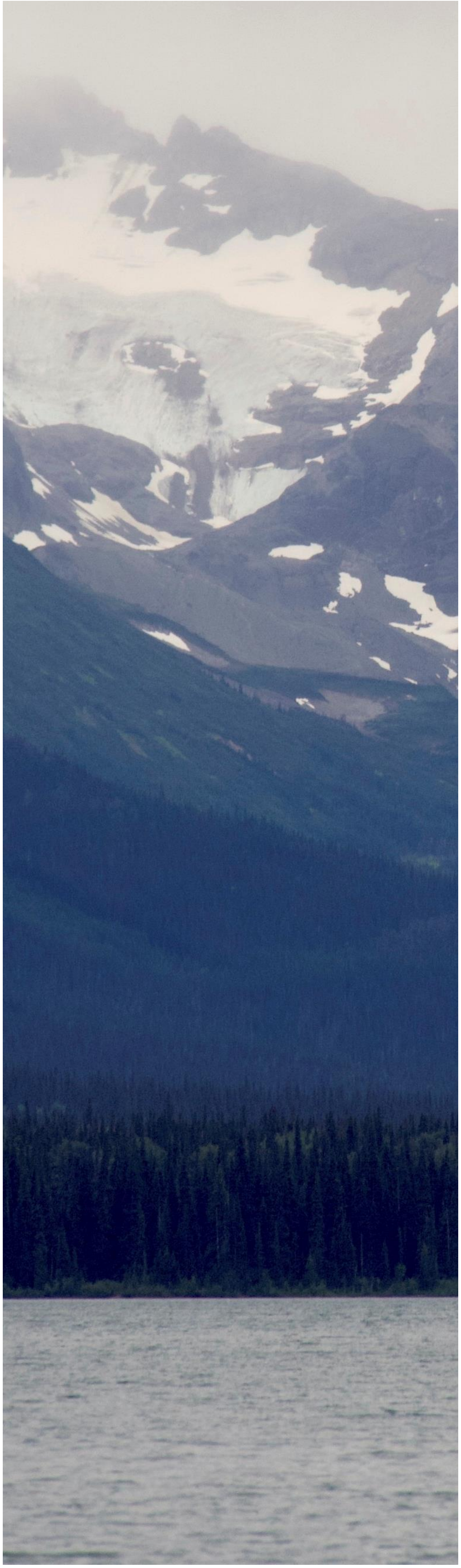

Coast Mountain College

# Future Glacier Change and Hydrologic Impacts in the Morice River Watershed

A report on behalf of the
Morice Watershed Monitoring Trust

MORICE WATERSHED
MONITORING TRUST

Matthew J. Beedle

June 6, 2022

June 6, 2022

**Future Glacier Change and Hydrologic Impacts in the Morice River Watershed**

A report on behalf of the Morice Watershed Monitoring Trust

Matthew J. Beedle, PhD
Professor of Geography, Coast Mountain College
mbeedle@coastmountaincollege.ca

## Contents

## About the Author

Matt is a Professor of Geography at Coast Mountain College in Terrace and Adjunct Professor of Geography at UNBC. His PhD research at UNBC focused on glacier change and relations to climate variability in the Cariboo Mountains. His current research investigates the impacts of a changing climate and melting glaciers on stream temperatures and salmon in sub drainage of the Kitsumkalum, Meziadin and Morice Rivers.

## Introduction

This report presents modeled changes in glaciers and seasonal snowpack to 2100 for subdrainages of the upper Morice River region (Fig. 1). These projections are then used to forecast changes in discharge and stream temperature. This work is the final of three reports. The first report, Morice River Watershed Morphometry (Work Point 1), assessed the topographic and landcover characteristics of each subdrainage of the upper Morice River region (Beedle, 2020). The second report, Morice River Watershed Glacier Inventory (Work Point 2), reconstructed recent glacier change, mapped current glacier extent, and detailed hydrologic impacts of glacier change since the late-20$^{th}$ century (Beedle, 2021). All together, these three reports aim to detail the dominant landscape and cryospheric determinants of water quality and quantity in the upper Morice River region from the late-20$^{th}$ century, through today and to forecast conditions to 2100.

Glaciers and seasonal snowpack are declining globally (e.g., Huss et al., 2017) due to enhanced summer melt but also reductions in the snowfall fraction in winter, both of which are driven by increased temperatures (e.g., Barnett, Adam and Lettenmaier, 2005; Larsen et al., 2015; and Li et al., 2020). Shifts in atmospheric circulation patterns drive changes in temperature and precipitation on decadal time scales resulting in variable melt rates within the broad pattern of a global glacier decline (e.g., Menounos et al., 2019). This loss of snow and ice has multiple impacts on downstream aquatic systems, including 1) increased summer stream temperatures (e.g., Mantua, Tohver, and Hamlet, 2010; and Fellman et al., 2014), 2) reductions in streamflow, particularly in the late-summer dry season (e.g., Marshall et al., 2011; Frans et al., 2018; and Moore et al., 2020), and 3) water quality changes such as reductions in turbidity, depletion of dissolved oxygen and higher concentrations of dissolved organic carbon and nitrogen (e.g., Hood and Berner, 2009; Fellman et al., 2015; and Barouillet et al., 2019). These impacts combine to dramatically alter downstream freshwater ecosystems and the marine environment, with the potential for marked impacts on Pacific salmon (e.g., O'Neel et al., 2015; Milner et al., 2017; and Pitman et al., 2020). Models of 21$^{st}$ century climate show continued increases in temperature and cryosphere melt, further reductions in the snowfall fraction along with a subtle increase in total precipitation, and increased stochasticity of stream discharge (e.g., Shanley et al., 2015). Previous work modeled 21$^{st}$ century glacier melt in western Canada, forecasting a 70%

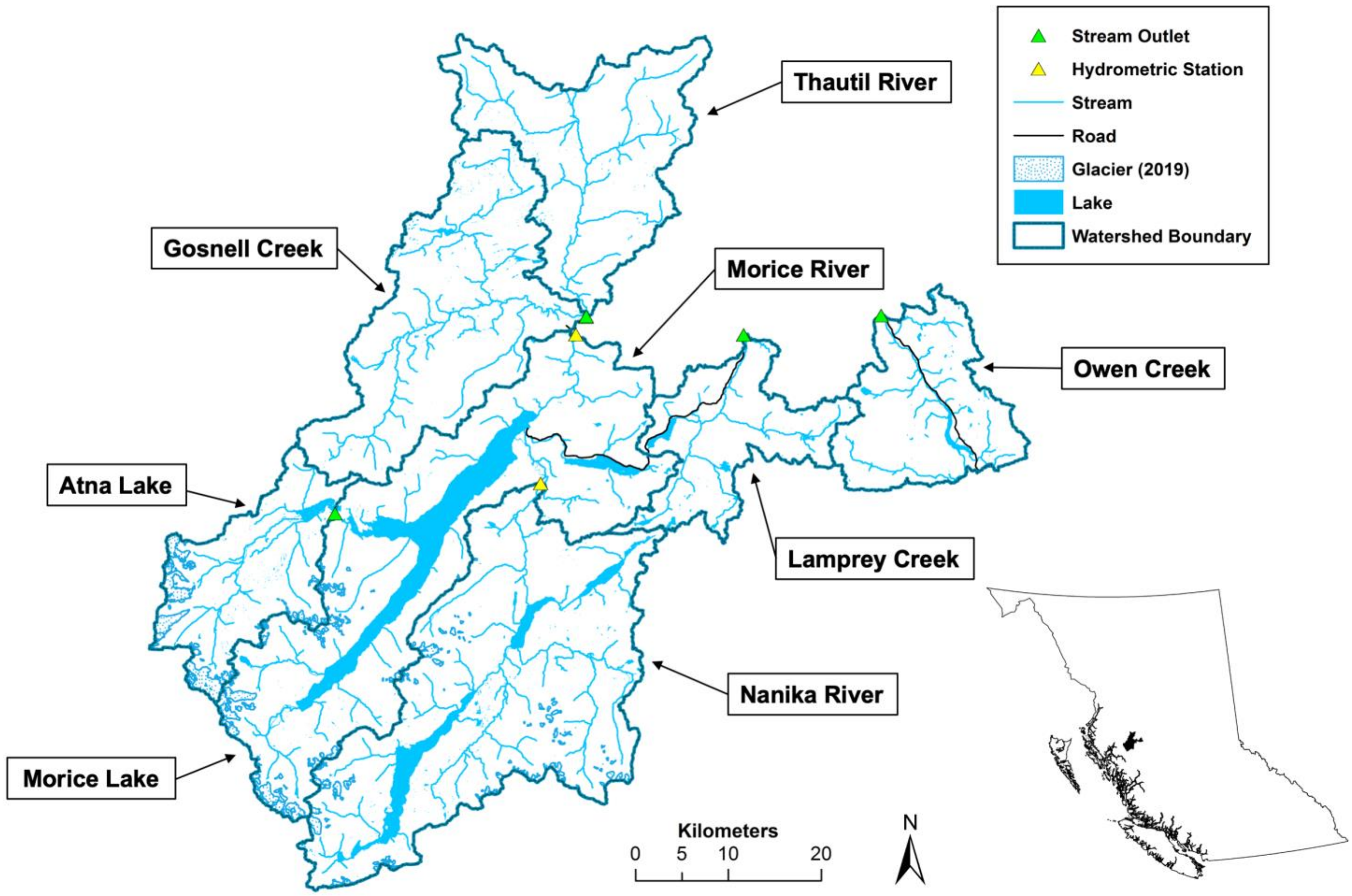


**Figure 1: Upper Morice River watersheds and 2019 glacier cover.** Location of watersheds, respective hydrometric stations, or stream outlets and 2019 glacier cover.

reduction in glacier volume by 2100, with little glacier cover remaining in the Interior and Rocky Mountain regions, but with some glaciers remaining in a reduced state in northwest BC (Clarke et al., 2015). This finding of some glaciers remaining in northwest BC, however, is dominated by the large icefields of the northern Coast Mountains and is not necessarily reflective of lower-elevation watersheds in the region with less present-day glacier coverage. In this study, we model 21st century glacier and seasonal snowpack change, and the hydrologic impacts for subdrainages of concern in the upper Morice River region, particularly those that feed Nanika River and Morice Lake, critical salmon spawning and rearing habitat within the Skeena River system of northwest BC.

We are defining the upper Morice River area as inclusive of the eight basins in Figure 1. The Nanika River, Morice Lake and Atna Lake watersheds combine to form what we are referring to as the Morice River watershed. The Atna Lake and Nanika River sub-drainages are investigated separately; all remaining surface area within the Morice River watershed is referred to here as the Morice Lake watershed, and is comprised of shorter, smaller basins that drain more directly to Morice Lake. The Gosnell Creek, Thautil River, Lamprey Creek and Owen Creek watersheds flow into Morice River below the Morice River hydrometric station (Fig. 1).

*Topographic and Landcover Characteristics of Subdrainages*

Two previous reports have detailed the topographic and landcover characteristics (Beedle, 2020), and recent glacier change and current glacier inventory (Beedle, 2021) of the upper Morice River area, yielding unique characteristics for subdrainages of interest. The Atna Lake watershed is unique with the highest mean elevation (1,325m) and the most relative glacier cover (10.4%). The total glacier surface area of the Atna Lake watershed (28.42km$^2$) represents 41% of the total glacier area that feeds Morice River. The Morice Lake and Nanika River basins have mean elevations slightly lower than that of Atna Lake and have total glacier surface areas of 23.74km$^2$ (2.7% relative glacier cover) and 16.99km$^2$ (2.0% relative glacier cover) respectively. These watersheds represent the most important basins for glacier and snowpack meltwater contributions to the wider Morice River system. The fractional lake cover for both the Morice River and Nanika River watersheds (8.3 and 5.7% respectively) causes longer water residence times and subsequent warming of downstream temperatures, as well as sediment load from glacier erosion to settle, and turbidity to decrease. The Lamprey and Owen creek watersheds are noteworthy for their lower average elevations (985 and 1,007m respectively) and the large surface area that has seen marked landcover change, with 50.8 and 19.8% having been clearcut in the last ~50 years. The final two subdrainages, Gosnell Creek and Thautil River, have average elevations of 1,151 and 1,254m respectively, but no glacierized area to buffer streamflows in late summer.

## Methods

### *Future Temperature and Precipitation*

We use ClimateNA to determine changes in temperature, precipitation, and snowfall to 2100 (Wang et al., 2016; http://climatena.ca). ClimateNA is a freely available, standalone application that extracts gridded climate data from the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al., 2008) to individual points based on physiographic characteristics (e.g., location, elevation, coastal proximity). For future climate, ClimateNA relies on the Coupled Model Intercomparison Project phase 6 (CMIP6) data as used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. Future temperature, precipitation and snowfall data presented here use an ensemble of 13 CMIP6 general circulation models (Mahony et al., 2021). Future climate data presented here for Morice River area subdrainages is based on the geographic mid-point and average elevation of each subdrainage (Beedle, 2020).

The current version of the glacier model used here (Open Global Glacier Model, OGGM; discussed below) uses CMIP5 future climate scenarios (Representative Concentration Pathways, RCPs) based on the IPCC Fifth Assessment Report. Whereas the newest version of ClimateNA (used here) uses CMIP6 future climate scenarios based on Shared Socioeconomic Pathways (SSPs) (Table 1). The SSPs are a more nuanced approach to determining possible future climate scenarios and thus took longer to be developed than the RCPs. Broad adoption of CMIP6 within the modeling community is happening currently but has not yet been incorporated into the OGGM. While there are differences between the SSPs and their similar RCPs, the ranges of forecasted global warming are similar (Table 1). Additionally, it is important to note that uncertainty in modeled future climates and cryospheric responses are dependent primarily on the differences between the RCPs or SSPs (e.g., RCP2.6 versus RCP8.5), and not on the evolution of the pathways themselves (e.g., RCP2.6 versus SSP126). While increasing detail within SSPs will improve forecasting of potential future climates, determining which pathway humanity follows has the most important impact on model uncertainty (e.g., Marzeion et al., 2020). Throughout this report we reference the specific SSP or RCP to indicate a result for a particular climate scenario. Results for modeled $21^{st}$-century temperature, precipitation and snowpack are based on ClimateNA and thus refer to SSPs, whereas $21^{st}$-century glacier recession and stream temperatures are based on OGGM

| | Global Warming Increase by 2081-2100 (°C) |
|---|---|
| RCP | "Likely Range" (IPCC AR5) |
| RCP2.6 | 0.3-1.7 |
| RCP4.5 | 1.1-2.6 |
| RCP6.0 | 1.4-3.1 |
| RCP8.5 | 2.6-4.8 |

| | Global Warming Increase by 2081-2100 (°C) |
|---|---|
| SSP | "Very likely range" (IPCC AR6) |
| SSP1-2.6 | 1.0-1.8 |
| SSP2-4.5 | 1.3-2.4 |
| SSP3-7.0 | 2.1-3.5 |
| SSP5-8.5 | 3.3-5.7 |

**Table 1: Future climate scenarios – Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs).** Different climate scenarios used in this report include four RCPs used in the IPCC AR5 and four SSPs used in the IPCC AR6. Modeled glacier change using the OGGM is based on the four RCPs, while modeled temperature, precipitation, and snowfall from ClimateNA use the four SSPs. The projected ranges of temperature warming by the 20-year period 2081-2100 are similar but with some important distinctions. For brevity, the text labels the four SSPs as SSP126, SSP245, SSP370, and SSP585, and four RCPs as RCP26, RCP45, RCP60 and RCP85.

and refer to RCPs. Refer to Table 1 for clarification; plots throughout use a common color scheme (blue, green, yellow, orange) to denote the progression from less to more future warming respectively, depending on climate scenario.

*Snowpack Forecast*

We forecast changes in maximum seasonal snowpack based on watershed hypsometry (area-altitude distribution), a linear snow accumulation gradient based on regional snow pillows and manual snow courses, and a projected increase in the minimum snowline elevation based on ClimateNA modeled winter temperature (e.g., Shea et al., 2021). The hypsometry of each sub-drainage of interest is derived from the B.C. Terrain Resource Information Management (TRIM) digital elevation model (DEM), a B.C. Government product (www2.gov.bc.ca/gov/content/data/geographic-data-services/), and sub-drainage extents as determined in Work Point 1 (Watershed Morphometry) of the larger project (Beedle, 2020). The hypsometry of each watershed presented here is taken as the summed surface area within 50m elevation bands. It is presented here in plots of normalized surface area versus elevation (Fig. 2).

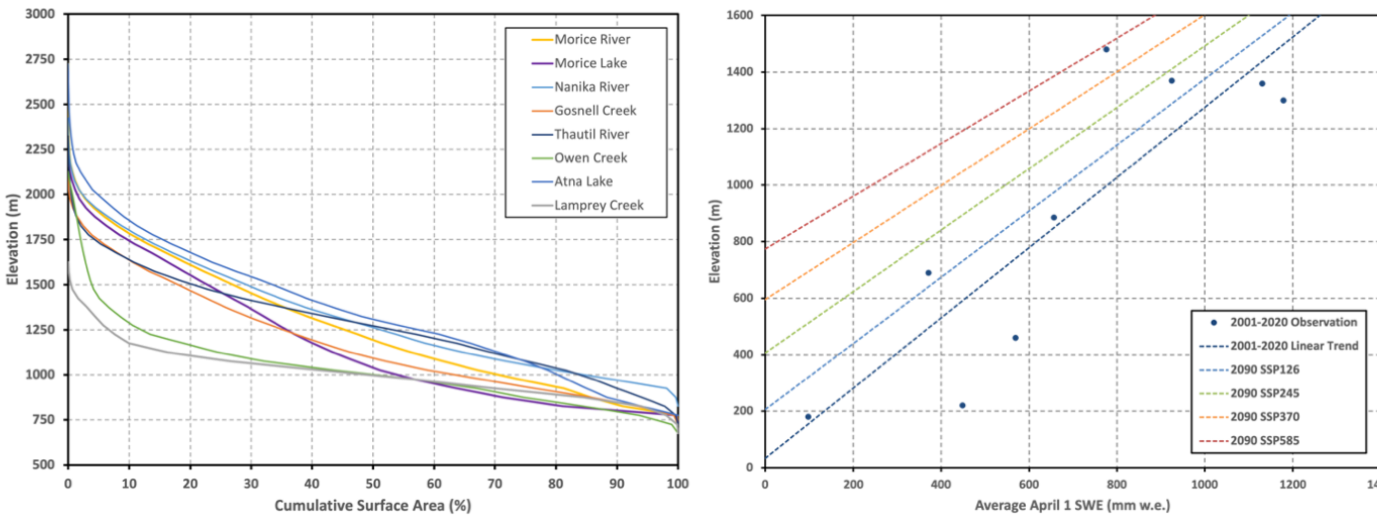


**Figure 2: Watershed hypsometry and linear trends of April 1 snowpack.** Watershed hypsometry (area-altitude distribution) on the left. Linear trends of April 1 snowpack with elevation used to forecast changes to the period 2081-2100 (2090) on the right. Increase in the snow line (y-intercept) for different climate scenarios is determined using modeled (ClimateNA) increase of winter (NDJFM) temperature and the normal lapse rate. Projected April 1 snowpack is integrated with watershed surface areas to estimate changes in basin-wide maximum snowpack. Note that the extents of the y-axes do not match.

To determine average present-day snow accumulation with elevation, we use the average for the period 2001-2021 of total April 1 snow water equivalent (SWE) for nine sites within the wider region (Fig 3). This data is from the Government of BC Snow Survey Data (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/snow-survey-data), includes data from both automated snow weather stations and manual snow survey sites, and is collected by various agencies (Table 2). The nine sites were selected based on proximity to the upper Morice River area but also as they have a similar precipitation regime and represent a range of elevations. Snow survey sites were included as far north as Ningunsaw Pass to achieve a more statistically robust sample, an expanded elevation range and to coordinate with similar work being done for Meziadin Lake watersheds. Additional sites within the region were excluded due to discontinuous data (e.g., Granduc Mine) or a markedly drier climate (e.g., Hudson Bay Mountain). April 1 is a target date for manual snow surveys to assess maximum snowpack in the mountains and is used here to represent average timing of maximum snowpack. Manual surveys are not always completed on April 1, and we omitted snowpack data for a year if it was collected more than five days before or after this date. We chose the period 2001-2021 to reflect average, current maximum snowpack for the region.

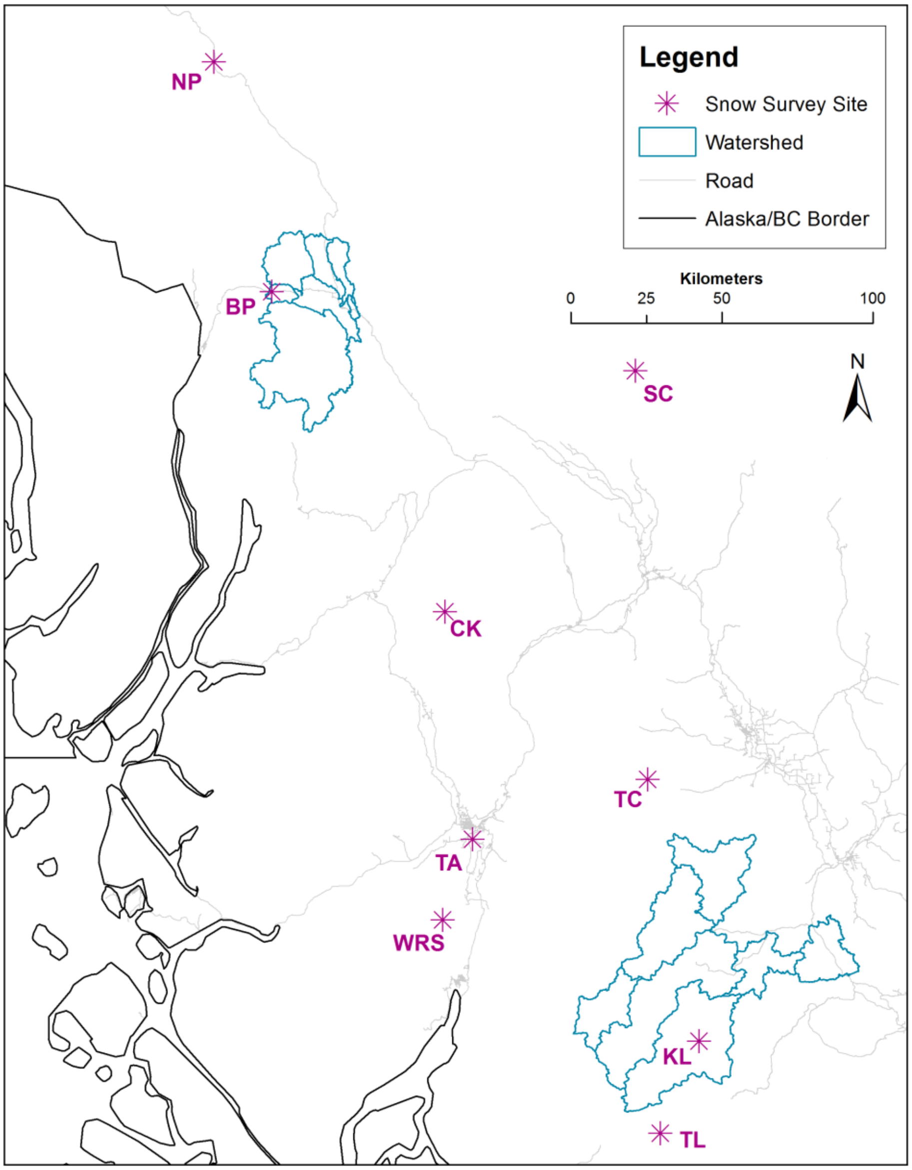


**Figure 3: Snow survey locations.** Regional snow survey sites shown here with respective abbreviations that match the site names in Table 2. Watersheds are shown in blue. The upper Morice River area watersheds are those to the south, while the watersheds to the north are those of the Meziadin Lake area – watersheds where similar work is being undertaken.

Previous work has shown that higher elevation snowpacks are less sensitive to climate change than those at lower elevations, with snow lines increasing in elevation with rising temperatures and high elevation snowpacks staying similar or even increasing with increased precipitation in a warming climate (e.g., Sproles et al., 2013; Harder et al., 2015). As such, to simulate future basin-wide snow

| Site Name | Site ID | Station Type | Latitude | Longitude | Elevation (m) | Avg. April 1 SWE (mm w.e.) |
|---|---|---|---|---|---|---|
| Terrace Airport | 4B13A | Manual Snow Survey Site | 54.4745 | -128.5761 | 180 | 97 |
| Wedeene River South | 3C07 | Manual Snow Survey Site | 54.2350 | -128.7295 | 220 | 449 |
| Bear Pass | 4B11A | Manual Snow Survey Site | 56.1017 | -129.6269 | 460 | 569 |
| Ningunsaw Pass | 4B10 | Manual Snow Survey Site | 56.7833 | -129.9529 | 690 | 371 |
| Cedar-Kiteen | 4B18P | Automated Snow Weather Station | 55.1520 | -128.7110 | 885 | 657 |
| Tahtsa Lake | 1B02P | Manual Snow Survey Site | 53.5931 | -127.6439 | 1300 | 1179 |
| Tsai Creek | 4B17P | Automated Snow Weather Station | 54.6459 | -127.6743 | 1360 | 1130 |
| Kidprice Lake | 4B01 | Manual Snow Survey Site | 53.8642 | -127.4406 | 1370 | 925 |
| Shedin Creek | 4B16P | Automated Snow Weather Station | 55.8617 | -127.6984 | 1480 | 776 |

**Table 2: Details of snow survey sites.** Nine snow survey sites used in this study organized by elevation from lowest to highest. Average April 1 SWE is for the period 2001-2021.

accumulation for subdrainages of interest, we shift the intercept (zero snow accumulation) of the snowpack gradient upwards with respect to modeled winter (NDJFM) temperature from ClimateNA based on the normal lapse rate (-0.0065°C/m). High-elevation snowpack is kept constant, reflecting previously observed and modeled constancy of snowpack at the highest elevations, and resulting in a steeper snow accumulation gradient with a warmer climate. Changes in maximum (April 1) snowpack are compared from one basin to another, and through time for each basin, by integrating these modified snowpack gradients with each basin's hypsometry (Fig. 2).

*Glacier Model*

To model glacier change from present day to 2100, we use the Open Global Glacier Model (OGGM; Maussion et al., 2019). The OGGM is an open source, modular model framework that simulates past and future glacier extents. Initial conditions of catchment areas, glacier flowlines and ice thickness are estimated based on glacier extent from the Randolph Glacier Inventory (RGI; Pfeffer et al., 2014), local topography that is automatically chosen for the region from the most suitable data source (e.g., Advanced Spaceborne Thermal Emission and Reflection Radiometer, ASTER or Shuttle Radar Topography Mission, SRTM), estimated glacier mass balance based on a temperature index model (Marzeion et al., 2012), and gridded temperature and precipitation observations (CRU TS4.01; Harris et al., 2014). A dynamical flowline model is used in concert with gridded monthly temperature and precipitation data from CMIP5 (Coupled Model Intercomparison Project phase 5, Taylor et al., 2012) to simulate future glacier area and volume to 2100. OGGM projections of future glacier extent are done for the four greenhouse gas concentration scenarios used in the IPCC Fifth Assessment Report (AR5), known as RCPs, and labeled numerically based on projected radiative forcing values in 2100 (RCP2.6, 4.5, 6.0 and 8.5). Additional, detailed descriptions of the OGGM can be found in Maussion et al., (2019), and in other studies that have applied the OGGM similarly (e.g., Khadka et al., 2020).

*Streamflow*

We present first-order estimates of changes to Nanika River and Morice River July – September (JAS) discharge as glaciers recede through the 21st century. This late-summer/early-fall period is assumed to be the duration when glacial melt and downstream meltwater contributions occur, when seasonal snowpack has largely melted, and before the end of the glacier melt season (e.g., Fountain and Tangborn, 1985). Historical discharge data for the Nanika and Morice rivers is from the Environment and Climate Change Canada Historical Hydrometric Data web site (https://wateroffice.ec.gc.ca/report/historical_e.html?stn=08DA005). We apply annual mass balance ($b_a$) from the closest benchmark glacier (Lemon Creek Glacier, AK; McNeil et al., 2019) to determine loss of water storage held in glaciers and contributions of meltwater to Nanika and Morice river discharge. Annual glacier mass balance provides an estimate of meltwater from glaciers independent of contributions from seasonal snow (e.g., Lambrecht and Mayer, 2009). We present glacial contributions to Nanika and Morice river discharge at present day (2019 glacial extent), and for mid-century (2050) and end-of-century (2100) for four climate scenarios based on modeled reductions in glacier surface area from the OGGM. Contributions to discharge from glacier melt integrate changing glacier surface area with surface mass balance. We present relative glacier contributions to discharge for three scenarios: 1) low melt/higher discharge, which uses average $b_a$ and discharge for the years 2001, 2002, 2007 and 2011, 2) average melt and discharge, which uses average $b_a$ and discharge for the years 2009, 2010 and 2017, and 3) maximum melt/lowest discharge, which uses average $b_a$ and discharge for the years 2018 and 2019. These periods of time are taken as representative of current conditions and the meteorological variability likely to occur in the coming decades. Refer to the Work Point 2 report for further discussion of historical Nanika and Morice river discharge and contributions from glacier meltwater (Beedle, 2021).

*Stream Temperature Model*

We model present-day maximum weekly average stream temperature (MWAT) and forecast future MWAT at each hydrometric station or stream outlet associated with Morice Lake region subdrainages using a multiple regression model introduced by Moore and others (2013) and applied in other stream temperature studies in British Columbia (e.g., Parkinson et al., 2016). Present-day MWAT is modeled as:

$$MWAT = 7.91 + 0.484T_a + 1.19\log(A) - 0.00306Z_m - 9.43\sqrt{f_g} + 17.5\sqrt{f_l} - 0.05296S - 0.719k_2 \qquad \text{(Eq. 1)}$$

where $T_a$ is the 2001-2021 average July-August air temperature (°C), $A$ is watershed surface area (km$^2$), $Z_m$ is mean watershed elevation in meters, $f_g$ is fractional glacier coverage of the watershed, $f_l$ is fractional lake coverage of the watershed, $S$ is channel gradient at the monitoring station (Fig. 1), and $k_2$ is an index of the magnitude of the mean annual flood. The non-linear relationship between fractional glacier cover and stream temperature ($-9.43\sqrt{fg}$), and the linear increase in stream temperature of 0.7°C for one degree increase in air temperature were derived empirically by Moore et al. (2013) from 418 stations across British Columbia. For basins without discharge measurements, mean annual flood is taken as the average maximum freshet discharge for the period 2000-2019 for Morice and Nanika rivers, which are monitored as part of Environment Canada's hydrometric data network (https://wateroffice.ec.gc.ca/report/historical_e.html?stn=08DA005). Applying Morice and Nanika river discharge data to the neighboring watersheds should capture climatic similarities, but also may result in MWAT estimates that are biased given that Morice and Nanika rivers have much larger basins, higher elevations and glacierization. Previous work has found the model to have an error of ±2.1°C (Parkinson et al., 2016). A comparison of measured and modeled (Eq. 1) MWAT of eight Kitsumkalum River subdrainages (115km northwest of Morice Lake) for the years 2016-2019 reveals a positive bias for the model of +2.32°C with a standard deviation of 1.50°C. Modeled MWAT presented here should be taken as a first-order estimate of current conditions.

Forecasted increases in MWAT are modeled based on projected increases in July-August air temperature from ClimateNA, and modeled change in fractional glacier cover from the OGGM:

$$MWAT_{ii} = MWAT_i + \left(\left(-9.43\sqrt{fg_{ii}}\right) - \left(-9.43\sqrt{fg_i}\right)\right) + (0.7°\mathrm{C} * \Delta JA_T)$$

(Eq. 2)

where $MWAT_i$ is modeled, present-day MWAT (Eq. 1), $MWAT_{ii}$ is a modeled future MWAT, $JA_T$ is future July-August air temperature (ClimateNA), $fg_i$ is fractional glacier cover at time one and $fg_{ii}$ is fractional glacier cover at time two. Catchment area, mean catchment elevation, fractional coverage of lakes, channel gradient and index of the mean annual flood are assumed to stay constant with time.

## Results

We present results for individual watersheds of the upper Morice River region, and for the Morice River watershed that includes numerous individual basins (Atna Lake, Morice Lake and Nanika River; Fig. 1). For results that are snapshots of future conditions (e.g., seasonal precipitation or temperature, MWAT, snowpack change), we do so using forecasted averages for the periods 2041-2060 and 2081-2100. For brevity in the text, these periods are labeled here as 2050 and 2090 respectively and represent mid- and late-21$^{st}$ century. We use '2100' in the manuscript for end-of-century conditions when using a model that relies on forecasted glacier conditions at this date.

| | | 2050 | | | | 2090 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SSP126 | SSP245 | SSP370 | SSP585 | SSP126 | SSP245 | SSP370 | SSP585 |
| Temp. (°C) | Winter | -5.96 (+0.96) | -5.64 (+1.28) | -5.54 (+1.38) | -5.06 (+1.86) | -5.59 (+1.34) | -4.45 (+2.48) | -3.31 (+3.61) | -2.10 (+4.82) |
| | Spring | 2.40 (+0.95) | 2.69 (+1.23) | 2.63 (+1.18) | 3.12 (+1.66) | 2.62 (+1.16) | 3.88 (+2.42) | 5.01 (+3.55) | 5.95 (+4.50) |
| | Summer | 12.36 (+0.84) | 12.65 (+1.14) | 13.02 (+1.50) | 13.38 (+1.87) | 12.59 (+1.08) | 13.92 (+2.40) | 15.53 (+4.01) | 16.62 (+5.11) |
| | Autumn | 3.89 (+0.83) | 4.18 (+1.12) | 4.28 (+1.22) | 4.61 (+1.55) | 4.07 (+1.00) | 5.19 (+2.12) | 6.52 (+3.46) | 7.48 (+4.41) |
| Precip. (mm) | Winter | 460.0 (+5.6) | 458.7 (+4.3) | 455.7 (+1.3) | 465.5 (+11.1) | 467.4 (+16.2) | 471.6 (+20.8) | 469.2 (+19.9) | 492.4 (+40.1) |
| | Spring | 229.0 (+12.6) | 226.5 (+10.1) | 228.0 (+11.6) | 232.4 (+16.0) | 225.5 (+7.2) | 235.9 (+14.8) | 240.1 (+20.2) | 251.8 (+33.5) |
| | Summer | 171.6 (+5.6) | 174.0 (+8.0) | 166.5 (+0.5) | 167.4 (+1.4) | 173.8 (+13.3) | 170.4 (+16.3) | 164.3 (+15.0) | 159.6 (+15.8) |
| | Autumn | 470.0 (+19.2) | 472.5 (+21.7) | 479.5 (+28.7) | 485.9 (+35.1) | 472.0 (+19.8) | 499.9 (+44.1) | 518.7 (+73.6) | 546.8 (+94.5) |

**Table 3: Modeled seasonal temperature and precipitation for Morice River.** ClimateNA modeled average seasonal temperature and total seasonal precipitation for the geographic mid-point and average elevation of the Morice River watershed. Data is presented as averages for the periods 2041-2060 (2050) and 2081-2100 (2090), and for four Shared Socioeconomic Pathways (SSPs). Values in parentheses show increase from present day.

*Future Temperature and Precipitation*

Temperatures are modeled to increase in all seasons and for all SSPs (Table 3, Fig. 4). These temperature increases ranges from 0.83-1.87°C by 2050, and 1.00-5.11°C by 2090 depending on season and SSP. Forecasted increases in temperature are similar across all four seasons but show a slightly larger increase in Winter and Summer (0.2-0.6°C), particularly for SSP370 and SSP585. The most optimistic scenario (SSP126) has temperatures rising by about 1°C by mid-century and then stabilizing, while the most dramatic (SSP585) has temperatures rising by up to 5°C by late-21$^{st}$ century.

The current winter season (months with temperatures averaging below zero) is from November through March. Warming in the shoulder months (November and March), however, will decrease the duration of the winter season, and the time during which snow accumulation can occur. Late-21$^{st}$ century November and March temperatures average below freezing only in the two more optimistic climate scenarios (SSP126 and SSP245; Fig. 5), and months with temperatures averaging below zero will decrease to December-February. By 2090, average winter temperatures in the SSP585 scenario reach -2°C.

Precipitation is also forecast to increase for all seasons and SSPs (Table 3). This increase, however, is less marked than temperature, with precipitation increases of 0.3-7% by 2050 depending on season and SSP. Increased precipitation to 2090 displays more variability, and noteworthy increases in

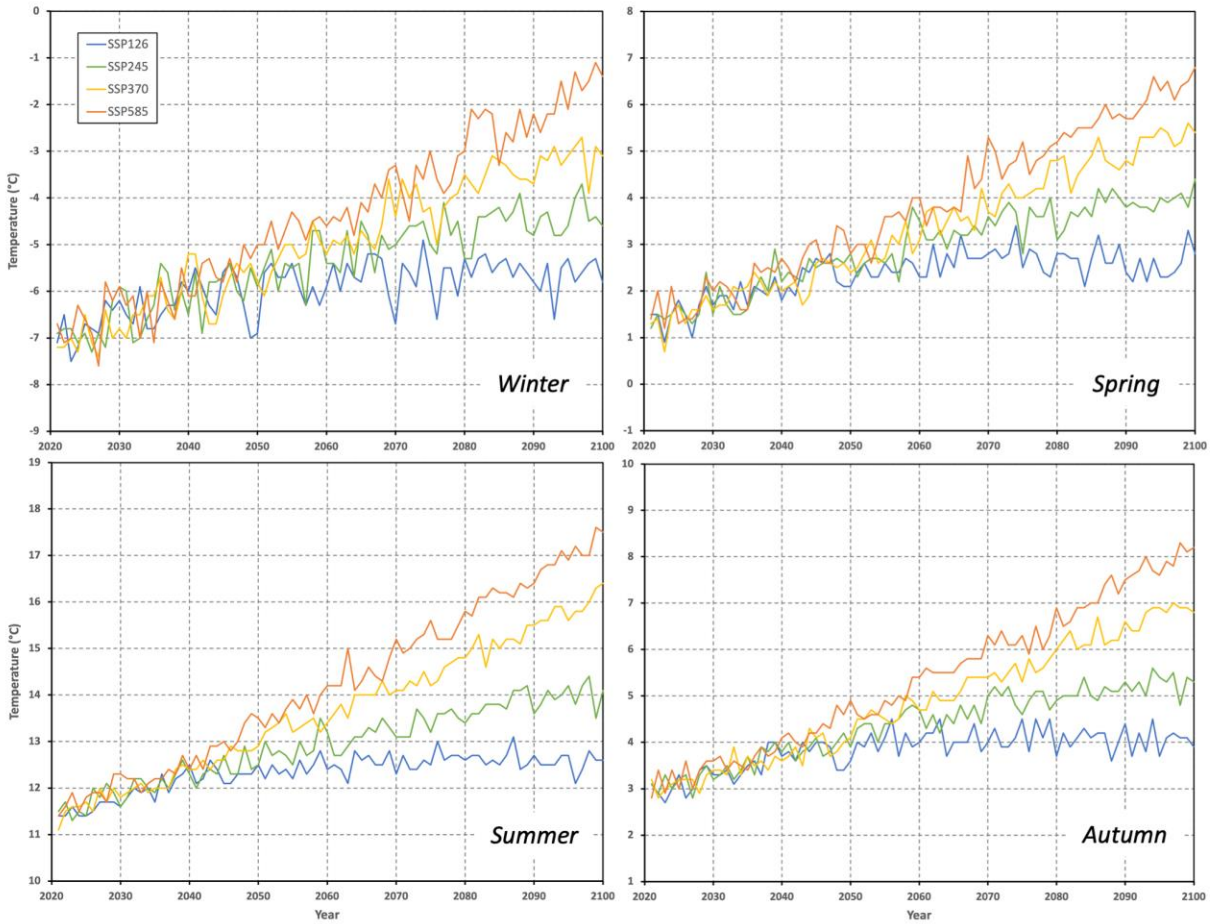


**Figure 4: Modeled average seasonal temperature (2021-2100).** ClimateNA modeled seasonal temperatures for four Shared Socioeconomic Pathways (SSPs ) for the geographic mid-point and average elevation of the Morice River watershed.

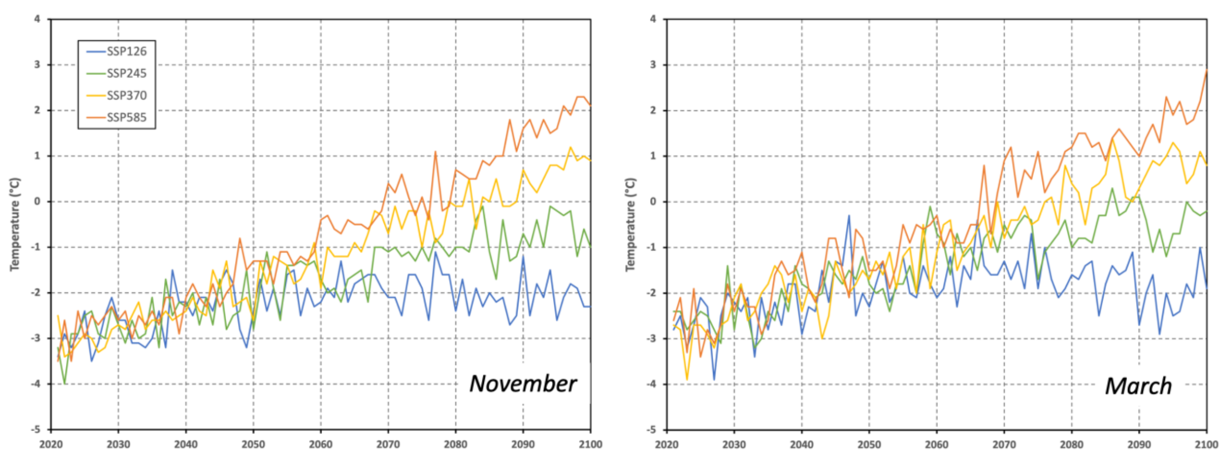


**Figure 5: Modeled Morice River watershed average November and March temperatures (2021-2100).** ClimateNA modeled November and March temperatures for four Shared Socioeconomic Pathways (SSPs) for the geographic mid-point and average elevation of the Morice River watershed.

| | 2050 | | | | 2100 | | | |
|---|---|---|---|---|---|---|---|---|
| | SSP126 | SSP245 | SSP370 | SSP585 | SSP126 | SSP245 | SSP370 | SSP585 |
| Watershed | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) | April 1 SWE (%) |
| Morice River | -6.9 | -9.2 | -10.0 | -13.9 | -8.9 | -20.1 | -32.0 | -45.9 |
| Morice Lake | -7.9 | -10.5 | -11.3 | -15.8 | -10.1 | -22.9 | -36.4 | -52.1 |
| Nanika River | -6.3 | -8.4 | -9.1 | -12.7 | -8.1 | -18.4 | -29.3 | -42.0 |
| Gosnell Creek | -7.8 | -10.4 | -11.3 | -15.7 | -10.0 | -22.8 | -36.2 | -51.8 |
| Thautil River | -6.8 | -9.0 | -9.8 | -13.6 | -8.7 | -19.7 | -31.3 | -44.8 |
| Owen Creek | -10.0 | -13.4 | -14.5 | -20.2 | -12.9 | -29.2 | -46.5 | -66.6 |
| Atna Lake | -6.8 | -9.0 | -9.7 | -13.6 | -8.7 | -19.6 | -31.2 | -44.8 |
| Lamprey Creek | -10.0 | -13.3 | -14.4 | -20.1 | -12.8 | -29.1 | -46.3 | -66.4 |

**Table 4: Modeled decline of April 1 snowpack.** Decreases in April 1 SWE (%) modeled using an empirical regional snow trend, ClimateNA projections of increased winter (NDJFM) temperature, and watershed hypsometry.

Winter, Spring and Autumn depending on SSP (up to 17%). Precipitation increases for Summer remain modest throughout the 21st century regardless of SSP (8-9%).

The modeled increases of temperature and precipitation from ClimateNA presented here for Morice River are nearly identical for the individual watersheds, with increases of temperature within 0.01°C and increases of precipitation within 3-5mm. There is a difference, however, in absolute temperature of about 1.0°C for the Atna Lake watershed, which has a markedly higher average elevation (Beedle, 2020).

*Snowpack Forecast*

Average April 1 snowpack from nine sites in the wider region is strongly related to elevation ($r$ = 0.86, $p < 0.01$; Fig. 2). The linear trendline based on these nine observations has a y-intercept, or zero-snow line, of 34 meters. By 2050 the zero-snow line is forecasted to move upwards by 166-296m depending on climate scenario, whereas by 2090 it is rises to 206-774m. These linear models are then integrated with subdrainage hypsometries to determine a change in snowpack volume. The subdrainages of interest in the upper Morice River area have different hypsometries (Fig. 2). Strahler (1952) classified watershed hypsometries as top-heavy, intermediate, or bottom-heavy, depending on where the bulk of the surface is located with respect to elevation. The watersheds of Owen and Lamprey creeks have bottom-heavy distributions. Thautil River is the only subdrainage with a more top-heavy distribution, although it is not strongly dissimilar from those with intermediate hypsometries. The remaining basins are all intermediate in form with roughly equal distributions of surface area throughout their elevation ranges.

Bottom-heavy basins (Owen and Lamprey creeks) are most susceptible to changes in winter snowpack with reductions of 10% respectively by 2050 for SSP126, and up to 20.2 and 20.1% for SSP585 (Table 4). The remaining higher elevation, intermediate hypsometry basins are less prone to loss of winter snowpack and broadly similar to one another, with reductions of 6.3-7.9% by 2050 for SSP 126 and 12.-7-15.8% for SSP585. Reductions of 6.9-13.9% for Morice River sum the changes for Morice Lake, Nanika River and Atna Lake.

The modeled winter temperatures from ClimateNA give a wide range of potential futures depending on climate scenario, particularly by 2090 (Fig. 4). The forecasted shift in the zero-snow line of 206-774m results in projected reductions in maximum snowpack of from 8.1 to 12.9% under SSP126 upwards to 42 to 66.6% under SSP585 (Table 4). The more moderate reductions are for the basins with higher average elevations (e.g., Atna Lake and Nanika River). Owen and Lamprey creeks are most vulnerable, with projected reductions 14-24% more than the other basins due to lower average elevations and bottom-heavy hypsometries.

*Glacier Model*

Glaciers of the upper Morice River subdrainages are forecasted to dramatically decrease in the 21st century (Figs. 6 and 7). By 2050, glaciers that feed Morice River (those of Atna Lake, Morice Lake and Nanika River) are projected to lose 79 to 93% of present-day ice volume depending on the climate scenario, and by the end of the 21st century continued melt results in a loss of 94 to 100% (Table A1). The glaciers that feed Nanika River are modeled to lose most of their volume by mid-century with a chance of only remnant ice remaining by 2100. Atna and Morice lake glaciers are projected to be

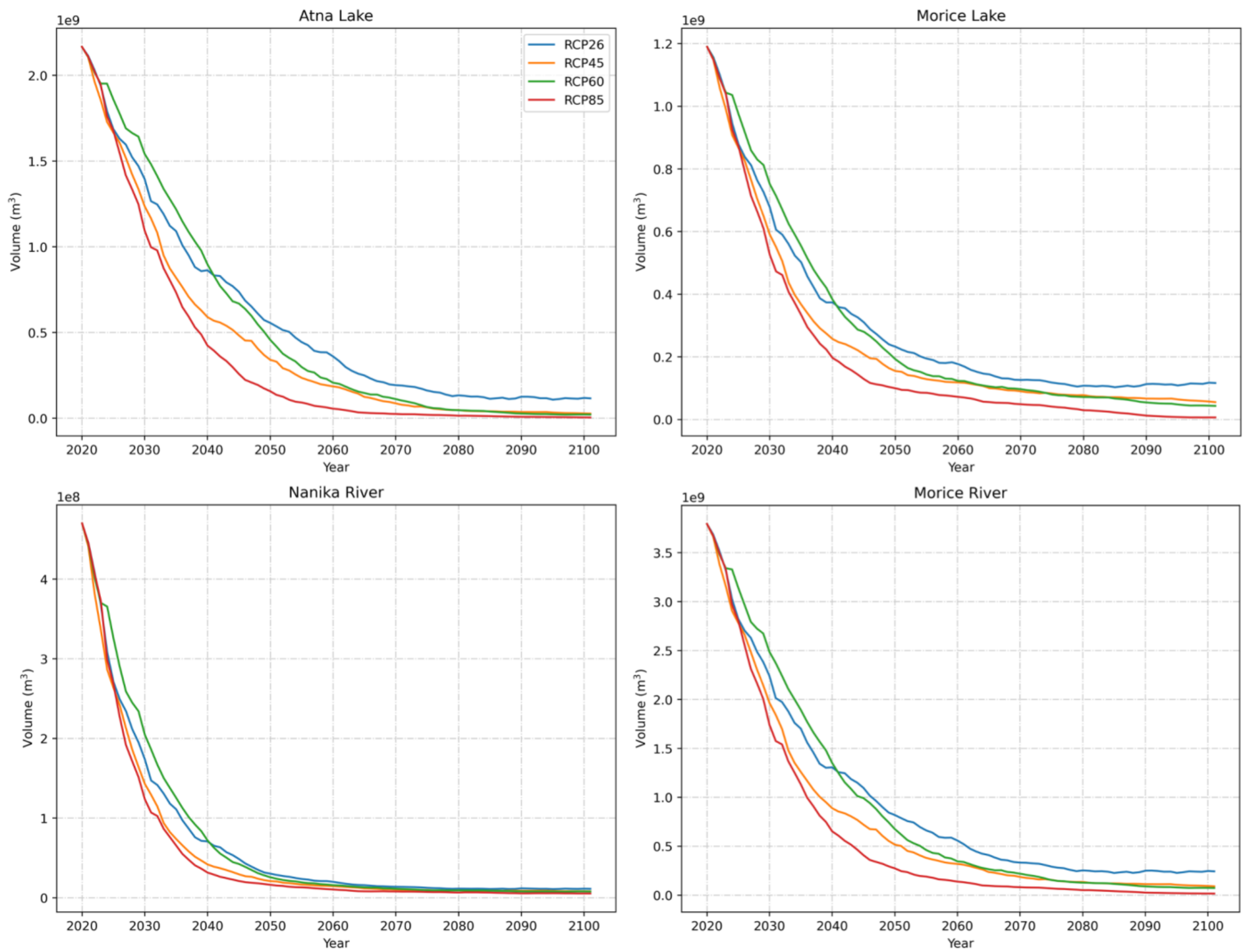


**Figure 6: Modeled glacier volume change for upper Morice River watersheds (2020-2100).** OGGM modeled glacier volume ($m^3$ w.e.) for three glacierized subdrainages of Morice River (Atna Lake, Morice Lake and Nanika River), and all glaciers that feed Morice River (the three subdrainages combined). Note that glacier volume (y-axis) is presented in scientific notation.

slightly more resilient with the possibility of glacier volumes stabilizing at 5-10% of present-day volumes under the most optimistic climate scenario (RCP2.6) by 2100. Only remnant ice patches are forecasted to remain in any of the subdrainages by the end of the century under the more dramatic climate scenarios.

Modeled reductions in 21st-century glacier surface area are similar to those of glacier volume and can be compared with observations of glacier recession of recent decades (Beedle 2001; Fig. 7). The rapid rates of recession forecasted to 2050 are a continuation of the recession observed in recent decades.

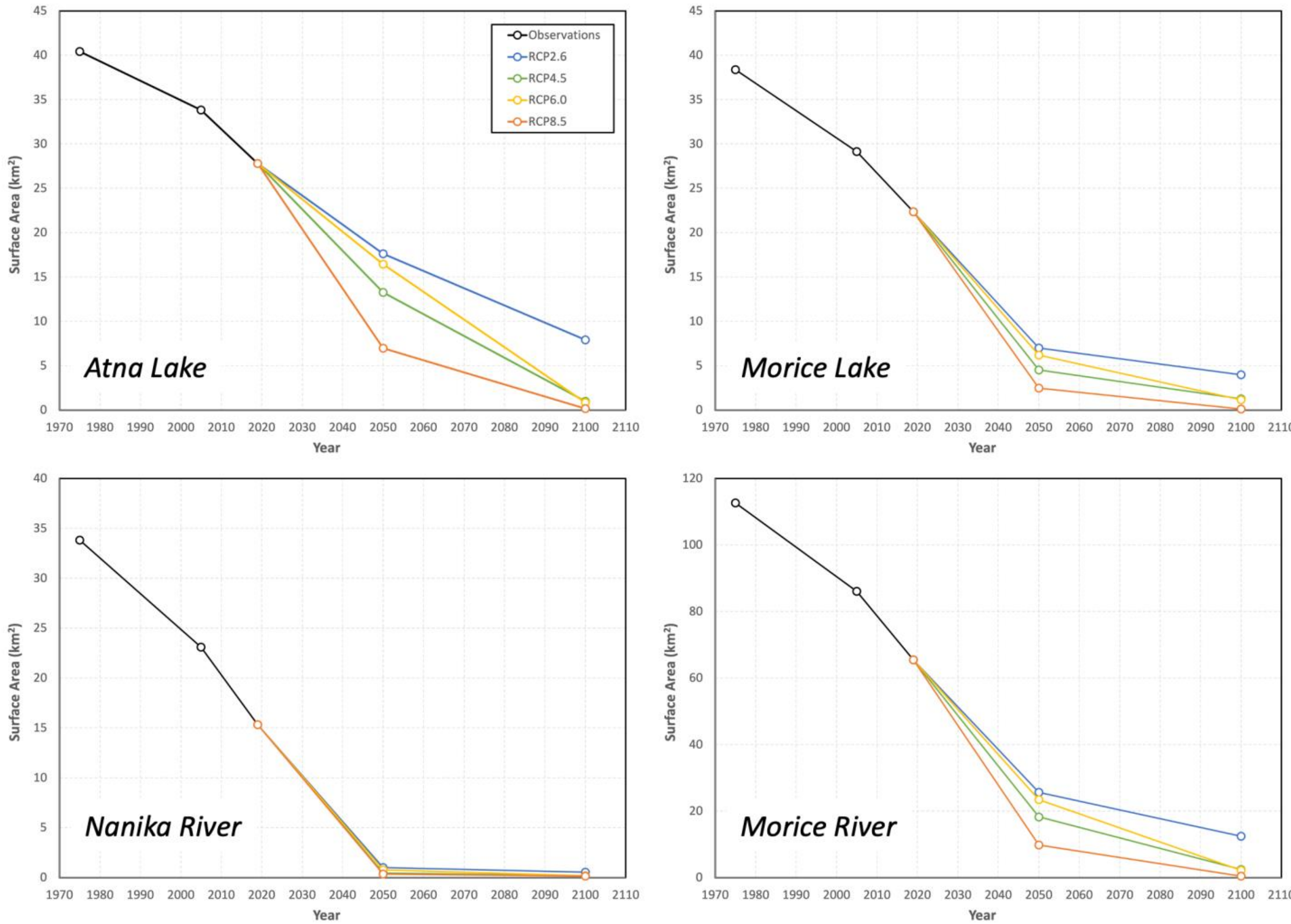


**Figure 7: Glacier Surface Area Change.** Observed and modeled glacier surface area change for three glacierized subdrainages of Morice River (Atna Lake, Morice Lake and Nanika River), and all glaciers that feed Morice River (the three subdrainages combined).

Only in the most optimistic climate scenario (RCP2.6) do glaciers persist in the Atna and Morice lake watersheds by the end of the century, but still with surface area reductions of 70-80%. Complete disappearance of Nanika River glaciers is likely, regardless of climate scenario, and as early as the middle of the 21$^{st}$ century. See Tables A2 (Appendix A) for modeled glacier surface area change by watershed.

*Streamflow*

The capacity for glacier meltwater to buffer streamflow will decline commensurately with glacier surface area. During a colder/wetter than average melt season ($b_a$ = -0.47), the glacier contributions of meltwater would be between 2-3% of total discharge respectively for Nanika and Morice rivers under present-day conditions and would reduce to 0-1% by 2100 (Fig. 8). In an average melt season ($b_a$ = -1.27), contributions of glacier meltwater increase as seasonal snowpack dwindles more rapidly and glacier surface melt increases. In this scenario glacier meltwater contributions wane from 7-9% of total discharge respectively under present-day conditions to 0-2% by 2100. In an extremely dry/warm summer when glacier meltwater is most important as a buffer, contributions reduce from 26-35% respectively under present-day conditions to 0-9% by 2100 depending on climate scenario. Contributions of glacier meltwater to discharge all but disappear in all climate scenarios for Nanika River, while modest buffering capacity remains for Morice River only in the most optimistic climate scenario (RCP2.6).

Reductions in seasonal snowpack (Table 4) will impact the timing and magnitude of the freshet, reduce the quantity of water stored as snow that is available later in the melt season, and reduce groundwater recharge. Our model of reduced seasonal snowpack also implies increases in winter and shoulder-season (November and March) low-elevation rain and melt events, which will increase winter discharge. Vulnerability to warmer winter conditions and reductions in seasonal snowpack is driven by basin hypsometry, with the low-elevation, bottom-heavy basins (Owen and Lamprey creeks) being the most heavily affected (Fig. 2). In these basins the freshet will occur earlier, the average magnitude of the freshet will be reduced, and little seasonal snow will be available to buffer discharge leading to progressively longer dry seasons. The other basins (higher-elevation, intermediate in form) will experience the same general trends, but the magnitude will be less.

*Stream Temperature*

Forecasted increases in MWAT, driven by changes in average July-August temperatures and fractional glacier cover, vary from one watershed to another, with those losing glacier cover increasing the most (Table 5). Increased stream temperatures of Thautil River and Gosnell, Owen and Lamprey creeks are forecasted to increase the least, given that they have little to no current glacier cover to lose, with a temperature rise of 0.7-1.3°C by mid-century depending on individual basin and climate scenario. This

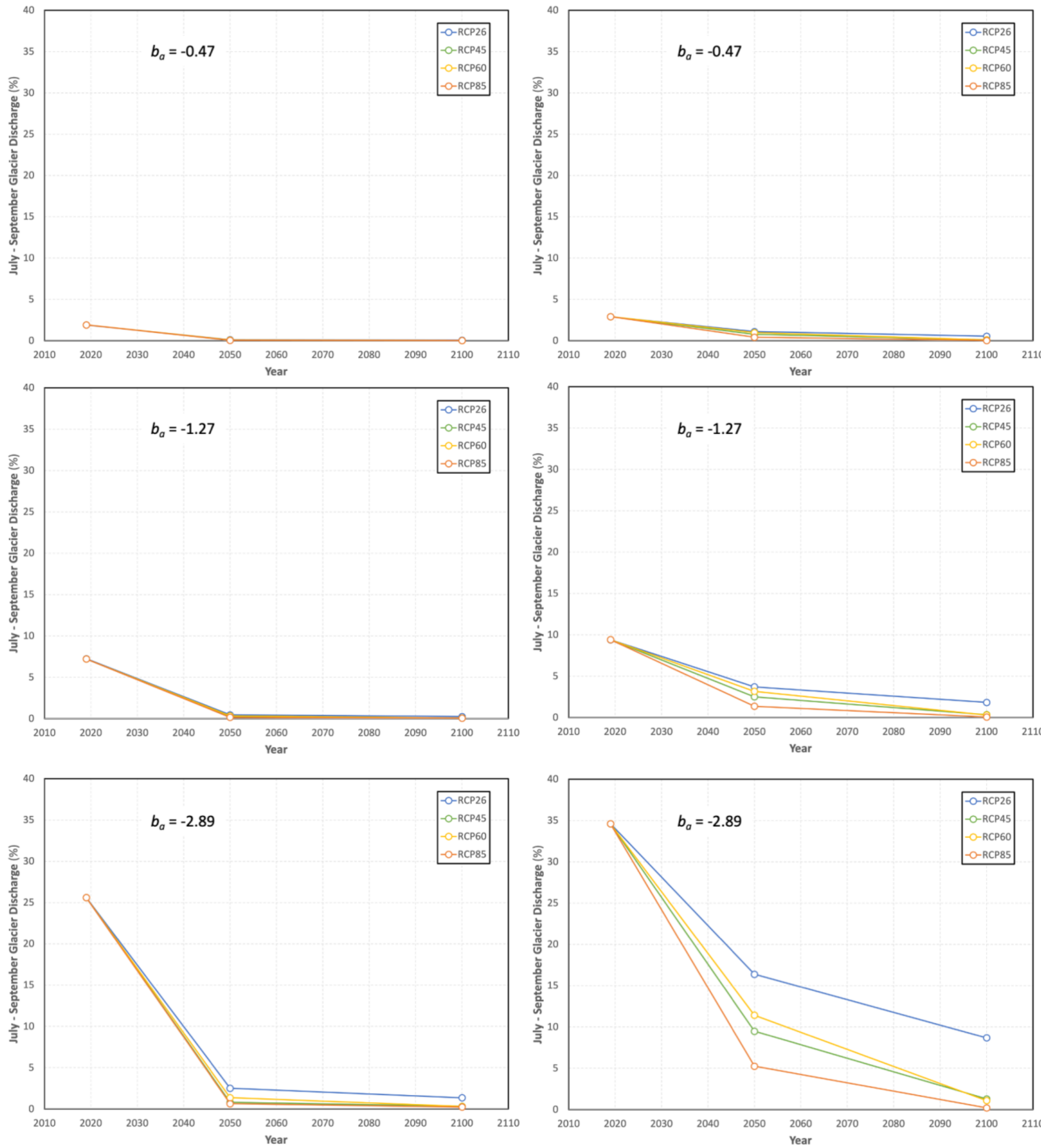


**Figure 8: July – September Glacier Meltwater Contributions to Discharge of Nanika and Morice Rivers.** Relative contributions of glacier melt to discharge of Nanika River (left column) and Morice River (right column) for four climate scenarios, and for three meteorological scenarios. The top figure is for a colder than average year with less glacier melt ($b_a$ = -0.47) and higher total discharge. The middle figure is for an average year with average glacier melt ($b_a$ = -1.27) and reduced total discharge. The bottom figure is for an extremely dry/warm year with maximum glacier melt ($b_a$ = -2.89) and least total discharge.

| | 2050 | | | | 2090 | | | |
|---|---|---|---|---|---|---|---|---|
| **Watershed** | **RCP26** | **RCP45** | **RCP60** | **RCP85** | **RCP26** | **RCP45** | **RCP60** | **RCP85** |
| Morice River | 1.5 | 1.8 | 1.9 | 2.4 | 1.9 | 3.0 | 3.9 | 4.6 |
| Nanika River | 1.8 | 2.0 | 2.2 | 2.4 | 2.0 | 2.8 | 3.6 | 4.2 |
| Gosnell Creek | 0.8 | 0.9 | 1.1 | 1.3 | 0.9 | 1.6 | 2.4 | 3.0 |
| Thautil River | 0.8 | 1.0 | 1.2 | 1.3 | 0.9 | 1.6 | 2.5 | 3.0 |
| Owen Creek | 0.8 | 0.9 | 1.1 | 1.3 | 0.9 | 1.6 | 2.4 | 3.0 |
| Atna Lake | 1.4 | 1.9 | 1.8 | 2.8 | 2.3 | 4.0 | 4.9 | 5.7 |
| Lamprey Creek | 0.7 | 0.9 | 1.1 | 1.2 | 0.8 | 1.5 | 2.4 | 2.9 |

**Table 5: Modeled increases in Maximum Weekly Average Temperature (MWAT).** Projected increases of MWAT (°C) by watershed for the periods 2041-2060 (2050) and 2081-2100 (2090) for four climate scenarios. Changes in July-August air temperature are from ClimateNA and use SSPs, while changes in fractional glacier cover are from the OGGM and use RCPs. For brevity, only the corresponding SSP is used in the table.

| | Present | 2050 | | | | 2090 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Watershed** | **MWAT** | **RCP26** | **RCP45** | **RCP60** | **RCP85** | **RCP26** | **RCP45** | **RCP60** | **RCP85** |
| Morice River | 16.8 | 18.3 | 18.6 | 18.7 | 19.2 | 18.7 | 19.8 | 20.7 | 21.4 |
| Nanika River | 15.7 | 17.5 | 17.7 | 17.9 | 18.1 | 17.7 | 18.5 | 19.3 | 19.9 |
| Gosnell Creek | 15.1 | 15.9 | 16.0 | 16.2 | 16.4 | 16.0 | 16.7 | 17.5 | 18.1 |
| Thautil River | 15.9 | 16.7 | 16.9 | 17.1 | 17.2 | 16.8 | 17.5 | 18.4 | 18.9 |
| Owen Creek | 16.5 | 17.3 | 17.4 | 17.6 | 17.8 | 17.4 | 18.1 | 18.9 | 19.5 |
| Atna Lake | 11.4 | 12.8 | 13.3 | 13.2 | 14.2 | 13.7 | 15.4 | 16.3 | 17.1 |
| Lamprey Creek | 17.2 | 17.9 | 18.1 | 18.3 | 18.4 | 18.0 | 18.7 | 19.6 | 20.1 |

**Table 6: Modeled Maximum Weekly Average Temperature (MWAT).** Modeled present-day MWAT (°C) and projected MWAT by watershed for the periods 2041-2060 (2050) and 2081-2100 (2090) for four climate scenarios. Changes in July-August air temperature are from ClimateNA and use SSPs, while changes in fractional glacier cover are from the OGGM and use RCPs. For brevity, only the corresponding RCP is used in the table. MWAT values shaded in orange are above 18.5°C, an important species assemblage thermal threshold identified in other studies (e.g., Parkinson et al., 2016).

temperature increase is forecasted to be 0.8-3.0°C by the end of the 21st-century. Stream temperatures for Atna Lake and Nanika River are forecasted to increase the most, both to 2050 and 2090, as they are projected to experience the most change in fractional glacier cover. These temperature increases are 1.4-2.8°C and 1.8-2.4°C for Atna Lake and Nanika River respectively by mid-century, and 2.3-5.7°C and 2.0-4.2°C by the end of the 21st-century.

Modeled increases in stream temperatures show Atna Lake, with greater present-day glacier cover, maintaining MWAT within the optimal range for salmon. Those watersheds at lower elevations (Owen and Lamprey creeks) and with the warming influence of Morice Lake (Morice River) likely reach MWAT values that stress salmon by the mid-21st century (Table 6 and Fig. 10).

## Discussion

*Future Temperature and Precipitation*

Modeled temperature and precipitation are both forecasted to increase under all SSPs using the ensemble of 13 general circulation models (GCMs) selected to best represent British Columbia from the 44 GCMs of the CMIP6 (Wang et al., 2016). Increases above present-day temperatures are roughly 1-2°C by mid-century and 1-5°C by the end of the 21st-century for four SSPs and across all seasons (Table 3 and Fig. 4). These results are similar to those presented in previous work for the northern coastal temperate rainforest (Shanley et al., 2015). The most optimistic climate scenario (SSP126) projects temperatures increasing to mid-21st century and then staying consistent at temperatures of roughly 1°C higher than present-day conditions (Fig. 4). It is only this climate pathway that leads to glacier cover remaining in the upper Morice River subdrainages of Atna and Morice lakes (Figs. 6 and 7) that provides a meaningful freshwater buffer (Fig. 8). The SSP245 climate pathway forecasts temperature increases to level off at 2-2.5°C higher than present-day conditions by the end of the 21st century. These temperature increases, however, do not allow for glaciers to persist. The two other climate scenarios (SSP370 and SSP585) project temperatures increasing steadily throughout the 21st-century but at slightly different rates (Fig. 4), and it is these potential futures that result in the largest changes in seasonal snowpack and most rapid demise of glaciers, particularly by the end of the 21st-century.

Forecasted increases in autumn, winter and spring temperatures will shorten the snow accumulation season and decrease the snowfall fraction, both of which will lead to reductions in seasonal snowpack and winter glacier mass balance. The warming in November and March, shoulder seasons with present-day average temperatures below freezing, may transition during the 21st century to above freezing average temperatures (SSP370 and SS585). Warming during these months, even if it is not as dramatic (SSP126 and SSP245), will shorten the winter accumulation season (Fig. 5). Lower-elevation watersheds (e.g., Owen and Lamprey), and lower-elevation portions of all watersheds, will be most strongly impacted by these changes, particularly as average winter temperatures approach 0°C. Projections of increased precipitation, however, are likely to yield increased snow accumulation at the highest elevations (discussed further below). Forecasted increases in spring and summer temperatures will shift the melt-season (and freshet) earlier, increase the duration of lower stream discharge in the drier months of July through September, and increase glacier surface melt, evaporation, and stream temperatures.

Projected increases in precipitation generally range from 0.5 to 7% by 2050, and 3 to 17% by 2090, amounts that are similar to previous work (Shanley et al., 2015). Modeled precipitation is more stochastic than those for temperature, with the quantity of increased rainfall varying between SSPs. While more variable, the projections for the end of the 21st-century all show generally linear upward trends. One exception is for Autumn precipitation where SSPs 245, 370 and 585 all yield markedly increased precipitation, a notable deviation from the other seasons. While a modest increase in precipitation, perhaps more prominent in Autumn, is probable through the 21st-century, it is important to note that models of precipitation struggle to resolve variability in complex topography (e.g., Wang et al., 2016).

*Snowpack Forecast*

Differences in future snowpack between basins is driven by hypsometry, the unchanging distribution of surface area with respect to elevation (Fig. 2). Watersheds with a lower average elevation and with bottom heavy hypsometries will be the most strongly impacted (e.g., Owen and Lamprey creeks), with more surface area exposed for a common rise in temperature (e.g., Shea et al., 2021). The other upper Morice River region watersheds will be less severely impacted as they have higher average elevations and intermediate hypsometries.

The linear relationship between April 1 SWE and elevation for nine sites in the region is significant ($r$ = 0.86, $p < 0.01$; Fig. 2), however, it is uncertain whether this linear relationship is representative of conditions in the Morice River region. While the nine snow survey sites are biased towards locations further south, closer to the Morice River region, there are other sites more than 300km north (e.g., Ningunsaw Pass). Additional snow survey sites within the region were omitted due to missing data (Granduc Mine) or as they exhibited conditions for a much more continental climate (Hudson Bay Mountain). Two of the highest elevation snow survey sites (Kidprice Lake and Tahtsa Lake; Fig. 3 and Table 2), however, are in the immediate vicinity, and at elevations similar to the average elevations of the Morice River subdrainages studied here. This likely results in the regional snow trend (Fig. 2) being generally representative, particularly of the large surface areas at middle elevations. An improved understanding of the effect of snowpack on water quality and quantity would require an enhanced observation network. The highest elevations may well see increased snowpacks with a warming climate (e.g., Sproles et al., 2013; Harder et al., 2015), but hypsometries are such that there is relatively little surface area at these highest elevations, resulting in little impact on basin-wide snowpack.

Projecting future SWE with respect to elevation based on modeled average winter temperatures (Fig. 2) is a simple approach and likely does not capture the spatial heterogeneity of complex mountain environments. A strong relationship between snowpack and elevation, however, does provide merit for such an approach. The skill of ClimateNA to model local temperature in the Morice River region is uncertain. Future work should monitor local temperatures and compare these with ClimateNA output.

It should be noted that snowpack projections presented here are decadal averages and do not reflect the stochastic nature of seasonal snowfall. Even in a significantly warmer 21st century, synoptic conditions will bring about large snow years, however the trend will likely be towards fewer average and above-average snow years, and more below-average snow years. The positions of the jet stream and synoptic meteorology of a given season will broadly determine snowpack each year but warming winter temperatures will result in change in the snowfall fraction leading to conditions that favor more winter rain, particularly at lower elevations. How climate change will enhance or diminish blocking patterns (e.g., those that led to the 2018/2019 drought, 2021 heat dome, or 2022 cold spring season), however, is an area of active research, and it is uncertain how this will force winter snowpacks in northwest BC on average during the 21st century (e.g., Woollings et al., 2018).

The significantly warmer winter temperatures forecasted by the end of the 21st century, particularly those for SSP375 and SSP585 (Fig. 4), and the likely related upward shifts in the zero-snow line (Fig. 2), present a winter that is greatly dissimilar to present-day and 20th-century conditions, with some forecasted decreases of maximum snowpack greater than 50% (Table 4). Efforts to mitigate and adapt to this change should be initiated, including additional studies of the current role of snowpack on freshwater ecosystems in upper Morice River region watersheds, and the extent to which past, current and future forestry practices impact snowpack (e.g., Hotovy and Jenicek, 2020; Schelker et al., 2013).

*Glacier Change*

Using the OGGM, we project glaciers of the upper Morice River region to melt rapidly to mid-century and to completely disappear or to only remain as remnant ice patches by the end of the 21st-century. There is a lag of decades between climate change and response of glaciers in terms of a corresponding change in surface area or volume for glaciers similar to those studied here (e.g., Zekollari et al., 2020). This means there is an imbalance between current glacier dimensions and present-day climate. This imbalance results in committed further recession even in the absence of ongoing climate change. Continued climate change, particularly the forecasted increases in melt-season temperature, will drive additional glacier melt.

Previous work finds that glaciers of western Canada will shrink by an average of 70% by 2100, but that glaciers of the Coast Mountains of BC will be more resistant to climate change (Clarke et al., 2015). This resilience, however, is associated with regions of the Coast Mountains where present-day ice volumes are much higher than in the subdrainages of the upper Morice River. These more resilient regions of the Coast Mountains are generally to the north and south, and Clarke et al. (2015) find that the smaller, generally lower-elevation glaciers of the Central Coast (of which the Morice River subdrainages are a part) will experience complete or near complete glacier wastage. These conclusions from previous work averaged over larger regions are similar to what we find here for specific watersheds. Projections for the glaciers of individual watersheds within a larger region, however, do show noteworthy differences that will have important implications for downstream aquatic ecosystems through the 21st-century.

The three subdrainages with present-day glacier cover that feed Morice River (Atna Lake, Morice Lake and Nanika River) are representative of those subregions where previous work finds complete or near complete glacier wastage. For all glaciers that feed Morice River, we find a 79 to 93% loss by 2050, and 94-100% loss by the end of the 21st-century (Fig. 6; Table A1). The generally larger, higher-elevation glaciers of Atna Lake will be the most resilient of those that feed Morice River, with a forecasted decrease in volume of 74 to 93% by 2050, compared with a decrease of 94 to 97% for Nanika River glaciers (Table A1). Atna Lake surface area change is projected to be 37 to 75% by 2050, compared with a decrease of 94 to 98% for Nanika River (Table A2). This modestly greater resilience of Atna Lake glaciers is important as they represent 57% of the total glacier volume (Table A1) and 42% of the total glacier surface area (Table A2) that feeds Morice River.

By the end of the 21st-century, however, it is unlikely that glaciers will be present in the Morice River subdrainages to an extent that is meaningful as a hydrologic buffer for downstream aquatic ecosystems. By 2100 forecasted volume loss of these glaciers is 94 to 100% and loss of surface area is 81 to 91% (Tables A1 and A2). Under the most optimistic climate pathway (RCP2.6), however, it is notable that glaciers of Atna Lake and Morice Lake are projected to stabilize by the end of the century, with 6 and 10% of present-day volume remaining respectively, and 28 and 18% of present-day surface area (Fig. 7). The remaining 7.9km$^2$ of surface area forecasted for Atna Lake by 2100 under RCP2.6 amounts to a fractional glacier cover of 2.9% (Table A2). This is markedly less than present-day extents but still of a quantity that some marginal thermal buffering could occur to the end of the 21st-century. The remaining 4.0km$^2$ of surface area projected to remain for Morice Lake by 2100 under the same optimistic scenario yields a fractional glacier cover of 0.5%, insufficient to have a meaningful impact beyond the immediate drainages in which the remnant glaciers remain. This stabilization of glacier extent is only possible with the most optimistic climate pathway. For each of the other RCPs, however, there is continued loss of glacier volume and surface area through the 21st century, and likely complete disappearance of glaciers by 2100 if not sooner.

The smaller glaciers of the Nanika River watershed are projected to recede more rapidly, all but disappearing by mid-century. They are modeled here to lose 94-97% of present-day volume by 2050, and 98-99% by 2100 depending on climate pathway (Fig. 6; Table A1). Even in the most optimistic climate scenario (RCP2.6) Nanika River glaciers are likely to only remain as remnants by mid-century. What remnant ice does remain will likely reside in steep, north-facing basins where shade in the summer months reduce surface melt and avalanching and wind deposit snow in the winter enhance accumulation. As such, Nanika River will cease to be a glacier-fed system, with capacity for downstream buffering likely negligible by mid-century.

The projected 21st-century change for all glaciers that contribute to Morice River is similar to the trajectories for Atna and Morice Lake glaciers, as they dominate the total present-day glacier cover with 75% of current glacier surface area and 88% of present-day glacier volume (Tables A1 and A2). The most optimistic climate scenario (RCP2.6) forecasts 12.41km$^2$ of surface area remaining by 2100. This total, however, represents a fractional glacier cover of only 0.6%. At such low relative coverage, glaciers are unlikely to play a meaningful role in buffering of Morice River discharge and stream temperatures by the end of the 21st century. The remaining ice masses in the Atna Lake watershed will have a small buffering effect and only in the immediate vicinity (e.g., Atna River and Atna Lake).

Previous glacier modeling (e.g., Clarke et al., 2015) and modeled results presented here (Figs. 6) visually indicate a near term rapid decline in glacier volume. It is important to note, however, that what is being modeled is a continuation of trends already underway. Figure 7 illustrates this by combining observations of glacier recession in recent decades (Beedle, 2021) with modeled 21st-century recession. The dramatic recession forecasted for the coming decades is not a reaction to as-of-yet unrealized climatic change, but a continuation of rates of recession we have observed in recent decades and continue today.

We suggest future glacier-specific research that will enhance the understanding of the role of glacial contributions to Morice River that will have a bearing on freshwater ecosystem health for the 21st century. Repeat glacier inventories with satellite remote sensing should be completed every five to 10 years, using the 2019 inventory (Beedle, 2021) as a benchmark. This will provide validation of the trajectory of 21st-century glacier recession and confirm related hydrologic impacts. Seasonal surface mass balance measurements should be considered on an accessible, representative glacier in the region to better understand local climatology and glacier change. At present, the glaciers of the Atna Lake and Morice Lake watersheds likely play an important role locally within Morice Lake itself, particularly for moderating temperatures and providing nutrients in near-shore spawning and rearing habitat. It is recommended that a study be completed that investigates the present-day water quality of these locations of Morice Lake, and the role that glaciers play in fostering these conditions.

*Streamflow*

Our first-order streamflow projections are limited to Nanika River and Morice River, where there is historical and ongoing monitoring of discharge. Current glacier extent is sufficient to provide important thermal and streamflow buffering in both Nanika and Morice rivers, which may reach as high as 26 and 35% of JAS discharge respectively in warm, dry summers with high rates of glacier mass loss (Fig. 8). This capacity, however, will diminish commensurately with 21$^{st}$-century glacier recession. In cooler, wetter summers discharge is high and glacier melt is reduced, meaning that loss of glacier surface area will have a minimal impact. The reductions of buffering capacity will be pronounced in average, and above average melt seasons. The proportion of discharge from glacier melt in Morice River during summers with maximum glacier melt (strongly negative mass balance) will decrease to 5.3-16.4% by 2050 and 0.2-8.7% by 2100 depending on climate scenario. While buffering capacity will reduce by mid-century, there remains some meaningful buffering capacity regardless of climate scenario. The projection of 8.7% of total discharge from glacial sources by 2100 only persists in the most optimistic climate scenario (RCP2.6), while glacial meltwater is negligible in the other three climate pathways as glacier surface area approaches zero.

The capacity for glacier melt to buffer downstream flows of Nanika River will likely be negligible by mid-century, and all but disappear by the end of the 21$^{st}$ century. In summers of maximum glacier melt, when relative contributions from glacier melt are greatest and most important, only 0.6-2.5% of Nanika River discharge is likely to be from glacier sources by mid-century. By 2100 this will drop to 0.2-1.4%. Only in the most optimistic climate scenario (RCP2.6) do glacial meltwater contributions exceed 0.3% of total summer Nanika River discharge.

While discharge is not currently measured in the minor tributaries that feed Atna and Morice lakes, it is likely that maintained relative importance of glacier cover in these small basins will offer meaningful meltwater buffering in the immediate vicinity where they enter these lakes. The proportion of glacier meltwater will be reduced through the 21$^{st}$ century, but there is a likelihood of localized cold-water refugia.

The remaining, non-glacierized basins (Thautil River and Gosnell, Owen and Lamprey creeks) will likely see further reductions in streamflow, but this will most likely be due to reduced groundwater recharge as these lower-lying basins will see significantly reduced seasonal snowpacks, an earlier freshet, and a longer dry season. For an understanding of changing discharge in these four watersheds, it will be important to gain an understanding of water withdrawal, impacts of forestry on snowpack retention and evapotranspiration, and to investigate the role of groundwater.

The application of Lemon Creek Glacier mass balance (located 400km to the northwest) is not ideal and introduces an important source of uncertainty in these projections of 21st-century streamflow. While this data likely does capture the larger context of annual variations in surface melt, the magnitude may not be appropriate. Lemon Creek Glacier, while located further north, is also more maritime and at a lower average elevation, likely resulting in greater mass turnover and generally higher rates of melt than what would be expected for the upper Morice River region. As was mentioned above, it will be important to gain an understanding of local glacier mass balance through a field monitoring program to better constrain the projections of 21st-century glacier melt and downstream impacts.

There are important known, yet unquantified feedbacks associated with glacier recession, particularly regarding the role glaciers play in enhancing accumulation and retention of seasonal snowpack. Loss of glacier ice reduces the elevation of significant portions of a watershed, reduces albedo and removes a persistent feature that causes localized cooling (e.g., Johnson and Rupper, 2020). Each of these will serve to reduce the meltwater available from seasonal snowpack. As the glaciers of the upper Morice River region recede there will be a direct impact from loss of the frozen glacier reservoir, but also an indirect impact due to reduced retention of seasonal snowpack.

The role that landcover change has on streamflow, particularly through forestry, is another critical concern for the 21st century, and one where natural resource practices might play an important mitigative and adaptive role. Forestry practices can markedly alter snow accumulation and melt, with previous work reporting up to 40% less accumulation and a 70% reduction in melt rates in forested areas (e.g., Varhola et al., 2010). This connection between snowpack and forests yields the potential to remedy past practice, which led to large areas of clearcut logging in the Owen and Lamprey creek watersheds (Beedle, 2020), and to modify future forestry practices to play an important role in adaptation to a warmer climate. Additional work should be done that investigates the role of forestry practices on seasonal snowpack and associated streamflow and water quality, particularly with a focus on adaptive capacity in the lower elevations of Morice River region watersheds.

*Stream Temperature*

We forecast stream temperatures of Morice River region watersheds to increase by 0.7-2.8°C by 2050 and 0.8-5.7°C by 2100 depending on basin and climate scenario (Table 5). This projection is based on modeled increased July-August temperatures and modeled reduced glacier surface area (Eq. 2). While these two factors will be critical in determining 21st-century stream temperatures it is important to note that all other factors in the empirical model of stream temperature used here (Eq. 1) are assumed to stay static, which is unlikely, particularly in the case of changing discharge with time, but also with respect to other factors not included in this model (e.g., land-use practices, groundwater influences, wetlands). It should also be noted that recent work has found that empirical models might systematically underestimate response to climate warming due to thermal memory in a basin associated with snowpack and a lagged response to temperature increase in groundwater fed streams (Leach and Moore, 2019). Given these considerations, stream temperature increases presented here should be understood as cursory.

In general, those basins with more present-day glacier cover will see larger increases of MWAT as this source of thermal buffering diminishes (e.g., Atna and Morice lakes). These basins will have markedly colder stream temperatures at present, compared with those of Owen and Lamprey creeks that have much lower average elevations and less thermal buffering from seasonal snowpack. Owen and Lamprey creeks will have much higher present-day stream temperatures and are more likely to reach MWAT thresholds critical to salmon in the near term.

Modeled absolute present-day and future MWAT is less certain (Table 6 and Fig. 9) and may yield values significantly different from actual values. A comparison of the model used here (Eq. 1) and

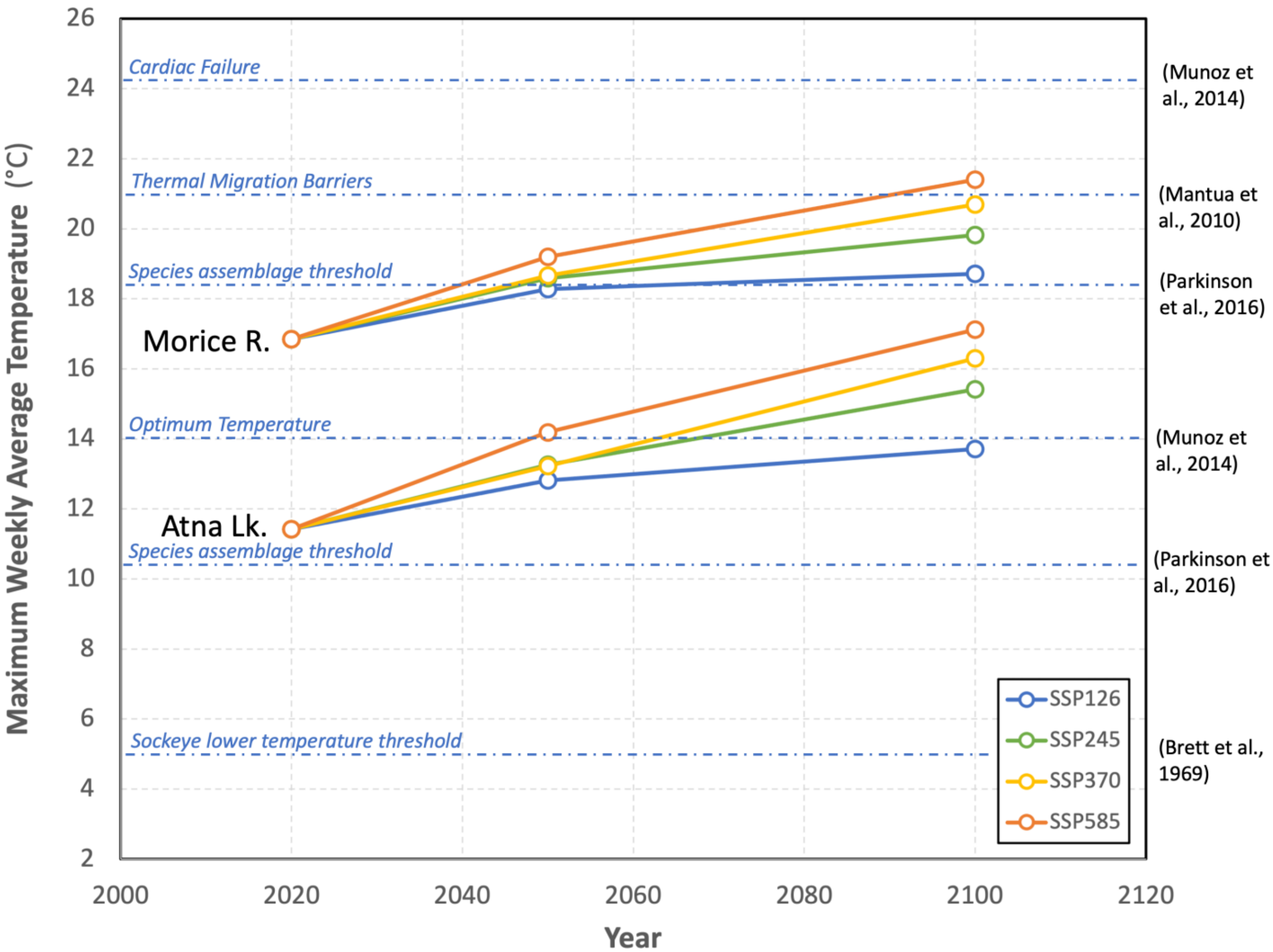


**Figure 9: Modeled MWAT of Morice River and Atna Lake (2020-2100).** Modeled MWAT for Morice River and Atna Lake for four climate scenarios. Morice River and Atna Lake are included here as they are modeled to be the warmest and coolest stream temperatures respectively (Table 6). Blue lines mark important thermal thresholds for salmon as discussed in previous publications (noted at right).

observations of MWAT for subdrainages of the Kitsumkalum River watershed show the model to accurately predict the MWAT of three basins across four years (±0.87°C), but to systematically overestimate stream temperature by an average of +3.18±0.40°C for the other five basins. This uncertainty is important in the following estimates of future MWAT.

Projections of future MWAT (Table 6 and Fig. 9) indicate stream temperatures reaching critical species assemblage thresholds or thermal migration barriers for Morice River, Nanika River, Thautil River, Owen Creek and Lamprey creek during the 21st century. This likely results in the lack of glacier buffering and lower elevations of Thautil River and Owen and Lamprey creeks, the rapid disappearance of Nanika River glaciers and the role the large lakes (e.g., Morice, Nanika and Kidprice lakes) play in increasing residence time and warming of Nanika and Morice rivers. Basins with greater glacier cover warm more through the 21st-century (Table 5) but are more likely to stay within an optimal thermal range later into the 21st century (Table 6 and Fig. 9). This general pattern of which basins remain cooler, and which reach critical thermal thresholds makes sense given the importance of glacier cover, elevation, and the warming influence of lakes, and it also matches the values monitored elsewhere (e.g., Kitsumkalum subdrainages). Some results, however, are likely spurious and require additional measurement and monitoring. The model is possibly overestimating the MWAT of Morice and Nanika rivers, which should have MWAT values much colder than Owen and Lamprey creeks, given high discharge, higher elevations, and thermal buffering from glacier melt. The model is likely underestimating present-day and future MWAT of Owen and Lamprey creeks.

Given the model uncertainty, and the importance of thermal regime for salmonids (e.g., Milner et al., 2009 and Munoz et al., 2014), follow-up research is required, including baseline measurements of, and monitoring of stream temperature and discharge. Quantification of MWAT in present-day conditions will provide a foundation from which to more accurately model the future thermal regime of upper Morice River region subdrainages, particularly with respect to thresholds of concern (Fig. 9). An improved understanding of present-day discharge in subdrainages of concern will enable a better test of the empirical model used here (Eq. 1), particularly given the application of the average discharge of Morice and Nanika rivers to the other basins. While this application will capture the broad climatic similarity of the region, it will not be representative of additional basin-specific characteristics that are important drivers of discharge (e.g., groundwater contribution, evapotranspiration, and land-use change). Once baseline measurements of MWAT are established, follow-up modeling should be completed to better constrain likely 21st-century thermal conditions.

## Conclusion

Climate change of the 21st century will drive rapidly diminishing glacier reservoirs and seasonal snowpack of the upper Morice River region. These reductions in cryospheric contributions to downstream freshwater systems will generally result in lower streamflow and higher stream temperatures, an earlier freshet, a longer dry season, and reduced groundwater recharge. There are, however, differences from one subdrainage to another that will result in freshwater refugia and/or opportunities for mitigative and adaptive response. Basins with higher elevations and greater present-day glacier cover (e.g., Atna and Morice lakes) will provide localized thermal refugia and higher stream flows. The most optimistic climate pathway (RCP2.6/SSP126) offers hope for some meaningful hydrologic buffering capacity remaining in highest subdrainages of Morice River by the end of the $21^{st}$ century. The smaller glaciers of the Nanika River watershed are forecasted to recede rapidly, leading to a near disappearance by mid-century and a commensurate loss of glacier meltwater within the basin. The lower-elevation basins of Owen and Lamprey creeks, with no present-day glacier cover and a seasonal snowpack that is likely to see dramatic reductions, will be prone to reach critical thermal thresholds and experience dewatering events in the near term. Historical forestry practices in these basins, however, presents an opportunity for remediation that could see these watersheds become less susceptible to hot, dry years than at present. The non-glacierized Gosnell Creek and Thautil River basins are at higher elevations than Owen and Lamprey creeks and have less landcover impacts. This will likely result in discharge and stream temperatures being not as heavily impacted as in Owen and Lamprey creeks, but more vulnerable than the basins with some present-day glacier cover. Future work should include: 1) repeated glacier inventories recurring every 5-10 years, 2) assessment of the variability of seasonal snowpack and streamflow impacts with respect to forestry practices, 3) establishment of surface mass balance monitoring of an accessible, representative glacier in the region, and 4) monitoring of stream temperatures to gain baseline MWAT in numerous summer seasons to establish variability in present-day conditions. This additional empirical evidence will help refine the modeling presented here and provide the ongoing monitoring necessary to be responsive to the likely changes of the $21^{st}$ century.

## References

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, 438, 303-309, doi:10.1038/nature04141

Barouillet, C., Cumming, B. F., Laird, K. R., Perrin, C. J., and Selbie, D. T. 2019. Influence of glacial flour on the primary and secondary production of sockeye salmon nursery lake: a comparative modern and paleolimnological study, *Canadian Journal of Fisheries and Aquatic Sciences,* 76, 12, doi:10.1139/cjfas-2018-0372

Beedle, M. J. 2020. Morice River watershed morphometry, *Report, Morice Watershed Monitoring Trust*, 27 pp.

Beedle, M. J. 2021. Morice River watershed glacier inventory, *Report, Morice Watershed Monitoring Trust*, 33 pp.

Brett, J. R., Shelbourn, and Shoop, C. T. 1969. Growth rate and body composition of fingerling sockeye salmon, *Oncorhynchus nerka*, in relation to temperature and ration size, *Journal of the Fisheries Board of Canada*, 26, 9, doi:10.1139/f69-230

Clarke, G. K. C., Jarosch, A. H., Anslow, F. S., Radic, V. and Menounos, B. 2015. Projected deglaciation of western Canada in the twenty-first century, *Nature Geoscience*, doi:10.1038/NGEO2407

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., and Pasteris, P. P. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *International Journal of Climatology,* 28, 15, 2031-2064, doi:10.1002/joc.1688

Fellman, J. B., Hood, E., Dryer, W., and Pyare, S. 2015. Stream physical characteristics impact habitat quality for Pacific Salmon in two temperate coastal watersheds, *PLoS ONE,* 10 (7), doi:10.137/journal.pone.0132652

Fellman, J. B., Nagorski, S., Pyare, S., Vermilyea, A. W., Scott, D. and Hood, E. 2014. Stream temperature response to variable glacier coverage in coastal watersheds of Southeast Alaska, *Hydrological Processes,* 28, 2062-2073, doi:10.1002/hyp.9742

Fountain, A. G. and Tangborn, W. V. 1985. The Effect of Glaciers on Streamflow Variations, *Water Resources Research*, 21, 4, 579-586.

Frans, C., Istanbulluoglu, E., Lettenmaier, D. P., Fountain, A. G., and Riedel, J. 2018. Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960-2099, *Water Resources Research,* 54, doi:10.1029/2017WR021764

Harder, P., Pomeroy, J. W., and Westbrook, C. J. 2015. Hydrological resilience of a Canadian Rockies headwaters basin subject to changing climate, extreme weather, and forest management, *Hydrological Processes,* 29, 3905-3924, doi:10.1002/hyp.10596

Harris, I., Jones, P., Osborn, T., and Lister, D. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, *International Journal of Climatology,* 34, 623-642, doi:10.1002/joc.3711

Hotovy, O., and Jenicek, M. 2020. The impact of changing subcanopy radiation on snowmelt in a disturbed coniferous forest, *Hydrological Processes,* 34, 26, 5298-5314, doi:10.1002/hyp.13936

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R., and Winder, M. 2017. Towards mountains without permanent snow and ice, *Earth's Future,* 5, 418–435, doi:10.1002/2016EF000514

Huss, M. and Hock, R. 2018. Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8, 135-140, doi:10.1038/s41558-017-0049-x

Johnson, E. and Rupper, S. 2020. An examination of physical processes that trigger the albedo-feedback on glacier surfaces and implications for regional glacier mass balance across high mountain Asia, *Frontiers in Earth Science,* doi:10.3389/feart.2020.00129

Khadka, A., Kayastha, R. B., and Kayastha, R. 2020. Future projection of cryospheric and hydrologic regimes in Koshi River basin, Central Himalaya, using coupled glacier dynamics and glacio-hydrological models, *Journal of Glaciology,* 66, 259, 831-845, doi:10.1017/jog.2020.51

Lambrecht, A. and Mayer, C. 2009. Temporal variability of the non-steady contribution from glaciers to water discharge in western Austria, *Journal of Hydrology,* 376, 353-361, doi:10.1016/j.jhydrol.2009.07.045

Larsen, C. F., Burgess, E., Arendt, A. A., O'Neel, S., Johnson, A. J. and Kienholz, C. 2015. Surface melt dominates Alaska glacier mass balance, *Geophysical Research Letters*, 42, 5902-5908, doi:10.1002/2015GL064349

Leach, J. A. and Moore, R. D. 2019. Empirical stream thermal sensitivities may underestimate stream temperature response to climate warming, *Water Resources Research,* 55, 7, 5453-5467, doi:10.1029/2018WR024236

Li, Z., Chen, Y., Li, Yupeng, and Wang, Y. 2020. Declining snowfall fraction in the alpine regions, Central Asia, *Nature,* 10:3476, doi.org/10.1038/s41598-0200603030z

Mahony, C. R., Wang, T., Hamann, A., and Cannon, A. J. 2021. A CMIP6 ensemble for downscaled monthly climate normal over North America, submitted to *EarthArXiv*, 26 pp. doi:10.31223/X5CK6Z

Mantua, N., Tohver, I., and Hamlet, A. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State, *Climatic Change,* 102, 187-223, doi:10.1007/s10584-010-9845-2

Marshall, S. J., White, E. C., Demuth, M. N., Bolch, T., Wheate, R., Menounos, B., Beedle, M. J., and Shea, J. M. 2011. Glacier water resources on the eastern slopes of the Canadian Rocky Mountains, *Canadian Water Resources Journal,* 36 (2), 109-133, doi:10.4296/cwrj3602823

Marzeion, B., Jarosch, A. H., and Hover, M. 2012. Past and future sea level change from the surface mass balance of glaciers, *The Cryosphere*, 6, 1295-1322, doi:10.5194/tc-6-1295-2012

Marzeion, B., Hock, R., Anderson, B., Bliss, A., Champollion, N., Fugita, K., et al. 2020. Partitioning the uncertainty of ensemble projections of global glacier mass change, *Earth's Future,* 8, e2019EF001470, doi:10.1029/2019EF001470

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A. H., Landmann, J., Oesterle, F., Recinos, B., Rothenpieler, T., Vlug, A., Wild, C. T. and Marzeion, B. 2019. The Open Global Glacier Model (OGGM) v1.1, *Geoscientific Model Development,* 12, 909-931, doi:10.5194/gmd-12-909-2019

McNeil, C. J., Campbell, S. W., O'Neel, S. R. and Baker, E. H. 2019. Glacier-wide mass balance and compiled data inputs: Juneau Icefield glaciers (ver. 1.0, November 2019): U.S. Geological Survey data release, https://doi.org/10.5066/P9YBZ36F.

Menounos, B., Hugonnet, R., Shean, D., Gardner, A., Howat, I., Berthier, E., Pelto, B., Tennant, C., Shea, J., Noh, M. J., Brun, F. and Dehecq, A. 2019. Heterogeneous changes in western North American glaciers linked to decadal variability in zonal wind strength, *Geophysical Research Letters,* 46, 200-209, doi:10.1029/2018GL080942

Milner, A., M., Brown, L. E., and Hannah, D. M. 2009. Hydroecological response to river systems to shrinking glaciers, *Hydrological Processes,* 23, 62-77, doi:10.1002/hyp.7197

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Fureder, L., Cauvy-Fraunie, S., Gislason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Olafsson, J. S., Robinson, C. T., Tranter, M., and Brown, L. E. 2017. Glacier shrinkage driving global changes in downstream systems, *PNAS,* 114, 37, 9770-9778, doi:10.1073/pnas.1619807114

Moore, R. D., Nelitz, M. and Parkinson, E. 2013. Empirical modelling of maximum weekly average temperature in British Columbia, Canada, to support assessment of fish habitat suitability, *Canadian Water Resources Journal*, 38, 135-147, doi:10.1080/07011784.2013.794992

Moore, R. D., Pelto, B., Menounos, B., and Hutchinson, D. 2020. Detecting the effects of sustained glacier wastage on streamflow in variably glacierized catchments, *Frontiers in Earth Science,* 8, 136, doi:10.3389/feart.2020.00136

Munoz, N. J., Farrell, A. P., Heath, J. W., and Neff, B. D. 2014. Adaptive potential of a Pacific salmon challenged by climate change, *Nature Climate Change*, vol. 5, 163-166, doi: 10.1038/NCLIMATE2473

O'Neel, S., Hood, E., Bidlack, A. L., Fleming, S. W., Arimitsu, M. L., Arendt, A., Burgess, E., Sergeant, C. J., Beaudreau, A. H., Timm, K., Hayward, G. D., Reynolds, J. H., and Pyare, S. 2015. Icefield-to-Ocean linkages across the Northern Pacific coastal temperate rainforest ecosystem, *BioScience*, 65, 5, 499-512.

Parkinson, E. A., Lea, E. V., Nelitz, M. A., Knudson, J. M., and Moore, R. D. 2016. Identifying temperature thresholds associated with fish community changes in British Columbia, Canada, to support identification of temperature sensitive streams, *River Research and Applications,* 32, 330-347, doi:10.1002/rra.2867

Pfeffer, W.T. and 18 others. 2014. The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of* Glaciology, 60(221), 537–552, doi: 10.3189/2014JoG13J176

Pitman, K., Moore, J. W., Sloat, M. R., Beaudreau, A. H., Bidlack, A. L., Brenner, R. E., Hood, E. W., Pess, G. R., Mantua, N. J., Milner, A. M., Radic, V., Reeves, G. H., Schindler, D. E., and Whited, D. C. 2020. Glacier retreat and Pacific salmon, *BioScience*, 70, 3, 220-236, doi:10.1093/biosci/biaa015

Schelker, J., Kuglerova, L., Eklöf, Bishop, K. and Laudon, H. 2013. Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses, *Journal of Hydrology,* 484, 105-114, doi:10.1016/j.hydrol.2013.01.015

Shanley, C. S., Pyare, S., Goldstein, M. I., Alaback, P. B., Albert, D. M., Beier, C. M., Brinkman, T. J., Edwards, R. T., Hood, E., MacKinnon, A., McPhee, M. V., Patterson, T. M., Suring, L. H., Tallmon, D. A., and Wipfli, M. S. 2015. Climate change implications in the northern coastal temperate rainforest of North America, *Climatic Change*, 130, 155-170, doi:10.1007/s10584-015-1355-9

Shea, J. M., Whitfield, P. H., Fang, X., and Pomeroy, J. W. 2021. The role of basin geometry in mountain snowpack responses to climate change, *Frontiers In Water,* 3, 604275, doi:10.3389/frwa.2021.604275

Sproles, E. A., Nolin, A. W., Rittger, K., and Painter, T. H. 2013. Climate change impacts on maritime mountain snowpack in the Oregon Cascades, *Hydrology and Earth System Sciences,* 17, 2581-2597, doi:10.5194/hess-17-2581-2013

Strahler, A. N. 1952. Hypsometric (area-altitude) analysis of erosional topography, *Geological Society of America Bulletin,* 63, 1117-1142, doi:10.1130/0016-7606(1952)63<1117.HAAOET>2.0.CO;2

Taylor, K. E., Stouffer, R. J. and Meehl, G. A. 2012. An overview of CMIP5 and the experiment design, *American Meteorological Society,* 93, 4, 485-498, doi:10.1175/BAMS-D-11-00094.1

Varhola, A., Coops, N. C., Weiler, M. and Moore, R. D. 2010. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results, *Journal of Hydrology,* 392, 219-233, doi:10.1016/j.jhydrol.2010.08.009

Wang, T., Hamann, A., Spittlehouse, D. L., and Carroll, C. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America, *PLoS ONE*, 11, 6, e0156720, doi:10.137/journal.pone.0156720

Woollings, T., Barriopedro, D., Methven, J., Son, S., Martius, O., Harvey, B., Sillmann, J., Lupo, A. R., and Seneviratne, S. 2018. Blocking and its response to climate change, *Current Climate Change Reports*, 4, 287-300, doi:10.1007/s40641-018-0108-z

Zekollari, H., Huss, M. and Farinotti, D. 2020. On the imbalance and response time of glaciers in the European Alps, *Geophysical Research Letters,* 47, e2019GL085578, doi:10.1029/2019GL085578

## Appendix A: Supplemental Data

| | | 2050 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Watershed | 2020 (Gt) | RCP26 (Gt) | % | % Change | RCP45 (Gt) | % | % Change | RCP60 (Gt) | % | % Change | RCP85 (Gt) | % | % Change |
| Morice River | 3.827 | 0.818 | 21.4 | -78.6 | 0.516 | 13.5 | -86.5 | 0.675 | 17.6 | -82.4 | 0.274 | 7.2 | -92.8 |
| Morice Lake | 1.190 | 0.232 | 19.5 | -80.5 | 0.155 | 13.0 | -87.0 | 0.192 | 16.2 | -83.8 | 0.100 | 8.4 | -91.6 |
| Nanika River | 0.470 | 0.030 | 6.4 | -93.6 | 0.021 | 4.5 | -95.5 | 0.026 | 5.5 | -94.5 | 0.016 | 3.5 | -96.5 |
| Atna Lake | 2.167 | 0.556 | 25.6 | -74.4 | 0.341 | 15.7 | -84.3 | 0.457 | 21.1 | -78.9 | 0.157 | 7.3 | -92.7 |

| | | 2100 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Watershed | 2020 (Gt) | RCP26 (Gt) | % | % Change | RCP45 (Gt) | % | % Change | RCP60 (Gt) | % | % Change | RCP85 (Gt) | % | % Change |
| Morice River | 3.827 | 0.248 | 6.5 | -93.5 | 0.094 | 2.4 | -97.6 | 0.074 | 1.9 | -98.1 | 0.017 | 0.4 | -99.6 |
| Morice Lake | 1.190 | 0.117 | 9.9 | -90.1 | 0.057 | 4.8 | -95.2 | 0.044 | 3.7 | -96.3 | 0.007 | 0.5 | -99.5 |
| Nanika River | 0.470 | 0.011 | 2.4 | -97.6 | 0.008 | 1.8 | -98.2 | 0.008 | 1.7 | -98.3 | 0.005 | 1.2 | -98.8 |
| Atna Lake | 2.167 | 0.119 | 5.5 | -94.5 | 0.028 | 1.3 | -98.7 | 0.022 | 1.0 | -99.0 | 0.005 | 0.2 | -99.8 |

**Table A1: Modeled glacier volume change.** Glacier volume modeled for 2050 (upper panel) and 2100 (lower panel) with the OGGM for four climate scenarios (RCP 2.6, 4.5, 6.0 and 8.5). Glacier volumes are presented in Gigatons (Gt). Volume change presented as a percentage of 2020 and as a percent change since 2020. Results for Morice River combine all glaciers within the Morice Lake, Nanika River and Atna Lake subdrainages (Fig. 1).

| | | 2050 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Watershed | 2020 ($km^2$) | RCP26 ($km^2$) | % | % Change | RCP45 ($km^2$) | % | % Change | RCP60 ($km^2$) | % | % Change | RCP85 ($km^2$) | % | % Change |
| Morice River | 65.47 | 25.59 | 39.1 | -60.9 | 18.22 | 27.8 | -72.2 | 23.40 | 35.7 | -64.3 | 9.77 | 14.9 | -85.1 |
| Morice Lake | 22.35 | 6.99 | 31.3 | -68.7 | 4.52 | 20.2 | -79.8 | 6.20 | 27.7 | -72.3 | 2.45 | 11.0 | -89.0 |
| Nanika River | 15.32 | 0.99 | 6.5 | -93.5 | 0.44 | 2.9 | -97.1 | 0.76 | 5.0 | -95.0 | 0.35 | 2.3 | -97.7 |
| Atna Lake | 27.80 | 17.62 | 63.4 | -36.6 | 13.26 | 47.7 | -52.3 | 16.44 | 59.1 | -40.9 | 6.96 | 25.1 | -74.9 |

| | | 2100 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Watershed | 2020 ($km^2$) | RCP26 ($km^2$) | % | % Change | RCP45 ($km^2$) | % | % Change | RCP60 ($km^2$) | % | % Change | RCP85 ($km^2$) | % | % Change |
| Morice River | 65.47 | 12.41 | 19.0 | -81.0 | 2.44 | 3.7 | -96.3 | 2.17 | 3.3 | -96.7 | 0.40 | 0.6 | -99.4 |
| Morice Lake | 22.35 | 3.96 | 17.7 | -82.3 | 1.27 | 5.7 | -94.3 | 1.15 | 5.1 | -94.9 | 0.12 | 0.5 | -99.5 |
| Nanika River | 15.32 | 0.53 | 3.5 | -96.5 | 0.18 | 1.2 | -98.8 | 0.17 | 1.1 | -98.9 | 0.13 | 0.8 | -99.2 |
| Atna Lake | 27.80 | 7.91 | 28.4 | -71.6 | 0.99 | 3.5 | -96.5 | 0.85 | 3.1 | -96.9 | 0.15 | 0.5 | -99.5 |

**Table A2: Modeled glacier surface area change.** Glacier surface area modeled for 2050 (upper panel) and 2100 (lower panel) with the OGGM for four climate scenarios (RCP 2.6, 4.5, 6.0 and 8.5). Glacier surface areas presented in square kilometers ($km^2$) for 2020, 2050, and 2100. Surface area change presented as a percentage of 2020 and as a percent change since 2020. Results for Morice River combine all glaciers within the Morice Lake, Nanika River and Atna Lake subdrainages (Fig. 1).

## Appendix B: Overview of Glaciological Characteristics by Area/Watershed

The following overviews present primary area- or watershed-specific results. They are listed in order from largest to smallest by surface area. Multiple watersheds are grouped together where results are similar.

*Morice River*

The Morice River watershed includes the Nanika River, Morice Lake and Atna Lake subdrainages and the glaciers therein (Fig. 1). Of these, the larger glaciers of the Morice and Atna lake watersheds represent the most important frozen reservoirs. These glaciers, however, will recede rapidly in the 21$^{st}$ century with 7 to 21% of present-day glacier volume projected to be present by mid-century, and 0.4-3% by 2100 depending on climate scenario (Fig. 6 and Table A1). Loss of glacier volume and surface area will be more rapid in the Nanika River basin, which has smaller glaciers, more susceptible to warming. The larger, higher-elevation glaciers of the Atna Lake subdrainage represent most important source of stored freshwater in the upper Morice River region. Meltwater from these glaciers will remain an important, yet dwindling hydrologic buffer to mid-century, helping to keep Morice River summer discharge higher by 5-16%. Notable buffering capacity (8.6% of total summer discharge), however, will persist to late-21$^{st}$ century only in the most optimistic climate scenario (RCP2.6; Fig. 8). Stream temperatures (MWAT) are likely to increase by up to 2.4°C by mid-century and 4.6°C by 2100 (Table 5), with the likelihood of reaching thermal thresholds that could impede salmonids by mid-century. Modeled MWAT presented here, however, is cursory and it is strongly recommended that stream temperature monitoring be established to gain understanding of current conditions. Seasonal snowpack is likely to decrease with rising winter temperatures and a shortening of the winter season (Figs. 4 and 5, Table 4), with reductions of 7-14% by mid-century and 9-46% by the end of the century depending on climate scenario. Reductions in seasonal snowpack will lead to an earlier freshet and a longer summer dry season. Winter warming will decrease the snow fraction and result in more rain and melt events in winter, leading to higher winter discharge and the potential for scouring of spawning habitat.

*Morice Lake*

The glaciers of Morice Lake represent the second largest glacier reservoir in the upper Morice River region after Atna Lake. These ice masses are slightly more resilient than those of Nanika River and are forecasted to have 8-20% of present-day glacier volume remaining by mid-century, representing a greatly diminished but important source of summer meltwater for the small local basins that feed directly into Morice Lake and the nearshore lake environment. Numerous, small streams flow from high-elevation catchments above Morice Lake, many with present-day glacier cover. As such, we do not present stream temperature estimates. We recommend that Morice Lake salmonid habitat that is fed by these small streams be identified for potential investigation of individual subdrainages of high importance.

*Nanika River*

The Nanika River watershed has the smallest glaciers, and the least total glacier cover of the three glacierized sub-basins of Morice River. We forecast to recede rapidly, and to all-but disappear as early as mid-century. Our modeling projects 4-6% of present-day ice volume remaining by 2050, and 1-2% by 2100 (Fig. 6 and Table A1). This rapid recession results from a continuation of observed recent rates of recession (Fig. 7; Beedle, 2021). Summer discharge will decrease commensurate with this glacier recession, with 0.6-2.5% of JAS discharge from glacier melt by mid-century and 0.2-1.4% by 2100 (Fig. 8). Increases in MWAT are forecasted to be 1.8-2.4°C by 2050 and 2.0-4.2°C by 2100 (Table 5). As with Morice River, it is strongly recommended that stream temperature monitoring be established for Nanika River to gain an understanding of baseline stream temperatures. With higher average elevations, seasonal snowpack is forecasted to decrease the least of the subdrainages, with reductions of 6-13% by mid-century and 8-42% by the end of the 21$^{st}$ century (Table 4). Reductions in seasonal snowpack, and changing temperature and duration of winter months, will lead to an earlier freshet and longer summer dry season. The large lakes will remain an important landcover component of the Nanika River watershed, imparting a warming influence but also potentially offering deeper, colder water refugia near the outlets of steep, headwater subdrainages.

*Gosnell Creek and Thautil River*

The Gosnell Creek and Thautil River watersheds have no present-day glacier cover but have higher elevations than Owen and Lamprey creeks. Neither has significant lake cover, as with the glacierized watersheds (Nanika River, Morice Lake and Atna Lake), however, and so don't have the increased residence time and associated warming. We forecast seasonal snowpack to diminish by 8-16% and 7-14% by mid-century for Gosnell Creek and Thautil River respectively, and by 10-52% and 9-45% by the end of the century (Table 4). This, along with changing winter temperatures and duration of winter (Figs. 4 and 5), will lead to an earlier freshet, longer dry season, and reduced groundwater recharge. As there is no glacier ice to lose, forecasted increases MWAT (Table 5) are not as dramatic, reaching +1.3°C by 2050 and 3.0°C by 2100. Stream temperatures might reach thresholds critical to salmonids by the end of the 21st century (Table 6), but without present-day measurements of MWAT, these projections remain cursory. We recommend monitoring Gosnell Creek and Thautil River stream temperature to establish a present-day baseline.

*Owen and Lamprey Creeks*

Owen and Lamprey creeks are the most vulnerable in a warming climate with no glacier clover, the lowest average elevations, and the potential for past and current logging practices to have had an important impact on seasonal snowpack, streamflow, and stream temperature. These two basins are likely to see the most dramatic changes in seasonal snowpack, with reductions of up to 20% by mid-century and 67% by the end of the 21st century (Table 4). The large clearcut area in these watersheds (Beedle, 2020) has the potential to have had, and to still have, a marked impact on snow accumulation and melt. The impact of forestry practices on snowpack and streamflow remains an important known unknown in these two basins, but also likely presents an opportunity for remediation, making these more resilient than they otherwise would be in a warming 21st century. It is likely that stream temperatures in these two basins will reach temperature thresholds by the end of the 21st century that will impede salmonids. Our cursory estimates of MWAT presented here likely underestimate stream temperatures. We recommend stream temperature monitoring to establish present-day conditions.

*Atna Lake*

The glaciers of Atna Lake represent the largest, most important frozen reservoirs for the Morice River. While these glaciers will be the most resilient, they are forecasted to recede dramatically with 7-25% of present-day glacier volume remaining by mid-century and 0.2-6% by the end of the 21$^{st}$ century (Fig. 6 and Table A1). Remaining glacier surface area is modeled to be 25-63% of present-day totals by 2050 and 0.5-28% my 2100 (Fig. 7 and Table A2). The only meaningful glacier area and volume remaining by the end of the 21$^{st}$ century is forecasted for the Atna Lake subdrainage and under the most optimistic climate scenario (RCP2.6). All other climate scenarios forecast a nearly complete disappearance of all glaciers in the upper Morice River region by 2100. The higher elevations of the Atna Lake watershed make it less vulnerable to changes in seasonal snowpack with forecasted reductions of 7-14% by 2050 and 9-45% by 2100 (Table 4). Our modeling indicates that stream temperatures in the Atna Lake watershed are unlikely to reach thresholds critical to salmonids (Table 6 and Fig. 9), but monitoring should be established to gain an understanding of present-day conditions.