

FIGURE 4.5-3

Estimated 100-Year Flood versus Drainage Area for Site-Specific Regional Analysis



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Coastal regions have proportionally larger peak-flows than interior regions, and therefore k -values tend to decrease rapidly along the transition from the coast to the interior. However, the estimates have been made using the best-available data.

**Table 4.5-4
Comparison of Results for Galore
and Sphaler Using Regional Equations**

Station	Watershed Area (km ²)	Q ₂ (m ³ /s)		Q ₁₀ (m ³ /s)		Q ₁₀₀ (m ³ /s)	
		k-Factor Method ¹	Curve Fitting Method ²	k-Factor Method ¹	Curve Fitting Method ³	k-Factor Method ¹	Curve Fitting Method ⁴
Galore Creek (at the mouth)	145	108	107	172	161	303	246
Sphaler Creek (at the mouth)	327	200	200	320	300	560	500

¹After Eaton et al (2002). Based on equation $Q = kA^x$, with $x = 0.75$ and regional average k -values calculated in Table 4.5-3

²After Obedkoff (2001). Based on equation $Q = kA^x$, with $x = 0.765$ and $k = 2.377$, calculated from regression analysis of data from regional hydrology stations.

³After Obedkoff (2001). Based on equation $Q = kA^x$, with $x = 0.764$ and $k = 3.586$, calculated from regression analysis of data from regional hydrology stations.

⁴After Obedkoff (2001). Based on equation $Q = kA^x$, with $x = 0.8602$ and $k = 3.405$, calculated from regression analysis of data from regional hydrology stations. Regression equation shown in Figure 4.5-3.

Multiple Regression Equations

Multiple regression methods for flood frequency analysis relate peak flows to a number of watershed characteristics, which can include watershed area, topography, soil type and precipitation. There have been few attempts at developing multiple regression equations for flood estimation in British Columbia. The main limitation is the lack of a consistent data set that provides a summary of watershed characteristics for all gauged watersheds in the province. The United States Geological Survey (USGS) has developed multiple regression equations for flood frequency analysis for rivers in Alaska and conterminous basins in Canada (*e.g.*, Jones and Fahl, 1994; Curran *et al.* 2003). These studies include both USGS and WSC gauge station data, and the assessment covers the present study area. However, an assessment of the methods indicated that they tended to predict lower Q_{100} flood flows for watersheds in the study area when compared to the simple regression equations discussed in the previous section. Given the lack of available data a conservative approach to return period flood flow predictions would appear to be warranted and as a result the multiple regression methods were not considered further in the present study. In addition, due to the lack of consistent datasets for watershed characteristics in British Columbia, further research is required before multiple regression equations will be suitable for flood frequency analysis in British Columbia.

4.5.2 Small Watersheds

Coulson (1991) recommends the use of the Rational Method for flood frequency analysis of small (< 25 km²) watersheds in British Columbia. The Rational Method is described in detail in this section along with discussion of alternative methods of flood flow estimation for small watersheds.

4.5.2.1 Rational Method

The Rational Method is one of the simplest and the most commonly used method for calculating return period peak flows for small watersheds. The rational method predicts the flows that would be generated from a given rainfall intensity falling onto a drainage basin, using the following formula:

$$Q_p = 0.28CPA/T_c$$

Where Q_p is the peak flow in m^3/s , C is a runoff coefficient, P is the total precipitation, A is the area of the drainage basin (km^2), and T_c is the time to concentration of flows. This approach assumes that rainfall intensity is uniform in time, rainfall is uniformly distributed over the drainage basin, and a single runoff coefficient is representative of basin characteristics. These criteria are not generally met in larger watersheds, and therefore this approach is typically limited to smaller watersheds ($<25 km^2$). To estimate Q_{100} requires an estimate of the 100-year rainfall event of duration equal to T_c . Rainfall, intensity, duration (IDF) curves are calculated based on statistical analysis of extreme rainfall distributions. The runoff coefficient (C) represents the proportion of rainfall that is available for runoff generation, and is dependent on basin characteristics such as surficial geology, slope, vegetation cover, antecedent soil moisture, and rainfall intensity. Recommended values of C for British Columbia given by Coulson (1991) are provided in Table 4.5-5. These values should be used as a guideline for coefficients used in peak-flow estimates. These coefficients should be adjusted for storms with a recurrence interval (RI) of greater than 25 years, and for events that include a snowmelt component. For Q_{100} estimates, there is a likelihood of rain-on-snow effects, therefore both of these adjustments should be included in coefficient estimates used with the Rational Method.

**Table 4.5-5
Estimates of Runoff Coefficient 'C'
for Rational Method from Coulson (1991)**

Physiography	Impermeable Surface	Forested
Mountain	1.00	0.90
Steep slopes	0.95	0.80
Moderate slopes	0.90	0.65
Rolling Terrain	0.85	0.50
Flat	0.80	0.40
RI >25 years	+0.10	+0.05
Snowmelt	+0.10	+0.10

There are a number of methods of estimating T_c for ungauged watersheds and Coulson (1991) recommends techniques for use in British Columbia. A number of studies have noted that standard equations used to estimate T_c for forested watersheds can often substantially underestimate the actual T_c for the watershed. However, in order to estimate site-specific values of T_c , one needs data on high flow events in the region of interest. Analysis of flow records on

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small watersheds within More Creek and Galore Creek identified that T_c for high flow events in 2004 and 2005 varied between 2 to 6 hours, 5 to 10 times greater than T_c estimated using standard formulae. However, none of the events observed during the monitoring period could be described as remarkably high flows and it is likely that during a 1 in 100 year event the value of T_c would be less than observed for smaller events. Hence, until more flow data is collected, it is thought that using values of T_c calculated using formulae given in Coulson (1991) should provide conservative estimates for design flow estimation.

For the study area a discussion of the derivation of return period precipitation events are provided in the Meteorological Baseline Report. Precipitation totals for use in the Rational Method are based on a storm duration equal to the time of concentration (T_c).

Peak-flow generation can also be estimated through more complex hydrological models that try to represent the runoff generating processes in a more physical manner. However, these models require a large investment in time for model development and calibration and are typically more useful for long-term water balance modeling applications than for flood analysis. More complex models also require the definition of storm events as inputs and not just the peak intensity. Given the limited amount of precipitation data, derivation of storm events is not warranted at present. UBC Watershed models have been developed for More Creek and Galore Creek and they will be used for long-term model runs, assessing the contribution of different sources of flows and running 'what if' scenarios assessing the impact of mine development. With collection of additional meteorological and flow data, it may be possible to use the models as tools for flood prediction in the future.

4.5.2.2 Other Methods of Estimating Peak Flows for Small Watersheds

There are other methods that could be applied to small watersheds within the study area. The California method is an approved method for culvert design on small streams in forested watersheds in the BC Forest Practices Code (B.C. Ministry of Forests, 2002). The Beaumont Method is commonly used for highway culvert design in British Columbia. Both these methods are discussed in this section.

California Method

The shape and size of a stream channel reflects the flows which occur in that channel. Therefore, assessments of channel geometry can be used to estimate peak-flow. The California method (Tolland *et al.*, 1998) estimates the Q_{100} flow in a channel based on the observed bankfull discharge. The California method is an approved method in the BC Forest Practices Code (B.C. Ministry of Forests, 2002) for culvert design on small streams.

The California method assumes that the bankfull area of a stream channel (the area of the channel cross-section below the high water) represents the channel area of the mean annual flood. The Q_{100} event is then assumed to occupy three times the bankfull area, and the culvert or bridge opening need to be designed to accommodate at least this area such that:

$$W=3A_b$$

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Where W is the estimated channel area of the Q_{100} event and A_b is channel area at bankfull. An alternative approach is to calculate Q_2 using Manning's formula and the measured bankfull area. The Q_{100} is then assumed to be three times the bankfull discharge (Q_b):

$$Q_{100}=3Q_b$$

This approach can be effective because of its simplicity. However, it is only appropriate for smaller streams and the Forest Practices Code (B.C. Ministry of Forests, 2002) recommends the use of this method for streams with a Q_{100} less than $6 \text{ m}^3/\text{s}$, or for culverts less than 2000 mm in diameter. One limitation of the method is the need for field survey information at each crossing site; data that may not be available at all sites.

Overall the methodology is considered to be conservative for mountain streams. It assumes that bankfull is equal to the Q_2 flood, although for mountain streams it is likely that bankfull corresponds to an event with a return period in excess of two years. Also the method assumes that the channel velocity during a Q_2 event is the same as for a Q_{100} event. This is unlikely to be true, with flow velocities higher for larger flood events. A limitation of the technique that has been discussed by Beckers *et al.* (2002) is that it assumes that the Q_{100} event is always three times greater than the Q_2 event. Although this is a reasonable estimate of average conditions for watersheds in the study area the Q_{100} flood is five times larger than Q_2 for the More Creek WSC station (see Appendix 6), which would imply that the California Method would underestimate peak flows in the study area. However, it is not clear that the scaling factor calculated for More Creek (a large watershed at 844 km^2) would be relevant for smaller watersheds. Hence, the California Method is thought to be suitable for application at the study area especially for the design of crossings for small streams.

Beaumont Method

The Beaumont Method (Beaumont, 1989) has been used for Highway Culvert design in Northern British Columbia. The Beaumont Method involves the application of multi-variate regression equations for peak-flow estimates, with parameters specified for different regional units. The Beaumont method has several limitations. Data were collected along highway routes in British Columbia, and the regional constants may not be suitable outside of the area in which they were calculated. As well, both peak-flow magnitude and return periods were not robustly calculated and relied heavily on judgment and experience. The approach is intended to provide guidelines for culvert design on smaller channels, and should be appropriate for that application. However, it was not thought suitable for the current study.

4.5.3 Summary for High Flows

This section has reviewed methods for calculating return period flows for the study area. A summary of the recommended methods for each watershed are provided in Table 4.5-6. Predictions of Q_2 , Q_{10} and Q_{100} flows for selected locations in watersheds of interest are provided in Table 4.5-7. All of the predictions presented here are for watersheds larger than 25 km^2 , however, the methods for smaller watersheds have been outlined to provide guidance for smaller

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basins. Flood estimates derived for other components of the Galore Creek project (*i.e.*, bridge and culvert design for the access road) have used the same methodologies discussed here.

**Table 4.5-6
Summary of Methodologies for Calculating Return Period Flow
Estimates for Watersheds Within the Study Area**

Watershed	Watershed Size	Methodology for flood frequency analysis
Galore Creek	> 25 km ²	Regional analysis: k-factor method
	< 25 km ²	Rational Method or California Method
More Creek	> 25 km ²	Scaling of results of single-site analysis for More Creek WSC station
	< 25 km ²	Rational Method or California Method
Sphaler Creek	> 25 km ²	Regional analysis: k-factor method
	< 25 km ²	Rational Method or California Method
Iskut River	> 25 km ²	Scaling of results of single-site analysis for Iskut-Johnson WSC station
	< 25 km ²	Rational Method or California Method
Scud River	> 25 km ²	Regional analysis: k-factor method
	< 25 km ²	Rational Method or California Method
Porcupine River	> 25 km ²	Regional analysis: k-factor method
	< 25 km ²	Rational Method or California Method
Stikine River	> 25 km ²	Single-site analysis for Stikine-Wrangell USGS station

**Table 4.5-7
Estimates of Return Period Flows
for Key Watersheds Within the Study Area**

Watershed	Watershed Area (km ²)	Q ₂ (m ³ /s)	Q ₁₀ (m ³ /s)	Q ₁₀₀ (m ³ /s)
Galore Creek at the mouth	145	110	170	300
More Creek at the mouth	876	330	640	1280
Sphaler Creek at the mouth	327	200	320	560
Iskut River	9400	2630	4150	9200
Scud River	1130	500	800	1410
Porcupine River	740	370	580	1030
Stikine River	51600	5880	7710	10600

Uncertainty exists for all flood estimates. For methods using historic gauge records, the accuracy is limited by the length of flow records, extrapolating floods beyond that record introduces uncertainty. Regional variability in hydrological processes and basin characteristics also creates uncertainty in estimating flood conditions in ungauged basins using regional approaches. Similarly, uncertainty exists in parameter characterization using the California (*i.e.*, estimation of Manning's

n) and Rational (*i.e.*, runoff coefficient, precipitation) methods. However, the major uncertainty stems from the lack of WSC flow gauging stations in northern British Columbia.

It is difficult to make a robust estimate of the uncertainty in the return period flow estimates given the available data. However, previous studies have estimated the uncertainty associated with Q_{100} estimates to be around 20 to 40%. Jones and Fahl (1994) and Curran *et al.* (2003) examined the variability in the flood magnitude-frequency relationships from gauged stations. Based on their regional regressions, standard error was 37% for Q_{100} estimates, and 40% for Q_{200} estimates. Beaumont (1989) suggests a 20% to 30% error in flow estimates.

4.6 Low Flow Regional Analysis

Predictions of low flow conditions are vital for managing water resources and assessing impacts on aquatic life. Different indices exist to characterize low flow, with the most common measure being the 7-day low flow. This is the minimum average seven day flow that occurs over a specified period, such as a month, season, or year. This is obtained by calculating a rolling seven day average and then finding the minimum average that occurred within the specified period. Streams naturally exhibit periods of low flow. The average annual low flow provides an estimate of the normal baseflow conditions of a stream and is important to the sustained health of a stream's aquatic community. Another common index of low flow is the 7-day Q_{10} . This is the seven day average minimum flow that is expected to occur once every ten years, and is the most common index considered for water use planning.

For streams at higher elevations or latitudes, the annual low flow will consistently occur during the winter, when most water is stored as either ice or snow. However, important aspects of a stream's health, such as the presence of certain aquatic species, or activities that could impact the quantity or quality of water in a stream may be restricted to the open water season. Therefore, it is also useful to identify the low flow that occurs during this period. For this study, estimates are made of the average annual 7-day low flow and the annual 7-day Q_{10} as well as the average 7-day low flow and 7-day Q_{10} that occurs from June through September.

To characterize the average low flow or 7-day Q_{10} requires an adequately long record of observed data. To be able to estimate the 7-day Q_{10} it is preferable to have an observed data that spans at least 10 years. This data set is not available for most streams that will be impacted by the Galore Creek Project, including Galore Creek. Therefore estimates were made using a regional analysis.

For ungauged watersheds in the Skeena region, Obedkoff (2001) suggests estimating the 7-day Q_{10} using regional curves based on watershed area and/or a nearby gauged watershed. Within the study area only More Creek has been monitored by a WSC gauging station. Hence, low flow estimates for More Creek can be based on data from the WSC site. For other watersheds directly impacted by mine development (Galore Creek and Sphaler Creek) low flow indices must be estimated using regional relationships. Obedkoff proposed that low flow estimates can be made for ungauged watersheds based on regional curves calculated using WSC data from the main hydrologic zones of Coulson and Obedkoff (1998). Galore Creek is located in hydrologic zone 9A, which includes 9 gauged stations. The stations of 9A are listed in Table 4.6-1. Low flow

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indices for watersheds in zone 9A are shown in Figures 4.6-1 to 4.6-4 along with all Skeena region watersheds.

The 7-day Q_{10} estimates for each hydrometric station were obtained by assuming that the annual low flow values for the entire year and for June through September follow a Weibull distribution, which is a common distribution used in general hydrologic analyses (Bedient and Huber, 2002) as well as low flow analyses (Stedinger *et al.*, 1992).

**Table 4.6-1
Stations Included in the Low Flow Regional Analysis**

Station Characteristics		Flow Estimate (m ³ /s)			
	Watershed	Annual	June - September	Annual	June - September
Station Name	Area (km ²)	7-Day Low Flow	7-Day Low Flow	7-Day Q_{10}	7-Day Q_{10}
Bear	289	2.04	22.90	1.24	15.0
Forrest Kerr	312	0.87	23.4	0.58	12.7
Iskut-Snippaker	7230	26.3	232	17.9	137
Iskut-Johnson	9350	46.6	403	32.8	260
More	844	4.68	40.2	3.34	19.6
Sloko	427	0.58	0.38	11.0	6.72
Stikine Butterfly	36000	81.5	538	65.6	373
Harding	175	2.02	1.38	14.0	8.42
Unuk	1480	10.8	94.7	6.61	55.4

Figures 4.6-5 and 4.6-6 present the regional curves relating low flow and watershed area developed in this analysis. One note of caution is that most watersheds that require low flow estimates for the Galore Creek Project are smaller than the range of watersheds used to generate the regional curve. However, the observed data from the 2004 and 2005 baseline program appear to be consistent with the regional curve, providing some confidence in the use of the curve for smaller watersheds. It should be noted that the observed low flow data is only available for June through September as a complete annual time-series was not recorded at any of the baseline stations. Due to the fact that the regional curves for all the low flow indices have similar slopes, it is expected that the observed June through September data provides a good indication of what the observed annual low flow would be.

Estimates of the average annual 7-day low flow and the annual 7-day Q_{10} as well as the average 7-day low flow and 7-day Q_{10} that occurs from June through September are presented in Table 4.6-2 for a number of watersheds in the Galore Creek area. For More Creek and Iskut River the low flow indices were weighted by the historical record of the WSC stations located at More Creek and Iskut-Johnson. For these stations the regional curve was shifted to pass through the data point calculated using the historical data at each station. Estimates for the Stikine River are based on analysis of historical data from Stikine-Wrangell USGS station.

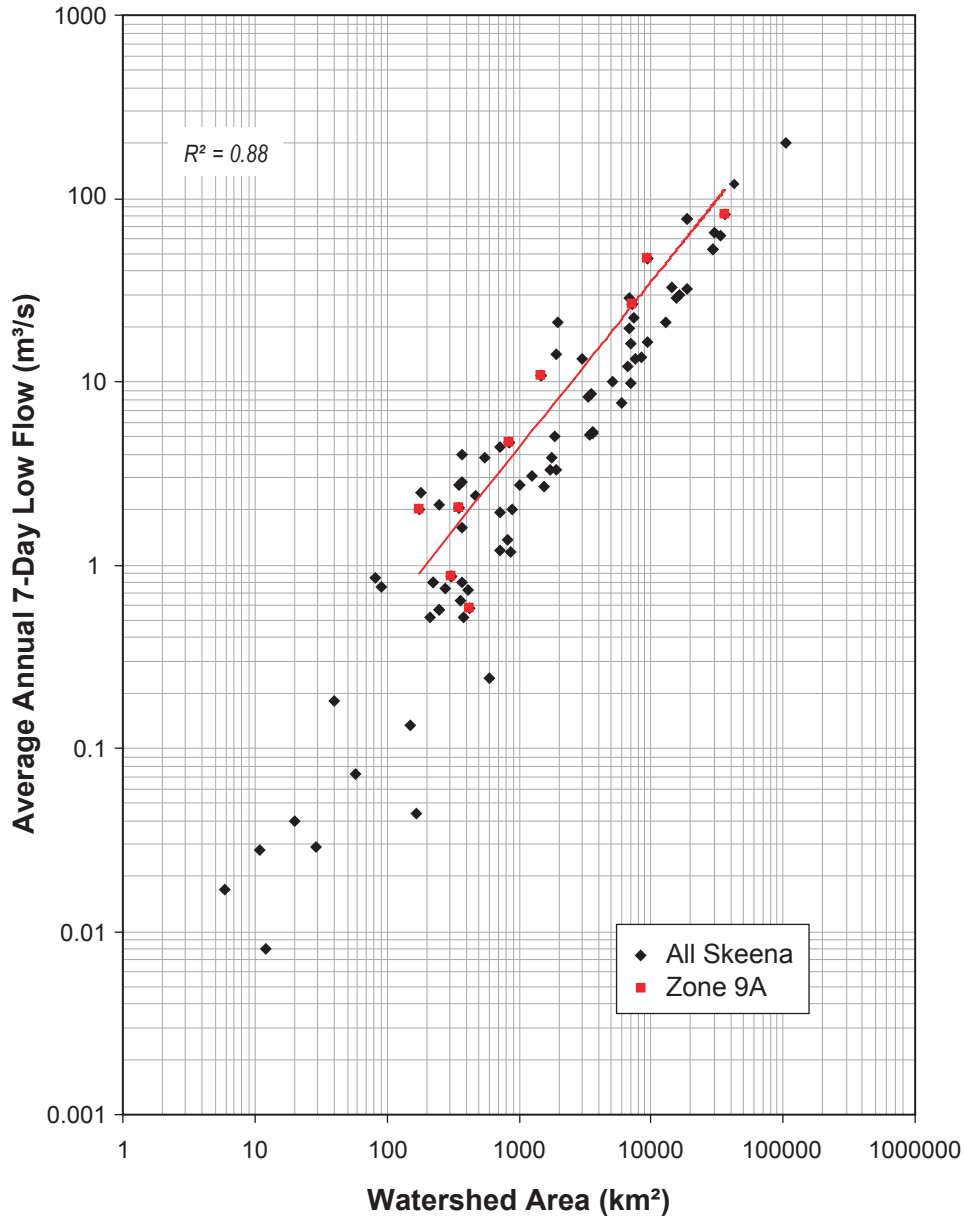
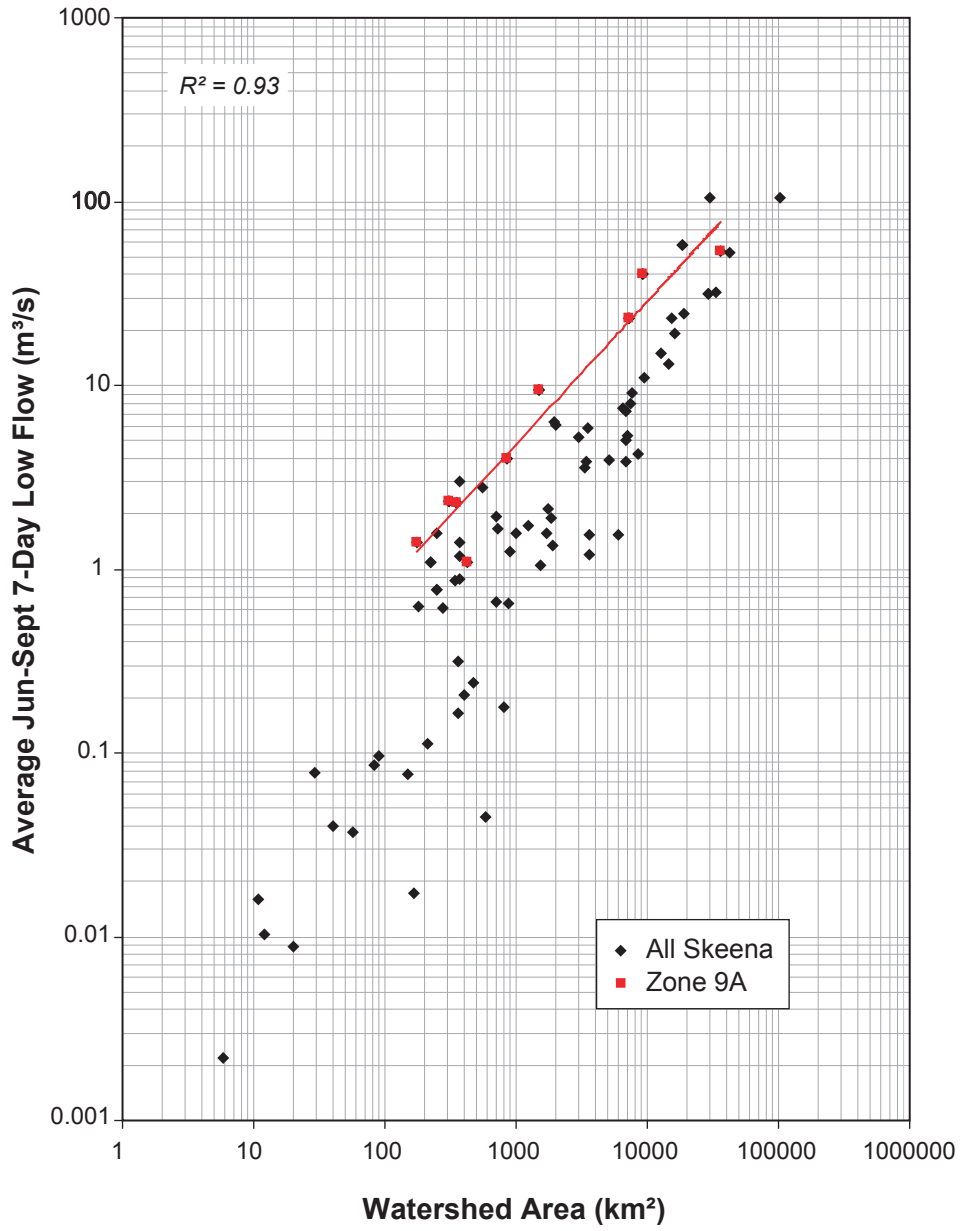


FIGURE 4.6-1

Average Annual 7-Day Low Flows in Skeena Region Watersheds

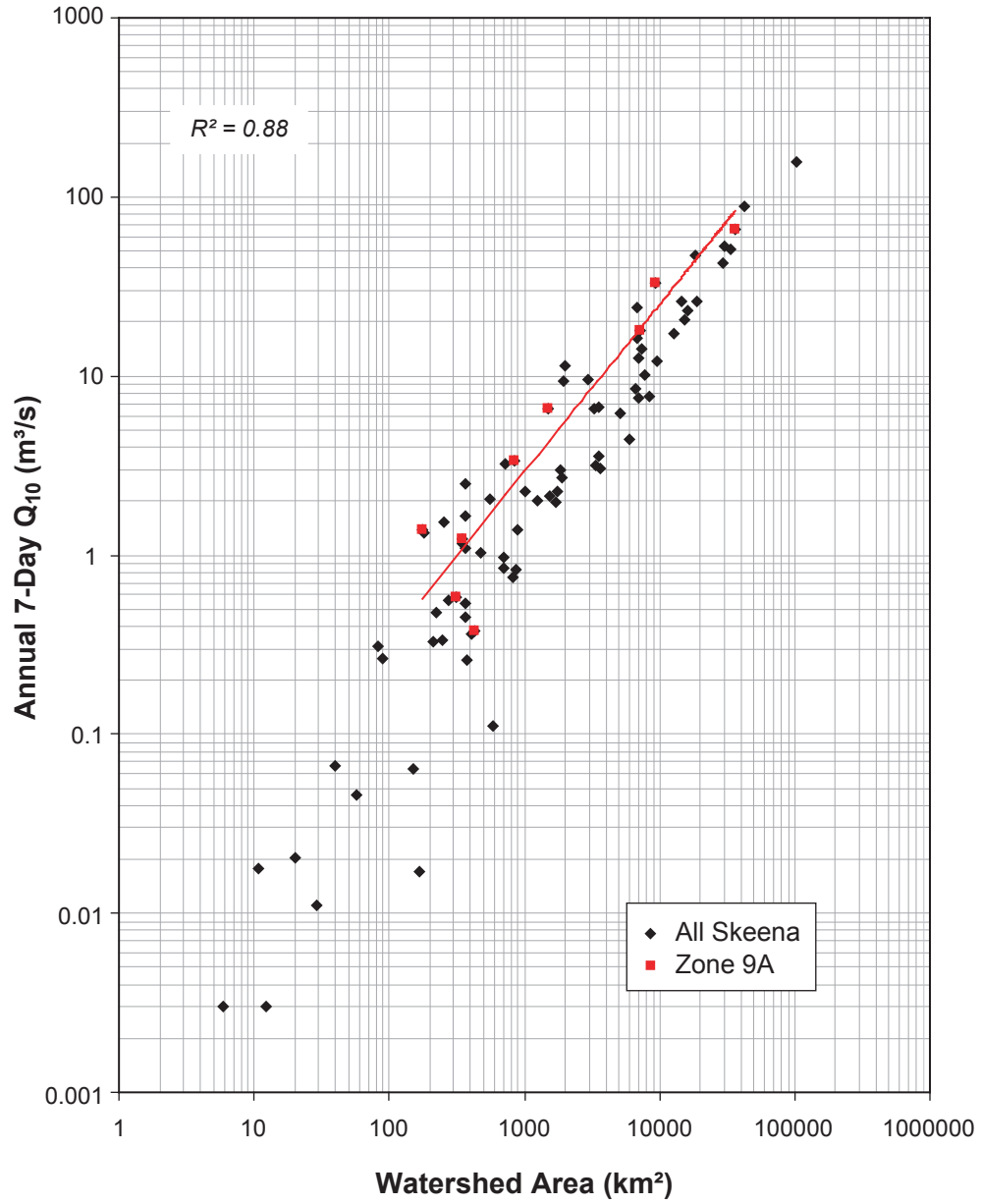




Average June - September 7-Day Low Flows in Skeena Region Watersheds

FIGURE 4.6-2





Annual 7-Day Q₁₀ in Skeena Region Watersheds

FIGURE 4.6-3



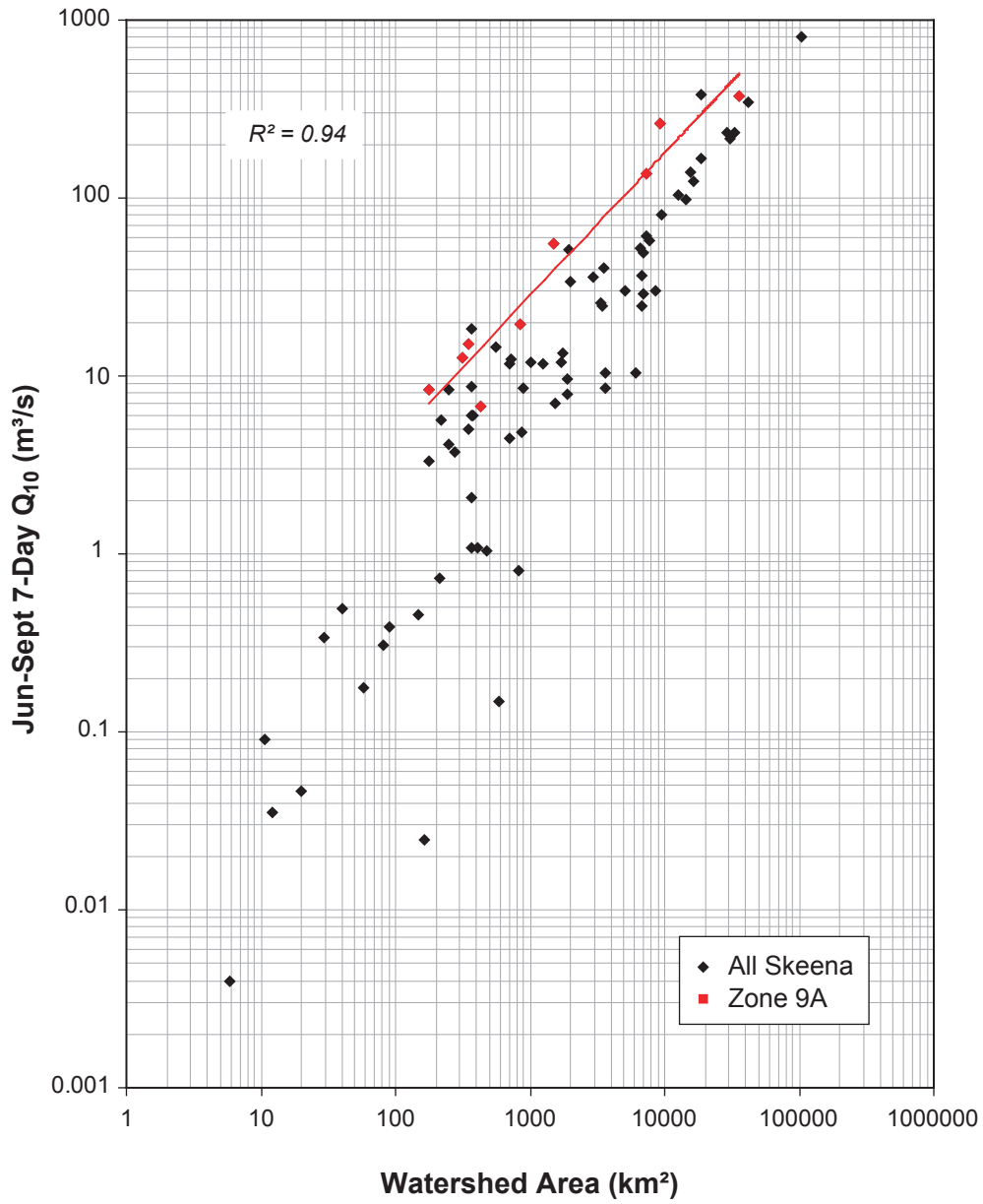


FIGURE 4.6-4



June - September 7-Day Q₁₀ in Skeena Region Watersheds

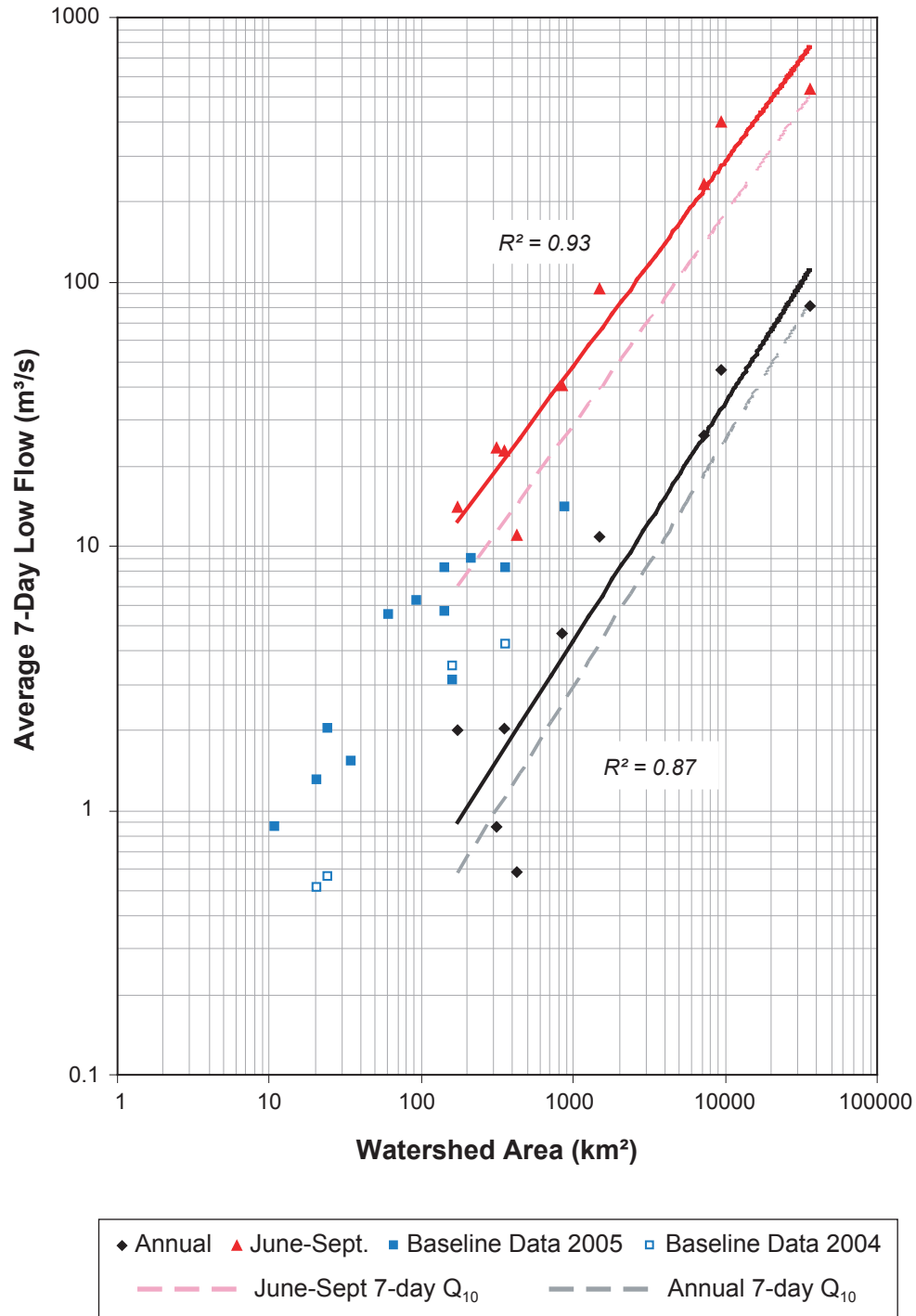


FIGURE 4.6-5



Average 7-Day Low Flow Curves for Galore Creek

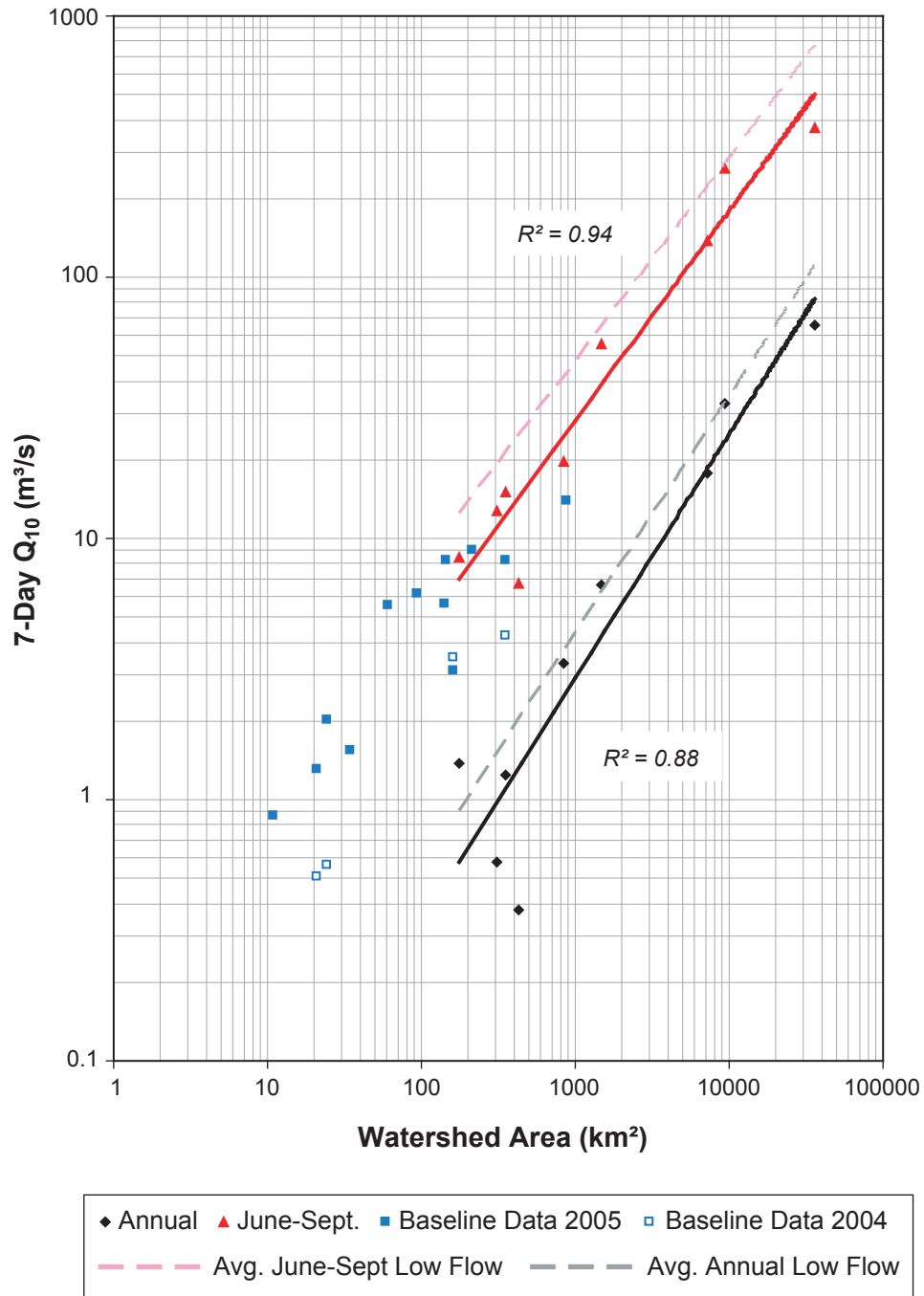


FIGURE 4.6-6



7-Day Q_{10} Curves for Galore Creek

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June through September low flows in 2005 in Galore Creek and surrounding watersheds appear to fall between the average low flow and the 7-day Q_{10} , while in 2004 low flows were below the estimated June through September 7-day Q_{10} .

**Table 4.6-2
Low Flow Estimates for Galore Creek and Surrounding Watersheds**

Flow Estimate	Annual 7-Day Low Flow	Jun-Sep 7-Day Low Flow	Annual 7-Day Q_{10}	Jun-Sep 7-Day Q_{10}
Low Flow Curve	$Q = 0.0086 * A_w^{0.9027}$	$Q = 0.2241 * A_w^{0.7764}$	$Q = 0.0046 * A_w^{0.9332}$	$Q = 0.1118 * A_w^{0.8016}$
Galore Creek at its mouth	0.77	10.7	0.48	6.04
More Creek at its mouth	4.84 ¹	41.4 ¹	3.46 ¹	20.2 ¹
Sphaler Creek at its mouth	1.51	19.1	0.96	11.0
Iskut River	46.8 ¹	404 ¹	33.0 ¹	2.61 ¹
Scud River	4.90	52.6	3.25	31.3
Porcupine River	3.35	37.9	2.19	22.3
Stikine River	167	1400	126	875

¹Estimates were made using the regional low flow curves weighted towards the More Creek and Iskut - Johnson WSC station data.

²Estimates were made using historical data from Stikine-Wrangell USGS station.

5. CONCLUSIONS

5. Conclusions

This report outlines the baseline surface water hydrology of the Galore Creek Project area. The report describes methods and results of a comprehensive field monitoring program undertaken during 2004 and 2005. It also provides estimates of key hydrological parameters for watersheds and sub-watersheds in the study area, for use in the EIA process and to assist in engineering design.

The Galore Creek Project area is located within the Coast Mountains of northwestern British Columbia a region characterized by high annual snowfall and precipitation totals. The watersheds typically have steep, mountainous topography, and many have glaciers in their headwaters. The project area lies in a transition zone between the very wet coastal region and the drier interior of British Columbia. The regional hydroclimate of northwestern British Columbia 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. In addition, the presence of large glaciated areas can impact snowmelt rates and produce high runoff volumes during summer months.

Due to the number of competing runoff generating processes and their varying spatial and temporal influences on stream flow hydrographs the hydrological regime of the region is very dynamic, temporally and spatially variable, and difficult to predict. Any hydrological assessment is dependant on the quality and quantity of available historical meteorological and stream flow data relevant to the study area. Due to the mountainous topography, and the distance from large population centres, there are only a limited number of meteorological and hydrological monitoring stations in northwestern British Columbia. Information on flows in smaller, glaciated watersheds is particularly lacking in regional stream flow datasets.

To address the requirements for site-specific hydrologic information, a network of 25 hydrometric stations were installed and monitored during 2004 and 2005. Monitoring stations were established in Galore Creek, More Creek, and Sphaler Creek, as well as reference stations in the Scud and Iskut watersheds. Watersheds that were monitored ranged in size from 3.3 to 876 km².

A regional hydrological analysis was undertaken to derive values of key hydrological parameters for the study area; namely, annual runoff totals, monthly flows, flood flows and low flows. The regional assessment used available data from Water Survey of Canada monitoring stations, combined with the field data collected during 2004 and 2005. Results from this analysis are summarized in Tables 5.1 through 5.4. In addition, UBC Watershed Models were developed for More Creek and Galore Creek in order to better understand runoff generating process and to make estimates of the relative contributions of snow-melt, rain-fall, glacial melt and groundwater to the annual flow hydrograph.

Estimation of Key Hydrological Parameters

A number of Appendices are also included that describe additional studies undertaken in support of the main hydrological work component. Appendix 1 describes an assessment of sediment transport rates within the study area. Appendix 2 provides quantitative estimates of the potential impact of climate change on precipitation, temperatures and runoff for the study area based on results of the UBC Watershed Model run using global climate model predictions. A description of the development of UBC Watershed Models of Galore Creek and More Creek is provided as a separate report.

**Table 5-1
Key Hydrological Parameters of the Galore Creek Area: Annual Runoff**

Return Period	Galore Creek at the Mouth					Scud River; Runoff (mm)	Iskut River Runoff (mm)
	More Creek at the Mouth Runoff (mm)	Sphaler Creek at the Mouth; Runoff (mm)	Porcupine River; Runoff (mm)	Scud River; Runoff (mm)	Iskut River Runoff (mm)		
1 in 100 dry year	1590	1380	1620	1580	1590	1060	
1 in 50 dry year	1660	1420	1720	1670	1680	1120	
1 in 20 dry year	1780	1490	1810	1760	1770	1180	
1 in 10 dry year	1920	1580	1930	1880	1880	1290	
1 in 5 dry year	2060	1660	2060	2010	2020	1390	
Average	2340	1820	2320	2260	2270	1580	
1 in 5 wet year	2620	1980	2580	2510	2520	1760	
1 in 10 wet year	2760	2060	2710	2640	2650	1860	
1 in 20 wet year	2900	2150	2830	2760	2770	1970	
1 in 50 wet year	3020	2220	2920	2850	2860	2030	
1 in 100 wet year	3090	2260	3020	2940	2950	2090	

**Table 5-2
Key Hydrological Parameters of the Galore Creek Area: Estimated Mean Monthly Flow**

	Mean Monthly Flow (m ³ /s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Galore Creek at the mouth	1.3	1.3	1.3	2.6	10.3	23.2	29.7	27.1	16.8	10.3	3.9	1.3
More Creek at the mouth	6.1	6.1	6.1	12.1	48.5	115	146	115	72.8	48.5	18.2	12.1
Sphaler Creek at the mouth	2.9	2.9	2.9	5.8	23.1	52.0	66.4	60.6	37.5	23.1	8.7	2.9
Iskut River at the mouth	56.8	56.8	56.8	170	511	1,080	1,190	1,020	682	511	227	114
Scud River at the mouth	9.6	9.6	9.6	19.1	86.1	201	210	163	105	76.5	28.7	19.1
Porcupine River at the mouth	6.4	6.4	6.4	12.7	57.3	134	140	108	70	50.9	19.1	12.7

**Table 5-3
Key Hydrological Parameters of the Galore Creek Area: Peak Flows**

Watershed	Watershed Area	Q ₂ (m ³ /s)	Q ₁₀ (m ³ /s)	Q ₁₀₀ (m ³ /s)
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Estimation of Key Hydrological Parameters

	(km ²)			
Galore Creek at the mouth	145	110	170	300
More Creek at the mouth	876	330	640	1280
Sphaler Creek at the mouth	327	200	320	560
Iskut River	9400	2630	4150	9200
Scud River	1130	500	800	1410
Porcupine River	740	370	580	1030

Table 5-4
Key Hydrological Parameters of the Galore Creek Area: Low Flows

Flow Estimate	Annual 7-Day Low Flow	Jun-Sep 7-Day Low Flow	Annual 7-Day Q ₁₀	Jun-Sep 7-Day Q ₁₀
Galore Creek at its mouth	0.77	10.7	0.48	6.04
More Creek at its mouth	4.84	41.4	3.46	20.2
Sphaler Creek at its mouth	1.51	19.1	0.96	11.0
Iskut River	46.8	404	33.0	2.61
Scud River	4.90	52.6	3.25	31.3
Porcupine River	3.35	37.9	2.19	22.3

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APPENDIX 1
FLUVIAL SEDIMENT TRANSPORT

Appendix 1 - Fluvial Sediment Transport

A1-1 Objective

Sediment transport rates within Galore Creek are expected to be high as a result of high stream gradients and velocities, coupled with an abundance of easily eroded, unconsolidated glaciofluvial materials. The objective of the fluvial sediment transport analysis is to try to characterize sediment transport rates within the Galore Valley, and to estimate annual transport volumes. It is recognized that mass wasting events such as debris flows and landslides will play an important role in the sediment budget of the basin; however, these processes are addressed in a separate geotechnical analysis. The current analysis focuses solely on fluvial transport. It must be noted that fluvial sediment transport estimates have a high degree of uncertainty associated with them, and results should be used with caution.

A1-2 Background

The Galore Valley is characterized by steep, rugged, mountainous terrain, with ~35% glacier cover. Due to relatively recent glacial recession, there are large sections of exposed, unvegetated glacial deposits in the valley bottom. These deposits provide a large source of potentially transportable material.

Sediment transport is generally divided into two modes, suspended load and bed load. Suspended load is fine material that is carried in the water column. Bed load is coarse material that moves in contact with the bed by either rolling, sliding or saltating (small jumps). Separate analyses are carried out for suspended and bed load transport.

There are two main controls on suspended sediment concentrations – sediment supply and stream discharge. Fine sediments are supplied to the channel through bank collapse and from surface erosion in the catchment area. Suspended sediment concentrations increase with discharge, as the stream widens and has access to new sources of sediment.

Suspended sediment transport is generally analyzed through empirical rating relations between suspended sediment concentration and discharge. These relations are usually power functions with exponents typically in the range 1 to 2 (Walling and Webb, 1982). However, these rating relations contain a high level of uncertainty. The timing of mass wasting events that supply sediment to the channel is independent of discharge, producing wide scatter in these relations. Also, seasonal hysteresis effects are often observed. Concentrations may be high on the rising limb of the hydrograph when sediment is readily available, but once the supply has been exhausted, the concentrations may be much lower (even at equally high discharge).

The transport of bed load material is generally assumed to depend on the transporting capacity of the flow. However, surface structures, and armouring of the bed surface significantly reduce transport (Church et al., 1998). Many different methods have been developed to measure bed load transport; however, none has been accepted as standard. For the streams in the Galore Valley, which are characterized by coarse boulder-cobble beds with steep gradients, there is no

method that can reliably measure transport. Instead, sediment transport formulae are used to estimate transport rates.

Many sediment transport formulae have been produced. Generally these formulae relate the sediment transport rate to either excess shear stress or excess stream power. All have the problem of determining the threshold for the initial entrainment of material. Results from the different formulae are wide ranging. Gomez and Church (1989) evaluated the performance of ten bed load transport formulae and concluded that no formula performs consistently well. They recommend the use of stream power based equations for streams with limited hydraulic information, and formulae sensitive to grain size distribution where possible. Due to the expected range in results, a number of common equations will be tested.

A1-3 Methodology

To estimate both suspended and bed load transport, general hydraulic information is required. Stream flow is being continuously monitored at a number of stations in the Galore Valley, as shown in Figure A1-1. Additional data specific for sediment transport analysis were collected at four of these stations: GAL1A, GAL1B, GWM6 and GAL3.

The hydrologic station GAL3 is located immediately upstream of the canyon within Galore Valley. The station was damaged during the high flows in 2004, and was not re-mobilized for the 2005 season due to safety concerns. Flows at GAL3 were extrapolated from GWM7, which is located a few kilometres upstream.

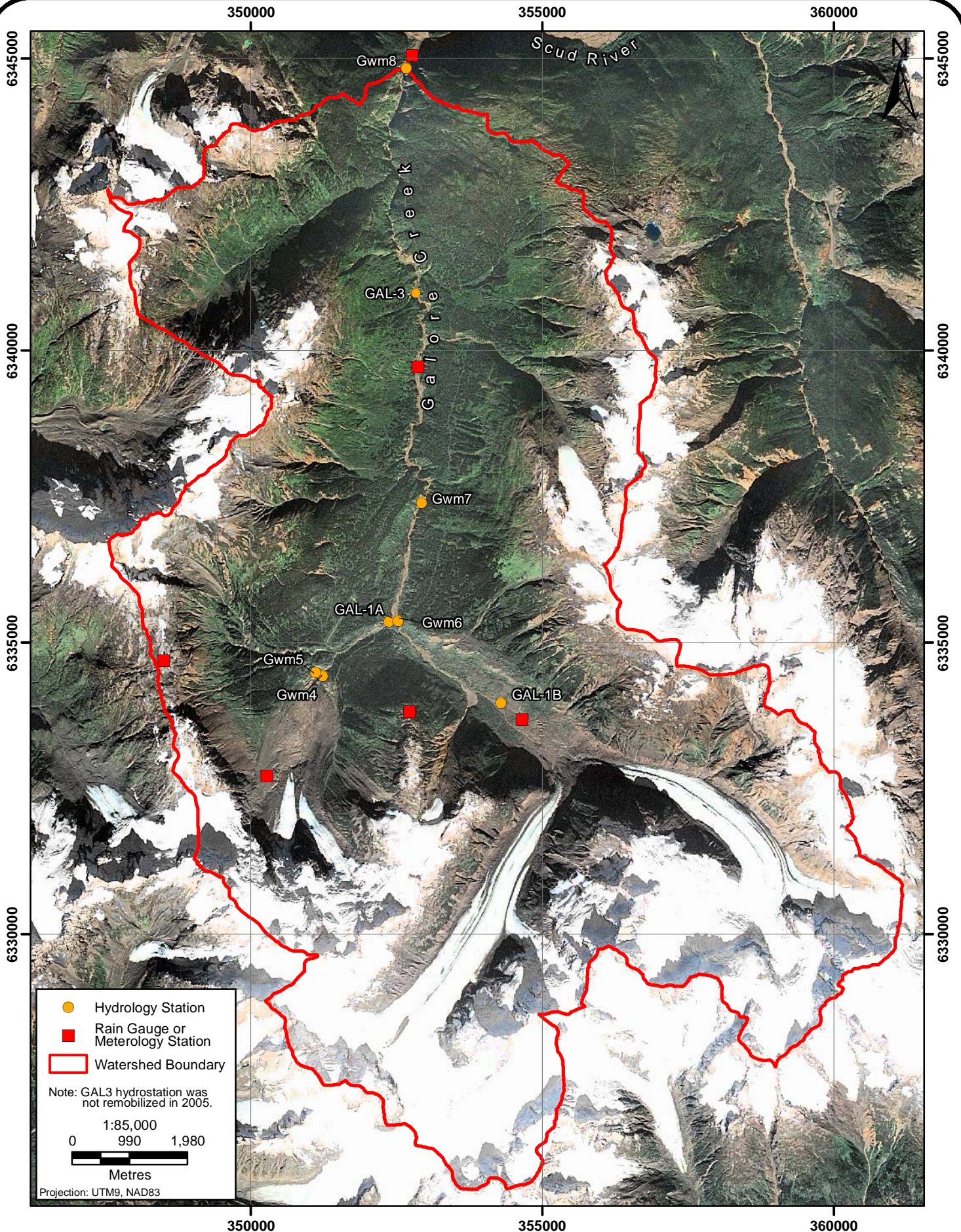
A1-3.1 Suspended Load

In order to estimate suspended load, water samples were collected at each station over a range of discharges. The traditional sampling method is to collect depth integrated samples at a number of locations at a stream cross section. Unfortunately this method was not possible in the Galore Valley. During moderate to high flows, the streams were unsafe to wade across; in order to address these safety concerns, an alternative sampling method was adopted.

As part of the water quality monitoring program, monthly water samples were collected at GAL1A, GAL1B and GAL3. The concentration of suspended sediment (total suspended solids (TSS)) is one of the parameters analyzed. Samples are collected as a 1L grab sample from a fast flowing section of the stream. Due to the turbulent, well mixed nature of the flow, the grab sample should be representative of the amount of suspended sediment being carried at the given cross section. A positional study was conducted, where samples were collected at different points across the stream, and at different depths. For suspended sediment concentration, no trend was evident in the data, supporting the turbulent, well mixed assumption. Additionally, replicate samples were taken some months, which give an indication of the variability.

A1-3.2 Bed Load

Bed load transport formulae all require similar input parameters of flow hydraulics and the grain size distribution of the bed material. Hydraulic parameters such as depth, width, energy gradient and discharge are monitored as part of the on-going baseline hydrology assessment. To



Hydrometric and Meteorological Stations in the Galore Creek Valley

determine the grain size distribution, a pebble count and volumetric bulk sample were collected at GAL1A, GAL1B, GWM6 and GAL3. A representative area for sampling was found at each site on either a medial or lateral bar.

Pebble counts were collected to determine the surface grain size distribution. The diameter of at least 200 stones was recorded along transects laid out over the bar surface. In order to produce a random sample, stones were selected along transects at 30cm intervals. Particle size was determined by passing the stone through a template; the template had square holes for 9 size classes from 8 to 128 mm. For stones larger than the template, the diameter of the intermediate axis (B-axis) of the stone was measured.

To determine the grain size distribution of the subsurface material, volumetric bulk samples were collected. A 1 m x 1 m section was identified and the surface material was removed. Approximately 1000 kg of the subsurface material was then sieved on site through 32, 22 and 16 mm sieves. Material larger than 32 mm was sorted using the template described above. The mass of sediment in 9 different size classes from 16 to 256 mm was weighed and recorded. The total mass of material less than 16 mm was also weighed, and a sub-sample was taken back to Vancouver for further analysis. In Vancouver the material was sieved at standard ½ phi increments down to 0.063 mm.

A1-4 Results and Analysis

A1-4.1 Suspended Load

From May through September 2004 and 2005, monthly suspended sediment samples were collected at each site. Samples were sent to the laboratory, where they were filtered to determine the suspended sediment concentration (TSS). Concentration values from each site were paired with the discharge at the time of measurement; these values are summarized in Table A1-1. The data were used to produce rating curves, as shown in Figure A1-2. Power functions were fit to the data to determine rating equations. Due to the wide scatter in the data, a rating equation could not be developed at GAL1B. The rating equations for GAL1A and GAL3 are summarized in Table A1-2.

Combining the rating equation with the discharge time series from each site, the daily mass of suspended sediment carried passed each site was calculated. Daily values were summed over the open water season to produce an annual estimate of the total mass of sediment for the two seasons. These values were converted into volumes by assuming a bulk density of 1800 kg/m³. The annual estimates for GAL1A and GAL3 are summarized in Table A1-3.

Appendix 1 - Fluvial Sediment Transport

**Table A1-1
Summary of Paired Suspended Sediment and Discharge
Measurements**

GAL1A				GAL1B				GAL3			
Date	Time	Discharge	TSS	Date	Time	Discharge	TSS	Date	Time	Discharge	TSS
30/06/2004		5.17	199	5/21/2005	9:45	5.5	10.8	9/29/2004		7.71	27.0
28/07/2004		5.2	390	5/21/2005	9:45	5.5	11.3	10/29/2004		3.76	7.0
01/09/2004		2.92	42	5/29/2005		7.28	268.0	5/29/2005		17.67	48
29/09/2004		0.41	5	6/3/2005	9:30	7.04	54.1	6/3/2005	9:50	15.29	28.6
5/28/2005		4.91	42.5	6/10/2005		7.93	331	6/3/2005	9:50	15.29	29.1
7/3/2005		4.49	64.3	6/19/2005		7.73	1300	6/10/2005		19.62	186
7/28/2005		4.89	257	6/25/2005		8.01	496	6/10/2005		19.62	177
9/1/2005		2.25	68.1	7/7/2005	10:45	0.98	274	6/19/2005		20.71	778
9/25/2005		2.05	13.5	7/7/2005	11:00	0.98	264	6/25/2005		17.29	264
9/25/2005		2.05	13.0	7/7/2005	11:15	1.08	312	7/8/2005	10:30	16.31	213
				7/7/2005	11:30	1.08	279	7/8/2005	11:00	16.66	181
				7/7/2005	11:45	0.88	273	7/8/2005	11:15	17	165
				7/7/2005	12:00	0.88	298	7/8/2005	11:30	17.33	163
				7/7/2005	8:00	1.09	423	7/8/2005	11:45	17.25	161
				7/7/2005	8:15	1	259	7/8/2005	8:45	15.85	214
				7/7/2005	8:30	1	291	7/8/2005	9:00	15.88	252
				7/7/2005	8:45	1.05	247	7/8/2005	9:15	16.25	239
				7/7/2005	9:00	1.05	286	7/8/2005	9:30	16.58	211
				7/7/2005	9:15	1.04	281	7/8/2005	9:45	16.75	225
				7/28/2005		10.24	513	7/8/2005	10:00	16.94	242
								7/28/2005		25.43	542
								9/1/2005		13.4	89.6
								9/25/2005		10.66	202
								5/21/2005	9:10	10.2	15.3

**Table A1-2
Suspended Sediment Rating Equations for GAL1A and GAL3**

Location	Rating Equation ¹	# of Observations	R ²
GAL1A	$SS = 11.04Q^{1.49}$	10	0.69
GAL3	$SS = 0.25Q^{2.30}$	24	0.59

Note 1. SS = suspended sediment concentration (mg/L), Q = discharge (m³/s)

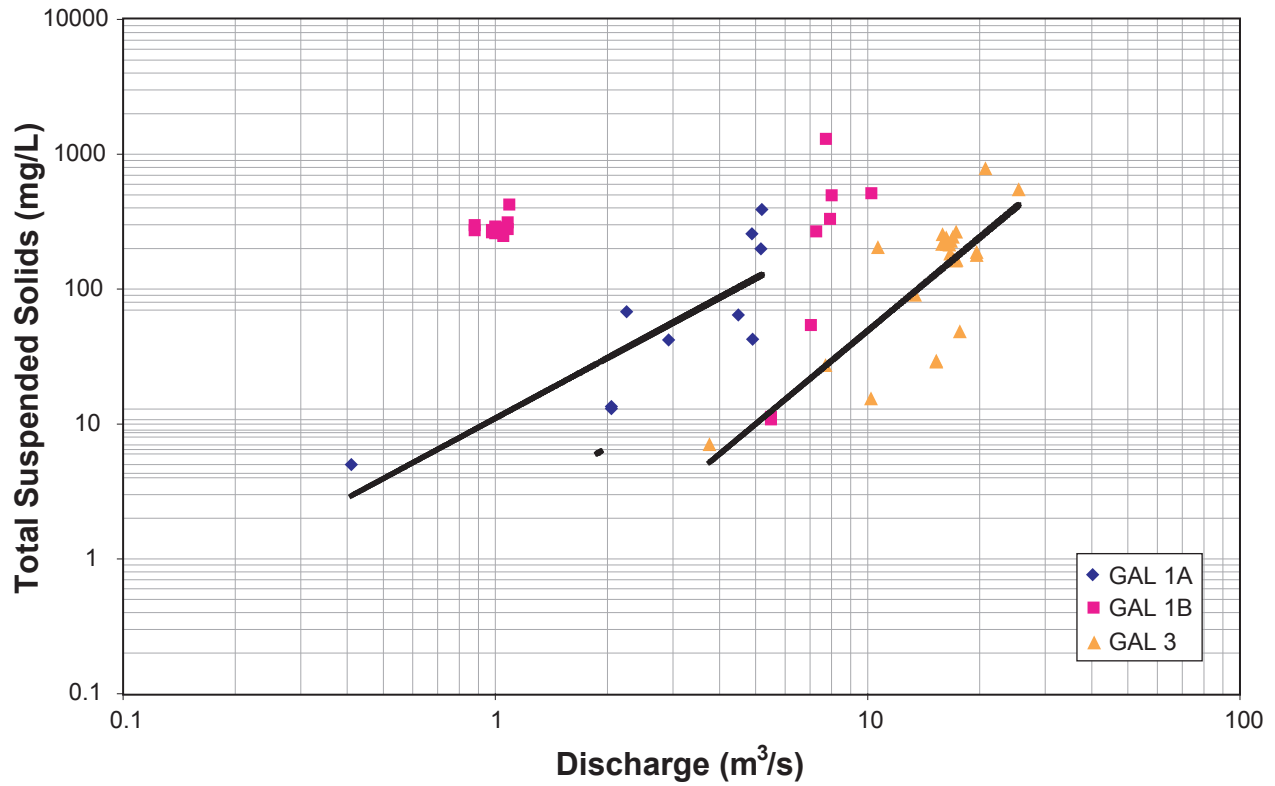


FIGURE A1-2

Suspended Sediment Rating Curves For GAL1-A and GAL3



**Table A1-3
Estimates of Annual Suspended Sediment Transport**

Location	Drainage Area (km ²)	Year ¹	Tonnes of Sediment ²	Error (%)	Volume of Sediment (m ³) ³	Sediment Yield (t/km ²)
GAL1A	24.4	2004	4670	±100	2595	191
		2005	4285	±100	2380	176
GAL3	117	2005	61200	±116	34000	523

Note 1. 2004 data for GAL3 not available as station was damaged
 2. Estimated over monitoring period (~May - Oct)
 3. Calculated assuming a bulk density of 1800 kg/m³

The sediment yield values for GAL1A seem reasonable for the region, as we would expect high sediment supply from the readily erodible glacial deposits in the basin. The values for GAL3 appear to be overestimated. There is a high degree of uncertainty with these results due to the amount scatter around the rating relations. Error was analysed by looking at the ratio of the difference between observed and predicted values to the predicted values. At two standard deviations, the error is ±100% and ±116% for the GAL1A and GAL3 rating curves respectively.

A1-4.2 Bed Load

Data from the pebble counts were used to produce grain size distributions of the surface material. Figure A1-3 shows the grain size distribution for the 4 sites, as well as a pooled distribution. It is recognized that the pebble count is biased towards under sampling the fine materials (Bunte and Abt, 2001); however, the method still accurately identifies important grain size parameters such as the median particle size (D₅₀) and the dominant particle size (D₉₀), which are important inputs for bed load transport formulae.

The surface material is often coarser than the subsurface because many of the fines have been winnowed away at the surface; the subsurface material often gives a better indication of the distribution of the material that is mobile in the stream. Data from the volumetric bulk samples were used to produce grain size distributions of the subsurface. Figure A1-4 shows the grains size distribution for the 4 sites, as well as a pooled distribution.

The grain size distributions are very similar between sites, producing only minor differences in transport estimates. Therefore, the pooled distributions were used for the final analysis. The hydrograph for GAL1B was incomplete for 2005, so instead, it was scaled using results from GWM6, which is ~2 km downstream. A number of different equations were used to calculate transport estimates; the equations used are summarized in Table A1-4. The Wilcock and Crowe (2003) equation was calculated using the BAGS software program from the USDA Forest Service, and the Parker (1990) equation was calculated using the ACRONYM program available from Parker. Results from the different equations are summarized in Table A1-5.

The bed load transport estimates shown in Table A1-5 range over four orders of magnitude for three of the four sites. A number of these estimates also appear to be unrealistically high. These results are not unexpected, given the acknowledged uncertainty associated with the transport

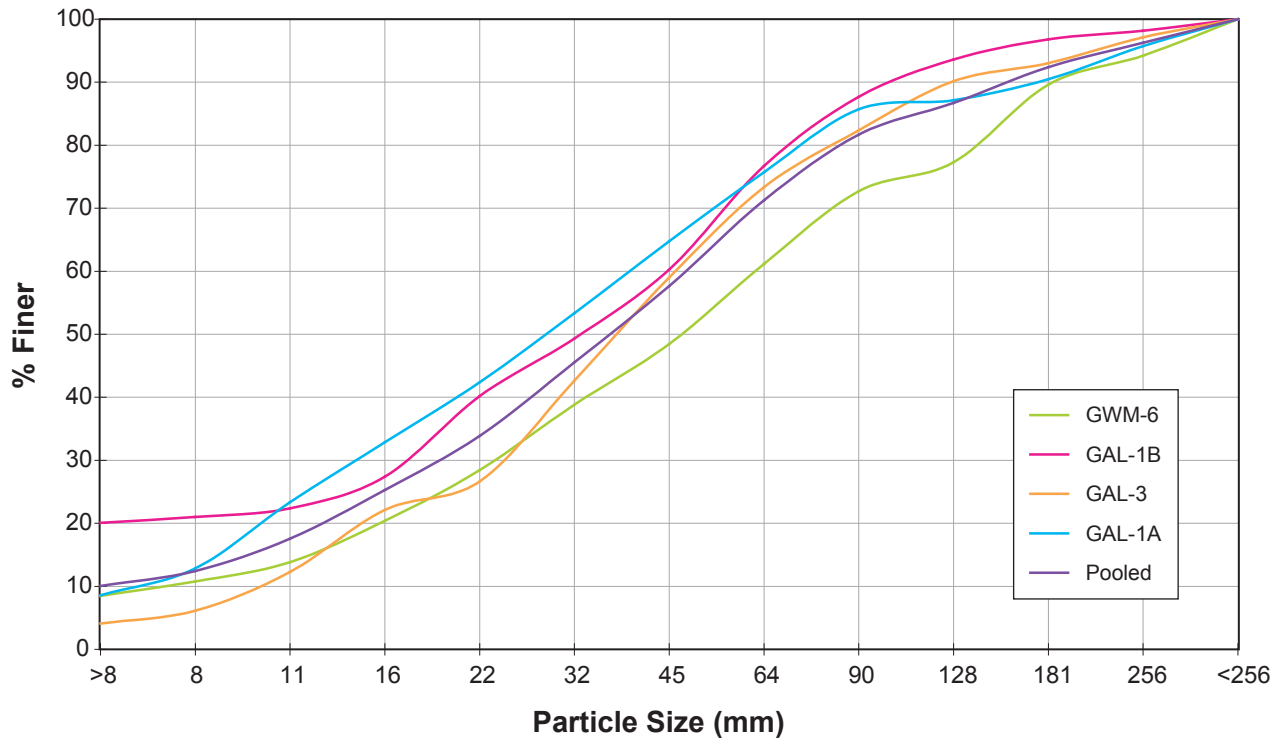
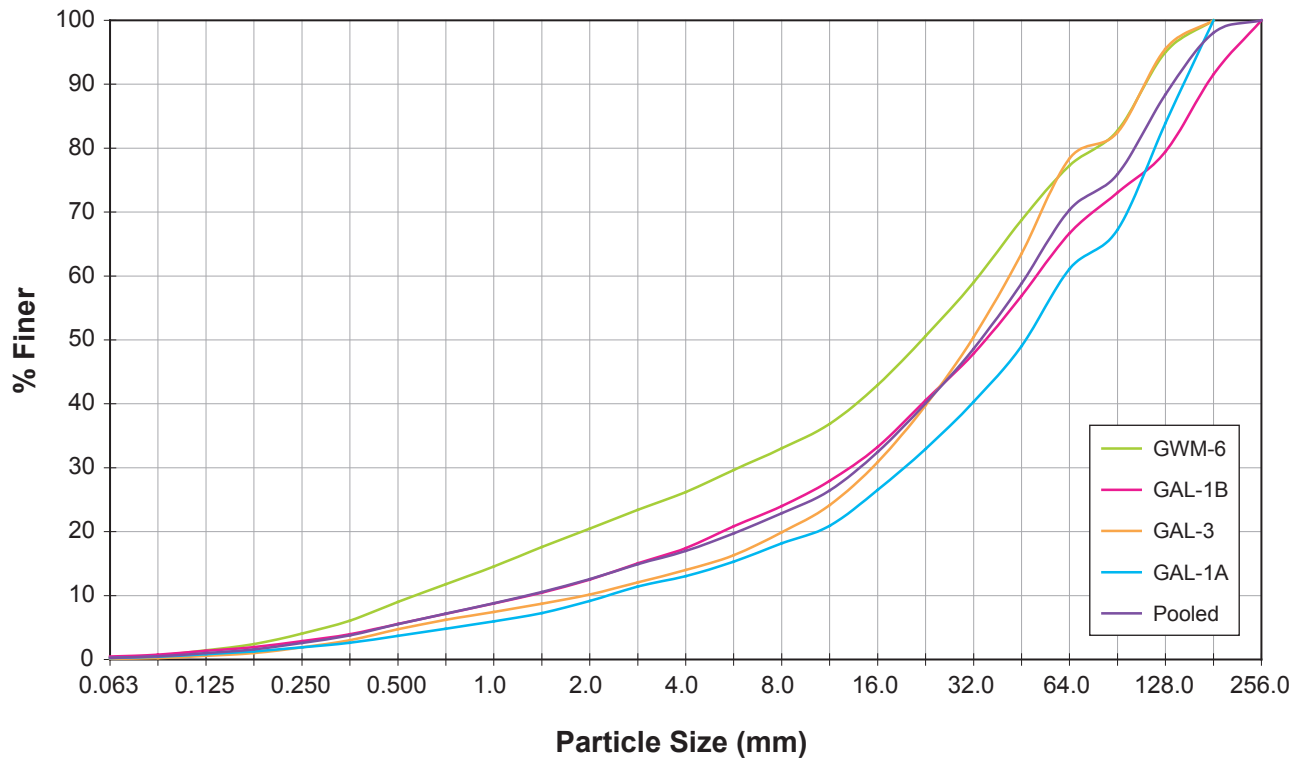


FIGURE A1-3

Grain Size Distributions for Surface Material





Grain Size Distributions for Subsurface Material

FIGURE A1-4



**Table A1-4
Summary of Sediment Transport Equations Used for Analysis**

Equation	Formula	Threshold value	Source
<u>Shear Stress Based Equations</u>			
Meyer-Peter and Muller (MPM)	$q_b^* = 8(\tau^* - \tau_c^*)^{3/2}$	$\tau_c^* = 0.047$	Meyer-Peter and Muller, 1948
MPM-revised	$q_b^* = 3.97(\tau^* - \tau_c^*)^{3/2}$	$\tau_c^* = 0.0495$	Wong and Parker, 2004
Ashida & Michiue	$q_b^* = 17(\tau^* - \tau_c^*)(\sqrt{\tau^*} - \sqrt{\tau_c^*})$	$\tau_c^* = 0.05$	Ashida & Michiue, 1972
Engelund & Fredsoe	$q_b^* = 18.74(\tau^* - \tau_c^*)(\sqrt{\tau^*} - 0.7\sqrt{\tau_c^*})$	$\tau_c^* = 0.05$	Engelund & Fredsoe, 1976
Luque & van Beek	$q_b^* = 5.7(\tau^* - \tau_c^*)^{1.5}$	$\tau_c^* = 0.037-0.0455$	Fernandez Luque & van Beek, 1976
<u>Stream Power Based Equation</u>			
Bagnold	$q_b^* = \frac{\gamma_s}{\gamma_s - \gamma} q_{bref} \left[\frac{\omega - \omega_o}{(\omega - \omega_o)_{ref}} \right]^{3/2} (d/d_{ref})^{-2/3} (D/D_{ref})^{-1/2}$ $\omega_o = 5.75[0.04(\gamma_s - \gamma)\rho]^{3/2} (g/\rho)^{1/2} D^{3/2} \log(12d/D)$; $q_{bref} = 0.1$; $(\omega - \omega_o)_{ref} = 0.5$; $d_{ref} = 0.1$; $D_{ref} = 0.0011$		Bagnold, 1980
<u>Grain-size Distribution Equations</u>			
Parker	$q_b^* = 0.00218 G(\phi_i)(\tau_i^*)^{3/2}$ $G(\phi) = \begin{cases} 5474 \left(1 - \frac{0.853}{\phi}\right)^{4.5} & \text{for } \phi > 1.59 \\ \exp[14.2(\phi - 1) - 9.28(\phi - 1)^2] & \text{for } 1 \leq \phi \leq 1.59 \\ \phi^{14.2} & \text{for } \phi < 1 \end{cases}$ $\phi_i = \omega \phi_{sgo} \left(\frac{D_i}{D_{sg}}\right)^{-0.0951}$, $\phi_{sgo} = \frac{\tau_{sg}^*}{\tau_{ssrg}^*}$, $\tau_{sg}^* = \frac{u_*^2}{RgD_{sg}}$, $\tau_{ssrg}^* = 0.0386$ $\tau_i^* \equiv \frac{\tau_b}{\rho RgD_i} = \frac{u_*^2}{RgD_i}$		Parker, 1990

**Table A1-5
Estimated Annual Bed Load Transport (tonnes)**

	GAL1A	GAL1B	GWM6	GAL3
Bagnold ¹	9	132	118	525
Bagnold ²	69	988	898	3050
Parker	130	28100	18900	201000
Wilcock and Crowe	93	40800	29700	22700
Meyer-Peter Mueller	292	415000	327000	1340000
Corrected MPM	29	189000	143000	638000
Ashida Michiue	6	316000	210000	1350000
Engelunde and Fredsoe	146	632000	486000	2170000
Fernandez Van Beek	1290	356000	303000	1060000

Notes 1. $\omega = \rho g d S_v$; 2. $\omega = \rho g Q S_w$; values in italics are unreasonably high

equations. Typically, these equations were developed for low gradient streams with fine grain-size distributions. Many of the equations are very sensitive to channel gradient, with small changes in the gradient making a large difference to the calculated transport rate. The channel gradient is very difficult to measure accurately in steep, mountain streams. Hence, equations with a high sensitivity to the gradient will not provide good results for mountain streams. Results for GAL-1A have a tighter range than estimates for other stations, with values ranging from 6 – 1290 tonnes/year. This is because GAL-1A has the shallowest stream gradient. In addition, the channels in Galore Valley contain a wide range of grain-sizes, with grain-sizes skewed to the coarser end. As a result bedload transport is not just a function of stream power. It is also affected by channel bed forms, with armouring (where larger particles protect smaller particles from erosion) significantly affecting the sediment transport rates. In such cases the bed load transport rate will be less than that predicted by standard sediment transport formulae.

Given the uncertainties associated with the estimation of bed load transport rates, it is difficult to assess which equation provides the best prediction of transport rates for Galore Creek. Bed load transport in mountain streams is still an area of active academic research. Hence, given the available field data it is not possible to make reliable estimates of bed load transport for Galore Valley.

A1-5 Summary

Sediment transport rates are expected to be high within the Galore Creek valley, as a result of high stream gradients, flow velocities, and an abundant supply of easily eroded, glaciofluvial material. Unfortunately, direct measurement of sediment transport was not possible; safety concerns precluded a standard suspended sediment sampling program and there is no device that can adequately measure bed load transport of large pebbles and cobbles. Using available data and sediment transport formulae, annual transport was estimated for suspended load and bed load; both estimates are associated with a high degree of uncertainty. Due to scatter in the data, reasonable estimates of suspended load could not be estimated for GWM-6 or GAL-3; for GAL-1A, suspended load over the monitoring period (May through October) was estimated to be 4500 ± 100% tonnes.

Appendix 1 - Fluvial Sediment Transport

Based on a number of different bed load equations, bed load estimates ranged over four orders of magnitude. Bed load transport in mountain streams is still an area of active academic research. Given the uncertainties associated with the estimation of bed load transport rates it was not possible to make reliable estimates of bed load transport for Galore Valley.

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**APPENDIX 2
SUMMARY OF CLIMATE CHANGE
PROJECTIONS FOR GALORE CREEK**

Appendix 2 – Summary of Climate Change Projections for Galore Creek

A2-1 Introduction

Over the past several decades there has been an increasing body of evidence to support a warming trend in the global climate. Global observations suggest a number of climate trends during the 20th century that include increased average surface temperature, precipitation, frequency of heavy precipitation events, and cloud cover; along with a reduction in the length of the freeze season, the frequency of extreme low temperatures, and the extent of snow cover and mountain glaciers. Many of these global observations have also been documented in British Columbia. These trends are likely to continue throughout the 21st century. All of the above listed variables are key elements of the hydrologic cycle and long term trends of such variables should be considered when assessing the future hydrologic regime of any watershed.

The purpose of this study is to provide projections of anticipated trends in precipitation and temperature in the Galore Creek Valley over the projected lifetime of the Galore Creek Project. It must be appreciated that there is a high degree of uncertainty in any climate change projection and this must be kept in mind when developing predictions of future climate trends for any specific region. To address this uncertainty, projections of the average change in temperature and precipitation will be made along with upper and lower estimates of the same variables, rather than providing one single estimate.

The report will discuss in detail:

- current climate trends in the Galore Creek region;
- climate change modelling; and
- the impact climate change may have on various aspects of the environment that could affect the hydrologic regime.

The report will provide quantitative estimates of:

- change in the annual and monthly precipitation into the 2020s, 2050s, and 2080s for the Galore Creek region;
- change in the annual and monthly average, minimum and maximum air temperature into the 2020s, 2050s, and 2080s for the Galore Creek region; and
- change in the annual, monthly, and daily runoff in Galore Creek near the proposed mine site based on UBC Watershed Model simulations.

A2-2 Recent Climate Trends

Regions in the higher latitudes of the Northern Hemisphere have exhibited some of the clearest evidence of climate change over the past century with observed trends such as warmer air

Appendix 2 – Summary of Climate Change Projections for Galore Creek

temperatures, glacial retreat, and longer, wetter summers. However, in some cases significant climate change trends are difficult to identify due to natural climate variability and lack of observed data. Both of these factors influence the identification of long-term climate trends within British Columbia.

Climate variables fluctuate over different temporal scales. Climate change refers to trends that occur over decades, centuries, or millennia, whereas climate variability refers to trends that occur over relatively shorter time periods of years or decades. Two significant natural cycles that affect the climate of British Columbia are the El Niño – Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO can have a period of between 5 and 15 years and the PDO of up to 60 years. Both cycles represent climate variability rather than climate change, and make the identification of climate change trends from historical data difficult. It has been suggested that only data records that extend longer than a full PDO cycle can be used to distinguish climate change rather than climate variability (MWLAP, 2002). This is an important consideration for observing climate change trends in Northern British Columbia where there are relatively few long-term climate records.

Nevertheless, in 2002, the former Ministry of Water, Land, and Air Protection (MWLAP), presented a summary of climate change trends for British Columbia in *Indicators of Climate Change for British Columbia (IndCC)*. The IndCC presents climate change trends for 8 eco-provinces in British Columbia. Galore Creek is located near the boundary of the Coast and Mountains eco-province and the Northern Boreal Mountains eco-province; therefore, trends from both eco-provinces will be presented in this report. According to the IndCC the climate change trends of the Coast and Mountains eco-province are:

- average annual temperature has increased by 0.6°C;
- average seasonal temperature has increased by 1.4°C and 0.8°C for winter and spring respectively with no corresponding trends in summer or fall temperatures;
- average annual night-time minimum temperature has increased by 0.9°C, with no corresponding trend in day-time maximum temperatures;
- average seasonal night-time minimum temperatures have increased by 1.2°C, 0.7°C, and 0.7°C for the spring, summer and fall respectively, with no corresponding trend in the winter;
- average seasonal day-time maximum temperature has increased by 1.9°C in the winter, decreased by 1.4°C in the summer with no trends evident in either the spring or fall;
- average annual precipitation has increased by 2% per decade; and
- snow pack depth has decreased by 6% per decade.

According to the IndCC the climate change trends of the Northern Boreal Mountains eco-province are:

- average annual temperature has increased by 1.7°C;
- average seasonal temperature has increased by 3.8°C for winter with no corresponding trends in the spring, summer, or fall temperatures;

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- average annual night-time minimum temperature has increased by 2.1°C, with no corresponding trend in day-time maximum temperatures;
- average seasonal night-time minimum temperatures have increased by 3.9°C and 1.3°C in the spring and summer respectively with no trends evident in either the winter or fall;
- average seasonal day-time maximum temperature has increased by 3.6°C in the spring with no corresponding trends in the summer, fall, or winter; and
- there is not enough data available to analyze precipitation climate change trends in this eco-province.

Both eco-provinces have experienced increases in annual temperature, winter temperatures, and night-time temperatures. Due to lack of historical data it is more difficult to observe common long-term trends in precipitation.

In order to assess whether there have been observable climate trends close to the study area, climate records were examined from weather stations in north western British Columbia. Three stations that had long term climate data (Dease Lake, Prince Rupert, and Stewart) were looked at; all are some distance from the project area. Significant trends in annual mean air temperature were observed at Dease Lake and Stewart, increasing by 2.0 and 1.4°C per century respectively. No significant trend was observed at Prince Rupert. None of the three stations exhibited a significant trend in annual precipitation. It is notable that most climate stations are located at lower elevations and it is difficult to extrapolate this data to higher elevations, which are more characteristic of the Galore Creek watershed.

Associated with recorded climate change, trends in historical flow records at a number of locations within British Columbia have been observed. These trends will be discussed later in this report along with potential impacts of future climate change on the hydrology of Galore Creek.

A2-3 Global Climate Models and Emission Scenarios

The most commonly used tools to project climate trends and climate change into the future are physically based general circulation models (GCMs). GCMs have the ability to simulate many climatologically significant processes as well as the interactions between the atmosphere, oceans, cryosphere, and land surface (Taylor and Barton, 2004). GCMs model the change in climate parameters as a result of climate forcers such as changes in the atmospheric concentration of greenhouse gases and aerosols. GCMs calculate changes in the long-term average, or normal, of a given parameter (temperature, precipitation, *etc.*). Climate normals are based on 30 year averages, so that GCM output is in the form of the amount of change in the annual value of a parameter averaged over 30 years from the current or baseline period. Generally the baseline period is considered to be from 1961-1990 and output is usually generated for the 2020s (2010-2039), 2050s (2040-2069), and the 2080s (2070-2099). These 30 year periods are often referred to as “time slices” and represent climate projections 20, 50, and 80 years into the future from the time this report was produced.

There are many different GCMs that have been developed and are maintained by a number of climate modelling centres. The Intergovernmental Panel on Climate Change (IPCC) recognizes

Appendix 2 – Summary of Climate Change Projections for Galore Creek

about 20 climate modelling centres that have their own series of GCMs. A few of the most common GCM series are listed in Table A2-1. Some of the major differences between GCMs are how oceans are treated and the resolution of the spatial grid used to discretize the earth's surface into separate uniform cells. As can be expected, each GCM produces slightly different climate projections. The diversity of future climate projections increases when the number of different emission scenarios, used as input to the various GCMs, is considered.

**Table A2-1
Common GCM Series**

Series Name	Modelling Centre
CGMC	Canadian Centre for Climate Modelling and Analysis
HadCM	British Hadley Centre for Climate Prediction and Research
GFDL-R	USA Geophysical Fluid Dynamics Laboratory
CSIROMk	Australian Commonwealth Scientific and Industrial Research Organization
ECHAM	German Climate Research Centre
CCSR	Japanese Centre for Climate Research Studies
NCAR	USA National Centre for Atmospheric Research

In 2000, the IPCC outlined a set of six plausible future greenhouse gas emission scenarios referred to as the SRES emission scenarios to be used as input to all GCMs. The most commonly used SRES scenarios are the A1, B1, A2, and B2 scenarios, which are summarized in Table A2-2. For a full description of the SRES scenarios see Nakicenovic *et al.*, 2000. Prior to the SRES scenarios; the IPCC had outlined a different set of scenarios in 1994 referred to as the IS92 scenarios, which some older studies reference but will not be discussed further in this study.

**Table A2-2
Summary of the Main SRES Emission Scenarios**

Name	Description
A A1	<ul style="list-style-type: none"> • Emphasis on continued economic development • Global population peaking in the middle of the century and declining after that • Global focus
A2	<ul style="list-style-type: none"> • Emphasis on continued economic development • Global population continuing to grow throughout the century • Regional focus
B B1	<ul style="list-style-type: none"> • Emphasis on environment and reduction in material wealth • Global population peaking in the middle of the century and declining after that • Global Focus
B2	<ul style="list-style-type: none"> • Emphasis on environment and reduction in material wealth • Global population continuing to grow throughout the century • Regional Focus

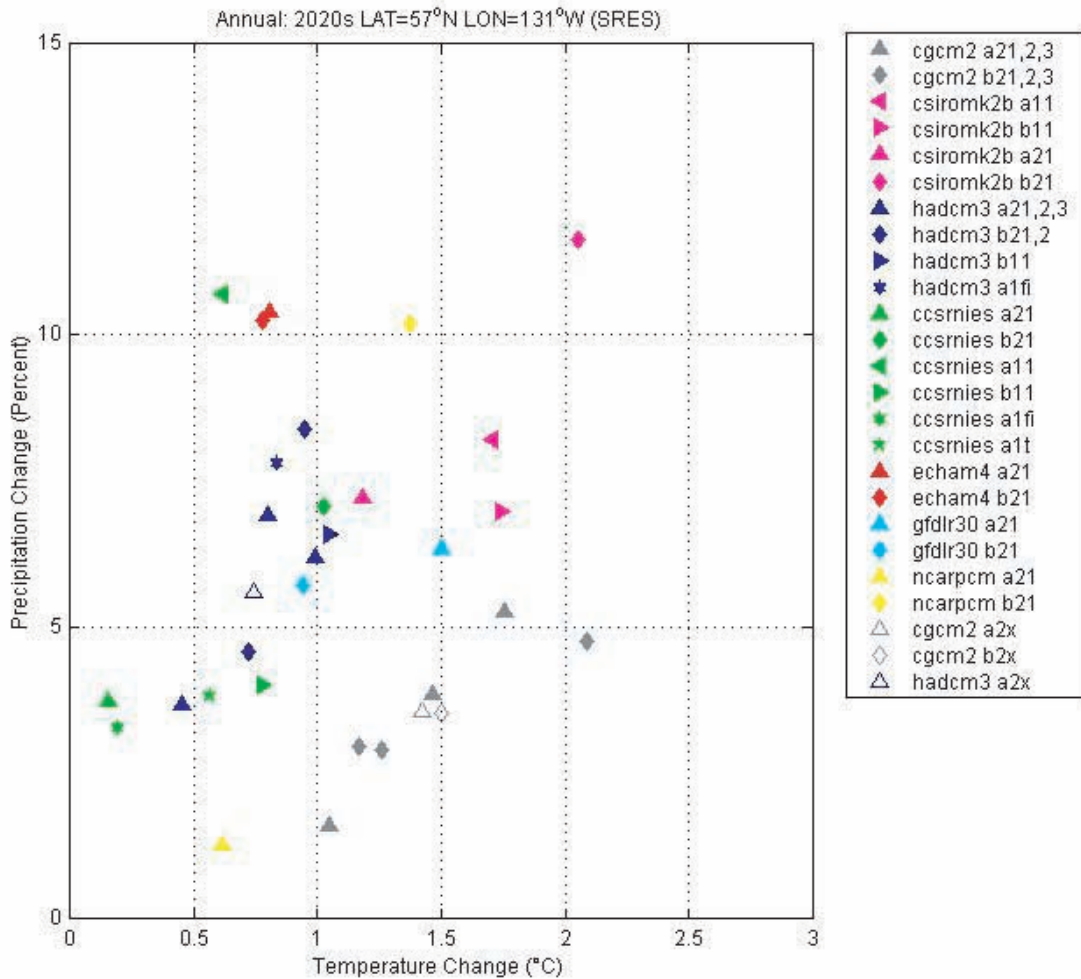
Appendix 2 – Summary of Climate Change Projections for Galore Creek

In addition to the various GCMs and emission scenarios, the initial values of parameters within each GCM may be different, further increasing the number of climate projections. Figure A2-1 shows an example of the array of climate projections produced by various combinations of GCMs, emission scenarios, and initial model conditions.

A difficulty arises in deciding which emission scenario and GCM to use in order to obtain climate change projections. Studies that have looked at future climate change in Western North America have used a variety of combinations of emission scenarios and GCMs. CGCM1 has been used under an emission scenario of double the current CO₂ concentration for a watershed on Vancouver Island and one in the Selkirk Mountains (Loukas *et al.*, 2002), however, the reason for using the CGCM1 model is not explicitly stated in the study report. The CCM3 model, one of the NCAR series of GCMs, was used in two watersheds in the Pacific Northwest of the US under an emission scenario of double the current CO₂ concentration (Leung and Wigmosta, 2000). The CCM3 model was used in this study because, as the authors state, it produces reasonable simulations of observed large scale conditions over the area of interest. Also based on an emission scenario of double the atmospheric CO₂ concentration, data from the CGCM2, a DFDL transient model, and the Goddard Institute for Space Studies (GISS) General Circulation Model were presented for the Yukon and British Columbia (Taylor, 1997). In the Okanagan Basin, the A2 and B2 emission scenarios were applied to the CGCM2, HadCM3, and CSIROmk2 models (Taylor and Barton, 2004). The use of two emission scenarios was so that one high (A2) and one low (B2) emission scenario was applied to each model. The selection of the three GCMs was based on a number of criteria suggested by the Canadian Institute for Climate Studies. For the Mackenzie Valley, 29 combinations of 7 GCMs and the 6 SRES scenarios were evaluated on a seasonal basis for climate projections for the 2020s and 2050s (Burn *et al.*, 2005). Although 29 output scenarios were originally evaluated only output that was the median and top and bottom 86th percentiles based on annual and winter change in temperature were selected for further use.

The suitability of applying any GCM to a specific location may be gauged by comparing the observed climate normals to normals of the same period simulated by that GCM. Bonsal *et al.* (2003) compared the ability of 7 GCM series to model current (1961-1990) climate conditions in the western cordillera of Canada. It was found that different models were the best at simulating air temperature and precipitation and that in general, all the GCMs were much better at modelling the magnitude and spatial variability of temperature than of precipitation. This observation is consistent with those from this study as well as a number of other previous studies (Hengeveld, 1997; MWLAP, 2002; and Taylor and Barton, 2004). A comparison of the same models specifically to the Galore Creek site is provided in Section A2-4.1.

Based on data presented in Section A2-4.1 of the present study and that done by Bonsal *et al.* (2003), it is difficult to state that any one GCM is the most suitable to apply to Galore Creek. The IPCC state that comparative strengths and weaknesses of the available GCMs do not allow assertion that one model is the “best” and that a number of GCMs should be used when considering climate change projections. Therefore, this is the strategy adopted in this study; data from all simulations using SRES scenarios available on the CCIS website are considered.



Range of Output from a Number of GCMs and SRES Scenarios.
(Obtained from the Canadian Climate Impacts and Scenarios (CCIS) Website)

FIGURE A2-1



When considering GCM output it is important to have an understanding of the main uncertainty of the model results. A major issue with using GCM data is that the spatial resolution of the models is so large that local and even regional topography is not represented within the models. In one model, the western coast of the United States is represented as a gentle slope rising from the Pacific Ocean to a summit in Utah (Giorgi and Mearns, 1991 referenced in Hauer *et al.*, 1998). The lack of topography in GCMs is a significant source of uncertainty in model output (Loukas *et al.*, 2002; Taylor, 1997). This uncertainty increases in areas of mountainous terrain and diverse topography, where weather conditions can vary greatly between mountain ridges, hill slopes, and valley bottoms (MWLAP, 2002). Uncertainty in precipitation projections is generally greater than temperature (MWLAP, 2002; Taylor and Barton, 2004), which is reflected in greater variability in future precipitation projections than temperature projections. Additionally, uncertainty in GCM output increases as the scale of application of the output decreases (Xu, 1999) and situations that require consideration of climate change are generally at the local scale (Xu, 1999). However, GCMs are currently the best available tools to project future climate change.

A2-4 Galore Creek Climate Projections

For the current study, a summary of the annual and monthly temperature and precipitation data for the baseline, 2020s, 2050s, and 2080s time slices will be presented based on data available from the Canadian Climate Impacts and Scenarios (CCIS) website. Data from GCMs from seven common climate modelling centres that have applied the SRES emission scenarios are included.

GCM output is produced at a very large spatial (>40 000km²) and temporal (annual and monthly) scales. Regardless of the uncertainty in GCM output, data at this spatial scale is often considered to be too large for hydrological applications. This is true for the Galore Creek area where the majority of the watersheds of interest are less than 1000km². Although annual or monthly data is appropriate for some hydrological applications, for certain applications, such as deterministic modelling, daily time-series are required. There are a number of methods that have been used to downscale GCM output to finer spatial and temporal resolutions. However, many of these methods, such as statistical downscaling, require adequate long-term historical weather records or others, such as nested modelling, require significant climate modelling expertise. Therefore, for this study, no spatial downscaling was performed and the “delta” method was used for temporal downscaling. The “delta” method is the adjustment of a known-time series by the projected climate changes generated by GCMs and has been used by a number of authors in climate change assessments in British Columbia including Loukas *et al.*, 2002 and Taylor and Barton, 2004. For this study, the monthly projected changes in degrees Centigrade in maximum and minimum temperatures and percent change in precipitation were applied to the observed daily data for 2004 to 2005 from Galore Creek. For a detailed discussion of downscaling methods, refer to Semenov and Barrow, 1997; Wilby *et al.*, 2002; and Xu, 1999.

Data was obtained from the single cell of each GCM that was centered the closest to the coordinates provided for Galore Creek. The centered coordinates for the cells used to obtain data for this paper are listed along with the grid resolutions of each GCM in Table A2-3.

**Table A2-3
Spatial Resolution and Coordinates of GCM Grids
Located Closest to Galore Creek**

GCM	Grid Resolution (km²)	Coordinates (decimal degrees)
Galore Creek		57.14, -131.44
CGCM2	74 000	57.52, -131.25
HadCM3	50 000	57.50, -131.25
GFDL-R30	44 000	57.02, -131.25
CSIROMk2b	95 000	55.75, -129.38
ECHAM4	41 000	57.21, -132.19
CCSRHIES	168 000	58.14, -129.38
NCARPCM	41 000	57.21, -132.19

A2-4.1 Baseline Climate (1961 to 1990)

It is important to first compare current climate normal data for Galore Creek to GCM output for the same time period. It must be noted that for all the GCMs the baseline period is considered to be from 1961 to 1990. Unfortunately, there is not sufficient historical climate data from Galore Creek to generate climate normals for this period. Therefore, the current climate data that has been recorded during Galore Creek Baseline Program is assumed to adequately represent the baseline period. Based on a comparison of data from 2003, the most recent year with complete climate data available from Environment Canada, to climate normal data for the baseline period at climate stations in the region, this is an acceptable assumption (see Table A2-4).

**Table A2-4
Climate Normals Compared to Data From 2004 at Climate Stations
Near Galore Creek**

Station	Variable	Climate Normals (1961 to 1990)	2003 Data
Dease Lake	Average Temperature (°C)	-1.1 ± 0.9	-0.3
	Annual Precipitation (mm)	421 ± 67	526
Prince Rupert	Average Temperature (°C)	7.0 ± 0.7	7.8
	Annual Precipitation (mm)	2535 ± 238	2708
Stewart	Average Temperature (°C)	5.6 ± 0.8	6.3
	Annual Precipitation (mm)	1830 ± 212	1875

Table A2-5 compares current annual and monthly climate data for Galore Creek to the baseline climate as modelled by several GCMs. Considering uncertainty in climate modelling and the differences in the spatial and temporal scales of model output to the observed data, the modelled data compares well to the observed data.

**Table A2-5
Monthly Precipitation and Temperature Data as Modelled by Several
GCMs for the Current Climate (1961-1990) of Galore Creek**

Month	Current Data	CGCM2	HadCM3	GFDL-R30	CSIROMk2b	ECHAM4	CCSRNIES	NCARPCM
<i>Mean Air Temperature (°C)</i>								
Annual	2.5	1.2	-3	2.1	4.6	1.8	1.1	-2.1
January	-11.5	-6.9	-10.2	-6.2	-5.2	-4.6	-7.2	-11.4
February	-4.7	-8.0	-10.5	-4.6	-4.7	-3.9	-9.4	-9.1
March	-1.3	-7.4	-7.2	-4.1	-0.5	-2.3	-8.5	-7.0
April	2.9	-3.6	-4.6	-0.8	5.1	-0.2	-0.6	-4.7
May	8.5	1.0	-1.9	5.5	10.7	2.6	6.2	0.5
June	11.5	7.5	4.8	9.8	13.9	7.9	10.6	4.6
July	11	10.7	7.7	12.0	15.5	11.0	12.3	6.5
August	12.6	11.4	6.0	11.4	12.4	10.1	10.8	5.9
September	7	8.4	2.2	7.9	8.7	6.8	7.4	3.9
October	1.7	4.5	-2.2	2.1	3.7	2.0	2.7	0.2
November	-2.3	1.5	-8.5	-3.1	0.1	-2.6	-3.5	-5.9
December	-5.3	-1.3	-10.0	-5.2	-3.8	-4.9	-7.3	-9.3
<i>Precipitation (mm/day)</i>								
Annual	6.1	5.8	3.9	3.8	5	4.8	3.1	5.3
January	8.7	7.0	4.4	4.1	5.3	5.8	4.1	4.9
February	8.8	6.2	3.2	3.7	5.0	5.3	3.3	3.8
March	4.3	4.9	3.5	3.1	4.1	4.9	2.3	4.3
April	5.2	4.0	2.7	3.2	3.9	4.1	2.2	3.4
May	2.9	4.5	2.0	2.9	4.0	3.9	2.4	3.3
June	1.5	3.8	2.1	2.5	3.6	2.3	2.1	2.9
July	2.2	3.9	3.2	2.4	2.8	2.6	1.9	3.6
August	3.6	4.4	4.3	3.3	3.8	4.2	2.7	7.1
September	9.0	7.1	5.6	5.0	6.5	6.3	3.8	9.9
October	10.1	8.5	5.7	6.3	7.4	5.7	4.7	9.0
November	9.0	7.3	4.8	4.9	7.4	6.2	4.1	6.4
December	8.7	7.8	4.7	4.5	5.9	6.1	4.0	5.5

A2-4.2 Future Climate Projections

Climate change projections into the 2020s, 2050s, and 2080s are presented below for the Galore Creek region. Projections were made of annual and monthly mean, maximum, and minimum air temperature as well as precipitation. All simulations using SRES scenarios that had data available on the CCIS website were considered. This resulted in the inclusion of projections from 29 separate simulations, which are listed in Table A2-6, for mean temperature and precipitation and 26 simulations for maximum and minimum temperature. In Table A2-6 the first two characters of the SRES emission scenarios represent the actual emission scenario and the last character, if present, represents different initial conditions for the simulations. For each individual projection, the results from all simulations were statistically ranked. The results representing the 10th percentile, median, and 90th percentile were then selected as low, median, and high estimates and are presented in Tables A2-7 to A2-12.

**Table A2-6
GCMs and SRES Emission Scenarios Included in the Current Study**

GCM	SRES	GCM	SRES	GCM	SRES
CGCM2	A2-1	ECHAM4	A2*	HadCM3	A1
	A2-2		B2		B1
	A2-3				A2-1
	B2-1	NCARPCM	A2		A2-2
	B2-2		B2		A2-3
	B2-3				B2-1
GFDL-R30	A2*	CCSRNIES	A1-1	CSIROMk2b	B2-2
	B2*		A1-2		A1
			A1-3		B1
		B1	B1		
		A2	A2		
		B2	B2		

**Table A2-7
Mean Temperature and Precipitation Projections
into the 2020s (2010-2039) for Galore Creek**

Period	Estimate		
	10th Percentile	Median	90th Percentile
<i>Mean Temperature (change from baseline, °C)</i>			
Annual	0.6	1.0	1.7
January	-1.2	0.7	2.7
February	-0.4	1.0	3.0
March	0.3	0.9	2.4
April	0.3	1.0	1.9
May	0.4	1.0	2.4
June	0.2	0.9	2.2
July	0.2	0.9	1.5
August	0.7	1.2	1.6
September	0.4	0.9	1.3
October	0.5	1.1	1.8
November	0.7	1.2	2.0
December	0.2	1.3	2.1
<i>Precipitation (change from baseline, %)</i>			
Annual	1.6	4.4	7.2
January	-6.9	1.6	14.7
February	-3.8	5.8	28.9
March	-1.3	12.2	19.3
April	-6.8	7.2	19.8
May	-2.5	4.1	16.0
June	-8.9	-1.0	20.0
July	-6.4	1.2	16.6
August	-7.0	3.5	15.6
September	-6.1	3.1	16.8
October	-2.3	5.8	21.8
November	1.5	10.4	17.4
December	-1.0	7.6	16.7

Table A2-8
Maximum and Minimum Temperature Projections
into the 2020s (2010-2039) for Galore Creek

Period	Estimate		
	10 th Percentile	Median	90 th Percentile
<i>Maximum Temperature (change from baseline, °C)</i>			
Annual	0.5	0.9	1.5
January	-1.2	0.6	1.9
February	-0.4	0.8	2.4
March	0.2	0.8	2.1
April	0.2	0.5	1.4
May	0.3	1.0	3.0
June	0.0	0.8	2.5
July	0.2	0.9	1.5
August	0.6	1.0	1.7
September	0.3	0.8	1.5
October	0.6	1.1	1.6
November	0.7	1.3	2.1
December	0.2	1.1	1.7
<i>Minimum Temperature (change from baseline, °C)</i>			
Annual	0.7	1.1	2.4
January	-1.2	0.6	4.3
February	-0.3	1.3	3.6
March	0.3	0.9	3.3
April	0.4	1.0	2.9
May	0.5	1.4	2.6
June	0.5	1.2	2.3
July	0.8	1.2	1.6
August	0.8	1.2	2.0
September	0.5	0.9	1.4
October	0.5	1.0	2.8
November	0.5	1.3	2.8
December	0.5	1.4	3.0

Table A2-9
Mean Temperature and Precipitation Projections
into the 2050s (2040-2069) for Galore Creek

Period	Estimate		
	10 th Percentile	Median	90 th Percentile
<i>Mean Temperature (change from baseline, °C)</i>			
Annual	1.6	2.5	3.1
January	0.5	2.6	4.0
February	0.9	2.7	4.1
March	-0.1	2.4	4.4
April	0.9	2.8	3.7
May	1.1	2.3	4.3
June	1.3	2.3	3.0

(continued)

**Table A2-9
Mean Temperature and Precipitation Projections
into the 2050s (2040-2069) for Galore Creek (completed)**

Period	Estimate		
	10th Percentile	Median	90th Percentile
July	1.3	2.1	2.9
August	1.8	2.3	2.9
September	1.6	2.0	2.5
October	1.4	2.3	3.1
November	1.2	2.7	4.6
December	1.5	2.7	5.2
<i>Precipitation (change from baseline, %)</i>			
Annual	1.2	9.7	19.7
January	0.4	13.8	23.1
February	4.4	12.1	35.4
March	1.1	18.4	29.4
April	3.8	13.3	37.4
May	-0.5	9.7	18.8
June	-6.3	4.5	16.8
July	-12.4	3.6	20.3
August	-3.8	6.3	16.1
September	-3.2	8.2	24.9
October	5.8	15.7	24.7
November	3.6	15.8	27.0
December	1.0	13.5	31.7

**Table A2-10
Maximum and Minimum Temperature Projections
into the 2050s (2040-2069) for Galore Creek**

Period	Estimate		
	10th Percentile	Median	90th Percentile
<i>Maximum Temperature (change from baseline, °C)</i>			
Annual	1.5	2.1	3.2
January	0.5	2.1	3.7
February	0.8	2.0	3.9
March	-0.1	2.4	3.7
April	0.6	1.8	3.4
May	0.8	2.3	5.0
June	1.2	2.4	3.3
July	1.5	2.1	3.1
August	1.6	2.2	3.2
September	1.6	1.9	2.8
October	1.6	2.3	3.1
November	1.3	2.5	5.2
December	1.1	2.2	5.9

(continued)

**Table A2-10
Maximum and Minimum Temperature Projections
into the 2050s (2040-2069) for Galore Creek (completed)**

Period	Estimate		
	10th Percentile	Median	90th Percentile
<i>Minimum Temperature (change from baseline, °C)</i>			
Annual	1.8	2.9	3.9
January	0.5	2.3	5.3
February	1.2	3.2	5.8
March	0.1	3.2	5.8
April	1.2	3.0	5.5
May	1.7	2.8	4.8
June	1.8	2.5	3.2
July	2.0	2.5	3.1
August	1.8	2.4	3.4
September	1.7	2.2	2.6
October	1.3	2.6	4.7
November	0.9	3.7	5.9
December	1.9	3.6	6.5

**Table A2-11
Mean Temperature and Precipitation Projections
into the 2080s (2070-2099) for Galore Creek**

Period	Estimate		
	10 th Percentile	Median	90 th Percentile
<i>Mean Temperature (change from baseline, °C)</i>			
Annual	2.2	4.0	5.9
January	0.2	4.4	7.6
February	1.7	5.0	7.9
March	1.2	4.2	7.5
April	1.7	4.3	6.8
May	2.2	4.0	5.7
June	1.6	3.5	5.4
July	2.5	3.5	5.3
August	2.5	3.6	5.6
September	2.2	3.3	5.0
October	2.1	3.6	5.1
November	2.0	4.1	7.9
December	2.4	3.7	8.5
<i>Precipitation (change from baseline, %)</i>			
Annual	3.4	11.6	38.1
January	4.4	17.6	35.5
February	4.8	15.9	37.7
March	-2.0	17.3	41.6
April	3.0	18.9	41.9
May	-5.2	9.6	24.5

(continued)

**Table A2-11
Mean Temperature and Precipitation Projections
into the 2080s (2070-2099) for Galore Creek (completed)**

Period	Estimate		
	10 th Percentile	Median	90 th Percentile
June	-4.8	11.2	29.2
July	-4.5	7.8	21.8
August	-2.0	14.2	25.5
September	1.7	13.6	39.4
October	4.3	19.9	41.9
November	11.0	26.4	53.3
December	3.3	26.1	47.2

**Table A2-12
Maximum and Minimum Temperature Projections
into the 2080s (2070-2099) for Galore Creek**

Period	Estimate		
	10 th Percentile	Median	90 th Percentile
<i>Maximum Temperature (change from baseline, °C)</i>			
Annual	2.1	3.7	6.8
January	0.3	3.9	7.4
February	1.2	4.1	7.6
March	0.8	3.4	7.7
April	0.9	3.3	6.2
May	2.8	4.6	6.8
June	1.2	3.8	5.7
July	2.5	3.2	5.5
August	2.3	3.4	5.7
September	2.2	3.5	5.1
October	2.2	3.4	6.2
November	2.2	3.5	8.8
December	2.1	3.1	9.6
<i>Minimum Temperature (change from baseline, °C)</i>			
Annual	2.6	4.7	7.0
January	0.4	6.0	8.3
February	1.8	5.6	9.5
March	1.5	5.3	9.3
April	2.1	4.8	8.2
May	3.1	4.8	6.7
June	2.6	3.9	5.7
July	2.9	3.9	5.7
August	2.7	4.2	5.7
September	2.3	3.3	5.2
October	2.0	3.9	6.7
November	1.7	5.0	8.8
December	2.8	4.3	10.0

A2-4.3 Summary of Climate Change Projections

The above tables summarize the current best projections of the impact of climate change on the temperature and precipitation in the Galore Creek study area. Although the projections exhibit a high degree of variability between the low, median, and high projections for each time slice, the overall trend is for warmer annual mean temperature and increased annual precipitation. Associated with the projected increase in mean temperature are increasing minimum and maximum temperatures; however minimum temperatures are projected to change more than maximum temperatures, which would result in a decreased annual temperature range.

A2-5 Potential Impacts of Climate Change on the Hydrologic Regime

Precipitation and air temperature are key variables that drive the hydrology of a watershed. Therefore, changes in those variables will lead to changes in watershed hydrology. However, the hydrologic cycle is very complex. Many characteristics of a watershed are liable to be influenced by changes in the climate and complicate the prediction of how runoff from a watershed will respond to changing climate variables. A general discussion is provided below on potential interactions between climate variables and watershed characteristics. This is followed by a presentation of historical trends and predicted future changes simulated by deterministic hydrologic models in discharge of a few British Columbian rivers.

A2-5.1 General Discussion of Interactions between Climate Change and Watershed Hydrology

A2-5.1.1 Increased Air Temperatures and Precipitation

The interaction of air temperature and precipitation is very influential on the form of the annual hydrograph. Although the total precipitation will determine the total annual runoff from a watershed, it is the temperature that will shape the annual hydrograph. Air temperature determines if precipitation is stored as snowpack and when the stored water is released. Increased precipitation will lead to greater annual rainfall; however an increase in temperature could result in decreased snowfall at lower elevations. This would lead to a decrease in snow pack depth at lower elevations, which is supported by current climate trends (MWLAP, 2002; Leung and Wigmosta, 2000).

A2-5.1.2 Glacial Cover

Warmer air temperatures would lead to increased glacial ablation and glacial retreat at lower elevations, while increased precipitation could lead to glacial growth at higher elevations (Brugman *et al.*, 1997). Recent trends in British Columbia have shown that whether a glacier has been melting, growing, or remained stable depends on its elevation (MWLAP, 2002). For glaciers that span a large range of elevations both processes could occur simultaneously. This appears to be the case for some of the glaciers and ice fields in More Creek, a neighbouring watershed of Galore Creek. Preliminary comparisons of glacial cover between TRIM data from the early 1980s and IRS satellite imagery from the late 1990s show that although glaciers have receded by as much as 200m, the total glacial or permanently ice-covered area within the

Appendix 2 – Summary of Climate Change Projections for Galore Creek

watershed has increased. On the other hand, glacial elevations have receded and glacial coverage has declined in the Galore Creek watershed.

Using the UBC Watershed Model (UBCWm), the impact of the reduction of glacial coverage in Galore Creek was investigated. A calibrated model of the sub-watershed that the Galore Creek mine site will be located in (sub-watershed GAL-1A) was run with observed 2004/2005 meteorological data and with the older TRIM glacial data and then with the more recent satellite imagery glacial data. This represented a 27% reduction in glacial area of the watershed. All other watershed and meteorological variables were held constant between the two runs. Results of this investigation are shown in Figure A2-2. The total annual runoff decreased by 5% and the total annual glacial melt decreased by 25%. As expected, all of the differences were observed between May and October.

A2-5.1.3 Vegetation

An additional complication is that changes in climate variables will affect the vegetation of an area which in turn can affect the hydrologic regime. Increased temperatures and precipitation may lead to changes in composition and productivity of the vegetative community. Increased temperatures could also increase the elevation of the tree line resulting in a greater area of a watershed under vegetative cover. A 1°C increase in air temperature has been observed to raise the elevation of the tree line by 100 - 180m (Fanta, 1992 and Korner, 1992 referenced in Loukas *et al.*, 2002). Increases in vegetative biomass due to either increased productivity or increased area would result in greater evapotranspiration within the watershed. However, this could be counteracted by a decrease in evapotranspiration due to closure of plant stomata as a result of increased CO₂ concentrations (Cure and Acock, 1986 and Parry, 1992 referenced in Loukas *et al.*, 2002). Increased vegetative biomass could also act to slow overland runoff, increase groundwater recharge (Loukas *et al.*, 2002), and alter the hydrograph shape of individual runoff events.

A2-5.2 Observed Historical and Predicted Future Trends in Watershed Hydrology

As can be seen in the above discussion the affects of climate change on the hydrology of a watershed are varied and sometimes opposing. However, based on previous studies involving observed historical data as well as hydrologic modelling of British Columbian watersheds there is general agreement that under warmer and wetter conditions the annual hydrograph will have an earlier, but potentially lower peak discharge during freshet, lower late summer discharges, and greater early winter discharges.

A2-5.2.1 Observed Historical Trends

On the Upper Similkameen River the spring freshet, on average, occurred earlier and had a lower peak flow and summer low flows were lower than during the late 1980s and early 1990s than the 1970s (MWLAP, 2002).

Although there is no significant trend in the date of the annual peak flow of the Fraser River between 1912 and 1998, the date that one third and one half of the annual cumulative discharge flows past Hope is advancing (occurring earlier) by 11 and 9 days/century, respectively (MWLAP, 2002).

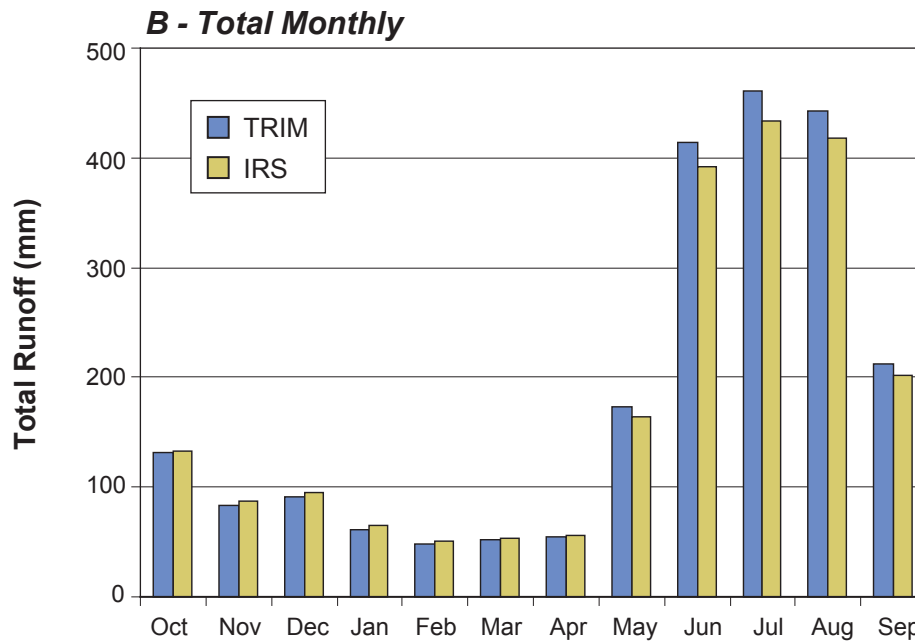
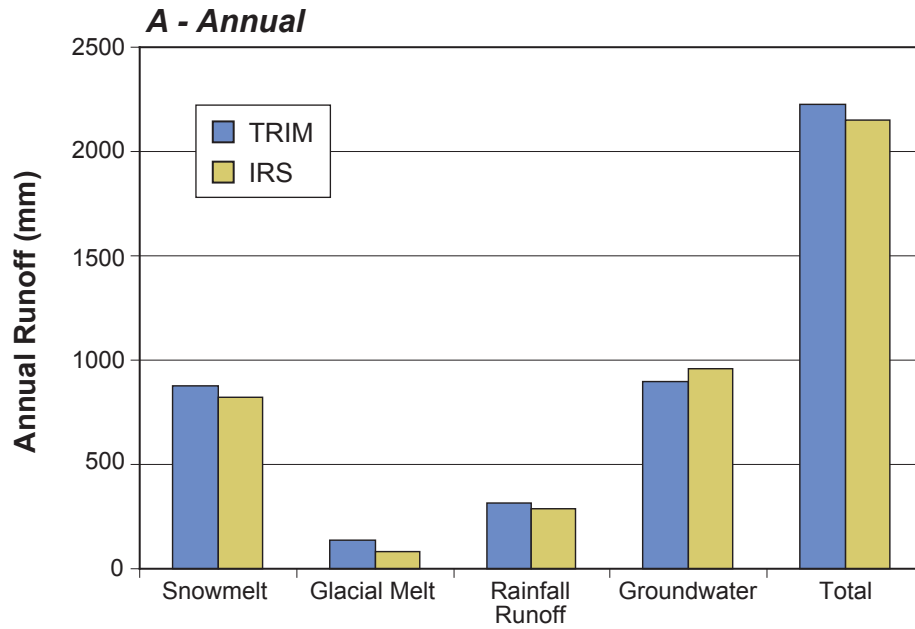


FIGURE A2-2

Modeled Annual and Total Monthly Runoff from Galore Creek using Glacial Cover Data Based on TRIM and IRS Satellite Data



Whitfield (2001) has examined the hydrologic trends between the mid 1970s and the mid 1990s at 275 gauging stations in British Columbia. All stations in north western British Columbia that were included in the study show a shift in peak annual flows to earlier in the year. Additionally, most have exhibited a lower peak in the annual hydrograph along with an increase in annual runoff, increased winter discharge, and a decrease in later summer discharge.

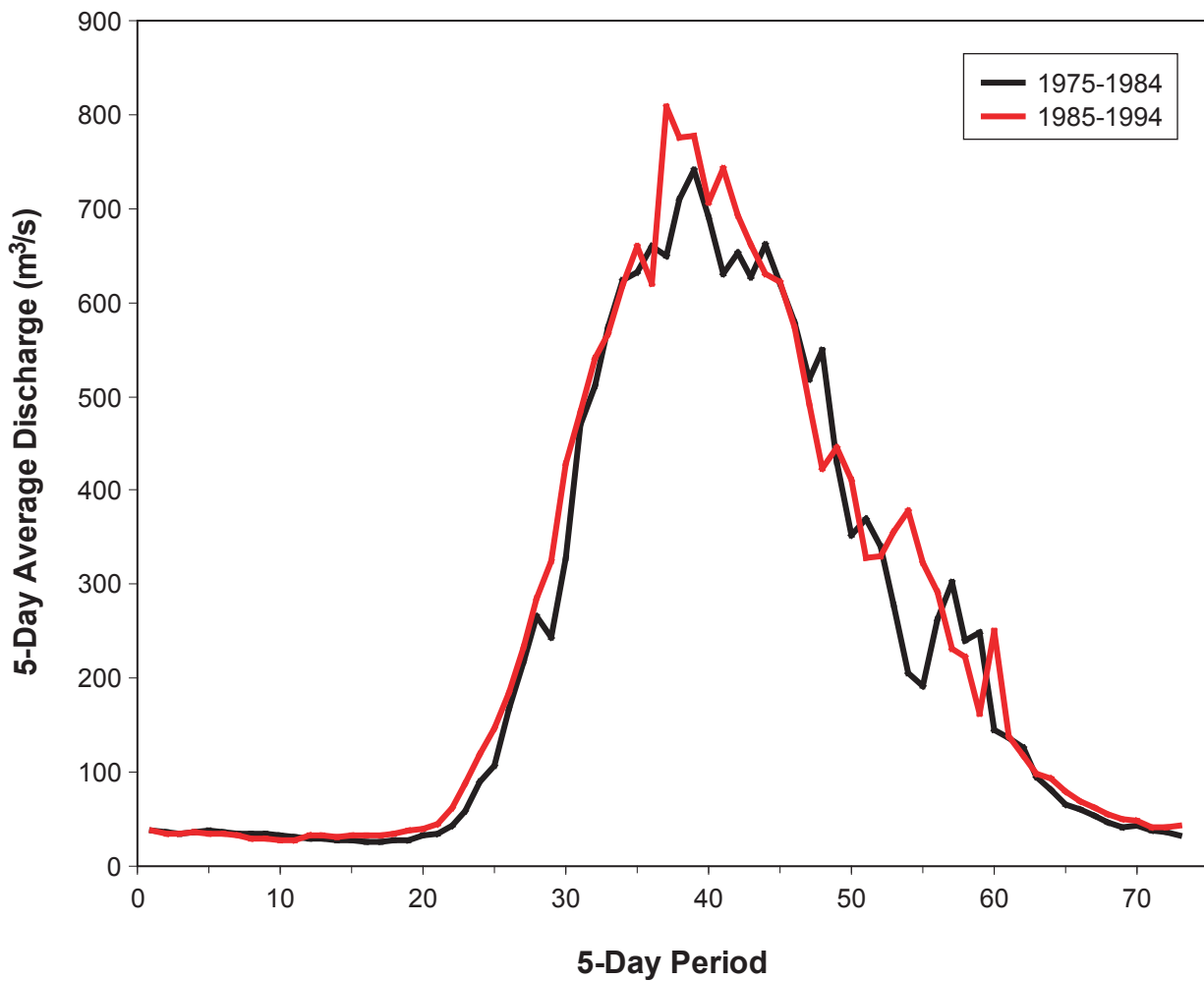
Following Whitfield (2001), Figure A2-3 presents the intra-decadal shift in the annual hydrograph of More Creek. The peak of the annual hydrograph is greater and occurs earlier in the year (10 days earlier) for the 1985-1994 period than the 1975-1984 period. Assuming a recent climate trend of warmer wetter weather, Figure A2-3 indicates that the increased precipitation leads to greater annual runoff (6.5% greater) and that the warmer weather affects the timing of the spring freshet but does not reduce the winter snowpack. Long term flow records of Galore Creek were not available.

A2-5.2.2 Simulated Future Trends

Loukas *et al.*, (2002) applied climate projections generated by a GCM based on conditions of twice the current atmospheric CO₂ concentrations to deterministic hydrologic models of two British Columbia watersheds, the Illecillewaet and Upper Campbell basins. In both watersheds, annual precipitation is projected to increase, however due to warmer temperatures the annual snowfall in both watersheds is projected to decrease, though 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 CO₂ condition to hydrologic models of a number of watersheds in British Columbia 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.

Using the UBC Watershed Model and GCM output summarized in Chapter 4, the impact that the climate change projections will have on hydrology of sub-watershed GAL-1A was investigated. A calibrated model of GAL-1A was first run with the daily meteorology data (maximum and minimum daily temperature and daily total precipitation) measured at Galore Creek for the period from October 1, 2004 to September 30, 2005. The “delta” method was then used to adjust the observed daily time series by the climate projections for maximum and minimum monthly temperature and monthly precipitation. 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.



Trend in Annual More Creek Hydrograph from the Mid 1970s to the Mid 1990s

FIGURE A2-3



Appendix 2 – Summary of Climate Change Projections for Galore Creek

Ideally, the climate projections would be applied to a time series representing the climate normal for the 1961 to 1990 period, as this is the baseline period that GCM output is generated for. However, because no observed data is available for Galore Creek for this period, data from 2004 and 2005 is assumed to be an adequate substitute, as discussed in Section A2-4.1. Time series were created based on the low, median, and high projections for both the 2020s and 2050s time slices.

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. Additionally, because the current climate data is based on a single year of observed data, the projected hydrographs are considered to be 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 A2-4 to A2-6, Table A2-13, and summarized in the list below.

Table A2-13
Modelled Percent Changes in Runoff for GAL-1A Using Various Climate Change Projections

Time Slice Projection	Percent Change from Modelled 2004 to 2005 Runoff					
	2020s			2050s		
	Low	Median	High	Low	Median	High
Annual	1	13	34	13	32	65
October	9	19	63	28	68	116
November	0	44	125	30	173	436
December	6	66	162	69	193	496
January	-2	13	75	9	41	137
February	-14	36	238	30	171	590
March	3	75	308	8	295	730
April	16	60	201	55	178	412
May	10	26	49	25	36	48
June	-2	3	3	3	-1	-13
July	-3	-1	0	0	2	3
August	-2	4	12	4	9	18
September	4	20	39	30	47	69

- Annual runoff is predicted to increase between 1 and 34% in the 2020s and between 13 and 65% in the 2050s.
- 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 keeps runoff during late spring and summer similar to current levels, for most scenarios. 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 modelled data for the two future time slices includes an over-estimate of the glacial melt contributing to spring and summer runoff.

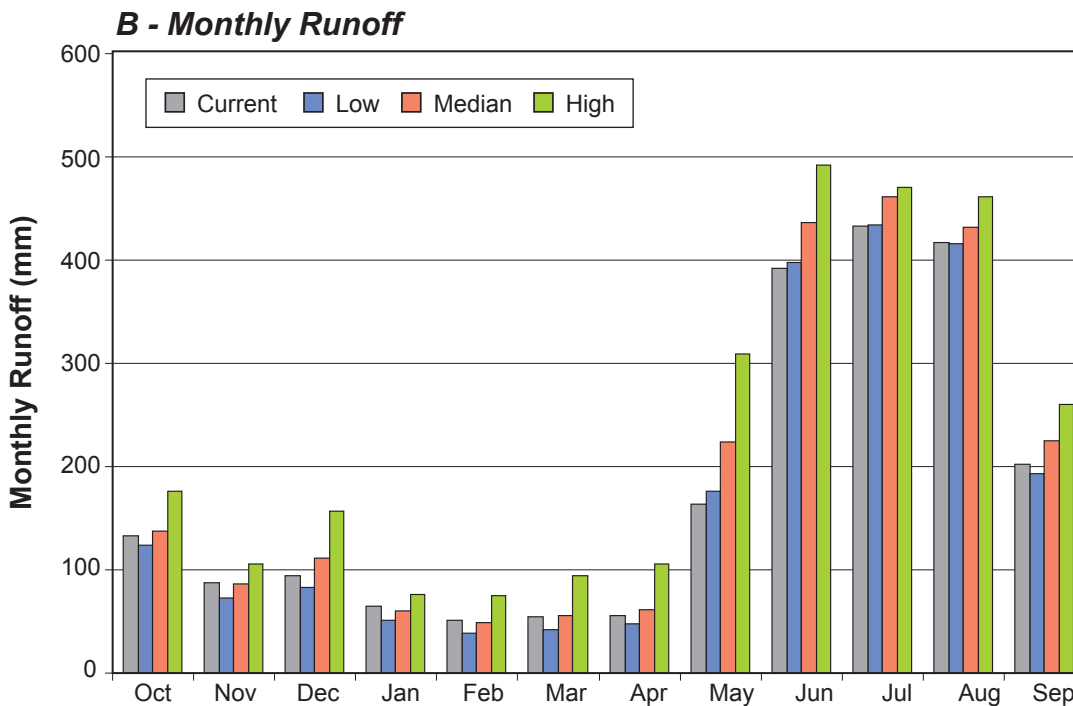
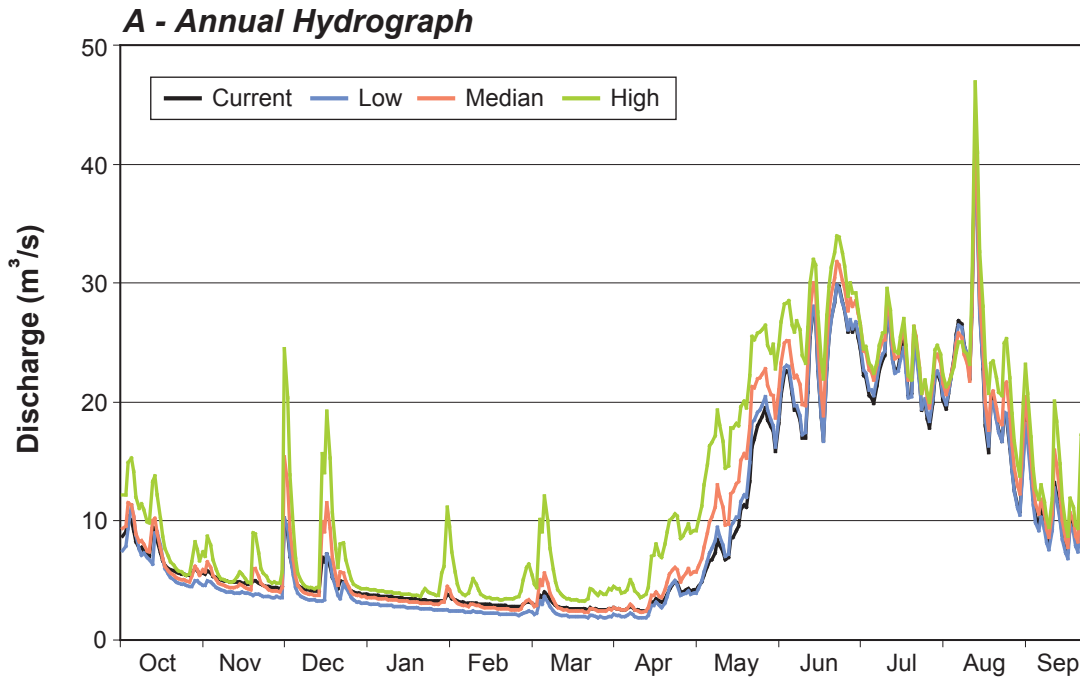


FIGURE A2-4

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

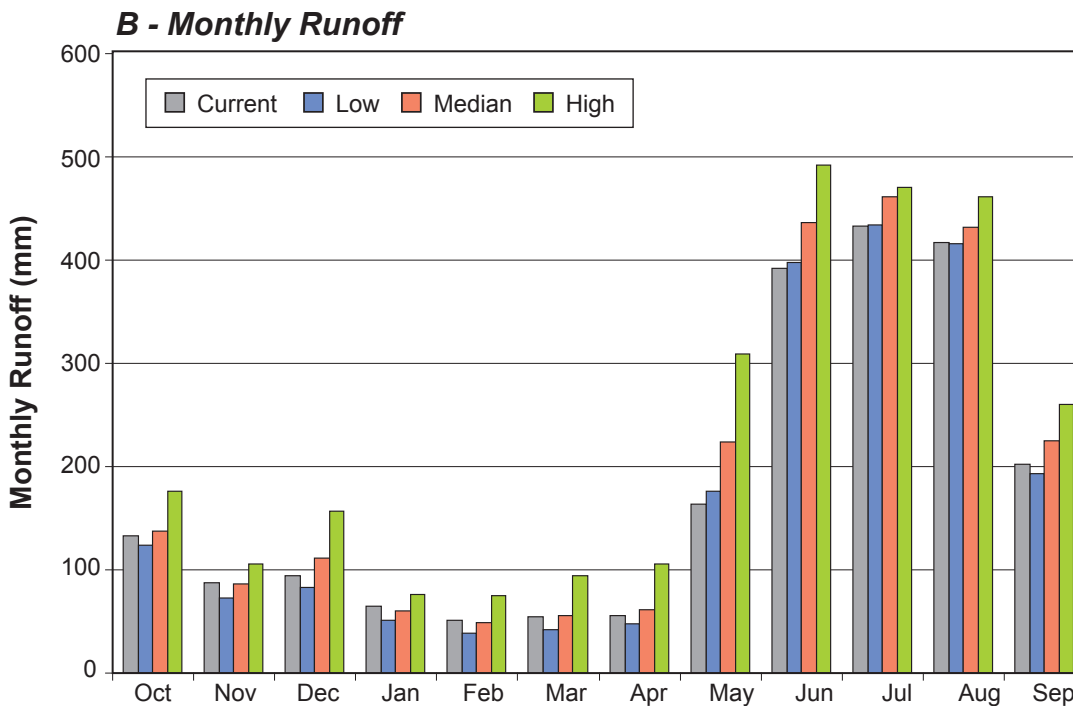
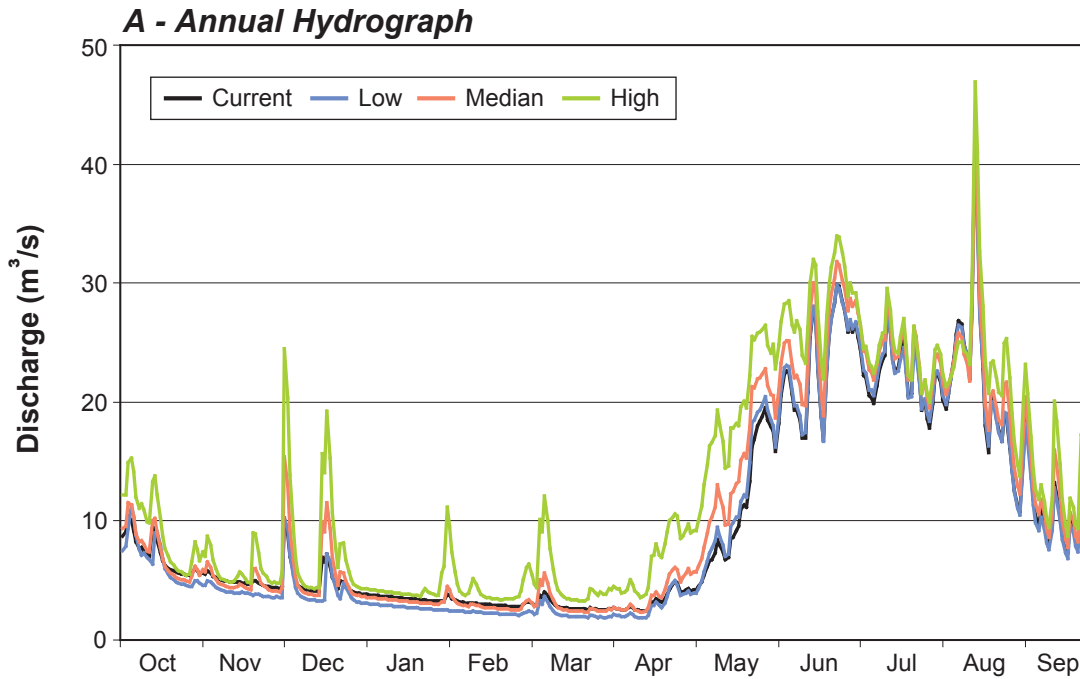
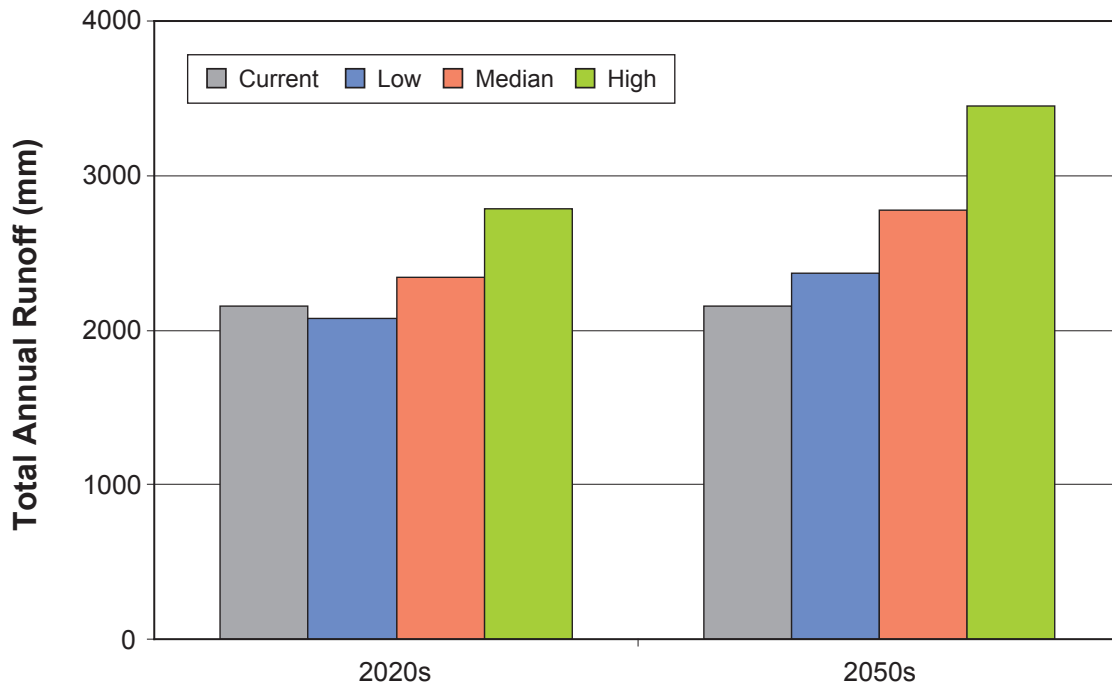


FIGURE A2-5

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



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

FIGURE A2-6



Appendix 2 – Summary of Climate Change Projections for Galore Creek

- 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.

A2-6 Conclusion

Climate variables such as precipitation and air temperature have shown long-term trends that are attributed to global climate change. These trends have in turn been linked to trends in stream and river flow and are expected to continue in the future. Any project that has a proposed lifespan of more than a few years should consider the impact that climate change will have on the project. The most common method of projecting climate change is with general circulation models (GCMs). Although these models are the best way to predict future climate variables, generated output is still uncertain, especially at a local scale. Therefore, output from a number of models and emission scenarios were considered to provide a range of possible future conditions, rather than a single best guess. The general trend of the projections is towards a warmer and wetter climate in the Galore Creek region. Applying these trends to a deterministic hydrologic model it is predicted that runoff in the Galore Creek watershed may change greatly under future climatic conditions.

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