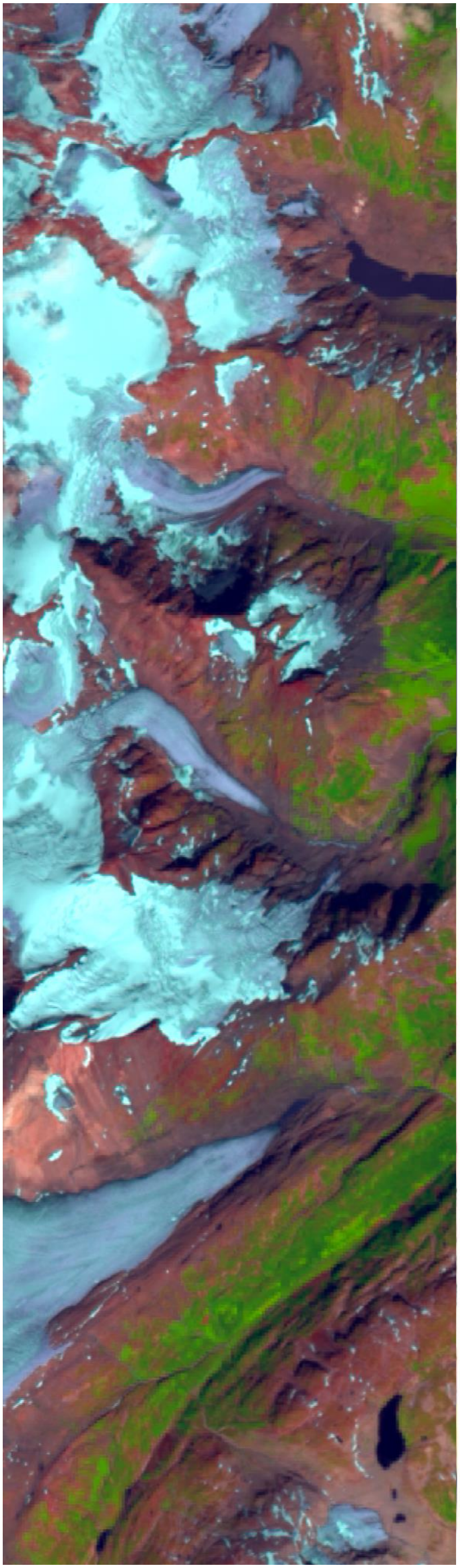

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Morice River Watershed Glacier Inventory

A report on behalf of the
Morice Watershed Monitoring Trust

MORICE WATERSHED
MONITORING TRUST

Matthew J. Beedle

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Contents

Introduction

This report presents a 2019 glacier inventory and glacier extent change (1975–2005–2019) for sub-drainages of the upper Morice River region (Fig. 1). This work comprises the second component of a multi-part project (Work Point 2 – Glacier Inventory). A previous report (Work Point 1 – Morice River Watershed Morphometry) assessed the topographic and landcover characteristics of each sub-drainage of the upper Morice River (Beedle, 2020). The goal of this report is to assess baseline (ca. early-21st Century) glacier conditions, recent glacier change and their ecological importance in their respective subdrainages.

With a warming climate, glacierized environments are currently in transition to a state of greatly reduced or eliminated snow and ice cover (e.g., Huss et al., 2017). This loss of glaciers decreases discharge during the melt season (e.g., Stahl and Moore, 2006) and increases water temperatures (e.g., Fellman et al., 2014), which in turn drive ecological changes in downstream aquatic ecosystems (e.g., Milner et al., 2009), including impacts on salmon (e.g., Munoz et al., 2014). This report presents the current (2019) state of glaciers, their recent recession (1975-2019), and their meltwater contributions to subdrainages of the upper Morice River.

The watersheds of interest investigated here are the same as those in the watershed morphometry report (Beedle, 2020) and are determined on one of two criteria: 1) the presence and location of hydrometric stations (Morice and Nanika rivers), or 2) the identification of a watershed as including important salmon and/or trout habitat in previous work (Bustard and Schell, 2002). Water quality is not currently monitored in watersheds defined by the second criteria. However, analysis presented here, in addition to previous work on watershed morphometry, will describe many underlying conditions that determine water quality in these watersheds with important aquatic ecosystems. Glacier cover in 2019 is almost exclusively in the Morice River watershed and its sub-drainages (Nanika River and Atna Lake); there is one small, remnant glacier in the Gosnell Creek watershed (Fig. 1). There are no glaciers in the Thautil River, Lamprey Creek and Owen Creek watersheds and these three watersheds are not discussed further in this report.

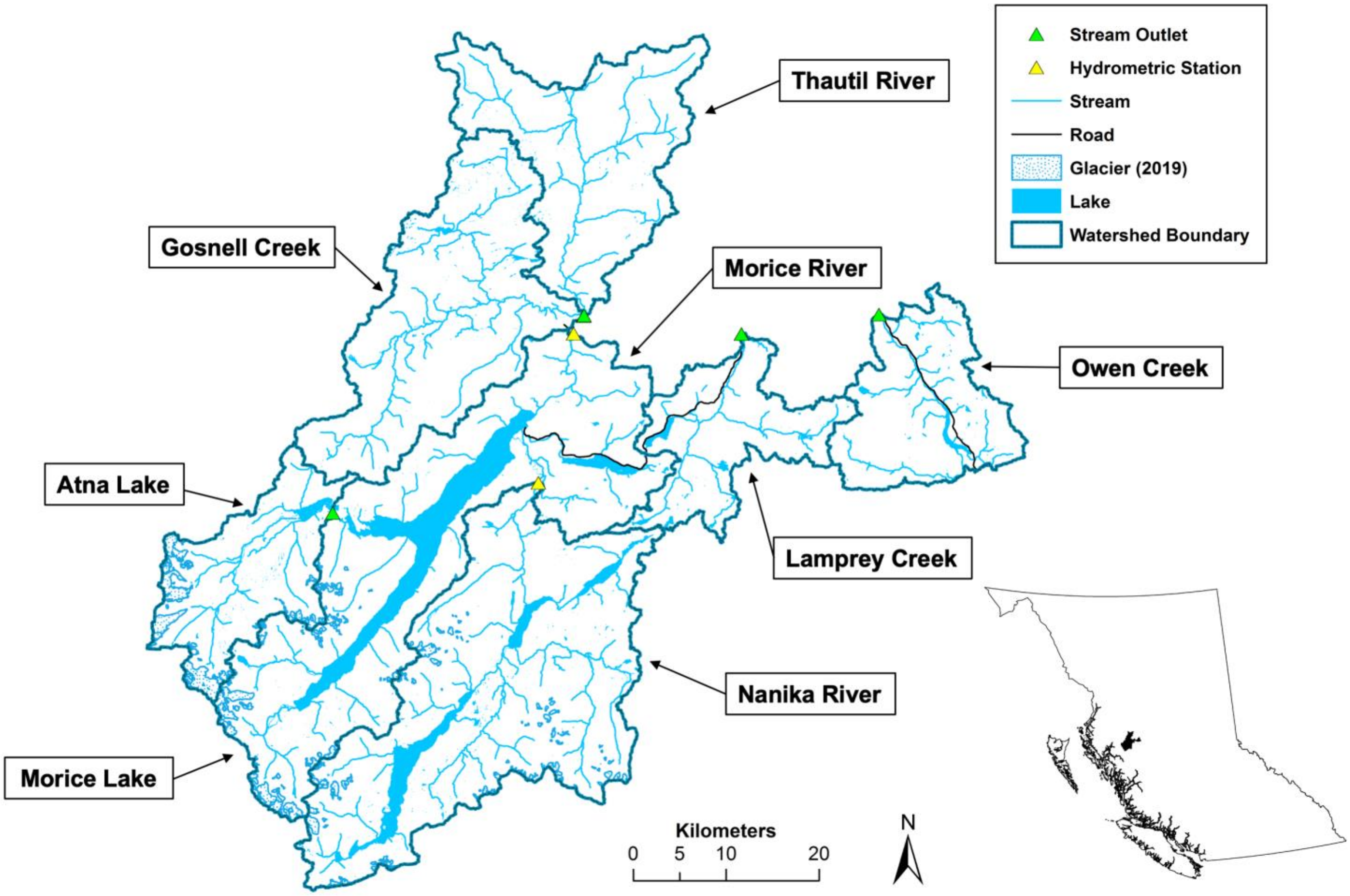

Figure 1: Upper Morice River area watersheds and 2019 glacier cover. Location of watersheds, respective hydrometric stations and 2019 glacier cover. The Morice River watershed includes the Nanika River and Atna Lake watersheds as subdrainages. Morice Lake refers to all Morice River watershed surface area other than the Nanika River and Atna Lake subdrainages.

Methods

Data

This report relies on glacier mapping from three different years. The 1975 glacier extents are from the B.C. Terrain Resource Information Management (TRIM) program, a B.C. Government product (www2.gov.bc.ca/gov/content/data/geographic-data-services/). These glacier extents were digitized manually with a stereoplotter from 1:20,000 black and white imagery taken primarily in early-July 1975 (British Columbia, 1992). Unfortunately, the aerial photographs in 1975 did not completely cover the glaciers of interest in this study; glaciers of the Atna Lake watershed were imaged in late-August

1983 (see maps of aerial photo flight lines in Appendix C). Change in glacier surface area and rates of recession presented in this report are calculated based on the 1983 imagery for Atna Lake glaciers. For simplicity, however, we refer to this earliest set of glacier extents as from 1975, except when change in Atna Lake watershed glaciers are addressed explicitly. Conditions were not optimal in early-July of 1975 for acquiring aerial imagery of glaciers. The nearest World Glacier Monitoring Service benchmark site (Lemon Creek Glacier, Alaska, 400km to the northwest) had a slightly positive annual mass balance in 1975 (+0.38 m water equivalent, w.e.; McNeil et al., 2019). This, and perhaps more importantly the date of imagery being not at the end of the melt season, may have resulted in a slight overestimation of 1975 glacier extents, particularly at upper elevations. For the Atna Lake watershed glaciers, however, conditions were much better for high-quality aerial photography, with a negative mass balance for Lemon Creek Glacier in 1983 of -1.53 m w.e. (McNeil et al., 2019), and a date of imaging much closer to the end of the melt season (1983-08-23). In addition to considerations of annual mass balance and seasonal snow cover, the TRIM product has a number of blunders due to errant mapping of debris-covered ice and some small glaciers that were excluded. We use the 1975 glacier extents here to derive decadal glacier change.

The 2005 glacier extents were derived from Landsat 5 TM imagery using a semi-automated process (Bolch et al., 2010), and are available as part of the Randolph Glacier Inventory (Pfeffer et al., 2014). Lemon Creek Glacier annual mass balance for 2005 was negative (-1.55 m w.e.; McNeil et al., 2019), and the date of imagery was August 24, near the end of the melt season. Thus, there is a reduced chance for error in the glacier extents derived from the 2005 imagery with seasonal snow cover lower than average and near the annual minimum. However, the Bolch et al. (2010) inventory includes only glaciers larger than 0.05 km^2, and so omits some smaller glaciers that we map here for the 2019 inventory. We use the 2005 glacier extents in this study to derive decadal glacier change.

To map 2019 glacier extents, we used two pan-sharpened, false-color composite (bands 6, 5 and 4) Landsat 8 scenes (L8_5122_20190808, L8_5123_20190808). The pan-sharpening results in a resolution of 15m. This Landsat imagery was accessed from the U.S. Geological Survey's EarthExplorer data portal (earthexplorer.usgs.gov). This date of imagery falls in the middle of a record-setting drought in northwest BC, and in a year when Lemon Creek Glacier experienced its lowest annual mass balance on record (-3.22 m w.e.; McNeil et al., 2019). This resulted in extremely low retained seasonal snowfall and ideal conditions for mapping glacier extents from satellite imagery. We use these 2019 glacier extents for the glacier inventory and to derive decadal glacier change.

All glacier elevation, aspect and slope data presented here is derived from the TRIM digital elevation model (DEM; www2.gov.bc.ca/gov/content/data/geographic-data-services/). Watershed delineation used here is the same as those in Work Point 1 of the project (Beedle, 2020), and are all surface areas upstream of their respective hydrometric station, or the lowest point of a watershed of interest (Fig. 1). Areas upstream of these points are determined from the TRIM DEM using ArcMap's Watershed Tools.

To estimate glacial meltwater inputs to Morice and Nanika rivers we use annual mass balance from the closest benchmark glacier (Lemon Creek Glacier, AK; McNeil et al., 2019). We extracted Morice and Nanika river discharge measurements from the Environment and Climate Change Canada Historical Hydrometric Data web site https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html on January 5, 2021.

Spatial Analysis

We mapped 2019 glacier extents manually from the August 8, 2019 Landsat 8 imagery. We map all multi-year ice bodies regardless of minimum size, whereas other inventories use certain minimum thresholds for glacier size: 0.01 km^2 in the Randolph Glacier Inventory (Pfeffer et al., 2014) and 0.05 km^2 in the inventory of western Canada glaciers (Bolch et al., 2010). Identification of smaller glaciers is made possible here by using manual digitization over a relatively small area, and the extremely low amount of seasonal snow in the summer of 2019 that often masks glacier ice.

We assessed nine different glacier attributes for each glacier in the 2019 inventory: total surface area, slope, aspect, maximum elevation, minimum elevation, elevation range, average elevation, and latitude/longitude of glacier centre. We calculated the elevation attributes, slope and aspect using the TRIM DEM and the 2019 outlines.

Additionally, we assessed glacier hypsometry for each watershed of interest. Hypsometry (area-altitude distribution) of the glacierized area in each watershed is taken as the summed surface area within 50m elevation bands. It is presented here in plots of cumulative surface area (Fig. 2). Each point on the lines of this plot indicates the total surface area (x-axis) that is above a given elevation (y-axis). Surface areas are normalized and presented as a percent so that watersheds with different surface areas can be compared.

Quantifying the extent of debris-covered ice is important as surface melt is significantly reduced once the thickness of debris exceeds 2-3cm (e.g., Nicholson and Benn, 2006). Debris-covered ice, however, is nearly completely absent on glaciers of the upper Morice River watersheds.

To derive decadal rates of glacier extent change, we used the 1975 extents as a mask, comparing only those glaciers that were mapped in each year (1975, 2005, and 2019). The 1975 inventory, and to a lesser extent the 2005 inventory, neglected to map some glaciers either because of blunders (1975) or a threshold for minimum glacier size (2005). Glacier-change analysis has been completed for a total glacier area of 65.47 km^2, 95% of the total glacier cover in the 2019 inventory (69.15 km^2).

We use the same definitions of individual glacier basins as used in the Bolch et al., (2010) inventory. As glaciers recede they separate into smaller parts that once contributed to a single, larger ice mass. Thus, the number of individual glaciers is increasing with time while the total surface area and volume are decreasing. Maintaining these historic glacier basins results in reductions in the quantity of individual glaciers that are present on the landscape but allows for the total glacier surface area to be compared through time.

Hydrologic Analysis

We estimate 1975-2019 glacial meltwater input to Morice and Nanika rivers using annual mass balance from the closest benchmark glacier (Lemon Creek Glacier, AK; McNeil et al., 2019), measurements of glacier surface area presented here, and historical discharge measurements from the hydrometric stations on the Morice and Nanika rivers (Fig. 1). Using annual mass balance as opposed to seasonal balance gives an estimate of meltwater from glaciers independent of contributions from seasonal snow (e.g., Lambrecht and Mayer, 2009). We omit the five years with positive annual mass balance from this analysis, as in these years there is a net gain of water equivalent by the glaciers, and high retention of seasonal snow, the melt of which will dwarf the meltwater from exposed glacier ice in the ablation area. We integrate surface area with annual balance to estimate a volume of glacier meltwater for a given year. To get annual changes in glacier surface area, we apply the annual average recession calculated for the periods 1975-2005 and 2005-2019, resulting in a piecewise linear function to interpolate surface areas between years of known surface area. Discharge measurements were extracted from the Environment and Climate Change Canada Historical Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html) on January 5, 2021. We estimate the relative contributions of glacial meltwater during the months of July, August and September, assuming that all glacial melt and downstream contributions occur in these months between when seasonal snow has largely melted, exposing glacier ice, and before the end of the melt season.

Results

Results presented here are only for those watersheds or areas with glacier cover and therefore there is no information presented for Thautil River, Lamprey Creek or Owen Creek (Fig. 1). We present data for the Morice River watershed and for its three subdrainages: Morice Lake, Nanika River and Atna Lake watersheds. Limited data is included here for the one glacier in the Gosnell Creek watershed as its small size (0.02 km^2) limits the relevance of much of the analysis. We present results here for 1) 2019 Glacier Inventory, 2) 1975-2005-2019 Glacier Change, and 3) 1975-2005-2019 Glacier Contributions to Streamflow.

2019 Glacier Inventory

There are 241 glaciers in the Morice River watershed totaling 69.15 km^2 (Table 1). The Morice Lake watershed has 83 of these glaciers (23.74 km^2), the Nanika River watershed 108 (16.99 km^2), and the Atna Lake watershed has 50 (28.42 km^2). These glacier surface areas, when compared with total

Watershed	Surface Area (km²)	Number of Glaciers (*n*)	Glacier Surface Area (km²)	Relative Watershed Glacier Cover (%)	Average Glacier Size (km²)	Min. Elev. (m)	Max. Elev. (m)	Elev. Range (m)	Mean Elev. (m)	Mean Slope (◦)
Morice River	1989.09	241	69.15	3.5	0.29	1184	2715	1531	1847	23.3
Morice Lake	871.13	83	23.74	2.7	0.29	1283	2244	961	1823	23.5
Nanika River	843.59	108	16.99	2.0	0.16	1283	2350	1067	1869	23.0
Gosnell Creek	533.63	1	0.02	0.0	0.02	1896	1988	92	1942	26.8
Atna Lake	274.37	50	28.42	10.4	0.57	1184	2715	1531	1839	23.8

Table 1: 2019 Glacier-cover Characteristics by Watershed. Watersheds are organized by total surface area from largest to smallest. Values for Morice River are for all glaciers in the Morice Lake, Nanika River and Atna Lake watersheds combined. Morice Lake refers to all remaining glaciers in the Morice River watershed that are not in the Nanika River or Atna Lake watersheds. The one remnant glacier in Gosnell Creek is outside of the Morice River watershed (as defined in this study as all surface area upstream of the hydrometric station).

watershed surface areas, yield a relative watershed glacier cover of 3.5% for the Morice River watershed, and 2.7, 2.0 and 10.4% respectively for the Morice Lake, Nanika River, and Atna Lake sub-basins. There is one remnant glacier in the Gosnell Creek watershed (0.02 km²).

Debris-covered glacier area is minimal in the upper Morice River watersheds and is limited to the ablation areas of four of the larger glaciers of the Morice Lake and Atna Lake watersheds. There is a total of 0.79 km² of debris-covered glacier in the Morice River watershed that is likely of a thickness to insulate underlying ice and limit surface melt (e.g., Nicholson and Benn, 2006). This represents 1.1% of the total glacier surface area in the Morice River watershed. Of this total, 0.65 km² is on the ablation areas of three larger glaciers in the Morice Lake watershed, representing 2.7% of the total glacier area in the watershed. In the Atna Lake watershed, 0.14 km² of debris cover is on the ablation area of one larger glacier, representing 0.5% of the total glacier area in the watershed.

The elevation ranges of glaciers in the Morice Lake and Nanika River watersheds are similar, whereas those in Atna Lake watershed are markedly different, reaching some 100m lower in elevation, and 400m higher (Table 1). Mean elevations vary little among the watersheds. The one small glacier in the Gosnell Creek watershed has little elevation range (92m) and a slightly higher mean elevation. The hypsometric curves (Fig. 2) all have similar shapes, flattening slightly in the middle which indicates

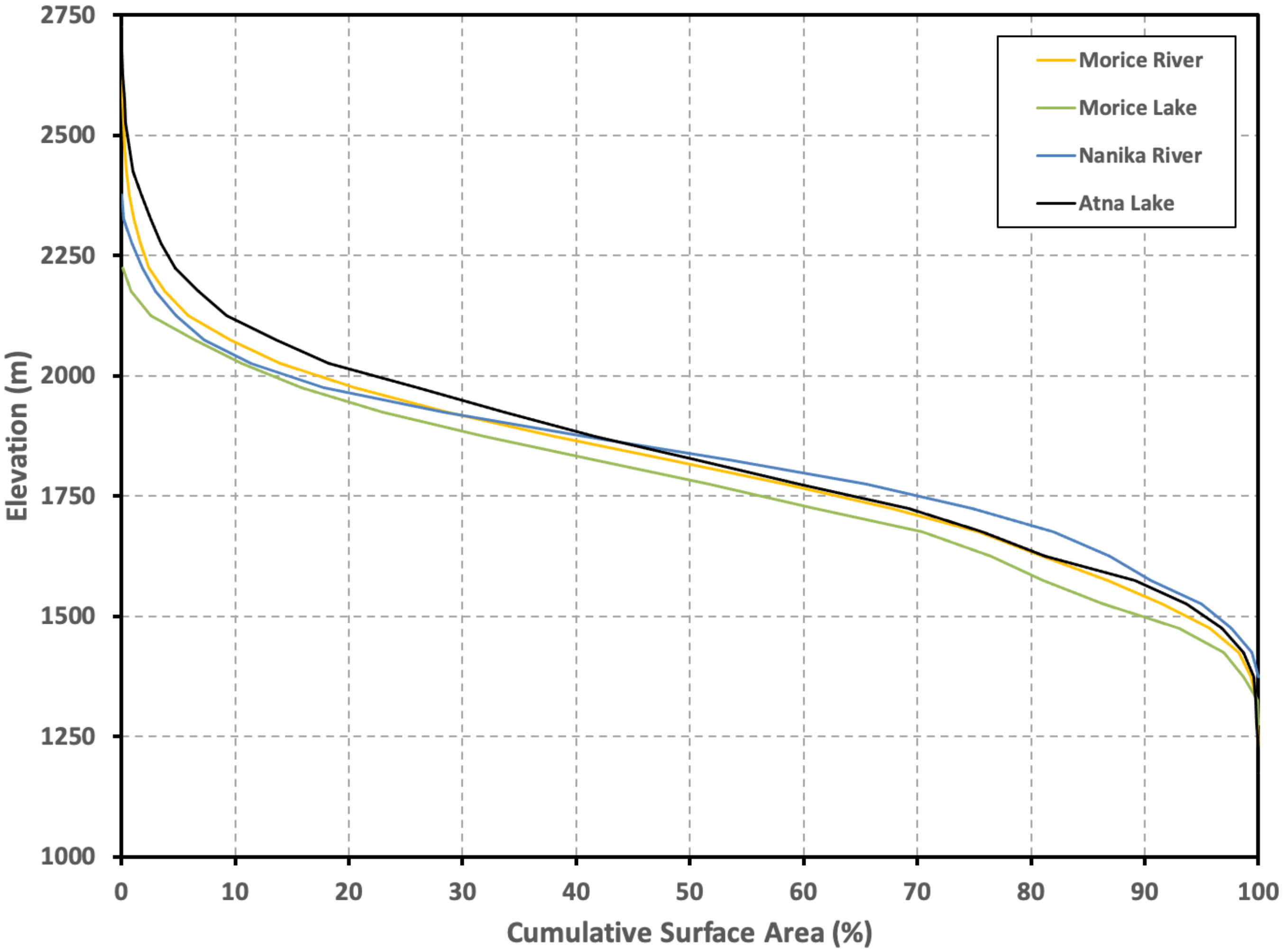

Figure 2: Glacier Hypsometry. Lines represent the hypsometry (area-altitude distribution) of the 2019 glacier surface area within each watershed. Points along each line represent the cumulative surface area above the respective elevation; curves can be used to represent unique response to a common climate signal. For example, an equilibrium line altitude of 1,750m in a given year would result in total accumulation areas that vary from 55% (Morice Lake) to 70% (Nanika River). The curve for Morice River (yellow) is an amalgamation of the other three with are all sub-drainages. The one Gosnell Creek glacier has been left off of this plot as the limited glacier elevation range results in negligible variability with elevation.

greater surface areas at these middle elevations (roughly 50% of total surface area between the elevations of 1,700 and 2,000m. There is more glacier surface area at higher elevations in the Atna Lake watershed, with ~22% above 2,000m versus ~13% above 2,000m for glaciers of the Morice Lake

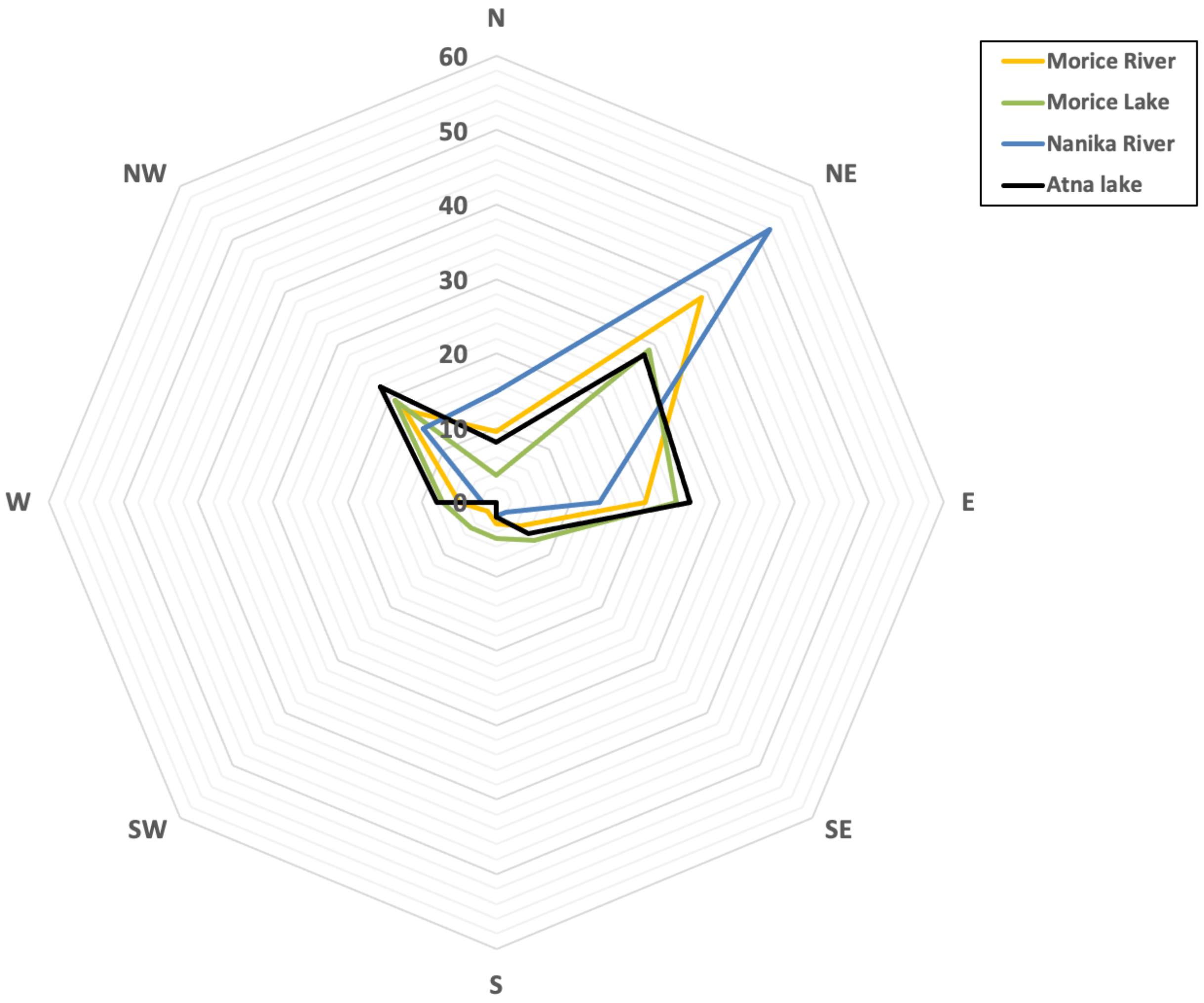

Figure 3: Glacier Aspect. Lines for each watershed indicate relative glacier aspect – the percent of glaciers with a particular aspect for a given watershed. Numbers on the figure are percent (0-60%). The one remnant glacier in the Gosnell Creek watershed has a northeast aspect.

and Nanika River watersheds. Glaciers of the Morice Lake and Nanika River watersheds are markedly different at lower elevations. Morice Lake glaciers have ~44% of their surface below 1,750m whereas Nanika River glaciers have 30% below 1,750m (Fig. 2).

There is no significant difference in slope of glaciers from one watershed to another. Mean slope as presented in Table 1 is the average slope of all individual glaciers, regardless of surface area. By this metric, all glaciers average a slope of ~23°. This value, however, is biased towards the smaller, steeper glaciers. Normalizing by surface area yields average slope angles of 18.3, 19.4 and 16.4° for total glacier surface area of the Morice Lake, Nanika River and Atna Lake watersheds respectively. This

		1975		2005		2019	
Watershed	**Watershed Surface Area (km^2)**	**Glacier Surface Area (km^2)**	**Watershed Glacier Area (%)**	**Glacier Surface Area (km^2)**	**Watershed Glacier Area (%)**	**Glacier Surface Area (km^2)**	**Watershed Glacier Area (%)**
Morice River	1989.09	112.60	5.66	86.04	4.33	65.47	3.29
Morice Lake	871.13	38.36	4.40	29.14	3.34	22.35	2.57
Nanika River	843.59	33.82	4.01	23.09	2.74	15.32	1.82
Atna Lake	274.37	40.42	14.73	33.82	12.32	27.80	10.13

Table 2: Change in relative glacier surface area of Morice River watersheds (1975-2005-2019). Watersheds are organized by total surface area from largest to smallest. Values for Morice River are for all glaciers in the remaining, smaller watersheds combined. Morice Lake refers to all remaining glaciers in the Morice River watershed that are not in the Nanika River or Atna Lake watersheds. Earliest surface mapping for Atna Lake glaciers was in 1983 and so the earliest surface areas presented here are from this year as opposed to 1975. Glacier surface area totals presented here are for glaciers mapped in each year and are not a complete inventory.

slightly more marked difference highlights the larger, slightly lower angle glaciers of the Atna Lake watershed.

Average aspects for Morice River glaciers are primarily northeast (39%), but with notable quantities of east (20%), northwest (17%), and north (10%) aspect glaciers (Fig. 3). There are few glaciers with southeast, south, southwest or west aspects, with glaciers of these aspects combined totaling 14%.

1975-2005-2019 Glacier Change

All glaciers in this study have receded since 1975, with rates of recession increasing from the 1975-2005 period to the 2005-2019 period (Tables 2 and 3). Relative glacier cover has decreased in all watersheds, most notably for Nanika River glaciers where it has dropped by more than half, from 4.01% to 1.82% (Table 2). Combined, glaciers of the Morice River watershed have lost 47.13 km^2 of glacier surface area since 1975, a loss of 41.86% (Table 3). Glaciers of the Nanika River watershed have receded the most, losing 54.71% of their surface area since 1975. Glaciers of the Atna Lake watershed receded the least, losing 31.22% of their total surface area since the TRIM-era aerial mapping. This result for Atna Lake, however, is likely at least partially driven by significant differences in photo dates (see further discussion below).

	Glacier Surface Area			Area Change 1975 - 2005			Area Change 2005 - 2019			Area Change 1975 - 2019		
Watershed	**1975** (km^2)	**2005** (km^2)	**2019** (km^2)	(km^2)	(%)	(%/a)	(km^2)	(%)	(%/a)	(km^2)	(%)	(%/a)
Morice River	112.60	86.04	65.47	-26.56	-23.59	-0.79	-20.57	-23.91	-1.71	-47.13	-41.86	-0.95
Morice Lake	38.36	29.14	22.35	-9.22	-24.04	-0.80	-6.79	-23.30	-1.66	-16.01	-41.74	-0.95
Nanika River	33.82	23.09	15.32	-10.74	-31.74	-1.06	-7.77	-33.64	-2.40	-18.50	-54.71	-1.24
Atna Lake	40.42	33.82	27.80	-6.61	-16.34	-0.74	-6.01	-17.78	-1.27	-12.62	-31.22	-0.87

Table 3: Glacier surface area change of Morice River glaciers (1975-2005-2019). Watersheds are organized by total surface area from largest to smallest. Values for Morice River are for all glaciers in the following, smaller watersheds combined. Morice Lake refers to all remaining glaciers in the Morice River watershed that are not in the Nanika River or Atna Lake watersheds. Rate of surface area change (%/a) is calculated for the 30-year period 1975-2005, the 14-year period 2005-2019 and for the 44-year period 1975-2019. Earliest surface mapping for Atna Lake glaciers was in 1983 and so rates of change for the earlier period and full period reflect this different period over which recession occurred. Glacier surface area totals presented here are for glaciers mapped in each year and are not a complete inventory.

The rate of recession has more than doubled for all Morice River glaciers combined, losing surface area more rapidly from the 1975-2005 period (-0.79 %/a) to the 2005-2019 period (-1.71 %/a; Table 3). The subsets of Morice Lake and Nanika River glaciers have also experienced a doubling in this rate of recession. The increased rate of recession for glaciers of the Atna Lake watershed is slightly lower than a doubling but still represents a marked increase (-0.74 to -1.27 %/a). The rate of recession for glaciers of the Nanika River watershed is significantly greater, particularly in the later period (2005-2019) when these glaciers receded at a rate of 2.4 %/a.

Recession of the one glacier in the Gosnell Creek is not available as the 1975 and 2005 mapping efforts did not include this small glacier.

Glacier Contributions to Streamflow

Our estimates of glacier meltwater indicate that the glaciers of the Morice River and Nanika River watersheds have contributed an average of 10.8 and 9.1% respectively of the total July-September discharge over the period 1975-2019 (Figs. 4 and 5). This has varied, however, from minimum contributions of 0.4 and 0.6% respectively in 2000, to maximum contributions of 30.0 and 25.4% respectively in the warm dry year of 2019. In general, as July-September discharge totals go down, glacier meltwater contributions go up (r = -0.50 and -0.54, p < 0.01).

Discussion

Discussion here follows the order in which glaciological characteristics were presented in the results section. See Appendix A for discussion that is focused for specific watersheds.

2019 Glacier Inventory

Relative glacier surface area is an important metric for understanding glacial contributions to downstream hydrologic systems (e.g., Fountain and Tangborn, 1985). The 50 glaciers of the Atna Lake watershed (28.42 km^2) cover 10.4% of the watershed's total surface area (Fig. 1, Table 1). This moderately high relative surface area means that there is currently ample glacial capacity to supply a thermal buffer and to augment streamflow during late-summer and early-fall in Atna River and Atna Lake. This buffering capacity, however, will become muted as meltwater reaches the much larger Morice Lake. There is less glacier surface area in the Morice Lake (23.74 km^2) and Nanika River (16.99 km^2) watersheds, and these watersheds are much larger than the Atna Lake watershed, resulting in relative watershed glacier cover of 2.7 and 2.0% respectively (Table 1). While absolute glacier surface areas are not greatly different from that of the Atna Lake watershed, the relative glacier cover is markedly less, which will result in less buffering capacity in these larger systems. Combined, the 241 glaciers of these three basins yields a relative watershed glacier cover of 3.5% for the Morice River watershed.

The low relative watershed glacier cover in the Morice River, Morice Lake and Nanika River watersheds means that there is currently limited capacity for glacier melt to supply a marked thermal buffer or augmentation of streamflow during the dry season of late-summer and early-fall. This low capacity is likely to dwindle further in the near term, with glaciers losing much of their hydrologic significance in the Morice River as a whole in the next 10-20 years. Smaller sub-basins of these larger systems, however, are likely to maintain ample thermal buffering capacity and ability to augment streamflow during late-summer and early-fall in their respective watersheds and in the immediate vicinity where they discharge into the large lakes of the upper Morice River area. The Atna Lake sub-basin is the most notable of these, still with 10.4% relative glacier cover. Ongoing recession in the Atna Lake watershed, however, will also reduce the quantity of glacier meltwater and capacity to provide a hydrologic buffer to Atna River and Atna Lake. This declining capacity will follow the same trajectory as the other basins but delayed by one to three decades.

Debris cover, if thicker than ~3cm, can insulate underlying glacier ice and delay melt (Nicholson and Benn, 2006). Areas with such debris cover can linger longer, supplying a slower, reduced supply of meltwater for many years after the parent glacier has receded. Such debris cover, totaling 0.79 km^2 (1.1%) in the Morice River watershed, is minimal, and unlikely to have a meaningful impact on glacier melt and downstream aquatic habitats. There will likely be small, local effects for the four glaciers with debris cover, three of which are in the Morice Lake watershed and one in the Atna Lake watershed. In these locations the underlying glacier ice will be preserved longer and melt rates will be lower. The extent of the debris cover is not sufficient to significantly delay glacier recession, or to result in significant delay in the reduction of meltwater as these glaciers continue to recede.

There are some differences in the elevation distribution of glacier surfaces that helps to explain their presence and their vulnerability in a warming climate. Glaciers of the Atna Lake watershed have a significantly larger elevation range (Table 1) and more area at higher elevations (Fig. 2). The higher maximum elevations are related to the higher topography of this watershed (Beedle, 2020). This higher topography, and position further west, closer to the maritime moisture source, has likely led to more winter accumulation, allowing for larger glaciers and flow to lower elevations. This higher-elevation zone of accumulation will help the glaciers of Atna Lake watershed persist longer as climate warms through the 21st century. The glaciers of the Morice Lake and Nanika River watersheds are similar at the highest elevations but differ at lower elevations with Morice Lake glaciers having more surface area at lower elevations. This will likely leave the Morice Lake glaciers slightly more vulnerable as climate warms. It should be noted, however, that significant thinning has occurred since the TRIM DEM (e.g., Schiefer et al., 2007) and that the elevation metrics presented here, while from a current mapping of extent, are derived from a significantly higher surface model. Use of an updated surface model is recommended but there will be significant challenges with this, most notably the small average size of glaciers in the upper Morice River area and the generally coarse resolution of satellite-derived DEMs. Regardless of updated surface information, topography of the Morice River watersheds

(Beedle, 2020) and glaciers therein, indicates that Atna Lake glaciers will be more resilient, and glaciers of the Morice Lake and Nanika River watersheds will be more vulnerable as climate warms.

Average slope angle of glaciers differs little from one watershed to another. Average slope angle for all individual glaciers within each basin yields a consistent slope of ~23° (Table 1). This metric is biased towards the more numerous, smaller and steeper glaciers. When normalized for glacier surface area, average slope angle is 18.3, 19.4 and 16.4° for total glacier surface area of the Morice Lake, Nanika River and Atna Lake watersheds respectively. This metric highlights the larger, lower slope angle glaciers of the Atna Lake watershed. The differences, however, are still marginal and there will be little influence on average glacier behavior in the different sub-basins due to slope angle.

Aspect is similar for glaciers of each of the watersheds with the majority of glaciers having average aspects of northeast (39.0%), east (19.9%) or northwest (17.4%; Fig. 3). This is largely due to the underlying topography of these watersheds on eastern slopes of the Coast Mountains (Fig. 1). However, previous work has also shown that similar glacier aspects are dominant throughout western Canada, indicating the role of solar radiation driving higher melt rates on south and southwest aspects (e.g., Schiefer et al., 2008; Bolch et al., 2010). A total of 66% of all glaciers in the Morice River watershed have northwest, north or northeast aspects. It is likely that portions of these glaciers, particularly high-elevation accumulation areas, will receive ample shading from ridges to the south. It is possible that the rate of recession of these glaciers will decrease and they could remain as small, remnant cirque glaciers well into the 21st century, even as the climate warms, protected from direct solar radiation in summer and fed by wind deposition and avalanching of snow in winter.

1975-2005-2019 Glacier Change

With ongoing glacier recession since 1975, the relative glacier cover in all watersheds has decreased (Table 2). This reduction in relative glacier cover equates to less capacity for glacier melt to provide a thermal and discharge buffer, particularly during drier, warmer summer months. Glacier recession has been most pronounced in the Nanika River watershed where relative glacier area has decreased by over half, from 4.01% glacier cover in 1975 to 1.82% glacier cover in 2019. Absolute glacier area change in the Nanika River watershed is -18.50 km^2, a decrease of 54.71% from the 1975 surface area (Table 3). This recession is larger than that of the neighboring Morice Lake watershed glaciers that have seen a loss of 41.74% since 1975. This is surprising in that the Morice Lake glaciers have lower elevations and should be more susceptible to surface melt and recession (Fig. 2). Nanika River glaciers, however, have the smallest average size (0.16 km^2), compared with an average glacier size of 0.29 km^2 for Morice Lake watershed glaciers. An inverse relation between recession rate and glacier size has been documented elsewhere (e.g., Bolch et al., 2010), and is seen here with smaller average glacier size (Table 1) matching increased rates of recession (Table 3). The greater recession of Nanika River glaciers, however, might be spurious, and related to the provincial TRIM analyst using a combination of aerial photography taken in both 1975 and 1983. The Nanika River watershed is almost exclusively covered by imagery from 1975, whereas the Morice Lake and Atna Lake watersheds were partially imaged in both 1975 and 1983 (Appendix C). It is our belief here, however, that the greater recession of Nanika River glaciers is real, given that the markedly higher recession rates are also found in the period 2005-2019, a period when date of imaging is not in question (Table 3).

The Atna Lake watershed differs markedly, still with 10% glacier cover, and a proportionately large influence of glacial meltwater some five times that of the relative contributions in the Nanika River watershed. Recession of Atna Lake glaciers, while at the slowest rates, has still been pronounced, with a loss of 12.62 km^2 (31.22%) of glacier surface area (Table 3). Note that for the early period for Atna Lake glaciers we are using 1983 as the earliest date of imagery, based on available information of aerial photo flight lines (Appendix C). The rate of area change for these glaciers presented in Table 3 (-0.74 %/a) is still the slowest rate even with this reduction in duration by eight years over which recession is averaged. This lower rate of recession for Atna Lake glaciers continues for the period 2005-2019 and so we conclude that this recession rate is real and that our assumption that the imaging date of 1983 is justified. It is logical that recession rates would be lower for these glaciers given more surface area at higher elevations (Fig. 2) and the inverse relation between glacier size and recession rate (e.g., Bolch et al., 2010).

Rates of glacier recession have doubled or nearly doubled in all watersheds from the earlier period (1975-2005) to the later period (2005-2019) (Table 3). Previous work has found similar increases in

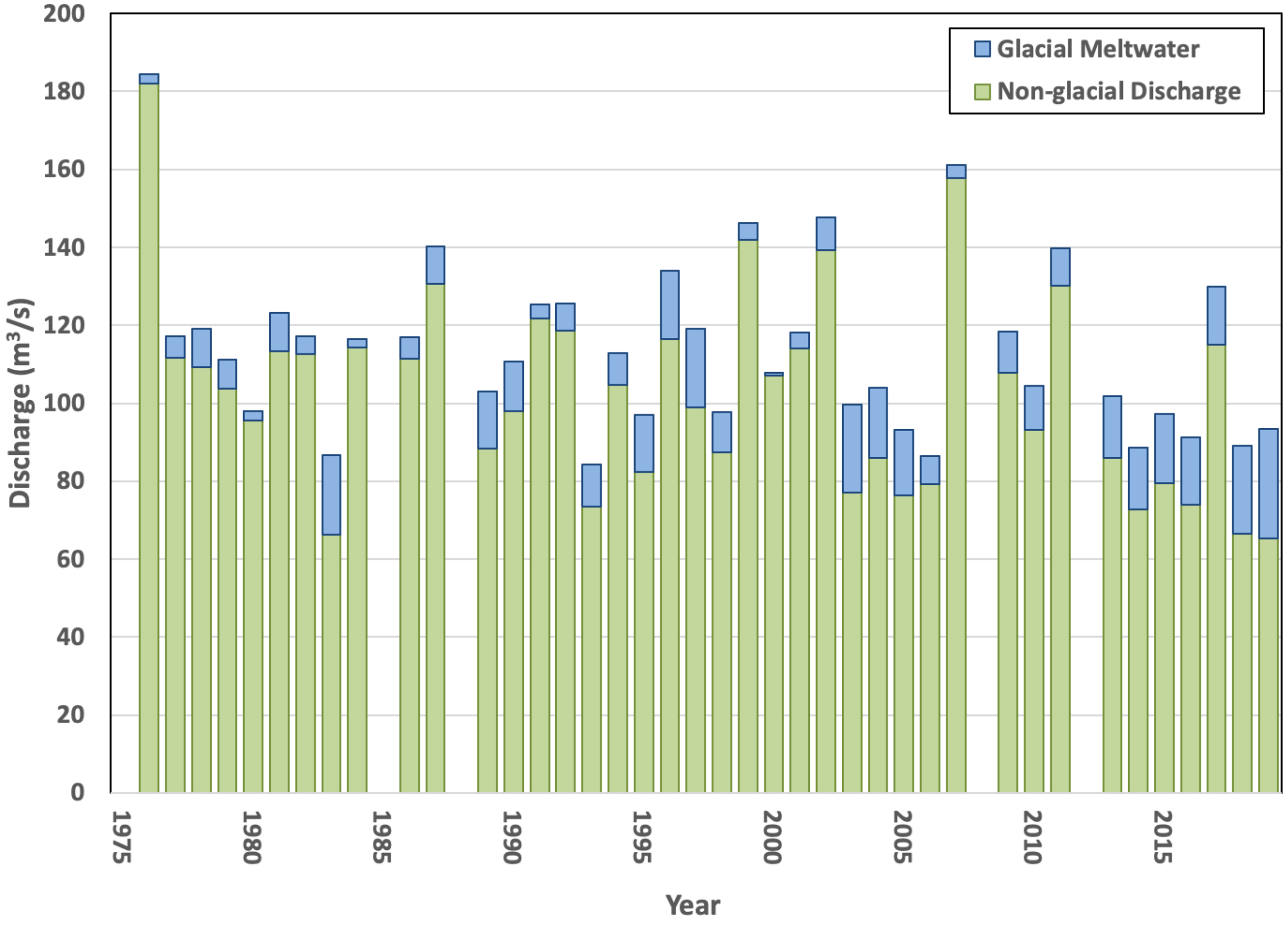

Figure 4: Estimated Contributions of Glacier Meltwater to Morice River Discharge, July - September (1976-2019). Each column represents July-August-September discharge for Morice River. Total discharge values (column heights, glacial and non-glacial sources combined) are as measured by the Water Survey of Canada. The blue portion of each column represents an estimate of the contribution to total discharge from glacial meltwater. The green portion of each column is the remaining, non-glacial sources of Morice River discharge combined. Missing data are for years when annual glacier mass balance was positive.

rates of melt and concluded that increasing summer temperatures are largely to blame (e.g., Larsen et al., 2015). The largely uniform increase in recession rate indicates a driver that is at least regional. When combined with similar findings on the continental and even global scale, however, increased rates of recession point to a universal cause - global temperature rise (e.g., Huss et al., 2017). Assuming recession rates as measured here for the period 2005-2019 (Table 3) continue, by 2050 Morice River glaciers would shrink to 40.51 km² (2.04% of total watershed area) and would further recede to 17.10 km² (0.86%) by the end of the century. This continuation of recent recession rates, however, is overly

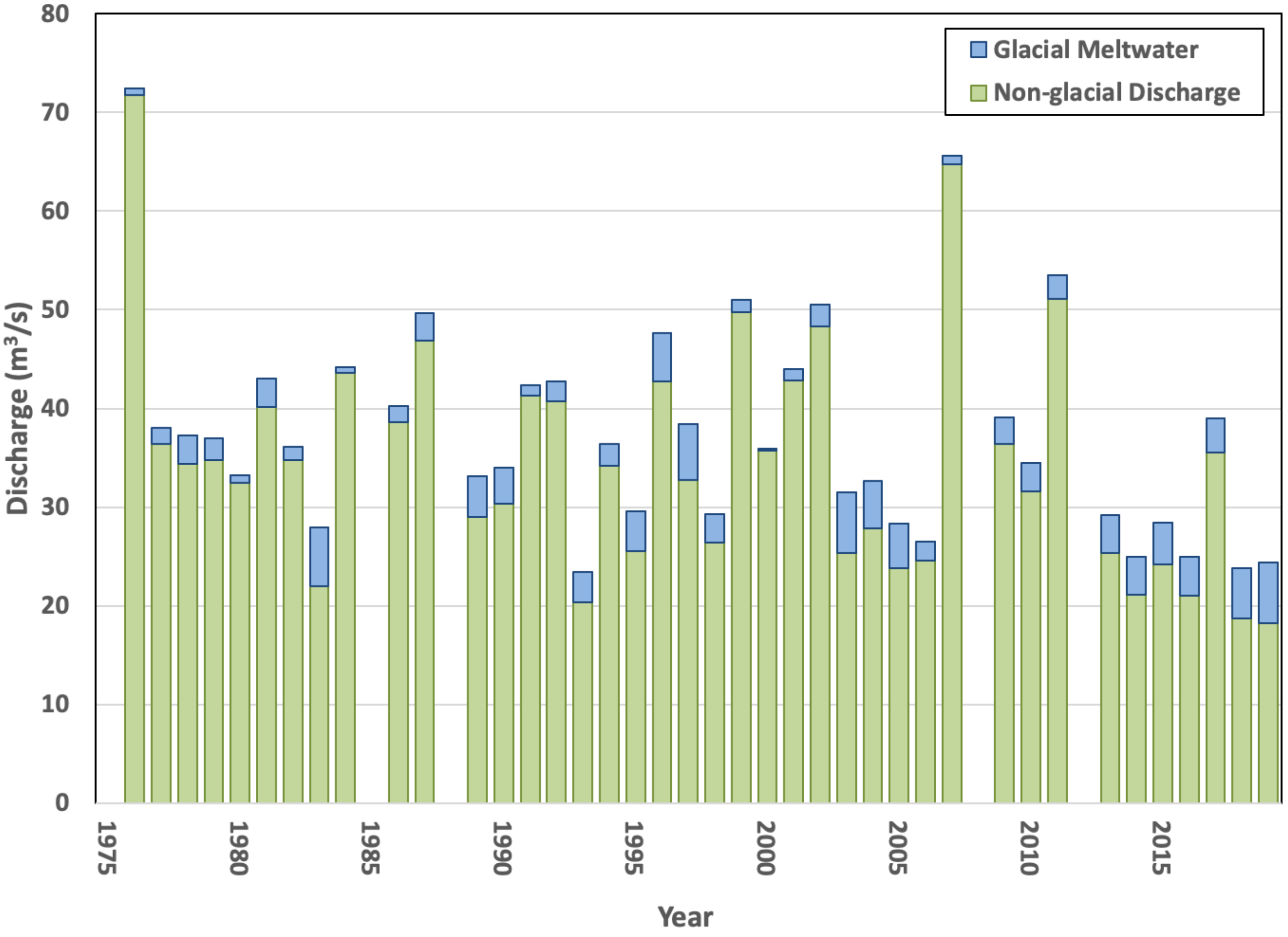

Figure 5: Estimated Contributions of Glacier Meltwater to Nanika River Discharge, July - September (1976-2019). Each column represents July-August-September discharge for Nanika River. Total discharge values (column heights, glacial and non-glacial sources combined) are as measured by the Water Survey of Canada. The blue portion of each column represents an estimate of the contribution to total discharge from glacial meltwater. The green portion of each column is the remaining, non-glacial sources of Nanika River discharge combined. Missing data are for years when annual glacier mass balance was positive.

simplistic and ignores important feedback mechanisms and modeled climate change (e.g., Shanley et al., 2015). Previous work projects a 70% decrease in glacier volume in western Canada by 2100 relative to 2005 (Clarke et al., 2015). This modeled remaining ice volume by 2100, however, is primarily what would remain of the large icefields present today in the northern Coast Mountains. The small glaciers of the Morice River watershed, however, are unlikely to persist to the end of the century. Regardless of a continued presence, their ability to contribute meltwater will be further reduced.

Glacier Contributions to Streamflow

Our quantification of meltwater contributions to Morice River and Nanika River streamflow are first-order estimates. We assume that the mass balance of Lemon Creek Glacier, 630 kilometers to the northwest, is representative of conditions at glaciers in our study. While the Lemon Creek Glacier record likely does capture regional climatology that is also relevant for our study area, there are also likely some significant differences. While most glacier melt will occur in the months of July - September, there will be some melt in other months and melt is likely concentrated in particular periods during this three-month window depending on weather conditions. Given these assumptions, we can still determine some details about contributions of glacier meltwater in the Morice and Nanika rivers. The contribution of glacial meltwater differs depending on weather in a given year, with increased glacier meltwater contribution in years where total discharge is lower. This is particularly visible in the warm, dry years of 2018 and 2019 when glacial meltwater was over 25% of total discharge in Morice River, and over 20% in Nanika River, demonstrating the buffering capacity of these glaciers. These years of extreme melt rapidly draw down the reservoir of glacier ice, however, leaving less capacity for future years with similarly dry conditions. All sub-basins of the upper Morice River area, Atna Lake watershed glaciers included, will be past peak water, the maximum of glacial runoff after which runoff steadily declines (Huss and Hock, 2018). While our calculations of glacial meltwater contribution to streamflow should be considered first-order, the magnitude and range do fit broadly with previous work (e.g., Marshall et al., 2011, Schaner et al., 2012).

Conclusion

Glaciers of the upper Morice River have receded markedly since 1975, with rates of recession doubling or nearly doubling from the early period (1975-2005) to the later period (2005-2019). While this glacier recession reduces the capacity of these glaciers to buffer water temperatures and stream discharge during late-summer and early-fall, there is still glacier cover today to contribute an average of ~10% of total discharge from glacial meltwater to the Morice and Nanika rivers in the months of July-September. This contribution reached ~25% in the warm, dry years of 2018 and 2019. This capacity, however, will be reduced as climate continues to warm, seasonal snowpack decreases and drought conditions such as those of 2018 and 2019 perhaps become more common place during the 21st century (e.g., Shanley et al., 2015). The larger, higher-elevation glaciers of the Atna Lake watershed are likely to be more resilient as climate warms, representing an important source of glacial meltwater in Atna River, Atna Lake and at least the immediate area where discharge meets Morice Lake (Fig. 1). The other two primary sub-basins of Morice River have smaller, lower-elevation glaciers than those of the Atna Lake watershed. These glaciers are likely to continue to recede more quickly and have their meltwater contributions to discharge dwindle rapidly.

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Appendix A: Overview of Glaciological Characteristics by Watershed

Morice River

The Morice River watershed has 241 glaciers, which total 69.15 km^2, resulting in a relative watershed glacier cover of 3.5% (Table 1). The most important sub-basins of the Morice River watershed are discussed separately below, including the larger, higher-elevation glaciers of the Atna Lake watershed, and the smaller, lower-elevation glaciers of the Nanika River watershed and remaining glaciers that feed Morice Lake directly (Fig. 1). The glaciers the Morice River watershed as a whole have lost 47.13 km^2 of surface area since 1975, a 41.86% decrease (Table 3, Appendix B). Recession rates have increased from -0.79 %/a during the earlier period (1975-2005) to -1.71 %/a for the later period (2005-2019). First-order estimates of glacial meltwater contributions to Morice River streamflow reveal an average contribution (1975-2019) of 10.67% of total Morice River discharge for the months July – September, and a maximum of 30.00% in the warm, dry year of 2019. Ongoing recession, however, will reduce this capacity for glacier meltwater to buffer streamflow levels and stream temperatures during the late-summer and early-fall melt season.

Morice Lake

The Morice Lake watershed includes all surface area in the larger Morice River watershed that does not contribute to either Nanika River or Atna Lake. Glaciers within this watershed contribute more directly to Morice Lake via shorter streams (Fig. 1, Appendix B). There are 83 glaciers in the Morice Lake watershed, which total 23.74 km^2, and result in a relative watershed glacier cover of 2.7% (Table 1). Average glacier size is 0.29 km^2, about double the average glacier size of Nanika River glaciers, and half of Atna Lake glaciers. Glacier size correlates inversely with recession rates (e.g., Bolch et al., 2010), a factor that is likely at least partially related to the glacier recession rates in the Morice Lake watershed being less rapid than those in the Nanika River watershed and more rapid than those in the Atna Lake watershed. Morice Lake watershed glaciers have lost a total of 16.01 km^2 of glacier surface area since 1975, a 41.74% decrease (Table 3). Recession rates have increased from -0.80 %/a during the earlier period (1975-2005) to -1.66 %/a for the later period (2005-2019). Glaciers of the Morice Lake watershed represent 34% of all glacier surface area in the Morice River watershed and will also represent a similar fraction of the total glacial meltwater contributions to discharge. These glaciers, however, have the lowest surface elevations and are perhaps more vulnerable in a warming climate. Discharge from surface melt of these glaciers will likely play an important role in the immediate vicinity where their meltwater streams discharge into Morice Lake (Fig. 1, Appendix B), even while their impact on the Morice River discharge will become more and more marginal as they continue to recede.

Nanika River

The Nanika River watershed has 108 glaciers, which total 16.99 km^2 and result in a relative watershed glacier cover of 2.0% (Table 1). Glaciers here are generally smaller with an average glacier size is 0.16 km^2 but have a slightly higher average elevation than those of the neighboring Morice Lake watershed (Fig. 2). Glacier recession has been the greatest in the Nanika River watershed, with glaciers losing 18.50 km^2 of surface area since 1975, a loss of 54.71% (Table 2, Appendix B). Rates of recession more than doubled from the earlier period 1975-2005 (-1.06 %/a) to the later period 2005-2019 (-2.40 %/a). The smaller average glacier size is likely a primary reason for the higher recession rates given the inverse relation between glacier size and rates of recession (e.g., Bolch et al., 2010). These higher rates of recession are surprising in that the glaciers of the neighboring Morice Lake watershed are at a slightly lower elevation on average (Fig. 2) and yet have lower rates of recession. It may be that the significantly smaller glacier size is driving this discrepancy, that there is a marked change in precipitation regime moving slightly further to the east, or that some Morice Lake watershed glaciers were mapped from 1983 instead of 1975 imagery (Appendix C). First-order estimates of glacial meltwater contributions to Morice River streamflow reveal an average contribution (1975-2019) of 9.14% of total Nanika River discharge for the months July – September, and a maximum of 25.40% in the warm, dry year of 2019. Ongoing recession will reduce this capacity for glacier meltwater to buffer streamflow levels and stream temperatures during the late-summer and early-fall melt season.

Gosnell Creek

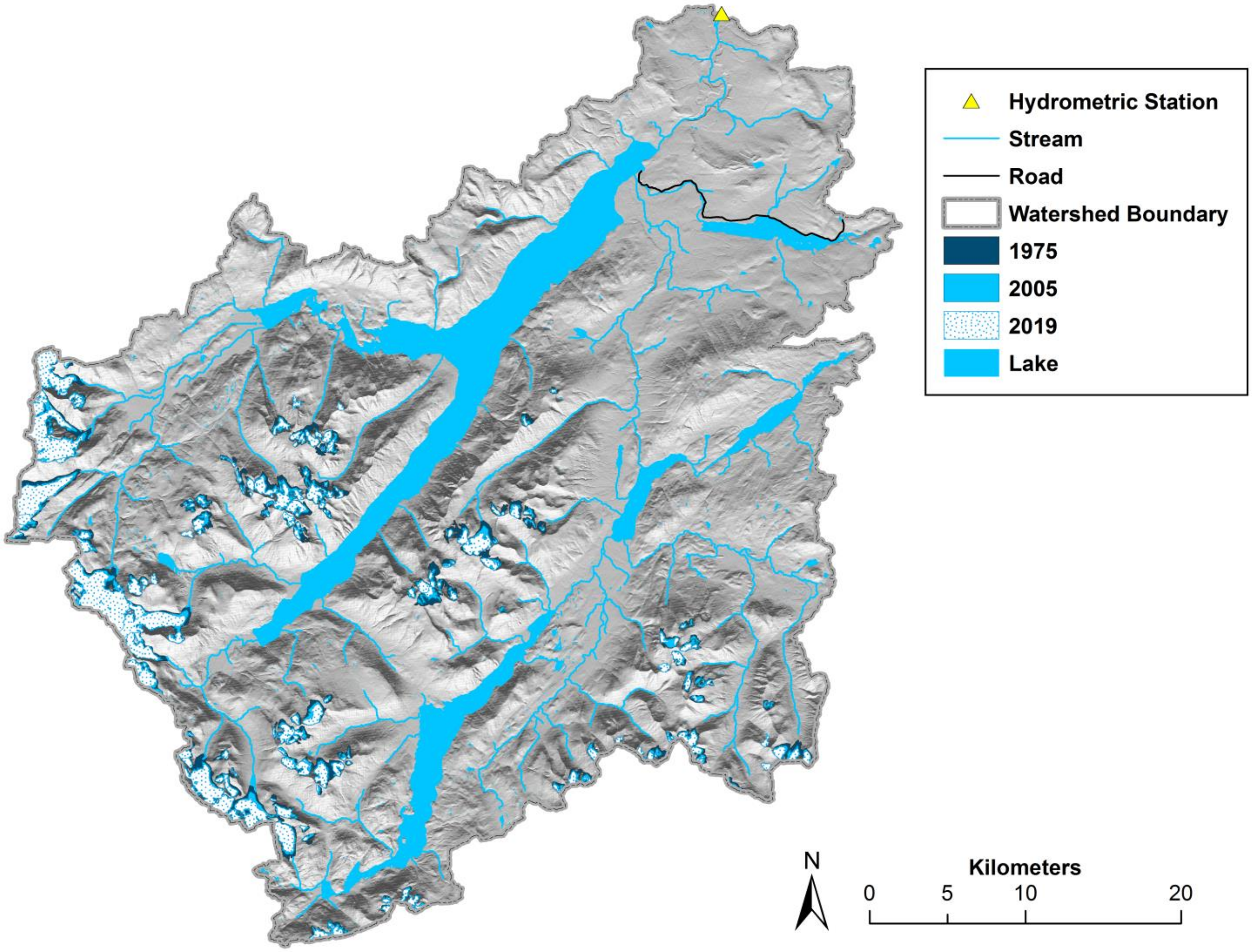
The one remaining cirque glacier remaining in the Gosnell Creek watershed totals 0.02 km^2. It is too small to have any significant influence on Gosnell Creek discharge or stream temperature. It will likely disappear within the next decade.

Atna Lake

The Atna Lake watershed has 50 glaciers, which total 28.42 km^2 and result in a relative watershed glacier cover of 10.4% (Table 1). This relative glacier cover is significantly higher than the other watersheds in this study, and the Atna Lake watershed will receive a commensurately higher relative contribution of glacier meltwater as a result. Glaciers here are the largest in the upper Morice River area with an average glacier size of 0.57 km^2, and they have a larger, high-elevation source area (Fig. 2). Glacier recession has been the least in the Atna Lake watershed when compared with neighboring watersheds but there has still been notable recession with glaciers losing 12.62 km^2 of surface area since 1983, a loss of 31.22% (Table 2, Appendix B). Rates of recession nearly doubled from the earlier period 1983-2005 (-0.74 %/a) to the later period 2005-2019 (-1.27 %/a). This reduced rate of recession in the earlier period (1983-2005) is likely due to the different imaging date, with at least half of the glacier surface area in the Atna Lake watershed only imaged in 1983 (Appendix C). The lower rates of recession in the later period (2005-2019), however, are not in question, and this likely demonstrates how the generally larger glaciers of the Atna Lake watershed are receding less than the smaller glaciers in the neighboring watersheds. Additionally, the greater surface area at higher elevations will help provide additional accumulation to these glaciers in general and may be helping to reduce recession rates. There is ample glacier cover in the Atna Lake watershed to provide a hydrologic buffer, with glacier meltwater supplementing discharge and moderating stream temperatures during the melt season. This buffering capacity, however, has been diminished in recent decades with glacier recession, and ongoing recession will reduce this capacity further as glaciers here are likely well past peak water (the time after which glacier meltwater contributions steadily decline with recession; Huss and Hock, 2018). Glacier meltwater will provide significant hydrologic buffering during the melt season to Atna River, Atna Lake and the immediate area where this meltwater discharges into Morice Lake (Fig. 1). This local influence of glacier meltwater is likely to remain relatively high in the near to medium term (10-30 years), even with ongoing climate change and glacier recession. These glaciers represent 41% of the glacier surface area in the Morice River watershed and so the hydrologic impact is muted further downstream, particularly with the moderating influence of Morice Lake.

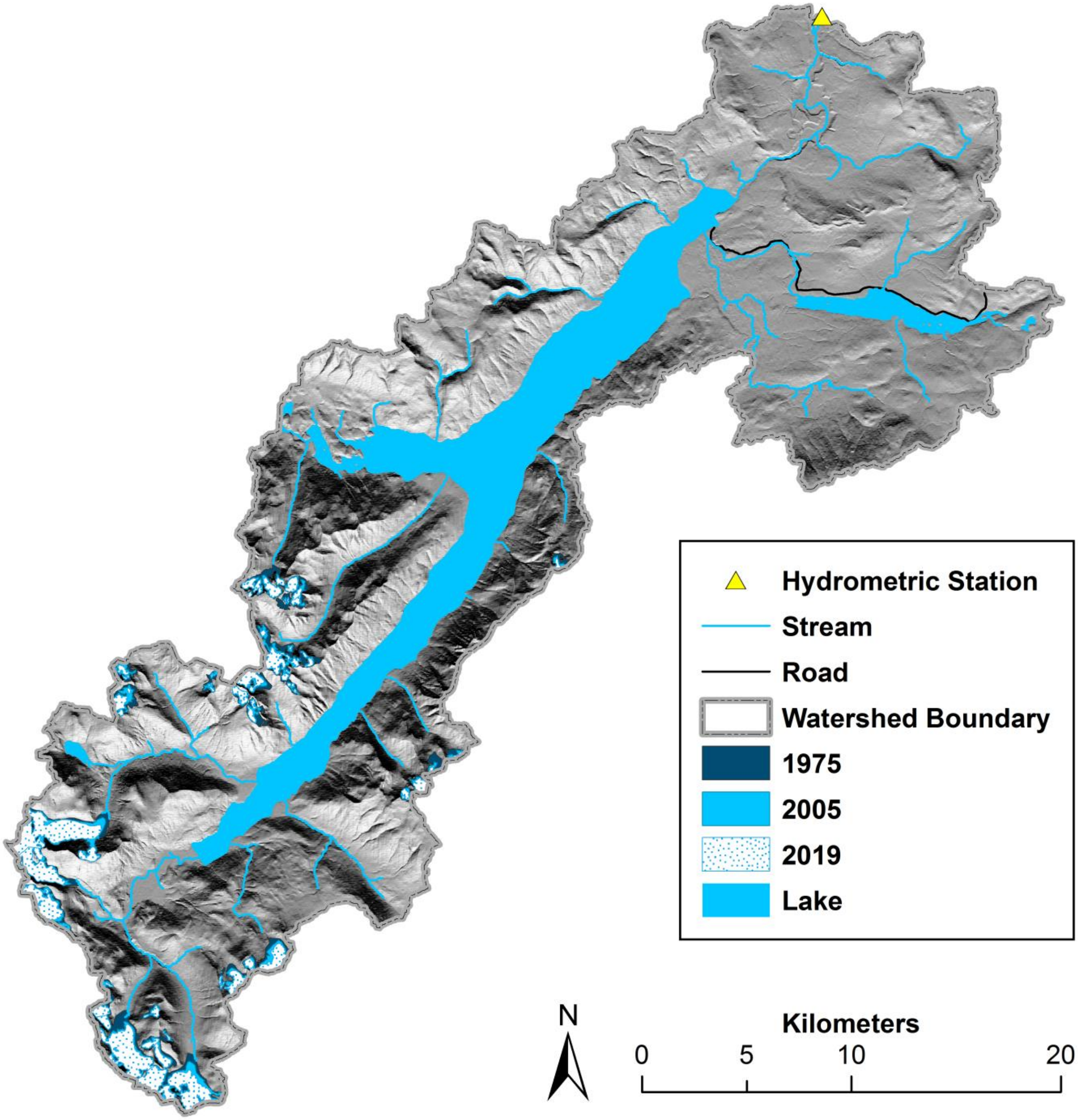
Appendix B: Maps of Glacier Change in Individual Watersheds

The following maps show glacier recession for the individual watersheds discussed in this report. They are in order of watershed size from largest to smallest. The Morice Lake, Nanika River and Atna Lake watersheds are all sub-basins of the Morice River watershed (Fig. 1). The Gosnell Creek watershed is not included as its one glacier (0.02 km^2) and associated recession would not be visible at the watershed scale.

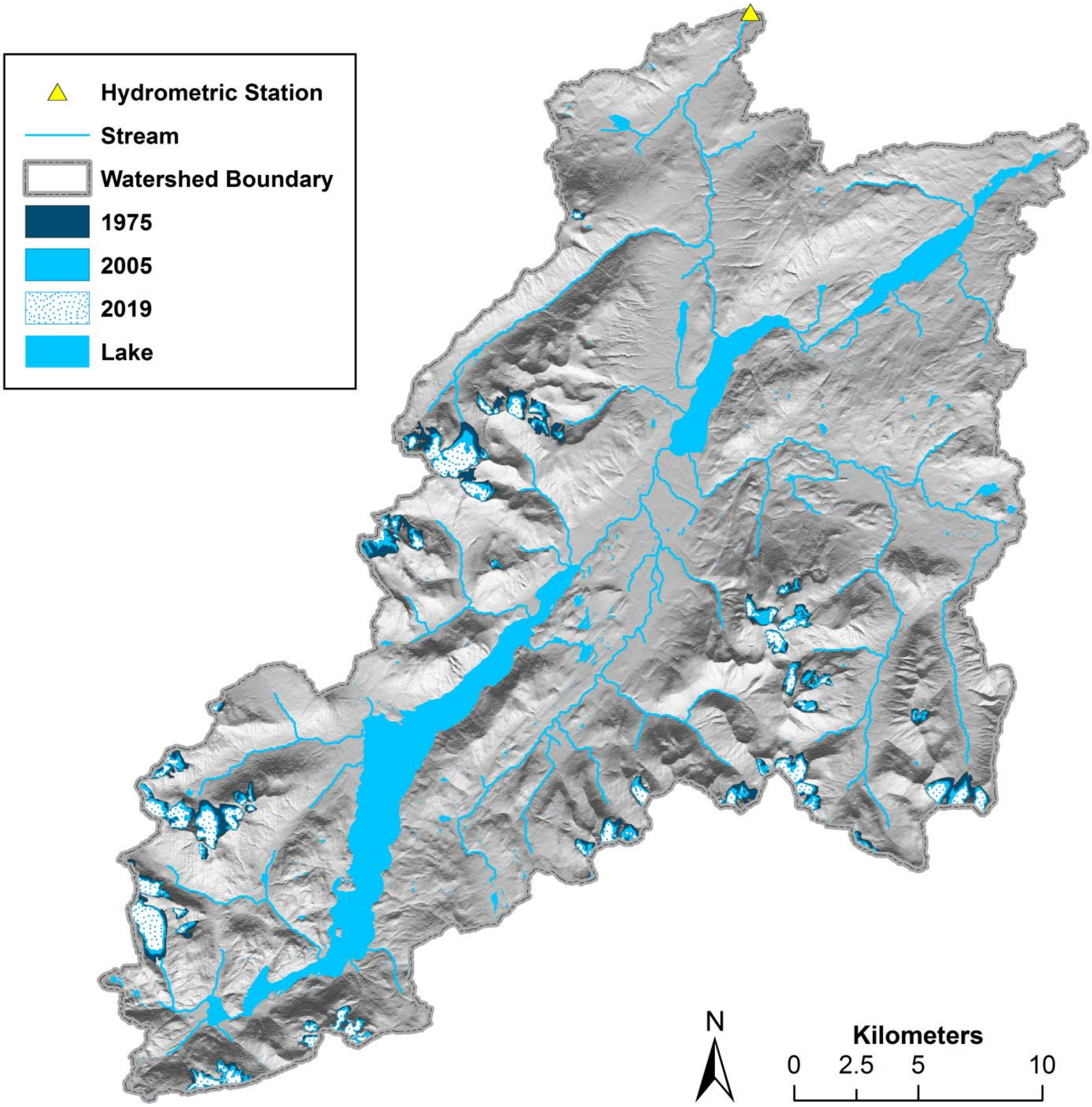


Morice River

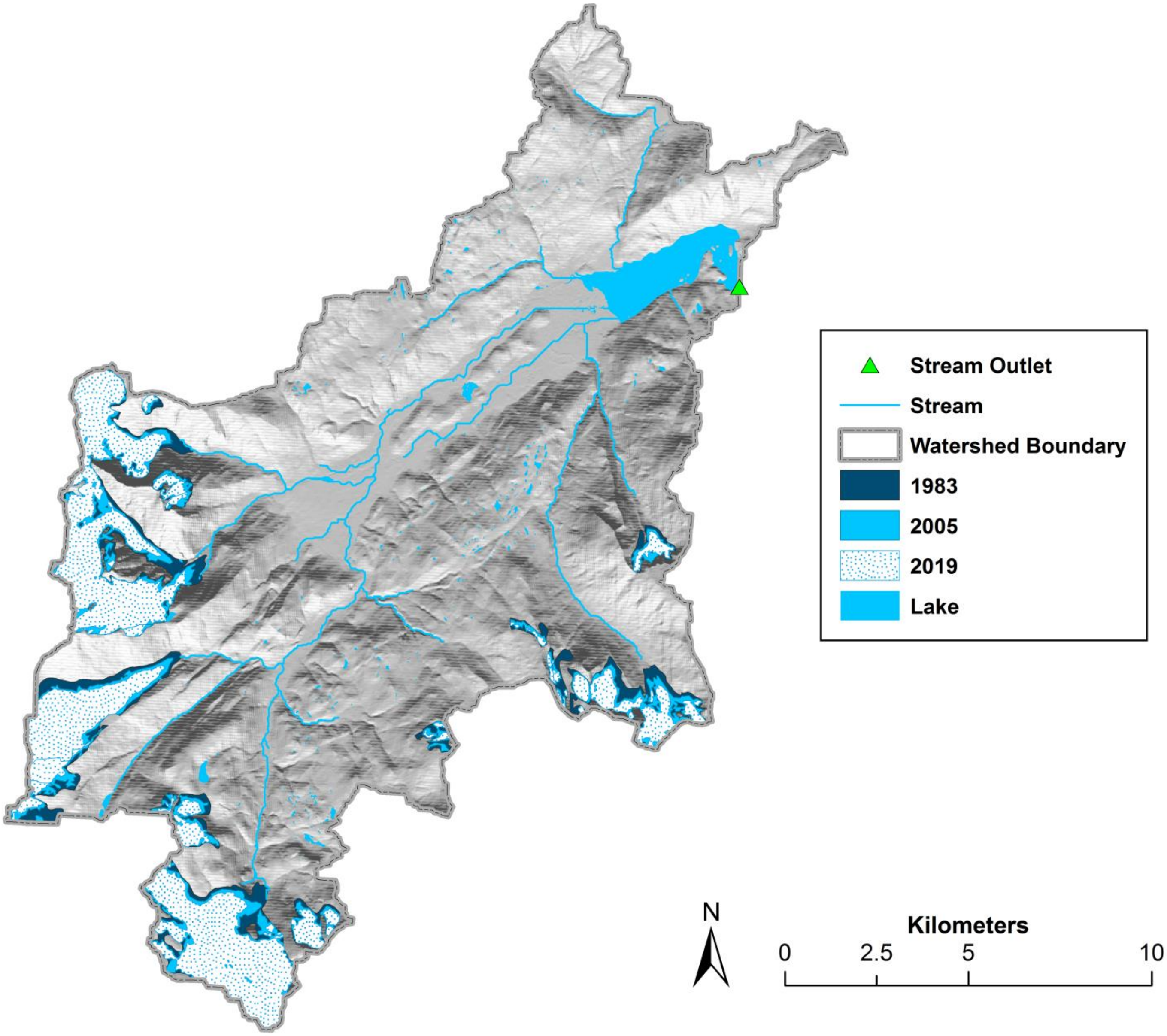
Glacier surface area in the Morice River watershed in 1975, 2005 and 2019. The gray-scale base map is a hillshade model of the TRIM DEM.



Morice Lake
Glacier surface area in the Morice Lake watershed in 1975, 2005 and 2019. Morice Lake is a sub-basin of the Morice River watershed. It is all surface area that contributes to Morice River but is not part of the Nanika River or Atna Lake watersheds. The gray-scale base map is a hillshade model of the TRIM DEM.

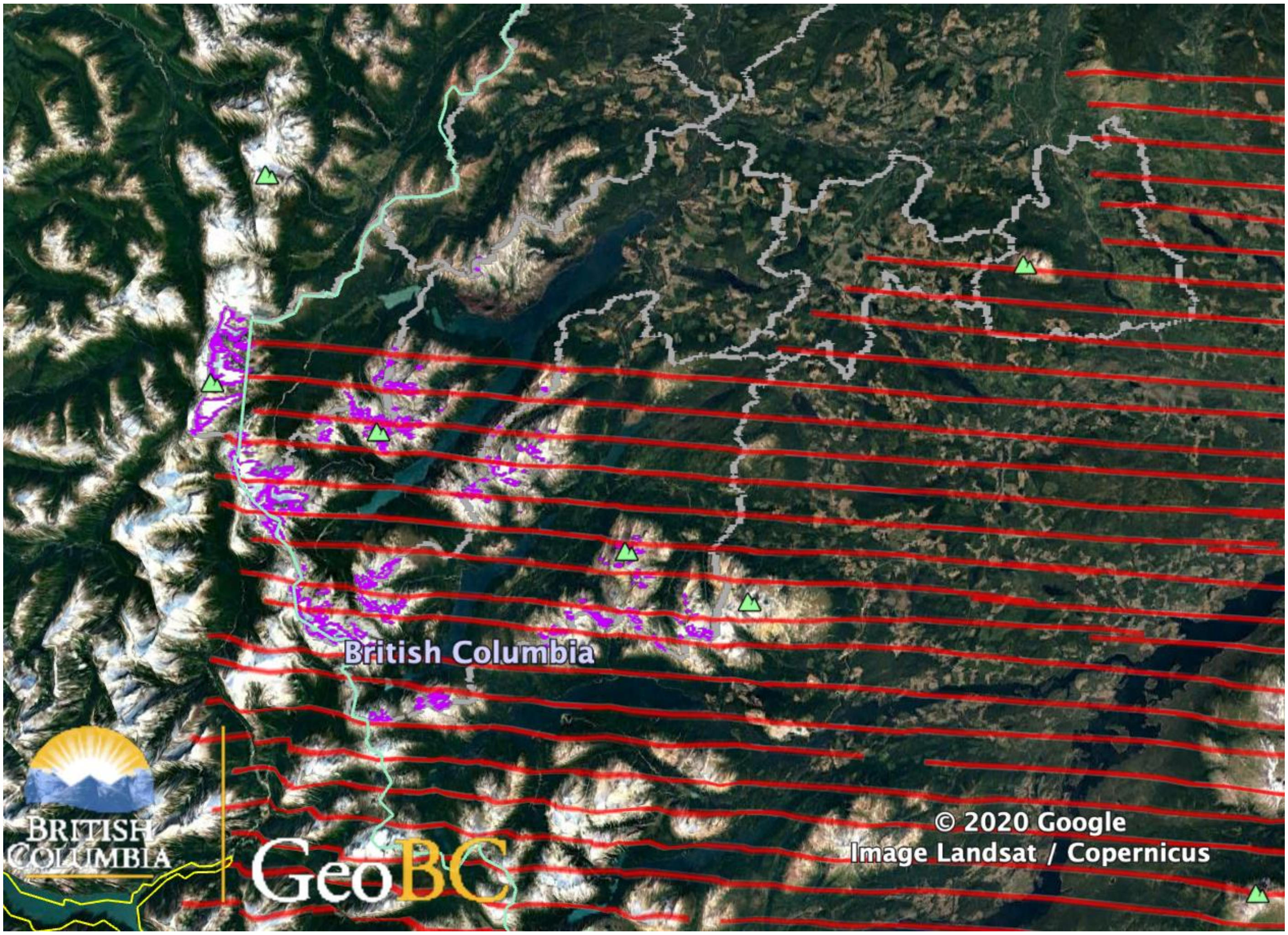


Nanika River
Glacier surface area in the Nanika River watershed in 1975, 2005 and 2019. The gray-scale base map is a hillshade model of the TRIM DEM.

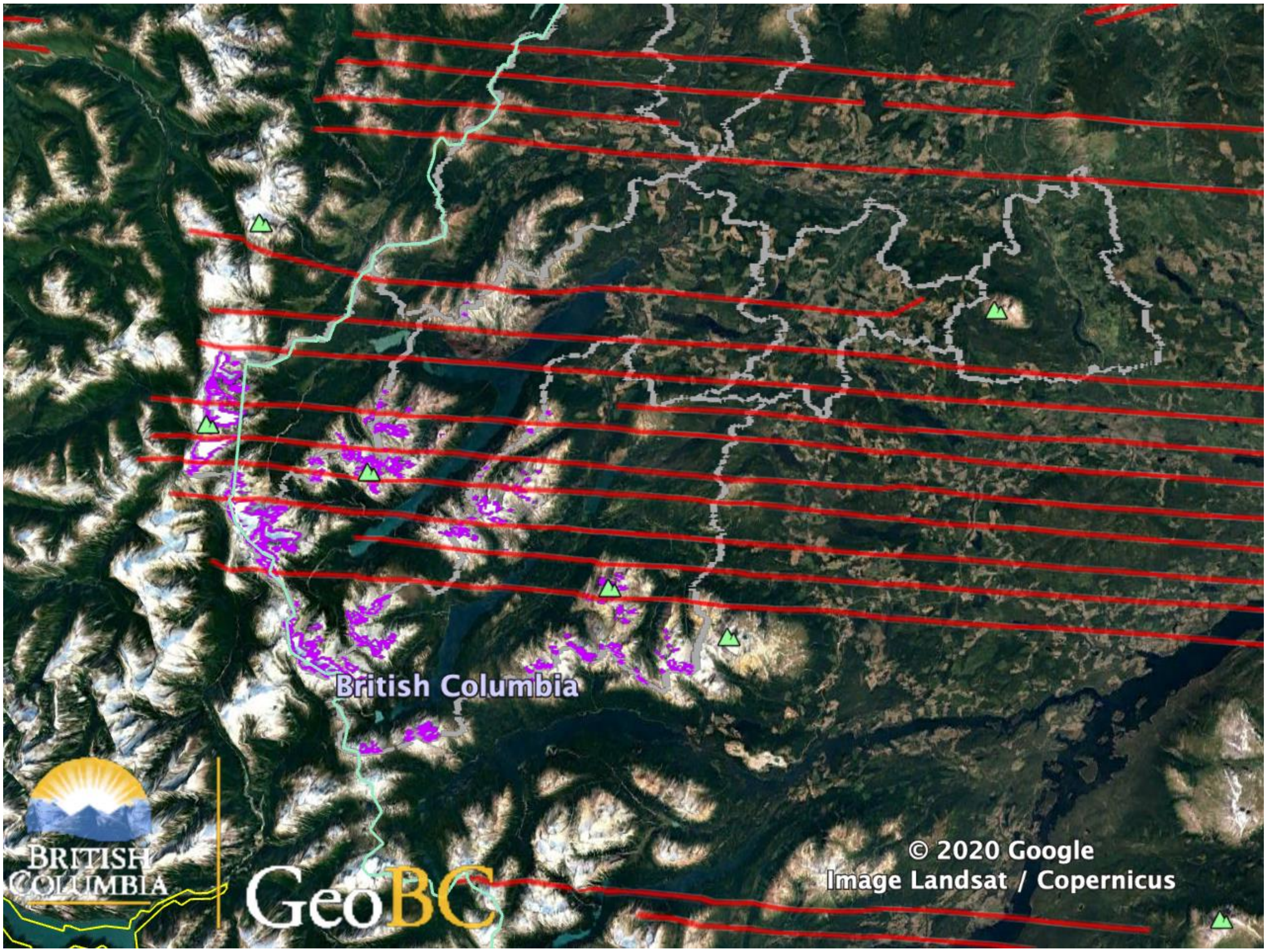


Atna Lake
Glacier surface area in the Atna Lake watershed in 1983, 2005 and 2019. Note that we use 1983 as opposed to 1975 for the first year of glacier extent mapping. The glaciers to the south and east in the Atna Lake watershed were imaged in both years, whereas those in the west were imaged only in 1983 (Appendix C). See the discussion section for more details on how we treat these different years of imaging. The gray-scale base map is a hillshade model of the TRIM DEM.

Appendix C: TRIM Aerial Photo Flight Lines



1975-07-05 1:20,000 Aerial Photo Flight Lines
The 2019 glacier outlines from this report are shown in purple. The outlines of watersheds of interest are shown in gray. Red lines are the aerial photo flight lines from 1975-07-05. Flight lines were accessed from the Province of British Columbia's Air Photo Viewer tool (https://www2.gov.bc.ca/gov/content/data/geographic-data-services/digital-imagery/air-photos/air-photo-viewer).



1983-08-23 1:20,000 Aerial Photo Flight Lines
The 2019 glacier outlines from this report are shown in purple. The outlines of watersheds of interest are shown in gray. Red lines are the aerial photo flight lines from 1983-08-23.