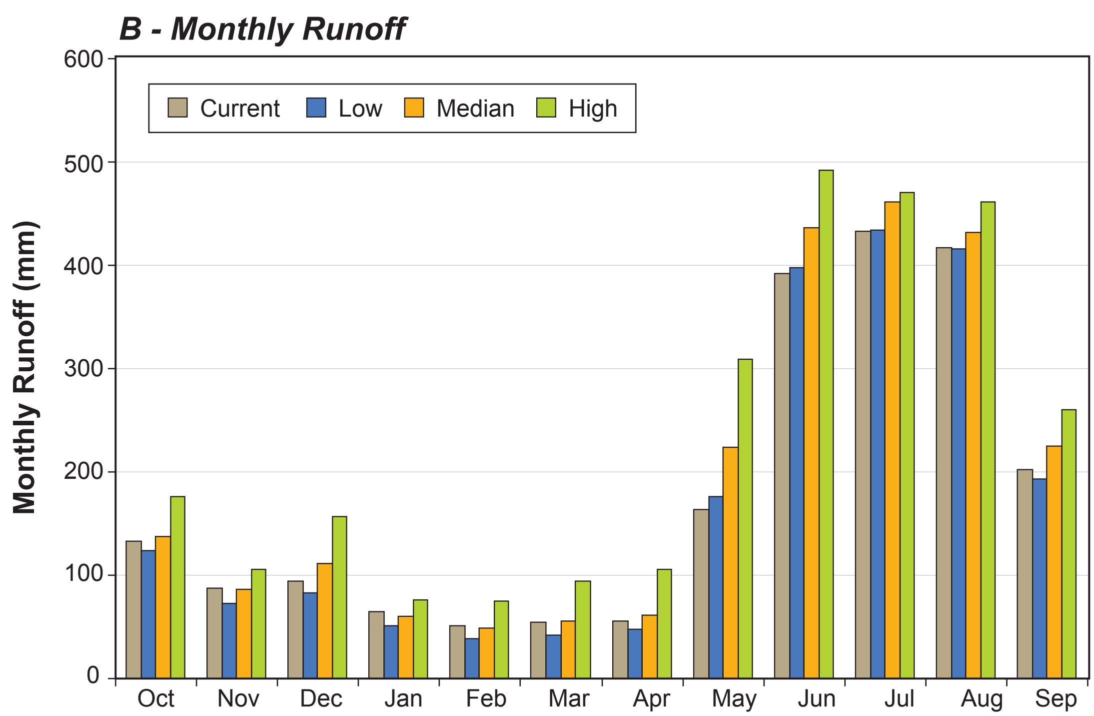
Due to the uncertainty in GCM output as well as the hydrologic modelling, the results are meant to provide an idea of how the future hydrology of the Galore Creek area may be affected by climate change. Furthermore, because the current climate data is based on a single year of observed data, the projected hydrographs are considered to be just one example of potential future flows near the proposed Galore Creek mine site, rather than an estimate of future average flows. The results of this investigation are presented in Figures 5-3 to 5-5 and summarized in the list below.

- Annual runoff is predicted to change by between - 4 and 29% in the 2020s and between 10 and 60% in the 2050s. The 4% decrease in runoff predicted for the 2020s using the low climate projections is due to many months of the projected climate data having less precipitation than the baseline climate.
- Proportionately, the largest increases in runoff will be experienced during the winter and early spring due to warmer air temperatures causing a greater percentage of precipitation to fall as rain rather than snow and earlier melting of the snowpack.
- Although a smaller percentage of precipitation will fall as snowfall, the projected increase in total precipitation increases runoff during late spring and summer but to a relatively lesser degree than winter and early spring runoff. It must be kept in mind that a change in glacial cover between the current and future conditions was not taken into account. If the current trend of receding glaciers in the Galore Creek watershed continues into the future, the modeled data for the two future time slices includes an over-estimate of the glacial melt contributing to spring and summer runoff.
- Progressing from low to high scenarios and from the 2020s to the 2050s time slices, the annual hydrographs exhibit broader and flatter freshet periods.
- As air temperatures increase, the period of the year that experiences large runoff events due to extreme rainfall will become longer, extending later into the fall and winter. Under current conditions large precipitation events during the winter occur mainly as snowfall and therefore do not immediately generate high runoff events.

Larger rainfall events produce larger runoff events. However, as discussed previously, the method used to adjust current climate data by climate change projections does not consider an associated increase in the frequency of extreme rainfall events. Therefore, it is believed that in reality the projected climate change would result in higher flood flows for extreme rainfall events than simulated in this study.

The results from the current study are generally consistent with results from other studies linking GCM output for British Columbian watersheds to deterministic hydrological models.





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Low, Median and High Projections of the Annual Hydrograph and Monthly Runoff from Galore Creek in the 2020s

FIGURE 5-3

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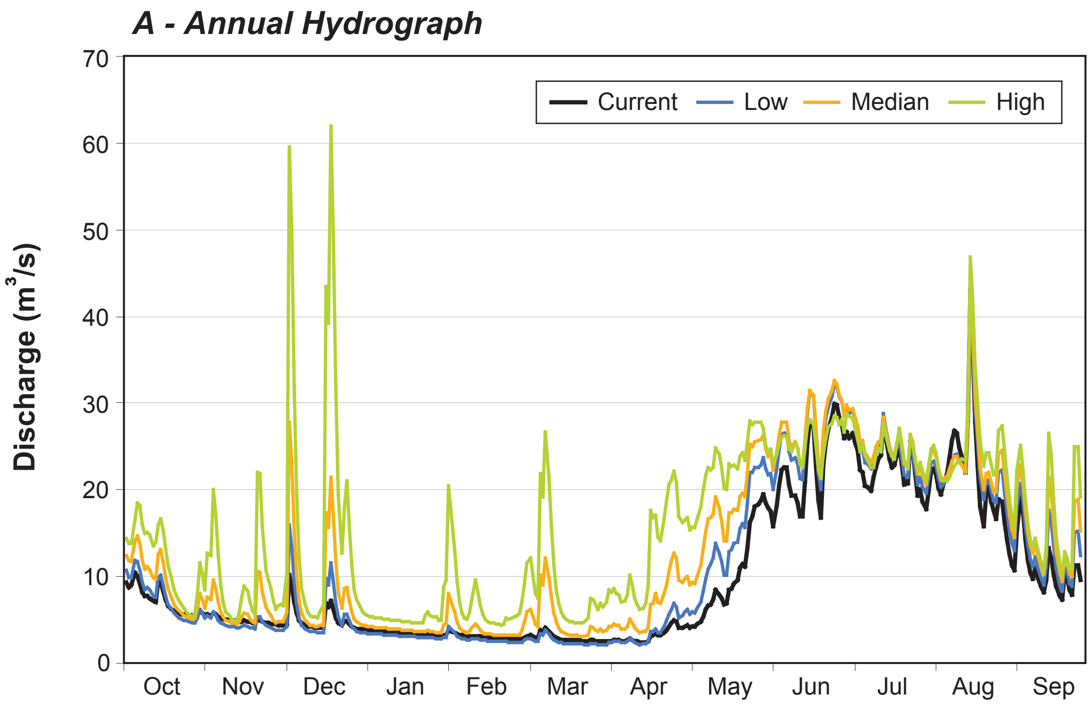

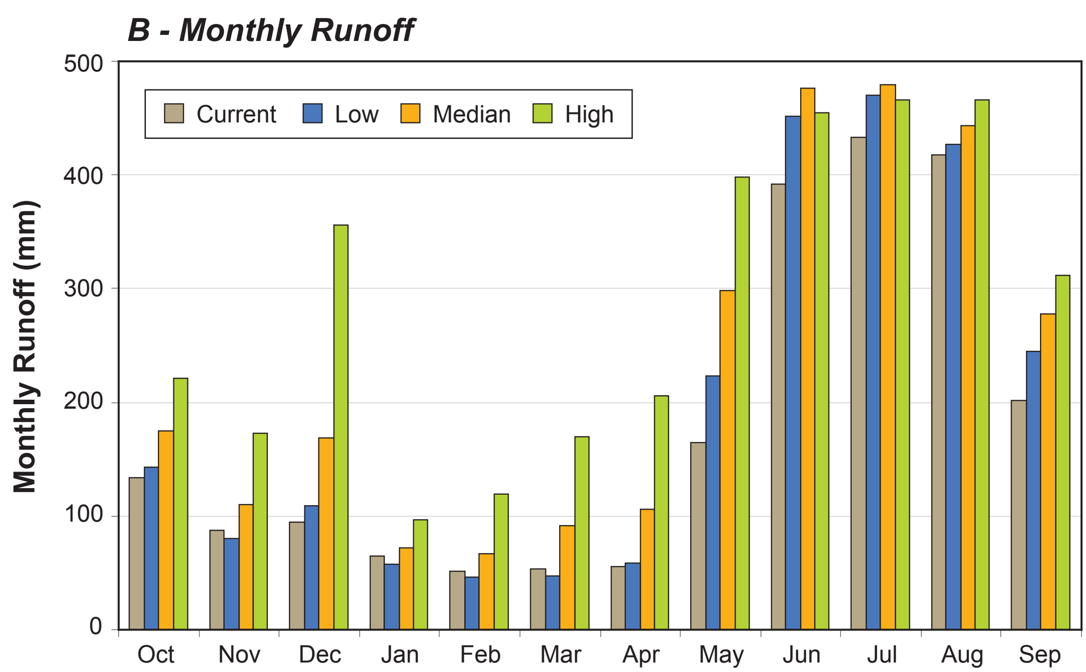

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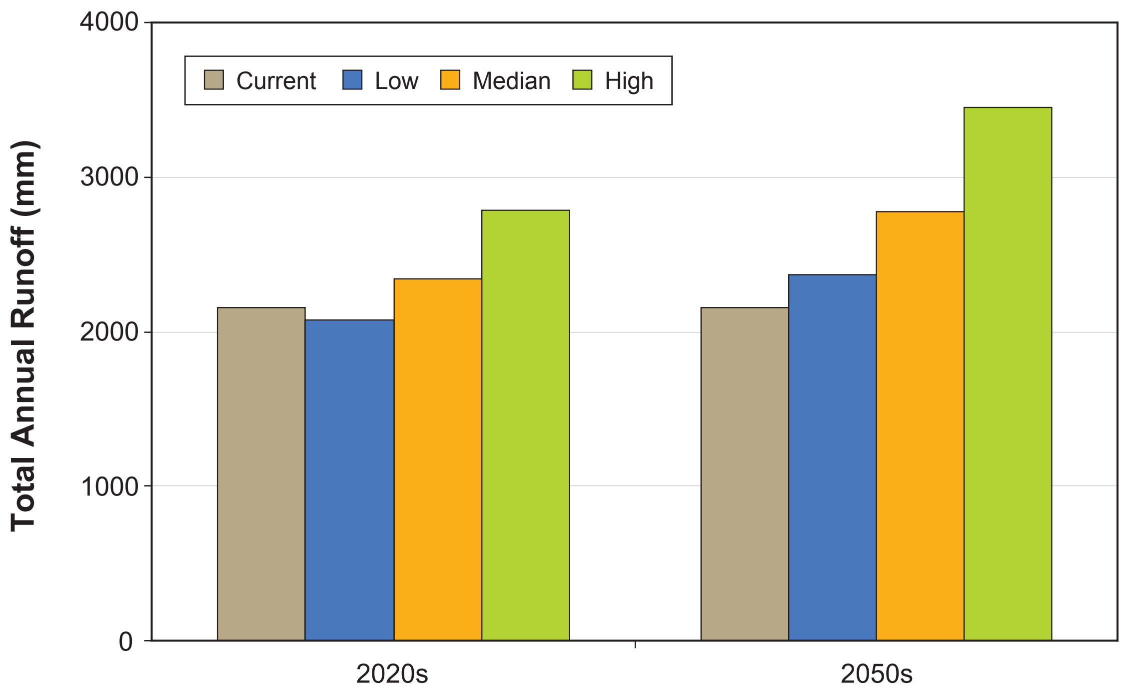
Low, Median and High Projections of the Annual Hydrograph and Monthly Runoff from Galore Creek in the 2050s

FIGURE 5-4

Rescan™



Modeled Projections of the Total Annual Runoff from Galore Creek for the 2020s and 2050s

FIGURE 5-5

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Loukas *et al*., (2002) applied climate projections generated by a GCM based on conditions of twice the current atmospheric CO_2 concentrations to deterministic hydrologic models of two British Columbian watersheds, the Illecillewaet and Upper Campbell basins. In both watersheds, GCM projections are for increased annual precipitation, however due to warmer temperatures the annual snowfall in both watersheds is projected to decrease, less so for the interior and partially glaciated Illecillewaet basin. The annual hydrographs in both basins are projected to exhibit peak flows one month earlier, with higher flows in fall, winter, and spring and decreased flows during the summer.

Coulson (1997) also applied climate projections generated by a GCM and double the current atmospheric CO_2 condition to hydrologic models of a number of watersheds in BC and the Yukon. Runoff increased under the projected climate in all watersheds, with the increase mainly occurring during the winter and spring. For watersheds in Northern British Columbia and the Yukon, summer runoff also exhibited a slight increase; watersheds in Southern British Columbia showed a slight decrease in summer flows.

5.3 Post-Development Scenarios

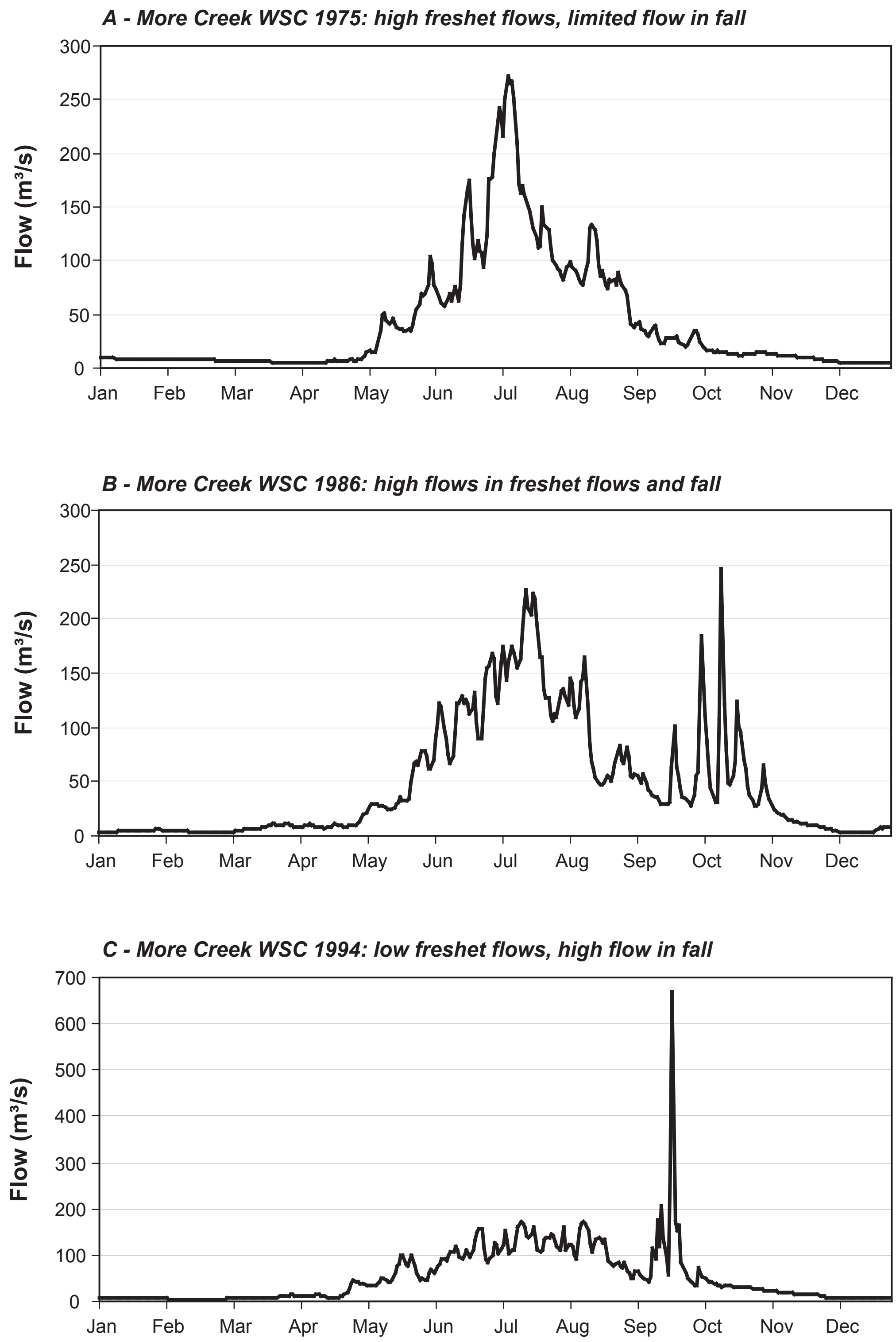
5.3.1 More Creek

Project infrastructure that could affect the hydrology of More Creek are the access road, power transmission line, and pipeline.

Along the road route all crossings have been designed to accommodate the 1 in 100 year (Q_{100}) or 1 in 200 year (Q_{200}) flood.

The UBCWM is a useful tool to forecast the impact that alteration of watershed conditions may have on daily and annual runoff. The UBCWM of More Creek was used for this purpose to examine the effects of forest clearing required for the access road and power transmission line corridor through the More Creek watershed.

To increase the diversity of flow conditions simulated in the post-development forecast scenario, 3 years of regional meteorological data were appended to the single year of observed baseline data. The years that regional data was taken from were 1975, 1986, and 1994. These years were specifically chosen because they represented a range of annual hydrographs in the former WSC More Creek hydrological station data series, as can be seen in Figure 5-6. However, there is no meteorological data for the area over the same time periods. Therefore, meteorological data was considered from a number of regional climate stations. Combinations of temperature and precipitation data from different regional stations were used as input to the More Creek UBCWM to see if the general hydrographs shown in Figure 5-6 could be simulated. The combination of regional data that generated annual hydrographs most similar in shape to the 1975, 1986, and 1994 hydrographs from the WSC More Creek data are listed in Table 5-2.



Annual Hydrographs for More Creek WSC Station showing Range of Hydrological Processes

FIGURE 5-6

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Table 5-2
Source of Climate Data Used to Generate Extended Meteorological Time-Series for More Creek UBCWM

Year	Maximum and Minimum Air Temperature	Precipitation
1975	Dease Lake	Stewart
1986	Stewart	Stewart
1994	Dease Lake	Unuk River - Eskay Creek

Forest clearing was represented in the calibrated More Creek UBCWM by reducing the conifer cover within More Creek by 410 ha, which is estimated to be the approximate amount of forest clearing required for the access corridor.

The post-development model and calibrated model were both run with the same 4-year time-series of meteorological input. The time-series consists of one year of observed baseline data and three years constructed from regional data sets as described above. The results are shown in Tables 5-3 and 5-4.

All measures of the modeled difference between pre- and post-development scenarios are less than 1 %. The largest differences in daily discharge at the mouth of More Creek occurred during early snowmelt events and the largest differences in monthly flows occurred during the freshet months from April through July. Additionally, the year most dominated by snowmelt also exhibited the greatest difference in all measures. This is due to snow melting sooner in un-forested areas than in forested areas. This also results in slightly lower summer and fall flows due to the available snowpack being exhausted earlier in the year. These results suggest that the clearing of vegetation for the access road and power transmission line corridor will mainly affect snow-related processes within the watershed. It must be noted that these results are based on an example 4-year time-series of data and only provide an indication of the degree that vegetative clearing may have on the discharge of More Creek.

Table 5-3
Effect of Vegetation Clearing on Hydrology of More Creek

Measure	Value
Mean absolute difference in daily discharge at the mouth of More Creek	0.23 m^3/s
Percent difference in mean annual flow	+0.3 %
Percent difference in magnitude of annual peak flow	+0.3 %
Difference in timing of annual peak flow	None
Percent absolute difference in minimum daily discharge	0.1 %

Table 5-4
Effect of Vegetation Clearing on
Monthly Flows at the Mouth of More Creek

Month	Difference in mean flow (%)	Month	Difference in mean flow (%)
January	+0.04	July	+0.37
February	+0.05	August	-0.09
March	+0.01	September	-0.07
April	+0.32	October	-0.01
May	+0.65	November	-0.03
June	+0.75	December	-0.02

5.3.2 Galore Creek

The Galore Valley will experience the greatest effects due to the Galore Creek Project. The baseline drainage pathways will be completely altered by the presence of open mine pits; freshwater, waste rock, and tailings impoundments; as well as multiple diversion channels. This will result in the alteration of baseline sub-catchments within the watershed. The UBCWM was used to simulate runoff based on the anticipated post-development sub-catchments. All operational parameters from the calibrated Galore Creek models were used to create UBCWMs for each post-development sub-catchment shown in Figure 5-7. These models were then used to:

- illustrate how the annual hydrograph at the mouth of Galore Creek may be affected by the Project under a variety of meteorological and operational conditions;
- provide simulated runoff data from the Q_{200} for each sub-catchment to be used as input for a hydraulic model of the East Diversion Channel; and
- provide simulated annual runoff data for each sub-catchment to be used as input for a hydraulic model of the post-closure tailings pond.

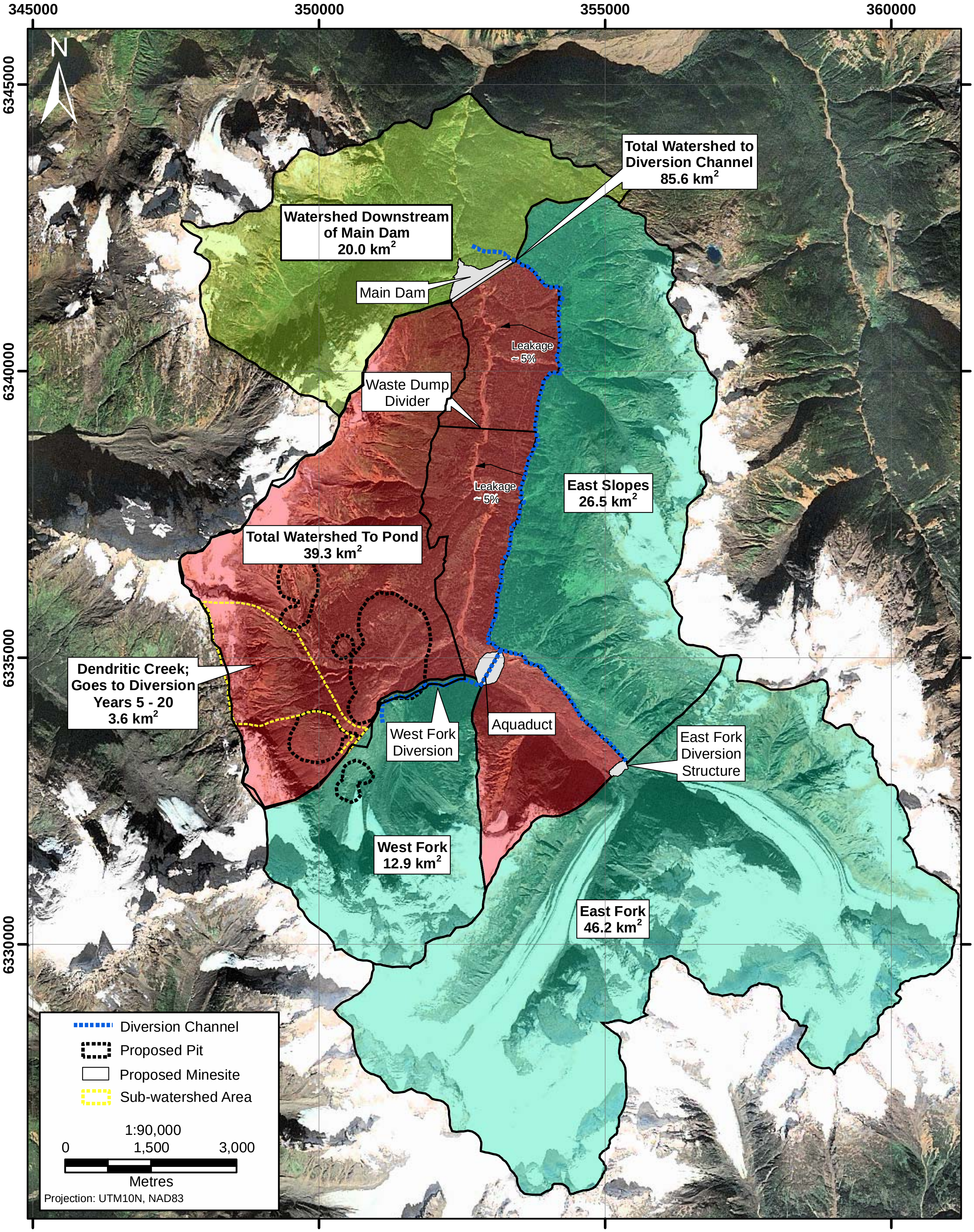

FIGURE 5-7

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Minesite Drainage Areas, Year 2 to 20

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5.3.2.1 Post-Development Annual Hydrographs

To illustrate the effect the Project may have on the annual hydrograph, the un-affected and diverted areas of the Galore Creek watershed were simulated using the UBCWM and then summed with the scheduled releases from the Main Dam. The synthetic four-year meteorological time-series described in Section 5.3.1 was also used for this simulation to allow the representation of a range of meteorological conditions.

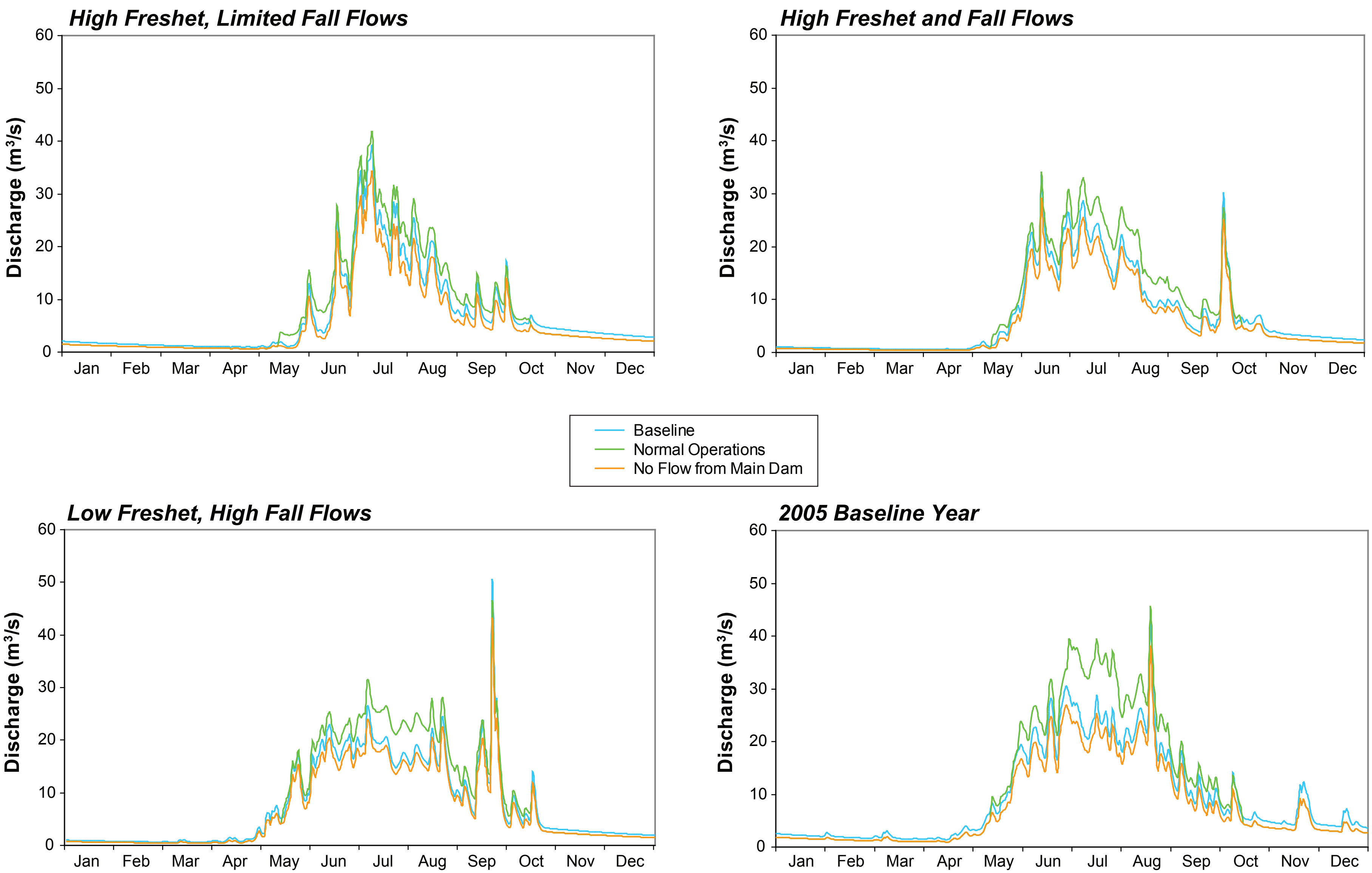
Based on the synthetic time-series the simulated annual runoff for three of the four years in the time series were relatively similar, ranging from 1480 to 1670 mm. The simulated runoff from the fourth year of the meteorological time series was 2070 mm. For the three drier years, the pumping scheme from the Main Dam for the 1 in 200 dry conditions was added to the simulated runoff from the un-affected and diverted areas of the Galore Creek watershed to provide total flows at the mouth of Galore Creek. For the wetter year, the pumping scheme for a year of average conditions was added to the simulated runoff from the un-affected and diverted areas of the Galore Creek watershed to provide total flows at the mouth of Galore Creek. The average monthly pumping rates from the Main Dam for 1 in 200 dry conditions and average conditions are presented in Table 5-5. The operating condition for the case of no water being discharged from the Main Dam due to operational or water quality issues was also modeled.

Table 5-5
Mean Monthly Pumping Rates from the Main Dam
Under Normal Operating Conditions

Condition	Annual Runoff (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 in 200 Dry	1500	0	0	0	0	1.3[1]	5.0	7.5	6.6	3.6	1.1[1]	0	0
Average	2340	0	0	0	0	1.5[1]	7.0	14.0	8.2	4.3	1.2[1]	0	0

1: Pumping only occurs during second half of the month for May and first half of the month for October.

The results from this modelling exercise are presented in Figure 5-8. It can be seen that for normal operating conditions discharge at the mouth of Galore Creek would be lower than the baseline conditions over the winter, when there is no pumped discharge from the Main Dam, as well as during very high precipitation driven runoff events. This is because the storage in the Main Dam at any time is likely much greater than the runoff produced from the catchment area upstream of the Main Dam would be. Therefore, the storm runoff would be captured by the Main Dam and be replaced by pumped discharge. During the spring and summer, discharge at the mouth of Galore Creek is expected to be higher than baseline conditions as the pumped discharge from the Main Dam will have to be greater, for at least a portion of the summer, than the inflow to the Tailings and Waste Rock Storage Facility to rid the water accumulated over winter.



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Effects of Galore Creek Project on the Annual Hydrograph at the Mouth of Galore Creek

FIGURE 5-8

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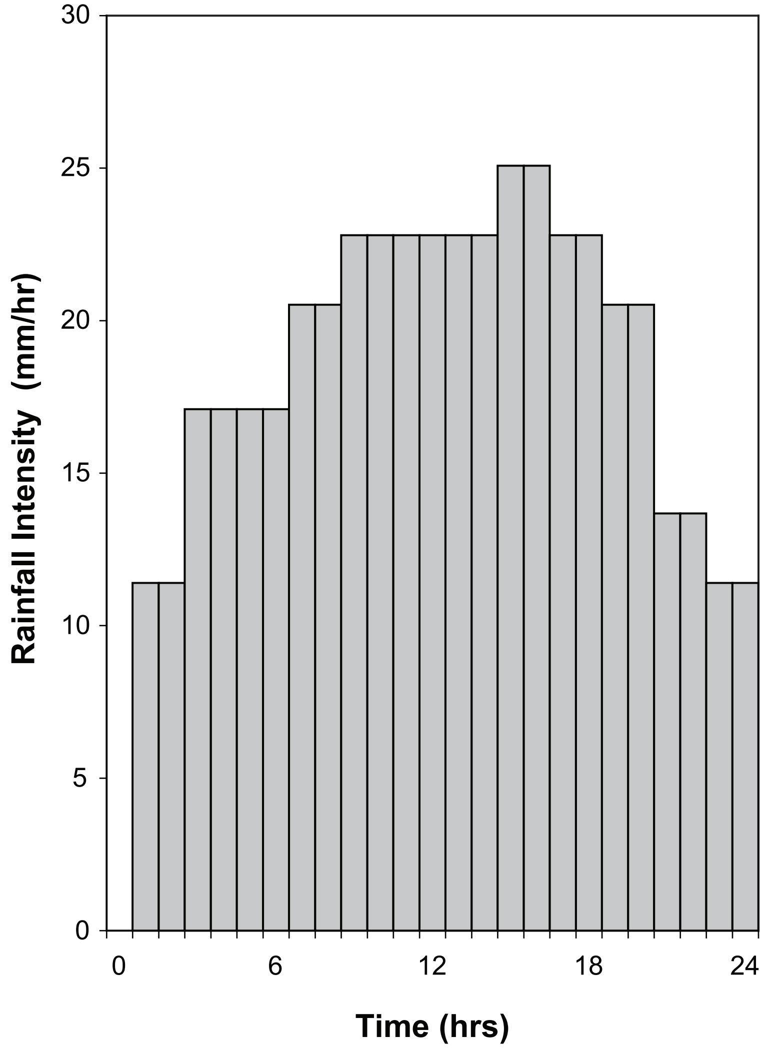
5.3.2.2 Simulation of the Q_{200}

One of the hydrological valued ecosystem components identified for Galore Creek as part of the EIA process is the magnitude and timing of peak flows. Of specific interest are the effects of retaining runoff from the tailings containment facility catchment behind the Main Dam as well as the conveyance of flood flows along the East Diversion Channel, which will be wider with a lower gradient than the natural channel. To examine these effects, runoff from individual sub-catchments within Galore Creek simulated by the UBCWM was used as input to a hydraulic routing model (HEC-HMS). A separate routing model had to be used as the UBCWM does not have a surface-routing component. The routing exercise is described in Section 7.5 of the EIA and will not be discussed here.

Due to the fact that many of the Project components and operations within the Galore Valley have been designed to the Q_{200}, this was chosen as the flood event to model. Based on a regional analysis, the Q_{200} for Galore Creek is estimated to be approximately 350 m^3/s. To obtain a precipitation event that would result in the Q_{200} at the mouth of Galore Creek, a 24 hr storm was incrementally increased until the simulated discharge from the UBCWM of the baseline Galore Creek conditions reached a peak equal to the estimated Q_{200}. The storm was given a temporal distribution the same as the 50% time distribution curve described by Loukas and Quick (1995) for coastal BC storms. The resulting hyetograph is shown in Figure 5-9. The storm was modeled as a rainfall runoff event occurring in early October, 2005. October 2005 baseline air temperature data was used and initial watershed conditions such as snowpack and soil moisture deficit were set based on a model run using the same meteorological data used in model calibration, which extended to the end of September, 2005. This period of the year was chosen as it is when the majority of annual peak flows occur in the area.

For the event simulation, the UBCWM was run at an hourly time-step, the finest temporal resolution possible in the model. The resulting pre-development hydrograph at the mouth of Galore Creek as well as from the individual sub-catchments are shown in Figure 5-10. Post-development and closure hydrographs for the same event are discussed and presented in Section 7.8 of the Galore Creek Project Environmental Impact Assessment.

It is interesting to note the total 24 hr rainfall depth that was found to cause the Q_{200} was 460 mm. This is approximately 150% greater than the estimated 1 in 100 year 24 hr precipitation event (Rescan, 2005). This is a large degree of relative increase considering the Q_{200} is approximately 20% greater than the Q_{100}. This may indicate that flow events in Galore Creek with very high return periods, such as the Q_{200}, may be caused by rain-on-snow events rather than rain-only events.



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Hydrograph Used to Generate Q_{200} at the Month of Galore Creek

FIGURE 5-9

Rescan™

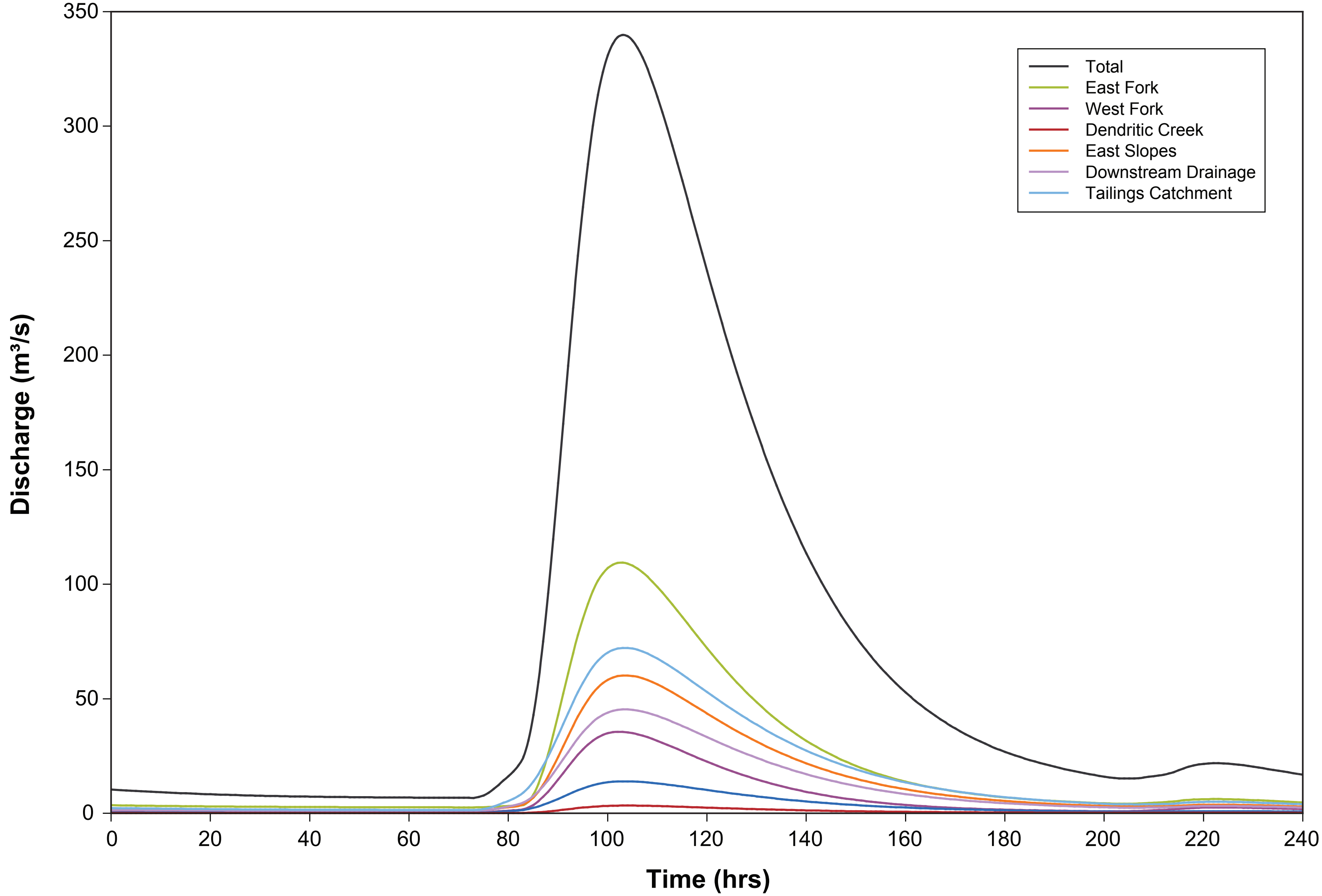

FIGURE 5-10

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Pre-Development Q_{200} Hydrograph for Galore Creek

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5.3.2.3 Post – Closure Runoff

Upon closure the Tailings Containment Facility will be permanently flooded and all runoff upstream of the Main Dam will drain into the resulting tailings pond. Although this will have little effect on mean annual or monthly flows, the tailings pond will affect the timing and shape of the hydrograph at the mouth of Galore Creek during individual runoff events. Following the procedure described in Section 5.3.2.2, the UBCWM was used to simulate runoff from all the sub-catchments of the Galore Creek watershed for the Q_{200}. This output was then used as input to a hydraulic model of the post-closure tailings pond. Results of the hydraulic model are presented and discussed in Section 7.5 of the Environmental Impact Assessment for the Galore Creek Project.

6. SUMMARY

6. Summary

The UBCWM is a deterministic hydrological model applicable for mountainous watersheds. The model uses observed meteorological inputs to simulate stream flow, snow pack accumulation, and individual components of total runoff such as rainfall runoff, snowmelt, glacial melt and groundwater.

Models were generated for the entire Galore Creek and More Creek watersheds as well as two main headwater tributary catchments of Galore Creek. The models were initially set-up using observed hydrological data from the former More Creek WSC station along with regional climate data. A sensitivity analysis was conducted on the UBCWM of Galore Creek to aid in identification of key parameters to be involved in the calibration process. Hydrological and meteorological data collected during the GCEBP was used to calibrate the four UBCWMs. The calibrated models generally showed a good-fit to observed data based on the overall shape of the annual hydrograph and monthly distribution of runoff.

The UBCWMs provide insight into the key hydrological processes of the Galore Creek area and were used in a number of “what if” scenarios to examine the potential effects of the Galore Creek Project on the hydrological regime of the Galore and More Creek watersheds. The models also facilitated a quantitative assessment of the impact that climate change may have on stream flows and runoff within the study area.

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