Seattle City Light Climate Change Analysis

Prepared for The City of Seattle, Seattle City Light

Prepared by The Climate Impacts Group,
Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

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Under a November 2009 memorandum of agreement, the Climate Impacts Group at the University of Washington agreed to provide Seattle City Light with information about climate change effects on regional climate, streamflow, and stream temperature in order to support City Light's assessment of impacts of projected climate change on operations at the Skagit and Boundary hydroelectric projects and on future electricity load in its service territory. The report, which follows, is divided into three parts:

Part I: Climate Extremes

Part II: Streamflow Scenarios

Part III: Water Temperature and Hydrologic Extremes

Appendix A: Responses to Seattle City Light's Queries About Interpretation of Results

The table on the following page summarizes how the information requested in the MOA is being provided via this report and the accompanying DVD of data.

The DVD contains:

- the results of the analyses described in this report (summarized in the following table)
- the data for each of the figures in this report
- an electronic copy of this report

The DVD is arranged by Task Number (as in the MOA and the following table) and contains *read_me* files providing information about the file format where necessary.

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Summary of tasks outlined in Memorandum of Agreement, documentation, data provided and researchers involved.

Task	Documentation	Data	Key Researchers
1. Provide hydrologic data from Columbia Basin Climate Change Scenarios Project for selected (Part II, Table 2.1) gauge locations	Methodology for data production described in Part II of this report.	Streamflow data provided for each site on DVD in folder "Task I/streamflow_data_by_site".	Se-Yeun Lee Alan F. Hamlet
2. Provide hourly time series data from Weather Research and Forecasting (WRF) simulations for the Seattle area to support SCL load forecast analyses	Models and methodology for data production described in Part I of this report.	Regional hourly time series data provided on DVD in folder "Task II & III/ regional_climate_data/wrf_hourly_data".	Eric P Salathé Jr Rick Steed
3. Perform analysis of extreme events (precipitation and temperature combinations) for the Skagit basin from WRF simulations	Analysis and key results detailed in Part I of this report.	Extreme events data provided on DVD in Excel file named "RCM_extremes_data.xls" in the folder "Task II & III/regional_climate_data"	Eric P Salathé Jr Rick Steed
4. Perform analysis of streamflow extremes and fish impacts for Skagit and Boundary	Analysis and key results detailed in Part III of this report.	Flood and low flow statistics provided on DVD by site in folder "Task IV/ extreme_flow_stats_by_site". Annual low flow data provided on DVD in files by model/scenario/time period in folder "Task IV/annual_streamflow_lows". Annual streamflow peaks data provided on DVD in files by model/scenario/time period in folder "Task IV/annual_streamflow_peaks". Weekly water temperature data provided on DVD in files by scenario and future time period in the folder "Task IV/water_temperature_data". (The historical simulation is included in each file.)	Ingrid Tohver Alan Hamlet Nathan Mantua

Part I: Projections of Future Regional Climate and Extreme Climatic Events from the Weather Research and Forecasting (WRF) Regional Climate Model

A. Introduction

The extreme values of precipitation and temperature are an important measure of the effects of weather and climate on the region. Changes in these parameters under future climate conditions could lead to substantial impacts on hydrologic conditions and, potentially, on water management. Global climate models provide the main guidance in assessing future climate impacts, but these models cannot adequately simulate the weather, terrain, and land-surface processes that produce local extremes of temperature and precipitation. Recent developments with regional climate models have provided more realistic simulations of extreme events under climate change scenarios. For this report, we have examined the projected future changes in extreme events over the areas critical to Seattle City Light's operations using simulations from a regional climate model.

B. Methods

The regional climate model simulations used for this study are described in detail in Salathé et al. (2010). The simulations use the Weather Research and Forecasting (WRF) model using boundary conditions from 1) the Max Plank Institute, Hamburg, global model (ECHAM5) and 2) the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3). The first simulation will be referred to as ECHAM5-WRF and the second as CCSM3-WRF. The performance of both global climate models in simulating the climate of the north Pacific region is highly ranked among the full set of IPCC models (Mote and Salathé 2010); the El Niño cycle, in particular, is well represented by ECHAM5 (Zhang et al. 2010). These models are among the most sophisticated of current climate models, and the two modeling centers have archived and distributed output data suitable for input to a regional model. The simulations span the 100-year period from 1970 to 2069. The historic period (1970-1999) simulation is based on observed greenhouse gas forcing. Projected greenhouse gas and aerosol emissions scenarios (Nakicenovic et al. 2000) are used for the future period (2000-2069). For the ECHAM5-WRF simulation, the A1B scenario is used; for the CCSM3-WRF simulation, the A2 scenario is used. Both scenarios project rapid greenhouse gas emissions over the early 21st century, with insignificant differences between the two until the 2050s. The A1B scenario projects stabilization of emissions in the late 21st century while the A2 scenario projects accelerated emissions. The WRF model is run at a grid spacing that resolves the important mountain ranges of the state of Washington (grid cells are 36-km and 20-km on a side for the ECHAM5-WRF and CCSM3-WRF simulations, respectively) (Salathé et al. 2010).

We examined the projected changes of 26 parameters, listed in Table 1.1, at eight station locations, listed in Table 1.2. Parameters included yearly measures of extreme temperature, extreme precipitation, and the occurrence of warm heavy precipitation. To evaluate the projected change in these parameters, each parameter is averaged over three 30-year periods, 1970-1999 (current climate), 2010-2039 ("2020s"), and 2030-2059

("2040s"). Future changes for the 2020s and 2040s are calculated as the difference to the current climate. The statistical significance of these changes was evaluated using a two-sided t-test at 95% and 99.9% confidence limits. Changes of approximately ½ the standard deviation are significant at 95% and changes of approximately 1 standard deviation are significant at 99.9%.

Table 1.1 Parameters used to evaluate the frequency of extreme temperature and precipitation events.

Parameter	Definition
tx	annual mean daily maximum temperature
tn	annual mean daily minimum temperature
sdii	annual precipitation divided by number of rainy days (pcp > 1 mm/day)
r01mm	annual number of days with precipitation >= 1 mm
r10mm	annual number of days with precipitation >= 10 mm
r20mm	annual number of days with precipitation >= 20 mm
dry	annual number of days with precipitation < 1 mm
cwd	annual maximum number of consecutive days with precipitation >= 1 mm
cdd	annual maximum number of consecutive days with precipitation < 1 mm
rx1d	annual maximum daily precipitation amount
rx5d	annual maximum 5-day precipitation amount
rx1h	annual maximum 1-hour precipitation amount
wwd10mm	annual number of days with temperature >=2 C and precipitation >= 10 mm
vwwd10mm	annual number of days with temperature >=10 C and precipitation >= 10 mm
wwd20mm	annual number of days with temperature >=2 C and precipitation >= 20 mm
vwwd20mm	annual number of days with temperature >=10 C and precipitation >= 20 mm
cwwd10mm	annual maximum number of consecutive days with temperature >=2 C and precipitation >= 10 mm
dtr	annual mean daily temperature range
txx	annual extreme maximum daily high temperature
txn	annual extreme minimum daily high temperature
tnn	annual extreme minimum daily low temperature
tnx	annual extreme maximum daily low temperature
tn90p	annual number of days with low temperature >= 90th percentile (based on 1970-2000 climatology)
tn10p	annual number of days with low temperature <= 10th percentile (based on 1970-2000 climatology)
tx10p	annual number of days with high temperature <= 10th percentile (based on 1970-2000 climatology)
tx90p	annual number of days with high temperature >= 90th percentile (based on 1970-2000 climatology)

Table 1.2 Stations for analysis.

Location	USGS	Latitude	Longitude
Skagit River			
SKAGIT AT DIABLO DAM	12176500	48.716	-121.131
SKAGIT RIVER NEAR MT VERNON	12200500	48.445	-122.334
ROSS RESERVOIR NEAR NEWHALEM	12175000	48.733	-121.067
BAKER RIVER AT CONCRETE	12193500	48.540	-121.742
SAUK RIVER NEAR SAUK	12189500	48.425	-121.567
Pend O'reille River			
PEND OREILLE RIVER AT BOX CANYON DAM	12396500	48.781	-117.415
PEND OREILLE RIVER AT BOUNDARY DAM	12398600	48.987	-117.348
Other			
Seattle SEA-TAC			

C. Hourly time series data (Task 2)

Hourly data for several parameters was archived from the regional climate model simulations and is suitable for understanding the sub-daily evolution of the climate. The results from both the ECHAM5-WRF and CCSM3-WRF simulations for the grid cells containing Seattle, WA, (47.62N, 122.33W) and Stateline WA (46.0372N, 118.807W) were extracted from the simulations for present and future climate periods. For each simulation, two files are provided, one for the current climate (1970-1999) and one for the future climate (2020-2059). Data are provided on DVD and (temporarily) on-line at http://www.atmos.washington.edu/~salathe/SCL/

D. Results for extreme event analysis (Task 3)

Projected changes in the frequency of extreme temperature and precipitation were analyzed only for the ECHAM5-WRF simulation. Results for all parameters considered are provided in the Excel spreadsheets on the DVD that accompanies this report. The spreadsheets include 1) statistical summaries for all parameters with results of statistical significance tests for changes at the 2020s and 2040s, 2) the annual values for each parameter for the period 1970-2059, and 3) values for the 90th percentile daily maximum and 10th percentile daily minimum temperatures for each calendar day at each station.

Here we provide a summary of key parameters that illustrate the important changes in extreme events as simulated for the region. Results at each station for 1) precipitation intensity (sdii), 2) the number of days with precipitation exceeding 10mm, and 3) the number of days with precipitation exceeding 10 mm and temperature exceeding 2°C are summarized in Tables 1.3-1.5. Figures 1.1-1.8 show the time series of a selection of extreme parameters over the period 1970-2060. For SeaTac (Figure 1.8), the observed values are also shown for comparison. Note that the climate simulation uses a free-running model, which means that simulated cycles of natural variability do not coincide with observed historical cycles; we do not expect the simulated and observed time series to be well correlated in time. Nevertheless, the absolute magnitude and range of variability of the simulated values should be comparable to those observed. The largest discrepancies are seen for annual daily minimum temperature, which shows the known cold bias in WRF (Zhang et al. 2010), and the annual average daily temperature range (Tmax-Tmin), which is too small in WRF.

Table 1.3 Results for changes in simple precipitation index (sdii) at each station. Statistically significant changes at 95% confidence are shown in bold and at 99.5% confidence in bold italic.

Station	1970-1999	Std Dev	Change 2020s	Change 2040s
Skagit Diablo Dam	14.79	1.51	-0.34	0.41
Skagit Mt Vernon	11.47	0.96	0.31	***1.11***
Ross Newhalem	10.06	0.90	-0.28	0.22
Baker Concrete	17.14	1.61	-0.18	**0.97**
Sauk	17.05	1.73	-0.50	0.67
Box Canyon	7.43	0.61	0.11	**0.43**
Boundary	7.50	0.68	0.15	**0.47**
Sea Tac	5.97	0.65	0.00	0.08

Table 1.4 As for Table 1.3, for changes in number of days with precipitation exceeding 10 mm (r10mm) at each station.

Station	1970-1999	Std Dev	Change 2020s	Change 2040s
Skagit Diablo Dam	101.57	14.44	0.30	1.93
Skagit Mt Vernon	69.57	12.33	4.83	**8.60**
Ross Newhalem	73.50	10.70	1.77	4.60
Baker Concrete	101.60	14.78	1.43	3.63
Sauk	98.70	14.05	-0.87	2.27
Box Canyon	43.57	6.92	3.43	**5.97**
Boundary	47.53	8.39	**5.43**	**7.30**
Sea Tac	22.70	5.80	0.93	1.87

Table 1.5 As for Table 1.3, for changes in number of days with precipitation exceeding 10 mm and temperature exceeding 2°C (wwd10mm) at each station.

Station	1970-1999	Std Dev	Change 2020s	Change 2040s
Skagit Diablo Dam	30.63	8.88	**5.67**	***11.87***
Skagit Mt Vernon	61.20	12.05	**6.53**	***11.17***
Ross Newhalem	15.10	5.37	1.90	***7.07***
Baker Concrete	59.77	13.59	**8.20**	***15.53***
Sauk	61.13	13.99	**7.00**	***14.60***
Box Canyon	16.00	5.01	**5.03**	***8.00***
Boundary	15.90	5.12	***5.40***	***7.73***
Sea Tac	20.80	5.64	0.97	2.10

1. Extreme temperature

Changes in extreme temperature were analyzed using parameters listed in Table 1.1. These include the annual maximum daily Tmax and Tmin and number of days in each year that exceed specific thresholds. The thresholds are computed from the 1970-1999 climatology for each calendar day, thereby removing the seasonal cycle. Thus, the 90^{th} percentile daily maximum temperature is defined for each calendar day from the 30 values for that day from each year. The values for these thresholds at each station are provided in the Excel spreadsheets included on the accompanying DVD. Results for extreme high temperature are well characterized by changes in the number of days exceeding the twentieth century 90^{th} percentile daily maximum temperature (tx90p). All stations show a steady increase in the annual number of days exceeding this threshold during the period 1970-2060, as is seen the lower-left panel of Figures 1.1-1.8. At all stations, there is a statistically significant increase in the number of days exceeding this threshold for maximum temperature for both the 2020s (at 95% confidence) and 2040s (at 99.9% confidence).

Likewise, the number of cold days steadily decreases. This is shown by the number of days with a daily minimum temperature below the twentieth century 10^{th} percentile (tn10p), which is also shown in Figures 1.1-1.8. At all stations, there is a statistically significant decrease in the number of days below this threshold for minimum temperature for both the 2020s (at 95% confidence) and 2040s (at 99.9% confidence).

2. Extreme Precipitation

A common measure of extreme precipitation is the precipitation intensity (sdii), defined as the annual total precipitation divided by the number of wet days (precipitation exceeding 1 mm). Precipitation intensity increases when the annual precipitation increases more rapidly than the number of wet days, which indicates heavier precipitation on rainy days. We also analyzed the number of days with precipitation exceeding thresholds of 1, 10, and 20 mm. Of these parameters, precipitation intensity provides the most consistent results (see Figures 1.1-1.8). Increases in precipitation intensity are statistically significant at only four stations (Mount Vernon and Concrete on the Skagit and Box Canyon and Boundary on the Pend Oreille). Except at Concrete, the increase in precipitation intensity is accompanied by an increase in the number of days with precipitation exceeding 10 mm. At Concrete, there is an increase at the 20 mm threshold (not shown in Figure 1.4; see Excel sheet), but not at 10 mm. In all cases, increases in precipitation intensity are modest with no statistical significance for the 2020s and 95% confidence for the 2040s.

3. Warm wet events

The occurrence of heavy precipitation on warm days is of particular concern for flood management. To assess the frequency of these events in the regional climate simulations, we considered two temperature and two precipitation thresholds, which combine to give four measures of warm-wet wintertime events. The temperature thresholds are 2°C (warm day) and 10°C (very warm day). The precipitation thresholds are 10 mm and 20 mm per day. This yields the parameters for the number of very warm wet days at 10 (vwwd10mm) and 20 mm (vwwd20mm) and for warm days at 10 (wwd10mm) and 20 mm (wwd20mm). Figures 1.1-1.8 show the time series of annual number of days exceeding 10°C and 10mm (vwwd10mm) in comparison with other parameters. Figure 1.9 shows time series at each station of the number of warm wet days per year at two thresholds, days with temperature over 10°C and precipitation over 20mm and over 2°C and 10mm.

At all stations except SeaTac, there is a statistically significant increase in the number of warm days with heavy precipitation at all thresholds by the 2040s. At most stations, the increase is significant by the 2020s, but several show less significant changes, particularly Ross reservoir at Nehalem. The increase in warm-wet events appears to be driven primarily by increases in temperature rather than precipitation. Increases in these parameters are found at stations irrespective of increases in the frequency of heavy precipitation. However, at those stations with increases in heavy precipitation, such as Skagit at Mount Vernon, the increased frequency of warm wet events is particularly acute.

The precipitation results from the WRF model presented here are not directly comparable to the hydrologic results presented in Parts II and III, below, since 1) these results are from dynamically downscaling a single model, ECHAM5, rather than from a suite of models, and 2) only extreme parameters are analyzed here, not mean statistics, which are better related to streamflow changes. Nevertheless, the ECHAM5 model is consistent with the multi-model average changes in precipitation and temperature over northern Washington (Mote and Salathé 2010) used in the (composite) delta method analysis in Parts II and III, which indicate warming and a modest increase in cool-season precipitation. These changes in turn yield the modest increases in annual streamflow to Ross Reservoir seen in the hydrologic results. Detailed evaluation of how simulated hydrologic response depends on downscaling method used (e.g., using driving data dynamically downscaled using WRF vs. the hybrid delta method) is an open question for future research.

E. References

Mote, P.W. and E.P. Salathé. 2010. Future climate in the Pacific Northwest. *Climatic Change*, in press.

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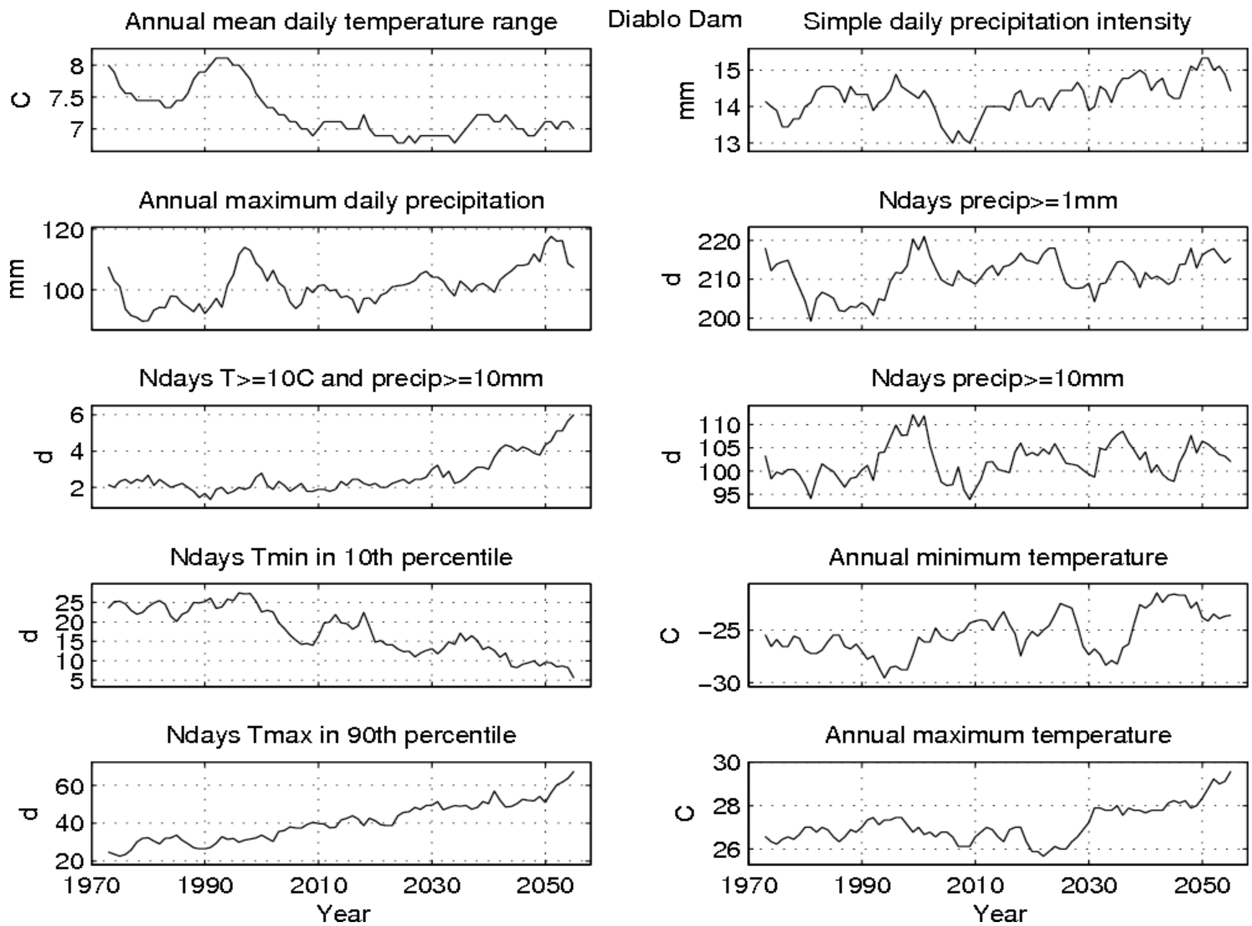

Figure 1.1. Time series of select parameters at Diablo Dam.

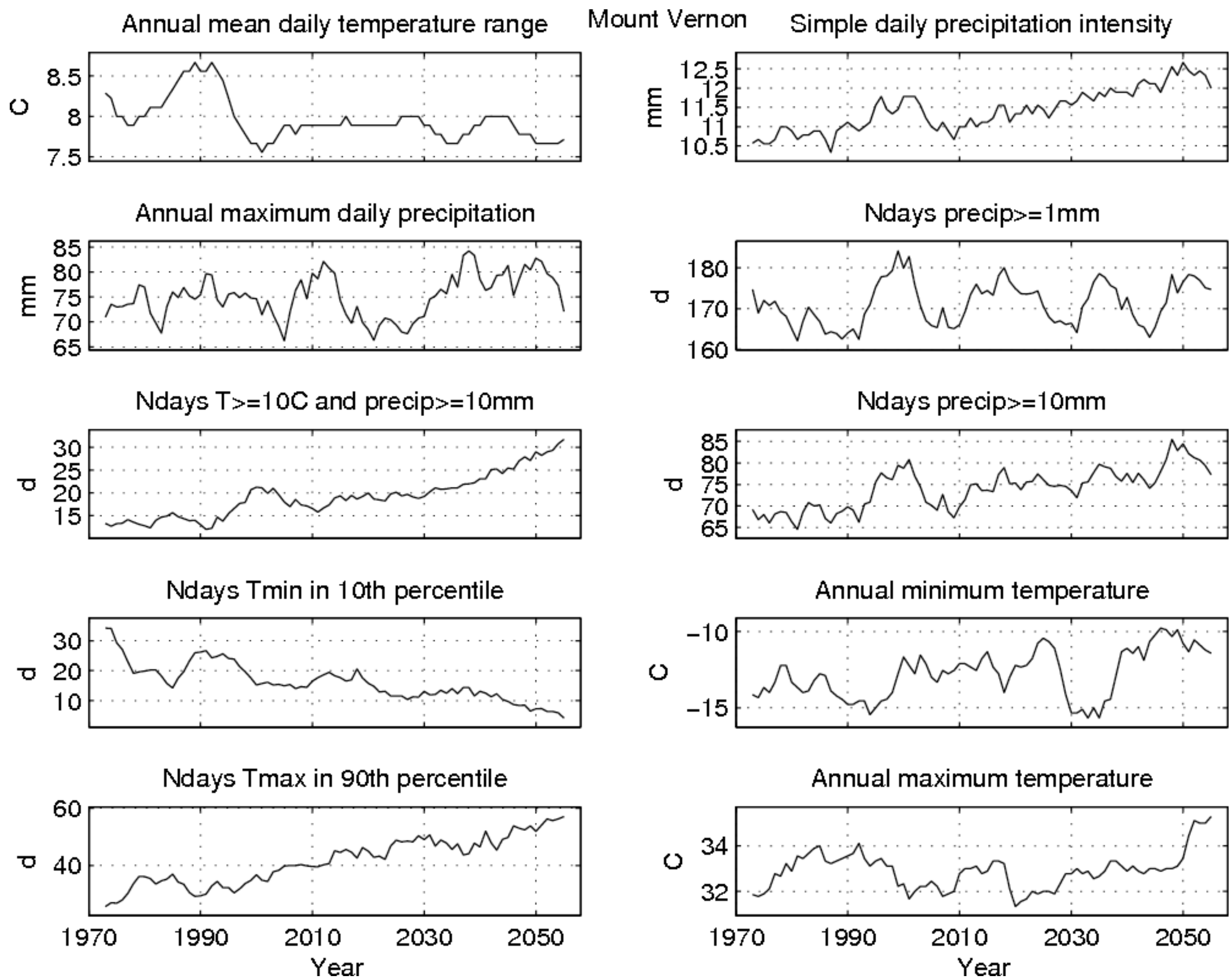

Figure 1.2. Time series of select parameters at Mount Vernon.

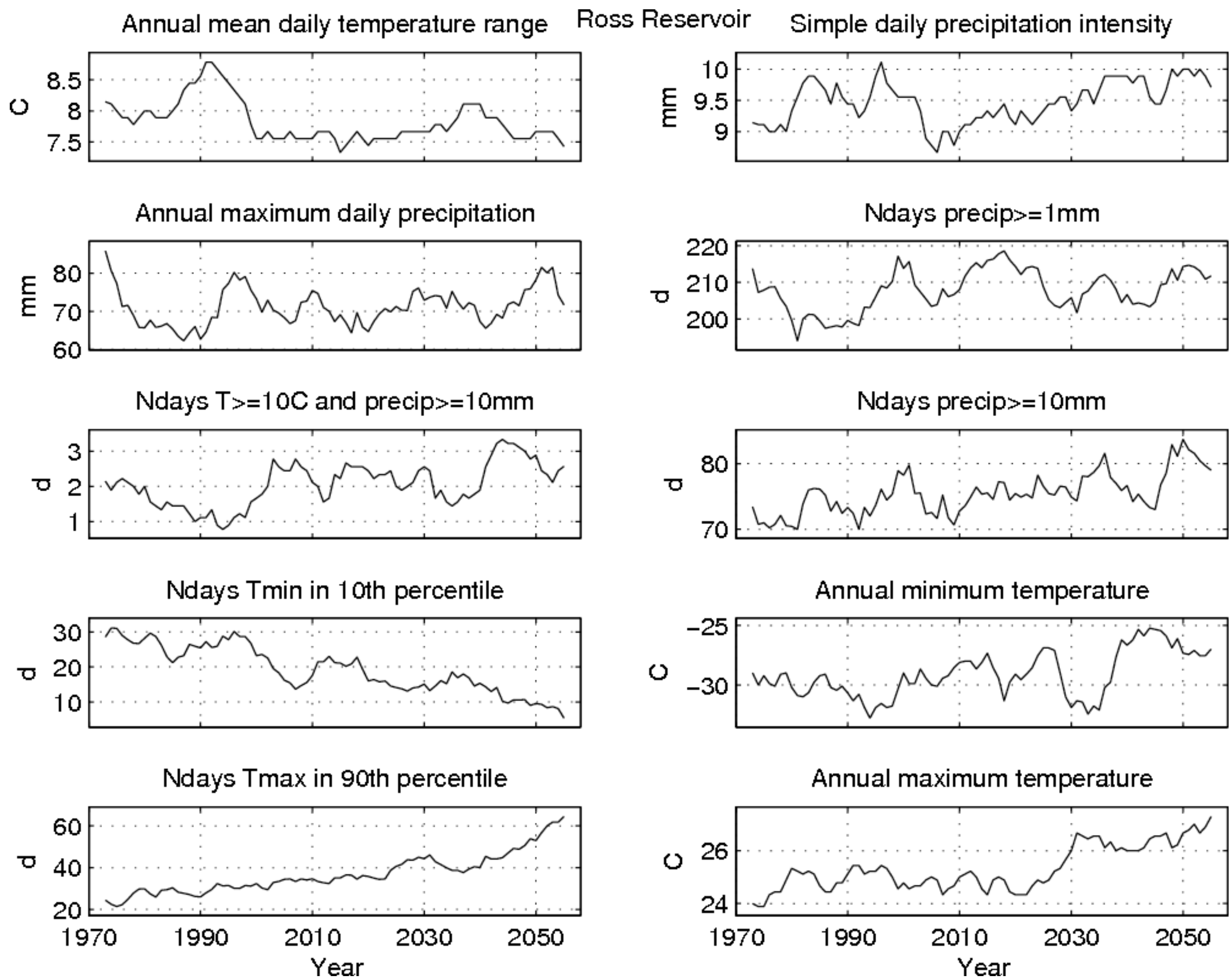

Figure 1.3. Time series of select parameters at Ross Reservoir.

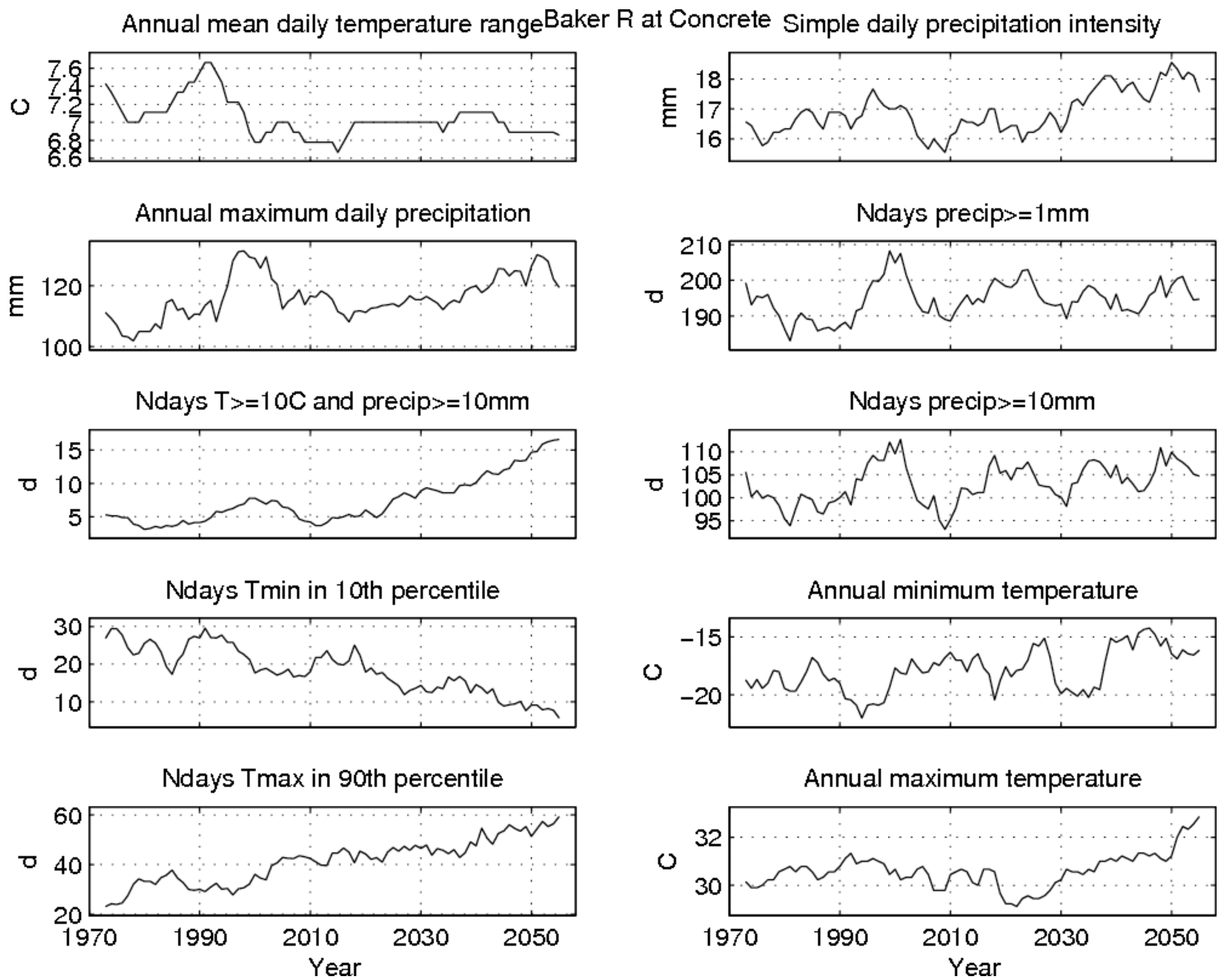

Figure 1.4. Time series of select parameters for Baker River at Concrete.

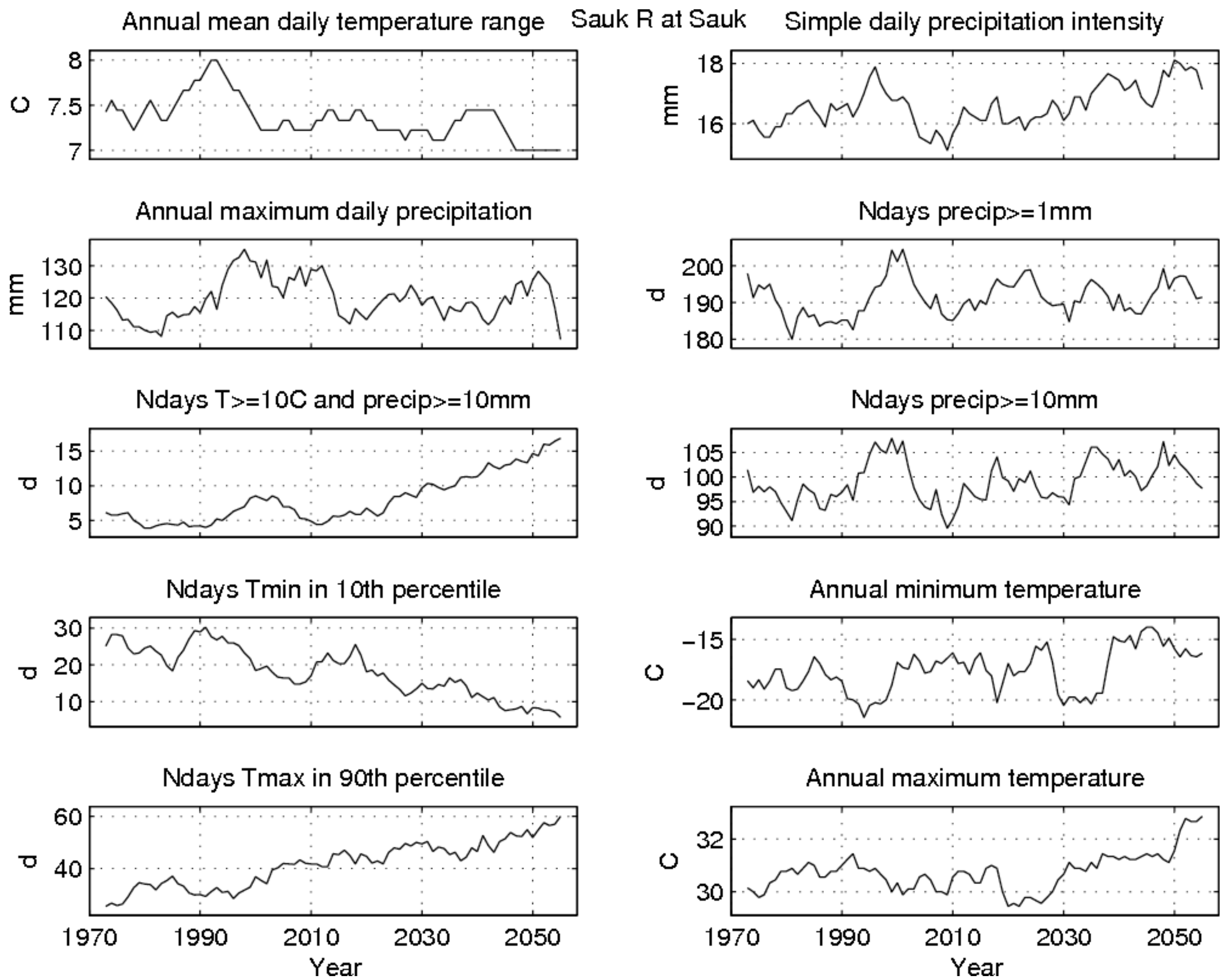

Figure 1.5. Time series of select parameters for Sauk River at Sauk.

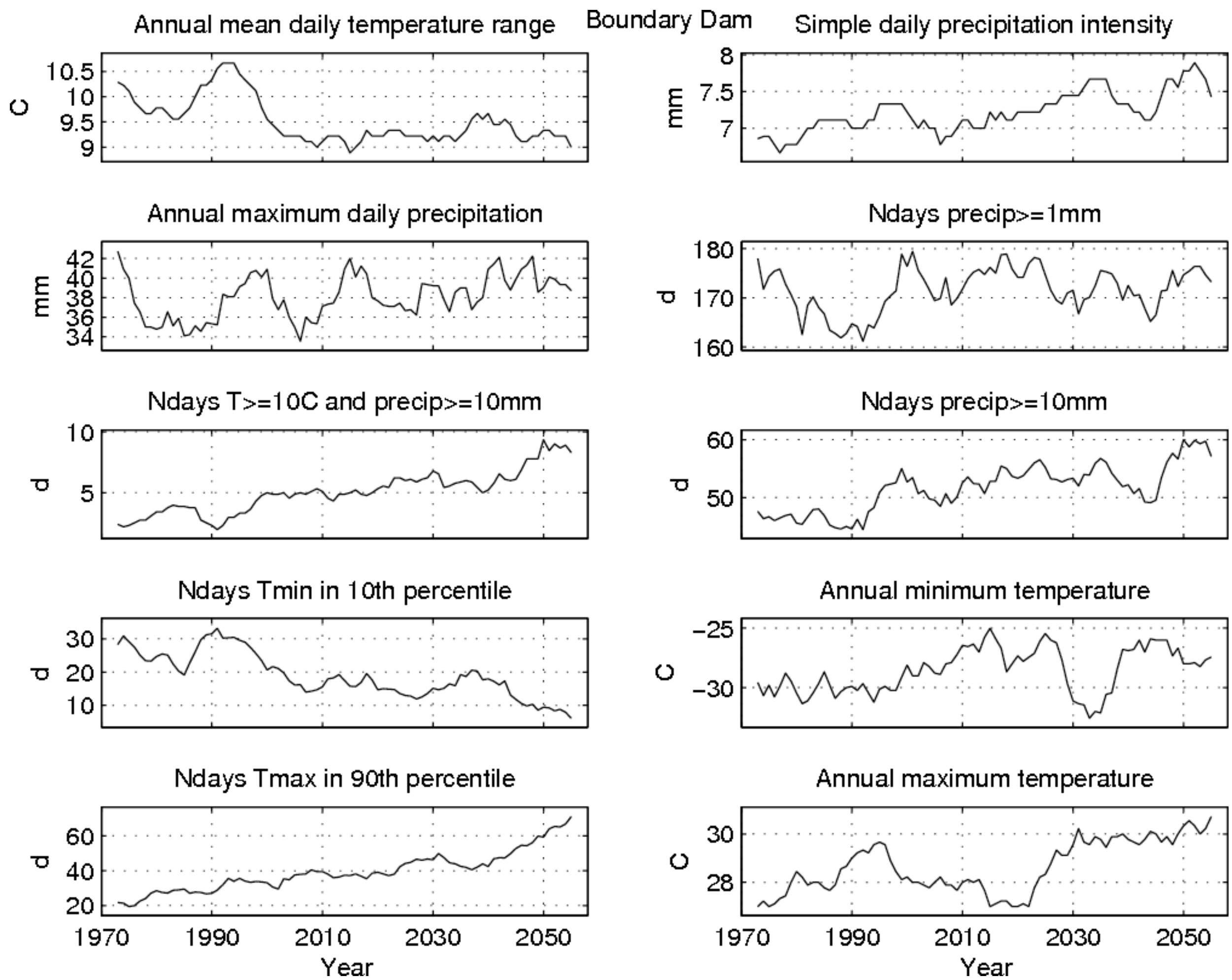

Figure 1.6. Time series of select parameters for Boundary Dam.

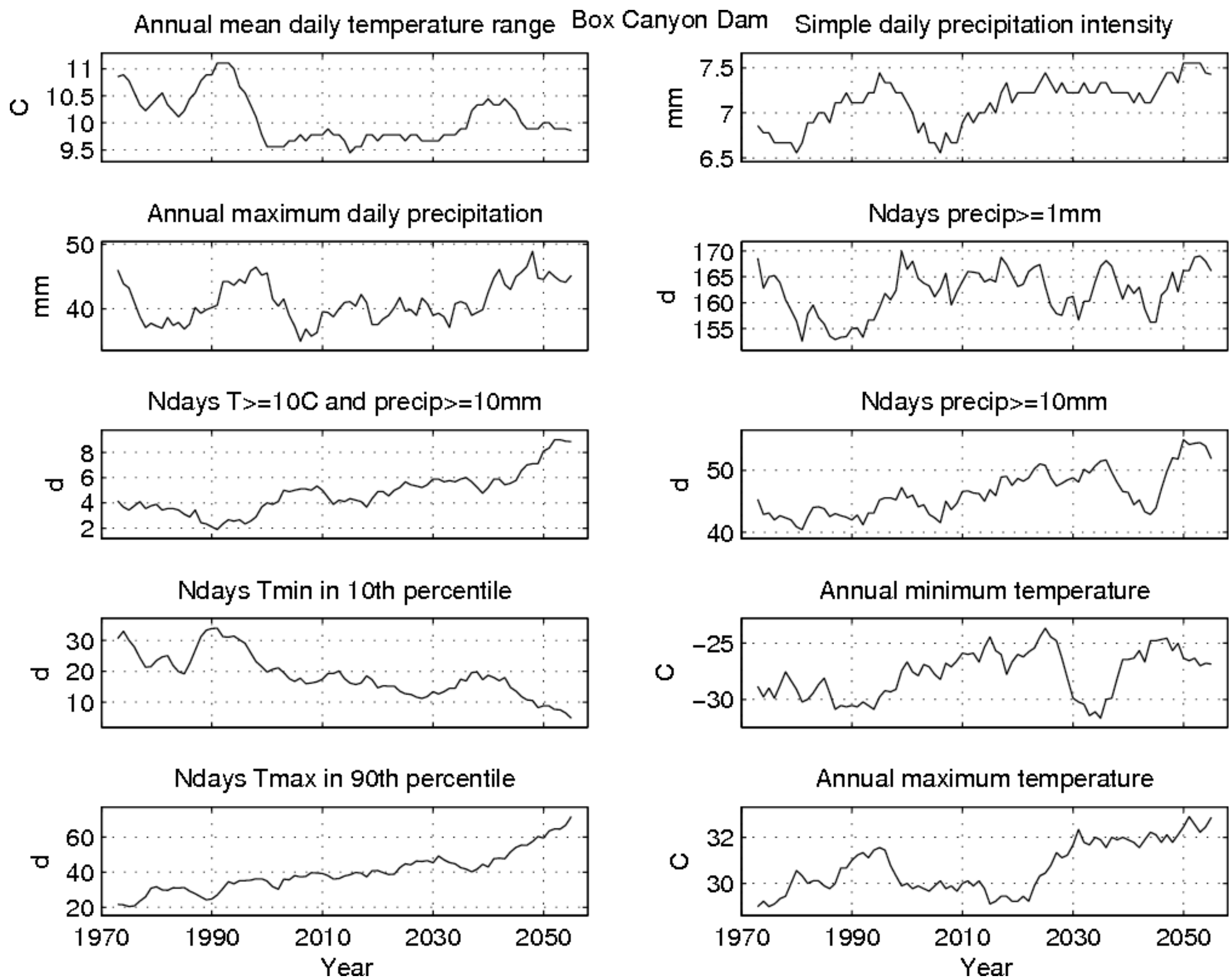

Figure 1.7. Time series of select parameters for Box Canyon Dam.

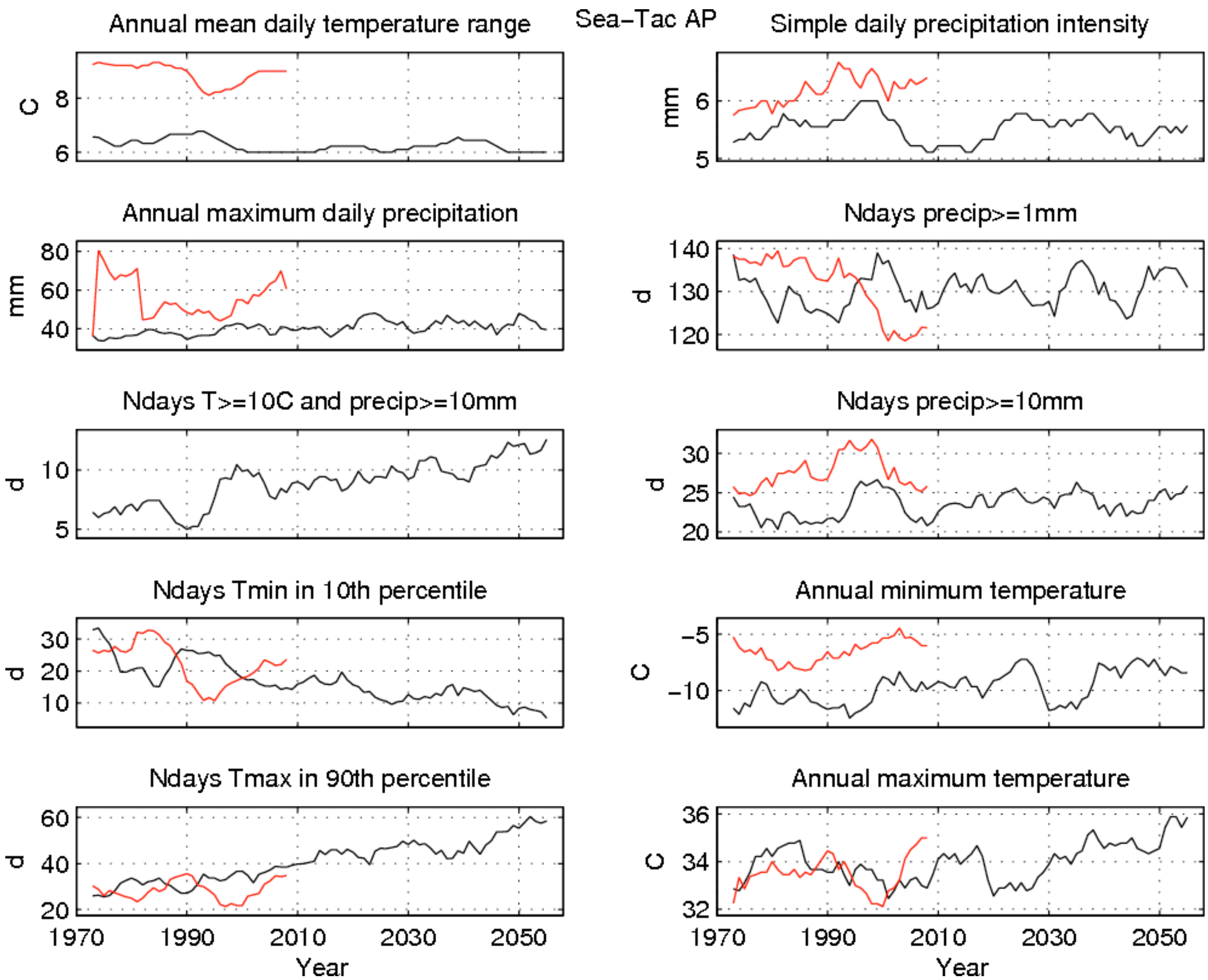

Figure 1.8. Time series of select parameters at Sea-Tac Airport. The red line shows observed values. Observed values are not provided for Ndays T>=10C and precip>=10 mm because that metric (calculated from WRF hourly data) cannot be duplicated from the observations (daily data).

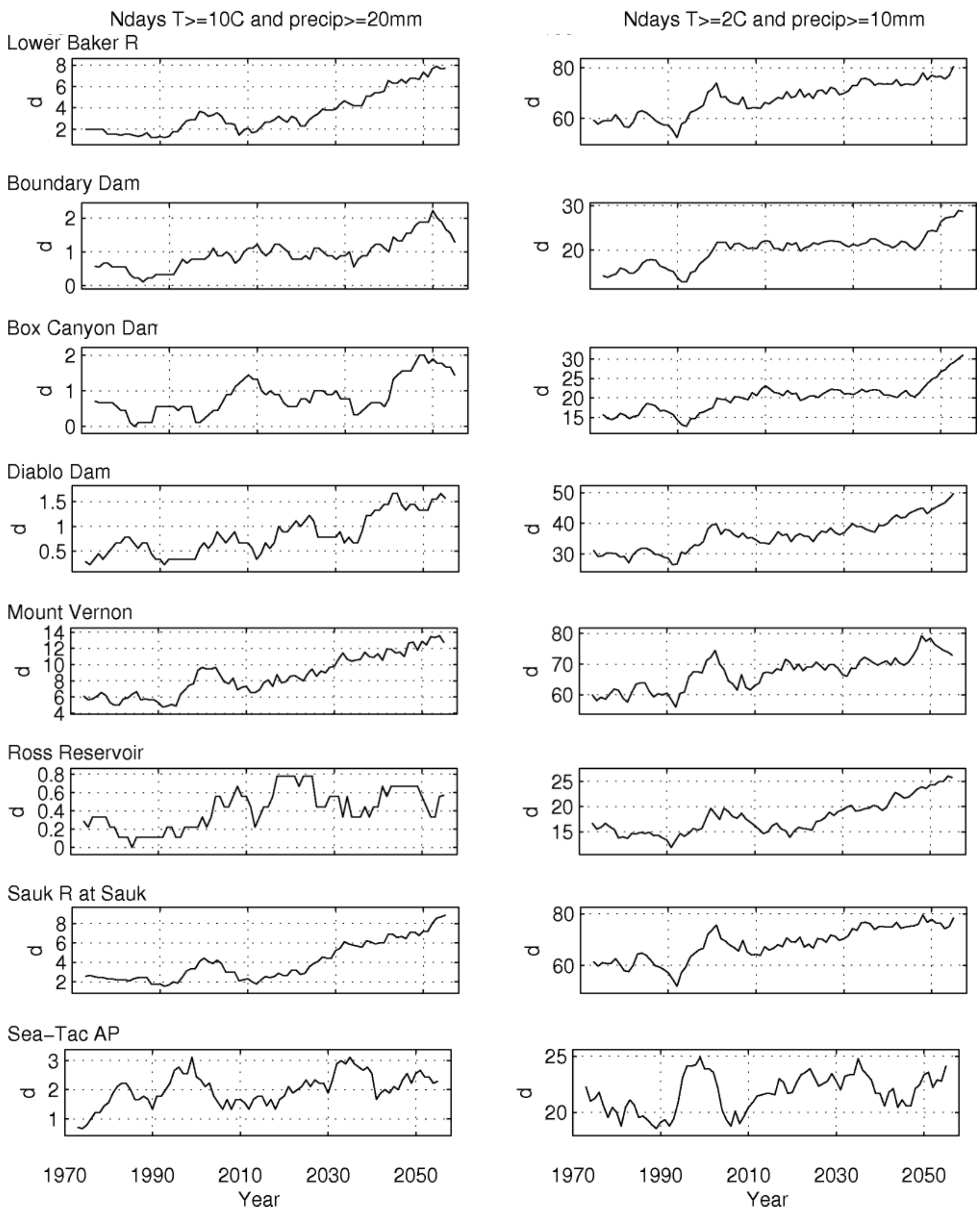

Figure 1.9. Time series at each station of the number of warm wet days per year at two thresholds, days with temperature over 10°C and precipitation over 20mm (left) and over 2°C and 10mm (right).

Part II: Overview of Methods for Producing Hydrologic Scenarios

A. Overview

This brief report describes the streamflow sites in the Skagit River Basin for which the Climate Impacts Group (CIG) has provided climate change data to Seattle City Light (SCL) (relevant to Tasks 1 and 4 of the November 2009 SCL/CIG MOA), the climate change scenarios and hydrologic model used, the source of observed naturalized streamflow used for bias correction, and the technical methods used to produce the simulated historical and climate change streamflow scenarios.

B. Streamflow Sites and Sources of Naturalized Streamflow Data

Sites for the study were selected based on two criteria: a) usefulness of the site for planning (SCL recommendation), and b) contributing upstream basin area larger than about 500 km^2 (approximately 200 sq mi).[1] Table 2.1 shows a brief summary of each site with more detailed information provided at http://www.hydro.uw.edu/2860/.

Observed naturalized streamflows were obtained from Seattle City Light for the Skagit River at Ross, Diablo, and Gorge Dams for water years 1910 to 2009 as shown in Table 2.1. For Ruby Creek and Cascade River, observed (unimpaired) flows were obtained from the USGS website for water years 1929-1948 and 1929-1979, respectively. The naturalized or observed USGS streamflows were used to produce bias-corrected streamflow simulations for historical and future conditions using the methods described below.

C. Climate Change Scenarios

Inflow sequences for the historical period from water year (WY) 1916 to 2006 as well as a total of 77 climate change scenarios were simulated using the Variable Infiltration Capacity (VIC) hydrologic simulation model (Liang et al. 1994) implemented at 1/16 degree latitude/longitude resolution. The IPCC “A1B” and “B1” global greenhouse gas and aerosol emissions scenarios (Nakicenovic et al. 2000), described in Part I, were selected for use in the study. The rationale for selecting the specific emissions scenarios and the methods used for ranking global climate model (GCM) performance are described in more detail in Chapter 4 of the Columbia Basin Climate Change Scenarios Project Report, which can be found via http://www.hydro.uw.edu/2860/.

Three types of downscaling approaches were used. The composite delta and hybrid-delta methods were applied to the three future time periods of the “2020s” (2010-2039), “2040s” (2030-2059), and “2080s” (2070-2099). The transient bias-corrected statistical downscaling (BCSD) approach was used to simulate the period 1950-2098. Table 2.2 lists the number of realizations that are available for each downscaling approach. Both the composite delta and BCSD approaches have different strengths and limitations, and are most suitable for different kinds of applications. The hybrid delta method combines the key

[1] Smaller basins are not adequately resolved by the 1/16th degree VIC hydrologic model implementation.

strengths of these two approaches, while largely avoiding their limitations. Although a few specific applications can only be addressed using the transient products produced by BCSD, the hybrid delta approach can be used successfully in most water resources applications. For example, because the hybrid delta method provides a static 91-year climate time series representing a 30-year future time horizon, it allows better representation of statistical parameters such as return periods of climatic or hydrologic extremes than does BCSD. For more information about the characteristics and appropriate application of these downscaling methods, see Chapter 4 of the Columbia Basin Climate Change Scenarios Project Report, which can be found via http://www.hydro.uw.edu/2860/.

Table 2.1 Information for selected streamflow sites in the Skagit River and Pend Oreille River basins.

Site Name	VIC ID #	VIC Name	USGS ID #	Basin Area (mi^2)	Source & Duration of Observed Naturalized Streamflow
Ross Dam	6111	ROSSL	12175000	999	SCL (WY 1910-2009)
Diablo Dam	6018	DIABL	12176500	1125	SCL (WY 1910-2009)
Gorge Dam	6019	GORGE	12177700	1159	SCL (WY 1910-2009)
Cascade River	6113	CASCA	12182500	172	USGS (WY 1929-2008)
Ruby Creek	6114	RUBYC	12174000	210	USGS (WY 1929-1948)
Baker River at Concrete	6112	SHANN	12193500	297	Puget Sound Energy
Sauk River at Sauk	6020	SAUKR	12189500	714	USGS
Skagit River at Mt. Vernon	6021	SKAMO	12200500	3093	N/A
Pend Oreille River at Box Canyon	6023	BOXCA	12396500	24,900	Modified flow only (BPA) (1928-1999)
Pend Oreille River at Boundary Dam	6024	BOUND	12398600	25,200	UW (from 1990 BPA modified flow) (1928-1989)

Table 2.2 Summary of climate change scenarios included in the study. Numbers in the table show the number of GCM scenarios used for each downscaling approach and/or time period. Note that data for the B1 emissions scenario were not available from one of the 10 GCMs used in the hybrid delta simulations.

Downscaling Approach		**A1B Emissions Scenario**	**B1 Emissions Scenario**
Hybrid Delta	2020s	10	9
	2040s	10	9
	2080s	10	9
Transient BCSD **(**Bias-Corrected Statistical Downscaling**)**	(1950-2098+)	7	7
Delta Method	2020s	1	1
	2040s	1	1
	2080s	1	1

D. Hydrologic Model

The Variable Infiltration Capacity (VIC) macro-scale hydrologic simulation model (Liang et al. 1994) is used in this study to produce streamflow scenarios associated with climate change by solving the water balance at each model grid cell (see Figure 2.1). The VIC hydrologic model successfully captures many important features of hydrologic variability but the model output is sometimes biased in comparison with naturalized observations, and also contains random errors associated with errors in the driving data, uncertainties in parameter estimation during calibration, etc. To eliminate these kinds of problems without significantly distorting the important physically based signals produced by the hydrologic model, the bias correction techniques discussed in following section were employed.

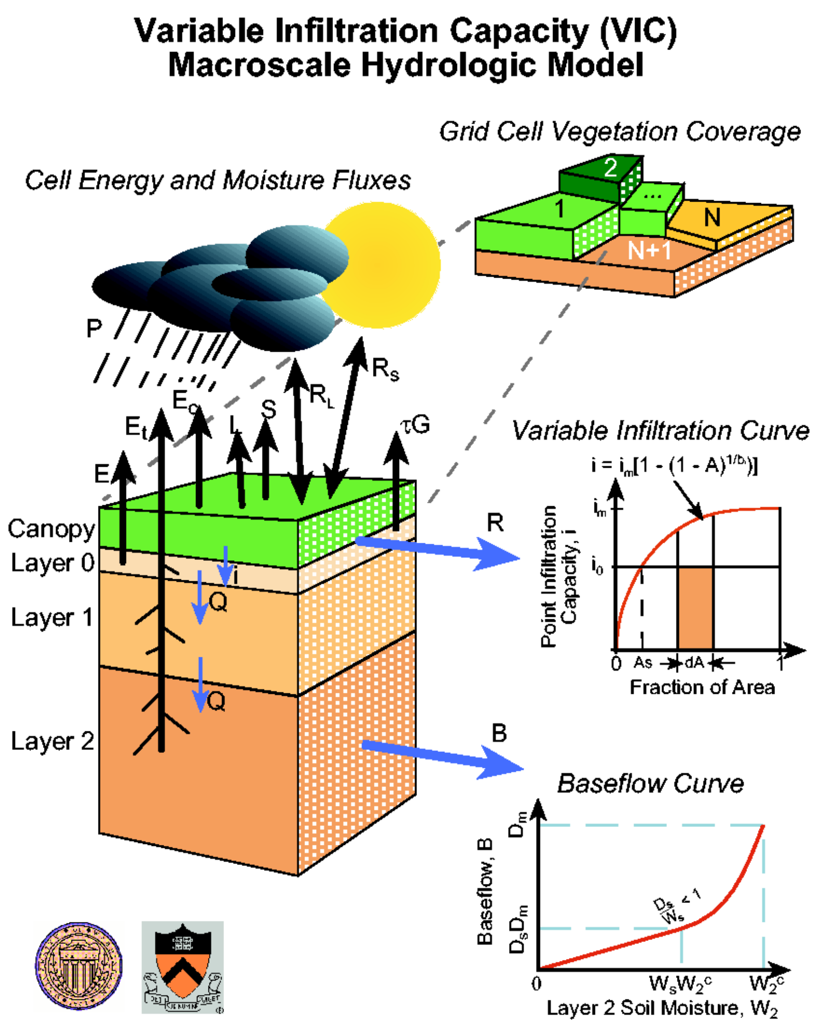

Figure 2.1. Schematic diagram of the land surface representation, and water and energy budgets in the VIC hydrologic model.

E. Bias Correction

A bias correction procedure was applied to remove systematic biases in the monthly time step streamflow simulation by using quantile-mapping techniques (Snover et al. 2003). The mapping technique is based on a simple nonparametric lookup procedure and produces a one-to-one mapping between simulated and observed cumulative distribution functions for each calendar month as shown in Figure 2.2. For example, if the “raw” simulated data for a particular month represents the estimated Xth quantile in the cumulative distribution function, then the Xth quantile is looked up in the observed distribution for the same period, and this quantile in the observed distribution becomes the bias corrected value for that month. The quantile mapping techniques are described in more detail at:
http://www.hydro.washington.edu/Lettenmaier/permanent_archive/hamleaf/bams_paper/technical_documentation.pdf.

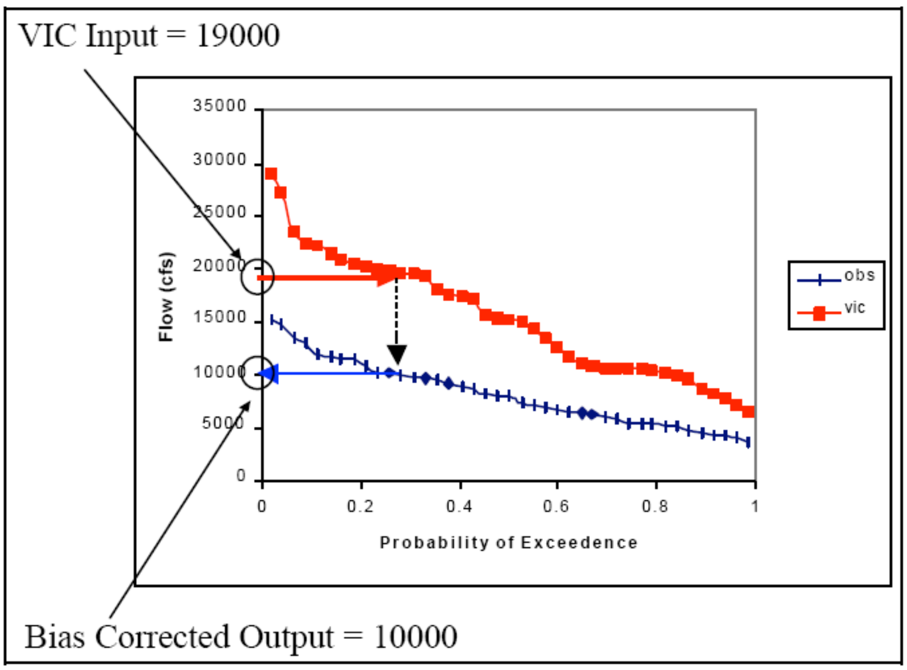

Figure 2.2. Schematic diagram showing the quantile mapping process (after Wood et al. 2002).

Figure 2.3 shows the comparison of bias corrected streamflows to observed naturalized streamflows for Ross Dam for WY 1957-1996. Note that the simulated, bias corrected time series is not perfect due to imperfect rank order in the simulations (i.e., the same quantile position does not always occur at the same time in simulated and observed conditions), but overall the time series very closely matches observations. For future simulations, the same quantile mapping is used; the assumption being that the bias structure of the hydrologic model is not altered by changes in temperature and precipitation in the driving data.

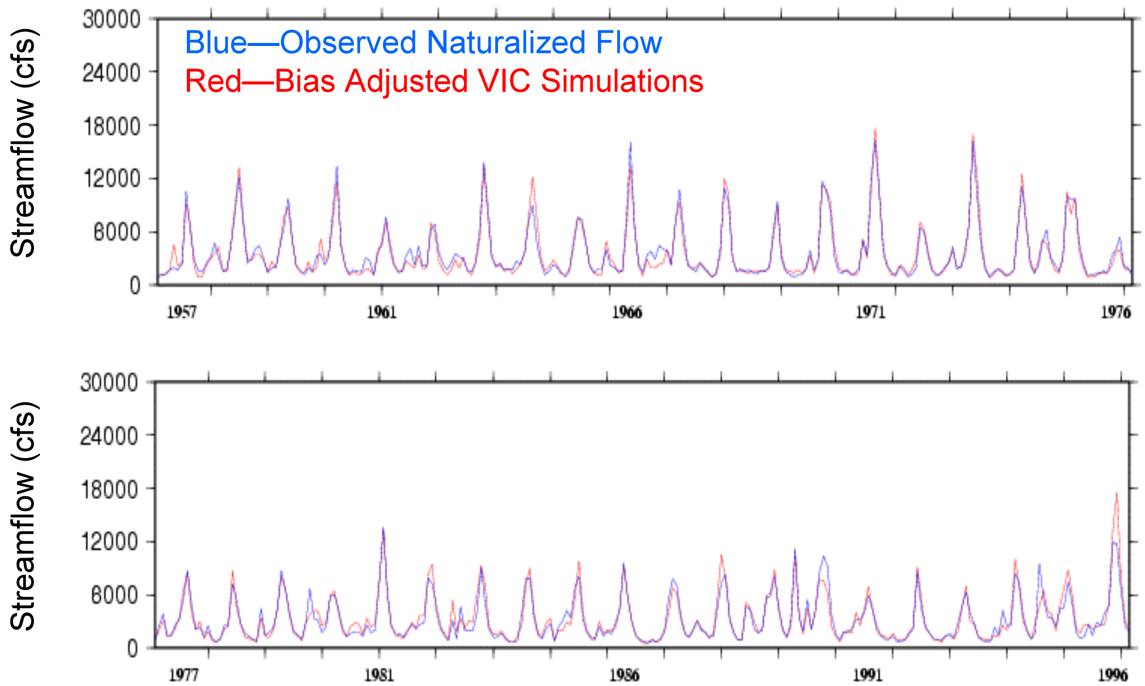

Figure 2.3. Bias corrected simulated streamflows for WY 1957-1996 compared to naturalized observations for the Skagit River at Ross Dam.

In the process of bias correcting individual months, annual streamflows (which hydrologic models usually simulate quite well) may be distorted somewhat. To remove this artifact of the monthly bias correction process, each month of the bias corrected simulation is adjusted to match bias corrected annual values. Thus the bias corrected annual streamflow is exactly reproduced by the rescaled monthly values, but the relative "shape" of the monthly values is defined by the monthly quantile mapping procedure.

Figure 2.4 shows a monthly summary of the VIC simulations before and after bias correction for the historical record and one of the climate change scenarios, i.e., ECHAM5 A1B for 2080s using the hybrid-delta downscaling method. Note that despite considerable differences between the raw and bias corrected simulations, the climate change signals present in the raw simulations are preserved in the bias corrected simulations.

The bias-corrected monthly values were then used to rescale the simulated daily flow sequences produced by the hydrologic model to estimate daily flows for both historical conditions and climate change scenarios. Bias corrected daily and monthly time step data for historical and a total of 77 climate change scenarios for the locations indicated in Table 2.1 are provided on the accompanying DVD.

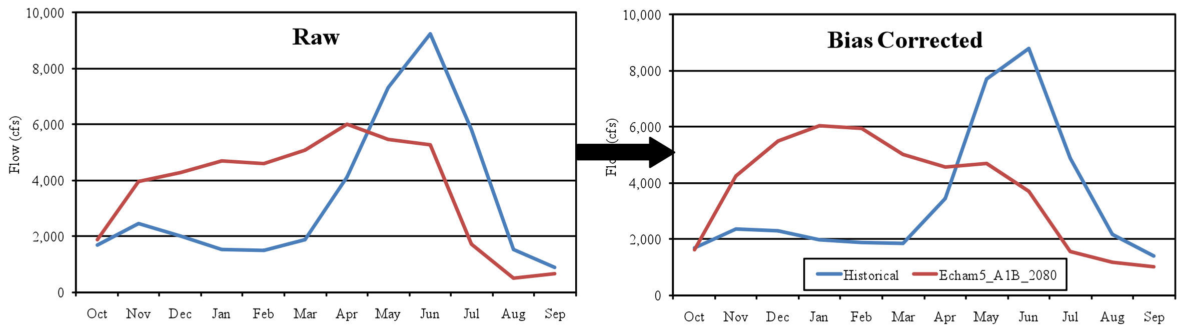

Figure 2.4. Comparison of long-term monthly mean simulated flows before and after bias correction for the Skagit River at Ross Dam for historical and projected future conditions.

F. Overview of Key Mechanisms and Assumptions Affecting Results

Streamflow timing shifts like those shown in Figure 2.4, which are common to most sites in the Skagit and (to a lesser degree) in the Pend Oreille are related primarily to shifts in snowpack, which in turn are related primarily to changes in temperature and secondarily to changes in the amount or seasonality of precipitation. Changes in annual runoff (in some cases small positive increases in average flow in the Skagit) result from fundamental tradeoffs between increasing cool season precipitation (which increases annual flow) and increasing evaporation with warming (which decreases annual flow).

The hydrologic simulation model implementation assumes constant historical land cover for all future scenarios and does not include dynamic effects associated with changing groundwater or glacial inputs. These assumptions may substantially affect the sensitivity to climate in some cases, particularly in the case of simulated extreme low flows (see also Part III). Some caution in interpreting the future scenarios is therefore required, even though the simulations have the historical bias associated with these factors removed from the simulations.

G. References

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III. Climate Change Impacts on (a) Water Temperature Thresholds for Salmon, Steelhead and Bull Trout: Skagit and Boundary Projects and (b) Extreme High and Low Flows

A. Introduction

Water temperatures and streamflow extremes are two key hydrologic parameters that determine the viability of salmon, steelhead and bull trout habitat in the Pacific Northwest. Regional projections of future increasing temperatures and shifts in precipitation patterns will provoke alter these two parameters. These fish are cold-water species and rely on certain thermal regimes during different phases of their complex life cycles. Depending on the species, increasing water temperatures will trigger changes in migration and spawning behaviors and in incubation durations. In extreme cases, prolonged exposure to higher water temperatures is lethal. Shifts in extreme flow are also projected under a warmer climate. Higher flood magnitudes and more severe low flows can negatively affect these species during critical stages of their life cycles. Increased flooding in the winter and early spring can scour redds and wash juveniles downstream before they are prepared to migrate. Extreme low flows in the summer can create barriers for adult salmon migrating upstream to spawn. Furthermore very low flows can exacerbate the higher water temperatures in the summer caused by increased air temperature alone, because shallower water will warm faster. This study examines changes in of water temperatures and extreme flow patterns under various climate change scenarios. The study includes temperature and streamflow projections for several sites along the Skagit River and its tributaries and temperature projections for three sites on the Pend Oreille River.

B. Methods

1. Water temperature analyses

The temperature analyses for this study estimate future average weekly water temperatures, given different climate change scenarios, using historical relationships between average weekly air temperatures and observed water temperature, following the methods outlined in Mohseni et al. (1998) and Mantua et al. (2009). Using the following equation, simple non-linear regressions were developed for each site correlating observed weekly water and air temperatures:

$$T_w = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_{a_i})}}$$

where T_w is the estimated weekly average stream temperature, μ is the estimated minimum stream temperature (here μ was set to ≥ 0 since the streams in this study rarely freeze), α is the estimated maximum stream temperature, γ is a measure of the steepest slope of the function, β indicates the air temperature at the inflection point, and T_a is the average weekly air temperature.

Weekly water temperature averages were calculated from observed daily water temperature data obtained from the Seattle City Light (SCL), US Geological Survey (USGS) and WA Department of Ecology (DOE) hydrologic monitoring sites. The WA DOE monitors water temperatures only during the summer months, so the projected water temperatures for this site are only applicable to that season (June – September). Weekly air temperature averages were calculated from 1) observed daily air temperatures from the National Climate Data Center and, separately, 2) station data from the National Climatic Data Center Cooperative Observer and Environment Canada that were re-gridded to generate air temperature datasets on a daily time step and at spatial resolution of 1/16 degree latitude and longitude (see http://www.hydro.washington.edu/2860/ for details on meteorological data). Comparisons of regression parameters and the goodness of fit statistic, the Nash and Sutcliffe Efficiency coefficient (Nash and Sutcliffe 1970), generated from each air temperature data source were similar, validating the use of modeled air temperature data for these analyses. The sites and regression parameters are listed in Table 3.1.

Projections of future weekly average water temperatures are based on future air temperatures from 10 global climate models under two global greenhouse gas emissions scenarios, A1B and B1 (see Part I), statistically downscaled using the hybrid delta method. (For a complete description of models and downscaling technique used, refer to Chapter 4 of the Columbia Basin Climate Change Scenarios Project Report, which can be found via http://www.hydro.washington.edu/2860/.) The A1B is a mid-range emission scenario and the B1 is a low emission scenario. Future water temperatures were calculated using these modeled air temperature fields and the regression parameters estimated for each site. The results are presented as an ensemble mean of all the modeled projections for each emissions scenario at three future time periods, 2010–2039 ("2020s"), 2030–2059 ("2040s") and 2070–2099 ("2080s"), and compared to the historical simulations for the base period from 1915–2006. On the accompanying DVD, we provide text files for each scenario/time interval that lists the modeled weekly water temperatures for each model ("Water_temperature_<scenario>_<time interval>").

The average number of weeks for each time interval that water temperatures exceeded WA DOE thermal thresholds for salmon and trout spawning/incubation (13˚C) and for "core" salmonid habitat (16˚C), were calculated for each site on the Skagit River and its tributaries. The average number of weeks that water temperatures are projected to exceed WA DOE temperature criteria for bull trout avoidance (18˚C), the threshold for avoidance and reduced growth by trout and steelhead and incipient lethal temperature for bull trout (22˚C), and the lethal temperature for trout and steelhead (25˚C) were estimated for the Pend Oreille River.

Table 3.1 Temperature sites for this study and the regression model parameters.

Site	Data source	latitude	longitude	alpha	beta	gamma	mu	nsc
Skagit at Sedro Woolley	DOE	48.53	-122.34	17.08	16.47	0.72	12.84	0.90
Skagit at Marblemount*	USGS	48.53	-121.41	12.42	9.37	0.20	3.35	0.91
Skagit at Newhalem*	USGS	48.66	-121.22	10.59	5.77	0.31	4.27	0.89
Stettatle Creek	SCL	48.72	-121.15	10.02	5.34	0.23	0	0.79
Upper Skagit at Diablo*	SCL	48.72	-121.15	10.21	7.52	0.30	4.04	0.84
Ruby Creek*	SCL	48.71	-120.98	23.49	12.84	0.14	0	0.96
Granite Creek*	SCL	48.71	-120.92	25.46	12.04	0.15	0	0.95
Canyon Creek*	SCL	48.71	-120.92	23.76	11.76	0.15	0	0.96
Big Beaver Creek	SCL	48.77	-121.07	11.24	5.92	0.17	0	0.86
Devils Creek	SCL	48.82	-121.03	13.16	8.63	0.18	0	0.92
Lightning Creek*	SCL	48.88	-121.01	17.16	7.57	0.14	0	0.96
Little Beaver Creek	SCL	48.91	-121.12	8.60	4.32	0.35	1.37	0.95
Pend Oreille at Albeni falls (forebay)*	USGS	48.16	-117.03	24.81	11.62	0.19	0	0.92
Pend Oreille at Albeni falls (tailrace)	USGS	48.16	-117.03	31.05	15.09	0.14	0	0.94
Pend Oreille at Canadian border*	USGS	48.91	-117.34	22.87	8.10	0.2	0.08	0.94

Mu is the estimated minimum stream temperature. Alpha is the estimated maximum stream temperature. Gamma is a measure of the steepest slope of the function. Beta indicates the air temperature at the inflection point.
*Sites where two regressions fit to the data resulted in a higher estimated Nash & Sutcliffe (nsc) goodness-of-fit than one regression.

2. Extreme Flow

The statistics for extreme flow events were calculated at three sites on the Skagit River (Ross reservoir, Diablo dam and Gorge dam) and three tributaries to the Skagit (Ruby Creek at Newhalem, Cascade River at Marblemount and the Sauk River near Sauk). Table 3.2 lists the sites and spatial information that were included in the streamflow analyses. The routed, bias corrected streamflows were generated using output from the macroscale hydrologic (Variable Infiltration Capacity (VIC)) model, using projected temperature and precipitation changes derived from 10 global climate models under two global greenhouse gas emissions scenarios, A1B and B1, for the 2020s, 2040s and 2080s, statistically downscaled using the hybrid delta and the composite delta methods. These streamflows do not take into account any management operations. (For a complete description of models and downscaling technique used, refer to Chapter 4 of the Columbia Basin Climate Change Scenarios Project Report, which can be found via http://www.hydro.washington.edu/2860/.)

Table 3.2 Sites included in the extreme flow analysis.

Site name	Site number	Latitude	Longitude	Basin area (mi^2)
Ross reservoir	6111	48.73	-121.07	999
Skagit at Diablo	6018	48.72	-121.13	1125
Skagit at Gorge	6019	48.70	-121.21	1159
Ruby Creek near Newhalem	6114	48.72	-120.97	205
Cascade Creek near Marblemount	6113	48.53	-121.34	166
Sauk River near Sauk	6020	48.42	-121.57	714

We estimated the extreme flow statistics by ranking the annual maximum streamflows for each time period (2020s, 2040s, 2080s) and fitting them to the Generalized Extreme Value (GEV) probability distribution and L – moments, a probability distribution useful for capturing infrequent extreme events (Hamlet and Lettenmaier 2007, Stedinger et al. 1993). For each site, the 20-, 50- and 100-year floods were calculated and plotted. The ratios of the mean annual historical flow to the average annual projected peak flows were calculated for each site. Note that these calculations estimate changes in extreme *natural* flows, and do not incorporate the effects of reservoir operations on extremes.

The streamflow data requested for the Skagit River at Marblemount was generated using an upstream site in the routing network, Gorge Dam, because Marblemount was not included in the routing network previously used for VIC hydrologic simulations. We assumed that the sites at Newhalem and the Gorge are comparable because there are no major tributaries between these two sites. A simple linear regression between USGS monthly streamflow data for Marblemount and Newhalem confirms a high correlation of flows at the two sites (R=0.82). Therefore, the upstream site at Gorge dam was used as a proxy; flows at Marblemount were estimated by multiplying daily streamflows at Gorge by the ratio of the drainage size of the two basins (i.e., 1.18). To assess the frequency of bedload movement and adverse impacts to salmonid redds, the average number of days that streamflows are projected to exceed 18,000 and 25,000 cfs annually was calculated for each model/scenario/time interval and compared to the historical average for the site at Marblemount.

Applying the same distribution, GEV L-moment, to the historical and projected streamflows, the 7-day minimum low flows for the 2- and 10- year return intervals were estimated for each site. The ratio of the historical mean annual flow to the average annual projected 7-day minimum low flows was calculated for each site. Data for the 20-, 50- and 100-year flood, the mean peak yearly flows and 7-day minimum flows with 10 and 2-year return intervals are provided as a text files.

C. Results

Results for all parameters considered and discussed below are provided on the data DVD that accompanies this report (refer to the data summary table at the beginning of this report). Here we provide a summary of key parameters that illustrates the important changes in water temperature and flow statistics simulated for the region.

1. Water temperature

For about half of the sites on the Skagit River or its tributaries and for all sites on the Pend Oreille River that were modeled, the number of weeks that water temperatures are projected to exceed cold-water species' thresholds increases with rising air temperatures. The rising temperature trends are more rapid under the medium emission scenario, A1B, than under the low scenario, B1. The results are depicted in a series of figures for thirteen sites on the Skagit River and its tributaries (Figures 3.1-3.12), and three sites on the Pend Oreille River (Figures 3.13-3.15), underscoring exceedances of given thermal thresholds.

a. Skagit River

Our analyses indicate that projected future increases in water temperature shift the timing of reaching thermal thresholds for cold-water species. Table 3.3 indicates the shift in the timing of temperature thresholds for Bull Trout spawning and egg incubation (9˚C) averaged over all models for each scenario/time period combination at ten sites on the Skagit River and its tributaries. (The WA DOE site is not shown because only summertime temperatures were modeled and projected temperatures for the SCL site on Little Beaver Creek did not exceed 9˚C.) All of the sites are projected to experience a longer period of time above this threshold, exceeding the 9˚C weekly average threshold earlier in the spring and dropping below the threshold later in the fall. This change is larger under the A1B scenario than the B1 and for the downstream sites at Marblemount and Newhalem than for upstream sites closer to the headwaters. Among the upstream sites, the longest season thermally favorable for bull trout migration is projected for the Stettatle Creek, Big Beaver and Little Beaver Creek.

Table 3.3 The week number that weekly average water temperatures exceed 9˚C in the spring and drop below 9˚C in the fall at sites in the Skagit River watershed.

Site	Historical		A1B 2020s		A1B 2040s		A1B 2080s		B1 2020s		B1 2040s		B1 2080s	
	Spr	Fall	Spr	Fall	Spr	Fall	Spr	Fall	Spr	Fall	Spr	Fall	Spr	Fall
Skagit at Marble-mount	21	40	20	41	19	42	17	43	20	41	19	42	19	42
Skagit at Newhalem	22	41	20	42	19	42	18	43	21	42	20	42	19	42
Stettatle Creek	28	35	27	36	26	38	23	39	27	36	27	37	25	38
Upper Skagit at Diablo	25	38	23	39	23	40	22	40	23	39	23	40	22	40
Ruby Creek	23	40	22	40	21	40	19	41	22	40	22	40	20	40
Granite Creek	23	40	21	40	20	41	19	42	22	40	21	40	20	41
Canyon Creek	23	40	22	40	21	40	19	41	22	40	22	40	20	41
Big Beaver Creek	28	35	27	36	26	38	24	40	27	36	27	37	26	38
Devils Creek	23	38	23	39	22	40	21	40	23	39	23	40	22	40
Lightning Creek	23	40	22	40	22	40	20	41	23	40	22	40	21	40

An interpretation of the results requires a closer look at the hydrogeology of these river systems. The sites along the Skagit River and its tributaries are fed by a diverse system of groundwater seepage, glacial run-off, snowmelt and managed releases from dams. The headwaters of the Skagit River lie in the high North Cascade Mountain Range and the river snakes down steep slopes, flowing through lowland forests and wide open valleys to the Puget Sound. Most upstream sites in this study are smaller tributaries in the highlands. The tributaries flowing from the east to the mainstem Skagit, including Ruby (Figure 3.6), Granite (Figure 3.7), Canyon (Figure 3.8), Devils (Figure 3.10) and Lightning (Figure 3.11) Creeks, are subject to orographic "east slope" influences, resulting in less precipitation and warmer air temperatures. The effects of the warmer air on these "east side" tributaries are evident in the greater number of weeks stream temperatures are projected to exceed thermal thresholds of 13˚C and 16˚C. However groundwater inputs cool the waters of a few of these creeks in the summertime, as seen for Devils and Lightning Creeks. The west-side tributaries, Big Beaver (Figure 3.9), Little Beaver (Figure 3.12) and Stettatle (Figure 3.4) Creeks, are exposed to cooler air temperatures and are fed predominantly by glacial run-off and snowmelt, which keep these tributaries below the thermal thresholds for salmon and steelhead.

Temperature projections for sites along the mainstem Skagit are differentiated by their location. Upstream sites closer to the cooler headwaters, Marblemount (Figure 3.2), Newhalem (Figure 3.3) and Diablo (Figure 3.5), are projected to remain below thermal thresholds through the 2080s. These upstream sites are also located downstream of the nearby Seattle City Light Ross powerplant, which manages instream flows below Ross Dam and releases cooler water in the summer resulting in relatively lower stream temperatures. The downstream site on the Skagit, at Sedro Woolley, shows the effects of warmer air temperatures as the water flows through the valley and lowlands closer to Puget Sound. The site at Sedro Woolley is projected to undergo the most weekly excesses of thermal thresholds for salmon and steelhead (Figure 3.1).

<u>b. Pend Oreille River</u>

The Pend Oreille River valley in the state of Washington has a north-south orientation with a change in latitude of about 0.8°, or nearly 60 miles. This watershed drains from Lake Pend Oreille, Idaho, and is predominantly fed by snowmelt from the Rocky Mountains in Montana, where the headwaters of its main tributary, the Clark Fork River, lie. The Pend Oreille River is a highly managed watershed with several dams in Montana, Idaho, Washington and Canada. There is not a large groundwater contribution to streamflows because the extensive dams control river levels to maintain a nearly constant flow, not allowing levels to fall below underlying groundwater levels. The upstream sites included in this analysis at the dam on Albeni Falls at the border of Washington and Idaho (Figures 3.13 and 3.14) are projected to maintain higher water temperatures than downstream sites on the Canadian Border with Washington (Figure 3.15). The upstream sites are projected to exceed the 18˚C thermal threshold less frequently than the downstream site and neither area is projected to surpass the 22˚C threshold. Since the flows in this system remain fairly constant with minimal groundwater inputs, the thermal differences among these sites are attributable to the change in latitude, where cooler air temperatures farther north maintain cooler water temperatures.

Note that neither the effects of reservoir operations (which could be used to mitigate increases in temperature) nor changes in groundwater or glacial inputs to stream reaches are incorporated in the simulations. In river reaches substantially affected by glacial input in the historic record, for example, the simulations may underestimate the actual increase in temperature associated with warming because the glacial contribution could decrease over time. Likewise potential increases (decreases) in groundwater flow could mitigate (exacerbate) temperature increases shown in the simulations.

2. Extreme flow

<u>a. Flood statistics</u>

The results for the flood and low flow statistics are depicted graphically below. Based on the projected changes in regional temperature and precipitation, projected flood risk, as defined by 20, 50 and 100-year return intervals, for the Skagit and its tributaries does not rise precipitously in the first half of the 21st century (Figures 3.16–3.21). However, for most sites modeled in the Skagit basin, the flood risk is unambiguously elevated by the mid to late 21st century. This pattern could be attributable to the shift of these basins from a snowmelt dominant behavior to runoff fed by a mix of snowmelt and rainfall. The risk of spring flooding in some cases even declines as snowmelt contribution diminishes, for example Ruby Creek at Newhalem (Figure 3.19), before rising again later in the century as more precipitation falls as rain with rising temperatures, rather than being stored as snow.

The ratio of the peak yearly flows to the historical annual mean flow indicates that future peak flows will exceed annual mean streamflows by a factor of about two by mid-century, a slight increase compared to historical values of this ratio for Ross, Diablo, Gorge, Cascade and Sauk (Figures 3.22–3.27).

The average number of days of exceedances at the Skagit River Marblemount site is shown for 18,000 cfs (Figure 3.28) and 25,000 cfs (Figure 3.29) for each climate model/scenario and time interval (Table 3.4). Under simulated historic conditions (1916–2006) this site exceeds 18,000 cfs for an average of about 11 days annually. By the 2020s, only two models project a higher number of average days exceeding this streamflow threshold for each emission scenario. Interestingly, by the 2040s only one model under the B1 scenario projects an increased number of days surpassing this threshold compared to the historical simulation. This is possibly due to the mid-century transition of the downstream Skagit watershed to a basin dominated by a mix of rain and snow, where the timing of future simulated peak flows shifts earlier in the year.

The historical model estimates that an average of nearly six days annually exceed 25,000 cfs. Most models for all future time periods indicate fewer days on average exceeding the 25,000 cfs threshold under both the A1B and B1 scenarios and there is no significant projected increase in the number of days exceeding this threshold, by any model for either emissions scenario. This is likely because modeled snow accumulation in the Skagit basin declines with rising air temperature, lowering the snowmelt contribution to peak flow events in the spring and summer (particularly for higher elevation sites, like Marblemount). However by the end of the century, the contributing basin size could increase as a result of decreasing snow accumulation at higher elevations as temperatures rise, transitioning the basin into a more rain-dominant behavior.

Table 3.4 Average number of days per year with peak flows exceeding flow thresholds on the Skagit at Marblemount. (Simulations projecting increased number of days over historical are shown in bold.)

Average number of days flows exceed 18,000 cfs in Skagit River at Marblemount.							
Climate Model	historical*	A1B 2020	A1B 2040	A1B 2080	B1 2020	B1 2040	B1 2080
	11.39						
ccsm3		**12.70**	9.62	7.18	6.78	8.36	7.23
cgcm3.1_t47		9.82	9.04	10.18	7.13	9.32	7.58
cnrm_cm3		**13.43**	**12.10**	**16.86**	**11.81**	**11.44**	**12.76**
echam5		8.17	10.54	8.41	10.98	8.83	7.85
echo_g		9.57	9.90	8.26	8.72	7.94	8.02
hadcm		11.28	**13.00**	8.16	10.58	9.73	**11.54**
hadgem1		9.16	7.10	9.51			
ipsl_cm4		11.09	9.03	**13.10**	8.35	9.05	10.43
miroc_3.2		11.08	11.76	**15.71**	**13.10**	10.61	**12.15**
pcm1		7.83	6.58	8.32	9.46	8.39	6.85
composite delta		9.69	8.20	8.25	9.29	8.47	7.56

Average number of days flows exceed 25,000 cfs in Skagit River at Marblemount.							
Climate Model	historical *	A1B 2020	A1B 2040	A1B 2080	B1 2020	B1 2040	B1 2080
	5.83						
ccsm3		5.19	4.09	3.57	3.27	4.31	3.32
cgcm3.1_t47		4.12	3.92	3.90	3.33	4.12	3.45
cnrm_cm3		5.65	5.42	**6.10**	5.71	**5.95**	4.83
echam5		3.68	4.32	3.96	**6.00**	4.35	3.87
echo_g		4.43	4.38	3.45	4.18	4.29	3.55
hadcm		**6.04**	**6.11**	3.26	5.19	4.41	4.97
hadgem1		4.21	3.22	4.35			
ipsl_cm4		4.74	3.66	5.24	4.05	4.79	3.87
miroc_3.2		4.10	4.56	**6.36**	5.74	3.75	4.97
pcm1		4.18	3.30	3.49	4.33	3.60	3.47
composite delta		4.63	4.89	3.54	5.00	5.06	3.41

*historical refers to the simulated historical time period (1916-2006) *b. Low flow statistics*

Results for 7-day minimum low flow statistics indicate that low flows in the future will be more severe for the Skagit River basin (Figures 3.30–3.35). The projected lowest consecutive 7-day flows with a 2 and 10-year return interval (7Q2 and 7Q10) for many of the sites in the Skagit basin are nearly half of the simulated historical (1916 – 2006) value by the end of the 21st century. This pattern could be attributed to the earlier timing and lower contribution of snowmelt to summer flows. Concurrent with the decline in the lowest flows is a shift in their timing of low flows from late summer to earlier in the summer as summer snowmelt contributions decline. The ratios of the simulated future 7-day average minimum flows to the simulated historical annual mean streamflows show fairly monotonic declines across all sites with each progressive future interval, with future low flows decreasing to only 1/3 to 1/4 of historical annual flows by the mid to late 21st century for all sites (Figures 3.36–3.41).

As noted in section II, potential changes in groundwater and glacial inputs are not included in the future scenarios of low flow. Although the historical bias is removed from the simulations, future reductions in flow are probably underestimated in areas with significant glacial contribution, and may be over or underestimated in areas with significant groundwater contributions depending on uncertain changes in this resource.

D. References

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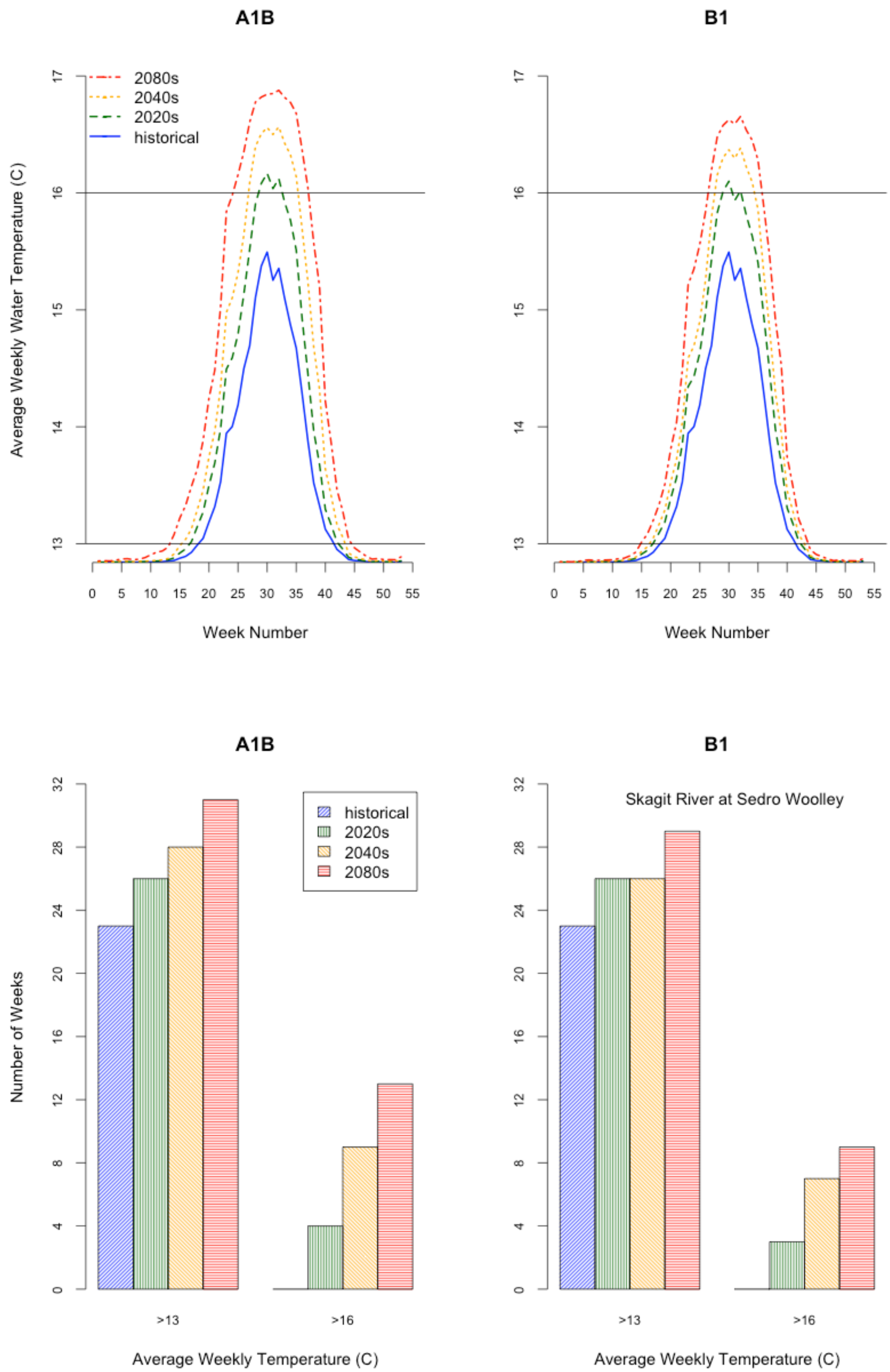

Figure 3.1 The top two plots show projected weekly average water temperatures averaged over each time period for the A1B scenario (left) and the B1 scenario (right) for the Skagit River above Sedro Woolley. Black horizontal lines indicate temperature thresholds (13˚C and 16˚C) for spawning salmon and trout. The bottom two bar graphs show the increase in number of weeks that temperatures exceed thermal thresholds of 13˚C and 16˚C.

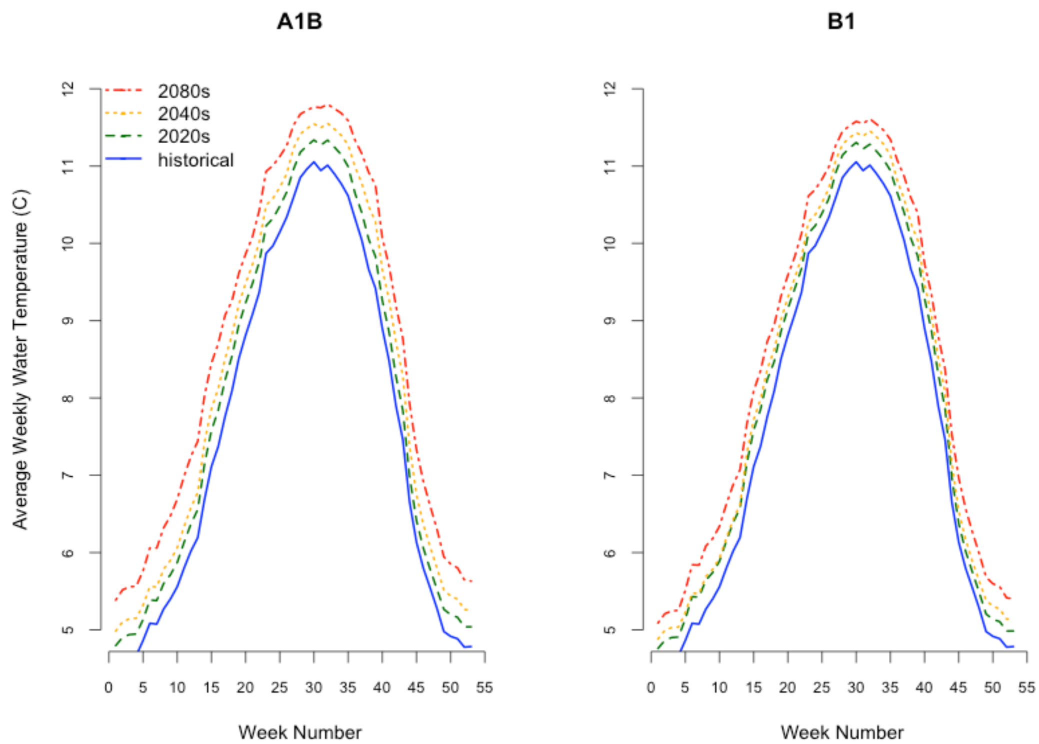

Figure 3.2 As in Figure 3.1, line plot for Skagit River at Marblemount. Note: identified temperature thresholds are never exceeded in these projections.

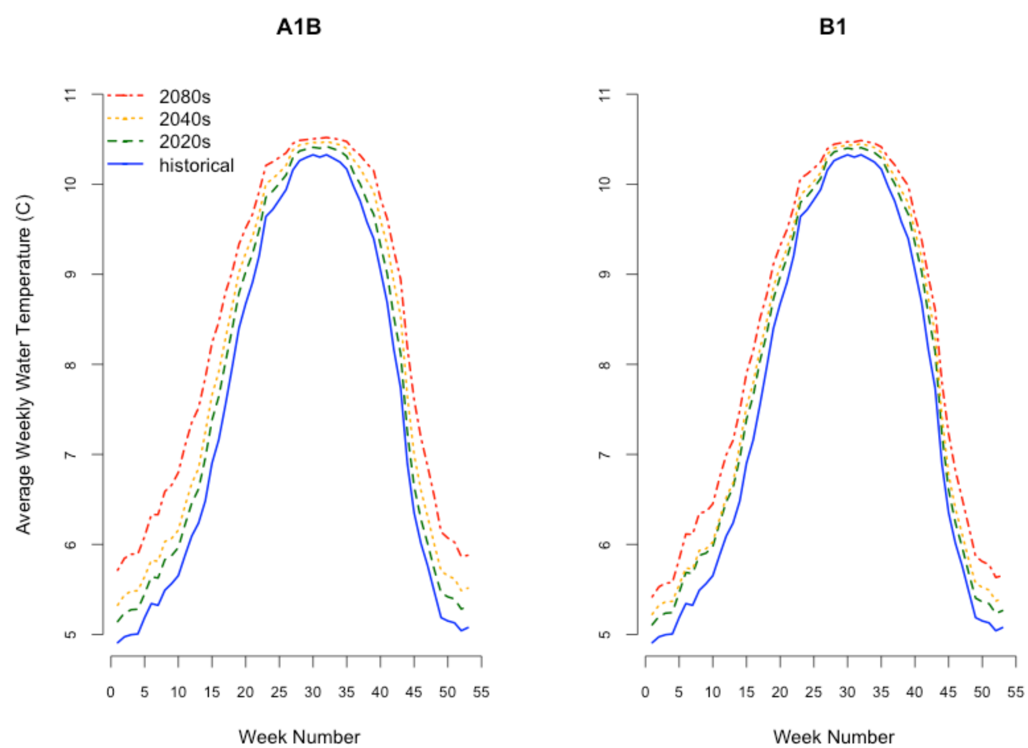

Figure 3.3 As in Figure 3.1, line plot for Skagit River at Newhalem. Note: identified temperature thresholds are never exceeded in these projections.

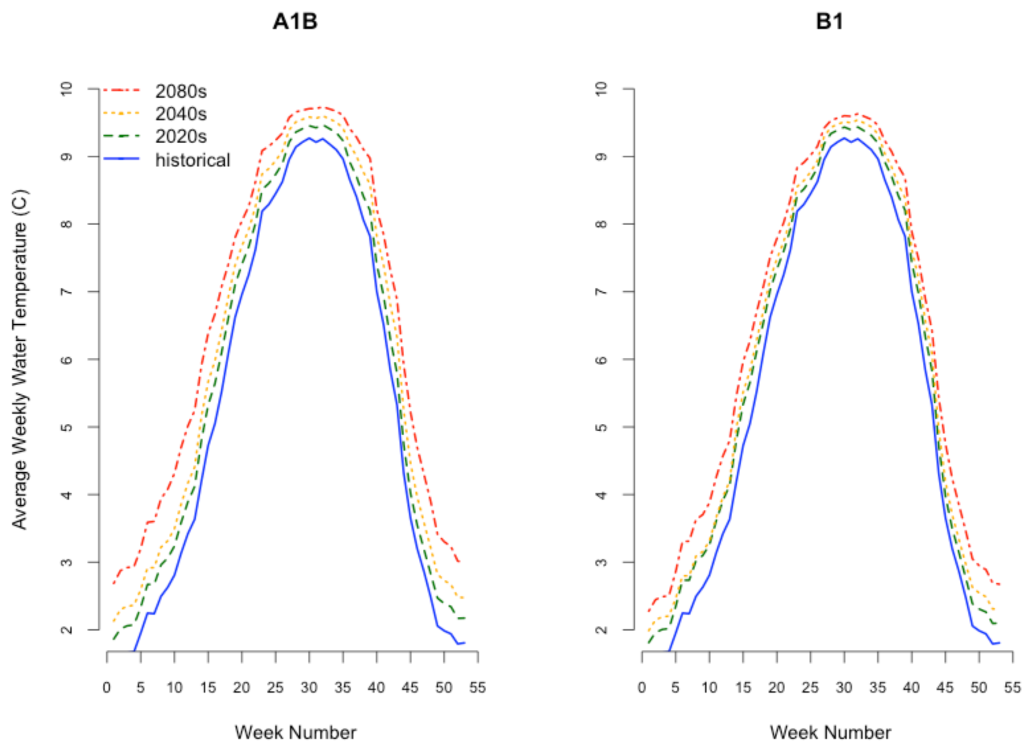

Figure 3.4 As in Figure 3.1, line plot for Stettatle Creek. Note: identified temperature thresholds are never exceeded in these projections.

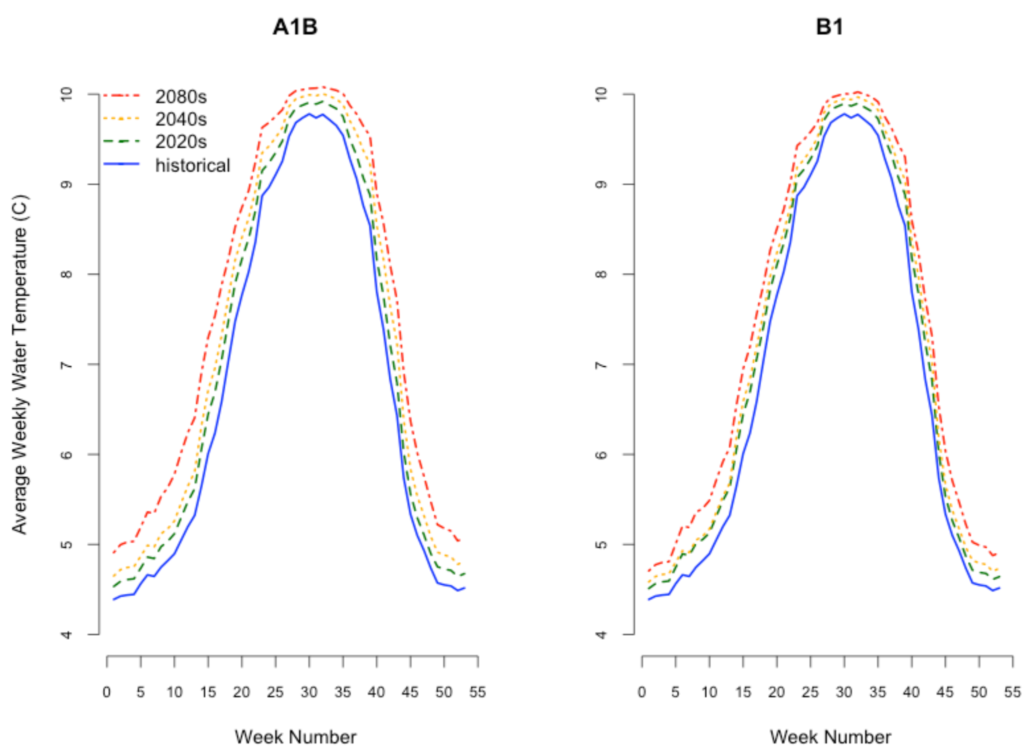

Figure 3.5 As in Figure 3.1, line plot for Skagit River at Diablo. Note: identified temperature thresholds are never exceeded in these projections.

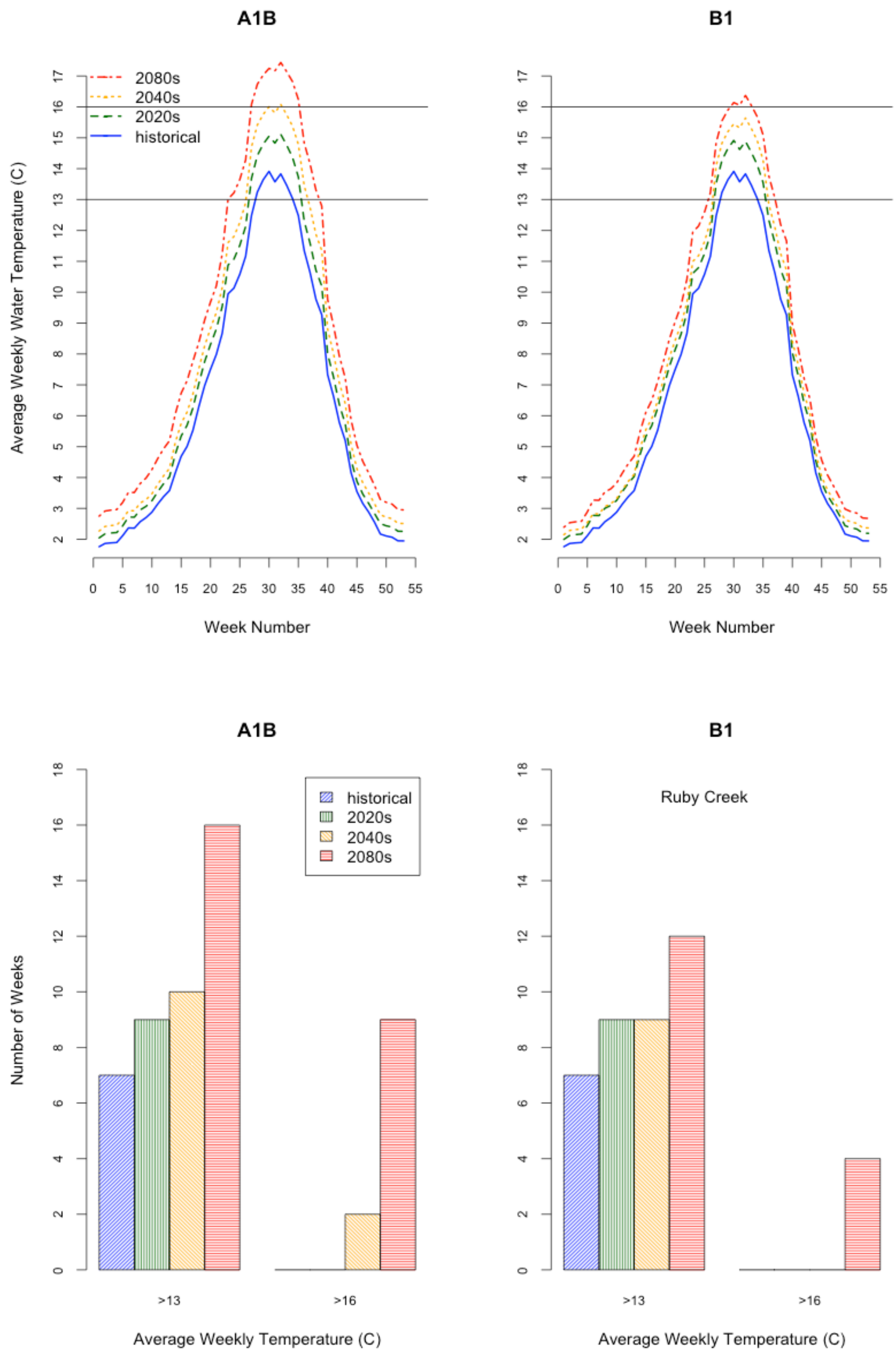

Figure 3.6 As in Figure 3.1, line and bar graphs for Ruby Creek. Black horizontal lines indicate temperature thresholds (13˚C and 16˚C) for spawning salmon and trout.

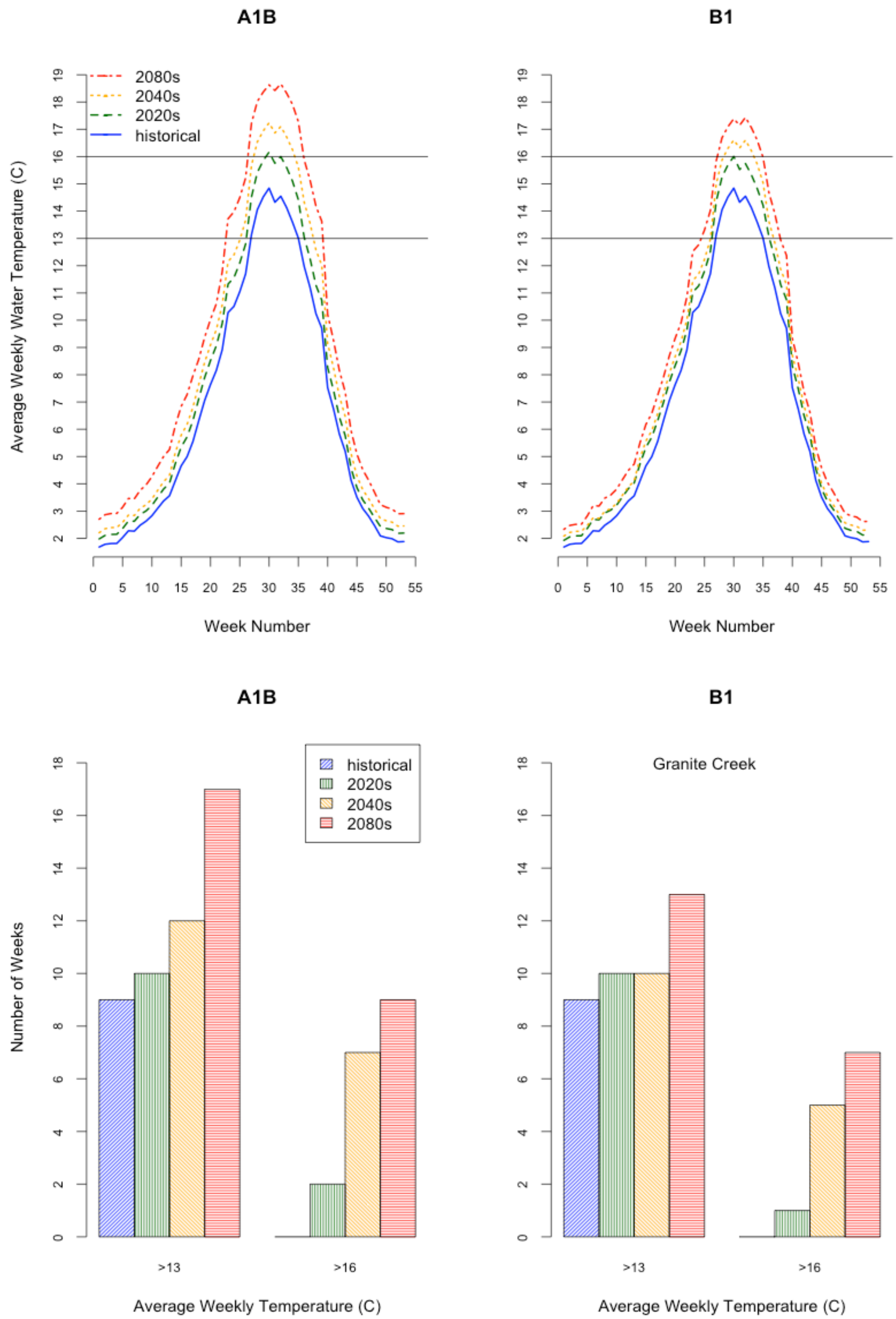

Figure 3.7 As in Figure 3.1, line and bar graphs for Granite Creek. Black horizontal lines indicate temperature thresholds (13˚C and 16˚C) for spawning salmon and trout.

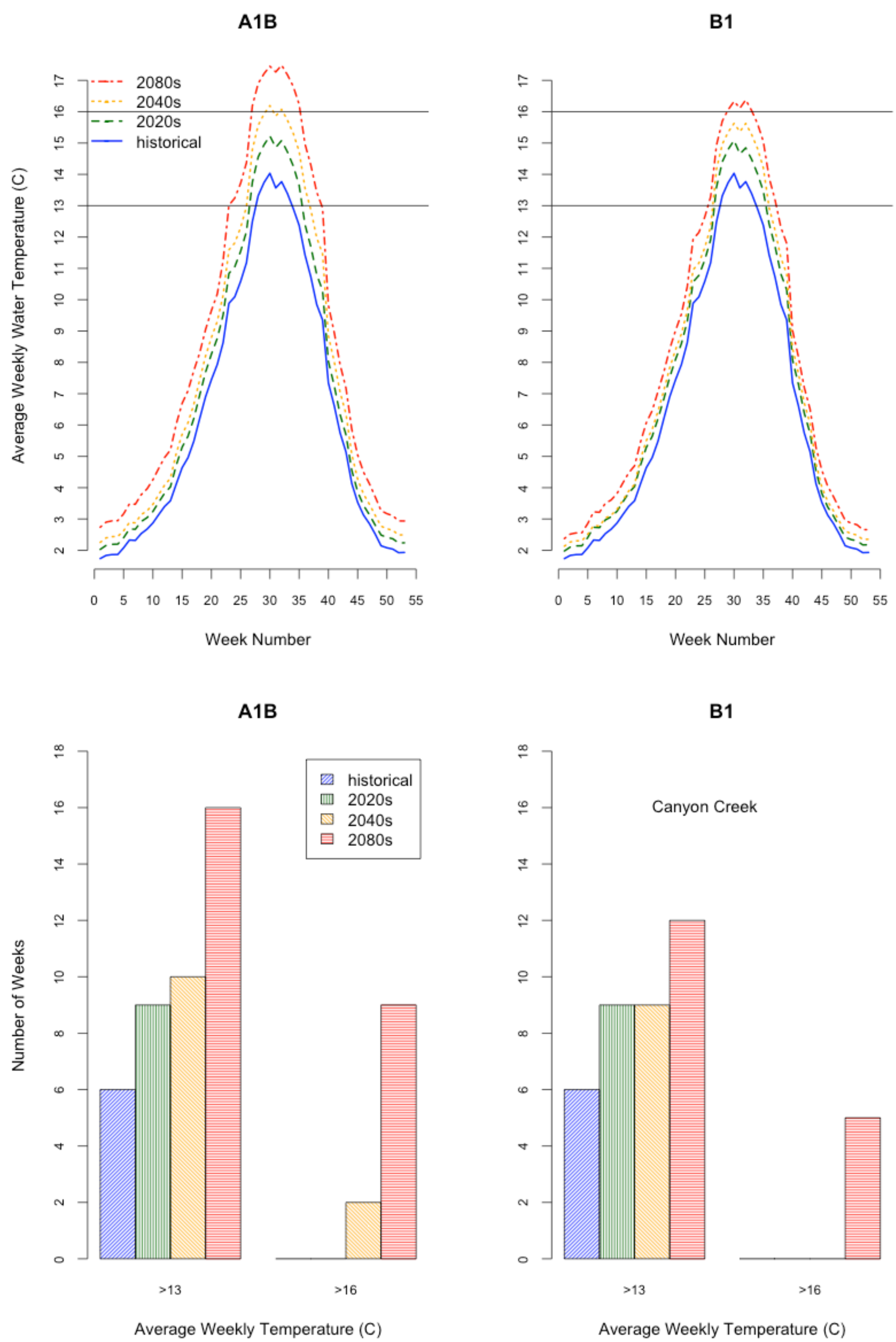

Figure 3.8 As in Figure 3.1, line and bar graphs for Canyon Creek. Black horizontal lines indicate temperature thresholds (13˚C and 16˚C) for spawning salmon and trout.

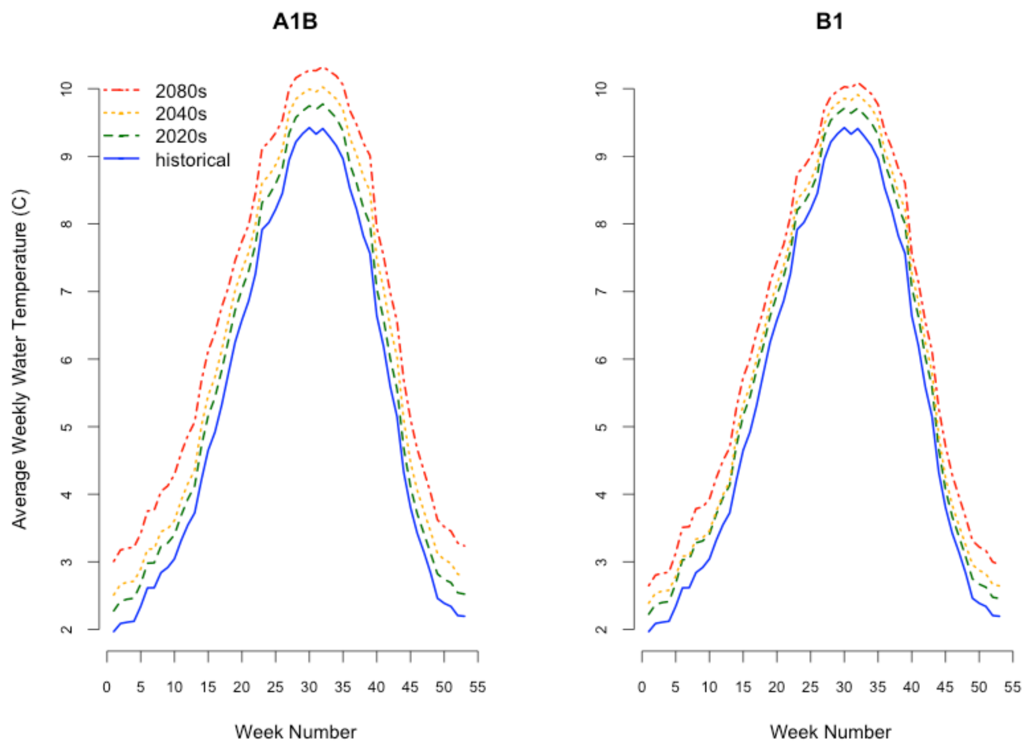

Figure 3.9 As in Figure 3.1, line plot for Big Beaver Creek. Note: identified temperature thresholds are never exceeded in these projections.

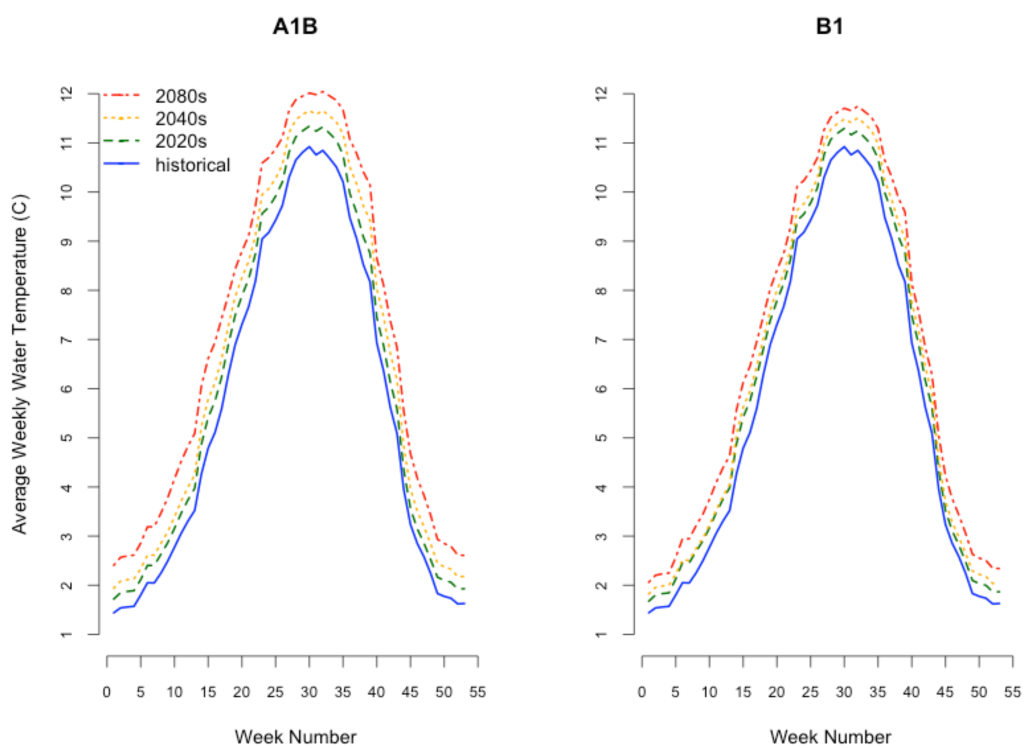

Figure 3.10 As in Figure 3.1, line plot for Devil's Creek. Note: identified temperature thresholds are never exceeded in these projections.

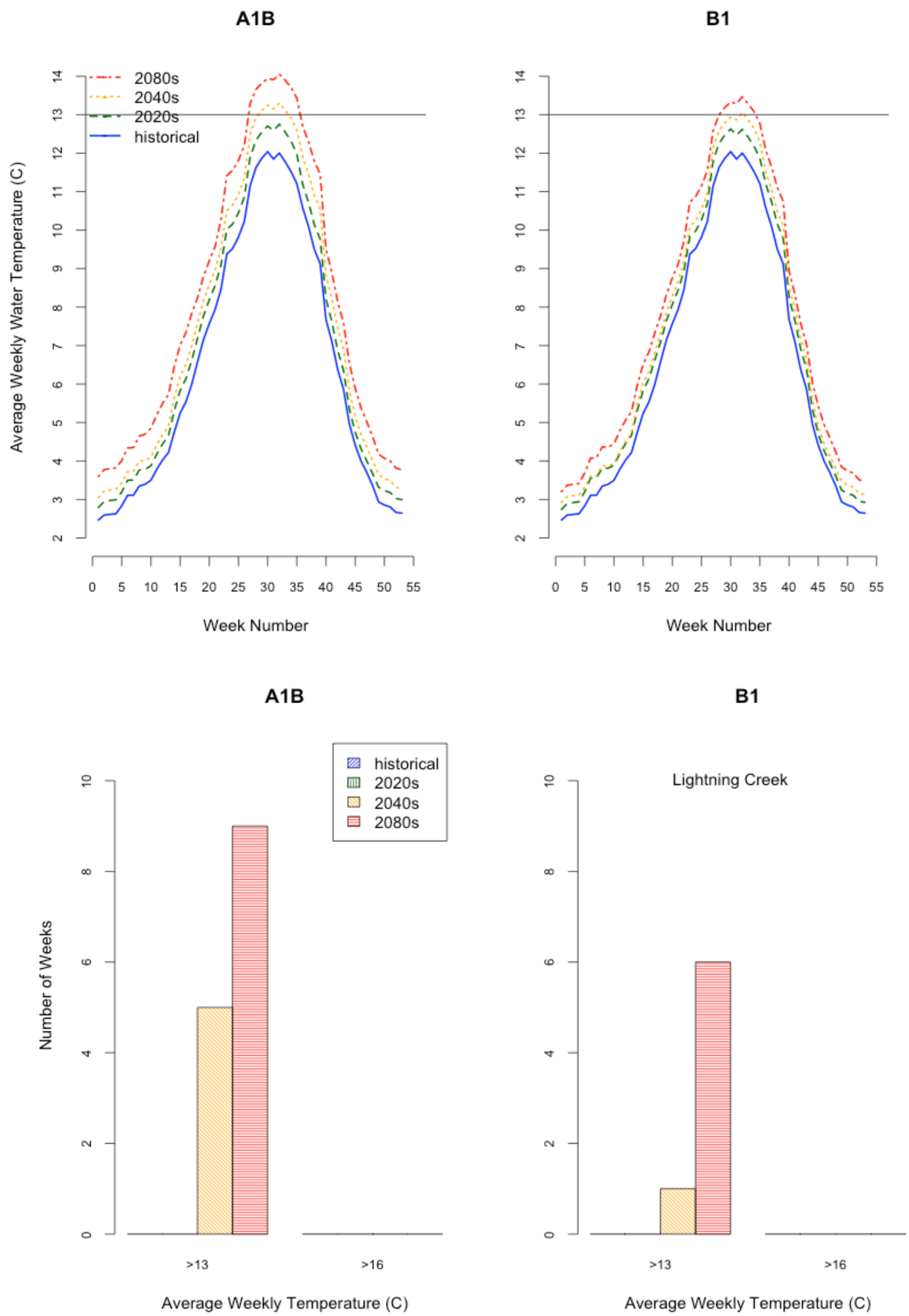

Figure 3.11 As in Figure 3.1, line and bar graphs for Lightning Creek. Black horizontal lines indicate temperature threshold (13˚C) for spawning salmon and trout.

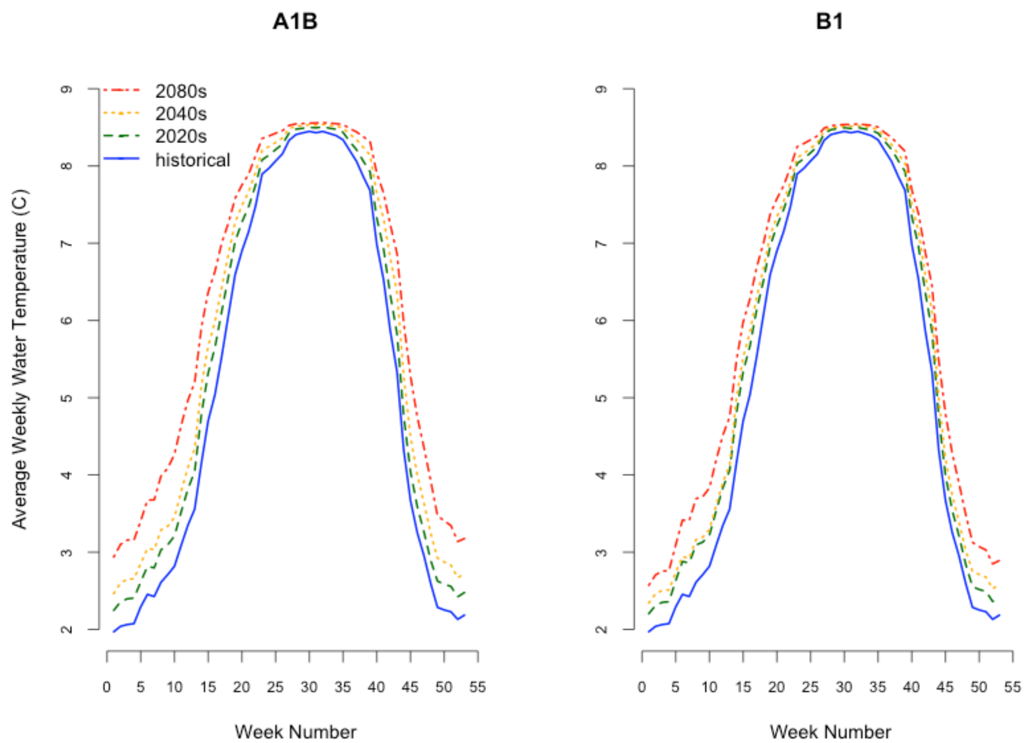

Figure 3.12 As in Figure 3.1, line plot for Little Beaver Creek. Note: identified temperature thresholds are never exceeded in these projections.

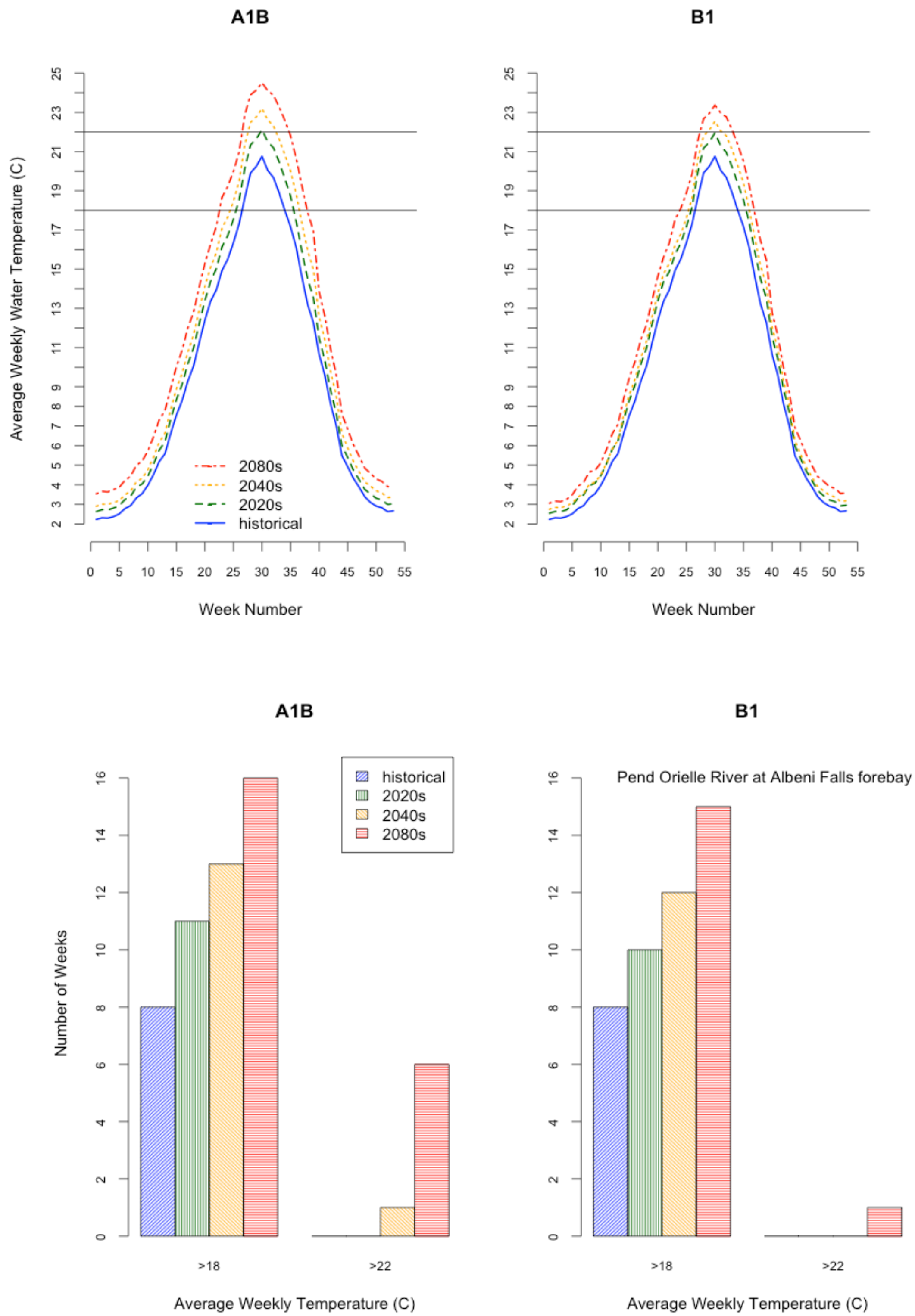

Figure 3.13 As in Figure 3.1, line and bar graphs for the Pend Oreille River at the Albeni Falls dam (forebay). Black horizontal lines indicate temperature thresholds (18˚C and 22˚C) for spawning salmon and trout. *Note:* The temperature thresholds for salmon and trout on the Pend Oreille River differ from those on the Skagit River.

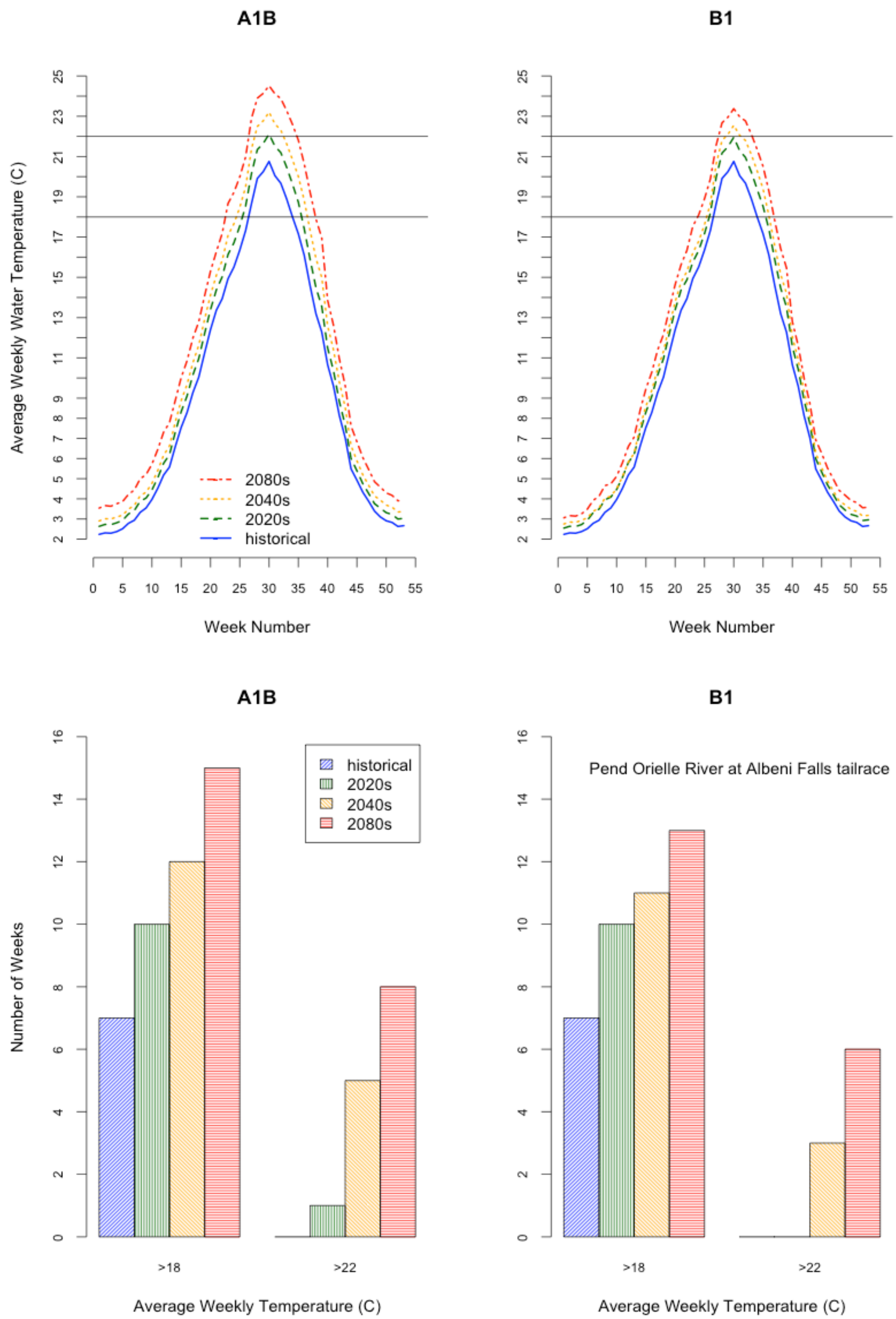

Figure 3.14 As in Figure 3.1, line and bar graphs for the Pend Oreille River at the Albeni Falls dam (tailrace). Black horizontal lines indicate temperature thresholds (18˚C and 22˚C) for spawning salmon and trout. Note: The temperature thresholds for salmon and trout on the Pend Oreille River differ from those on the Skagit River.

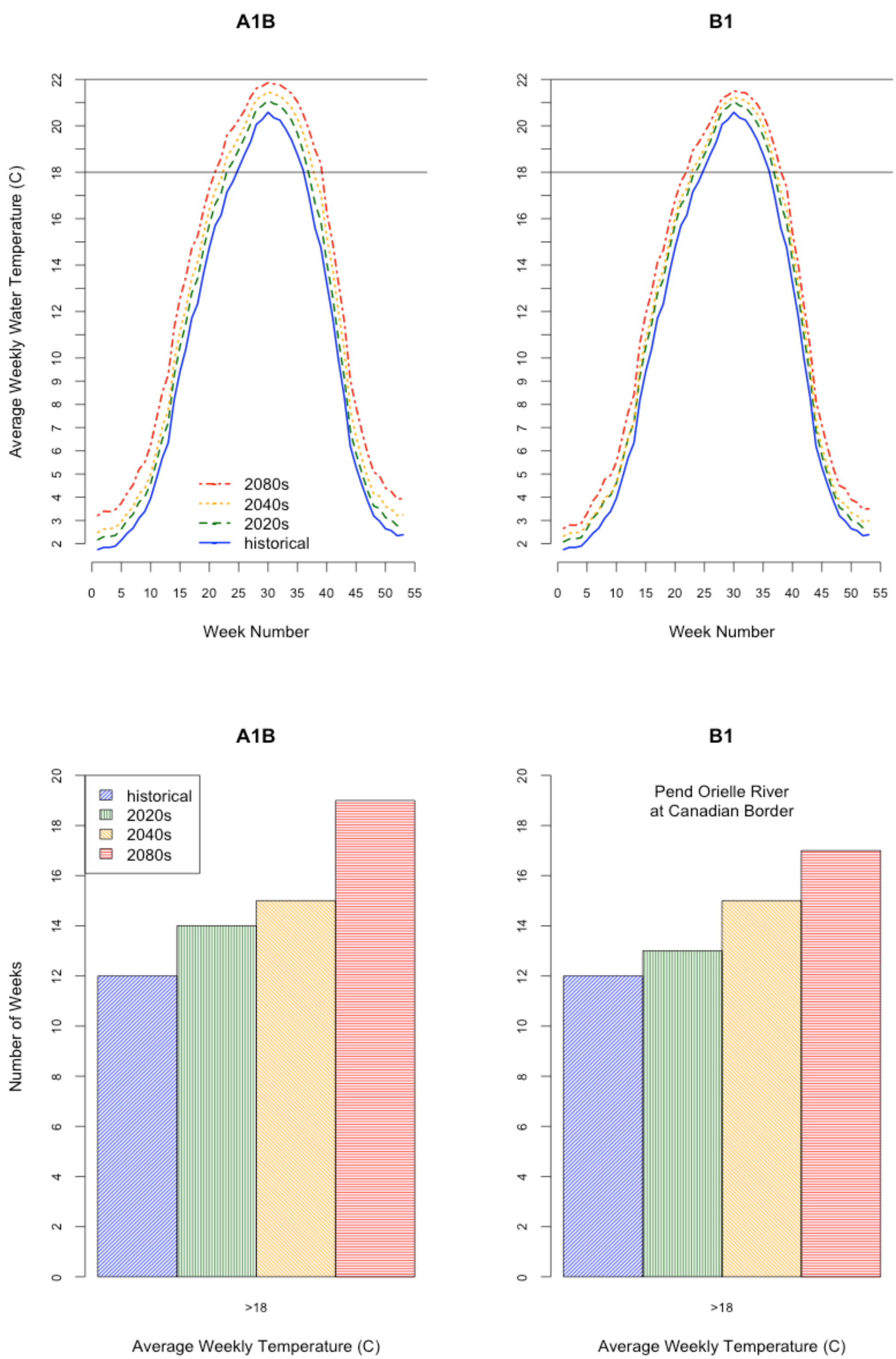

Figure 3.15 As in Figure 3.1, line and bar graphs for the Pend Oreille River at the Canadian border. Black horizontal lines indicate temperature thresholds (18˚C) for spawning salmon and trout. Note: This site does not exceed the 21˚C temperature threshold.

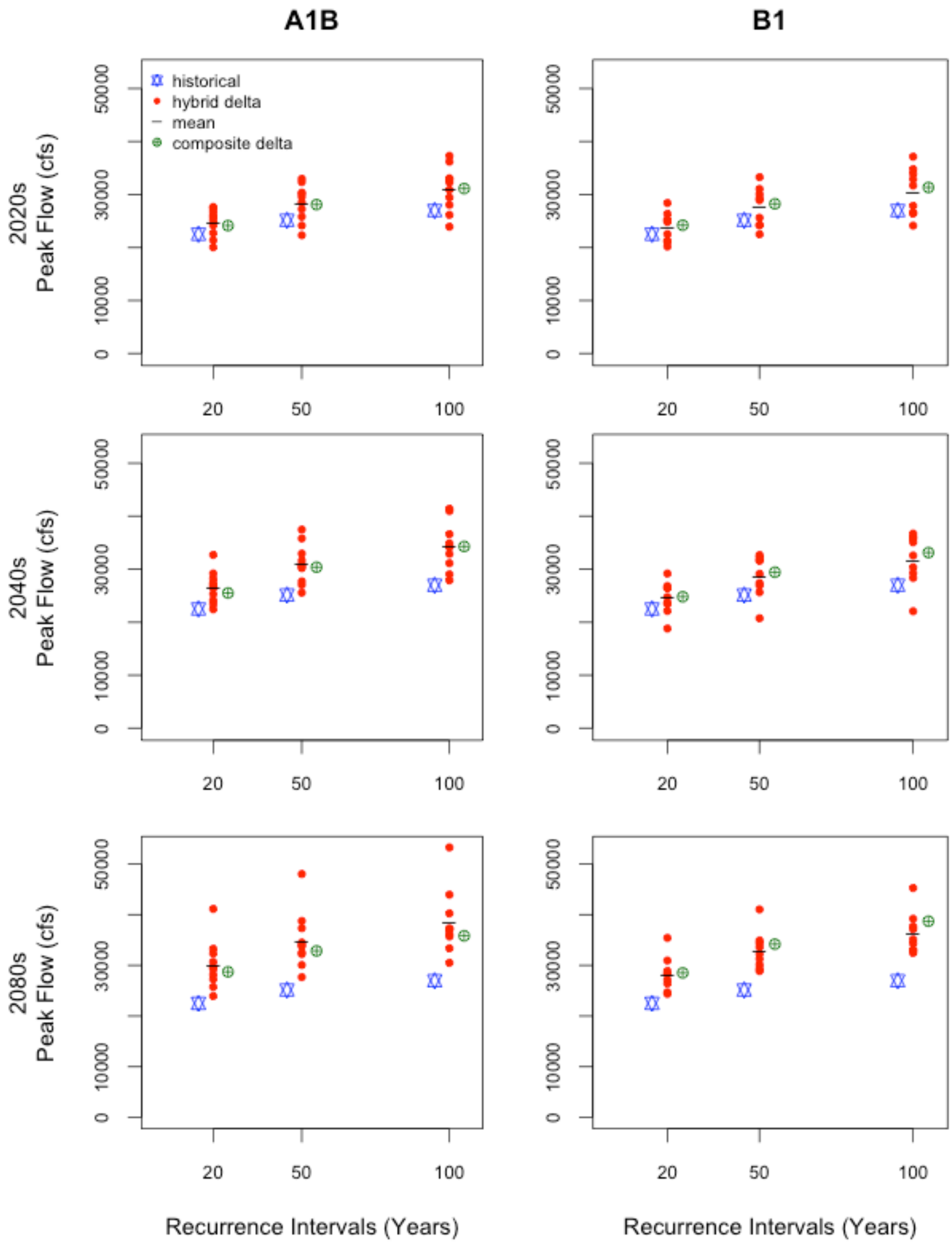

Figure 3.16 The 20-year, 50-year and 100-year flood statistics for the Ross reservoir (total inflows above the dam) on the Skagit River for the historical, hybrid delta, composite delta and composite delta means. The right vertical panel shows results for the A1B scenario and the left panel shows results from the B1 scenario for the 2020s (horizontally top two plots), 2040s and 2080s.

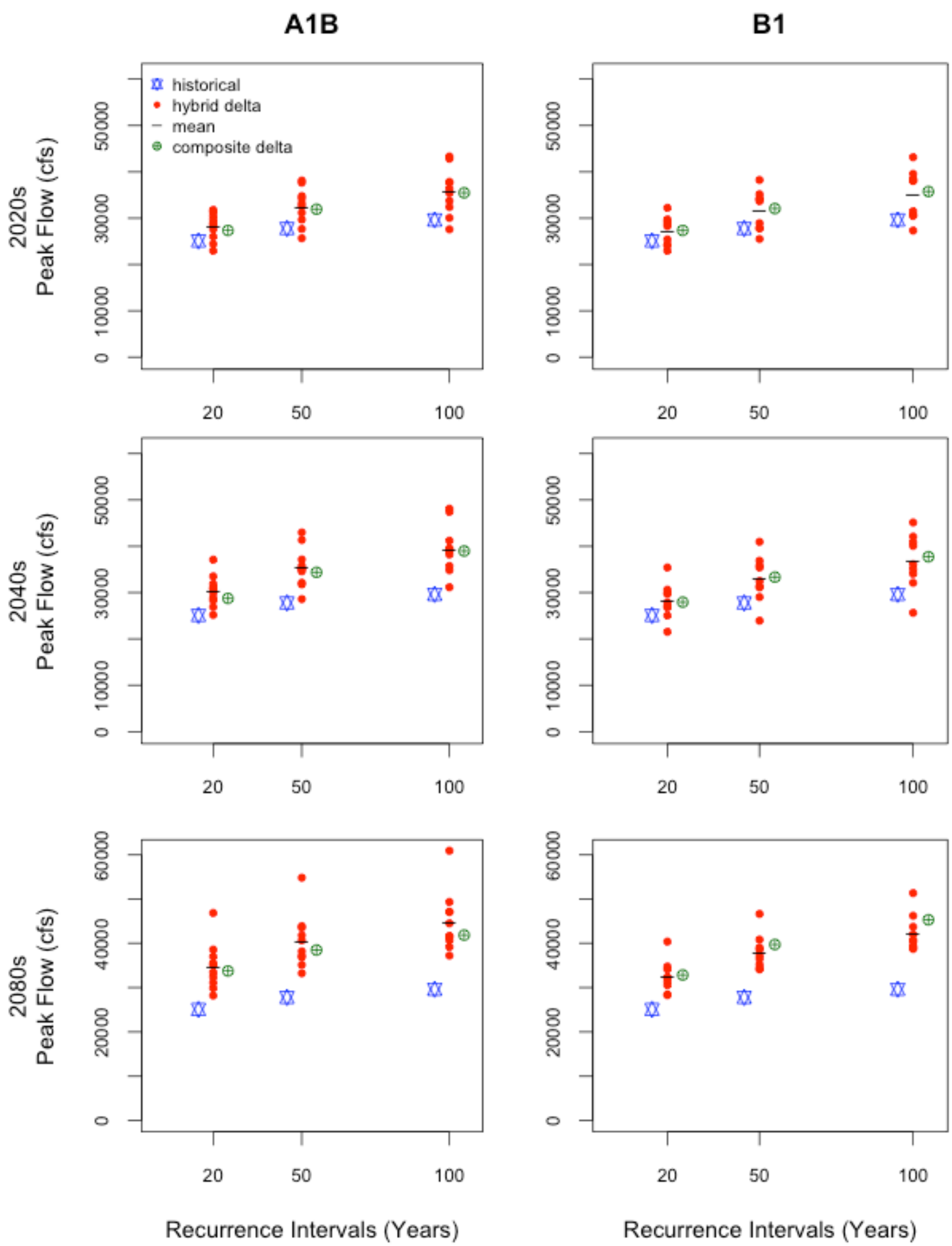

Figure 3.17 As in Figure 3.16, flood statistics for the Diablo dam on the Skagit River.

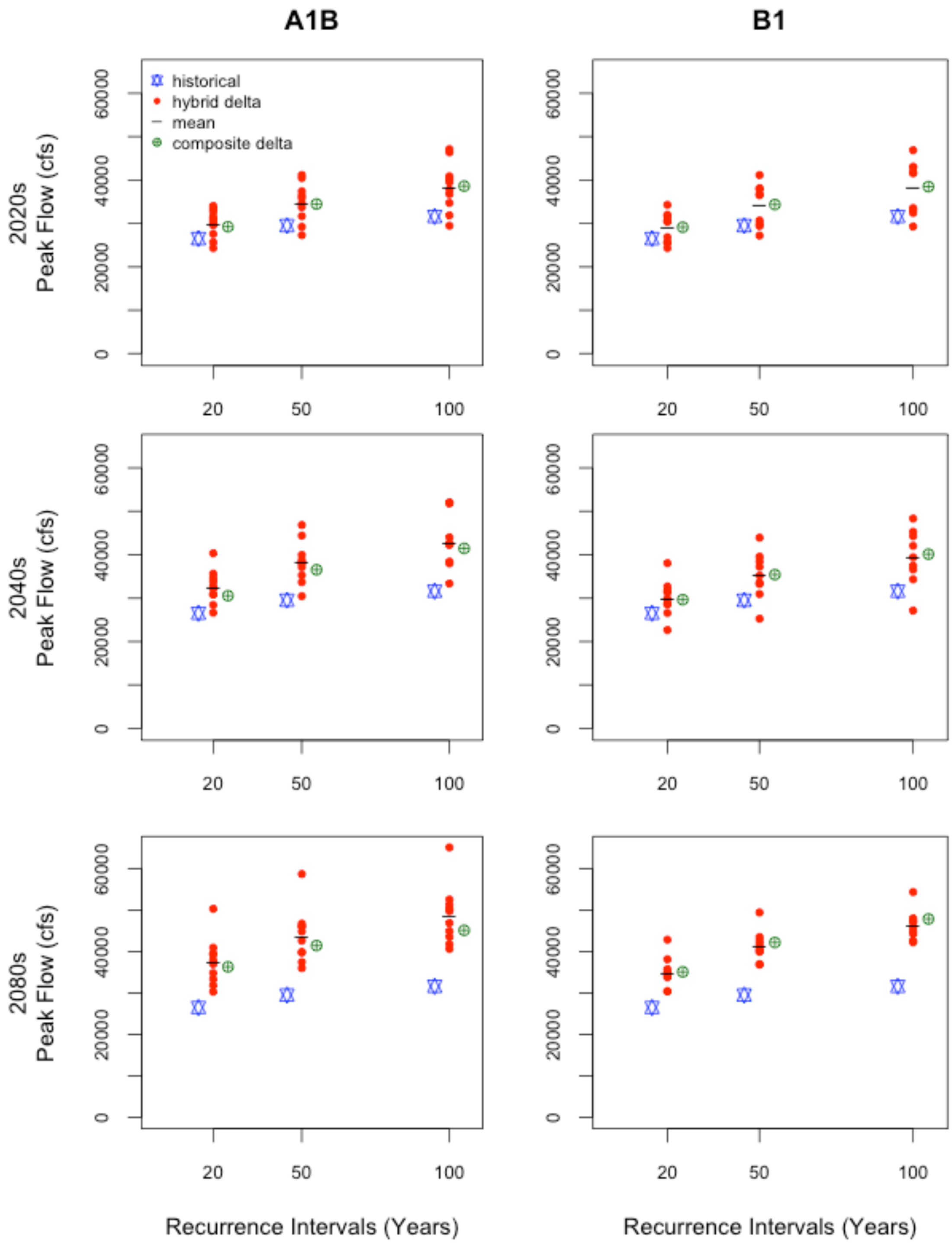

Figure 3.18 As in Figure 3.16, flood statistics for the Gorge dam on the Skagit River.

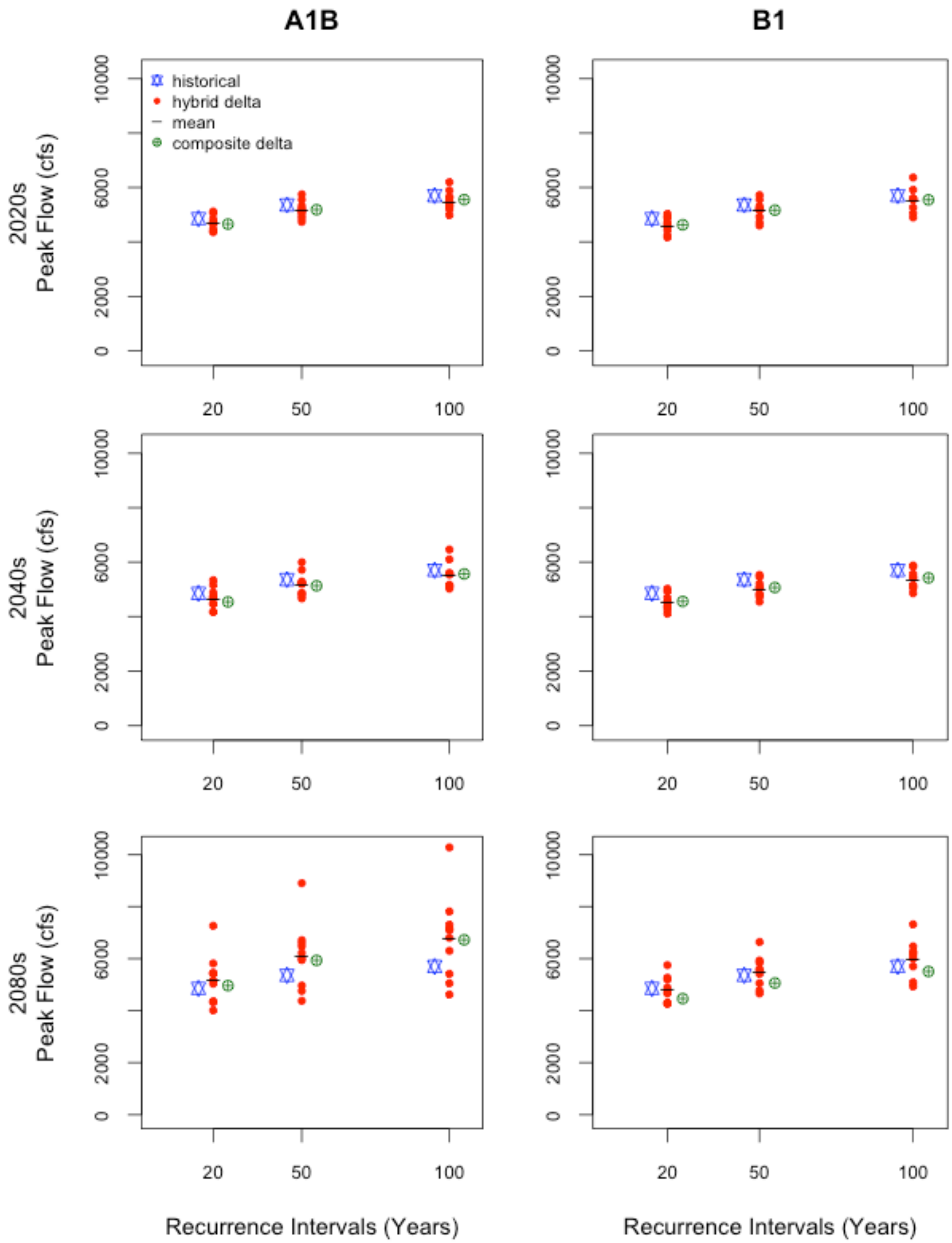

Figure 3.19 As in Figure 3.16, flood statistics for Ruby Creek near Newhalem.

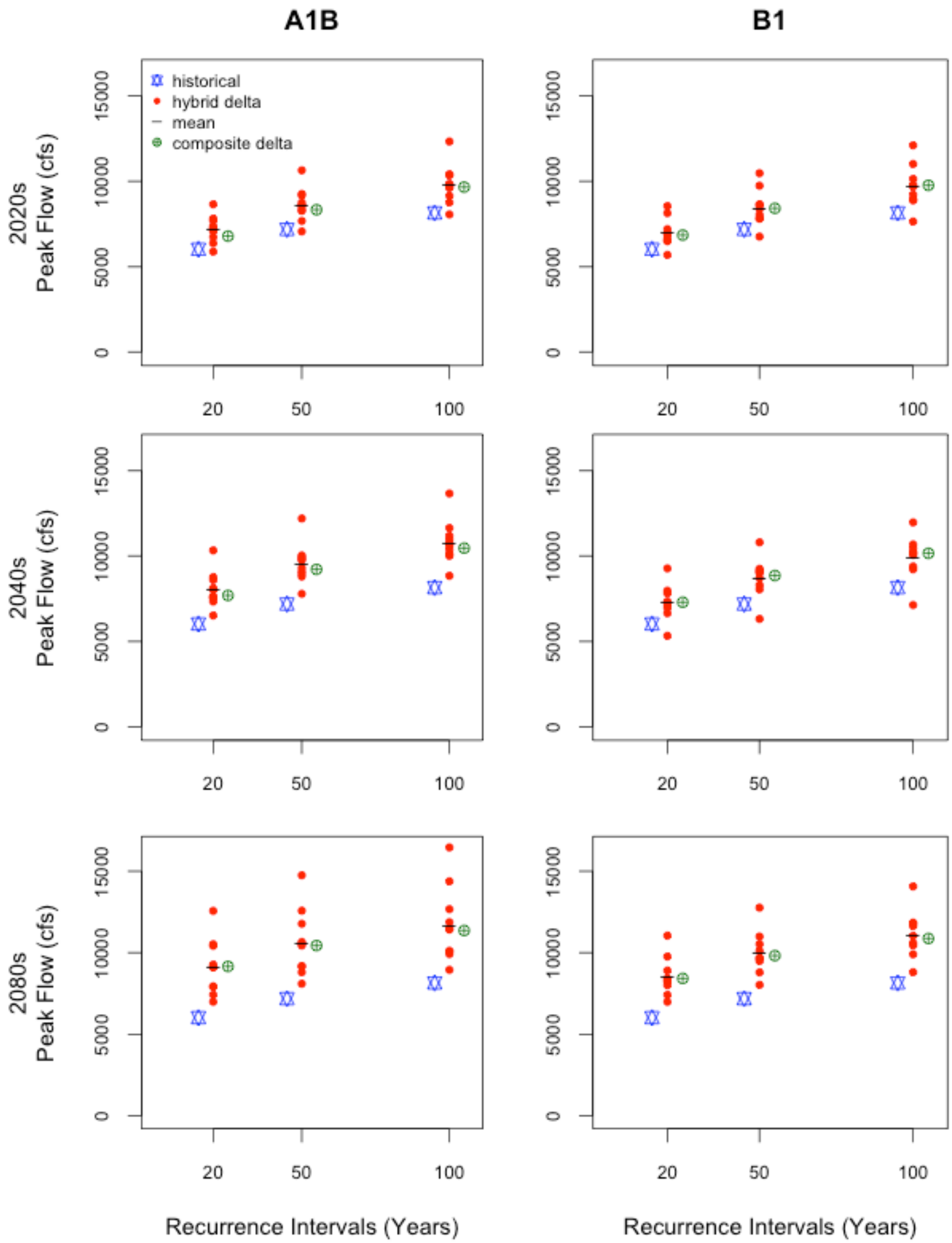

Figure 3.20 As in Figure 3.16, flood statistics for the Cascade River near Marblemount.

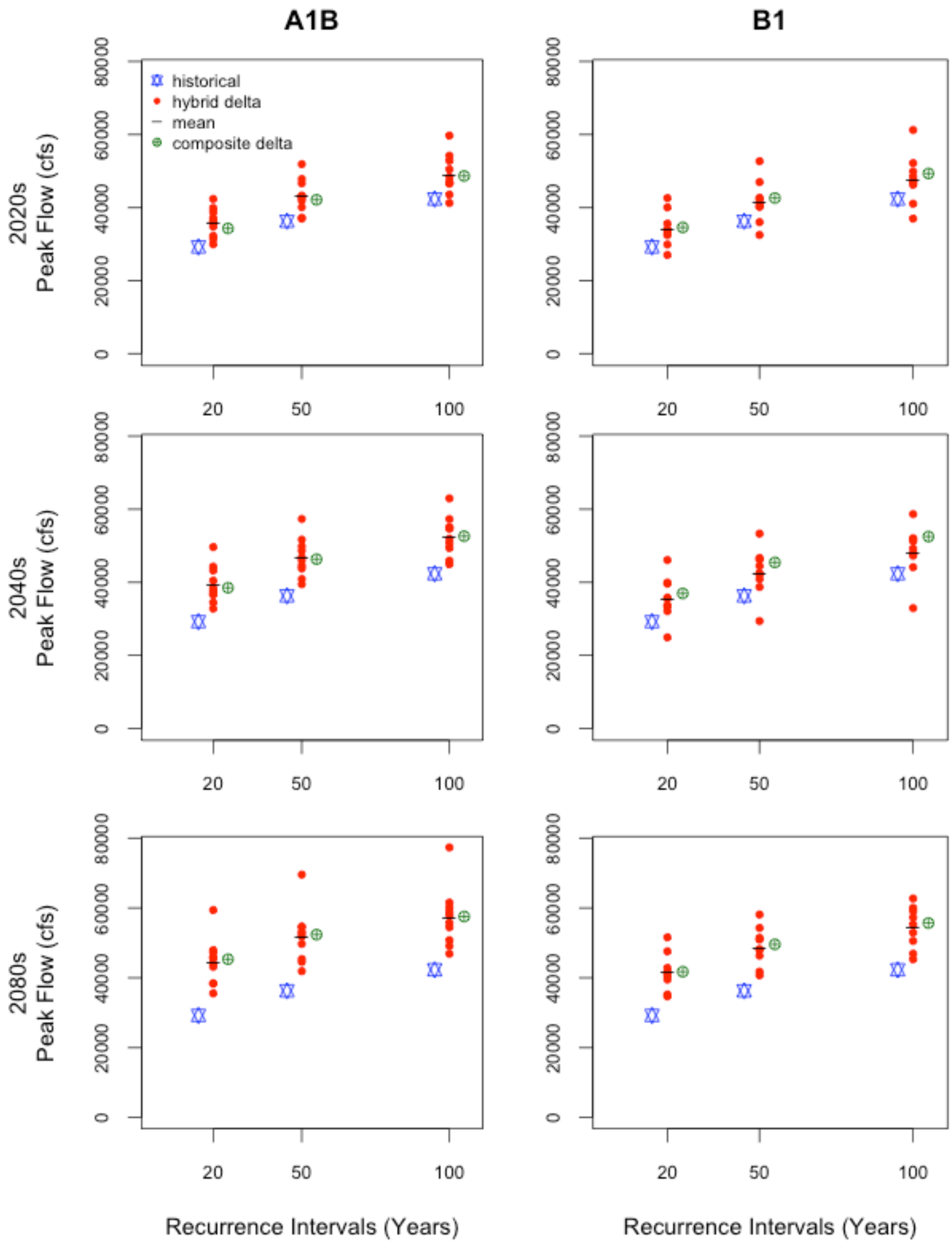

Figure 3.21 As in Figure 3.16, flood statistics for the Sauk River near Sauk.

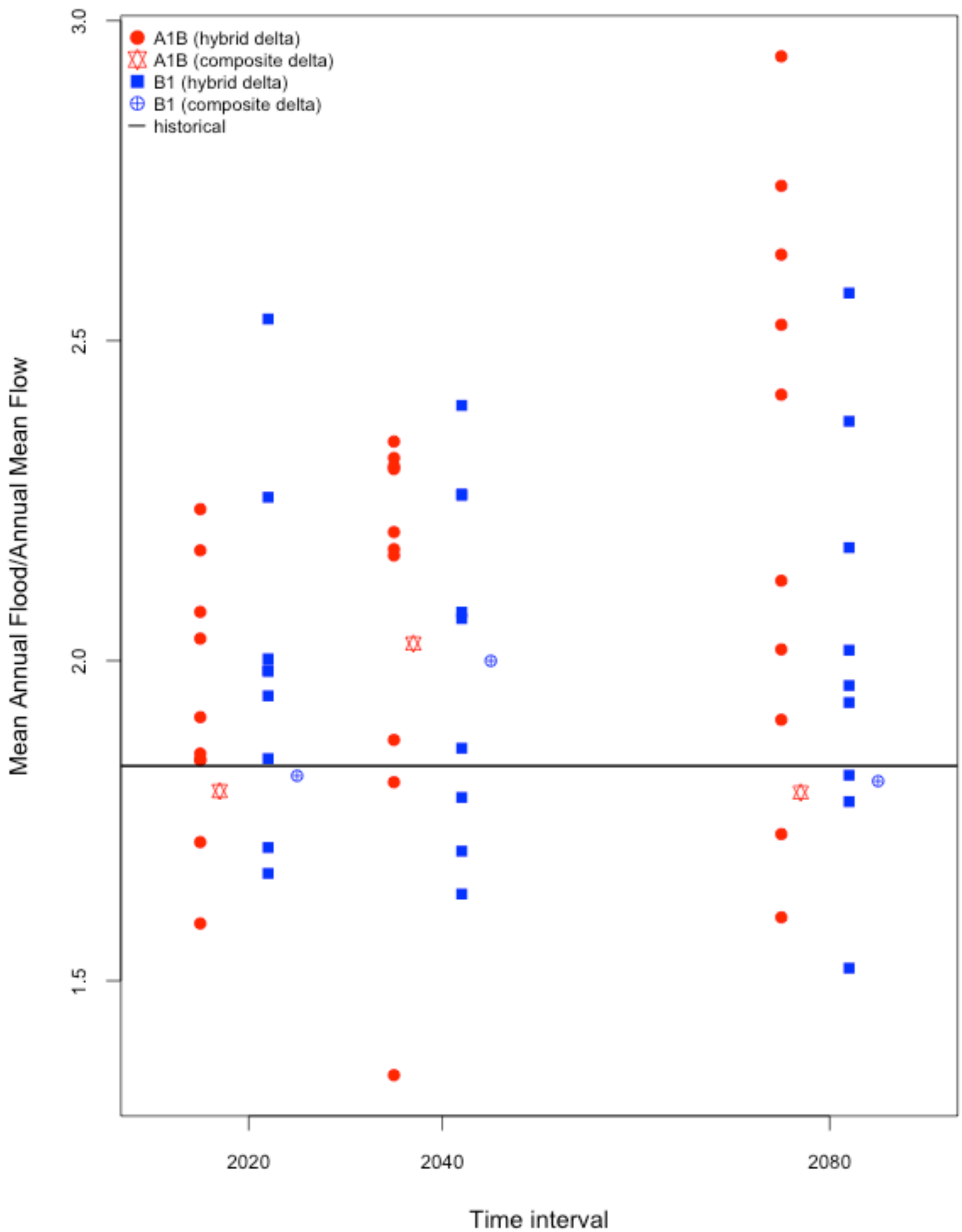

Figure 3.22 Ratio of future peak flows to historical mean annual streamflows at Ross reservoir on the Skagit River. Results are shown for the A1B and B1 scenarios for the hybrid delta and composite delta.

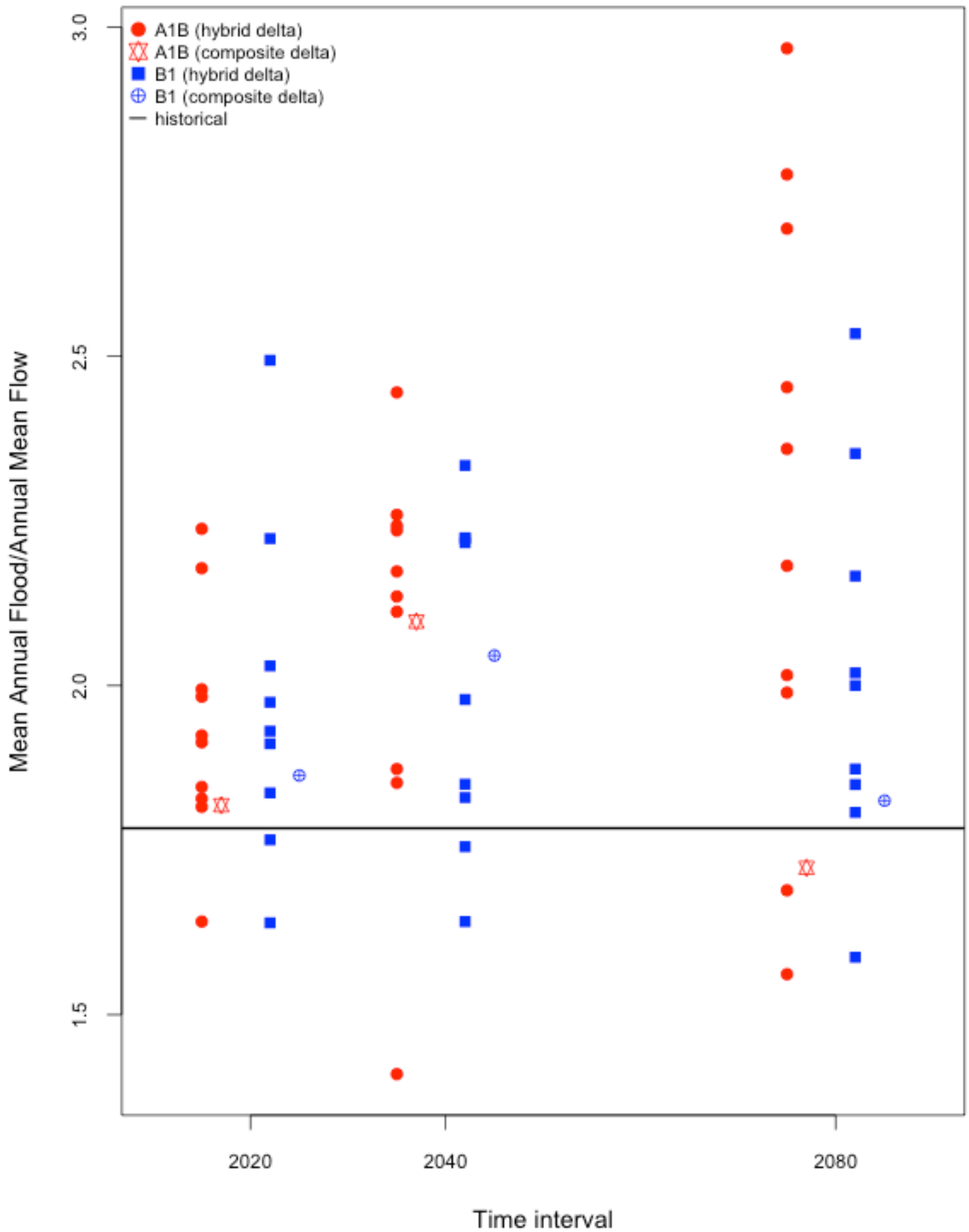

Figure 3.23 As in Figure 3.22, ratio of flood statistics for the Diablo dam on the Skagit River.

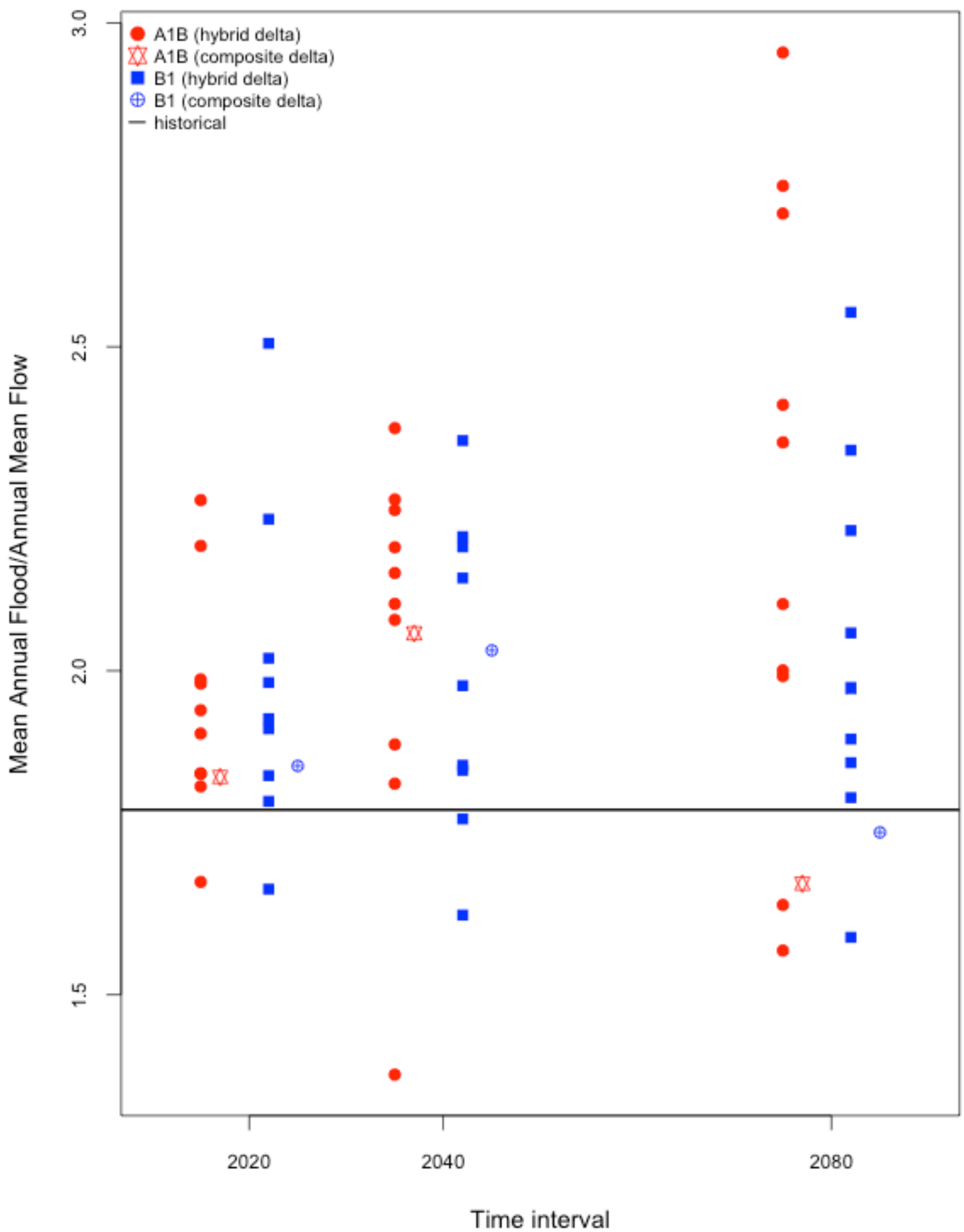

Figure 3.24 As in Figure 3.22, ratio of flood statistics for the Gorge dam on the Skagit River.

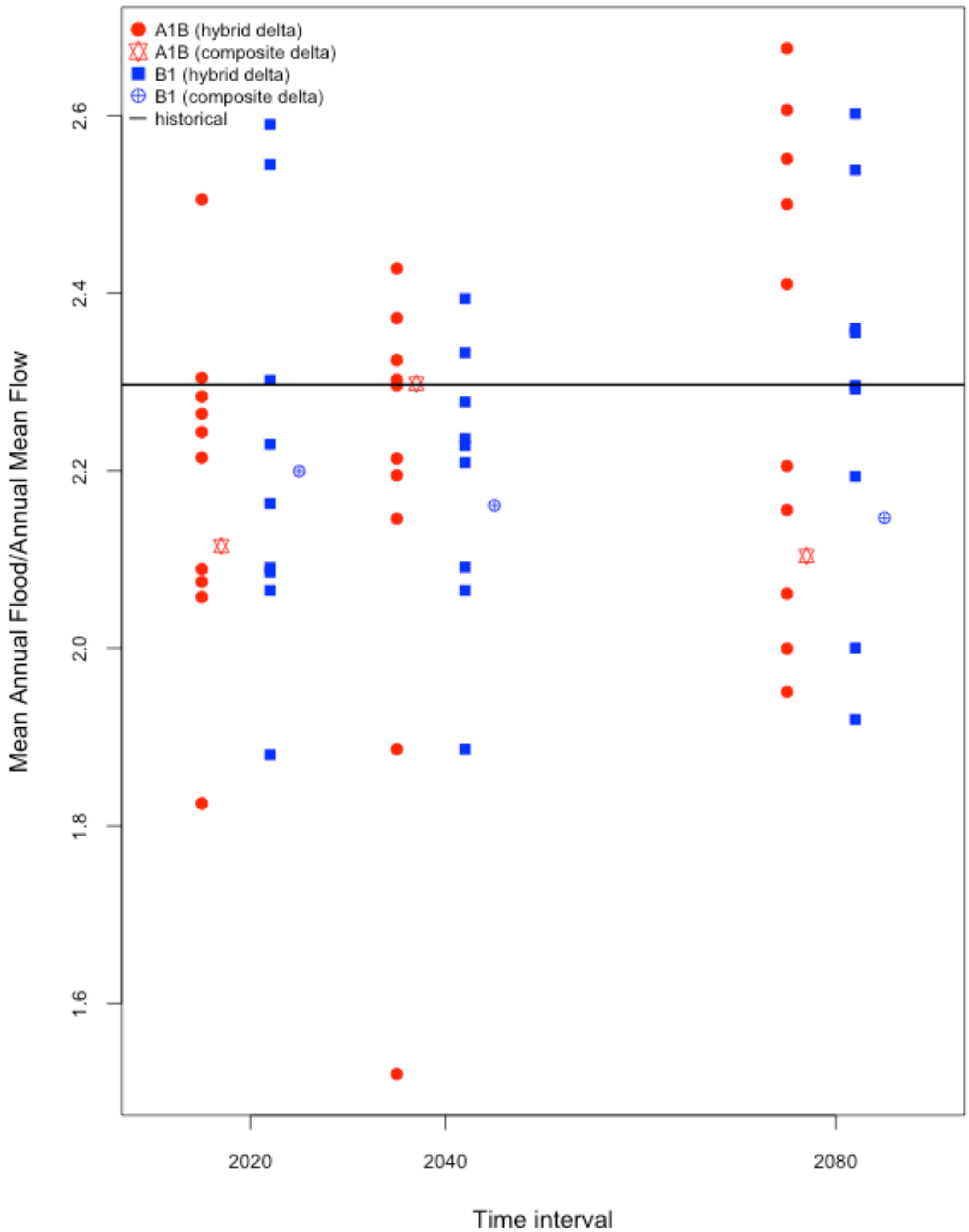

Figure 3.25 As in Figure 3.22, ratio of flood statistics for Ruby Creek near Newhalem.

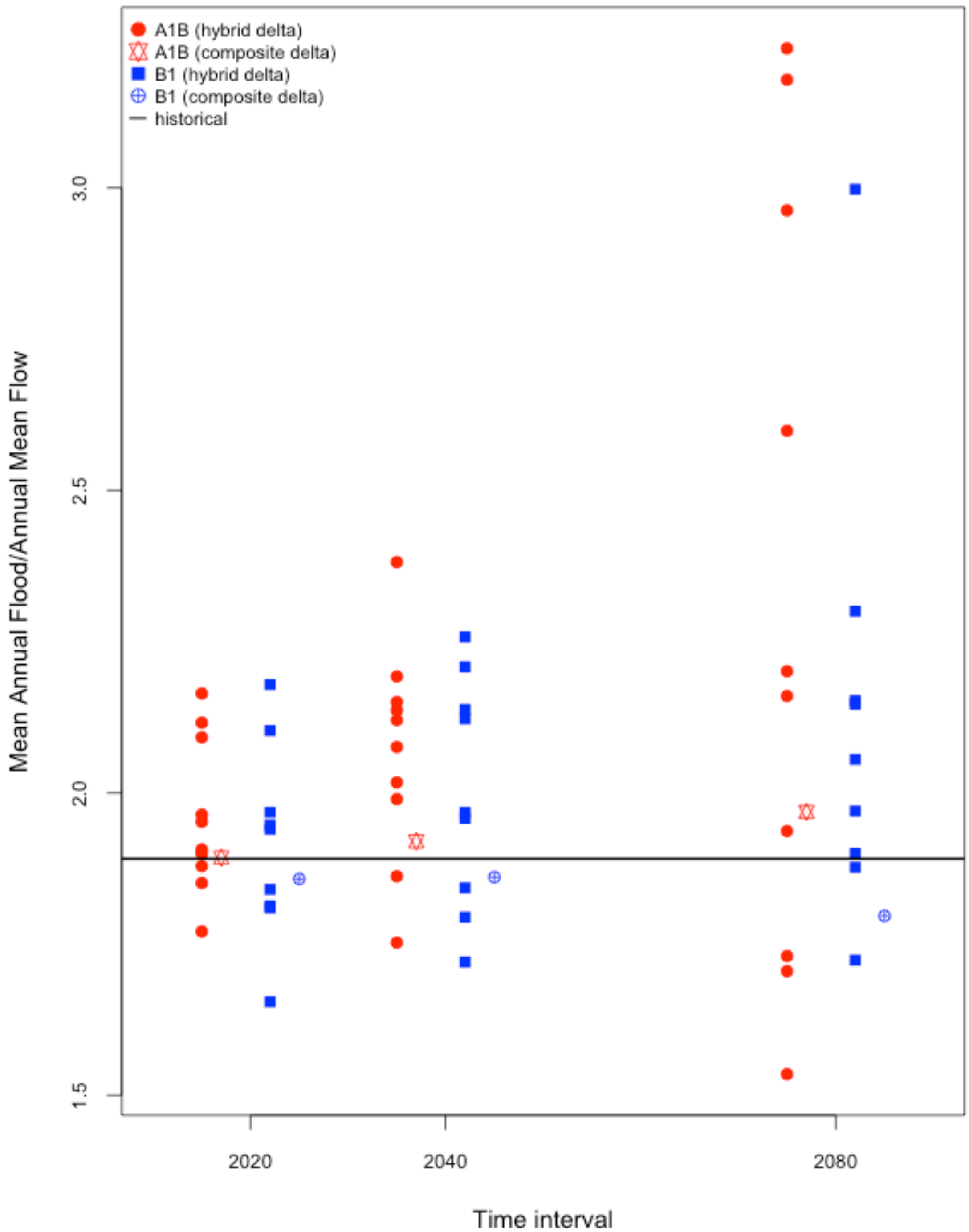

Figure 3.26 As in Figure 3.22, ratio of flood statistics for the Cascade River near Marblemount.

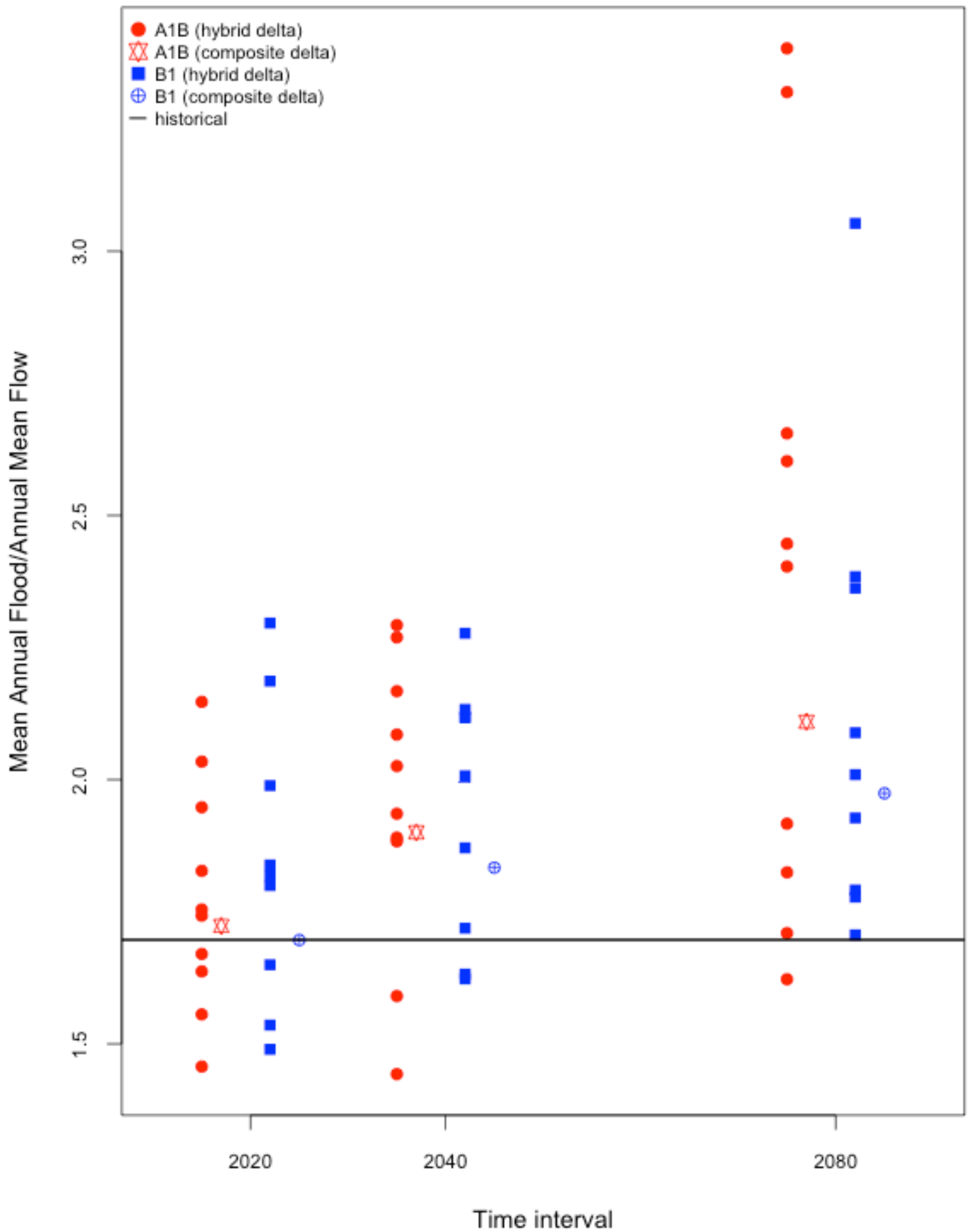

Figure 3.27 As in Figure 3.22, ratio of flood statistics for the Sauk River near Sauk.

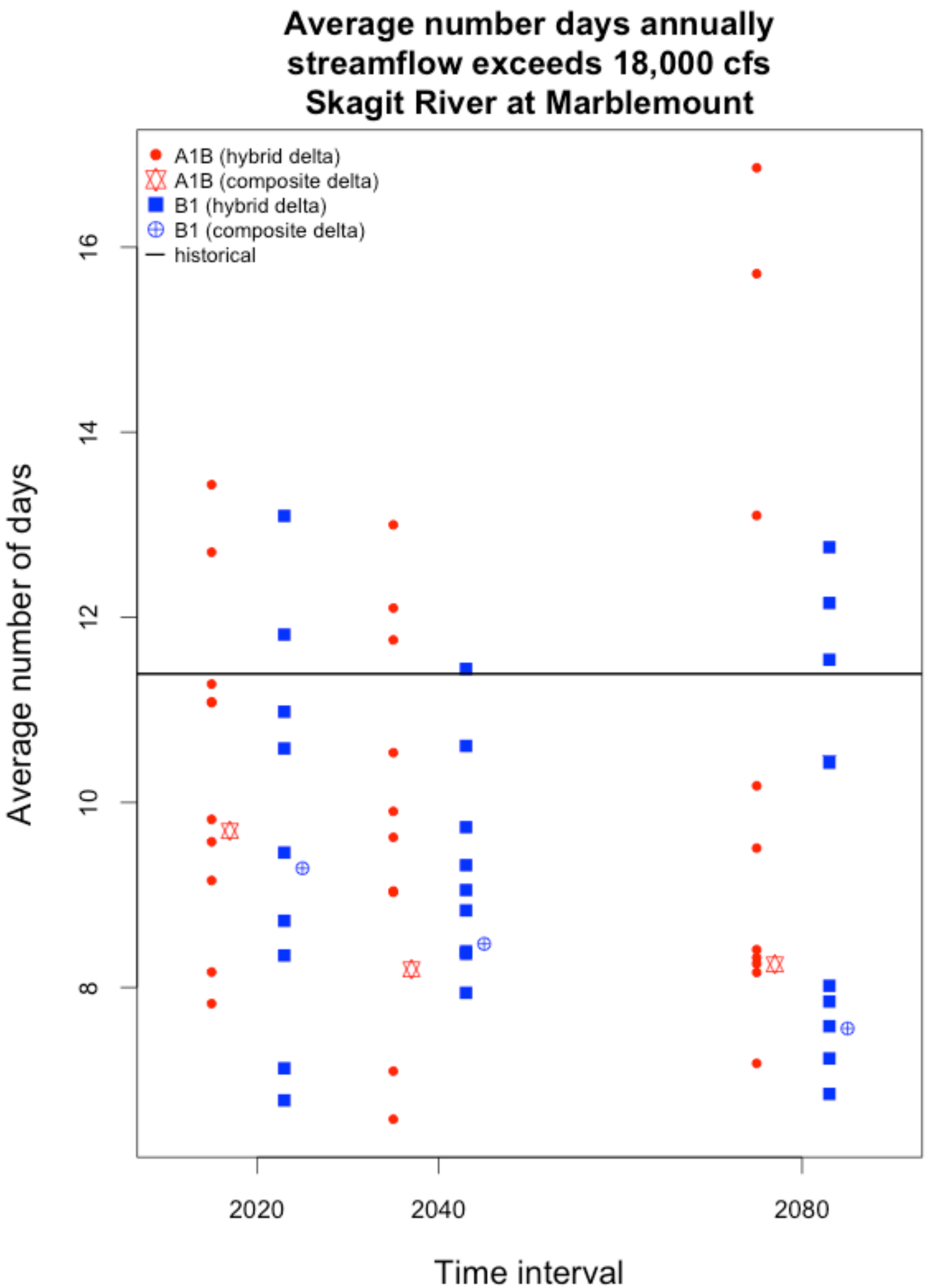

Figure 3.28 Average number of days streamflows exceed 18,000 cfs for the Skagit River at Marblemount.

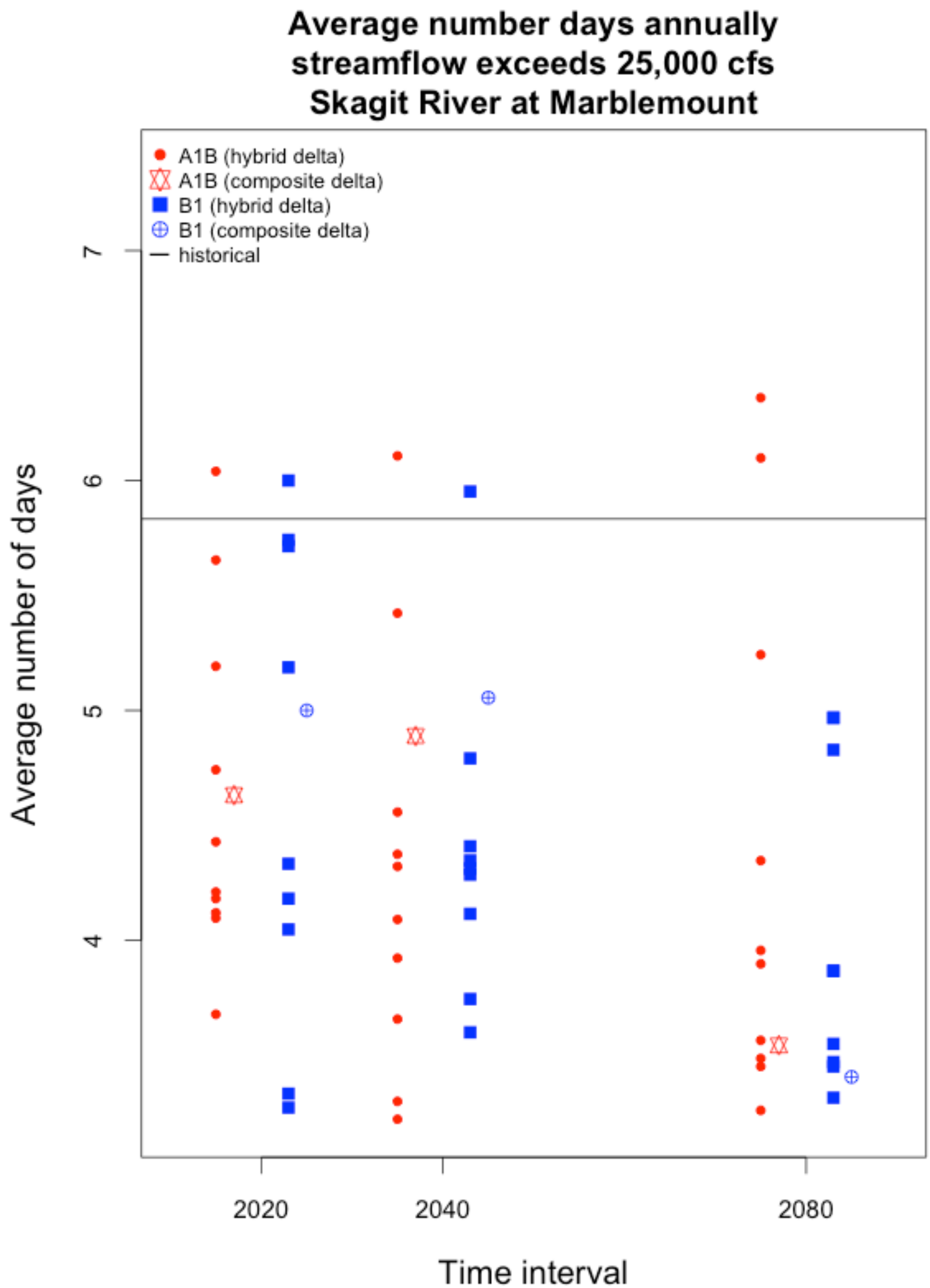

Figure 3.29 Average number of days streamflows exceed 25,000 cfs for the Skagit River at Marblemount.

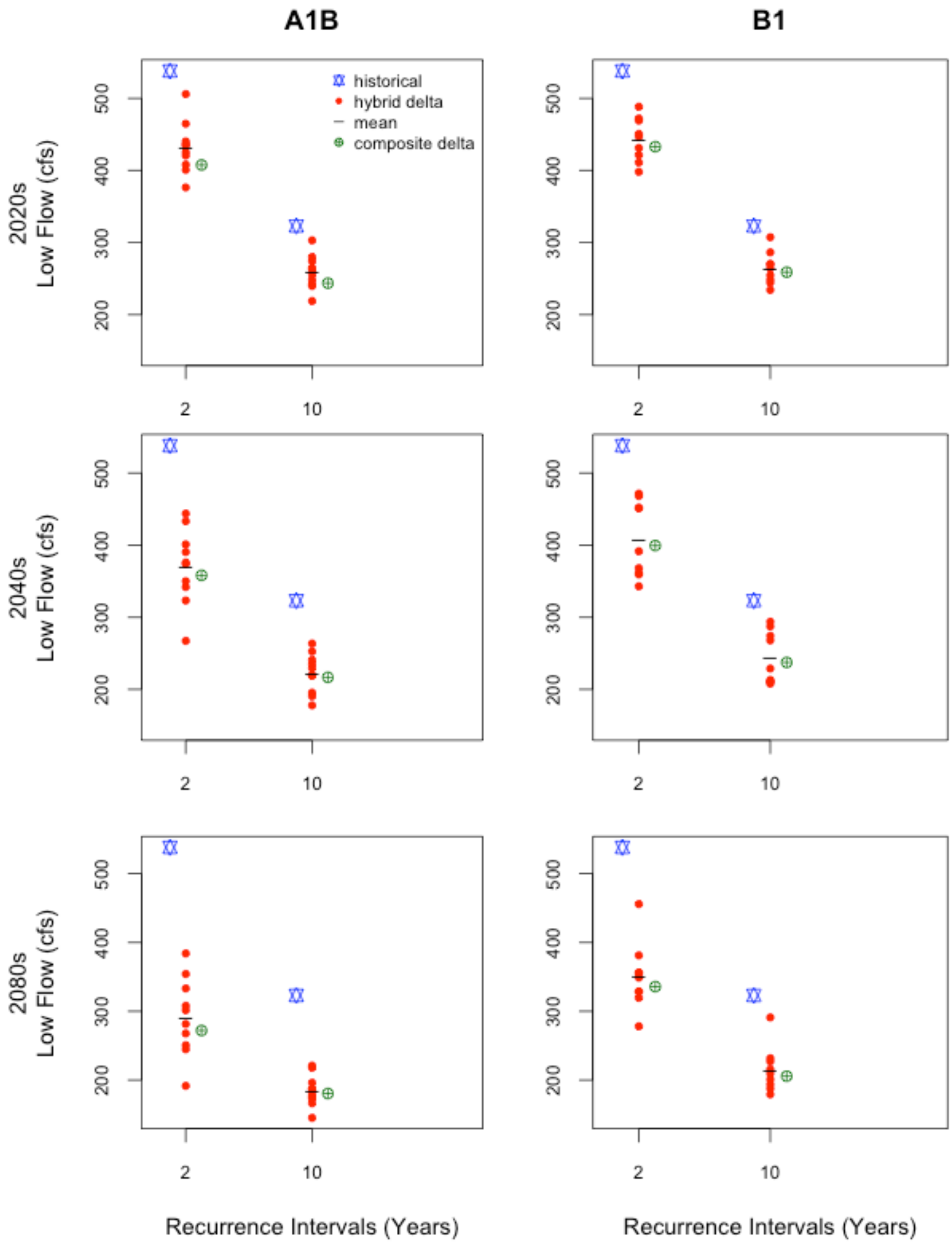

Figure 3.30 The 7-day minimum low flow statistics with a 2-year and 10-year return interval for the Ross reservoir on the Skagit River for the historical, hybrid delta, composite delta and composite delta means. The right vertical panel shows results for the A1B scenario and the left panel shows results from the B1 scenario for the 2020s (top row), 2040s (middle row) and 2080s (bottom row).

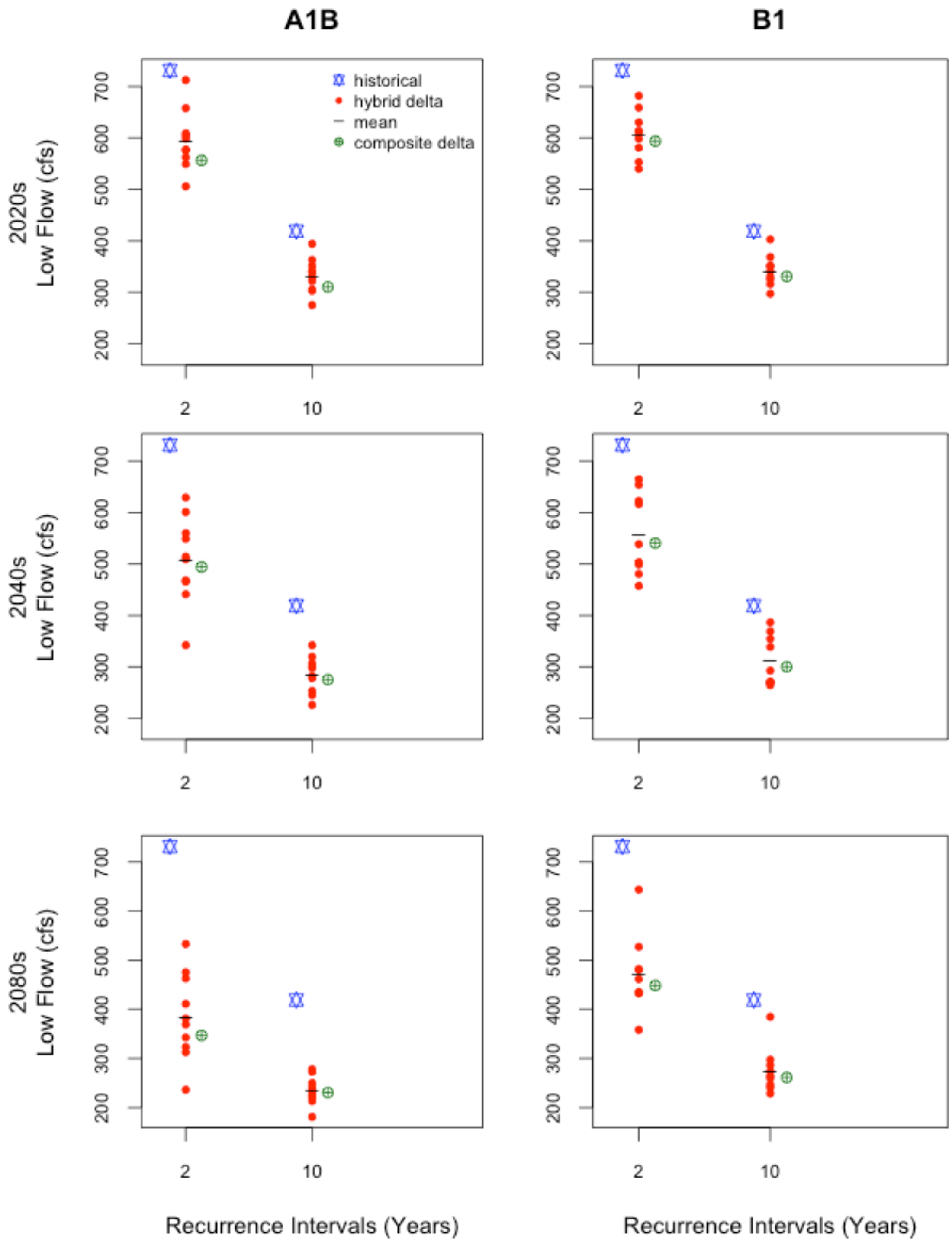

Figure 3.31 As in Figure 3.30, low flow statistics for the Diablo dam on the Skagit River.

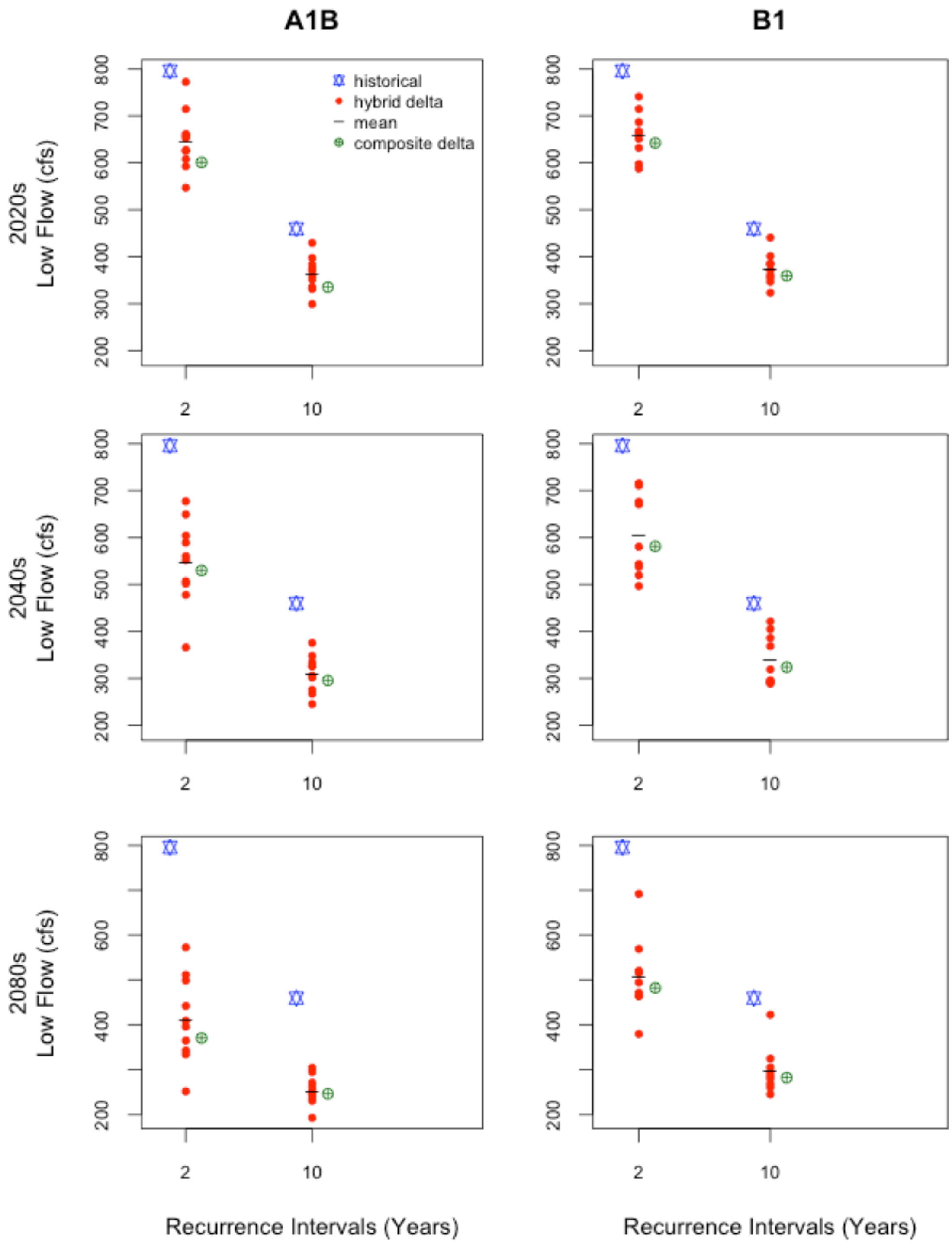

Figure 3.32 As in Figure 3.30, low flow statistics for the Gorge dam on the Skagit River.

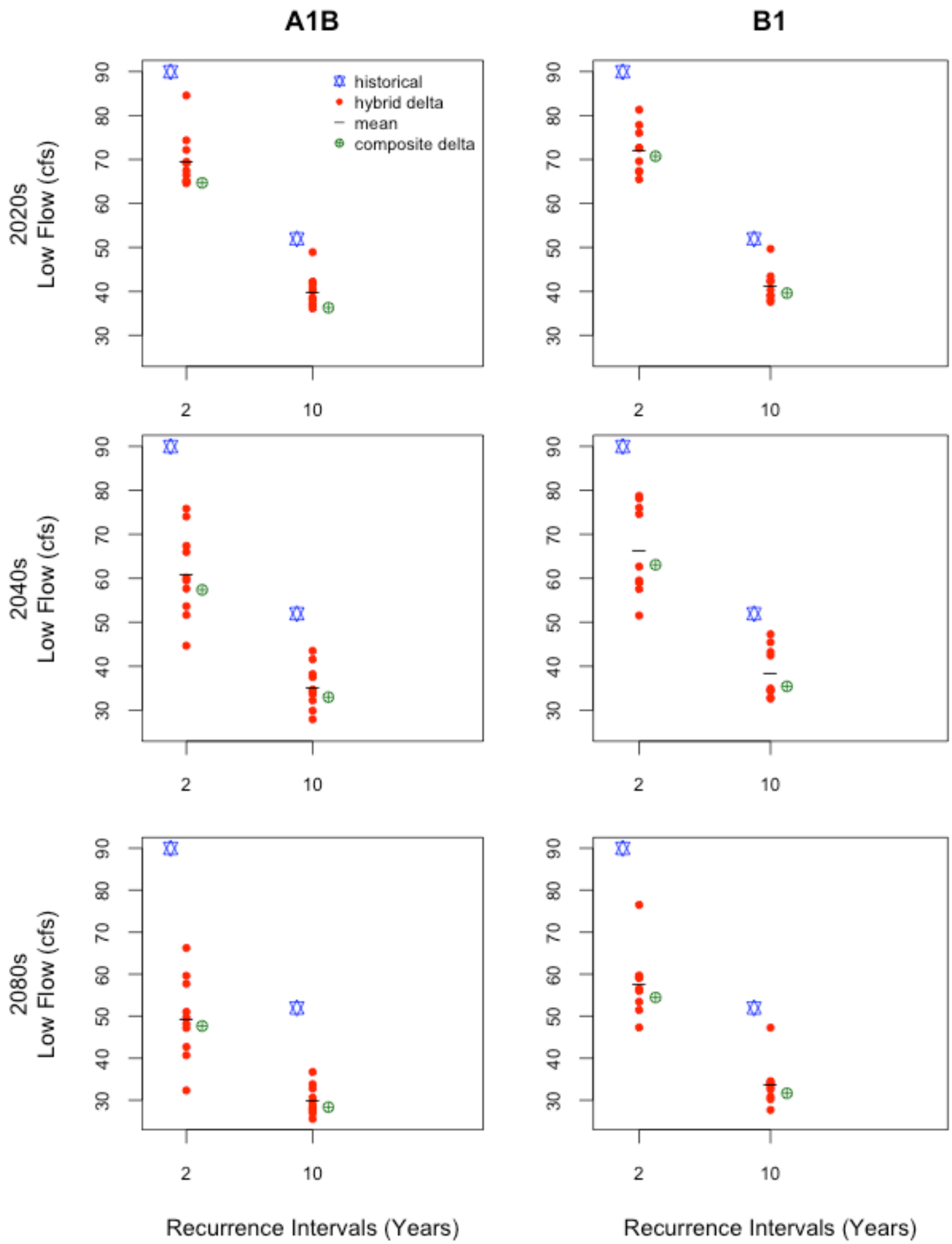

Figure 3.33 As in Figure 3.30, low flow statistics for Ruby Creek near Newhalem.

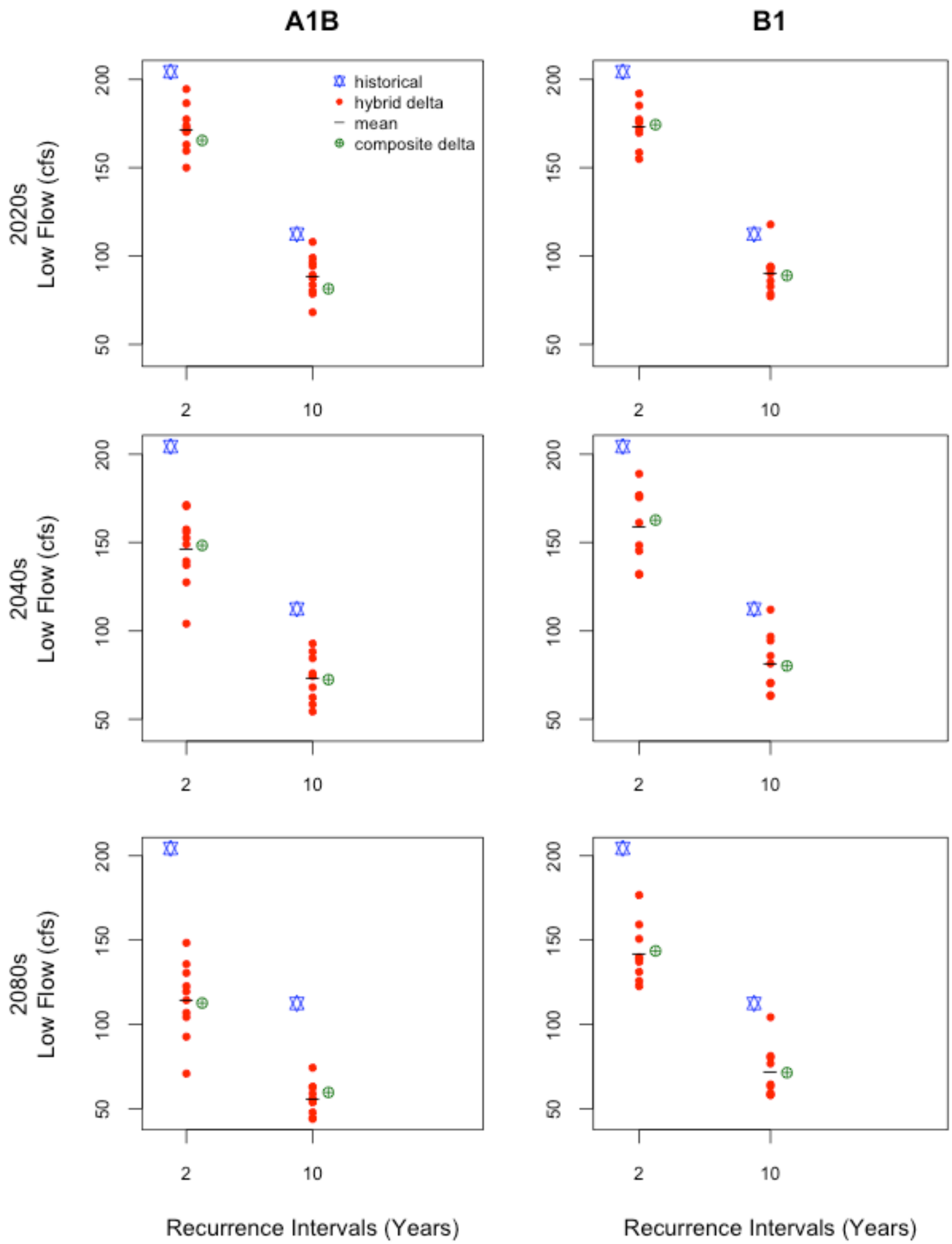

Figure 3.34 As in Figure 3.30, low flow statistics for the Cascade River near Marblemount.

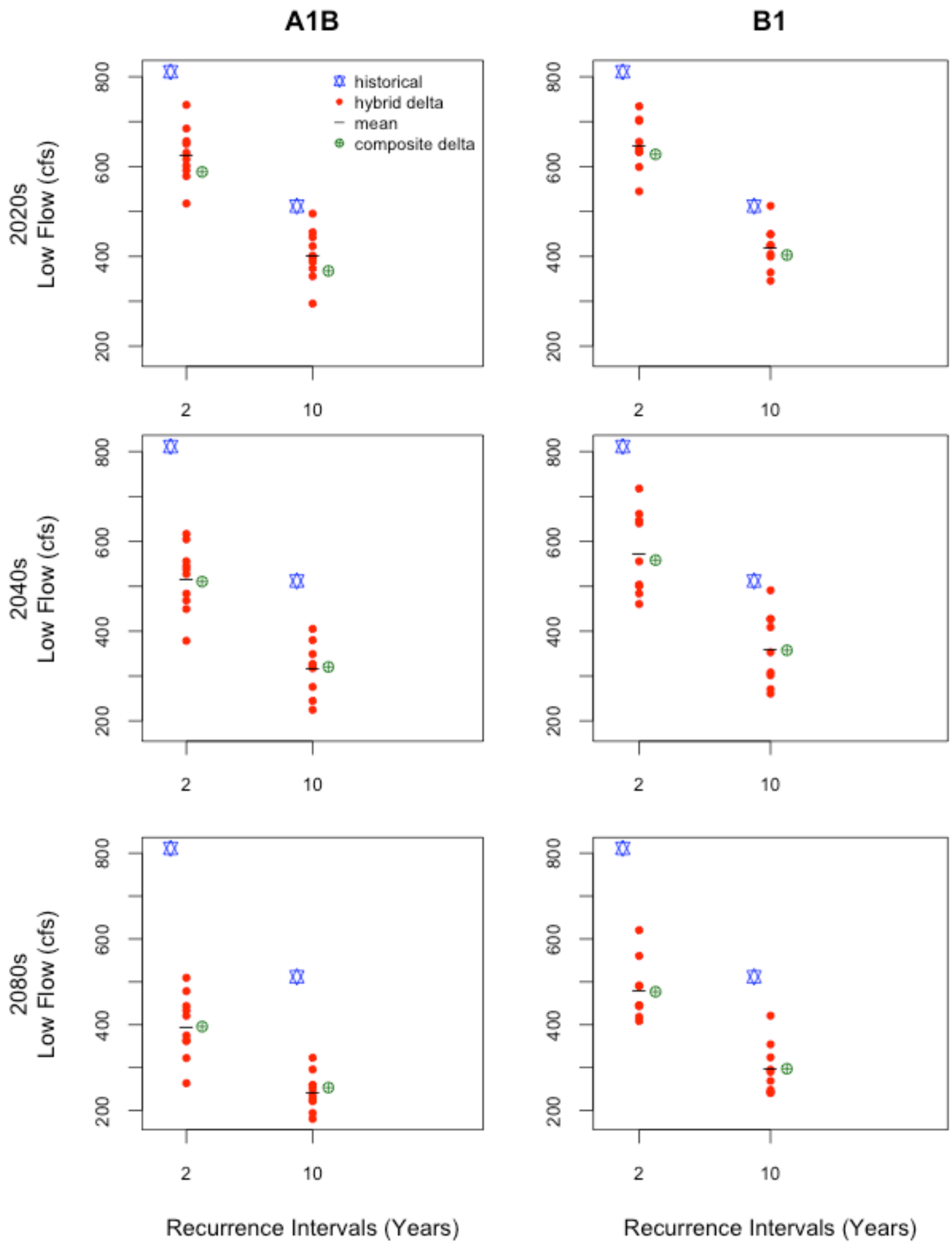

Figure 3.35 As in Figure 3.30, low flow statistics for the Sauk River near Sauk.

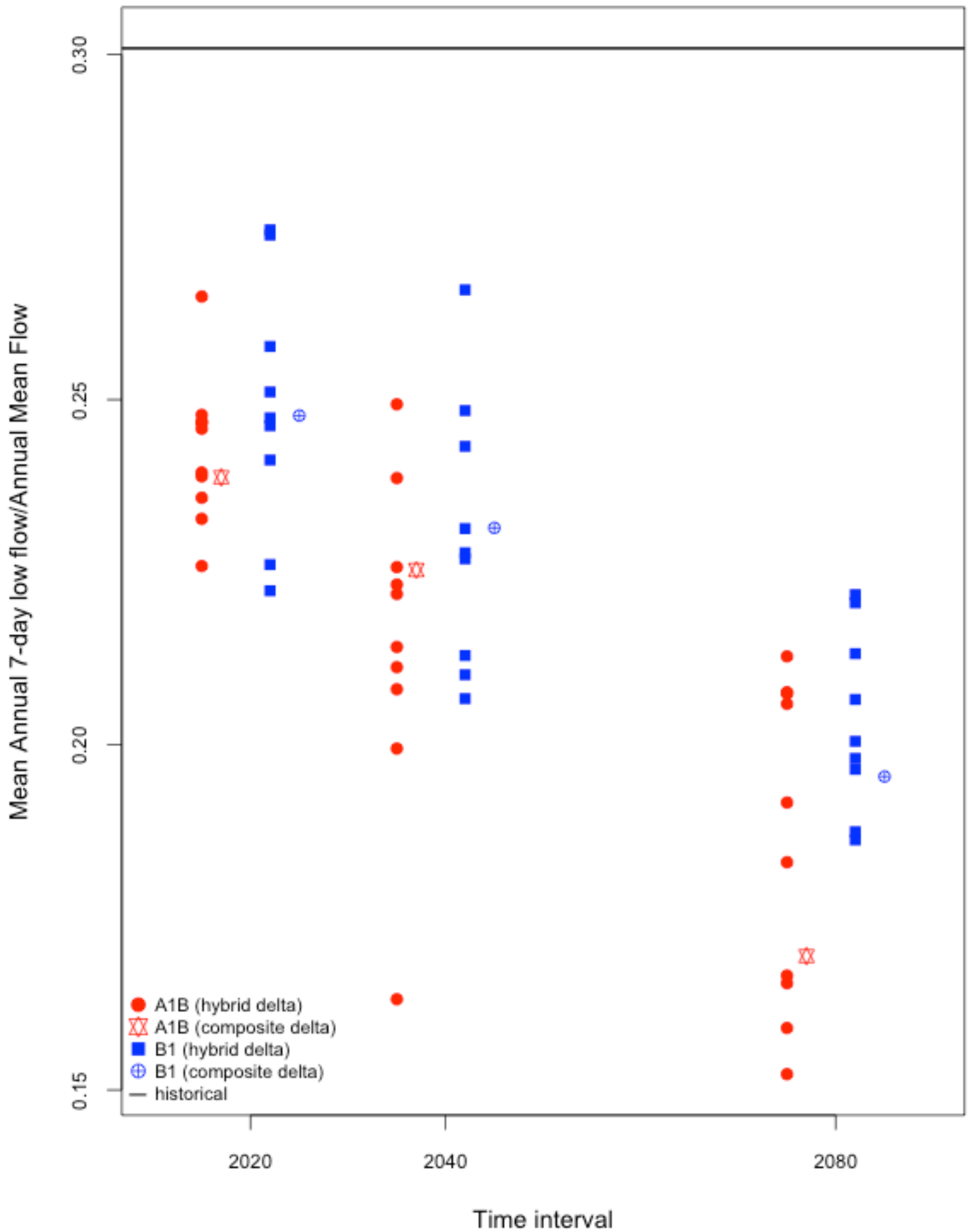

Figure 3.36 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for the Ross reservoir.

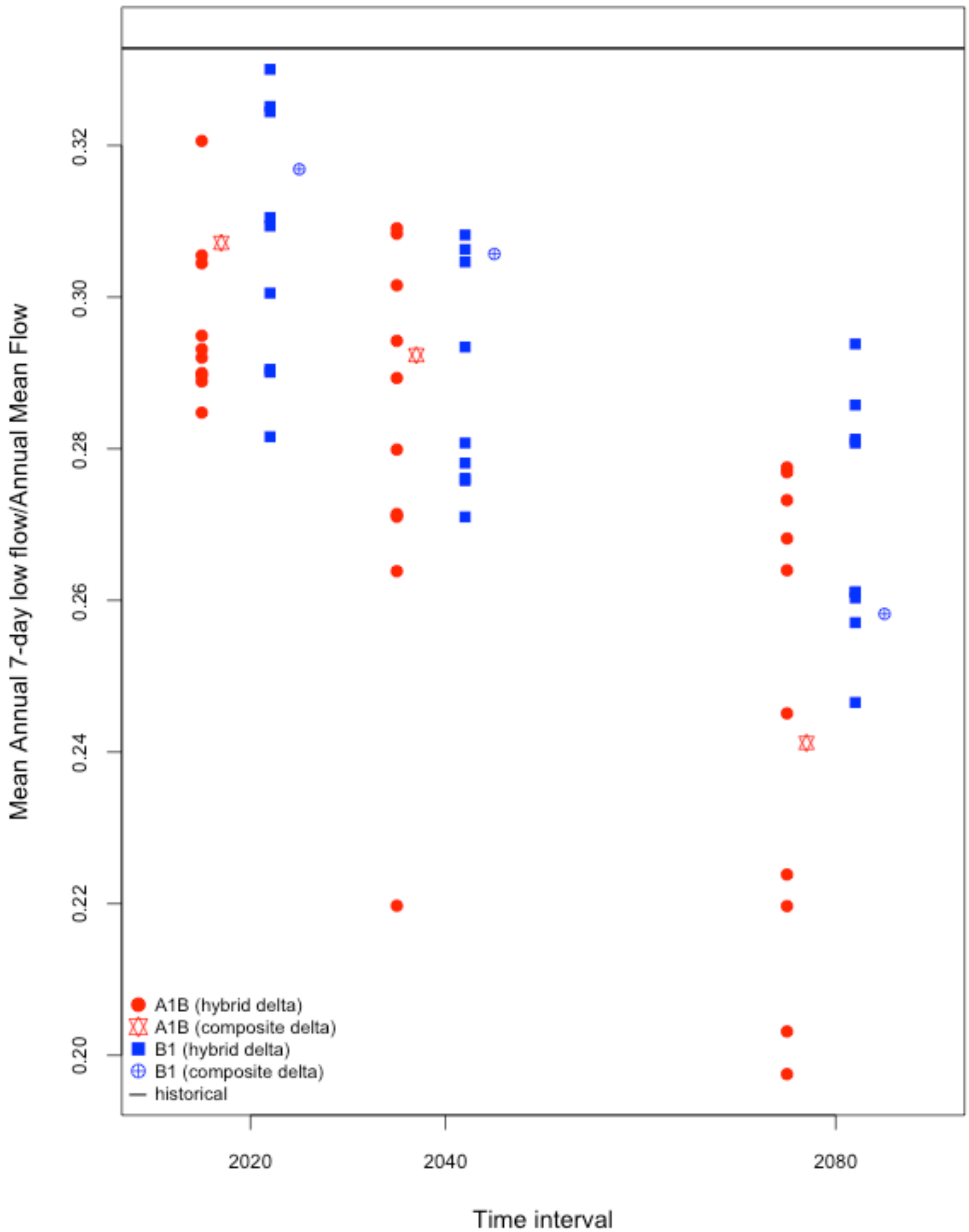

Figure 3.37 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for the Diablo dam.

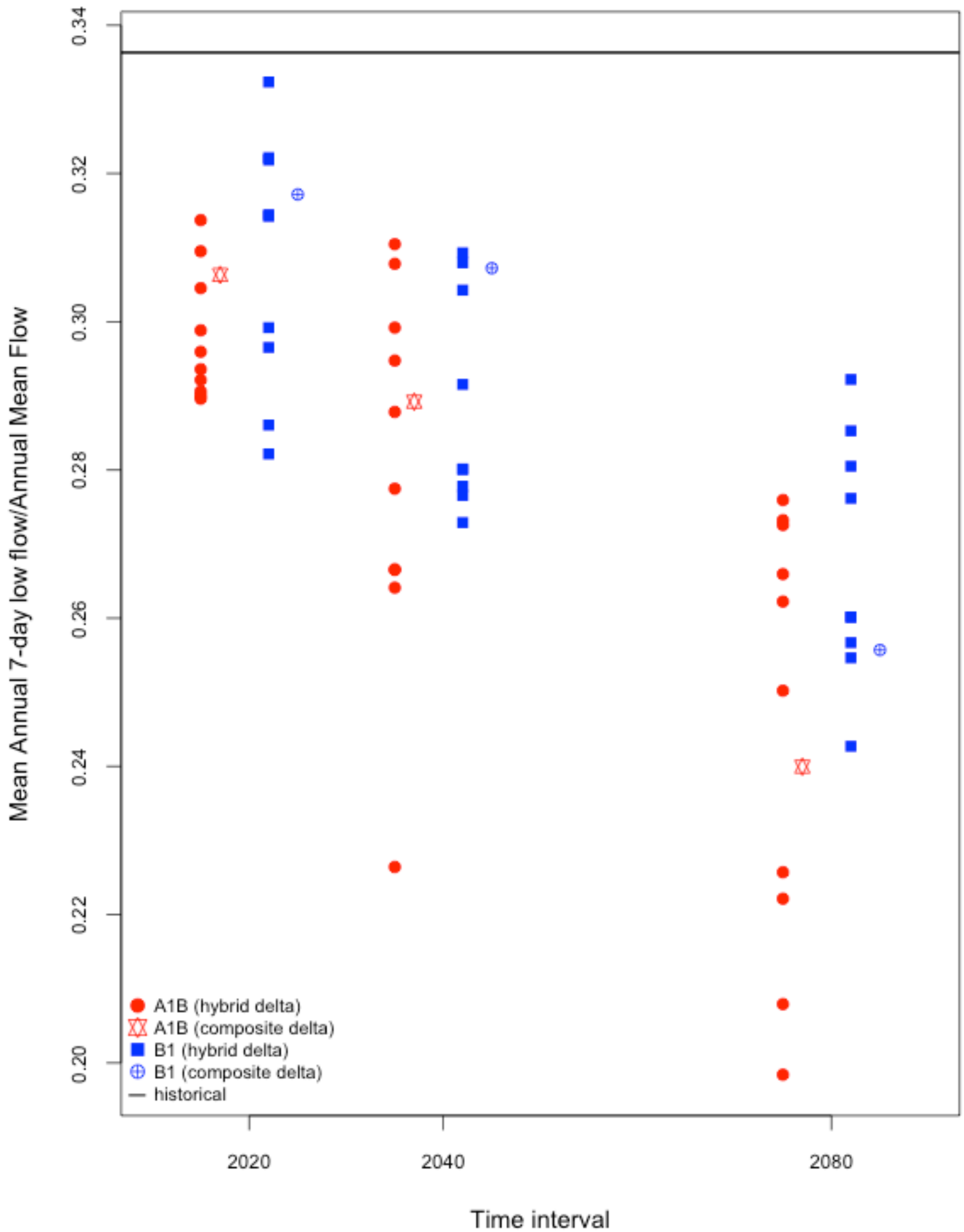

Figure 3.38 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for the Gorge dam on the Skagit River.

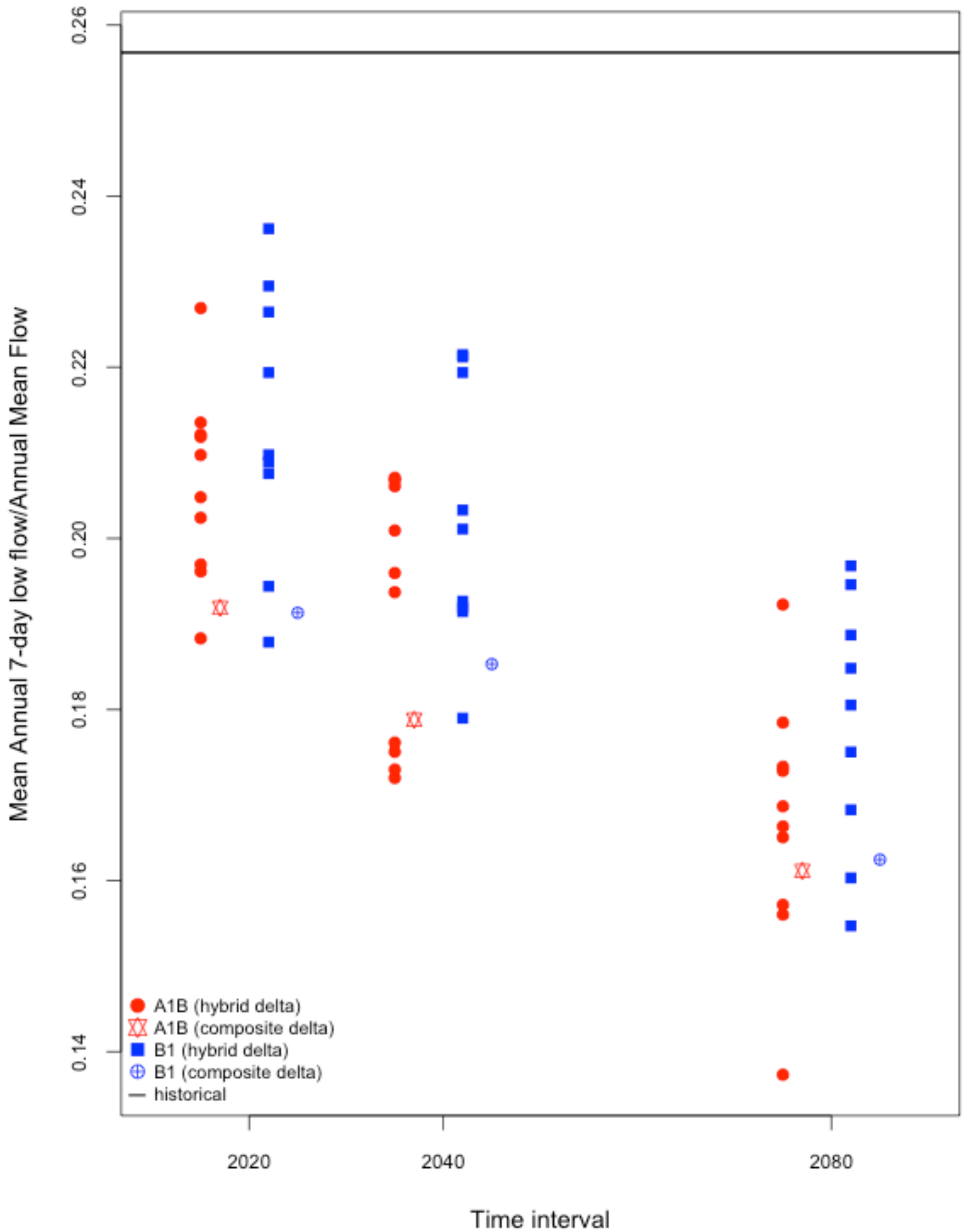

Figure 3.39 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for Ruby Creek near Newhalem.

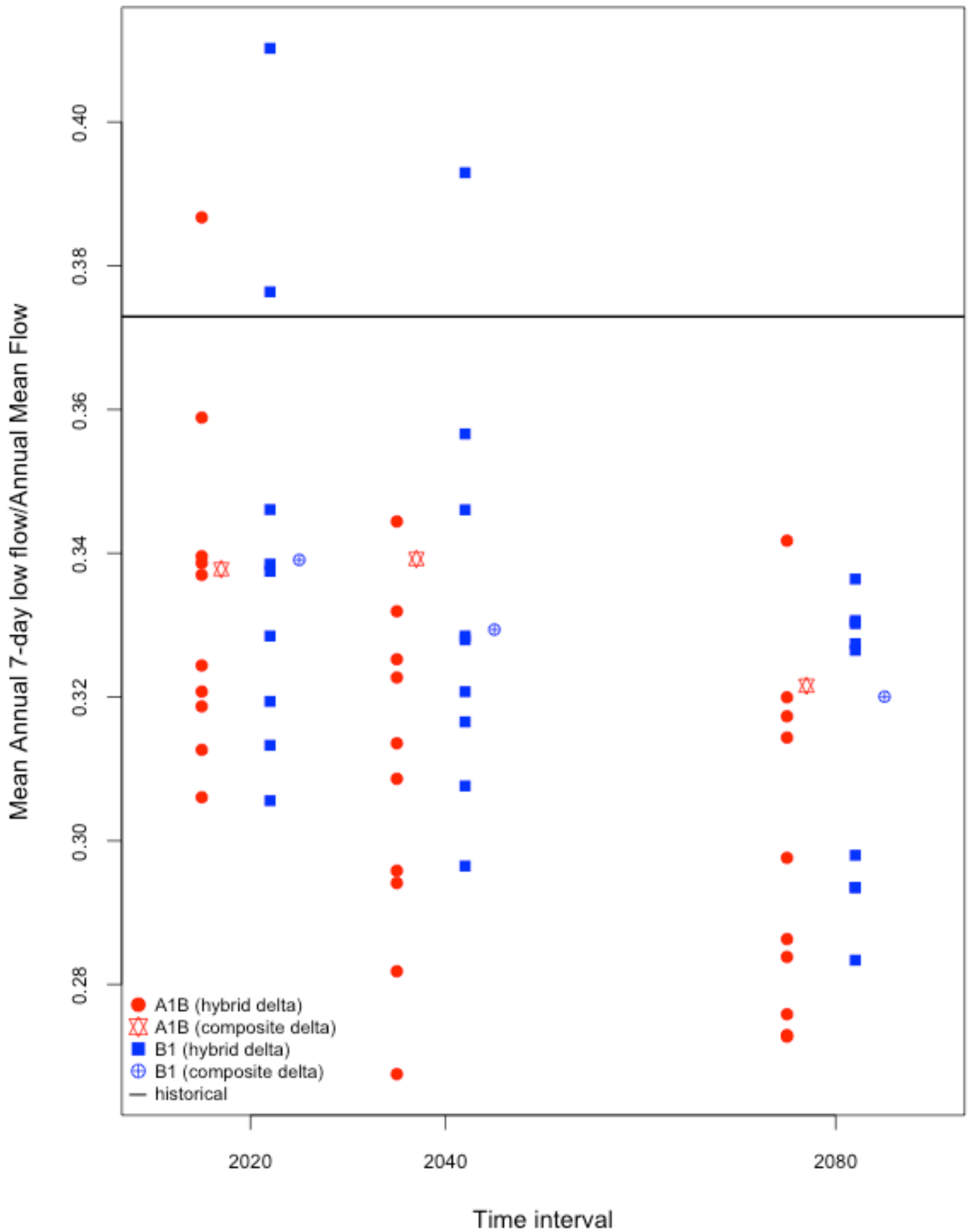

Figure 3.40 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for the Cascade River near Marblemount.

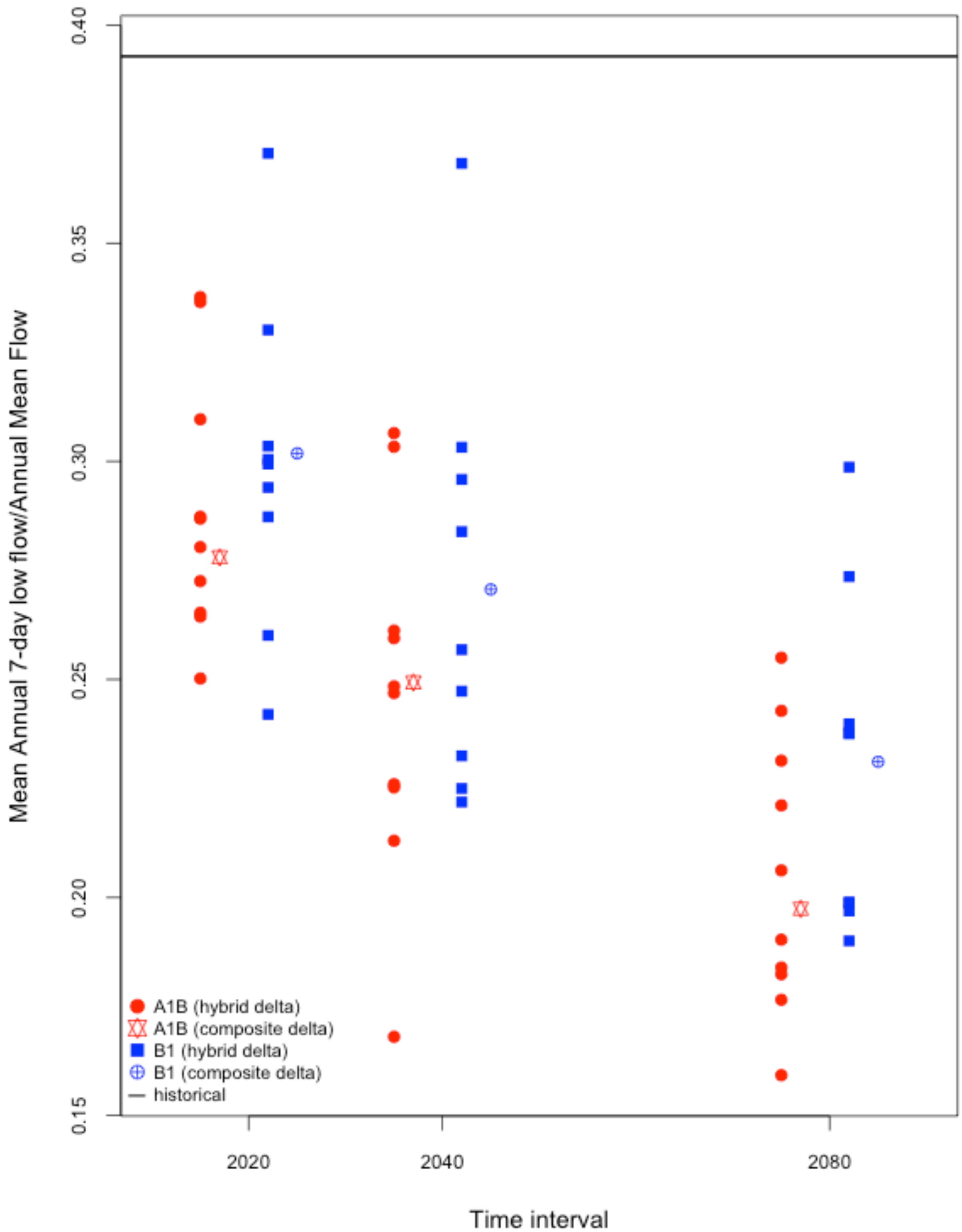

Figure 3.41 Ratio of future 7-day minimum streamflows to historical mean annual streamflows for the Sauk River near Sauk.

Appendix A: Responses to Seattle City Light's Queries About Interpretation of Results

CLIMATE IMPACTS GROUP

Climate Science in the Public Interest

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Climate Impacts Group
UNIVERSITY OF WASHINGTON

100% POST-CONSUMER RECYCLED PAPER

June 2010

To: Ron Tressler

From: CIG project team (Alan Hamlet, Se-Yeun Lee, Nathan Mantua, Eric Salathé, Amy Snover, Rick Steed, Ingrid Tohver)

The following responses were prepared to address the questions that arose from Seattle City Light's review of the report submitted by the Climate Impacts Group. Additionally, the edited report includes these responses in the text, where appropriate.

1. Under A1B, what is causing the increase in average annual inflow to Ross? (For A1B ensemble, Wing estimates 1.6% increase in median Ross Res. inflow in 2020s and 5.4% increase by 2040s.) Does it have to do with the increase in storm tracks?

   Increases in annual flow result from increases in Oct-Mar precip that exceed the changes in annual evaporation due to warming. This is consistent with a northward shift in the storm track when considering the North Cascades. These features of the changing cool season circulation are present in both GCM simulations and RCM simulations, although we have more realizations in the case of the GCM projections.

2. What causes A1B to produce higher inflow than B1? Is it because of the higher CO2 emission?

   The differences probably are not statistically meaningful and reflect different decadal and/or seasonal precipitation changes in future time periods, which are very noisy. These are not as robustly connected to greenhouse gas concentrations as temperature change.

3. Negative monthly sidestream flows were corrected by interpolating adjacent months. Is it acceptable?

   We found these were usually very small values, so how you deal with them doesn't affect outcomes very much. It's probably equally appropriate (and clearer) to just make them zero if the reservoir model can't handle negative incremental flows.

4. Monthly flow data are based on average of outputs from all climate models CIG provided. Should there be any weight on any particular model?

There is not one preferred weighting scheme. Some options are 1) weight by historical performance, 2) uniform weighting (based on the idea that models are all different versions of the same forcing), 3) use a quantile estimator (assumes extremes are less likely). It's important to note that the small sample does not span the full range of modeling uncertainties. More comprehensive analyses show a much longer tail to the distribution on the warm side, for example.

5. What drives the fluctuations in the future years? Is ENSO/PDO incorporated at all? For example, why is there a dip in annual max temp in the 2020s? Why is there a dip in the annual min temp in the 2030s?

   Unique versions of decadal and interannual variability are present in each scenario, and future changes reflect these variations from decade to decade. You see these same kinds of variations in historical records. Climate models are not equally skillful at reproducing patterns of observed variability. These variations are why it is important to include multiple realizations of climate in a future decade in your planning process. Any single model scenario is strongly influenced by decadal precipitation variability in the future time window. Temperature changes have the same problems, but the signal to noise ratio is fortunately much higher.

6. What is the explanation for the reduction in the mean daily temperature range vs. historic period?

   The WRF model has a known deficiency in simulated nighttime (minimum) temperatures, see Zhang et al (2010). This is likely due to deficiencies in the land-surface model used in WRF and is the subject of on-going research. These deficiencies result in the bias for daily temperature range and annual minimum temperatures relative to observations at SeaTac (Fig 1.8).

7. What is the correlation between observed and modeled period means/percentiles for each of the parameters? At least at Diablo and SEATAC…

   Since the simulation presented here uses a free-running global climate model, the simulated cycles of natural variability do not correspond to observed historical cycles. Thus, the time series are not expected to be well correlated. The issue of bias in WRF is treated in detail in Zhang et al (2010), Duliere et al (2010a, 2010b). These papers are available here: http://www.atmos.washington.edu/~salathe/Papers.html

Dulière, V, Y Zhang, EP Salathé 2010a: Changes in 20th century extreme temperature and precipitation over the western United States from regional climate model simulations and observations. Submitted to *Climatic Change*.

Dulière, V, Y Zhang, P Mote, EP Salathé 2010b: Extreme precipitations and temperatures over the U.S. Pacific Northwest : A comparison between observations, reanalysis data and regional models submitted to *J. Climate.* [Draft PDF]

Zhang, Y, V Dulière, P Mote, EP Salathé 2009: Evaluation of WRF and HadRM Mesoscale Climate Simulations over the United States Pacific Northwest. *J. Climate* 22:5511-5526.