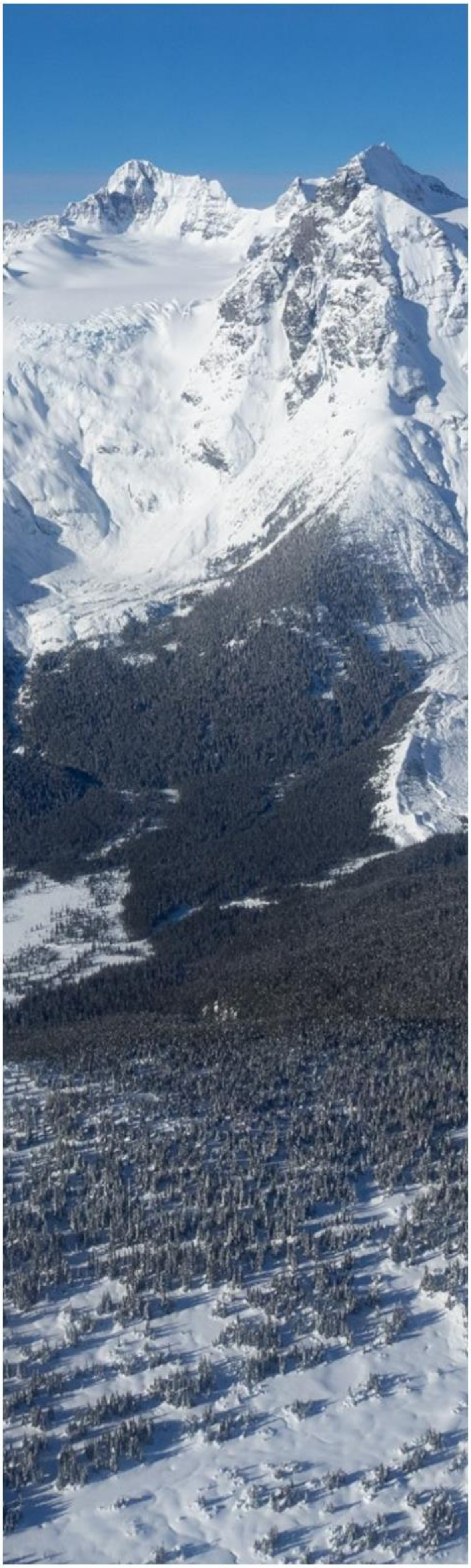

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Morice River Watershed Morphometry

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 morphometry (landcover and topographic characteristics) for selected watersheds of the upper Morice River (Fig. 1). Forthcoming work focuses exclusively on glacier extents and contributions to stream flow for the present day (Work Point 2 – Glacier Inventory). Glacier contributions to stream flow, while important, are not the only determinants of water quality, and this report presents other metrics that have an important bearing on water quality (e.g., Lisi et al., 2015). Here we present details of the landcover (glaciers, lakes, wetlands and logging) and topography (elevation, slope, and aspect) of each watershed of interest in the upper Morice River area and discuss in general how these characteristics impact stream temperature, discharge and turbidity.

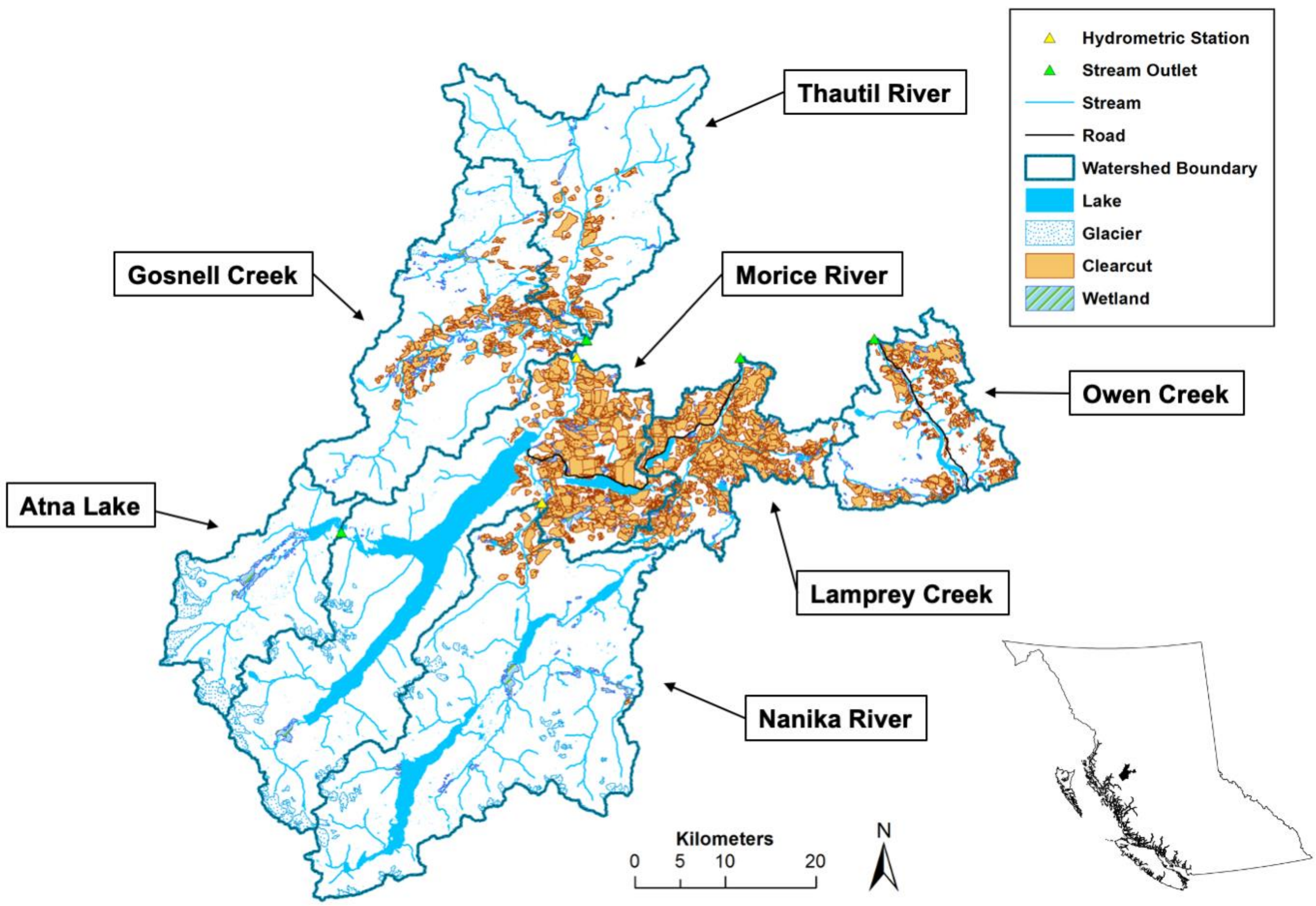

Figure 1: Upper Morice River area watersheds Major land-cover characteristics and general location of watersheds discussed in this report. The Morice River watershed includes Nanika River and Atna Lake as sub-drainages.

Methods

Areas of Interest

Definition of watersheds of interest presented here is based 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 forthcoming analysis on present-day glacier conditions, will describe many underlying conditions that determine water quality in these watersheds with important aquatic ecosystems.

Data

The topographic analysis and results completed here are derived primarily 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/). The TRIM DEM has a resolution of 25m and was derived from aerial photography acquired in the 1970s and 1980s.

Two Landsat 8 scenes from August 2019 (L8_5122_20190808, L8_5123_20190808) were used here for spatial reference and to determine the accuracy of the glacier, wetland and forestry data that were accessed from other sources. A pan-sharpened false-color composite of bands 6, 5 and 4 was used; 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/).

Glacierized areas presented here are from the Randolph Glacier Inventory (RGI) 6.0 (Pfeffer et al., 2014, www.glims.org/RGI/rgi60_dl.html). These glacier extents are from 2004 – 2006 satellite imagery and therefore present conditions significantly different from today. The RGI glacier extents presented here are included to illustrate the relative glacier cover in each watershed. A current (2019) inventory will be completed in a forthcoming report (Work Point 2 – Glacier Inventory).

Spatial data on clearcut areas mapped here are from the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development – Forest Analysis and Inventory (catalogue.data.gov.bc.ca/dataset/harvested-areas-of-bc-consolidated-cutblocks). This data depicts cut block boundaries for crown lands up to 2019. Areas depicted as wetland in this report are from Natural Resources Canada (NRCAN, geogratis.gc.ca).

Analysis

All spatial analysis presented here was completed with the use of ArcMap 10.8. Individual watersheds were delineated as the area upstream of a particular stream outlet (pour point). Each watershed pour point corresponds with its 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. The Nanika River and Atna Lake watersheds are sub-drainages of the larger Morice River watershed.

The South-North ratio (S/N ratio) was calculated as the total surface area of a watershed with a southwest, south or southeast aspect (112.5° – 247.5°) divided the total surface area with a northwest, north or northeast aspect (0° - 67.5°, 292.5° - 337.5). Watersheds with a S/N ratio of greater than one are those with more south aspects, whereas those with a S/N ratio of less than one are those with more north aspects. The S/N ratio is intended as a metric that quantifies potential for topographic shading, but also likely indicates retention of seasonal snow.

While mean slope is a watershed-wide average of surface slopes derived from the TRIM DEM, river length and slope are measures of the primary (longest) river channel in each watershed. This is taken as the longest extent from each watershed's hydrometric station or outlet to the terminus of a glacier or to tree line if glaciers are absent. The intent is to determine the distance to the lowest point of the watershed from a location where stream temperature is likely 0°C, an indicator of residence time in the channel and potential for warming before reaching the station. Channel slope is presented as a percent and is calculated from this length and the vertical rise from the station to this upper extent. Note that river length and slope include distances across large lakes in the case of the Morice River, Nanika River, and Atna Lake watersheds (Fig. 1). This increases total distance, decreases slope angle, and does not relate directly to the river channel. While potentially spurious, this data is included for these watersheds to give an idea of water residence time, a residence time driven mostly by the presence of the large lake and not necessarily characteristics of the river channel.

The hypsometry (area-altitude distribution) of each watershed presented here 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 here as a percent so that watersheds of different surface areas can be compared.

Results

Throughout this report, tables and plots are organized in order of total watershed surface area, from the largest (Morice River, 1,989.09 km^2) to the smallest (Lamprey Creek, 241.41 km^2) (Table 1). Glacier cover differs markedly between the watersheds, ranging from 0 to 13.1%. Atna Lake (13.1%), Morice River (4.5%) and Nanika River (2.9%) are the only three watersheds with glacier cover. Glacierized area of the Morice River (4.5%) include the same glaciers as those in the Atna Lake and Nanika River watersheds. There are no glaciers in the Gosnell Creek, Thautil River, Owen Creek and Lamprey Creek watersheds.

The presence of large lakes is an important landcover characteristic in most of the Morice River watersheds. The Morice River and Nanika River watersheds have the most lake cover with 8.3 and 5.7% lake area respectively (Table 1). Lamprey Creek (3.1%), Atna Lake (2.3%) and Owen Creek (2.1%) all have large lakes that will impact water quality. Gosnell Creek (1.0%) and Thautil River (0.3%) have the least amount of lake cover.

Forestry practices differ markedly between drainages. The most heavily impacted are Lamprey and Owen creeks with 50.1% and 19.8% of their total surface area clearcut respectively (Fig. 1, Table 1, Appendix B). Gosnell Creek (9.2%), Morice River (7.6%), and Thautil River (6.7%) all have large clearcut areas. Nanika River (1.7%) has minimal relative clearcut area and Atna Lake has none. While not quantified here, there are many locations where cut blocks run adjacent to wetlands, streams or lakes, particularly in the Lamprey Creek, Owen Creek and Morice River watersheds (Fig. 1, Appendix B). The consolidated cut blocks data from the Province aligns well with what is visible on the August 2019 satellite imagery, except for additional, plainly visible clearcuts in the Owen Creek and Morice River watersheds. Inclusion of these would not increase total clearcut area markedly within their respective watersheds but will have local impacts. Although not quantified here, the Lamprey Creek, Owen Creek and Morice River watersheds have sections of forest service roads that run adjacent to stream channels and/or lakes (Appendix B).

Watershed	Area (km^2)	RGI Glacier Cover (km^2)	RGI Glacier Cover (%)	Lake Cover (km^2)	Lake Cover (%)	Clearcut (km^2)	Clearcut (%)	Wetland (km^2)	Wetland (%)
Morice River	1989.09	89.87	4.5	164.188	8.3	150.9	7.6	20.6	1.0
Nanika River	843.59	24.31	2.9	48.440	5.7	14.7	1.7	8.2	1.0
Gosnell Creek	533.63	0.00	0.0	5.258	1.0	49.1	9.2	7.1	1.3
Thautil River	421.98	0.00	0.0	1.426	0.3	28.3	6.7	1.5	0.3
Owen Creek	276.61	0.00	0.0	5.697	2.1	54.8	19.8	5.0	1.8
Atna Lake	274.37	35.91	13.1	6.198	2.3	0.0	0.0	5.2	1.9
Lamprey Creek	241.41	0.00	0.0	7.514	3.1	122.5	50.8	2.6	1.1

Table 1: Land cover characteristics of upper Morice River watersheds. Watersheds are organized by total surface area from largest to smallest.

Wetland areas are most extensive in the Atna Lake and Owen Creek watersheds, with 1.9 and 1.8% of their total surface classified as saturated soil respectively (Table 1). The watersheds of Gosnell Creek, Lamprey Creek, Nanika River and Morice River all have notable wetland area. Thautil River has little wetland area (0.3%).

The minimum elevations for each watershed are similar and so it is the variation in maximum elevation that determines differences in elevation range (Table 2). The highest maximum elevation is found in the Atna Lake watershed (2,718m), whereas the lowest is found in Lamprey Creek (1,638m). Mean elevation is an average of all pixels within the watershed from the TRIM DEM and so quantifies spatial variability of elevations and not just an average of minimum and maximum elevations. The highest mean elevations are of the Atna Lake (1,325m) and Nanika River (1,302 m) watersheds. Lamprey Creek (985m) and Owen Creek (1,007m) have the lowest mean elevations.

Plots of hypsometry reveal more detail in how each watershed is distributed with respect to elevation (Fig. 2). The two lowest elevation watersheds (Owen and Lamprey creeks) are markedly different from the others with both having ~90% of their surface area below 1,250m. By contrast, the highest elevation watershed (Atna Lake) has 40% of its surface area below 1,250m. The shapes of the hypsometric curves – illustrating surface area distribution at various elevations – are similar. Subtle but noteworthy differences include the more linear Atna Lake and Nanika River watersheds, and the more downwardly bowed Owen, Lamprey and Gosnell creeks. The more linear curves have a more equal distribution of surface area with respect to elevation, whereas the downwardly bowed curves have more surface area at lower elevations.

Watershed	Min. Elev. (m)	Max. Elev. (m)	Elev. Range (m)	Mean Elev. (m)	Mean Slope (°)	River Length (km)	River Slope (%)	South-North Ratio (S/N)
Morice River	729	2718	1989	1237	16.3	75.9	0.8	1.03
Nanika River	805	2403	1598	1302	16.5	54.0	1.0	0.98
Gosnell Creek	715	2138	1423	1151	14.4	42.2	1.4	1.12
Thautil River	716	2309	1593	1254	13.1	39.9	2.1	1.63
Owen Creek	650	2118	1468	1007	10.5	37.7	1.8	1.22
Atna Lake	777	2718	1941	1325	18.7	26.6	2.0	1.00
Lamprey Creek	679	1638	959	985	8.7	28.6	2.3	1.05

Table 2: Topographic characteristics of upper Morice River watersheds. All data is derived from the TRIM DEM. Mean slope is an average of the entire watershed. River length and slope are for the longest stream from the respective hydrometric station or outlet to the furthest upper-elevation catchment (either glacier terminus or alpine area). South-north ratio is the total surface area of all south-facing areas (112.5° – 247.5°) divided by the total surface area of all north-facing areas (0° - 67.5°, 292.5° - 337.5°). Values greater than one indicate that south-facing areas of the watershed are larger than north-facing areas.

Mean slope of each watershed varies from a maximum for Atna Lake (18.7°) to a minimum for Lamprey Creek (8.7°) (Table 2). The watersheds of the Morice and Nanika rivers, containing higher elevation mountains in their upper reaches, are also steeper (16.3 and 16.5° respectively). Mean slope is an average for the entire watershed and so differs from the river slope discussed below.

Channel characteristics (river length and slope) show few marked differences (Table 2). The longest and lowest angle channels are Morice River (0.8%) and Nanika River (1.0%). This, however, is reflective of the long lakes in these watersheds and not necessarily of characteristics of the main channel. The presence of these lakes is more important than river channel characteristics with regard to water residence time. The Atna Lake watershed also includes relatively large lake cover (2.0%). Distance and slope angle from nearby glaciers in the Atna Lake watershed will result in relatively rapid movement of cold meltwater to the Lake (Appendix B). The Lamprey Creek and Thautil River watersheds have the steepest river channels (2.3 and 2.1% respectively), due partly to the absence of larger lakes.

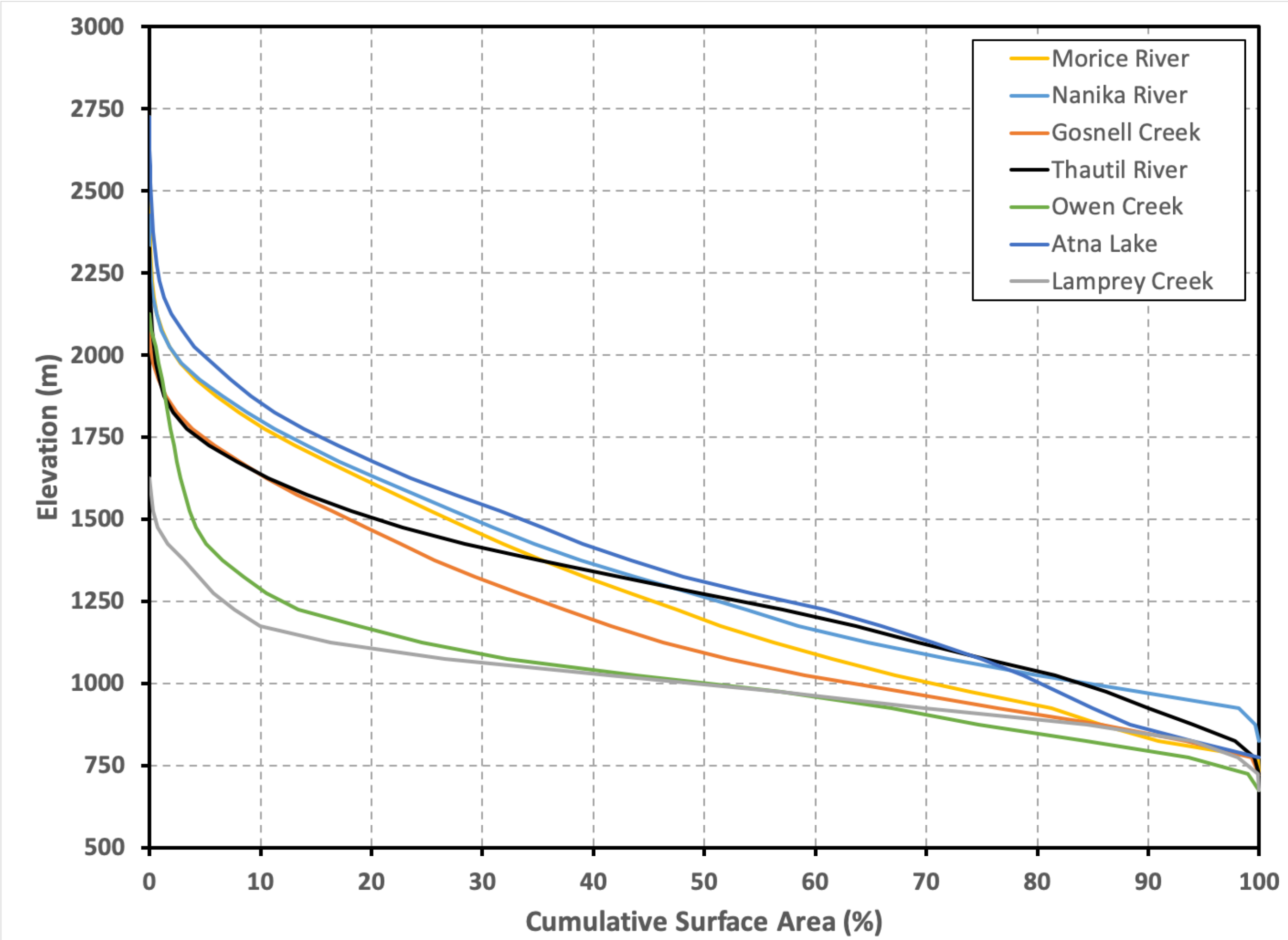

Figure 2: Hypsometry (area-altitude distribution) of each watershed. Lines for each watershed display the cumulative surface area with respect to elevation. Lines that are lower on this plot generally indicate watersheds at lower elevations, while shapes of lines indicate at what elevations portions of surface areas are located. Normalized surface areas allow individual watersheds to be compared. For example, the uppermost 30% (x-axis) of the total surface area of the Nanika River watershed is between 1,500 and 2,250m (y-axis), whereas the uppermost 30% of the Lamprey Creek watershed is between 1,050 and 1,600m.

The S/N ratio for each watershed (Table 2) can be seen visually in the hillshade model (Fig. 3). The Thautil River watershed, with a S/N ratio of 1.63, has more south aspect surface areas. The other watersheds all have S/N ratios close to 1, meaning that areas of south and north aspects are nearly equal. Figure 3 shows south aspects as colors (yellow, orange, and red) and the underlying hillshade model shows the north aspects as the darkest gray. This image helps show watersheds with potential for topographic shading. Some sub-drainages of the Atna Lake, Morice River, and Nanika River watersheds have steep slopes and more east-west orientation, which likely results in some localized topographic shading.

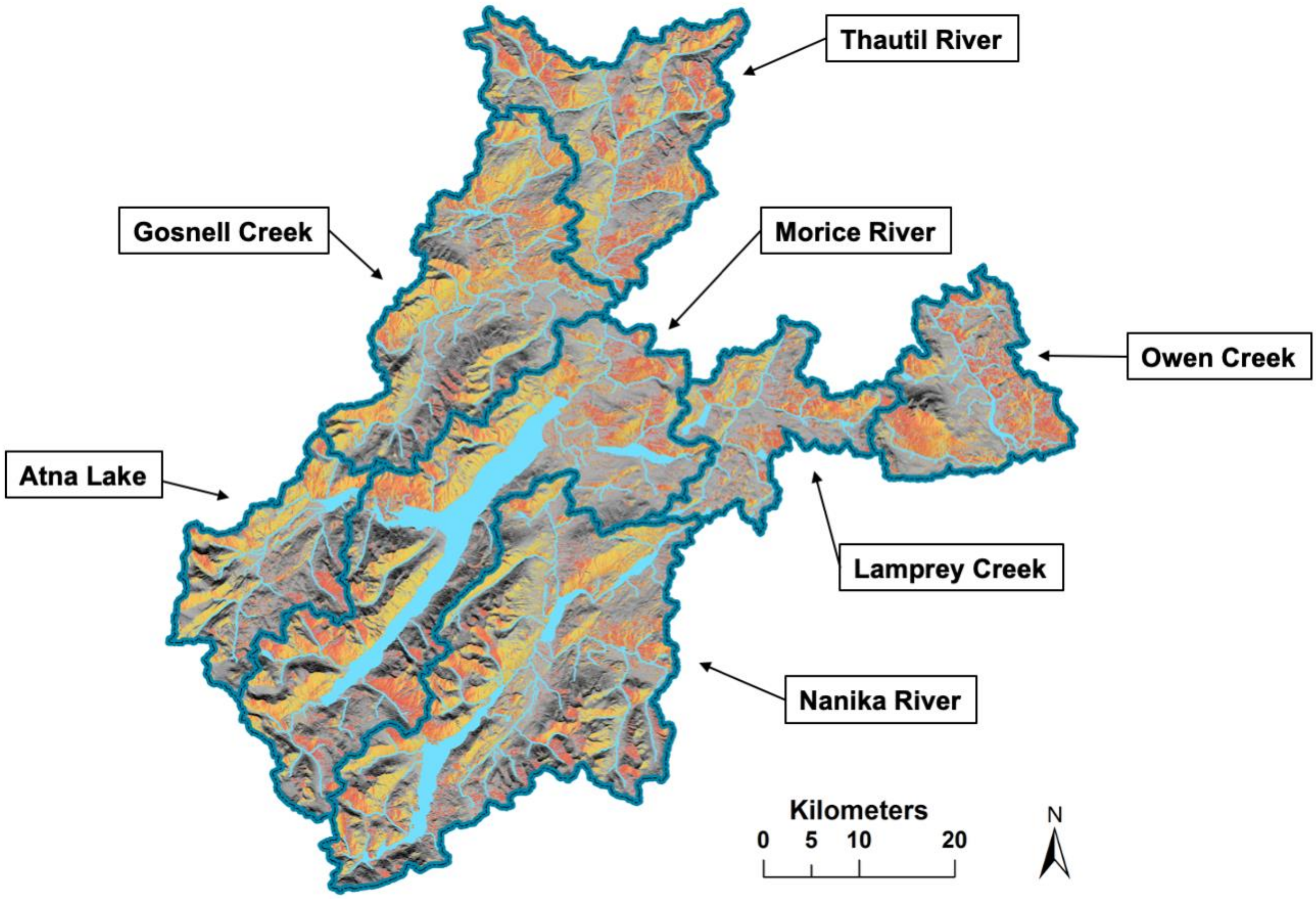

Figure 3: Topography of upper Morice River area watersheds. The base map here is a hillshade model from the TRIM DEM with a sun azimuth of 180° (south) and sun angle of 45°. Colored areas (yellow, orange, red) are south-facing slopes ((112.5° – 247.5°). The Morice River watershed (Tables 1 and 2) includes Nanika River and Atna Lake as sub-drainages.

Discussion

Discussion here follows the order in which morphometric characteristics were presented in the Results section (above). See Appendix A for discussion that is focused for each specific watershed.

Land cover varies markedly between the upper Morice River area watersheds and will play a large role in modulating water quality. Previous work finds that even basins with little glacierized area (2-3%) can help moderate late-summer stream flows (Stahl and Moore, 2006). The Atna Lake, Morice River and Nanika River watersheds contain all of the glacierized area in the upper Morice River area with 13.1, 4.5 and 2.9% glacier cover respectively (Table 1). The remaining four watersheds contain no glacier cover and will have no glacier-related buffering effects. The Atna Lake watershed, with the most relative glacier cover (13.1%), will have a substantial portion of late-summer discharge from glacier melt and will have high turbidity. This will result in higher discharge and lower water temperatures during late-summer/early-fall when seasonal snow has melted. With markedly less relative glacier cover than Atna Lake, the Morice River and Nanika River watersheds will experience less of the discharge and temperature buffering due to glacier meltwater. These three glacierized watersheds in the upper Morice River area will have already passed peak water (maximum rate of water release from glacier storage, Huss and Hock, 2018), and inputs from glacier melt will wane in the near term. Note that these results use the RGI, a glacier inventory that relied on satellite imagery ~15 years old (Pfeffer et al., 2014). The forthcoming glacier inventory using 2019 imagery will include glacier recession since the RGI and the glacier cover will be less.

The Morice River and Nanika River watersheds (4.5 and 2.9% glacier cover respectively) likely receive some thermal buffering and maintained discharge through the melt season from glacier melt, but the influence of large lakes will be significant (8.3 and 5.7% of total surface area, respectively). The long residence time of water in the lakes and exposure at the surface to solar radiation will result in significantly increased water temperatures. Suspended glacial silts from headwater sub-drainages will fall out in the lakes, resulting in lowered turbidity. The Lamprey Creek, Atna Lake, and Owen Creek watersheds (3.1, 2.3, and 2.1% lake cover area) will also see increased water residence times and warming of water due to exposure to solar radiation. Suspended glacial silts will largely fall out in Atna Lake before discharge into Morice Lake. Lakes in the Gosnell Creek (1.0%) and Thautil River (0.3%) watersheds will result in some warming of stream temperatures, but the impact will be minimal in comparison with the effects of the large lakes in the Morice River and Nanika River watersheds. Lakes in the Gosnell Creek and Thautil River watersheds are much smaller, generally do not impact primary channels, and some lakes are closed hydrologic systems fed by groundwater.

Anthropogenic impacts on land cover in the upper Morice River area are primarily due to forestry and concentrated in the watersheds of Lamprey and Owen creeks (50.8 and 19.8% clearcut area respectively, Table 1, Appendix B). Clearcut area is less but may still impact water quality significantly in the watersheds of Gosnell Creek, Morice River, and Thautil River (9.2, 7.6 and 6.7% respectively). While riparian conditions are not investigated in detail here, it is possible that logging in these watersheds has resulted in some increases in stream temperature (e.g., Moore et al., 2005), and possibly increased turbidity. Recent work in a non-glacierized watershed in Oregon has shown that shade from riparian vegetation has the largest influence on stream temperatures (Wondzell et al., 2019). Accumulation and retention of snowfall, and associated melt-season runoff, may also be impacted by logging in these watersheds. Previous work has found increased snow accumulation and variable impacts on meltwater depending on weather during the melt season (Schelker et al., 2013). The loss of interception by the forest canopy and altered sublimation and melt may have the net result of increased meltwater from seasonal snow and decreased stream temperatures in the most heavily logged watersheds. Any thermal buffering from increased meltwater from seasonal snow, however, will only occur early in the melt season as these clearcut areas are at lower elevations where seasonal snow does not remain late into the melt season. Forestry in the Nanika River watershed (1.7%) is significantly less than in the other upper Morice River watersheds and associated impacts are likely minimal. There has been no logging in the Atna Lake watershed.

The stretches of forest service roads that run adjacent to lakes and stream channels may also play a role in determining water quality, particularly of the Morice River, Owen Creek and Lamprey Creek watersheds (Fig. 1, Appendix B). These transportation alignments may have impacts on the canopy of riparian habitat that may drive increased solar radiation and warming, and increased turbidity from erosion and dust (e.g., Forman and Alexander, 1998).

Wetland areas that are connected to stream channels may impact water quality of Atna Lake, Owen Creek and Gosnell Creek, with relative wetland areas of 1.9, 1.8 and 1.3% respectively (Table 1, Appendix B). The lag associated with riparian watersheds will result in delayed transfer downstream and related impacts on water quality (e.g., Fritz et al., 2018), potentially increased stream temperatures. The role of wetlands in the larger Morice River area, however, is likely minimal in comparison with the effects of other land-cover characteristics (e.g., lake cover and forestry).

Elevation characteristics of individual watersheds will result in differences in ambient air temperature, and accumulation and retention of seasonal snow. The Atna Lake, Nanika River, Thautil River and Morice River watersheds have the highest mean elevations, which will result in lower air temperatures, and seasonal snow being retained longer and contributing to discharge for more of the melt season (Table 2). The highest maximum elevations are in the Atna Lake watershed (which is part of the larger Morice River watershed), and retention of seasonal snow at these highest of elevations may provide additional thermal buffering during the melt season. The Owen and Lamprey creek watersheds have markedly lower elevations (Table 2, Fig. 2), which will result in warmer air temperatures, and seasonal snow being lost earlier in the melt season.

Basin-wide average slope will indicate generally how rapidly meltwater can runoff, but also potential for topographic shading. The Atna Lake, Nanika River and Morice River watersheds are steeper than the other watersheds with average slopes of 18.7, 16.5 and 16.3° respectively. In these three watersheds it is likely that cold snow and glacier melt can more rapidly reach lower elevation lakes. Owen and Lamprey creeks have lower average slopes (10.5 and 8.7° respectively), which will result in slower runoff of meltwater and more potential for warming. Topographic shading due to steep north-facing slopes (east-west trending valleys) is minimal throughout the upper Morice River area and limited to small sub-drainages of the upper Morice River, Nanika River and Atna Lake watersheds (Fig. 3, Appendix B).

River channel length and slope is presented here as a metric for how rapidly 0°C melt water from high-elevation seasonal snow or glaciers reaches hydrometric stations or stream outlets in watersheds of interest. The distance to upper elevations is the shortest in the Atna Lake watershed. This likely results in a shorter residence time in the channel and less opportunity for stream temperatures to increase. River channel characteristics in the other watersheds are not markedly different from one another and are unlikely to have a significant impact on water quality. Channel length and slope measurements for the Morice River and Nanika River watersheds presented are not reflective of stream channel characteristics due to the inclusion of large lakes that will have a significant impact on water residence time. The role of these large lakes in increasing residence time will play a primary role in these two watersheds, regardless of stream channel characteristics.

The S/N ratio indicates surface areas with topographic shading, which will relate to snow retention, and potential for solar radiation to influence air temperature and stream temperature directly. The Thautil River watershed is notable with a S/N ratio of 1.63, south aspects being markedly more extensive than north aspects (Table 2). This indicates more surface area with exposure to direct sun and associated increases in ambient air temperature and more rapid snow melt during the melt season. Each of the other watersheds have S/N ratios close to 1, indicating nearly equal distribution of south and north aspects. Small, upper elevation sub-drainages within these basins, however, do have steep slopes and an east-west orientation. This likely results in portions of these higher-elevation basins with topographic shading and potential for greater retention of seasonal snow (Fig. 3 Appendix B).

Conclusion

The analysis discussed here helps to illustrate the land cover and topographic characteristics that will contribute to water quality within the watersheds of the upper Morice River area. Although they are adjacent to one another, these watersheds have a wide range of morphometric characteristics, each of which will play a role in determining water quality. These characteristics should be taken into account when assessing how climate change will impact water quality.

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Appendix A: Overview of Morphometric Characteristics by Watershed

Morice River

The Morice River watershed is the largest watershed in the upper Morice River area. It includes the Nanika River and Atna Lake watersheds (discussed individually below). It has the second largest relative glacierized area (4.5%) and the largest amount of lake-covered area (8.3%). Glacier and lake cover are likely the two most important morphometric characteristics shaping water quality of this watershed. Glacier meltwater will provide some thermal buffering, particularly in late-summer/early-fall during dry years when most of the seasonal snow has melted. Discharge from these upper, glacierized sub-drainages will likely remain high during these times and will also deliver suspended silts to the large lakes. The large lakes, and long water residence times therein, will result in warming and the falling out of suspended silts. This lake regulation of glacial inputs is important for the salmon productivity of the Morice River watershed (e.g., Dorava and Milner, 2000). Logging is significant in the lower reaches of the drainage with 7.6% of the total area of the watershed clearcut (Appendix B). Some of these clearcuts may impact riparian habitat and result in more direct solar radiation in lakes or streams and increased water temperatures. It is also likely that the large areas of clearcut also impact seasonal snow accumulation and retention (e.g., Schelker et al., 2013). Wetlands are 1.0% of the total watershed area and their influence on water quality is likely minimal given the extent of other morphometric characteristics, particularly the large lakes. The Morice River watershed has one of the higher average elevations, the highest elevations in the larger area (Atna Lake watershed), and the largest elevation range. Its overall S/N ratio (1.03) indicates a nearly equal distribution between south and north aspects, but complex terrain in some of the upper reaches likely results in some topographic shading (Fig. 3, Appendix B). The relatively high elevation of the watershed, and micro-climatological impacts of glaciers in the upper reaches, is likely to increase the accumulation of seasonal snow and retention later into the melt season. While there will be some thermal buffering from glacier contributions at present, this impact is likely to wane rapidly in the near term (10-20 years) as the relatively small glaciers of this watershed recede. The large lakes, however, likely have the single largest impact on water quality of this watershed, increasing water residence time which allows for suspended silts to fall out and water to warm. It is unlikely that salmonids will face thermal stress (e.g., Richter and Kolmes, 2005) in this watershed in the near term, and there is potential for cold-water refugia in many parts of this watershed. Large areas of the watershed (most of the Nanika River watershed), however, are inaccessible to anadromous salmonids due to physical barriers (Nanika Falls, Appendix B).

Nanika River

The Nanika River watershed is part of the larger Morice River watershed (Fig. 1), has 2.9% glacier cover and 5.7% lake cover. Similar to the Morice River watershed, Nanika River will receive some thermal buffering from glaciers in late-summer/early-fall, but this influence will wane rapidly in the near term as the relatively small glaciers of this watershed continue to recede. Residence time of water in the lake, and exposure to solar radiation, will have a significant warming influence. Clearcut area (1.7%) and wetlands (1.0%) will likely have minimal impact on water quality. The Nanika River watershed has the second highest average elevation (1,302m), which will result in cooler ambient air temperature, and likely result in seasonal snow persisting later into the melt season, providing some thermal buffering into mid-summer. The S/N ratio (0.98) indicates nearly equal south and north aspects. Average watershed slope (16.5%) and river channel slope (1.0%) are not steep, but these values include lake area. Steeper slopes and channels in upper sub-drainages will result in rapid runoff to the large lakes, bringing cold meltwater rapidly to lower elevations. Complex terrain in the upper reaches may provide some topographic shading of the smaller streams before entering Nanika and Kidprice lakes (Appendix B). With relatively high elevations, persistence of some seasonal snow to mid-summer, and some glacier cover, it is unlikely that there will be thermal stress in the Nanika River watershed in the near term. Relatively cool waters will likely continue to be contributed to Nanika River in the near term (below Nanika Lake/Falls, Appendix B), an important spawning and rearing habitat (Bustard and Schell, 2002). Continued warming and glacier recession, however, are likely to rapidly diminish these meltwater inputs to Nanika River and result in increased water temperatures in the coming decades.

Gosnell Creek

Gosnell Creek has no glacier cover and little lake area (1.0%). There is a significant amount of forestry in the watershed, with 9.2% of the watershed clearcut. Wetland area is minimal (1.3%). Average elevation (1,151m) is lower than the neighboring Atna Lake and Thautil River watersheds, and the hypsometric curve (Fig. 2) shows a slight bow downwards, indicating more surface areas at lower elevations. The S/N ratio (1.12) indicates slightly more surface area with south aspects. Average watershed slope (14.4%) and channel slope (1.4%) are not remarkably steep, but the little lake and wetland area means that water residence times will be lower than other watersheds in the area, and cooler water from higher elevations will runoff more rapidly and have less opportunity to warm. With no glacier cover and lower elevations, thermal buffering from meltwater will be minimal, particularly as seasonal snow is unlikely to persist late into the summer. Cooler water from higher elevations, however, will runoff more rapidly than neighboring watersheds with large lakes. Clearcut area is significant and may have a marked impact on riparian habitat, perhaps increasing direct solar radiation and warming of streams. Clearcut area may also impact accumulation of seasonal snow, potentially increasing the amount of snow available as meltwater (e.g., Schelker et al., 2013). These clearcut areas are at lower elevations, however, and thermal buffering from any increases in snow accumulation due to forestry are unlikely to last later than early summer. With thermal buffering from meltwater only from seasonal snow, it is likely that Gosnell Creek could experience thermal stress in the near term during hot summers (e.g., Richter and Kolmes, 2005). Little lake area, however, will reduce water residence time and opportunity for warming, meaning that Gosnell Creek likely has cooler water temperatures than nearby Lamprey and Owen creeks).

Thautil River

Thautil River has no glacier cover, the least amount of lake cover in the area (0.3%), and little wetland area (0.3%). Clearcut area comprises 6.7% of the total watershed. Average elevation (1,254m) is 100m higher than the neighboring Gosnell Creek watershed. The hypsometric curve (Fig. 2) indicates that the distribution of lower elevations is similar to the Atna Lake and Nanika River watersheds, watersheds with higher average elevations. This generally high elevation likely results in slightly cooler ambient air temperatures and perhaps retention of seasonal snow slightly longer into the melt season. The S/N ration of 1.63 (Table 2, Fig. 3), however, indicates a markedly larger area of south aspects than north aspects, meaning more surface area with direct solar radiation and reduced retention of seasonal snow during the melt season. The average watershed slope and channel slopes are not remarkable, but a lack of lake cover means that water residence time will be less, and runoff from colder high-elevation areas to lower areas will be more rapid and provide less opportunity for water to warm. No glacier cover and the highest S/N ratio likely results in minimal thermal buffering capacity from snow melt during the melt season. The clearcut areas may have an important influence on seasonal snow retention (e.g., Schelker et al., 2013) and increased direct solar radiation if riparian buffers have not been maintained (e.g., Wondzell et al., 2019). Without the thermal buffering capacity that glaciers provide, it is likely that Thautil River will have higher water temperatures, and could reach levels of thermal stress for salmonids in the near term (e.g., Richter and Kolmes, 2005), particularly during late-summer/early-fall in years when seasonal snow for the previous winter was low and when melt season temperatures are high.

Owen Creek

Owen Creek has no glacier cover and the second lowest mean elevation (1,007m). The relative lake cover is only 2.1%, but a long lake in the southern portion of the drainage sill serve to markedly increase water residence times and provide ample potential for water to warm (Appendix B). Forestry practices are an important land-cover characteristic in the Owen Creek watershed, with 19.8% of the watershed clearcut, and areas where riparian habitat has not been maintained likely see significant increases in water temperature (e.g., Wondzell et al., 2019). It is likely that seasonal snow accumulation has also been impacted for these clearcut areas (e.g., Schelker et al., 2013). The lower elevation of Owen Creek (Table 2, Fig. 2) means that ambient air temperatures will be higher and seasonal snow will be lost earlier in the melt season. The S/N ratio of 1.22 means that areas with south aspects are more dominant, resulting in more direct solar radiation and related impacts on air temperature and snow melt. Average watershed slope is markedly lower than all but Lamprey Creek. This will result in slower runoff and more opportunity for water to warm. The lack of glaciers, lower elevations, presence of long lakes, lower slope angles, and significant area of clearcut likely all combine to amplify stream temperatures and reduce discharge, particularly in late-summer/early-fall. It is highly likely that Owen Creek already experiences some thermal stress for salmonids (e.g., Richter and Kolmes, 2005). This thermal stress is likely to increase in the near term. Maintaining riparian habitat (and restoration where applicable) will be important to reduce thermal stress in Owen Creek (e.g., Wondzell et al., 2019).

Atna Lake

The Atna Lake watershed has the most glacier cover (13.1%) and the highest average elevation (1,325m) in the upper Morice River area. Lake cover is 2.3% of the watershed. There is no clearcut area, but the largest relative wetland area (1.9%). The Atna Lake watershed has the steepest average slope (18.7%), and the shortest distance from high-elevation sources of meltwater to stream outlet. The S/N ratio of 1.00 means that there are equal areas of south and north aspects. The higher elevation glaciers of the Atna Lake watershed will keep discharge into Atna Lake high and provide a significant thermal buffer during late-summer and early-fall. The high elevations and colder microclimates near glaciers will result in increased retention of seasonal snow during the melt season. With higher average slope angles, meltwater from glaciers and seasonal snow will runoff to Atna Lake relatively rapidly. The large wetland area southwest of Atna Lake (Appendix B) will result in some slowing of runoff and warming of stream temperatures, but residence times and opportunity for warming will generally be low, resulting in marked thermal buffering throughout the melt season. Atna Lake itself will moderate glacial inputs in ways that benefit freshwater ecosystems, increasing water residence times that drives slightly warmer water temperatures and fallout of suspended silts (e.g., Dorava and Milner, 2000). It is highly likely that water in this watershed is the coldest in the upper Morice Area. The Atna Lake watershed likely provides an important input of cold water, and areas of cold-water refugia for salmonids. The relative amount of glacier cover here is much higher than in the other upper Morice River watersheds. These larger glaciers, at higher elevations and generally north facing, will likely persist longer than the other glaciers in the upper Morice River watershed. The amount of melt-season discharge and thermal buffering, however, will likely wane in the near term (10-20 years) with continued glacier recession.

Lamprey Creek

The Lamprey Creek watershed has no glacier cover and the lowest mean elevation (985m). It has 3.1% lake cover and there is a relatively large lake near the head of each of its sub-drainages (Appendix B). Wetland area (1.1%) is mostly found adjacent to these lakes. Anthropogenic impacts on water quality in the Lamprey Creek watershed are likely significant, with 50.8% of the watershed clearcut, and with a great deal of clearcut area immediately adjacent to lakes and streams. The average watershed slope is the lowest in the upper Morice River area (8.7%). The S/N ratio (1.05) reveals nearly equal areas of south and north aspects. With generally low elevations and no glacier cover, Lamprey Creek will receive little to no thermal buffering from meltwater persisting into late-summer/early-fall. The lakes and low slope angles will result in longer residence times and more time for water to warm before it reaches the stream outlet. The impacts of forestry on water quality are likely important and potentially extreme, depending on whether riparian buffers have been maintained (e.g., Wondzell et al., 2019). The large clearcut area also may have significantly altered the accumulation of seasonal snow, potentially having a marked impact on meltwater discharge, particularly early in the melt season (Schelker et al., 2013). It is highly likely that Lamprey Creek has the warmest waters in the upper Morice River area, and water temperatures are likely to exceed important thermal thresholds for salmonids during mid- to late-summer (Richter and Kolmes, 2005). Occurrence of thermal stress on salmonids is likely to increase in the near term, and management and/or remediation of riparian habitat adjacent to clearcut areas might be important to maintain the viability of this watershed for use by salmonids.

Appendix B: Maps of Individual Watersheds

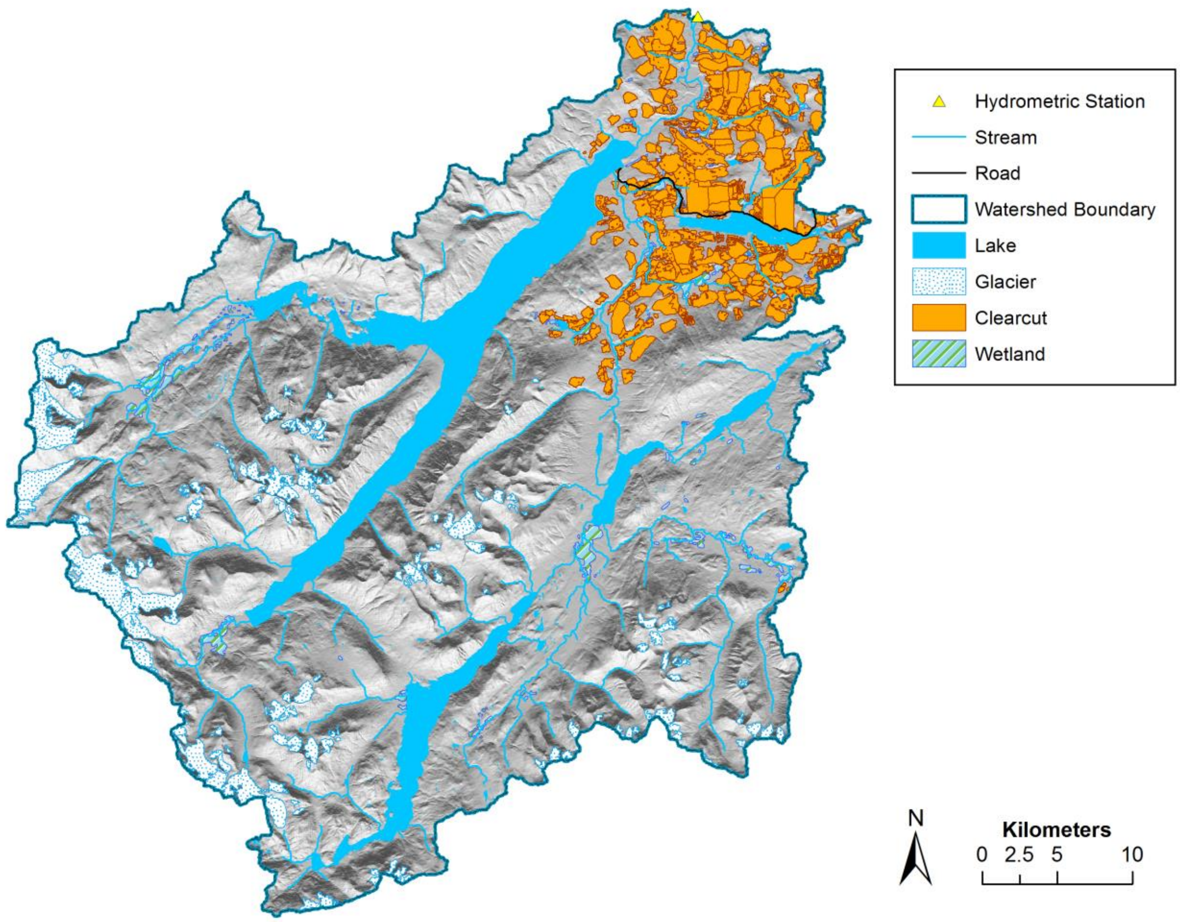

Figure 4: Morice River
The Morice River watershed. The gray-scale base map is a hillshade model of the TRIM DEM. The Morice River watershed includes the smaller Nanika River and Atna Lake watersheds as sub-drainages.

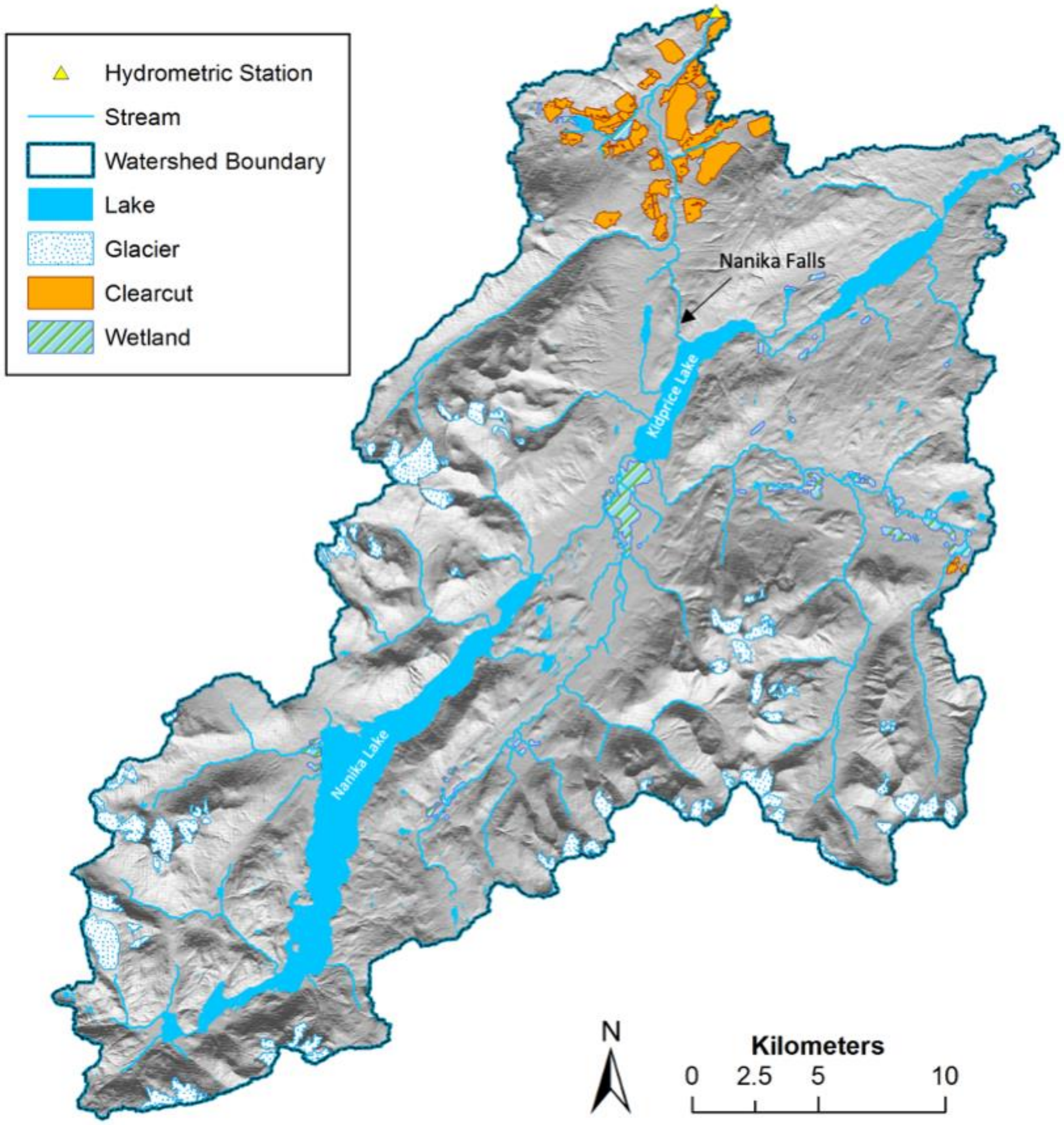

Figure 5: Nanika River
The Nanika River watershed. The gray-scale base map is a hillshade model of the TRIM DEM.

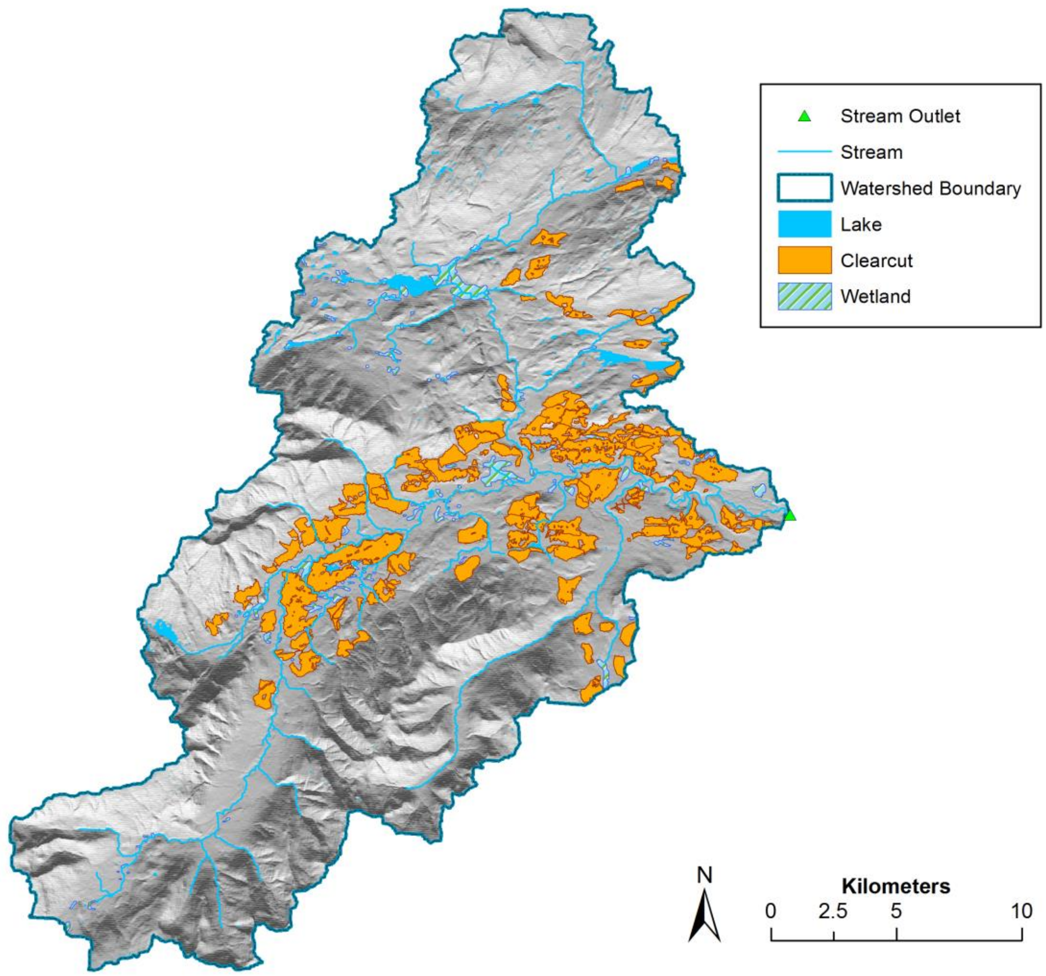

Figure 6: Gosnell Creek
The Gosnell Creek watershed. The gray-scale base map is a hillshade model of the TRIM DEM. There are no glaciers and no major roads in the Gosnell Creek watershed. Logging roads, however, are present and connect cutblocks (not mapped).

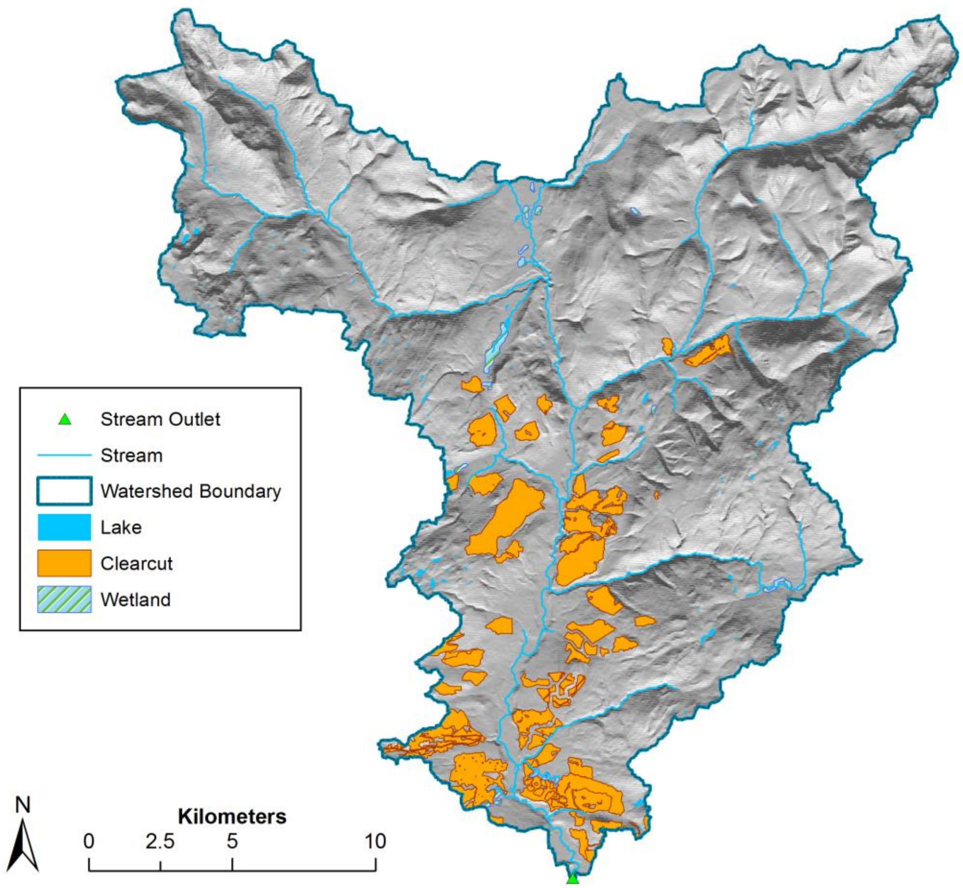

Figure 7: Thautil River
The Thautil River watershed. The gray-scale base map is a hillshade model of the TRIM DEM. There are no glaciers and no major roads in the Thautil River watershed. Logging roads, however, are present and connect cutblocks (not mapped).

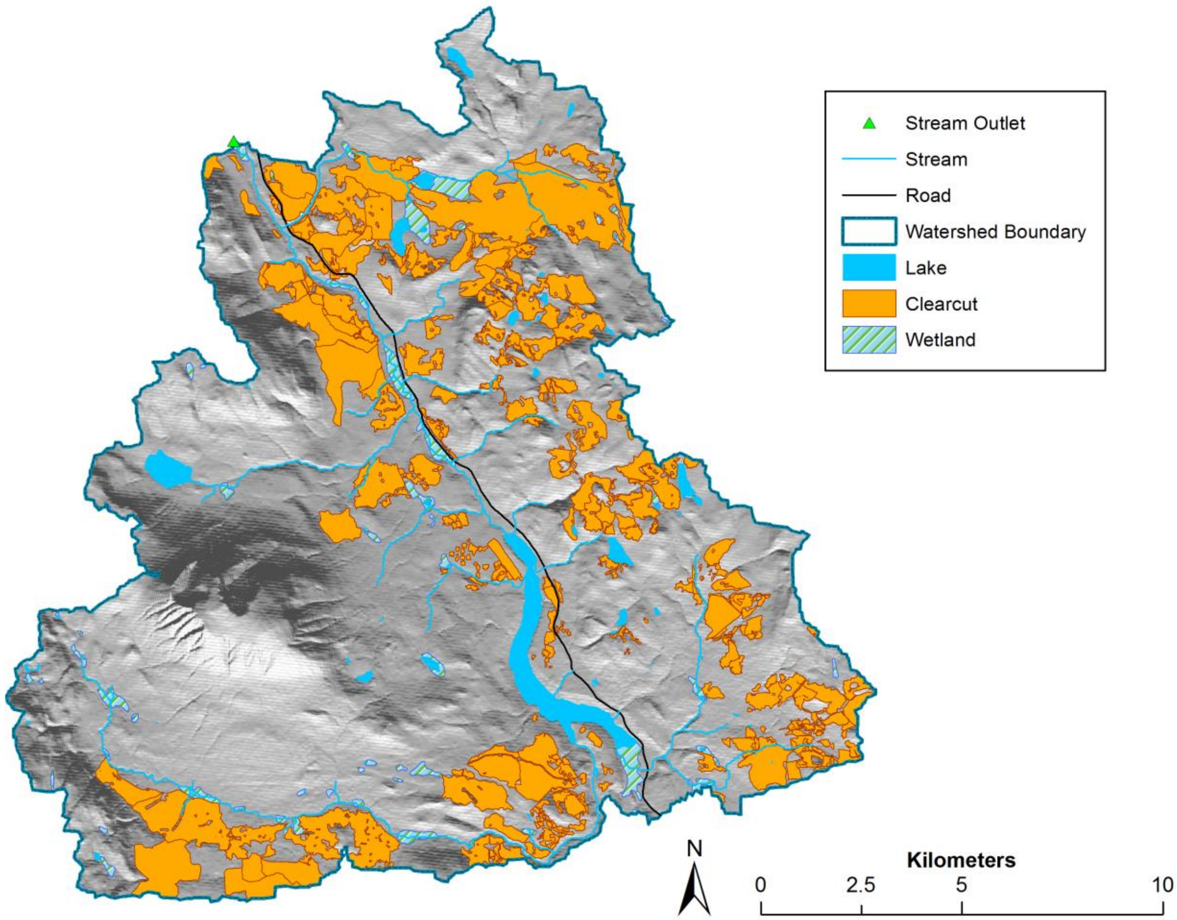

Figure 8: Owen Creek
The Owen Creek watershed. The gray-scale base map is a hillshade model of the TRIM DEM. There are no glaciers in the Owen Creek watershed.

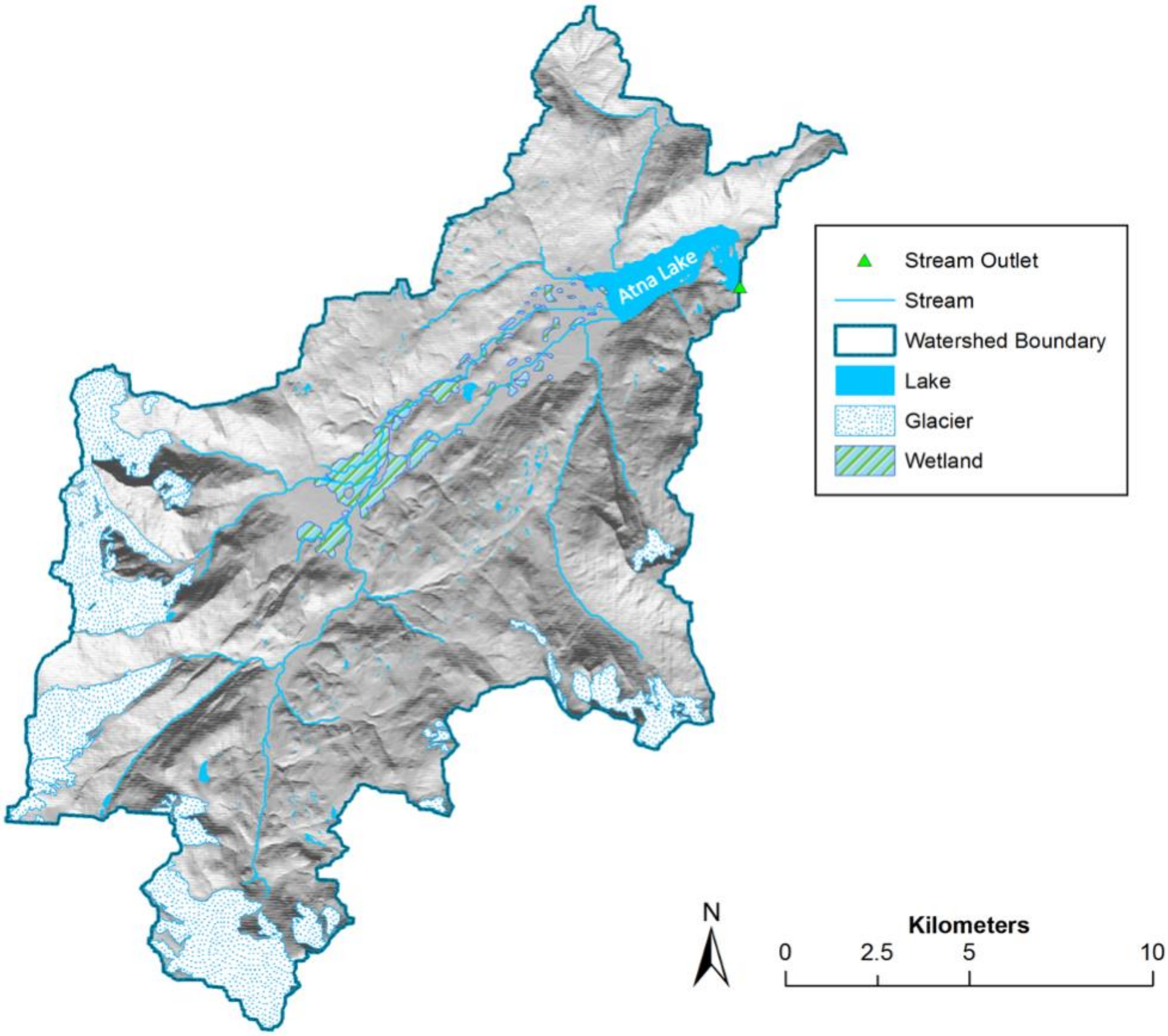

Figure 9: Atna Lake

The Atna Lake watershed. The gray-scale base map is a hillshade model of the TRIM DEM. There are no clearcut areas or roads in the Atna Lake watershed.

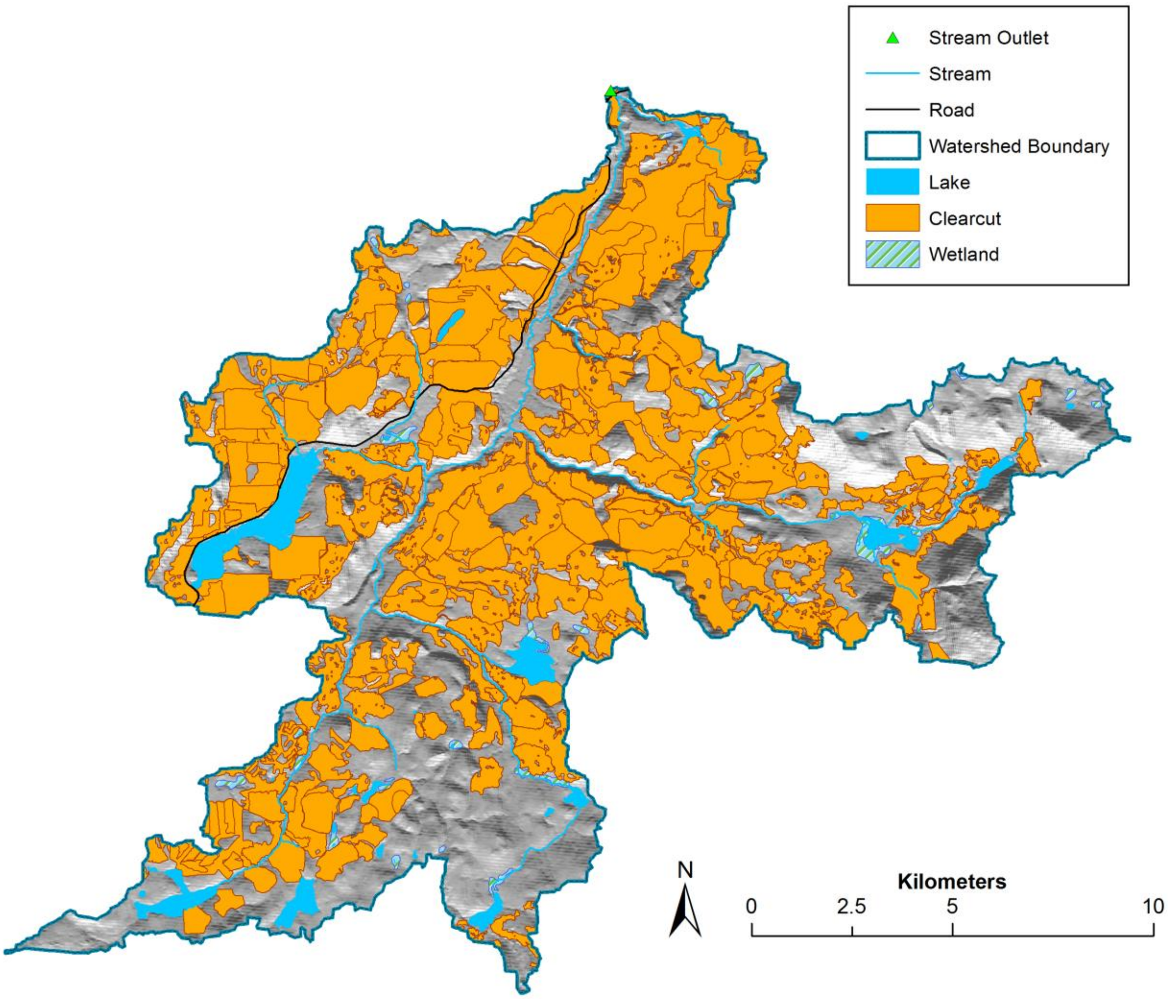

Figure 10: Lamprey Creek
The Lamprey Creek watershed. The gray-scale base map is a hillshade model of the TRIM DEM. There are no glaciers in the Lamprey Creek watershed.