APPENDIX 13-B
KSM UBC WATERSHED MODELLING

Seabridge Gold Inc.

KSM PROJECT
UBC Watershed Modelling

SEABRIDGE GOLD

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UBC Watershed Modelling

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Acronyms and Abbreviations

Terminology used in this document is defined where it is first used. The following list will assist readers who may choose to review only portions of the document.

ASL	Above Sea Level
BCCR BCM2.0	Bjerknes Centre for Climate Research, Bergen Climate Model 2.0
CCMA CGCM3	Canadian Centre for Climate Modelling and Analysis, Canadian Global Climate Model 3.
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
GCM	Global Climate Model
GFDL CM21	Geophysical Fluid Dynamics Laboratory, Climate Model 2.1
IPCC	Intergovernmental Panel on Climate Change
NTWM-H1	Hydrometric station in South Teigen Creek near the mouth
SRES	Special Report on Emissions Scenarios
SC-H1	Hydrometric station in the Unuk River watershed at the mouth of Sulphurets Creek
STWM-H1	Hydrometric station in North Treaty Creek near the mouth
UBCWM	University of British Columbia Watershed Model

1. Introduction

Deterministic hydrologic modelling was performed for three catchments within the KSM Project area. The University of British Columbia Watershed Model (UBCWM) was used, and flow was simulated at stations SC-H1, NTWM-H1, and STWM-H1. Models were first calibrated using hydrologic and meteorologic data collected *in-situ* from 2008-2012.

The major goal of this report is to simulate the hydrologic responses to climatic change in the 21st century. This includes changes in air temperature, precipitation, and glacierized area. Models were run with conditions anticipated for 2020, 2050, and 2080 for two 'Intergovernmental Panel on Climate Change' (IPCC) emissions scenarios (A2 and B1). The Canadian Global Climate Model (GCM) CCMA CGCM3 was used for this analysis.

A large number of GCMs exist, which produce a wide variety of climatic predictions given the same sets of Special Report on Emissions Scenarios (SRES) scenarios. To assess the effects of uncertainty and sensitivity to changing inputs, hydrologic model climatic inputs were varied, and the hydrologic responses were examined. Air temperature and precipitation were systematically altered while keeping all other hydrologic model inputs the same. The amount of variability represented the amount of variability found in three GCMs.

An additional complicating factor is the glacier cover in the study catchments. Future glacierized areas are subject to a great deal of uncertainty. Fortunately, detailed glaciological studies have been performed in the project area (Rescan 2011, 2012b), yet responses to future climate remain uncertain. To assess the hydrologic effects of this uncertainty, the glacierized area in a catchment (SC-H1) was systematically altered. This uncertainty and sensitivity analysis allows a range of likely future hydrologic conditions to be assessed, and is a measurement of the certainty of the hydrologic predictions.

2. Methods

2.1 The University of British Columbia Watershed Model (UBCWM)

UBCWM is a hydrologic model designed for forecasting runoff from mountainous watersheds (Quick and Pipes 1977). The model divides watersheds into elevation bands (up to eight), and model parameters can be set within each band. UBCWM climatic inputs include maximum and minimum daily air temperature, and daily precipitation. Outputs include total daily discharge, and discharge from rainfall-runoff, glacial melt, and snow melt. Infiltration and runoff are simulated empirically. Glacial runoff is controlled by the percent glacial coverage within each elevation band, a model parameter.

UBCWM has been widely applied and assessed, particularly in mountainous catchments. It is currently being used in operational flow forecasting by the BC River Forecast Centre and BC Hydro. In a model-intercomparison, UBCWM was chosen as the top-ranked medium complexity hydrologic model for mountainous watersheds in British Columbia and Alberta (Beckers, Smerdon, and Wilson 2009).

2.2 Modelled KSM Catchments

Three catchments were modelled (Figure 2.2-1). The Sulphurets Creek watershed was selected to be representative of the Project area specific to the Mine Site. The SC-H1 hydrometric station is located near the outlet of Sulphurets Creek, and was selected for modelling purposes. In addition, South Teigen Creek (NTWM-H1) and North Treaty Creek (STWM-H1) were modelled because of their proximity to the proposed Tailings Management Facility in the South Teigen and North Treaty watersheds. These three watersheds provide a range of representative case studies of typical KSM catchments in terms of their size, elevation, and glacial cover (See Table 3.6-1, and Table 3.6-2 in Rescan 2012a).

2.3 Terrain Classification

Each watershed to be modelled was divided into eight equally-spaced elevation bands (Figure 2.3-1, Figure 2.3-2, Figure 2.3-3). Glacierized area, forested area, and bare ground area were determined within each band (See Table 3.3-1, Table 3.2-2, Table 3.2-3). Watershed boundaries and glacier area were calculated using the 1:50,000 BC Fresh Water Atlas watershed layer (Freshwater Atlas; GeoBC; Ministry of Forests 2012). Elevation data are from the Terrain Resource Information Management (TRIM) DEM, and forested area is based on predictive ecosystem mapping datasets already completed for the KSM Project.

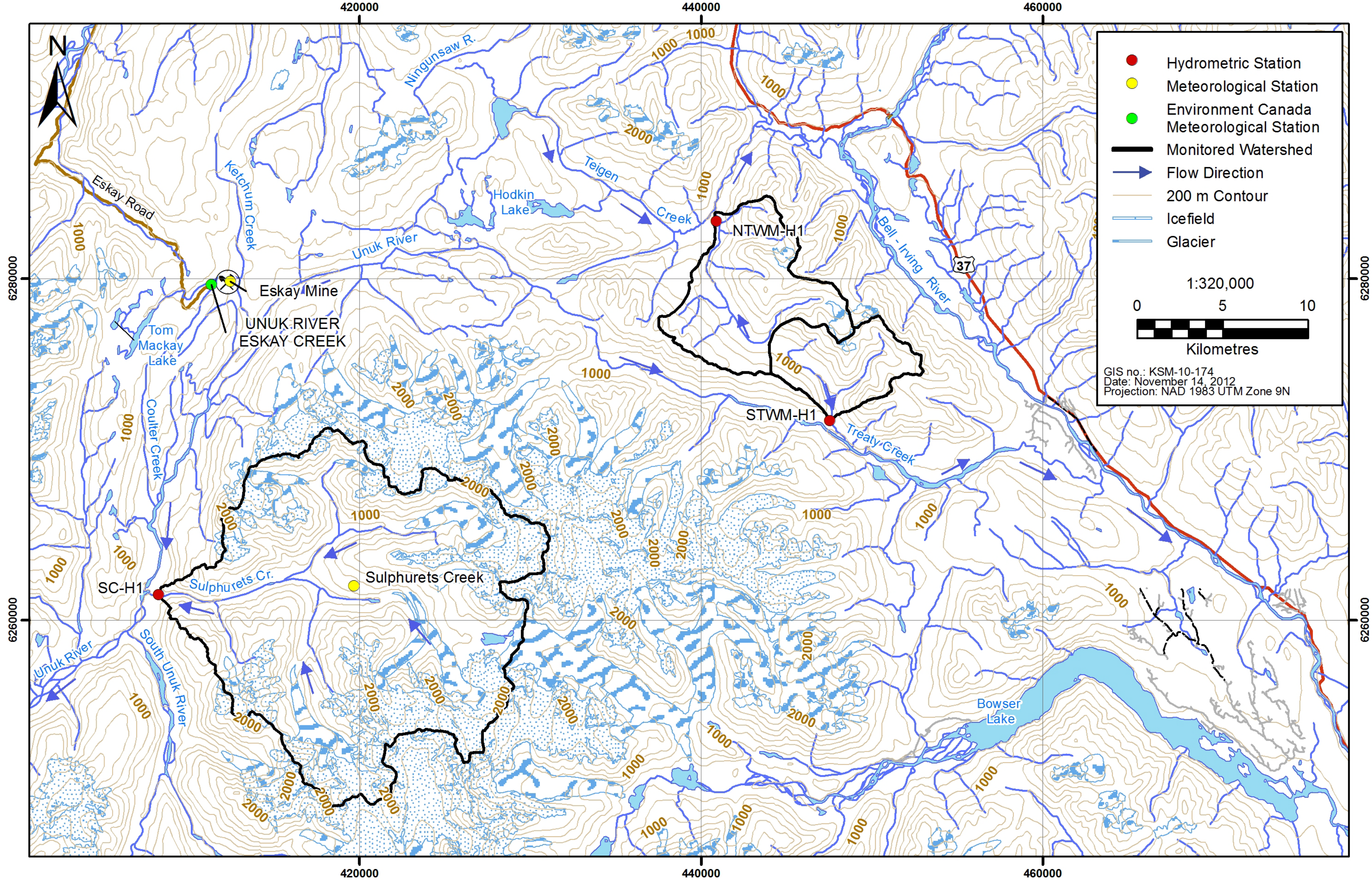

Figure 2.2-1

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KSM Hydrometric Stations and Watersheds (SC-H1, NTWM-H1, STWM-H1)

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Figure 2.2-1

PROJECT # 868-016-23 GIS No. KSM-10-176 November 19, 2012

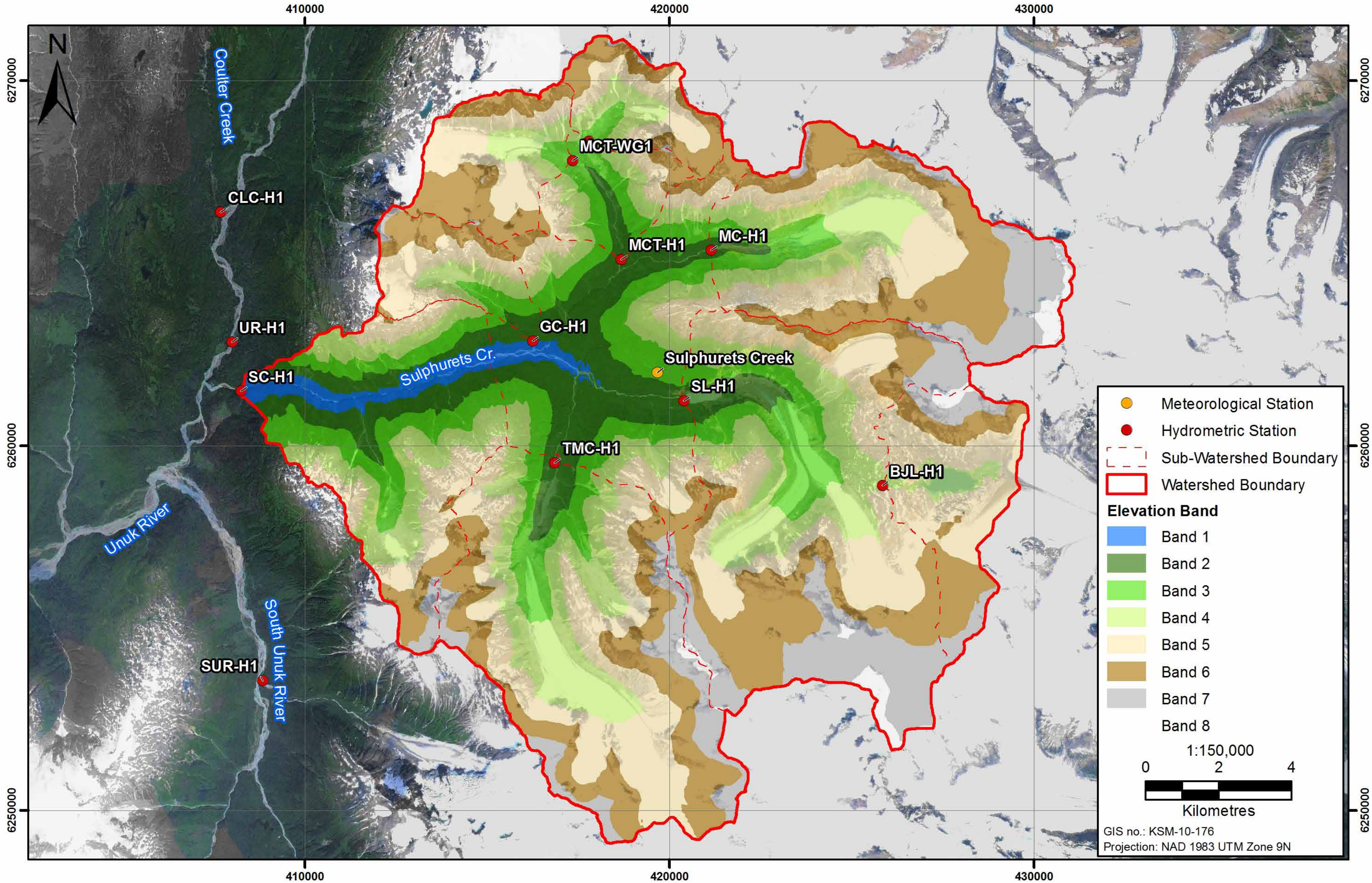

Figure 2.3-1

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Sulphurets Creek Watershed (Upstream of SC-H1) Divided into Eight Equal-elevation Bands

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Figure 2.3-1

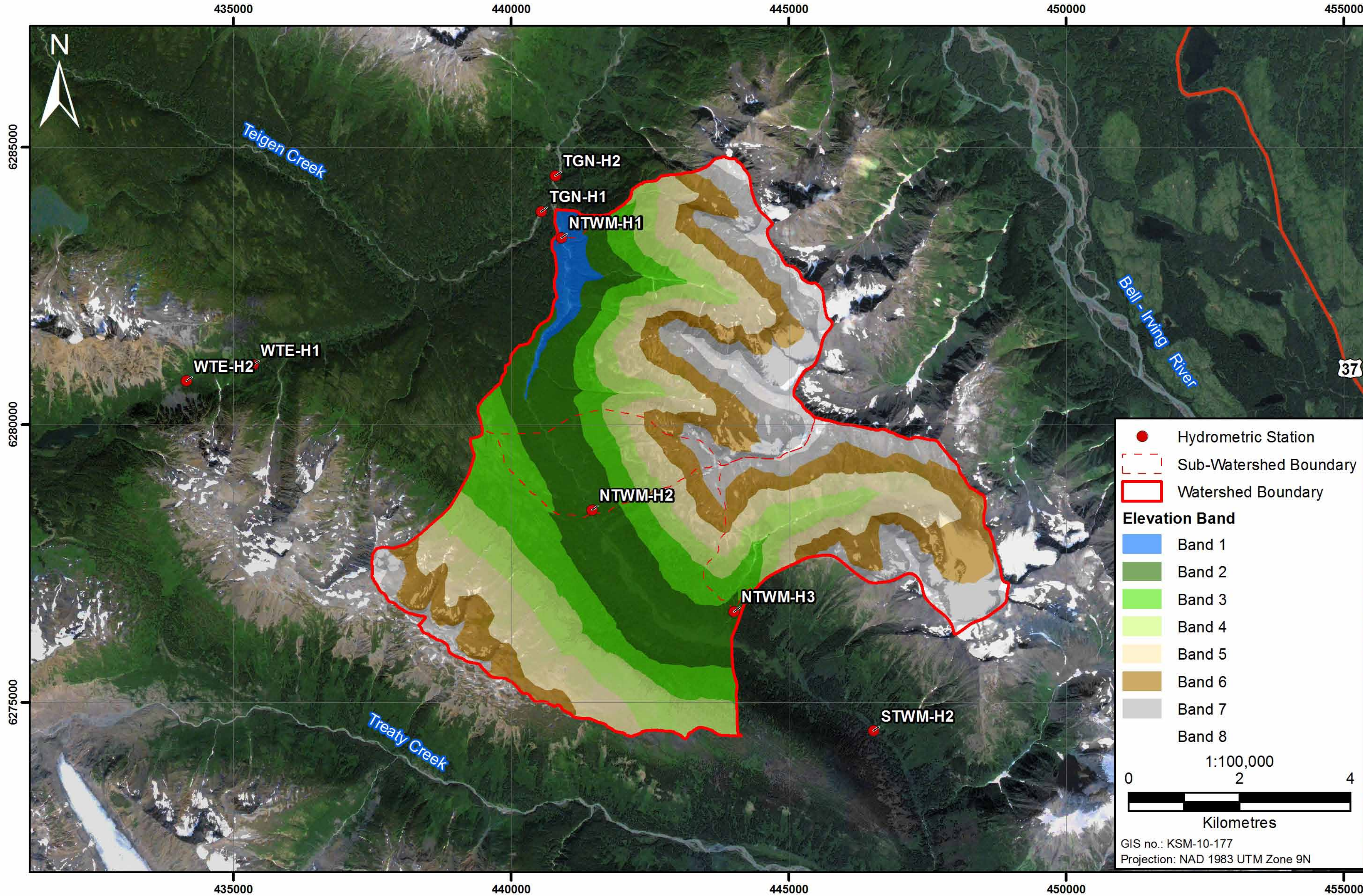

Figure 2.3-2

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South Teigen Watershed (Upstream of NTWM-H1) Divided into Eight Equal-elevation Bands

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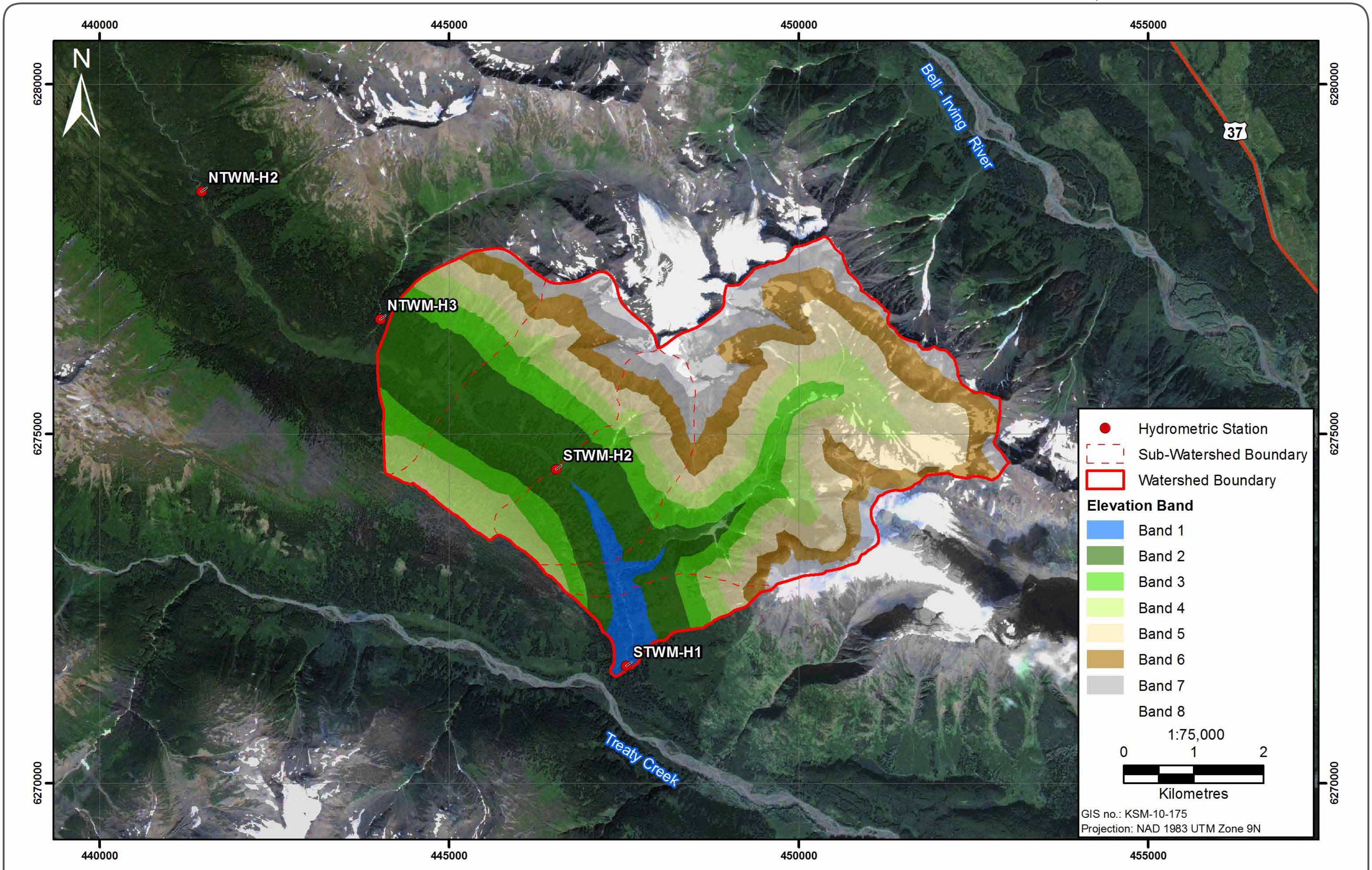

Figure 2.3-3

North Treaty Watershed (Upstream of STWM-H1) Divided into Eight Equal-elevation Bands

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Figure 2.3-3

2.4 Monitored Meteorologic Time Series

Daily air temperatures (minimum and maximum) and precipitation time series are the UBCWM meteorologic inputs. For station SC-H1, the Sulphurets Creek meteorologic station was used (Figure 2.2-1). For hydrometric stations NTWM-H1 and STWM-H1, the meteorologic stations at Eskay Creek was used (Figure 2.2-1). The Seabridge Eskay Creek weather station record was used after September 2010, and data from the Environment Canada Eskay Creek weather station was used before this time. Details of the meteorologic station location, elevation, and instrumentation are provided in the 2008-2011 KSM meteorology baseline report (Rescan 2012b).

2.5 Model Calibration

Each watershed was calibrated by adjusting model parameters within ranges typically found in mountainous British Columbia catchments (Quick et al. 1995; Rescan 2006). In each catchment, four years (2008-2011) of monitored discharge data were used for calibration. The UBCWM calibration tool was run 500 times on each catchment, and parameters were iteratively and automatically adjusted. The best performing combination of parameters was chosen. A subset of key UBCWM parameters have been identified in terms of controlling discharge in mountainous British Columbia catchments (Rescan 2006); these parameters are summarized in Table 2.5-1. The parameter 'C0IMPA' is the fraction of impermeable area in each band, and is presented separately in Table 2.5-2. Further details of UBCWM parameters are available in Quick et al. (1995).

Table 2.5-1. Summary of Key UBCWM Parameters

Parameter	Description	Typical Range[a]	SC-H1	NTWM-H1	STWM-H1
P0ALBMIN	Albedo of very aged snowpack	-	0.3	0.3	0.3
A0STAB	Precipitation gradient modification factor	0-1	0	0	0
E0LHI	Elevation above which the precipitation gradient P0GRADU applies. (m)	-	3000	2050	1950
E0LMID	Elevation above which precipitation gradient P0GRADM applies. (m)	-	500	1230	707
P0GRADU	Precipitation gradient factor (%) for elevations above E0LHI	0-20	16	13	19
P0GRADM	Precipitation gradient factor (%) for elevations below E0LHI	0-20	8	4	11
P0PERC	Groundwater percolation. (Maximum capacity of sub-surface storage. Excess runoff goes to interflow; mm)	0 - 50	32	38	32
P0DZSH	Deep zone share (lower fraction) of groundwater	0-1	0.89	0.07	0.54
P0PADJ	Precipitation adjustment factor for each band	-	0	0	0
P0UGTK	Upper groundwater runoff time constant (days)	10-50	35.8	34.8	30.2

(continued)

Table 2.5-1. Summary of Key UBCWM Parameters (completed)

Parameter	Description	Typical Range[a]	SC-H1	NTWM-H1	STWM-H1
A0TLNM	Lapse rate for minimum temperatures when the station elevation is less than 2000 m; ºC / 1000 m	-	0.5	0.5	0.5
A0TLXM	Lapse rate for maximum temperatures when the station elevation is less than 2000 m; ºC / 1000 m	-	10	10	10

[a]Missing values denote that no information on typical values is provided in UBCWM documentation.

Table 2.5-2. Fraction of Impermeable Area (C0IMPA Parameter) by Watershed and Elevation Band

Watershed	Band								Average	Standard Deviation
	1	2	3	4	5	6	7	8		
SC-H1	0.86	0.88	0.91	0.94	0.97	1.00	1.00	1.00	0.94	0.06
NTWM-H1	0.65	0.67	0.68	0.69	0.70	0.71	0.72	0.74	0.69	0.03
STWM-H1	0.61	0.74	0.86	0.99	1.00	1.00	1.00	1.00	0.90	0.15

2.6 Hydrologic Response to Future Climate Scenarios

2.6.1 Air Temperature and Precipitation

Statistically downscaled GCM data for the study sites was obtained using the software package ClimateBC (Wang et al. 2006; Wang et al. 2012). Air temperature and precipitation 'normals' (1981-2009) from ClimateBC were first compared to *in-situ* data from nearby weather stations to assess the representativeness of the extracted time series. No site-specific adjustments were deemed necessary (Section 3.2.1).

Next, climate predictions for the 21st century were obtained from the Canadian GCM GCM3 using ClimateBC. Monthly data were obtained for 2020, 2050, and 2080. Air temperature and precipitation were extracted from the A2 and B1 IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). The A2 scenario uses consistently increasing global carbon dioxide emissions until 2100. The scenario assumes a divided, regional world with continuously increasing population. The B1 scenario uses emissions that increase until about 2050, and then begin to decrease. This scenario assumes an integrated world where population begins to decline after 2050, and where an information economy becomes increasingly dominant (Nakicenovic et al. 2000).

Daily estimates of future air temperature and precipitation were calculated by determining the difference between modern and future conditions, and applying this difference to 1981-2009 the climatic normal for Sulphurets Creek, determined by ClimateBC (the 'delta method'). It should be noted that the delta method does not account for future changes in precipitation intensity, duration of events (ex. sustained drought or wetness), or weather patterns (ex. convection or frontal precipitation).

2.6.2 Glacierized Area

DGPS surveys of the Mitchell Glacier terminus show average retreat rates of about 30 m/year (Rescan 2011). Glacier terminus velocities at McTagg South, West, and East conducted in 2010 and 2011 support that this is a typical retreat rate for valley glacier termini in the project area (Rescan 2012c). The retreat rate was therefore applied uniformly to valley glacier termini. Terminus retreat was assumed to be 330 m by 2020, 1230 m by 2050, and 2130 m by 2080, using 2009 as the base year. The boundaries of high altitude icefields in the project area likely have much lower retreat rates than the termini of valley glaciers. Estimates of icefield retreat rates were made based on distributed mass balance maps of Mitchell, McTagg, Kerr, and Gangras glaciers, topography, elevation, and measured ice velocities (Rescan 2012c). In each catchment, estimated glacier areas at 2020, 2050, and 2080 within each elevation band were calculated using image analysis software (Rasband 1997-2012).

Future retreat rates are subject to climate, mass balance, and glacier dynamics; however, the procedure described above is a best estimate of future glacier position. To assess uncertainty in future glacier area, sensitivity analysis was conducted by adjusting the glacierized area within each elevation band (Section 2.7.2).

2.7 Inter-GCM Variability and Hydrologic Model Sensitivity Analysis

Different GCMs produce different climatic responses to the same emissions scenarios. To investigate inter-GCM variability, air temperature and precipitation from CGCM3 were compared to results from GFDL CM21 and BCCR BCM2.0. The SRES scenario A2 for 2080 was used in all cases.

2.7.1 Sensitivity to Varying Air Temperature and Precipitation

By comparing CGCM3 climate results to the outputs of two other GCMs (Section 3.3), estimates of inter-model variability were obtained. These estimates were then input into UBCWM hydrologic models, and the hydrologic impacts were examined.

Specifically, to assess the effects of inter-GCM air temperature variability, the warmest and coolest air temperature estimate from GCM3, GFDL CM21, and BCCR BCM2.0 were chosen for each month for the A2 scenario at 2080. The 'delta method' was then used to estimate the warmest and coolest departures from the 1981-2009 climate normal (*cf.* section 2.6.1). In this analysis, air temperature was varied between runs, and precipitation was kept constant (GGCM3, A2, 2080).

In the case of precipitation, GCM3 produced the wettest of the three GCM estimates. Therefore, the precipitation record from the driest GCM, BCCR BCM2.0 was input into UBCWM to test the hydrologic response. The same delta method described above was used to produce precipitation estimates for the A2 scenario in 2080. In these tests, precipitation was varied between runs, and air temperature was kept constant (GGCM3, A2, 2080).

2.7.2 Sensitivity to Varying Glacerized Area

As discussed in section 2.6.2, a great deal of uncertainty surrounds the estimation of glacier area, especially by 2080. To test the effects of this uncertainty on discharge and runoff, the UBCWM model was run with the 2080 estimates of glacierized area increased and decreased by 25%.

3. Results

3.1 Hydrologic Model Calibration

Calibration results are presented in Sections 3.1.1 to 3.1.3, and discussed in Section 4.1.

3.1.1 Sulphurets Creek (SC-H1)

Modelled and measured results compare quite favourably for SC-H1 in terms of the timing and magnitude of discharge, runoff, and winter flows (Figure 3.1-1, Figure 3.1-2, Table 3.1-1). Some hydrologic events are not well simulated, such as early season high flows in 2008, and late season flows in 2010 and 2011, and response to some precipitation events (Section 4.1).

Table 3.1-1. Measured and Modelled Hydrometeorologic Indices for SC-H1, 2008-2011

	Measured				Modelled			
	2008	2009	2010	2011	2008	2009	2010	2011
Snow (mm)[a]	n/a	n/a	n/a	n/a	661.7	330.2	698.8	877.2
Rain (mm)[a]	n/a	n/a	n/a	n/a	1156.6	2092.2	1588.7	1466.2
Melting degree days[b]	584.9	965.7	842.3	644.7	n/a	n/a	n/a	n/a
Runoff (mm)	2274.6	2453.1	2304.3	2482.5	2094.1	2586.5	2447.1	2382.4
Peak daily flow (m^3/s)	106.8	128.2	132.1	127.1	90.4	119.8	100.0	177.0
7-day low flow (m^3/s)	4.3	2.1	2.3	2.2	1.9	1.1	1.0	0.8

[a]Snowfall and rainfall are listed as modelled because UBCWM partitions measured total precipitation into snow and rain, and makes elevation adjustments
[b]UBCWM uses a lapse rate to adjust air temperature by elevation, and reports watershed-averaged air temperature

3.1.2 South Teigen Creek (NTWM-H1)

The same issues mentioned in Section 3.1.1 apply to NTWM-H1, and are discussed in Section 4.1. Results of the calibration process are presented in Figure 3.1-3 and 3.1-4, and Table 3.1-2.

Table 3.1-2. Measured and Modelled Hydrometeorologic Indices for NTWM-H1, 2008-2011

	Measured				Modelled			
	2008	2009	2010	2011	2008	2009	2010	2011
Snow (mm)[a]	n/a	n/a	n/a	n/a	435.6	501.2	817.5	1021.9
Rain (mm)[a]	n/a	n/a	n/a	n/a	512.3	818.7	504.5	524.6
Melting degree days[b]	889.6	1080.2	1455.0	936.0	n/a	n/a	n/a	n/a
Runoff (mm)	1236.1	1233.8	1209.7	1463.8	1012.2	1270.0	1282.9	1482.0
Peak daily flow (m^3/s)	10.9	19.3	14.7	23.1	10.3	11.2	13.9	25.2
7-day low flow (m^3/s)	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.0

[a]Snowfall and rainfall are listed as modelled because UBCWM partitions measured total precipitation into snow and rain, and makes elevation adjustments
[b]UBCWM uses a lapse rate to adjust air temperature by elevation, and reports watershed-averaged air temperature

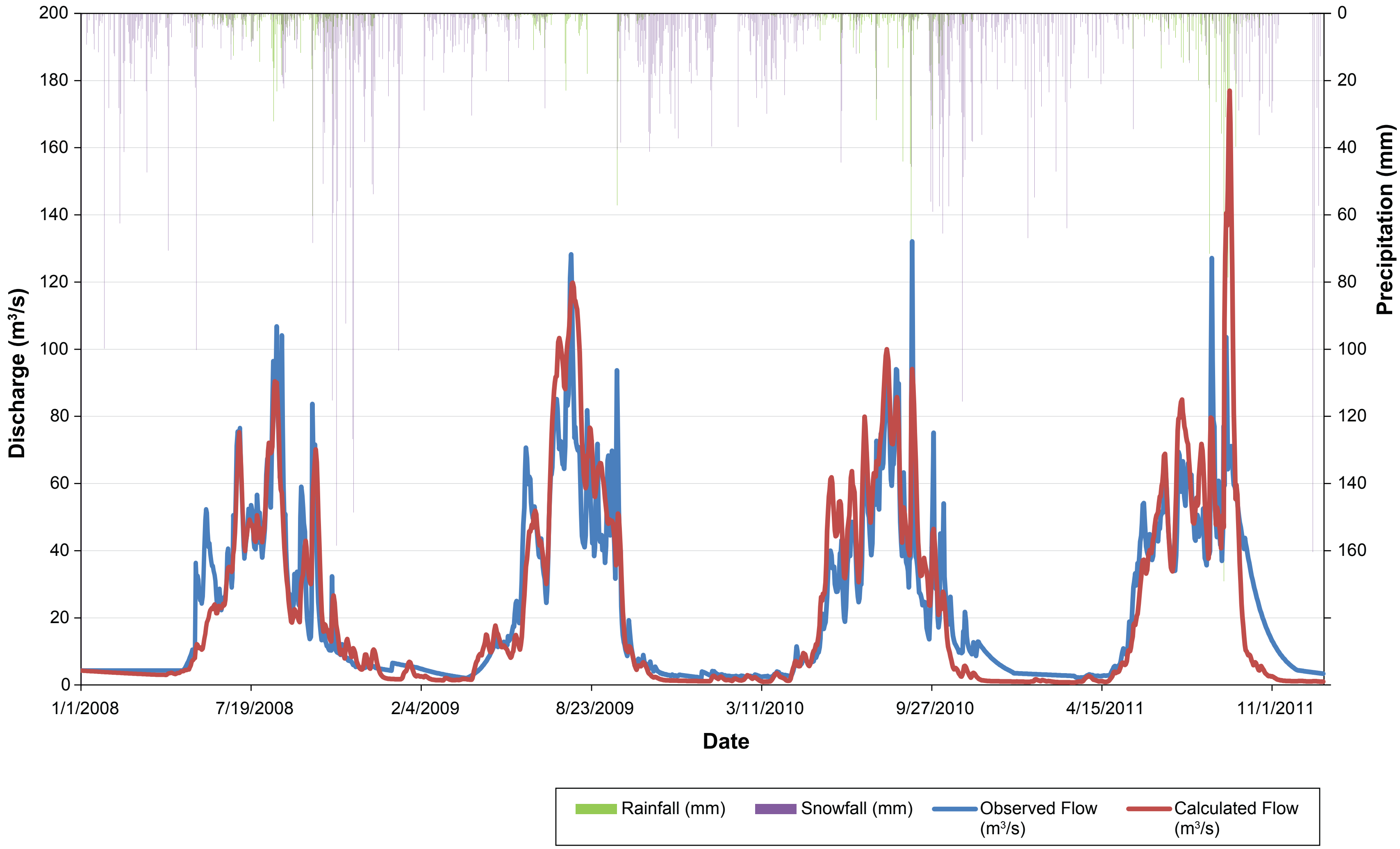

Figure 3.1-1

Modelled and Measured Discharge and Precipitation at Station SC-H1, from 2008 to 2011

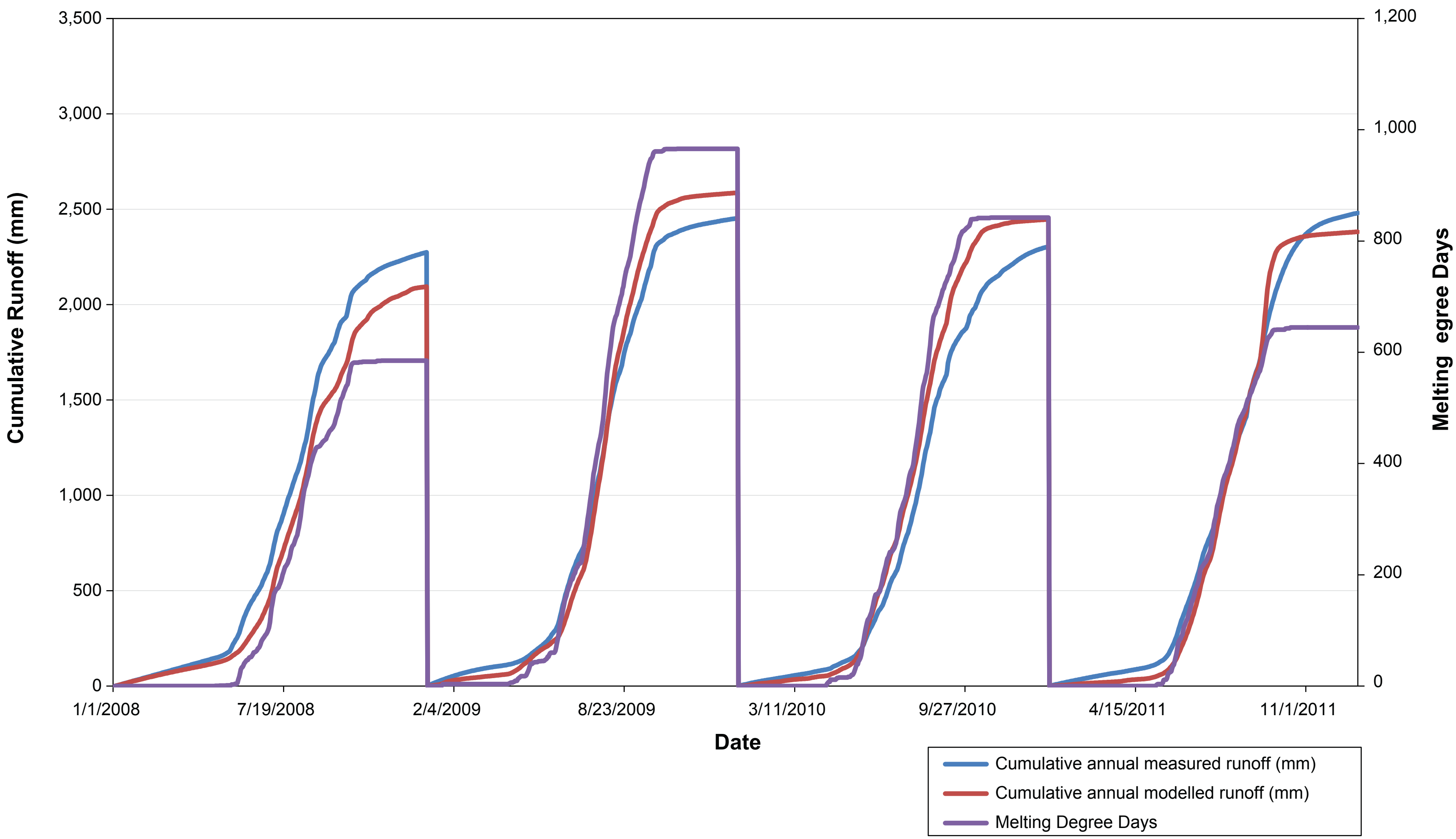

Figure 3.1-2

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Modelled and Measured Cumulative Annual Runoff and Melting Degree Days at Station SC-H1, 2008 to 2011

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Figure 3.1-2

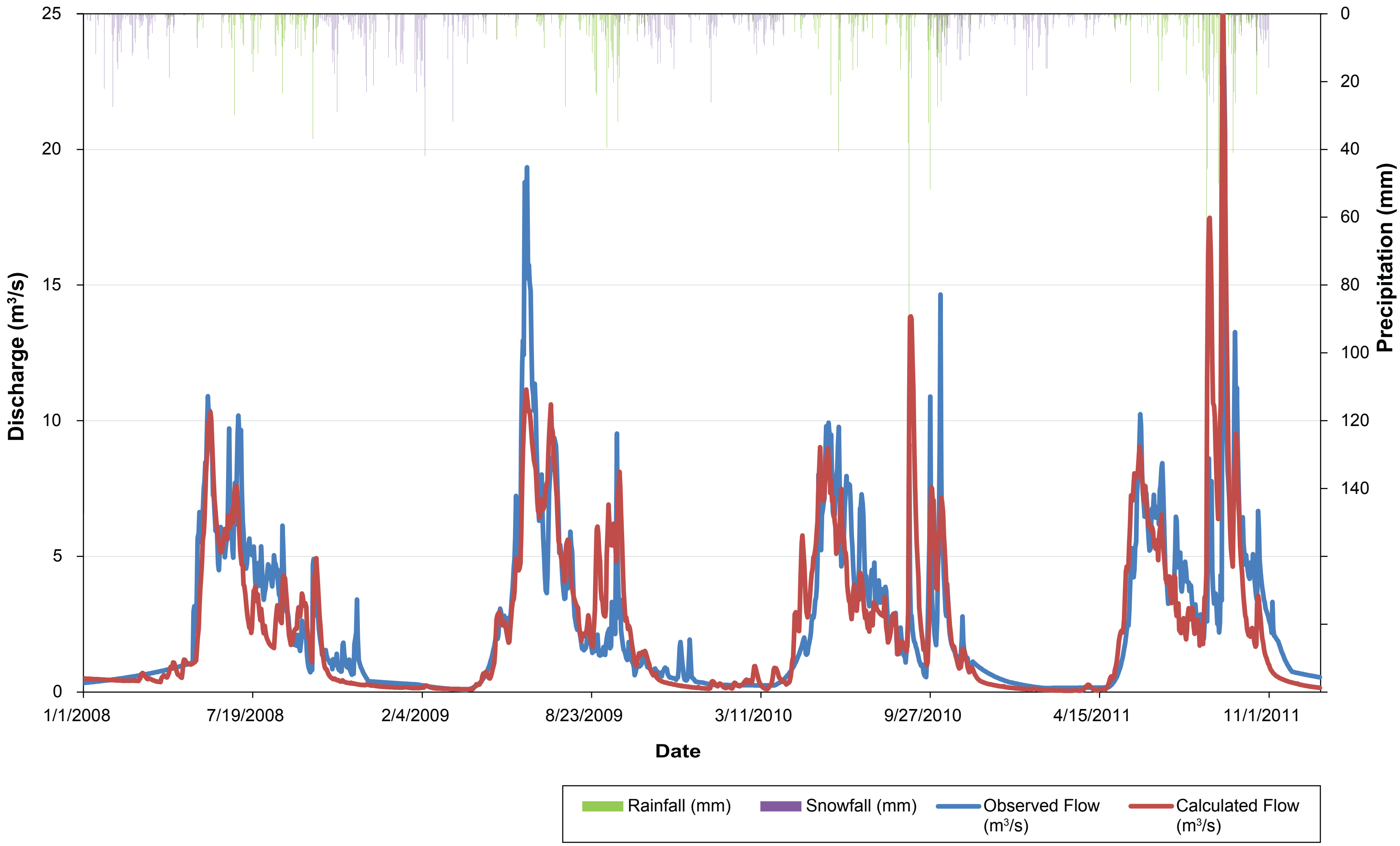

Figure 3.1-3

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Modelled and Measured Discharge and Precipitation at Station NTWM-H1, 2008 to 2011

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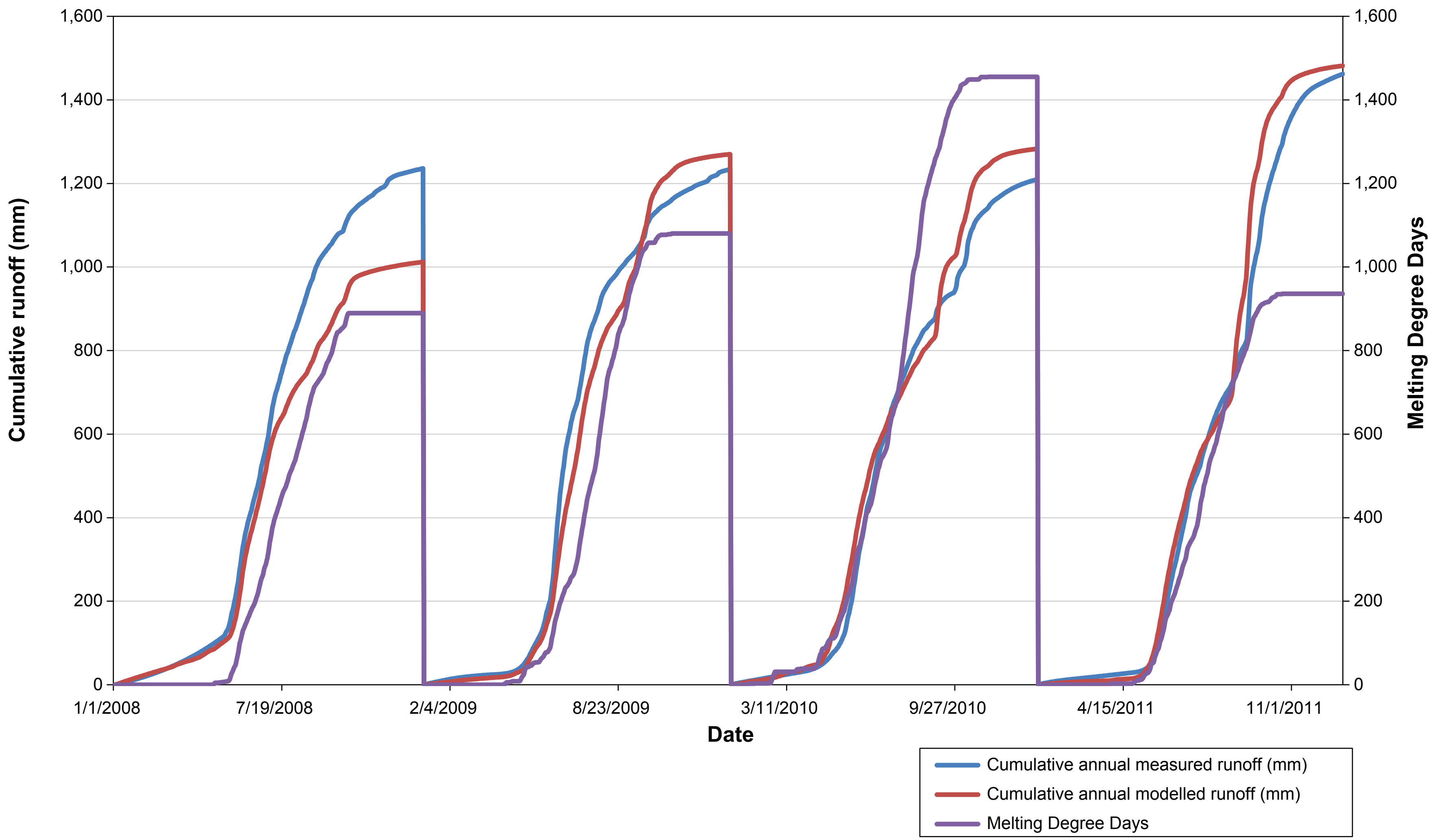

Figure 3.1-4

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Modelled and Measured Cumulative Annual Runoff and Melting Degree Days from 2008 to 2011 at Station NTWM-H1

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3.1.3 North Treaty Creek (STWM-H1)

The same issues mentioned in Section 3.1.1 apply to NTWM-H1, and are discussed in Section 4.1. Results of the calibration process are presented in Figure 3.1-5 and 3.1-6, and Table 3.1-3.

Table 3.1-3. Measured and Modelled Hydrometeorologic Indices for STWM-H1, 2008-2011

	Measured				Modelled			
	2008	2009	2010	2011	2008	2009	2010	2011
Snow (mm)[a]	n/a	n/a	n/a	n/a	354.2	409.3	687.4	832.3
Rain (mm)[a]	n/a	n/a	n/a	n/a	515.3	1167.0	671.1	705.6
Melting degree days[b]	1029.6	1231.9	1626.1	1087.6	n/a	n/a	n/a	n/a
Runoff (mm)	1162.1	1553.6	1283.5	1283.6	915.9	1479.9	1304.9	1452.8
Peak daily flow (m^3/s)	9.2	14.7	5.7	6.5	5.8	9.6	6.7	11.8
7-day low flow (m^3/s)	0.3	0.1	0.2	0.1	0.1	0.0	0.0	0.0

[a]Snowfall and rainfall are listed as modelled because UBCWM partitions measured total precipitation into snow and rain, and makes elevation adjustments
[b]UBCWM uses a lapse rate to adjust air temperature by elevation, and reports watershed-averaged air temperature

3.1.4 Calibration Summary

Model performance is best in the largest catchment, SC-H1, and worst in the smallest catchment, STWM-H1 (Table 3.1-4; Section 4.1). A metric commonly used to evaluate the goodness of fit between observed and synthetic hydrologic data is the Nash-Sutcliffe model efficiency value (Nash and Sutcliffe, 1970). This value was applied to the results for each station, for all four years (Table 3.1-4).

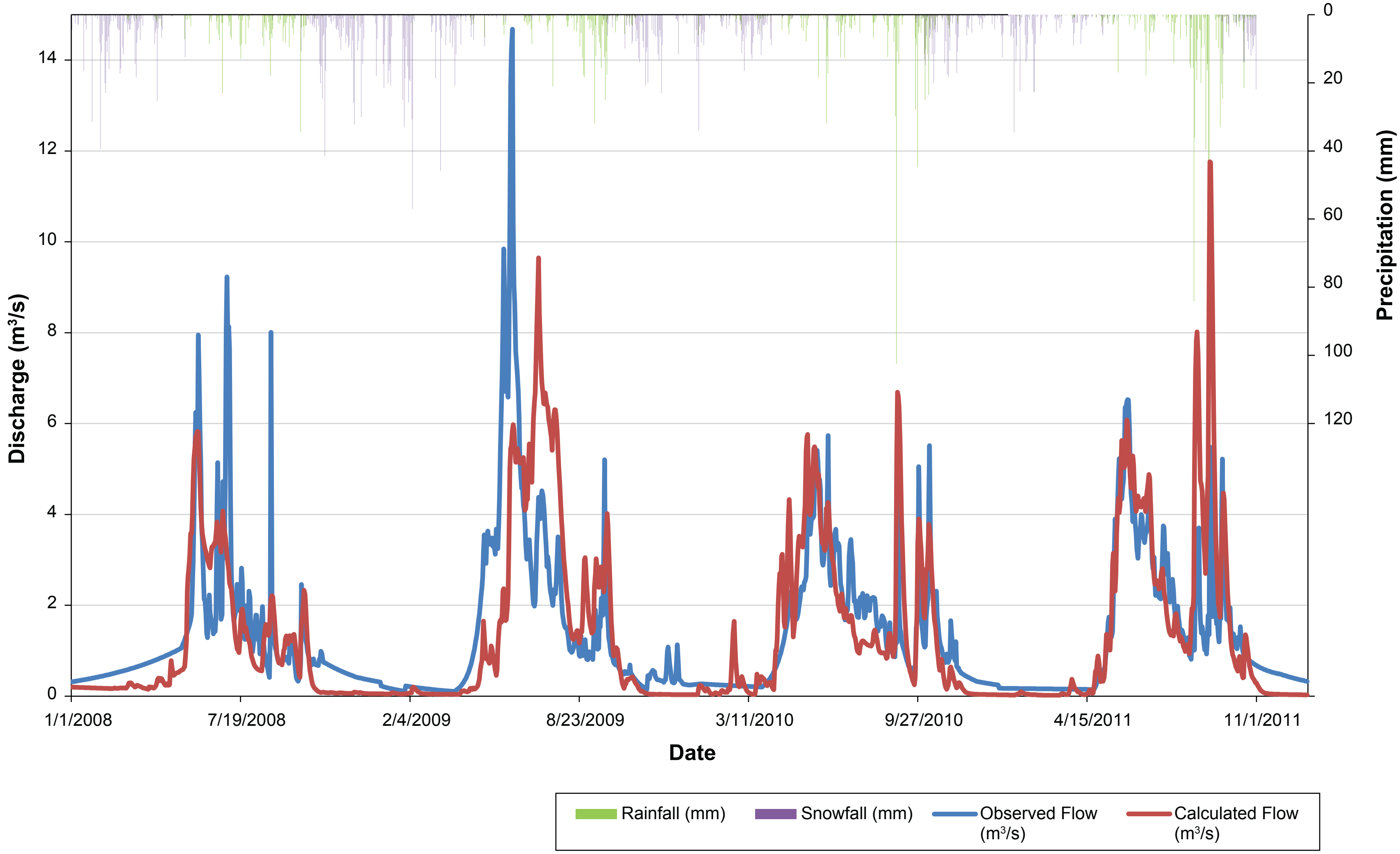
Table 3.1-4. Nash-Sutcliffe Efficiency Values for the Calibration Period. Coefficients are Calculated for the Entire Calendar Year

	2008	2009	2010	2011
SC-H1	0.87	0.89	0.90	0.78
NTWM-H1	0.84	0.77	0.55	0.70
STWM-H1	0.60	0.40	0.68	0.68

3.2 Twenty-first Century Predictions of Climatic Conditions, Glacier Position, and Hydrology

3.2.1 21st Century Air Temperature and Precipitation

Modern air temperature measured at Sulphurets Creek is very close to the ‘climate normal’ statistically downscaled air temperature from ClimateBC for the same location and elevation (Figure 3.2-1). This provides confidence that GCM-derived statistically downscaled predictions of air temperature are representative of conditions at the study area. By 2080, air temperatures in the A2 scenario are projected to increase by 3 to 6 ^{o}C. Air temperature increases are slightly larger in winter compared to summer (Figure 3.2-1).



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Modelled and Measured Discharge and Precipitation at Station STWM-H1, 2008 to 2011

Figure 3.1-5

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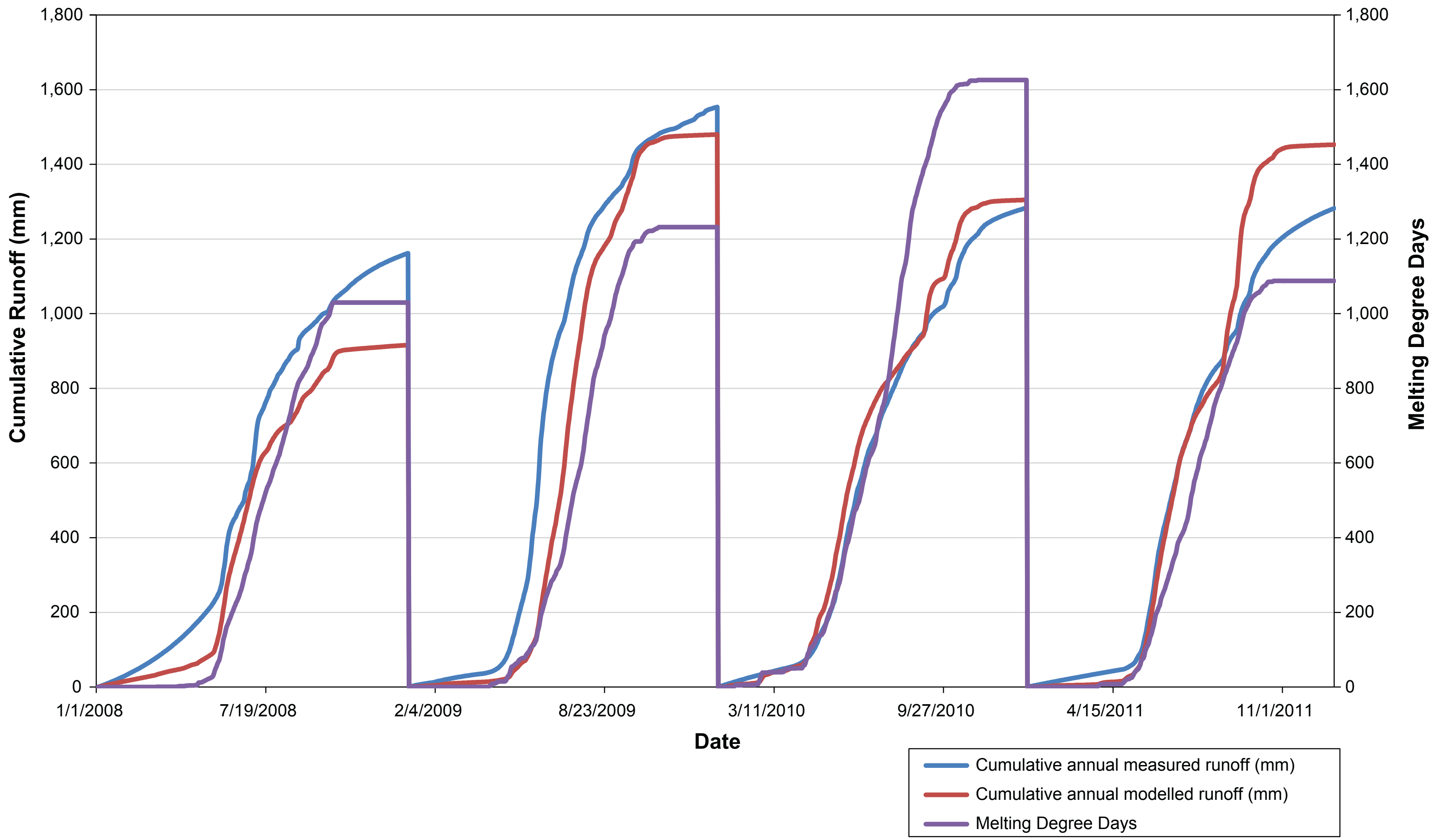

Figure 3.1-6

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Modelled and Measured Cumulative Annual Runoff and Melting Degree Days at Station STWM-H1, 2008 to 2011

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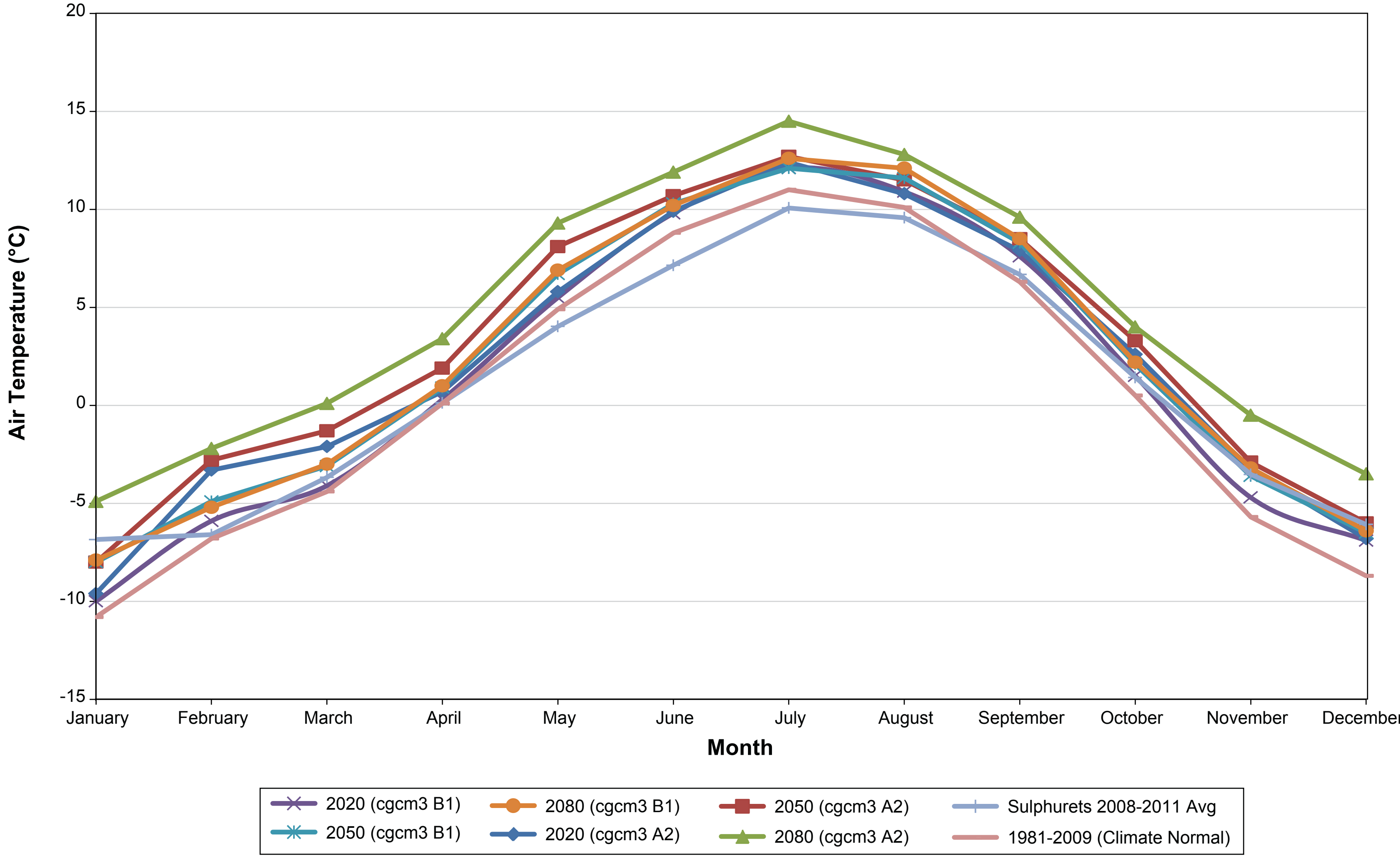

Figure 3.2-1

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Modern and Predicted Air Temperatures in the Sulphurets Creek Meteorologic Station

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Accurate measurement of precipitation is difficult in the area, and large spatial changes occur. However, it appears the estimation of precipitation by ClimateBC is reasonable in the project area (Figure 3.2-2). The ClimateBC 'climate normal' overestimates recorded precipitation at Sulphurets Creek from 2008-2011. ClimateBC underestimates precipitation at the Environment Canada Unuk River / Eskay Creek station, which is at a similar elevation, but in an adjacent valley. This discrepancy is not likely problematic, since the delta method of applying GCM-predicted precipitation simply adds relative changes to the recorded 2008-2011 precipitation data sets. The seasonal trend in precipitation is also well simulated in ClimateBC, with an annual peak in October, and minimum in April and May.

3.2.2 21st Century Glacierized Areas

Predicted glacierized areas in each modelled catchment are presented in Table 3.2-1 to Table 3.2-3. Very little areal change is predicted by 2020, eight years from the time of writing. The largest changes are always predicted at the lowest elevations (Section 2.6.2). Hydrologic model sensitivity to varying predicted glacierized areas is presented in Section 3.3.3.

Table 3.2-1. Modern and Predicted Glacierized Areas in the Sulphurets Creek (SC-H1) Watershed, Presented within the Eight Elevation Bands Used by UBCWM

Band	Mean elevation (m ASL)	Total band area (km^2)	Glacierized area in 2009 (km^2)	Estimated Area (km^2)			Areal change since 2009 (%)		
				2020	2050	2080	2020	2050	2080
1	718.1	4.92	0.00	0.0	0.0	0.0	0.0	0.0	0.0
2	893.6	26.17	0.00	0.0	0.0	0.0	0.0	0.0	0.0
3	1069.2	36.39	0.00	0.0	0.0	0.0	0.0	0.0	0.0
4	1244.7	58.12	11.66	9.8	6.8	4.0	-16.1	-41.7	-65.7
5	1420.1	78.49	30.11	25.4	18.1	14.5	-15.6	-39.9	-52.0
6	1595.7	62.42	41.41	37.2	24.7	19.9	-10.1	-40.4	-52.0
7	1771.2	28.44	21.97	22.0	18.6	18.6	0.0	-15.5	-15.2
8	1946.2	3.37	2.42	2.4	2.1	2.4	0.0	-12.6	0.0
Sum	-	298.33	107.57	100.8	73.1	59.4	-	-	-

3.2.3 21st Century Hydrology

Hydrologic responses to precipitation events are progressively increased throughout the 21st century, especially in the A2 scenario (Figures 3.2-3 to 3.2-7). The same is also true for flows in winter, which are currently very low. Total runoff almost doubles in some years, but more typically increases by 20 to 30% (Figure 3.2-4, Figure 3.2-6, Figure 3.2-8). The largest departures from modern conditions occur in late summer, when glacial melt is at its annual peak.

Total runoff is projected to increase in all catchments, and for all emissions scenarios, with one notable exception. In STWM, both the 2080 scenarios produced less runoff than modern when applying GCM 'deltas' to 2009 meteorologic records (Figure 3.2-8; Section 4.2). This could be attributed to the predicted total loss of glacial cover in the STWM catchment by 2080.

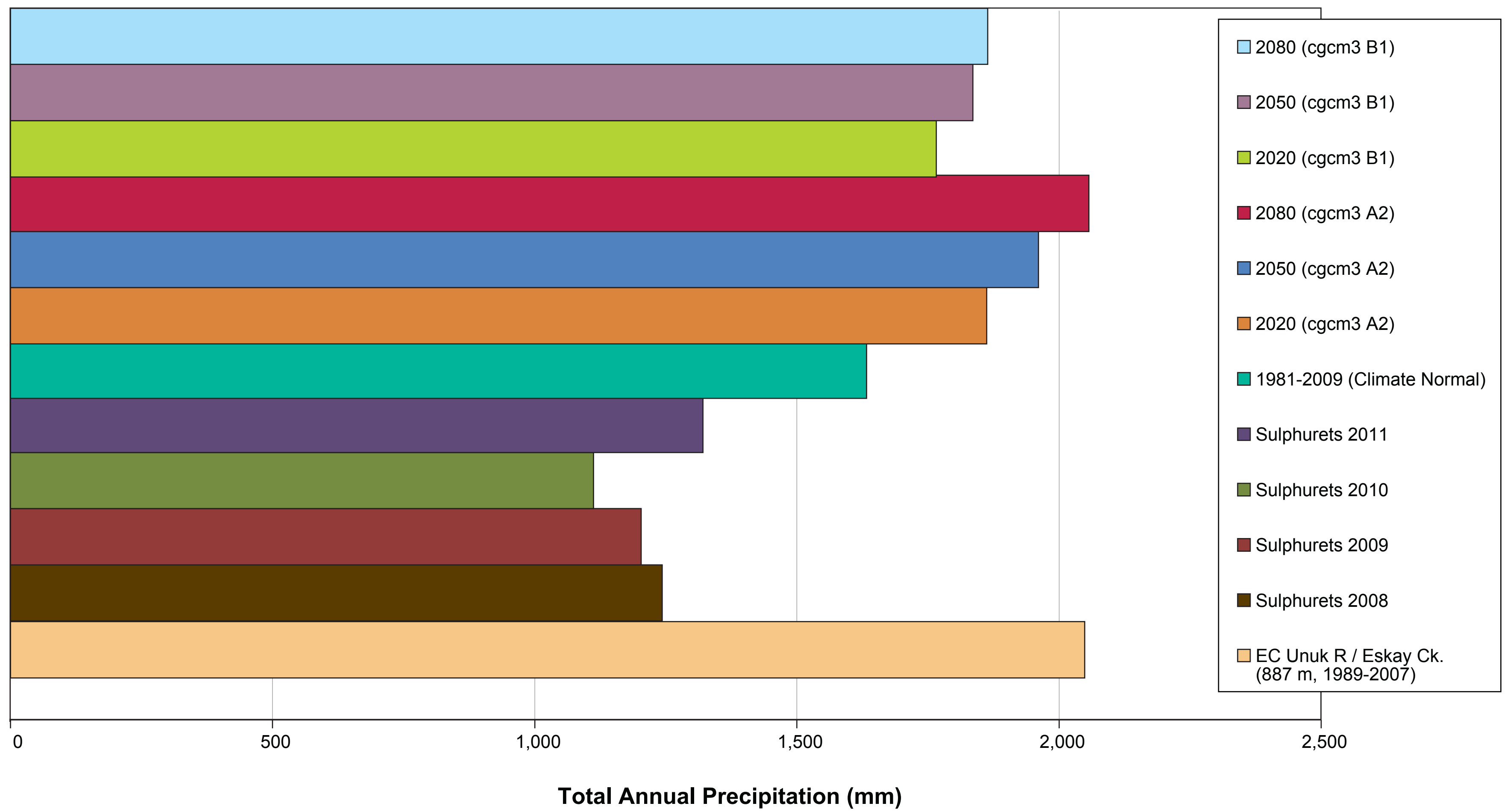

Figure 3.2-2

SEABRIDGE GOLD
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Modern and Predicted Precipitation in the KSM Project Area

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Figure 3.2-2

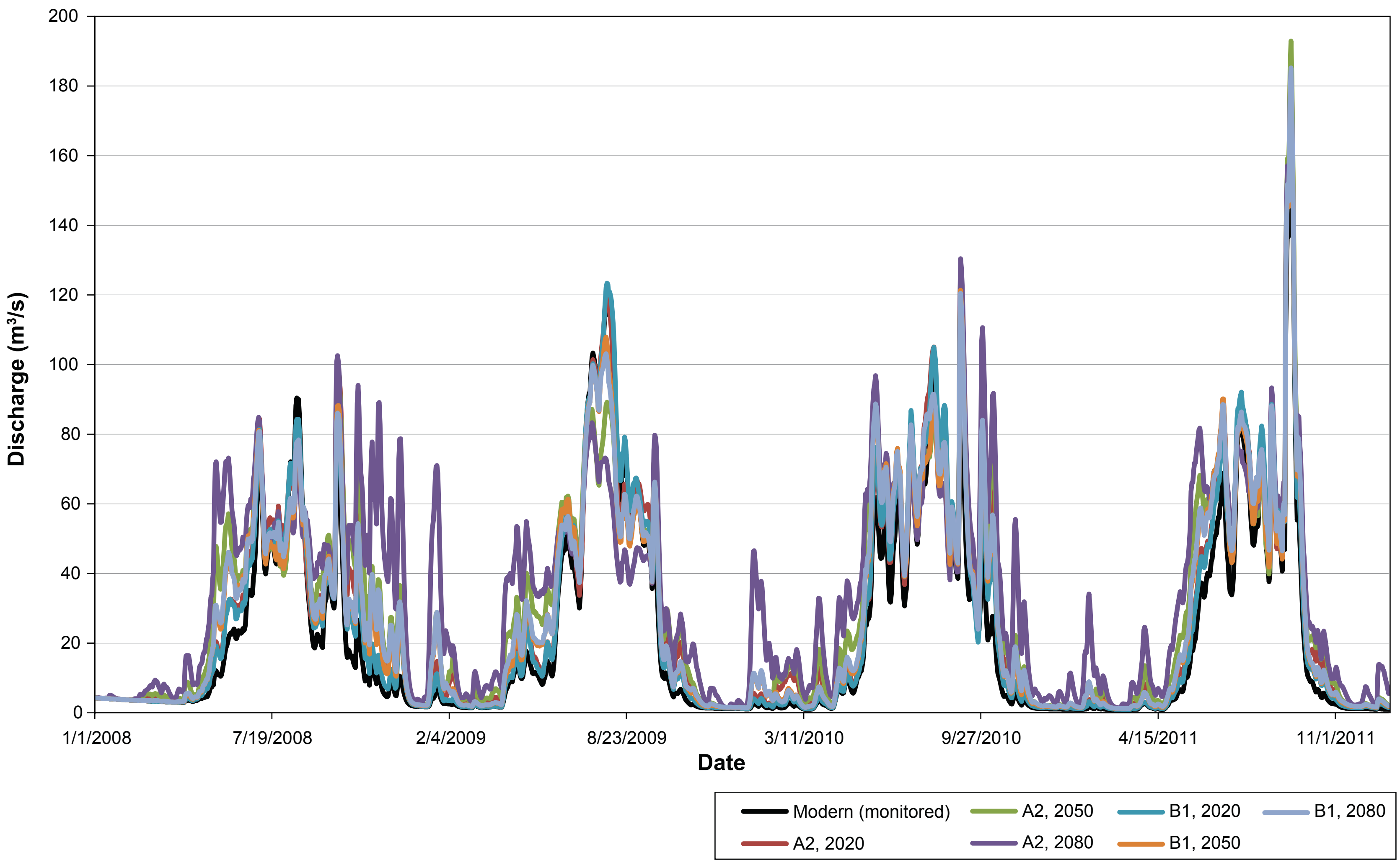


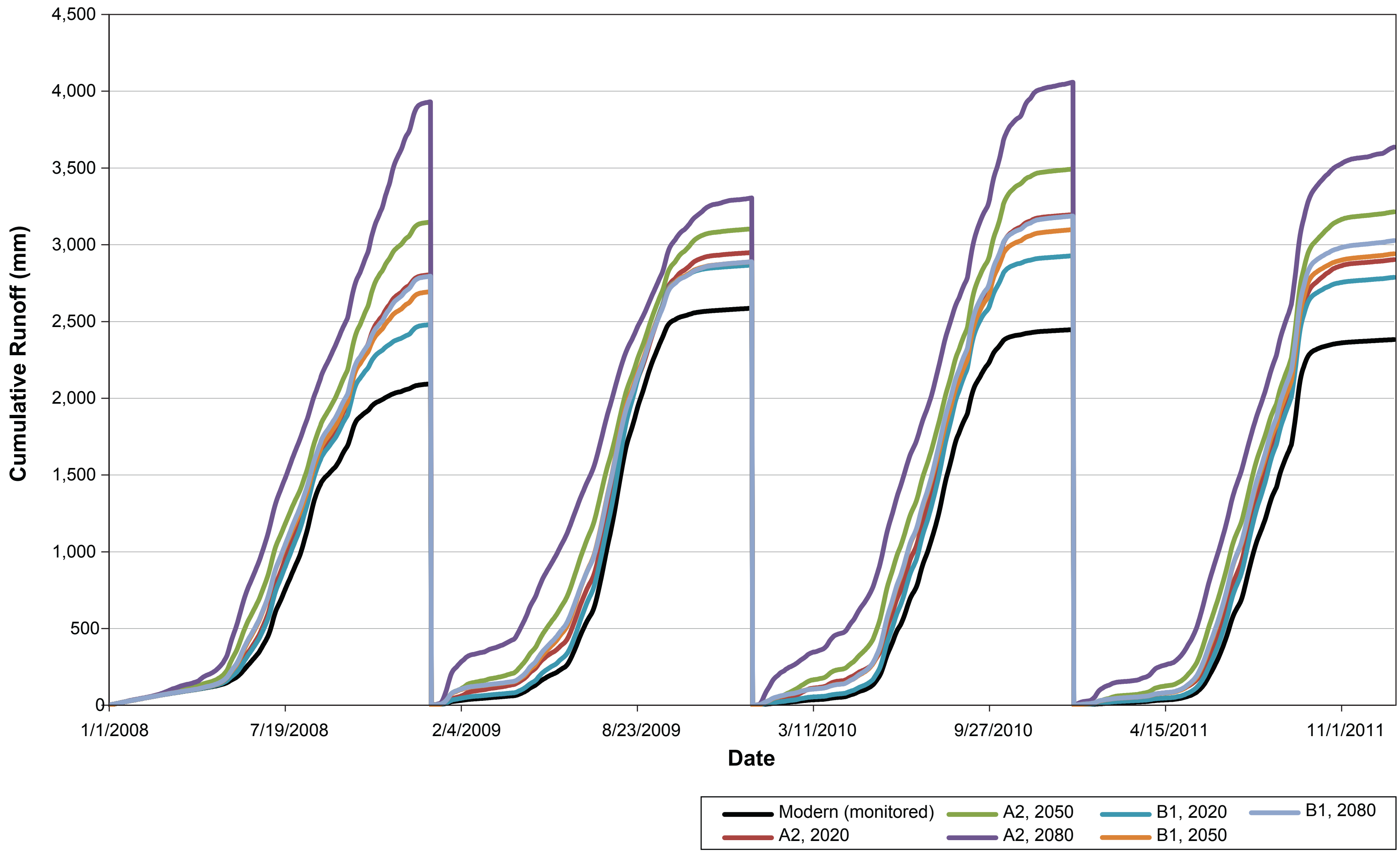
Figure 3.2-3

Modelled Daily Discharge at SC-H1 for Modern and Future Weather and Climatic Conditions

SEABRIDGE GOLD
KSM PROJECT

Rescan Engineers & Scientists

Figure 3.2-3



Seabridge Gold
KSM PROJECT

Modelled Cumulative Runoff at SC-H1 for Modern and Future Weather and Climatic Conditions

Figure 3.2-4

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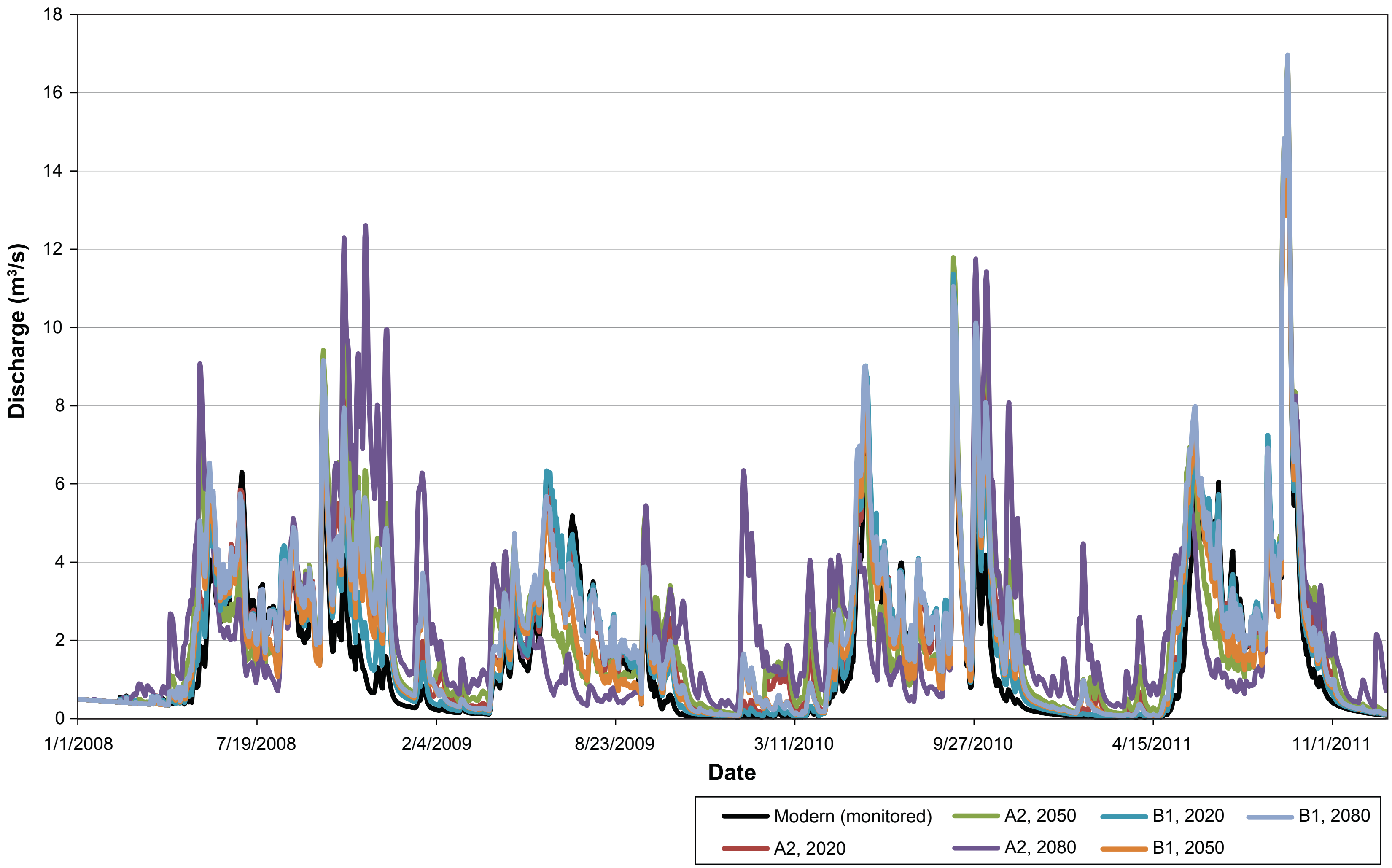

SEABRIDGE GOLD
KSM PROJECT

Modelled Daily Discharge at NTWM-H1 for Modern and Future Weather and Climatic Conditions

Figure 3.2-5

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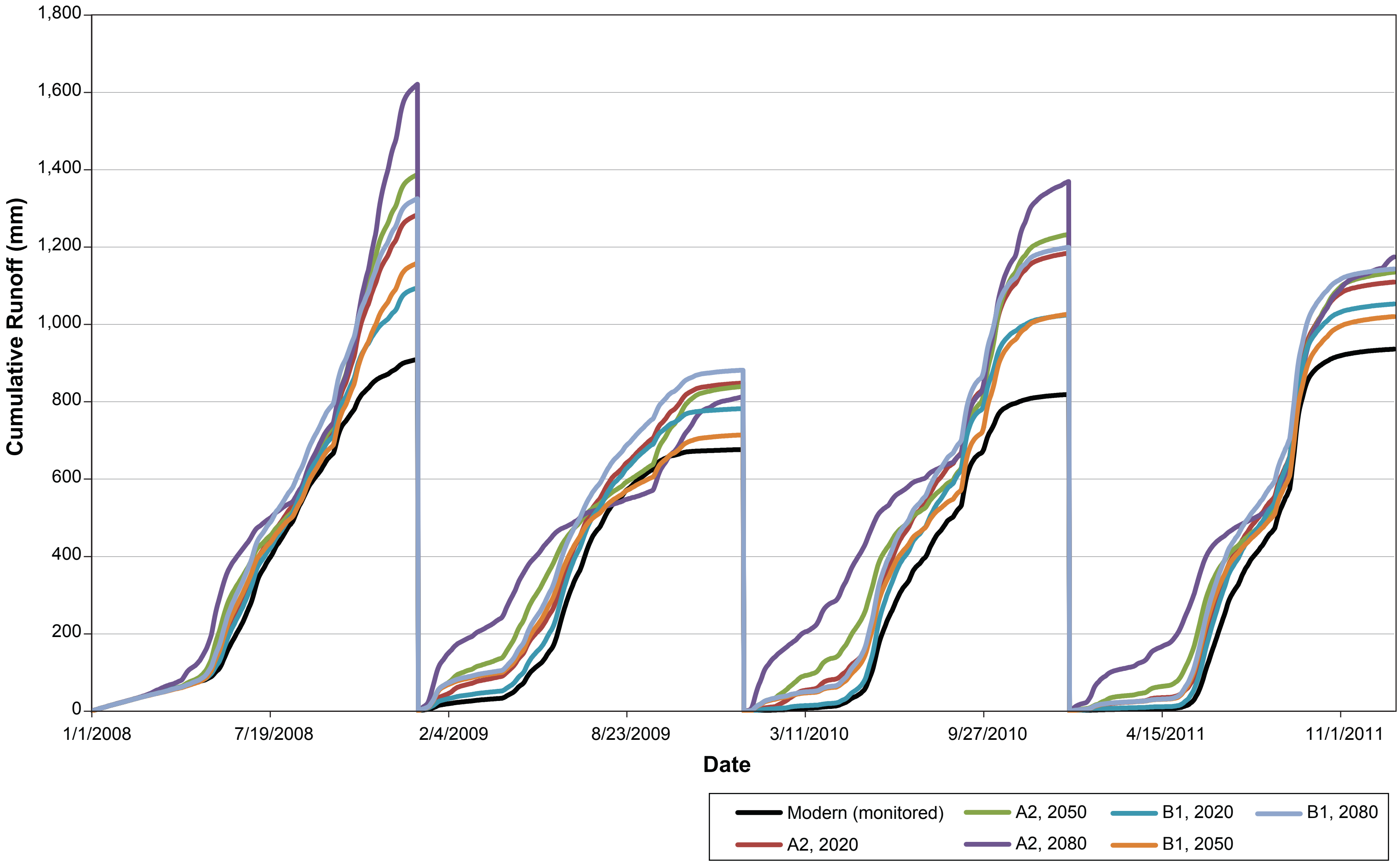

SEABRIDGE GOLD
KSM PROJECT

Modelled Cumulative Runoff at NTWM-H1 for Modern and Future Weather and Climatic Conditions

Figure 3.2-6

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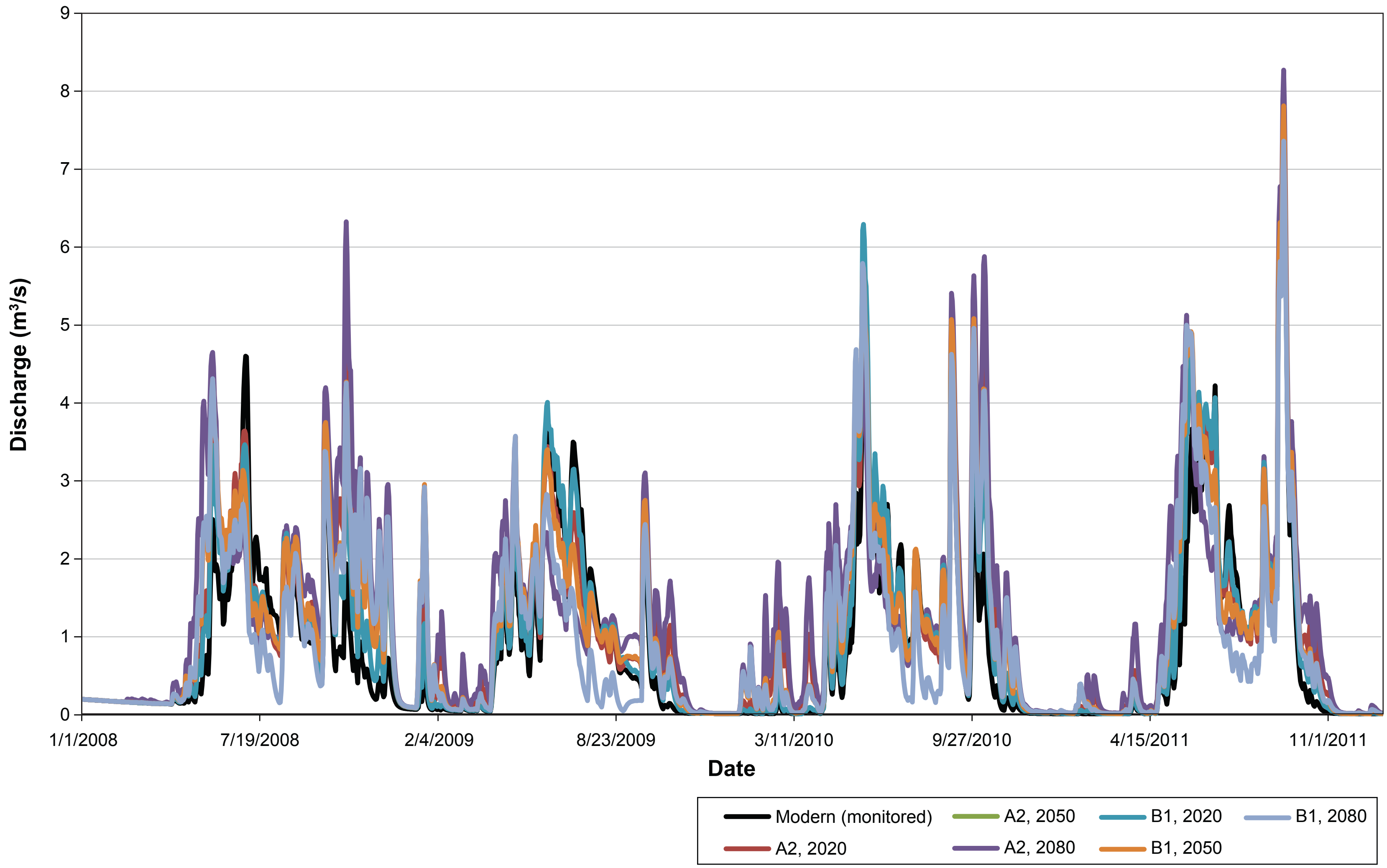

Figure 3.2-7

SEABRIDGE GOLD
KSM PROJECT

Modelled Daily Discharge at NTWM-H1 for Modern and Future Weather and Climatic Conditions

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Figure 3.2-7

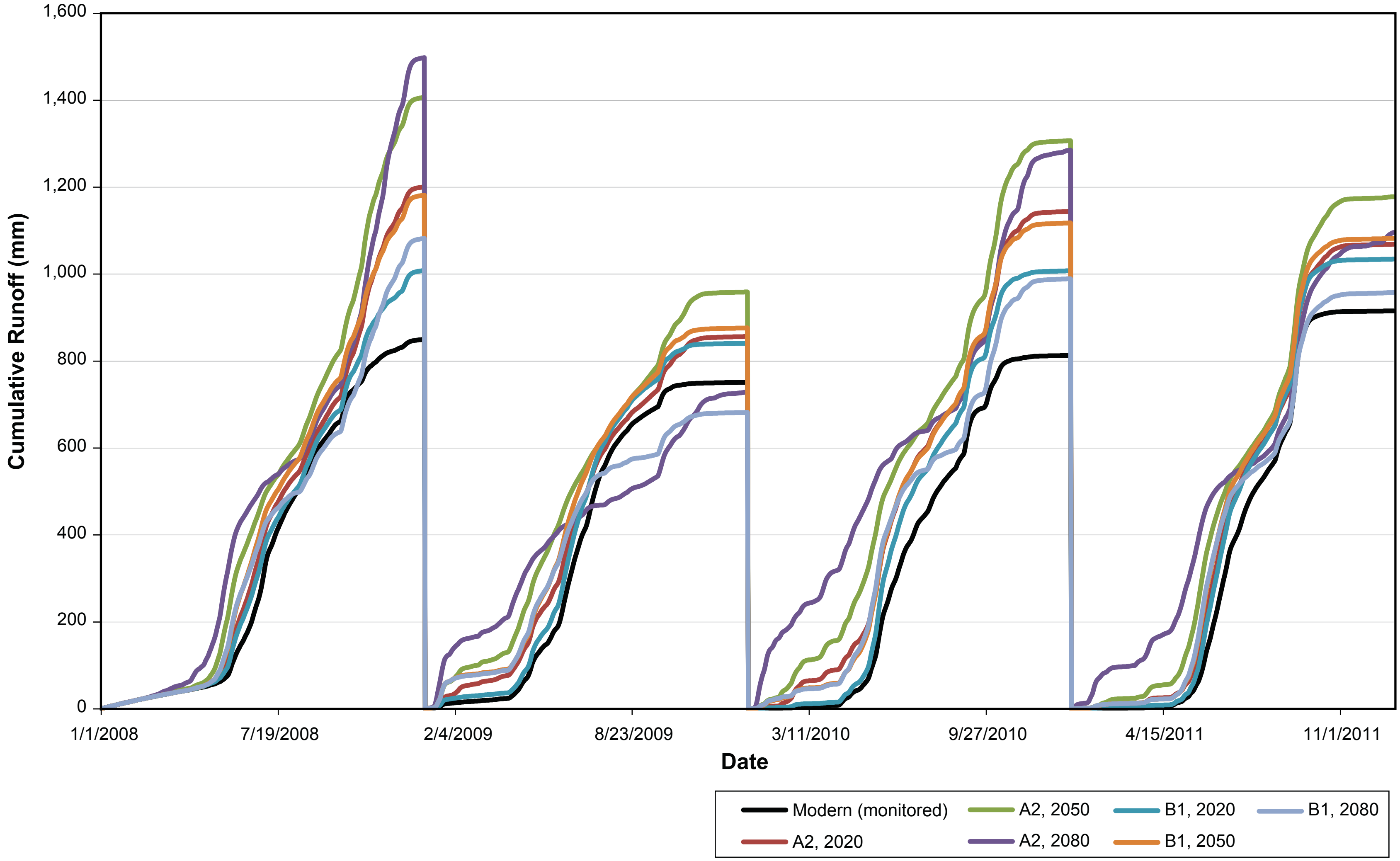

Figure 3.2-8

SEABRIDGE GOLD
KSM PROJECT

Modelled Cumulative Runoff at STWM-H1 for Modern and Future Weather and Climatic Conditions

Figure 3.2-8

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Table 3.2-2. Modern and Predicted Glacierized Areas in the South Teigen Creek (NTWM-H1) Watershed, Presented within the Eight Elevation Bands Used by UBCWM

Band	Mean elevation (m ASL)	Total band area (km^2)	Glacierized area in 2009 (km^2)	Estimated Area (km^2)			Areal change since 2009 (%)		
				2020	2050	2080	2020	2050	2080
1	718.1	1.20	0.00	0.0	0.0	0.0	0.0	0.0	0.0
2	893.6	9.50	0.00	0.0	0.0	0.0	0.0	0.0	0.0
3	1069.2	9.20	0.00	0.0	0.0	0.0	0.0	0.0	0.0
4	1244.7	9.10	0.00	0.0	0.0	0.0	0.0	0.0	0.0
5	1420.2	10.40	0.19	0.0	0.0	0.0	0.0	0.0	0.0
6	1595.7	10.80	1.19	1.2	0.4	0.0	-2.3	-64.1	-100.0
7	1771.2	8.40	1.34	1.3	0.7	0.2	-3.0	-46.5	-86.7
8	1946.8	2.20	0.12	0.1	0.1	0.1	-8.3	-8.3	-8.3
Sum	-	60.80	2.84	2.6	1.3	0.3	-	-	-

Table 3.2-3. Modern and Predicted Glacierized Areas in the North Treaty Creek (STWM-H1) Watershed, Presented within the Eight Elevation Bands Used by UBCWM

Band	Mean elevation (m ASL)	Total band area (km^2)	Glacierized area in 2009 (km^2)	Estimated Area (km^2)			Areal change since 2009 (%)		
				2020	2050	2080	2020	2050	2080
1	711.5	1.10	0.00	0.0	0.0	0.0	0.0	0.0	0.0
2	888.4	6.60	0.00	0.0	0.0	0.0	0.0	0.0	0.0
3	1065.2	4.70	0.00	0.0	0.0	0.0	0.0	0.0	0.0
4	1242.0	5.70	0.15	0.1	0.0	0.0	0.0	0.0	0.0
5	1418.8	5.40	0.61	0.6	0.3	0.0	0.0	0.0	0.0
6	1595.7	5.40	0.27	0.2	0.2	0.0	-11.1	-25.9	-100.0
7	1772.5	3.50	0.23	0.2	0.2	0.0	-9.1	-21.7	-100.0
8	1949.3	0.70	0.11	0.1	0.0	0.0	0.0	-100.0	-100.0
Sum	-	33.10	1.37	1.2	0.7	0.0	-	-	-

3.3 Testing the Effects of Varying Hydrologic Model Inputs

3.3.1 Varying Air Temperature

CCM3 air temperature predictions are warmer than the other two GCMs assessed here (BCCR BCM2.0 and GFDL CM21). For example, average annual air temperature in 2080 for the A2 scenario is 4.2 ^{o}C for CGCM3, compared to 3.5 ^{o}C for GFDL CM21 and 1.6 ^{o}C for BCCR BCM2.0 (Figure 3.3-1).

UBCWM was run with time series produced with the 'delta method' using the warmest and coolest GCM predictions *for each month* (Section 2.7.1). Although CGCM3 produced the warmest *annual* predictions, this test uses the warmest *individual months* from each GCM, so the result is a hybrid time series of the warmest and coolest predicted months.

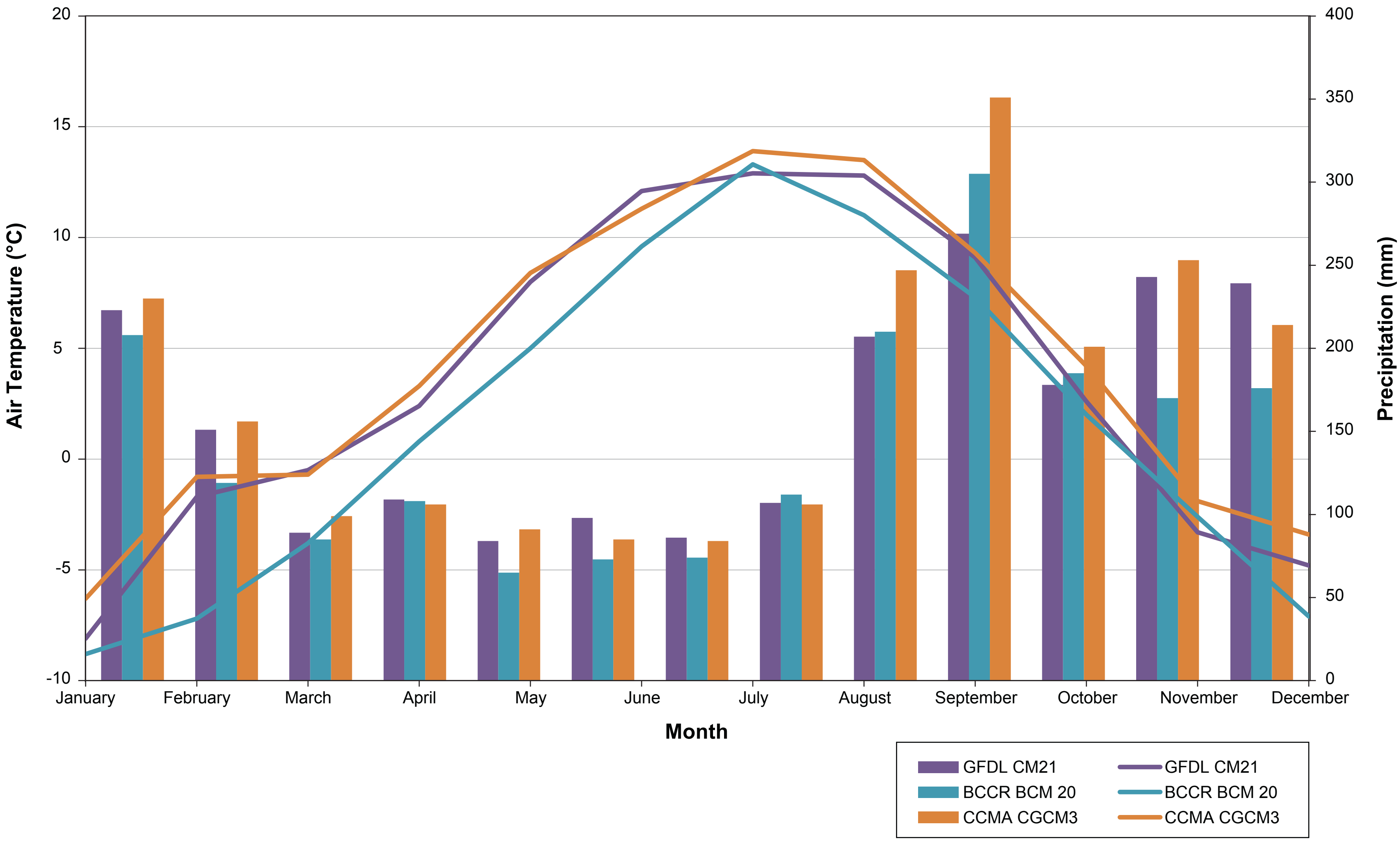

Figure 3.3-1

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Intercomparison of GCM Air Temperature and Precipitation for SRES A2 in 2080 for Sulphurets Creek

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UBCWM was run with time series produced with the ‘delta method’ using the warmest and coolest GCM predictions *for each month* (Section 2.7.1). Although CGCM3 produced the warmest *annual* predictions, this test uses the warmest *individual months* from each GCM, so the result is a hybrid time series of the warmest and coolest predicted months.

The coolest predicted climate produces a total annual runoff of about 1000 mm less than the CGCM3 prediction. The warmest predicted climate produces more discharge (Figure 3.3-2) and total annual runoff of 100-700 mm more than the CGCM3 prediction (Figure 3.3-3). Warmer air temperatures cause more glacially-derived discharge, and vice-versa. The largest differences between the three scenarios occur in late summer, when glacial melt is the largest contribution to runoff (Figure 3.2-6).

3.3.2 Varying Precipitation

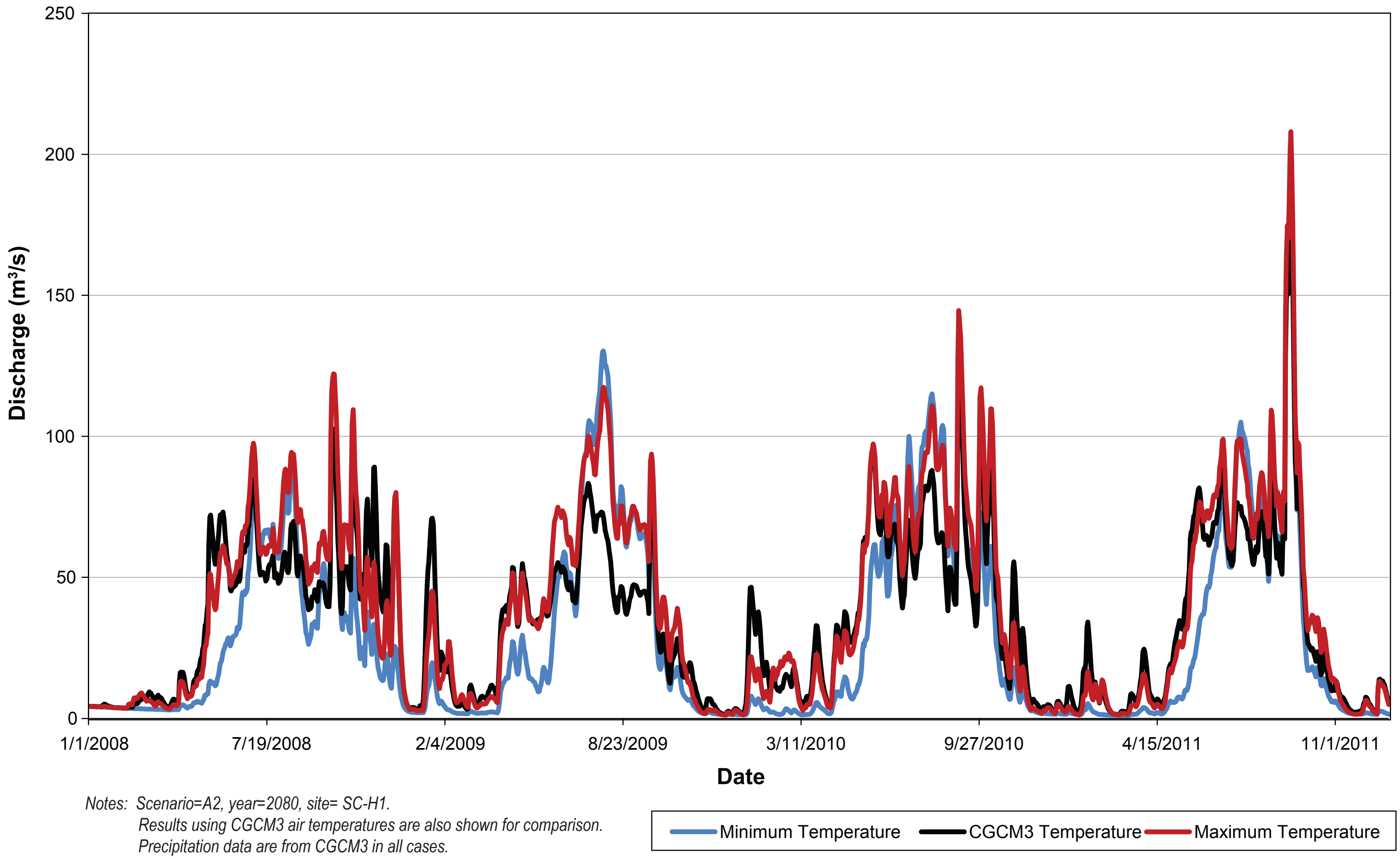
To test the hydrologic effects of inter-model precipitation variability, precipitation time series from the GCM that predicted the driest climate (BCCR BCM2.0) was input into UBCWM, while keeping all other inputs the same. CGCM3 predicts an anomalously wet climate of 2009 mm of annual precipitation, compared to 1714 mm for BCCR BCM2.0 and 1844 mm for GFDL CM21. To assess the hydrologic effects of the wettest and driest GCMs, UBCWM was run with time series produced with the ‘delta method’ using CGCM3 and BCCR BCM2.0 (Section 2.7.1).

The GCM with the driest climate produces lower discharges (Figure 3.3-4), and 400-600 mm less runoff per year than using the CGCM3 precipitation record (Figure 3.3-5).

3.3.3 Varying Glacierized Area

The process of estimating future glacier position is highly uncertain. The hydrologic sensitivity to this uncertainty was tested in the highly glacierized SC-H1 catchment. Glacier position in 2080 was first estimated using knowledge of modern mass balance, glacier retreat rates, and topography (Section 2.6.2). These ‘best-guess’ areal estimates (Tables 3.2-1 to 3.2-3) were then adjusted by ±25%, and the hydrologic responses were modelled in UBCWM (Figure 3.3-6, Figure 3.3-7).

Increasing and decreasing glacierized area by 25 percent only varies total annual runoff by about 100 mm (Figure 3.3-7). These changes are relatively small compared to the runoff change between modern glacierized area and 2080 ‘best-guess’ predictions (about 200 mm). These changes are also small compared to varying air temperature and precipitation time series (Section 3.2.1). This indicates that UBCWM models are relatively insensitive to changing glacierized area, at least for the SC-H1 modelled catchment.



Notes: Scenario=A2, year=2080, site= SC-H1.
Results using CGCM3 air temperatures are also shown for comparison.
Precipitation data are from CGCM3 in all cases.

Figure 3.3-2

SEABRIDGE GOLD
KSM PROJECT

Comparison of the Impacts on Discharge of Using the Warmest and Coolest of Three GCM Results

Figure 3.3-2

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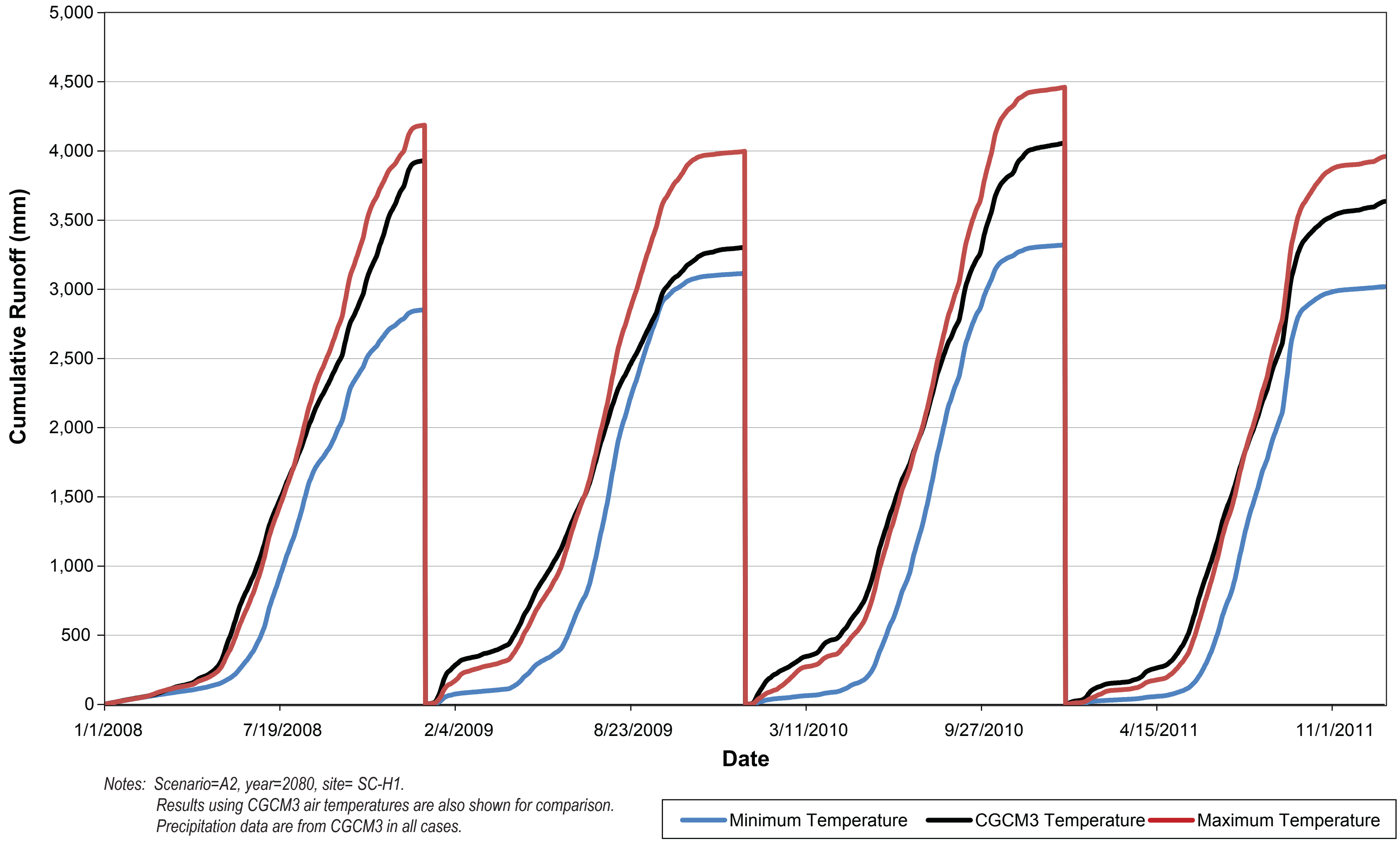

Notes: Scenario=A2, year=2080, site= SC-H1.
Results using CGCM3 air temperatures are also shown for comparison.
Precipitation data are from CGCM3 in all cases.

Figure 3.3-3

SEABRIDGE GOLD
KSM PROJECT

Comparison of the Impacts of Runoff of Using the Warmest and Coolest of Three GCM Results

Figure 3.3-3

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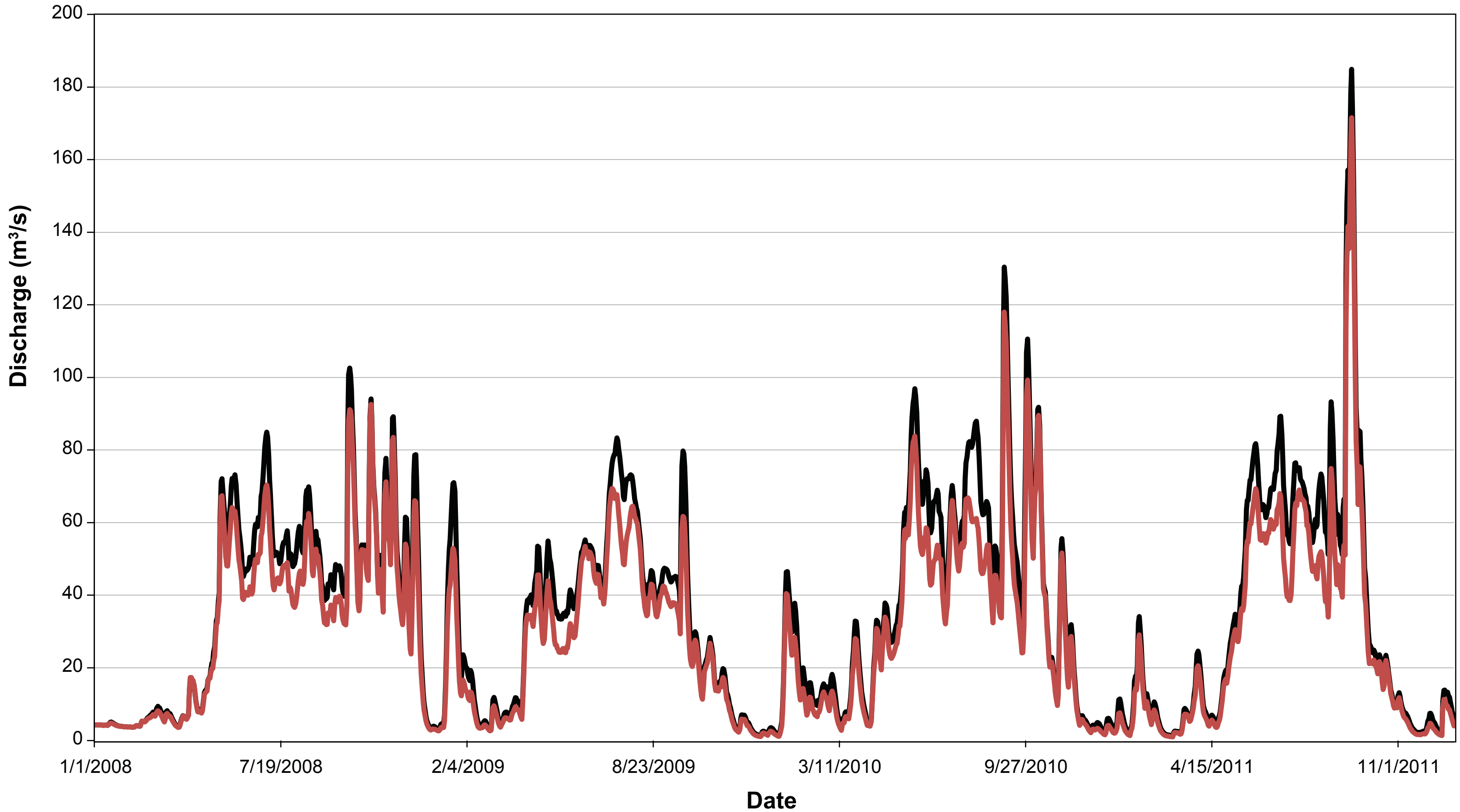

Note: Precipitation data are from CGCM3 and BCM 2.0. CGCM3 air temperature is used in both cases.

Figure 3.3-4

SEABRIDGE GOLD
KSM PROJECT

Comparison of the Impacts on Discharge of Using Two Different GCM Predictions of Precipitation, Scenario = A2, Year = 2080 and Site = SC-H1

Figure 3.3-4

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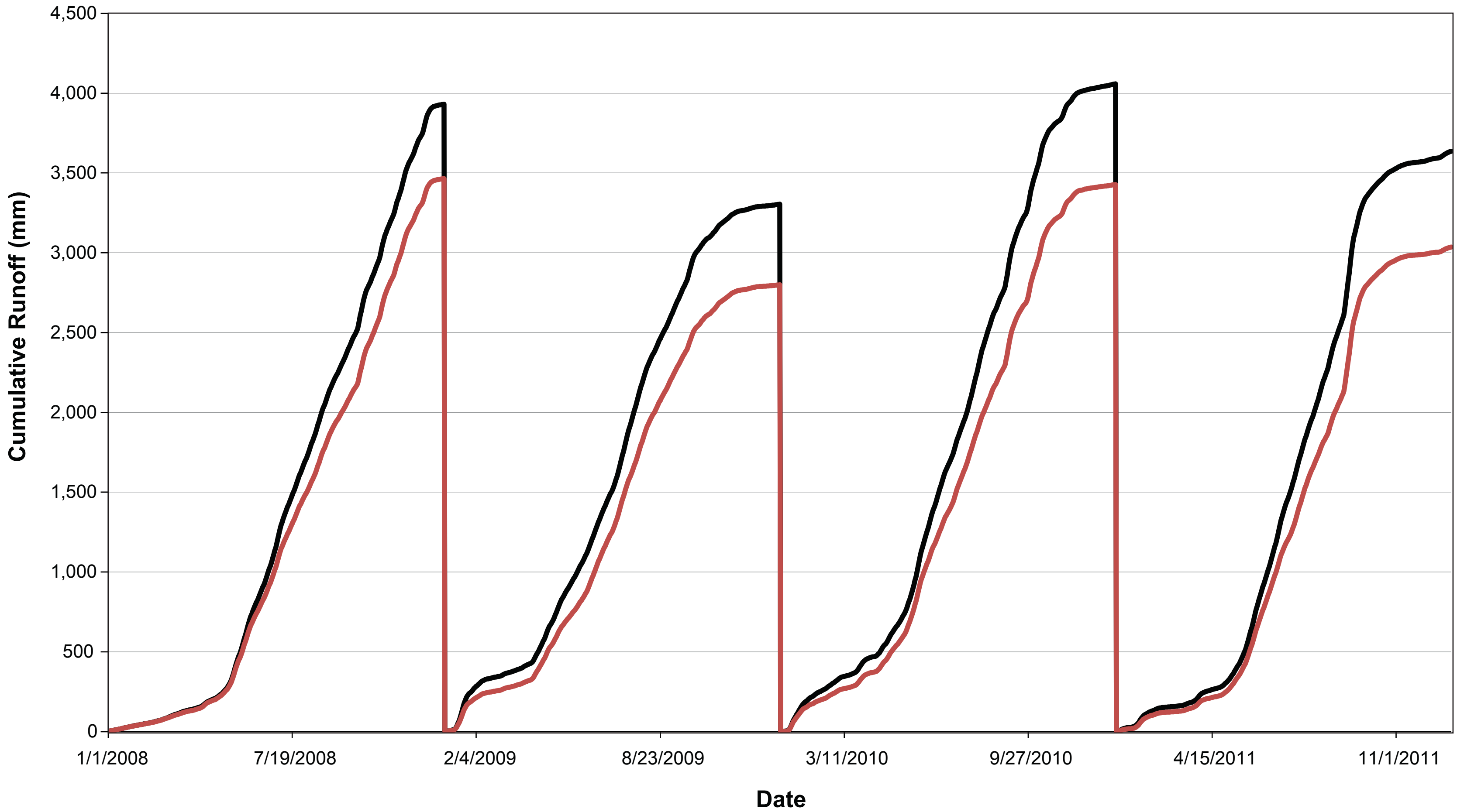

Note: Precipitation data are from CGCM3 and BCM 2.0. CGCM3 air temperature is used in both cases.

SEABRIDGE GOLD
KSM PROJECT

Comparison of the Impacts on Runoff of Using Two Different GCM Predictions of Precipitation, Scenario = A2, Year = 2080 and Site = SC-H1

Figure 3.3-5

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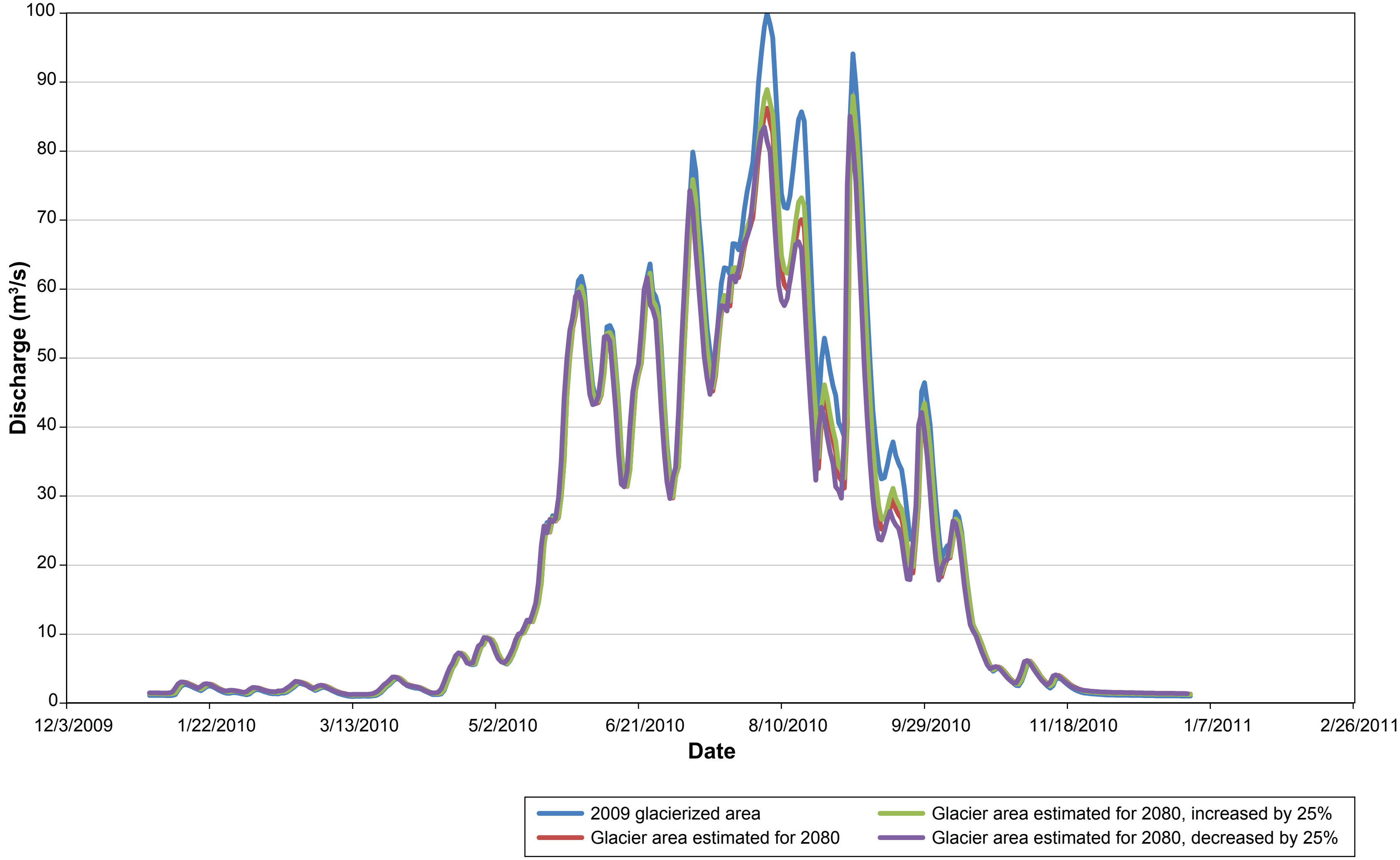

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Sensitivity Analysis; Adjusting Glacier Area; Discharge from SC-H1

Figure 3.3-6

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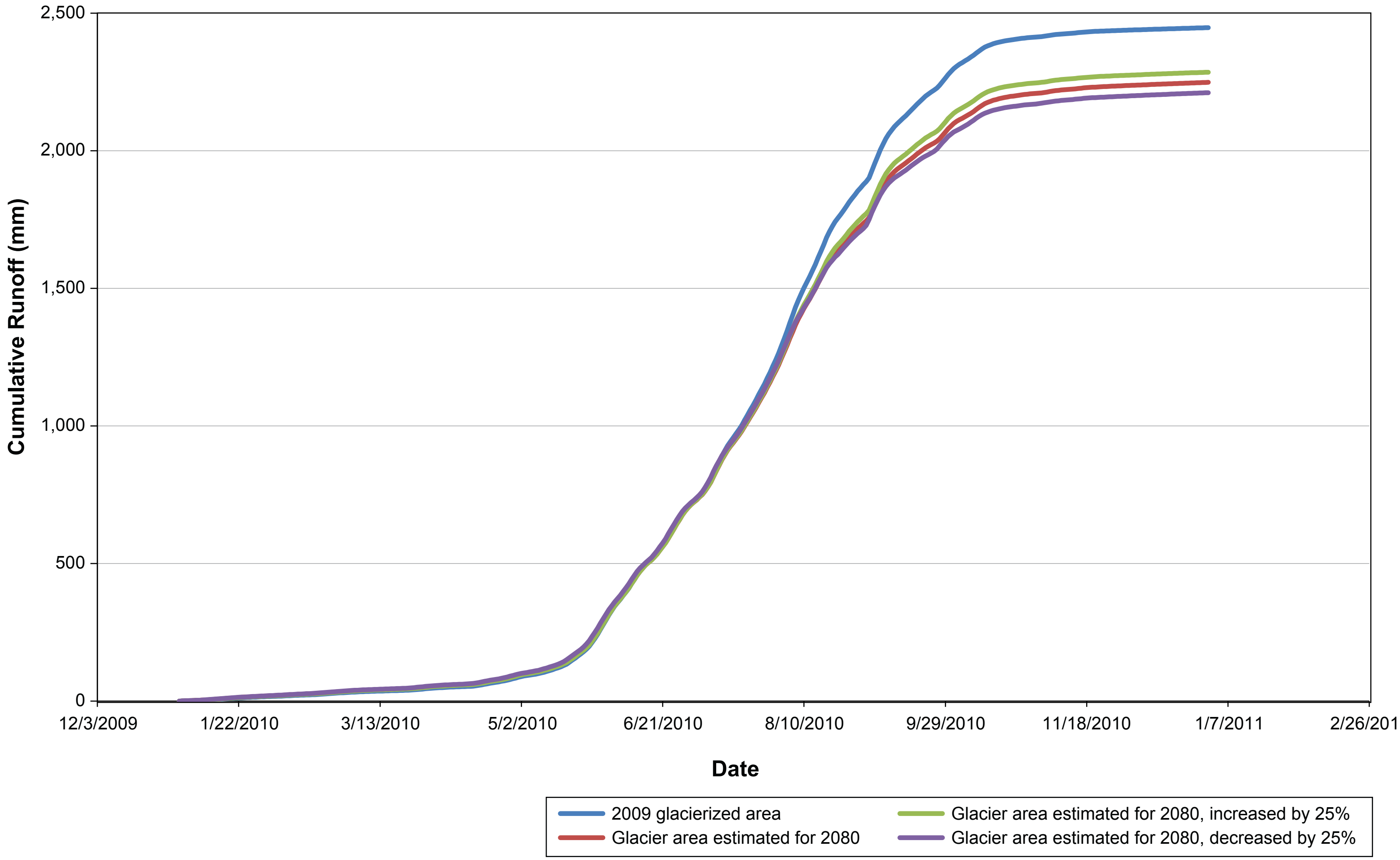

SEABRIDGE GOLD
KSM PROJECT

Sensitivity Analysis; Adjusting Glacier Area; Cumulative Runoff from SC-H1

Figure 3.3-7

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4. Discussion

4.1 Watershed Calibration

Generally, in the calibration period (2008-2011), watersheds calibrated in UBCWM adequately simulate the timing, onset, and winter flows, as well as indices such as peak daily flow and runoff.

The largest catchment, Sulphurets Creek (SC-H1) produced model results that were closest to measured (Table 3.1-4). Smaller catchments respond more quickly to short-term events such as rainfall and the nival melt period, making the simulation of these events more difficult. Watershed parameters may be easier to generalize in larger catchments, and may be more sensitive in smaller catchments. Also, the weather stations used to calibrate South Teigen Creek (NTWM-H1) and North Treaty Creek (STWM-H1) are in an adjacent valley (Figure 2.2-1), and may not be wholly representative of conditions in the watersheds themselves.

In some cases, discrepancies exist between modelled and monitored discharge at the beginning and end of the calendar year. The inability of the model to simulate some early season flows may be due to discrepancies between higher and lower elevation air temperatures, which are particularly important when air temperatures are near freezing (ex. Figure 3.1-1, June 2008). Discrepancies at the end of the calendar year (ex. Figure 3.3-1, October-November 2011) could have the same source, but late season monitored records are often estimated, so the model may actually provide better estimates of indices such as the 7-day low flow.

Other discrepancies between modelled and measured flows are likely due to spatial changes in precipitation. For example, at SC-H1, two large precipitation events occurred in late August and early September, 2011 (Figure 3.1-1). The model under-predicted flow in the first event, and over-predicted flow in the second event. Precipitation measured at one station in a valley is not necessarily representative of precipitation conditions in the catchment as a whole. Meteorologic instrumentation is also prone to undercatch (Mekis and Hogg 2011). UBCWM compensates for undercatch by uniformly increasing precipitation time series; however, in reality undercatch is controlled by temporally variable conditions, like wind.

4.2 Hydrologic Response to Future Climate Scenarios

In almost all catchments, and for almost all GCM scenarios, discharge and runoff are projected to increase until 2080, when modelling stopped (Figure 3.2-3 to Figure 3.2-8). The largest increases are for the A2 scenario in 2080. This is a response to increased air temperatures leading to increased glacial melt, and increased precipitation (Figure 3.2-2). Generally, results indicate that total annual runoff will increase by 20-60% by 2080 for the A2 scenario, and about half that increase for the B1 scenario.

Differences in discharge and runoff between the two SRES scenarios (A2 and B1) are large at equivalent times (ex. Figure 3.2-3, Figure 3.2-4). This illustrates the range in possible hydrologic responses that are possible given different future economic and political conditions.

In some years, discharge and runoff respond much more dramatically than in other years to the application of the same GCM predictions. For example, at SC-H1, total runoff almost doubles for the A2 scenario in 2080 using 2008 data (Figure 3.2-4). However, using 2009 data, the increase is much more modest. This illustrates the complexity of the water balance modelled catchments, with rainfall, snowfall, glacial melt, and evaporation responding to a large number of hydrometeorologic processes, which affect total runoff in a variety of ways. It also illustrates the benefits of multi-annual monitoring in the project area.

GCMs predict increasing air temperature and precipitation in the 21st century in this region. When air temperature increases in glacierized catchments, discharge would be expected to increase, as glacial melt increases (Fleming and Clarke 2003; Rescan 2006). Increased runoff would also be expected when precipitation increases. Thus, to some extent, the results presented here are not surprising. This is especially true when assessing the relative insensitivity of SC-H1 runoff to significantly varying its glacierized area (Figure 3.3-7).

By contrast, some research in glacierized British Columbia catchments has predicted decreased discharge in the 21st century (Stahl et al. 2008). In this scenario, increased air temperatures would initially cause increased glacial melt and discharge; however, sustained warmth and glacial retreat would cause eventual decreases in discharge. Unlike the KSM catchments modelled here, the Bridge River catchment described above is highly glacierized (Bridge River Basin, 62% glacier cover). Therefore, a large proportion of total runoff in this catchment would be from glacial melt, and glacier recession would cause a proportionally large decrease in water availability for surface runoff. By contrast, the catchments modelled here are 38%, 2%, and 5% glacierized. The proportion of runoff from glacier melt in the KSM catchments would be comparatively smaller, and this reduction is more than balanced by increases in precipitation-derived runoff. Furthermore, the gauging site at SC-H1 receives about 300 mm less precipitation per year on average than the gauging site at Bridge River, which would further increase precipitation-derived runoff relative to glacially-derived runoff. Finally, the Bridge River basin is about 800 km south of the KSM project area, so glacial mass balance and retreat rates might be significantly different there.

Modelled discharge decreased in only one catchment (STWM-H1) in one modelled year (2009, with 2080 GCM deltas applied; Figure 3.2-8). STWM-H1 is unique in that by 2080, all glaciers are projected to have melted in the catchment (Table 3.2-3). As glacial retreat continues throughout the 21st century, this will likely occur in the NTWM-H1 catchment as well, where only small glacierized areas are projected to remain by 2080 (Table 3.2-3). Therefore, the 'tipping point' of reduced discharge and water availability that is predicted the Bridge River Basin, might occur later than 2080 in the catchments modelled here.

Another striking result of the hydrologic modelling is the increased frequency and magnitude of major runoff events in winter, particularly in the 2080 runs (Figure 3.2-3, Figure 3.2-5, and Figure 3.2-7). These events occur when air temperatures rise above freezing, precipitation falls as rain, and rainfall and elevated air temperatures cause snow melt.

4.3 Inter-GCM Variability, and Model Sensitivity to Temperature, Precipitation, and Glacierized Area

4.3.1 Varying Air Temperature and Precipitation

Varying air temperature has a very large effect on the amount of modelled melt and runoff (Figure 3.3-3), due to glacial melt. The timing of melt is also affected, with more snowmelt occurring earlier in warmer scenarios (Figure 3.3-2).

As noted in Section 4.2, some climate scenarios produce dramatically higher winter discharges when air temperatures are sufficiently high to cause snow and ice melt in winter. This is a strikingly different hydrologic regime compared to modern conditions. Sensitivity testing (Figure 3.3-2), and the use of multiple emissions scenarios (Figure 3.2-3), shows that this regime shift is most pronounced for the warmest scenarios towards the end of the century.

4.3.2 Varying Glacierized Area

While future glacier positions are uncertain, the hydrologic effects of this uncertainty are relatively small (Figure 3.3-6, Figure 3.3-7). In the early part of the melt season, when flow at SC-H1 is primarily fed by snowmelt (and rainfall runoff to a lesser extent), there is almost no difference between the three estimates of runoff produced by varying glacier position in 2080 (Figure 3.3-6), or between discharge estimates using the modern glacier position. As air temperature warms through the summer, and melt begins at higher elevations, the four scenarios (2009, 'best-guess' estimate, 'best-guess' area increased by 25%, and 'best-guess area decreased by 25%) begin to diverge in early August (Figure 3.3-7). However, the effects of adjusting 2080 glacierized area by ±25% are remarkably subtle (±75 mm of runoff). Differences between the modern and 'best-guess' areas are much larger (about 200 mm of runoff).

It should be noted that uniformly adjusting the glacierized area within each band does not produce realistic representations of glacier position. In reality, much of the uncertainty in position occurs at lower elevations. Nevertheless, it appears that runoff in the modelled catchments is relatively insensitive to changing as glacier area. As noted in section 4.3.1, the catchments modelled here are most sensitive to precipitation and air temperature.

5. Summary

Despite the complexity of the hydrometeorologic systems at KSM, modelled discharge correlated well with measured discharge (Table 3.1-4). This provided confidence that the catchments could be adequately modelled using climate change scenarios. The most striking conclusion of this study is the increase in discharge and runoff that is predicted to occur in all modelled catchments and for all emissions scenarios (with a one year exception). A large amount of variability in climatic predictions exists between different GCMs, and between different emissions scenarios. The GCM used here (CCMA CGCM3) appears to produce wet and warm climates relative to the two other assessed GCMs. This would increase predictions of discharge and runoff. However, the sensitivity testing results show that it is unlikely that discharge will decrease in the modelled catchments, as has been found in the Bridge River Basin, Southern Chilcotin Mountains, British Columbia. Another striking result of the study is the increasing importance of winter melt events towards the end of the century, especially in for the A2 SRES scenario.

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