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# Assessing the "Snow Sensitive Zone" at Multiple Scales in the Kettle River Watershed, Southern British Columbia

Natasha Neumann

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**Author's Affiliation:**
Natasha N. Neumann Ph.D., P.Ag.
Research Hydrologist
B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development
Kootenay Boundary Region
401-333 Victoria Street
Nelson, B.C. V1L 4N2

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Neumann, N.N.

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## EXECUTIVE SUMMARY

The area contributing snow meltwater during the peak flow period is referred to as the 'snow sensitive zone' (SSZ) of a watershed. Forest harvest and other forms of vegetation cover disturbance within the SSZ alters the accumulation and melt of snow relative to adjacent forest stands, potentially leading to the synchronised delivery of meltwater from multiple parts of the catchment that had previously been decoupled. Identification of the SSZ, then, is important for planning harvesting and resource development activities to minimize impact on snowmelt-generated peak flows. In British Columbia, early guidelines recommended estimating the SSZ using the H60, the elevation above which 60% of the total basin area lies. This recommendation was assumed to be a conservative estimate of the snowline elevation based on a seminal study of snow hydrology in Colorado (Gartska et al. 1958). Attempts have been made to validate the H60 concept in the southern interior of B.C. using visual analysis of aerial photographs, efforts that were costly and labour intensive and therefore limited in geographic coverage (e.g., Gluns 2001; Smith et al. 2008). The more recent availability of modelled spatial snow cover datasets has opened the opportunity to assess the SSZ across larger areas than was possible in the past.

This report describes the method developed to map the SSZ using modelled 1 km$^2$ spatial resolution SNODAS snow water equivalent (SWE) product produced by the U.S. National Operational Hydrologic Remote Sensing Center to identify the snow covered area (SCA) at the onset of the peak flow period. Two drainage basins, Redfish Creek in the West Kootenays and Mission Creek in the Okanagan River basin, were used to refine the methods though comparison with previous studies (Gluns 2000, 2001; Whitaker et al. 2002; Smith et al. 2008). The refined method was applied to eight nested catchments in the Kettle River basin in the Boundary area. The nested catchments ranged in area between 148 and 9943 km$^2$ and spanned from dry valley bottoms to forested mountains that accumulate more than 800 mm SWE per winter on average. Maps of SCA at the onset of the peak flow period were derived for each of the Kettle River basins for 2010 to 2020. Maps of SCA over the eleven years demonstrated variability in melt timing but consistent patterns in snow melt from year to year. The median SCA for the 2010-2020 period was used to delineate the SSZ for each study basin, and the elevation of the SSZ lower limit was estimated from hypsometric curves (Table ES1).

*Table ES1. Summary of 2010-2020 snowline results for the Kettle River basins. Because of the small sample size, both mean and median values are shown. The lower limit elevations of the snow sensitive zone and the H60 elevations were estimated from hypsometric curves.*

| Basin | Median SCA at Peak Flow Onset (%) | SSZ Lower Limit Elevation (m) | H60 Elevation (m) | Difference (m) |
|---|---|---|---|---|
| Trapping Creek | 86 | 1120 | 1295 | -175 |
| Burrell Creek | 100 | 900 | 1380 | -480 |
| West Kettle River near McCulloch | 99 | 1030 | 1580 | -550 |
| West Kettle River at Westbridge | 74 | 1200 | 1285 | -85 |
| Granby River | 69 | 1130 | 1230 | -100 |
| Kettle River near Westbridge | 80 | 1150 | 1350 | -200 |
| Kettle River near Ferry | 64 | 1190 | 1250 | -60 |
| Kettle River near Laurier | 51 | 1270 | 1195 | 75 |
| | **Mean** | **1124** | **1321** | **-197** |
| | **Median** | **1140** | **1290** | **-150** |

Modelled climate normal data and a hydrologic model were used to verify aspects of the SSZ in the Kettle River basin. Elevation bands were identified where annual precipitation was dominated by rain, snow or mixed rain and snow, and the lower limit of the SSZ occurred slightly below the boundary between the rain dominated and mixed rain and snow zones, estimated at 1250 m. Output from a hydrologic model verified that snowmelt occurred at all elevations in the SSZ at the start of the peak flow period, and that the lower limit of the SSZ fell between 1100 and 1400 m.

The lower limit of the SSZ was slightly lower than the H60 elevation in all but the largest watershed analysed in the Kettle River basin, and the differences increased as median basin elevation increased. This indicated that using a fixed SCA value (e.g., the H60) when assessing the hydrologic impacts of forest harvesting or disturbance in the Kettle River watershed without regard to basin characteristics may not accurately reflect potential impacts on snow accumulation and melt patterns. Further work is planned to expand this analysis across the upper Columbia River basin, to compare SSZ characteristics across a wider range of climates and topographic conditions.

The methods used in this analysis provide an objective, repeatable way to identify the SSZ for watersheds that have hydrometric data. The SSZ maps can provide information to inform specialist's planning of harvest activities in ways that reduce the potential for snowmelt synchronization and resultant increases in peak flow in the Kettle River basin. Snowmelt synchronization can be reduced by considering differences in snow accumulation and melt with slope, aspect and harvest practises within the SSZ. The SSZ maps can also be used by land and resource managers when evaluating the cumulative effects of multiple disturbances on watershed processes.

Climate change will likely continue to alter the timing and rates of snowfall and melt, most importantly by reducing the amount and persistence of snow at mid-elevations. As a result, the size of the SSZ will likely decrease over time, although the rate of change is uncertain. The maps presented in this report provide information for modern forest development planning and should be updated in the next few decades.

## CONTENTS

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## ACRONYMS

| | |
|---|---|
| B.C. | British Columbia |
| BEC | Biogeoclimatic Ecosystem Classification |
| DEM | Digital elevation model |
| DD>5 | Degree days warmer than 5°C |
| ECA | equivalent clearcut area |
| ENSO | El Niño/Southern Oscillation |
| FWA | B.C. Freshwater Atlas |
| GIS | Geographic information system |
| HBV-EC | Hydrologiska Byråns Vattenbalansavdelning hydrologic model modified by Environment Canada |
| HRU | Hydrologic response unit |
| ID | identifier or identification number |
| IWAP | Interior Watershed Assessment Procedures |
| JFM | January-February-March |
| LTMAD | long term mean annual discharge ($m^3/s$) |
| NSIDC | National Snow and Ice Data Center (U.S.) |
| MAM | March-April-May |
| MAP | Mean annual precipitation |
| MAT | Mean annual temperature |
| MRS | mixed rain and snow |
| ONI | Oceanic Niño Index |
| PAS | precipitation as snow |
| PDO | Pacific Decadal Oscillation |
| ROS | rain-on-snow |
| SCA | snow covered area |
| SNODAS | Snow Data Assimilation System |
| SSZ | snow sensitive zone |
| SWE | snow water equivalent |
| U.S. | United States of America |
| USGS | United States Geological Survey |
| WSC | Water Survey of Canada |

## 1. INTRODUCTION

In the interior mountainous catchments of British Columbia (B.C.), anthropogenic and natural forest disturbance at mid- and high elevations has the potential for (a) greater snow accumulation in openings relative to adjacent forests and (b) earlier snowmelt in openings relative to adjacent forests which can synchronize with snowmelt at lower elevations. These two effects can potentially combine to increase spring peak flows, causing flooding and damage to downstream communities and infrastructure, and altering aquatic and riparian ecosystems. The area contributing snow meltwater during the peak flow period is referred to as the 'snow sensitive zone' (SSZ) of a watershed. In B.C., early guidelines recommended estimating the SSZ using the H60, the elevation above which 60% of the total basin area lies. This recommendation was assumed to be a conservative estimate of the snowline elevation based on a seminal study of snow hydrology in Colorado (Gartska et al. 1958). Attempts have been made to validate the H60 concept in southern B.C., efforts that were costly and labour intensive. The recent availability of spatial snow cover products has opened the opportunity to assess the SSZ at a broader scale than was possible in the past. This report describes a method developed to map the SSZ in the Kettle River basin in the Boundary region using hydrometric data and gridded snow water equivalent (SWE) products available for southern B.C. since 2010 from the U.S. National Operational Hydrologic Remote Sensing Center.

Snow water equivalent (SWE) in forest openings has been shown to be 5-70% greater than in mature forests depending on the year, aspect, elevation and forest stand characteristics, and melt rates in openings can be the same to double that in adjacent forest stands (Teti 2003; Winkler et al. 2004; Jost et al. 2007; Varhola et al. 2010; Boon 2012; Winkler et al. 2015). The factors that determine differences in snow accumulation and melt processes between disturbed and undisturbed forested stands include snowfall magnitude and interannual variations, topography (elevation, aspect and slope), wind speed, specific weather conditions during the melt period, opening size and forest canopy geometry and tree distribution (Winkler et al. 2004; Varhola et al. 2010). A meta-analysis of snow studies across North America and Europe found that forest cover changes explained 57% and 72% of the variance in the differences in snow accumulation and melt, respectively, between open and forested sites (Varhola et al. 2010). As a result, consideration of snow accumulation and melt processes at the watershed scale in forest development planning can be important to avoid impacts on peak flow. This may be accomplished through identification of the SSZ.

Guidance for forestry planning in snow dominated watersheds in B.C. was provided under the Forest Practices Code through the Watershed Assessment Procedure Guidebook (B.C. Ministry of Forests 2001). The Interior Watershed Assessment Procedures (IWAP) included assessment of forest openings by elevation band to assess and avoid the potential for snowmelt synchronisation and subsequent increases in peak flow. Within the IWAP guide, the equivalent clearcut area (ECA) index was used to assess the potential risk of forest disturbance affecting peak flow as a measure of the total disturbed area, adjusted for the type of disturbance and regrowth since disturbance. While the *Forest Practices Code of British Columbia Act* was superseded by the *Forest and Range Practices Act* in 2004, the IWAP procedures still provide a foundation for land management that considers watershed values. Additionally, the ECA concept has been more widely applied through consideration of natural and non-forestry disturbances (e.g., insect outbreaks and wildfires).

Central to the IWAP procedures was the use of the H60 elevation, or another value derived by a hydrologist, as the elevation above which the majority of the water delivered as peak flow originates. Under IWAP, the forest disturbance metrics in calculating the ECA for a watershed were differentially weighted based on elevation; disturbances below the elevation threshold were assigned a weighting of 1, while those above the threshold were given a weighting of 1.5 or 2. The weighting values were not selected to quantify actual increases in the magnitude of peak flows but to flag areas where further information was needed on potential increased hazard of elevated peak flows due to forest disturbance in the SSZ. Following the publication of the IWAP guidelines, there have been several studies in southern B.C. using aerial photographs to identify the SSZ in the West Kootenays (Gluns 2000, 2001), Okanagan basin (Smith et al. 2008; Dobson Engineering Ltd. 2003a-c, 2004a, 2004c, 2005a-d; Dobson 2013) and Thompson region (Dobson Engineering Ltd. 2004b) (Table 1).

*Table 1. Summary of snow sensitive zone studies in southern British Columbia.*

| **Basin** | **Area (km$^2$)** | **SSZ** | | **Notes and References** |
|---|---|---|---|---|
| | | **Elevation (m)** | **% of basin area** | |
| West Kootenays | | | | |
| Redfish Creek | 27 | n/a | 64 | 1994-1998 average; Gluns (2000, 2001) |
| Laird Creek | 15 | n/a | 65 | 1994-1998 average; Gluns (2000, 2001) |
| Thompson Region | | | | |
| Chase Creek | 150 | n/a | 40 | 1999-2001 average; Dobson Engineering, Ltd. (2004b) |
| Horsefly River | 2860 | n/a | 60 | Dobson Engineering, Ltd. (2007) |
| Okanagan Basin | | | | |
| Inkaneep Creek | 185 | 1560 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |
| KLO and Hydraulic Creeks | 78 and 90 | 1550 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |
| Mission Creek | 845 | 1460-1575 | n/a | 1999-2004 average: Dobson Engineering, Ltd. (2005a) |
| | | n/a | 30 | Reported in Dobson Engineering, Ltd. (2004b) |
| Peachland Creek | 145 | 1400-1525 | n/a | 2001-2004 average; Dobson Engineering, Ltd. (2005b) |
| | | 1340 | n/a | Scherer (2018) |
| | | n/a | 22 | Reported in Dobson Engineering, Ltd. (2004b) |
| Penticton Creek | 175 | 1520 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |
| | | 1660 | n/a | Dobson Engineering, Ltd. (2013) |
| Shatford Creek | 101 | 1400 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |
| Shingle Creek | 299 | 1550-1650 | n/a | Measured in 2003; Dobson Engineering, Ltd. (2005c) |
| | | 1350-1450 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2005c) |
| | | n/a | 26 | Reported in Dobson Engineering, Ltd. (2004b) |
| Shuttleworth Creek | 90 | 1590 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |
| Trout Creek | 746 | 1400-1550 | n/a | 2001-2004 average; Dobson Engineering, Ltd. (2005d) |
| | | n/a | 36 | Reported in Dobson Engineering, Ltd. (2004b) |
| Vaseux Creek | 292 | 1570 | n/a | Measured in 2004; Dobson Engineering, Ltd. (2004b) |

Interannual variability in SCA during peak flow underscores the need to consider multiple years of data when identifying the SSZ for a watershed. In addition, it is expected that there are regional differences in the SSZ in southeastern B.C. because of spatial variability in the topographic and climatic drivers that control snow accumulation and melt. Gluns (2000, 2001) used aerial photography to monitor the snowline in two adjacent basins in the West Kootenays (Redfish and Laird Creeks) over five melt periods (1994-1998) and found that peak flow occurred when SCA was between 40 and 80%, averaging at 65%. The wide range of values measured over the five years reflects both the effects of winter precipitation amounts and timing (SCA tends to be higher in years with more winter snowfall) and the dependence of snowmelt and therefore peak flow on weather during the melt period. Results for the two basins monitored supported the use of the H65 elevation to represent the average snowline at the time of peak flow and therefore the SSZ. This project demonstrated that basin properties and climate determine the applicability of the H60 concept. Gluns' (2001) results may be more widely applicable to small, steep catchments in the same climatic region where more snow accumulates at higher elevations. The Redfish and Laird Creek catchments also have significant non-forested alpine areas. Subsequent modeling work in the Redfish Creek basin using data for 1992-1997 assessed the effects of forest harvesting in different elevation bands, and supported the finding that the SSZ covered approximately 60% of the basin area (Whitaker et al. 2002).

Analyses using aerial photography in ten tributaries of Okanagan Lake and one in the Thompson River basin identified the SSZ as covering 22 to 40% of the total drainage basin area (Smith et al. 2008; Dobson Engineering Ltd. 2003a-c, 2004a-b, 2005a-d; Dobson 2013). Some of the variability in these results was attributed to watershed aspect, but a more comprehensive assessment of the basin properties and climate factors that determine the SSZ is needed. This requires more studies in watersheds with different characteristics across a wider area and covering different time periods.

Gridded daily SWE data at 30 arc second (~1 km$^2$) resolution are produced by the U.S. National Operational Hydrologic Remote Sensing Center (NOHRSC), available online through the U.S. National Snow and Ice Data Centre (Barrett 2003; NOHRSC 2004). The Snow Data Assimilation System (SNODAS) integrates information from weather forecast and snow process models with remote sensing and ground-based observations to simulate snow cover in order to support hydrologic modeling and analysis (Carroll et al. 2001; Dietz et al. 2012). SNODAS SWE and snow depth products have been used as comparison and validation data sets for field measurements, remotely sensed data and weather models (Lea 2007; Tedesco and Narvekar 2010; Clow et al. 2012; Artan et al. 2013; Guan et al. 2013b; Schneiderman et al. 2013; Vuyovich et al. 2014; Boniface et al. 2015; Hedrick et al. 2015; Zheng et al. 2015; Bair et al. 2016; Broxton et al. 2016; X. Liu et al. 2016; Wrzesien et al. 2017; Keum et al. 2018; Musselman et al. 2018; Siren et al. 2018; X. Liu et al. 2019; Zahmatkesh et al. 2019; Gan et al. 2021), and as inputs for (or to derive inputs to) large basin hydrologic modeling (Bair et al. 2013; Guan et al. 2013a; Pomeroy et al. 2015; Driscoll et al. 2017; Hammond et al. 2018; Massmann 2019; Arsenault et al. 2020). The SNODAS SWE data product was selected for this project because the spatial resolution was appropriate for large watersheds, the daily temporal resolution matched the hydrometric data used, its availability back in time to 2010 and its relatively wide use in the literature.

There were two objectives to this analysis. The first was to develop a method to map the SSZ using hydrometric and SNODAS data, and to assess the approach through comparison with previous studies in the West Kootenays (Redfish Creek: Gluns 2000, 2001) and the Okanagan River basin (Mission Creek: Smith et al. 2008). The second was to apply the method to eight watersheds nested within the Kettle River basin in southern B.C. and to compare the results with available modelled and measured weather and streamflow data. As part of this objective, detailed results for each of the study watersheds are provided in appendices to provide basin-specific information on watershed properties, peak streamflow patterns, snowmelt patterns, and spatial and temporal variability.

The SSZ maps created from this analysis represent the effects of “average” snow accumulation and melt processes that occur every year and that are affected by forest disturbance (i.e., spring melt dominated by net radiation and turbulent energy fluxes). Rain-on-snow (ROS) events, which have occurred less frequently in the past, can cause extreme flooding (Jones and Perkins 2010; A.Q. Liu et al. 2016; Pomeroy et al. 2016). ROS events are more common during the spring in southeastern B.C. (McCabe et al. 2007; Musselman et al. 2018), but in 2021 high rainfall associated with atmospheric rivers caused disastrous flooding during the fall in numerous rivers. It will be important to understand climate change effects on ROS frequency, intensity and seasonality in the future (Freudiger et al. 2014; Guan et al. 2016; Jeong and Sushama 2018; Musselman et al. 2018). In terms of forest landscape management, the research literature indicates that the effects of forest harvest on ROS-generated peak flow is highly variable and depends on the characteristics of the snowpack, vegetation cover and weather (Harr 1986; Marks et al. 1998, 2001; Jones 2000; Jones and Perkins 2010; Garvelmann et al. 2014, 2015; Wayand et al. 2015; Pomeroy et al. 2016; Würzer et al. 2016; Würzer and Jonas 2018). Analysis of the impacts of forestry on streamflow during ROS events would require detailed modeling, which was outside the scope of this study.

Section 2 of this report describes the Redfish and Mission Creek sub-basins used for methods development and the eight nested sub-basins within the Kettle River watershed used in the remainder of the analysis, as well as the methods developed to delineate and verify the SSZ. In Section 3, the results of the method testing in the Redfish and Mission Creek basins are compared to previous studies, followed by summaries of the results for the Kettle River sub-basins. The section ends with comparisons of the derived SSZ’s with climate data and a hydrologic model. Section 4 is a discussion of results including forestry management considerations, and the results are summarised in Section 5. Detailed results and maps for each sub-basin are included as appendices, along with a summary of annual snow accumulation and melt conditions derived from provincial Snow Survey and Water Supply Bulletins (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/drought-flooding-dikes-dams/river-forecast-centre/snow-survey-water-supply-bulletin).

## 2. DATA AND METHODS

The method for identifying the SSZ used a combination of daily hydrometric data and spatially distributed SNODAS snow data products and were developed using Redfish and Mission Creek basins, the subjects of previous SSZ studies (Gluns 2000, 2001; Smith et al. 2008). The methods were then applied to eight basins nested within the Kettle River watershed, in southern B.C., to delineate SCA at the onset of the 2010-2020 peak flow periods. The following sections describe the study basins, and the data and methods used to identify and validate the SSZ.

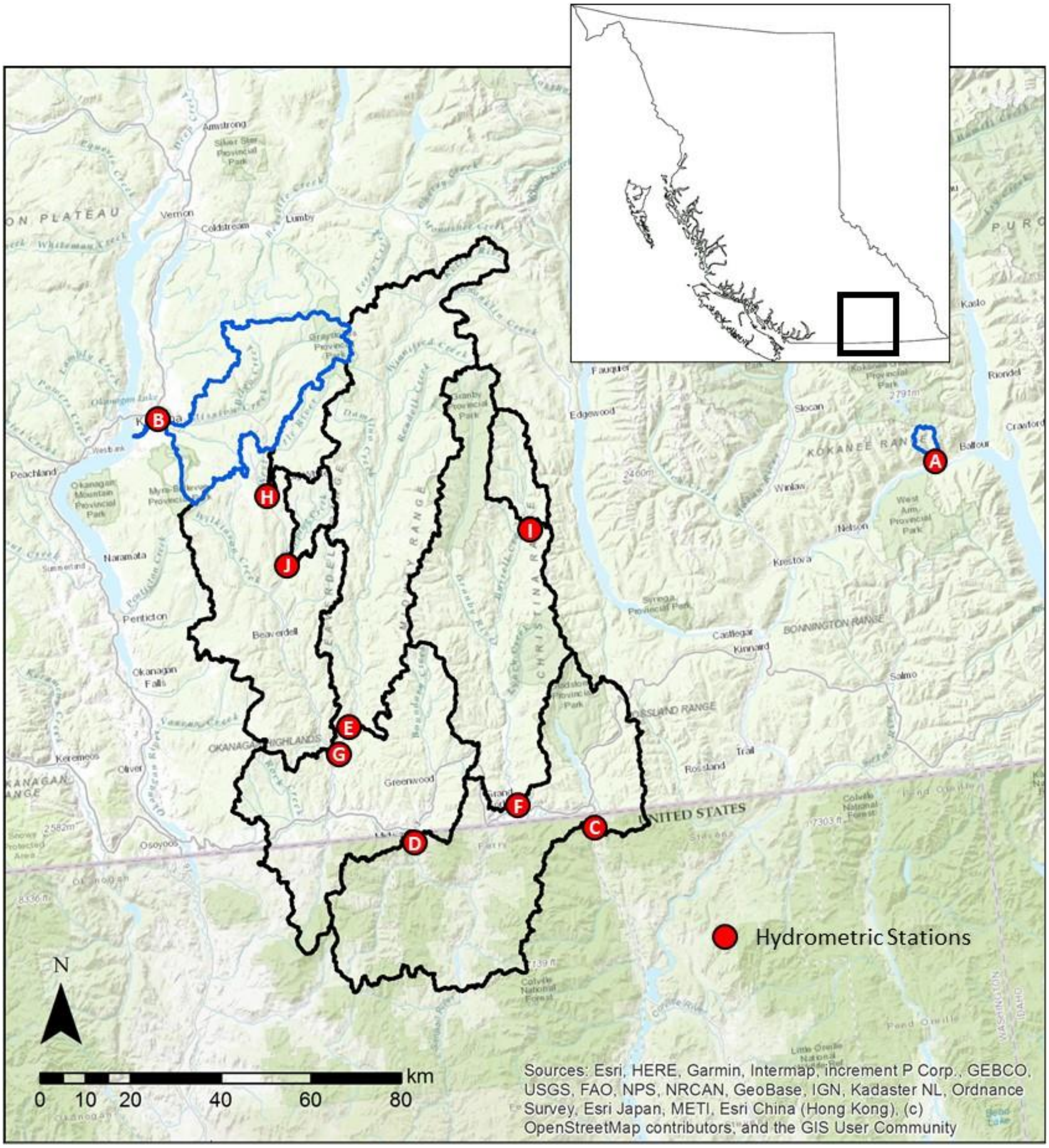
### 2.1 Study Area

Two basins that were the focus of previous work in southern B.C. were selected to test the method. Redfish Creek, located in the West Kootenays, was analysed by Gluns (2000, 2001) while Mission Creek, in the Okanagan River basin, was reported on by Smith et al. (2008) (Table 2 and Figure 1). SSZ results for these two test basins were compared to the published studies to compare (a) different methods and (b) results across different decades.

*Table 2. Details of the ten study basins. Letters in the second row correspond to locations in Figure 1 as well as the appendices where detailed information can be found for each basin.*

| **WSC Station Identifier** | **08NJ061 Redfish Creek near Harrop** | **08NM116 Mission Creek near East Kelowna** | **08NN012 Kettle River near Laurier (USGS ID 12404500)** | **08NN013 Kettle River near Ferry (USGS ID 12401500)** | **08NN026 Kettle River near Westbridge** | **08NN002 Granby River at Grand Forks** | **08NN003 West Kettle River at Westbridge** | **08NN015 West Kettle River near McCulloch** | **08NN023 Burrell Creek above Gloucester Creek** | **08NN019 Trapping Creek near Mouth** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Identifier** | A | B | C | D | E | F | G | H | I | J |
| **Station Lat (N) and Long (W)** | 49°37’21”<br>117°03’20” | 49°52’40”<br>119°24’48” | 48°59’04”<br>118°12’55” | 48°58’53”<br>118°45’55” | 49°13’48”<br>118°55’41” | 49°02’35”<br>118°26’25” | 49°10’11”<br>118°58’30” | 49°42’10”<br>119°05’32” | 49°35’20”<br>118°18’42” | 49°33’55”<br>119°03’07” |
| **Avg Slope (°)** | 45 | 18 | 29 | 24 | 23 | 32 | 22 | 16 | 26 | 15 |
| **Min Elevation (m)** | 532 | 341 | 434 | 564 | 632 | 512 | 625 | 1028 | 901 | 880 |
| **Max Elevation (m)** | 2364 | 2171 | 2248 | 2316 | 2410 | 2412 | 2170 | 2315 | 2329 | 2314 |
| **Median Elevation (m)** | 1805 | 1392 | 1117 | 1180 | 1446 | 1338 | 1313 | 1629 | 1443 | 1361 |
| **H60 Elevation (m)[a]** | 1715 | 1320 | 1195 | 1250 | 1350 | 1230 | 1285 | 1580 | 1380 | 1295 |
| **% of Basin with N Aspect** | 8% | 24% | 19% | 19% | 19% | 18% | 18% | 20% | 14% | 10% |
| **% of Basin with E Aspect** | 28% | 21% | 29% | 29% | 27% | 29% | 33% | 20% | 39% | 25% |
| **% of Basin with S Aspect** | 36% | 22% | 22% | 21% | 21% | 23% | 20% | 22% | 22% | 37% |
| **% of Basin with W Aspect** | 28% | 32% | 30% | 30% | 33% | 30% | 28% | 38% | 25% | 28% |
| **% of Basin that is Flat (No Aspect)** | 1% | 1% | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Basin Area (km$^2$)** | 27.3 | 791 | 9943 | 5663 | 2156 | 2062 | 1898 | 230.5 | 221.8 | 148.0 |

*a. Estimated from hypsometric curves.*



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure 1. Map of study area in southern British Columbia. Letters used for hydrometric stations correspond to Table 2. Sub-basins within the Kettle River watershed are outlined in black.*

The methods were then applied to eight catchments nested within the Kettle River basin, which saw major flooding in 2017 and 2018 and is the focus of recent cumulative effects and hydrologic modelling work by the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development. Analysis of the nested catchments allowed comparison of results across different scales, topographies, climates and forest types, and assessment of the appropriate scale at which forestry and natural disturbance impacts on snowmelt-generated peak flow could be considered in the Kettle River basin.

Watershed boundaries were defined by matching the location of Water Survey of Canada (WSC) and United States Geological Survey (USGS) hydrometric stations with the Assessment Watershed boundaries in the B.C. Freshwater Atlas (FWA) (https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/freshwater, accessed 21 May 2021). The watershed boundaries were matched as closely as possible to the location of the hydrometric station by adding or removing smaller drainage units listed as 'Watersheds' in the FWA. The resulting watershed areas differed from those published by WSC by -2.1 to 1.1 %. Because the difference in areas was small it was assumed that flow measured at the hydrometric station was representative of conditions for the basin areas used in this study. Brief descriptions of each study basin are provided below, and supplemental maps are in the appendices.

Two basins that were the subjects of previous studies were selected for methods development. Redfish Creek basin is a small, relatively steep catchment that drains directly to Kootenay Lake's West Arm, northeast of the City of Nelson (Table 2 and Figure 1). The steep slopes and thin, coarse grained soil mean that precipitation inputs tend to move to streamflow rather than remain stored in the landscape (Whitaker et al. 2002). The Redfish Creek basin was selected for this analysis because it was the subject of two previous snowline studies. Gluns (2000, 2001) conducted a snowline study here, as well as in adjacent Laird Creek, to test the validity of the H60 concept, and a separate study was completed that modelled the effects of forest harvesting at different elevations on peak flow (Whitaker et al. 2002). Mission Creek, the largest tributary to Okanagan Lake, flows southwest from the Okanagan Highlands and through the City of Kelowna (Figure 1). Steep slopes occur near incised stream channel sections, but the mean slope for the basin is only 18° (Table 2). A few large upland lakes are managed as reservoirs for irrigation and domestic water use, and there are some large wetland complexes identified in the northeast. In addition to the reservoirs in the upper part of the basin, lakes and wetlands provide water storage and therefore can moderate peak flows. The Mission Creek basin was selected for this analysis because it was the subject of a previous snowline study. Smith et al. (2008) used aerial photographs collected during the freshet period to test the H60 concept. The results of this analysis will be compared to the previous studies in Section 4.1.

The largest basin studied in the Kettle River watershed was defined for the USGS hydrometric station near Laurier (Table 2), and includes the West Kettle River, Kettle River, Boundary Creek, Granby River and Christina Lake drainages. The headwater valleys in this drainage basin are oriented roughly north-south, while the large main valley near the Canada-US border has an east-west orientation. It covers a wide range of Biogeoclimatic Ecosystem Classification (BEC) zones, from Ponderosa Pine (PP) and Interior Douglas-fir (IDF) at low elevations to Engelmann Spruce – Subalpine Fir (ESSF) at high elevations (Figure C2). The driest climates with low winter snow accumulation are found at low and middle elevations in the south and west portions of the basin, and the wettest are in the north and east. There are no glaciers or permanent snowpacks in the basin, and forest cover extends to the highest elevations. Because of a mild winter climate and low snowfall there is often little or no snow at the valley bottoms at the start of the peak flow period. The selected eight nested catchments ranged in size from 148 to 9,943 km$^2$, with median elevations varying between 1117 to 1629 m.

## 2.2 Hydrograph Analysis

Data from ten hydrometric stations in the study region were acquired from the WSC online database (approved data) and directly from WSC staff (provisional data) (Table 3). The two stations in the U.S. are cooperatively managed by WSC and USGS, and data are available from the WSC online database. For every stream, each year of hydrometric data were analysed to identify the following nine hydrologically significant dates:

- the date of maximum daily flow;
- the start and end dates of the freshet flow period (following Smith et al. 2008);
- the start and end date of the peak flow period (following Smith et al. 2008); and
- the dates when 20, 40, 60 and 80% of the cumulative freshet flow volume had occurred (constrained by the start and end dates of the freshet flow period).

*Table 3 Details of the hydrometric station data used in the analysis. Letters in the first column correspond to locations in Figure 1.*

| | **WSC Station Name** | **WSC Station ID** | **Basin Description** | **Period of Published Data (complete years)** | **Period of Provisional Data** | **Long Term Mean Annual Discharge ($m^3/s$)[a]** |
|---|---|---|---|---|---|---|
| A | Redfish Creek near Harrop | 08NJ061 | Tributary of Kootenay Lake | 1967-2018[b] | n/a | 0.86[b] |
| B | Mission Creek near East Kelowna | 08NM116 | Tributary of Okanagan Lake | 1967-2017 | 2018 | 6.22 |
| C | Kettle River near Laurier | 08NN012 | Kettle River basin | 1929-2018 | 2019-20 | 84.36 |
| D | Kettle River near Ferry | 08NN013 | Kettle River basin | 1929-2018 | 2019-20 | 45.19 |
| E | Kettle River near Westbridge | 08NN026 | Headwater sub-basin | 2008-2018 | 2020 | n/a |
| F | Granby River at Grand Forks | 08NN002 | Tributary of Kettle River | 1967-2019 | 2020 | 30.38 |
| G | West Kettle River at Westbridge | 08NN003 | Tributary of Kettle River | 2008-2019 | 2020 | n/a |
| H | West Kettle River near McCulloch | 08NN015 | Headwater sub-basin | 1975-2019 | 2020 | 3.51 |
| I | Burrell Creek above Gloucester Creek | 08NN023 | Tributary of Granby River | 1974-2019 | 2020 | 4.24 |
| J | Trapping Creek near Mouth | 08NN019 | Tributary of West Kettle River | 1966-2018 | 2019-20 | 1.44 |

*a. Mean for the period 1975-2014.*
*b. Data missing 1987-1993.*

In this analysis, the freshet flow period was defined as when the daily mean discharge was greater than the long term mean annual discharge (LTMAD) for that station (Smith et al. 2008). The first step to identifying the start and end dates of the freshet flow period, then, was to calculate LTMAD for the selected stations. Most of the stations had records between 1975 and 2014 (40 years), so this period was used. Year-round measurements were not available until 2008 for Kettle River at Westbridge (station E in Figure 1) and West Kettle River near Westbridge (station G), so the long-term mean could not be calculated for these stations; instead, dates from one of the other stations were used (see Sections E.1

and G.1 in the appendices for more details). The mean for the same 40 year period was calculated for Redfish Creek although it was missing data for 1987-1993; it was assumed that the mean for the remaining 33 years would be a reasonable estimate of the long term mean. The date when discharge exceeded the LTMAD for five or more consecutive days was identified as the start of the freshet flow period, and the last date that flow remained above the LTMAD was the end of the freshet flow period (Smith et al. 2008).

The peak flow period for each year between 2010 and 2020 were defined following Smith et al. (2008) as when the daily mean discharge was greater than the mean for that freshet flow period.

While most of the systems selected for this analysis have licensed water withdrawals, their volumes will be small relative to the flows occurring in the freshet period, which is the focus of this study. In the case of Mission Creek, which is classified as regulated in the WSC database, a network of reservoirs in the headwaters affects streamflow during the spring. Modeling work for Mission Creek shows an offset between actual (referred to as residual) and naturalised streamflow between mid-May and late August, when the median weekly naturalised flow for 1996-2010 was higher than that measured by WSC at the 08NM116 hydrometric station (Associated Environmental 2019). This suggests that the mean peak flow period discharge value calculated using WSC data would be lower than for the naturalised flow, resulting in identification of an earlier start date for the peak flow period. However, between February and mid-May the naturalised streamflow is lower than the residual flow, which would offset the effect of the lower mean peak flow discharge and result in identification of peak flow period start dates that represent the natural flow pattern reasonably well.

In many cold continental or high elevation climates where snowmelt is the primary driver of peak flow, the hydrograph would be expected to have a single annual peak (Gluns 2001; Tennant et al. 2014). In the temperate climate of the southern interior of B.C. and in watersheds that span a wide range of elevations, freshet hydrographs tend to have multiple peaks, sometimes of similar magnitude, influenced by periods of rapid snowmelt, rainfall and/or rain-on-snow events (Gluns 2001; Tennant et al. 2014). In this analysis, SCA was evaluated and compared for both the date of peak flow and the start of the peak flow period.

Finally, the cumulative daily discharge during the freshet flow period ($m^3$) was used to identify the dates when 20, 40, 60 and 80% of the total freshet flow volume had occurred each year. These data were used to plot changes in SCA over each freshet period.

### 2.3 SWE Data and Snowline Delineation

Catchment SCAs for each date of interest were derived from SNODAS daily SWE data products (Barrett 2003; NOHRSC 2004). The SNODAS 30 arc second gridded SWE data product was selected for this project because the spatial resolution was appropriate for large watersheds, the daily temporal resolution matched the hydrometric data used, it is available starting in 2010 and is relatively widely used in the literature. For SWE threshold testing, SNODAS data for the period 2010-2018 were used; for analysis of the Kettle River basin, the period was extended to 2020.

The unmasked tar files were retrieved from the National Snow and Ice Data Center (ftp://sidads.colorado.edu/DATASETS/NOAA/G02158/). The daily products represent conditions at 06:00 UTC, which is 22:00 Pacific Standard Time, so the date stamp in file name had to be matched carefully with the date needed for analysis. A script was written to uncompress the tar files and extract the SWE product (Product Code 1034; scripts are available from the author upon request), which then had to be uncompressed. Header files were created for each SWE product file following Barrett (2003) and online instructions (https://nsidc.org/support/how/how-do-i-import-snodas-data-arcgis, last accessed on 25 May 2021). The SWE data was imported to ArcGIS, reprojected and subset to cover the study area. Binary maps of snow covered and snow free pixels were derived using a SWE threshold (discussed in the following paragraph). The binary maps were clipped to the watershed boundaries and SCA was calculated as the area of all snow covered pixels or sub-pixels divided by the watershed area, expressed as a percent.

Generation of binary snow presence/absence maps from SWE data required identification of a SWE threshold to represent “snow covered” versus “snow free”. Thresholds of 1 mm (Brown et al. 2007; Gan et al. 2021) and 20 mm SWE (Shamir and Georgakakos 2007) have been reported in the literature. In order to select the SWE threshold for the present analysis, the Redfish and Mission Creek basins were analysed using thresholds of 1, 10, 25, 50 and 100 mm SWE using the same hydrograph analysis methods described for Redfish Creek by Gluns (2001) (i.e., the date of peak flow) and for Mission Creek by Smith et al. (2008) (i.e., the date of onset of the peak flow period). The resulting SCA values for each threshold were (a) compared to see how similar they were, and then (b) compared to the original study results of Gluns (2001) and Smith et al. (2008) for Redfish Creek and Mission Creek, respectively. Similarities and differences in results between this analysis and the Mission Creek study were further explored using meteorological and climatological data (described in Section 2.5).

Once the appropriate SWE threshold was identified, SCA for each study basin was measured on the hydrologically significant dates described in Section 2.2. Obtaining values over the freshet period provided information in changes in SCA through the snowmelt period and allowed comparison between basins and with published studies.

## 2.4 Other Spatial Data

Digital elevation model (DEM) products for B.C. and the U.S. were combined to map the distribution of slopes and aspects in each basin as well as to derive the hypsometric curves. For the portions of the watersheds in B.C., the 25 m provincial DEM produced by GeoBC was used (https://catalogue.data.gov.bc.ca/dataset/digital-elevation-model-for-british-columbia-cded-1-250-000). For the U.S., the 10 m USGS DEM was downloaded (https://apps.nationalmap.gov/downloader/#/) and resampled to 25 m resolution before being combined with the B.C. DEM.

## 2.5 Meteorological and Climate Data

Meteorological and climatological data were used to meet two objectives in this study. The first was to provide context for the comparison between results for Mission Creek from this analysis with those reported by Smith et al. (2008). The second was to verify the elevation of the SSZ lower limit in the Kettle River watersheds.

This study compared 2010-2018 SCA results for Mission Creek with results for 1999-2003. Differences and similarities between these time periods were contextualised using snow accumulation, air temperature and climate index data. To compare snow accumulation (high vs. low years), monthly snow survey data were downloaded from the B.C. Data Catalogue (https://catalogue.data.gov.bc.ca/dataset/705df46f-e9d6-4124-bc4a-66f54c07b228). April 1 data for the McCulloch manual snow survey station were used to represent peak SWE at mid-elevation in the Mission Creek basin (Snow Course Number 2F03, 1280 m elevation), and May 1 data for the Graystoke Lake station were used to represent peak SWE at high elevation (Snow Course Number 2F04, 1840 m elevation). SWE values were expressed as a percent of normal.

Mean April air temperature for the Kelowna A (1999-2003, Climate ID 1123970, elevation 429.50 m) and Kelowna climate stations (2010-2018, Climate ID 1123939, elevation 433.10 m), and the 1981-2010 station normal for Kelowna A were downloaded from Environment Canada (https://climate.weather.gc.ca/index_e.html - Historical Data and Canadian Climate Normals). The difference between the mean April air temperature and the station normal was calculated for each year; values were not used if more than 3 days were missing from the monthly record.

Interannual variability in snow accumulation has been found to be associated with El Niño/La Niña conditions and north Pacific Ocean temperature patterns (Moore et al. 2010; Bevington et al. 2019). The Oceanic Niño Index (ONI) describes patterns in sea surface temperature in the equatorial Pacific Ocean between South America and Asia related to the El Niño/Southern Oscillation (ENSO) atmosphere-ocean dynamic. In the southern interior of British Columbia, La Niña years tend to be associated with higher SWE and cooler temperatures which can prolong the melt period, while winters occurring after the shift into El Niño conditions tend to be warmer and drier than normal (Moore et al. 2010). The U.S. National Center for Environmental Prediction's ONI index values were used to identify warm phase (value > 0.5, El Niño), cold phase (< -0.5, La Niña) and neutral phase (-0.5 to 0.5) ENSO conditions (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). Three month running mean values for January-February-March (JFM) and March-April-May (MAM) were used to represent, respectively, conditions during the main snow accumulation period for all elevations and when snowmelt was occurring from the valley bottoms (primarily in March and April) to mid- and high elevations (primarily April and May, though considerable volumes of meltwater are also produced from high elevation snowpacks in June).

The Pacific Decadal Oscillation (PDO) index describes sea surface temperature patterns in the North Pacific that result from a complex interaction of atmospheric and oceanic circulation patterns and are often referred to as a more persistent form of ENSO expressed in the north Pacific Ocean. The warm/positive phase of the PDO is associated with cold water off the Aleutian Islands and warmer sea surface temperatures along the B.C. coastline, while the opposite pattern is found for the cold/negative PDO phase (Moore et al. 2010). The warm phase is often associated with warmer temperatures in western Canada and lower SWE in the interior of B.C. The monthly phases for JFM and MAM of the U.S. National Centers for Environment Information's monthly PDO index were used to compare synoptic conditions during the 1999-2003 and 2010-2018 periods (https://www.ncdc.noaa.gov/teleconnections/pdo/).

In B.C., precipitation patterns are affected by numerous factors not limited to distance from the coast, latitude, season, patterns of sea temperature/air circulation patterns and, importantly, topography. Within the mountainous southern B.C. region, orographic effects (i.e., elevation, exposure to winds and rain-shadow effects) strongly control regional relationships between elevation and the percent of annual precipitation that falls as snow. Further, elevation is an important control on air temperature and snowmelt rates. These relationships were explored for locations across the Kettle River basin to help verify the snow sensitive zones. Specifically, the relationships were explored to verify the elevation of the SSZ lower limit. In this study, annual and monthly climate variables (mean air temperature, degree days greater than 5°C, total precipitation and precipitation as snow) across a wide range of elevations in the Kettle River basin area were examined.

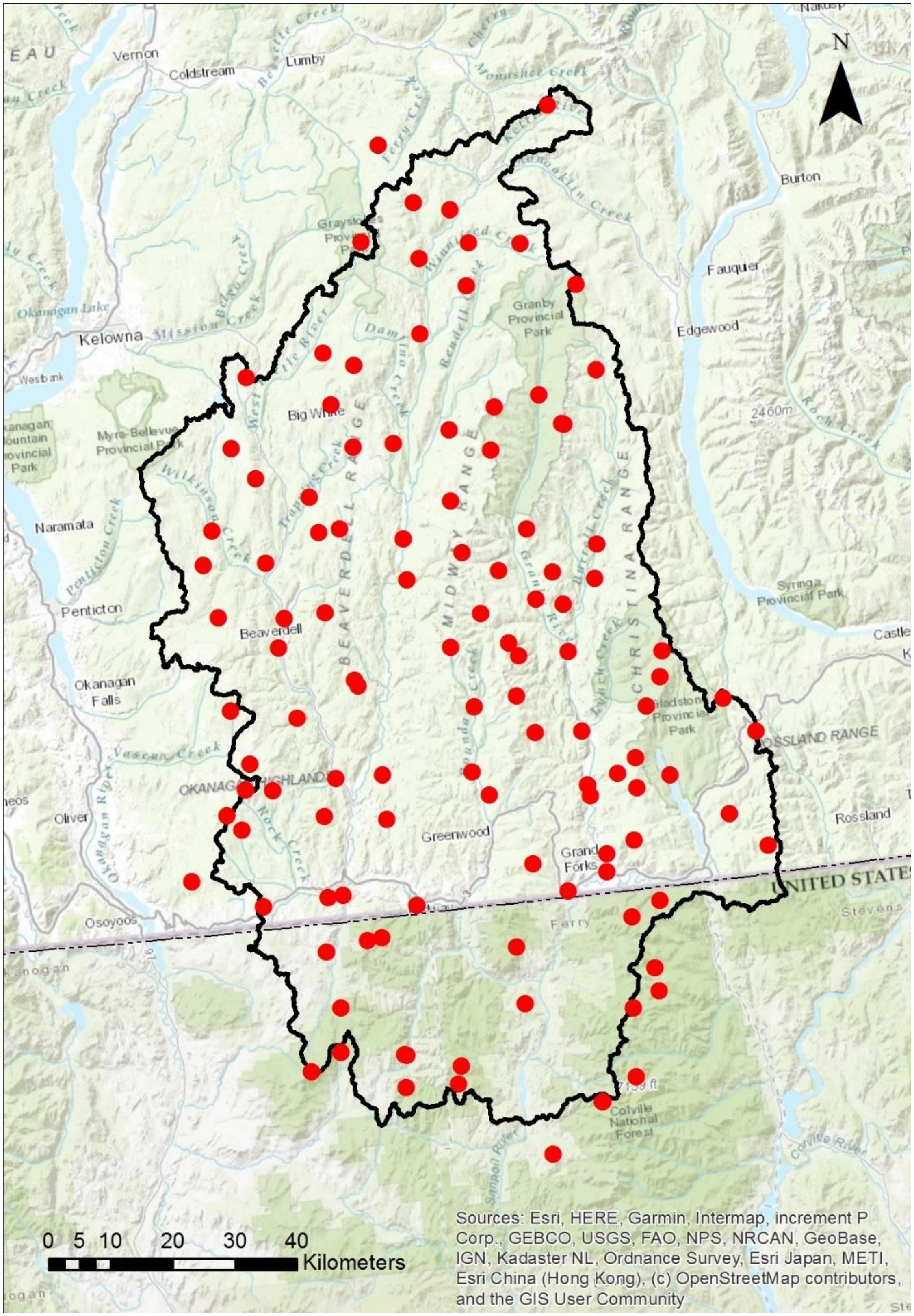
Tennant et al. (2014) used climate data in the Salmon River catchment, Idaho, to identify elevation ranges where annual precipitation was dominated by rain or snow or was mixed rain and snow (MRS). Within the MRS zone, higher elevations remained snow covered over the winter, but snow cover was transient at lower elevations. Within the rain-dominated zone, snow cover was temporary. In basins that lay primarily within their snow-dominated elevations the hydrograph tended to have a single dominant peak, while those in the rain dominated and MRS elevations had multiple peaks. Basins within the MRS range were more likely to have peaks of similar magnitude over the melt period because of earlier and more frequent rain as well as a higher number of melt events compared to those at higher elevations. In this analysis, the lower limit of the SSZ would likely fall within the MRS zone defined by Tennant et al. (2014).

Because climate stations in the study area tend to be located near towns at low elevations, the desktop tool ClimateNA (v. 7.01) was used to derive data for points throughout the Kettle River basin (Wang et al. 2016). Points were manually selected throughout and adjacent to the Kettle River basin to span the range of elevations in the watershed (Figure 2). For each point, the mean annual precipitation (MAP) and precipitation as snow (PAS) outputs were used to calculate the %PAS for each year between 2010 and 2020, inclusive, and for the most recent normal period 1991-2020. Monthly mean air temperature (MAT) and degree days above 5 °C (DD>5) were retrieved from the tool for the same years and normal period to provide information on average snowmelt conditions near the beginning of the freshet period. Mean air temperature during the months of April and May were used because the median date of onset of the peak flow period between 2010 and 2020 varied between 25 April and 10 May for all stations in the Kettle River basin.

## 2.6 Hydrologic Model

An important aspect in the definition of a snow sensitive zone is that all areas within the SSZ contribute water to streamflow from snowmelt. Not all of the watershed area covered in snow may actively contribute meltwater to a stream, especially in large watersheds and where there is considerable alpine area. DeBeer and Pomeroy (2010) explicitly distinguish between snow covered area and the 'snowmelt runoff contributing area'. In mountainous landscapes, the amount of energy available for melt is controlled by air temperature, slope, aspect and wind exposure, and snowpacks generally melt earlier at lower elevations. A hydrologic model was used to explore average melt rates at different elevations in the Kettle River basin to validate the extent of the SSZ.

A hydrologic model was previously developed for a variety of watersheds within the Kettle River basin as part of an assessment of forest disturbance effects on snowmelt-generated peak flows (Chernos et al. 2020a and 2020b). This study used the model developed for the Kettle River basin above Grand Forks, the largest watershed area used in the modeling analysis. It used the Hydrologiska Byråns Vattenbalansavdelning hydrologic model modified by Environment Canada (HBV-EC) within the Raven Hydrological Framework run at a daily time step, simulating streamflow and other hydrologic/climate variables using weather data for 1989-2018. Snowmelt rates were calculated using a degree day method, where the difference in the daily mean air temperature from a melt threshold was a proxy for the snowmelt energy balance. Degree day methods for calculating snowmelt are common approaches in mountainous terrain (Lindström et al. 1997; Jost et al. 2012; Bergström and Lindström 2015). The snowmelt rate results from this hydrologic model, reported as 39-year averages, were used to assess snowmelt rates at different elevations in the Kettle River basin.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure 2. Map of the Kettle River basin showing points used to generate climate data using the ClimateNA desktop tool (circles). The drainage area of the Kettle River basin above Laurier is outlined in black.*

# 3. RESULTS

The results of the SWE threshold tests in the Redfish and Mission Creek basins are described first. This is followed by a summary of the results for the eight nested sub-basins in the Kettle River watershed. Details on the hydrograph analysis and SCA mapping for each watershed are provided in separate appendices (Appendices A to J). Results from the climate data analysis and the hydrologic model are presented in Sections 3.3 and 3.4.

## 3.1 SWE Threshold for Snowline Delineation

SNODAS SWE products for the period 2010-2018 were analysed for the Redfish and Mission Creek basins using thresholds of 1, 10, 25, 50 and 100 mm in order to assess the sensitivity of snowline mapping to the SWE threshold used and to compare SWE-derived snowlines with previous studies. Results were also compared to previous studies for each basin to help identify an appropriate threshold. Although deriving snowline from SWE data differed from Gluns (2000, 2001) and Smith et al. (2008) who used visual analyses of aerial photographs, the same date selection methods in the original studies were used so that results could be compared.

SCA varied considerably over the nine years studied, providing a wide range of conditions for this analysis (Figure 3). As expected, SCA decreased as the threshold value increased in both catchments, but the decline was both greater and more consistent between years for Mission Creek. That is, for Mission Creek the decrease in SCA as the threshold increased from 1 to 100 mm SWE was consistent regardless of snow covered area. For Redfish Creek, the decrease in SCA was greater when SCA was lower in 2012 and 2013. SCA for Redfish Creek was derived for the date of peak flow, which can occur at any time during the freshet period, while for Mission Creek the SCA was derived for the date of onset of the peak flow period, which is always earlier than the date of peak flow and therefore associated with greater snow covered areas. This difference in methods explains the wider range in SCA values for Redfish Creek compared to Mission Creek.

Results for each basin were compared to previously published studies and are discussed separately in the following sections.

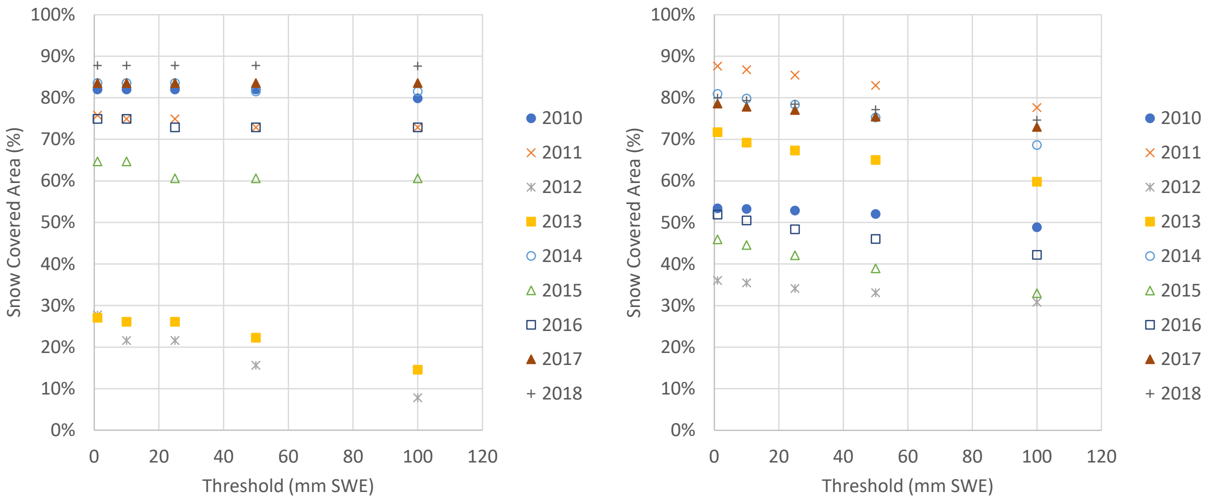


*Figure 3. Catchment snow covered area calculated using different SWE threshold values for Redfish Creek (left) and Mission Creek (right) between 2010 and 2018.*

### *3.1.1 Redfish Creek*

In the Redfish Creek basin, the SNODAS SCA for each year varied by only 0-4% between the different thresholds except when SCA was less than 30% (Table 4); in 2012 and 2013 the derived SCA was 20 and 12% less, respectively, using the 100 mm threshold compared to the 1 mm threshold.

Individual SCA values on the date of peak flow in Redfish Creek for each year 1994-1998 were not reported in Gluns (2000, 2001) but could be derived from tables in Gluns (2000) (Table 5). Some SCA values were interpolated between aerial surveys (noted with * in Table 5); average (median) SCA was 62% (63%). The range of SCA values between 1994 and 1998 was much smaller than during the period 2010-2018.

The SNODAS SCA for Redfish Creek basin was not sensitive to the threshold used as long as the SCA was more than ~30%. When the results for 2012 and 2013 were excluded, the average difference in SCA using the different thresholds was less than 2%. Direct comparison between the 1994-1998 and 2010-2018 periods indicated different mean and median values. While not useful for identifying the SWE threshold, it did suggest that there is value in using more than five years of data when drawing conclusions. Results from the current analysis and that of Gluns (2000, 2001) are compared further in Section 4.1.

*Table 4. Snow covered area (%) calculated for Redfish Creek from the SNODAS SWE product (2010-2018) using different SWE thresholds on the date of peak flow. Values have been rounded to the nearest whole number. Because of the small sample size, both mean and median values are shown.*

| Year | Date of Peak Flow | 1 mm Threshold | 10 mm Threshold | 25 mm Threshold | 50 mm Threshold | 100 mm Threshold | Range |
|---|---|---|---|---|---|---|---|
| **2010** | 3 June | 82 | 82 | 82 | 82 | 80 | 2 |
| **2011** | 30 June | 76 | 75 | 75 | 73 | 73 | 3 |
| **2012** | 23 June | 28 | 22 | 22 | 16 | 8 | 20 |
| **2013** | 20 June | 27 | 26 | 26 | 22 | 15 | 12 |
| **2014** | 24 May | 84 | 84 | 84 | 82 | 82 | 2 |
| **2015** | 3 June | 65 | 65 | 61 | 61 | 61 | 4 |
| **2016** | 8 May | 75 | 75 | 73 | 73 | 73 | 2 |
| **2017** | 31 May | 84 | 84 | 84 | 84 | 84 | 0 |
| **2018** | 25 May | 88 | 88 | 88 | 88 | 88 | 0 |
| **MEAN** | **5 June** | **67** | **67** | **66** | **64** | **62** | **5** |
| **MEDIAN** | **3 June** | **76** | **75** | **75** | **73** | **73** | **3** |

*Table 5. Snow covered area (SCA, %) for Redfish Creek (1994-1998), from Gluns (2000). Because of the small sample size, both mean and median values are shown.*

| Year | Date of Peak Flow | SCA |
|---|---|---|
| **1994** | 13 June | 52* |
| **1995** | 30 May | 70 |
| **1996** | 4 July | 52* |
| **1997** | 31 May | 75* |
| **1998** | 27 May | 63* |
| **MEAN** | **9 June** | **62** |
| **MEDIAN** | **31 May** | **63** |

**Value interpolated between aerial survey dates.*

### *3.1.2 Mission Creek*

For the Mission Creek basin, the annual dates of onset of the peak flow period were selected for deriving SCA for 2010-2018, as was used by Smith et al. (2008) for 1999-2003. The variability in SNODAS SCA values from year to year was smaller than for Redfish Creek (Figure 3 and Table 6), which was most likely attributable to the use of the date of onset of peak flow for the former, instead of the date of peak flow which is much more variable between years. SCA was more sensitive to the threshold value in Mission Creek than Redfish Creek. The average (median) SCA was 57% (60%) using the 100 mm threshold and 65% (72%) for the 1 mm threshold. Looking at individual years, the largest difference in calculated SCA between the 1 and 100 mm thresholds was 13% in 2015.

*Table 6. Snow covered area (%) calculated for Mission Creek from the SNODAS SWE products (2010-2018) using different SWE thresholds on the date of onset of the peak flow period. Because of the small sample size, both mean and median values are shown.*

| Year | Date of Onset of Peak Flow | 1 mm Threshold | 10 mm Threshold | 25 mm Threshold | 50 mm Threshold | 100 mm Threshold | Max – Min |
|---|---|---|---|---|---|---|---|
| **2010*** | 17 May | 53 | 53 | 53 | 52 | 49 | 4 |
| **2011** | 12 May | 88 | 87 | 86 | 83 | 78 | 10 |
| **2012*** | 5 June | 36 | 35 | 34 | 33 | 31 | 5 |
| **2013** | 5 May | 72 | 69 | 67 | 65 | 60 | 12 |
| **2014** | 2 May | 81 | 80 | 78 | 75 | 69 | 12 |
| **2015*** | 28 March | 46 | 45 | 42 | 39 | 33 | 13 |
| **2016*** | 18 April | 52 | 50 | 48 | 46 | 42 | 10 |
| **2017** | 4 May | 79 | 78 | 77 | 75 | 73 | 6 |
| **2018** | 3 May | 80 | 79 | 79 | 77 | 75 | 5 |
| **MEAN** | **4 May** | **65** | **64** | **63** | **61** | **57** | **8** |
| **MEDIAN** | **4 May** | **72** | **69** | **67** | **65** | **60** | **12** |

** SCA was in the same range as Smith et al. (2008).*

Smith et al. (2008) found an average SCA of 38% at the onset of the peak flow period for 1999-2003 (range 29 to 53%; Table 7). SCA for four years (2010, 2012, 2015 and 2016) fell within the range reported by Smith et al. (2008). Because SCA for the Mission Creek basin was more sensitive to the threshold value, a more detailed comparison with the results of Smith et al. (2008) was completed. Specifically, the effects of climatological differences over the two time periods were explored.

*Table 7. Snow covered area (SCA, %) for Mission Creek (1999-2003), from Smith et al. (2008). Because of the small sample size, both mean and median values are shown.*

| Year | Photograph Date | SCA |
|---|---|---|
| 1999 | 17 May | 36 |
| 2000 | 19 May | 30 |
| 2001 | 11 May | 42 |
| 2002 | 13 May | 53 |
| 2003 | 29 May | 29 |
| **MEAN** | **18 May** | **38** |
| **MEDIAN** | **17 May** | **36** |

The timing of snow disappearance at a location is determined by both the amount of snow present and how quickly it melts; to explore weather-related differences between the 1999-2003 and 2010-2018 periods, variability in factors representing winter snow accumulation and spring melt in the Mission Creek basin were compared (Table 8). Mean SWE from 1 April manual snow surveys at the McCulloch station (1280 m elevation) were used to represent peak snow accumulation at mid-elevations in the Mission Creek basin, while results from the 1 May snow surveys at the Graystoke Lake station (1840 m elevation) were used to represent peak SWE at high elevations. For this comparison, years when measured SWE was >125% of normal were considered to be significantly above normal, and when measured SWE was <75% of normal the value were considered significantly less than normal. Measurements indicated one year of above normal SWE during 1999-2003 (1999), and two years when SWE at one station was significantly lower than normal (2003 and 2001 for the McCulloch and Graystoke Lake stations, respectively). Missing data for Graystoke Lake during 2010-2018 made comparison difficult, but the record for the McCulloch station indicated that most years during this period had higher than normal peak SWE values at mid-elevations. If warm winter temperatures did not drive early melt at mid-elevations during these years, the SCA would be expected to be consistently higher during the 2010-2018 period compared to 1999-2003.

Cold and neutral phases of both the ONI and PDO indices persisted through most of the 1999-2003 snow accumulation periods, with a transition to mild El Niño conditions (warm phase) between 2002 and 2003 (Table 8). The cold and neutral phases were associated with normal and higher than normal SWE measured at the McCulloch and Graystoke Lake snow survey stations and elevated peak flows in Mission Creek, as well as with higher SCA values at the onset of the peak flow period. The 2010-2018 period included all three ONI phases and about equal numbers of warm and cold phase PDO conditions during the snow accumulation periods. Only two of the nine years had significantly lower than normal SWE at mid- and high elevations, and one of these years (2015) had very low streamflow and SCA values. Most of the years indicated higher than normal SWE at mid-elevations in the Mission Creek basin. Missing data for the Graystoke Lake station made comparison difficult, but available measurements indicate a similar pattern at high elevation. Unlike the 1999-2003 period, there were few years when SWE was near normal after 2010.

ONI and PDO are also associated with weather conditions during the spring melt period. There were no El Niño (warm phase) conditions in MAM during the 1999-2003 period, and most years were neutral or cold phases. All years except 2003 had cold phase PDO. Mean April air temperature anomalies at the Kelowna airport were generally negative (colder) in the years that had negative PDO index values, and were near normal in 2003 when the PDO phase was positive (warm). The Kelowna airport climate station is located in the valley bottom and can be used as an indicator of the potential presence of snow at low and mid-elevations at the onset of the peak flow period. The 2010-2018 period was dominated by neutral phase ONI, with two years of warm and one year of cold phase conditions, and there were an approximately equal number of years with warm and cold phase PDO. Mean April air temperatures at low elevation were generally near normal or below normal during this period, generally associated with cold or neutral phase ONI and PDO. An unusually warm April occurred in 2016 when there was a relatively strong warm phase of the ONI. These results suggest that the relationship between ONI, PDO and spring melt conditions may be less clear, potentially because of the time lag between changes in ocean temperatures near the equator and impacts on weather at mid-latitudes. A more thorough analysis of teleconnections was beyond the scope of this work.

*Table 8. Indices of winter snow accumulation and spring melt conditions in the Mission Creek basin for the 1999-2003 and 2010-2018 periods. Values in blue indicate above normal SWE, below normal April air temperature, or cool phases of the Oceanic Niño Index (ONI) and Pacific Decadal Oscillation (PDO) indices. Values in red indicate below normal SWE, above normal April air temperature, or warm phases of the ONI and PDO indices.*

| Year | SCA at Onset of Peak Flow (%) | Peak Daily Flow ($m^3/s$) | April 1 SWE (% of normal)[1] | May 1 SWE (% of normal)[2] | ONI[3] |  | PDO[6] |  | April Temperature Anomaly (°C)[7] |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | JFM[4] | MAM[5] | JFM[4] | MAM[5] |  |
| 1999 | 36 | 52 | 139 | 143 | -1.3 | -1 | - - - | - - - | -0.9 |
| 2000 | 30 | 52.5 | 118 | 113 | -1.4 | -0.8 | - - - | - - - | 0.4 |
| 2001 | 42 | 34.6 | 82 | 70 | -0.5 | -0.3 | + - - | - - - | -0.9 |
| 2002 | 53 | 59 | 117 | 122 | 0 | 0.2 | - - - | - - - | -0.7 |
| 2003 | 29 | 33 | 39 | 86 | 0.6 | 0 | + + + | + + + | 0.0 |
|  |  |  |  |  |  |  |  |  |  |
| 2010 | 53 | 39.1 | 64 | 60 | 1.3 | 0.4 | + + - | - - - | 0.0 |
| 2011 | 86 | 56.2 | 155 | 128 | -1.1 | -0.6 | - - - | - - - | -2.0 |
| 2012 | 34 | 86.2 | 143 | n/a | -0.6 | -0.4 | - - - | - - - | 0.0 |
| 2013 | 67 | 81.8 | 125 | n/a | -0.3 | -0.2 | - - - | - - - | -1.1 |
| 2014 | 78 | 45 | 129 | 128 | -0.4 | 0.1 | - - + | + + + | -0.3 |
| 2015 | 42 | 26.3 | 5 | n/a | 0.6 | 0.8 | + + + | + + + | 0.0 |
| 2016 | 48 | 68.6 | 127 | 68 | 2.2 | 1 | + + + | + + + | 3.2 |
| 2017 | 77 | 79.8 | 109 | 131 | -0.1 | 0.3 | - - + | + + + | n/a |
| 2018 | 79 | 95.1 | 201 | 164 | -0.8 | -0.4 | + - - | - - - | n/a |

[1] *McCulloch manual snow survey station (1280 m), representing peak SWE at mid-elevation. Normal SWE on 1 April is 132 mm.*

[2] *Graystoke Lake manual snow survey station (1840 m), representing peak SWE at high elevation. Normal SWE on 1 May is 343 mm.*

[3] *US National Center for Environmental Prediction's Oceanic Niño Index (ONI) (3-month running mean). Values >0.5, <-0.5 and between -0.5 and 0.5 indicate warm phase (El Niño), cold phase (La Niña) and neutral phase conditions, respectively.*

[4] *January-February-March, representing the main accumulation period.*

[5] *March-April-May, representing the main melt period.*

[6] *US National Centers for Environmental Information's monthly Pacific Decadal Oscillation (PDO) phase. Negative (cold) phases are shown as -; positive (warm) phases are shown as +.*

[7] *Mean April air temperature difference from 1981-2010 normal for Kelowna A (1999-2003) and Kelowna (2010-2018). April 1981-2010 normal for Kelowna A is 8.4°C. Values were not reported if more than 3 days were missing from the monthly record.*

### *3.1.3 Sensitivity Analysis*

Average SCA values were calculated for each threshold, and the difference between adjacent thresholds was compared to assess sensitivity. As noted earlier, the SNODAS SCA values for Mission Creek were more sensitive to the threshold than for Redfish Creek, though there was greater interannual variability for Redfish Creek (Figure 4). The average difference in SCA calculated for Mission Creek was less than 2% between thresholds smaller than 50 mm, and never exceeded 3.5% in any individual year (Figure 4, right). Based on the comparisons, 25 mm was identified as the threshold that would result in snowlines that were not considerably different from those derived using slightly lower or slightly higher thresholds. This was consistent with Shamir and Georgakakos (2007) who used a threshold of 20 mm.

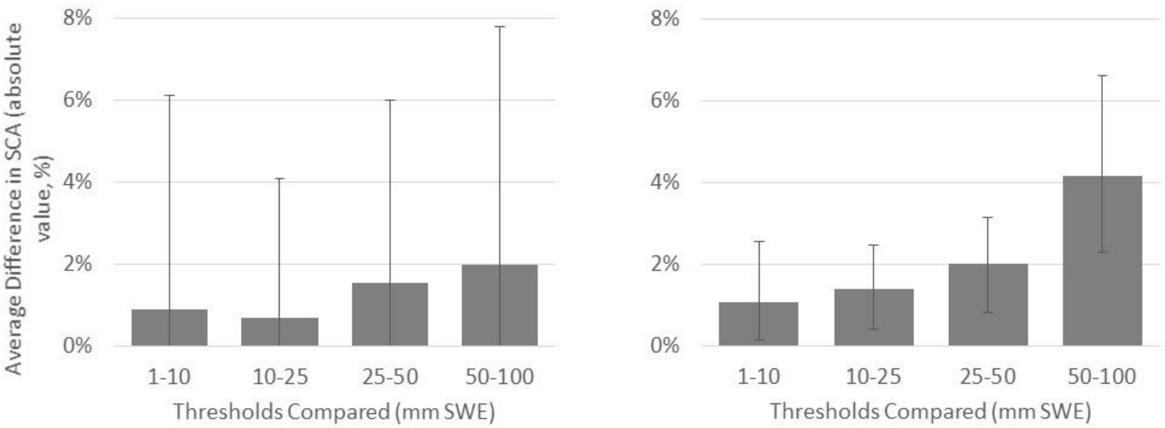


*Figure 4: Average difference in snow covered area (SCA) between SWE thresholds tested for Redfish Creek (left) and Mission Creek (right). Vertical bars show the minimum and maximum values.*

## 3.2 Results for the Kettle River Basins

Detailed results for each of the eight nested watersheds in the Kettle River basin are provided in Appendices C to J. This section provides a summary of the spatial and temporal patterns observed.

### *3.2.1 Freshet Hydrographs*

Freshet hydrographs for 2010 to 2020 at all stations in the Kettle River basin rarely showed a single dominant peak, indicating that multiple melt and potentially rain and rain-on-snow events occurred through the freshet periods (Figure 5). There is no significant attenuation by lakes or wetlands in any of the drainage basins studied, so the hydrographs are responsive to melt and precipitation inputs, with a lag related to basin characteristics (e.g., watershed area, soil thickness, groundwater recharge processes, slope and drainage density).

The date of peak flow was highly variable between 2010 and 2020, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. For the hydrometric station on Kettle River near Laurier, peak flow occurred between 8 and 81 days after the onset of the freshet period (median = 42 d), when 6 to 87% of the cumulative freshet flow occurred (median = 40%).

The onset of the annual peak flow period (defined as when daily mean discharge was greater than the mean discharge during that year's freshet period) was less variable from year to year than the date of peak flow. At the hydrometric station on Kettle River near Laurier, the onset of the peak flow period occurred when the median cumulative freshet flow was 14% (range 5-29%), between 7 and 47 days after the onset of the freshet flow period (median = 20 d). On average, the peak flow period at this station began on 26 April and ended on 12 June, lasting between 33 and 78 days (median = 44 d).

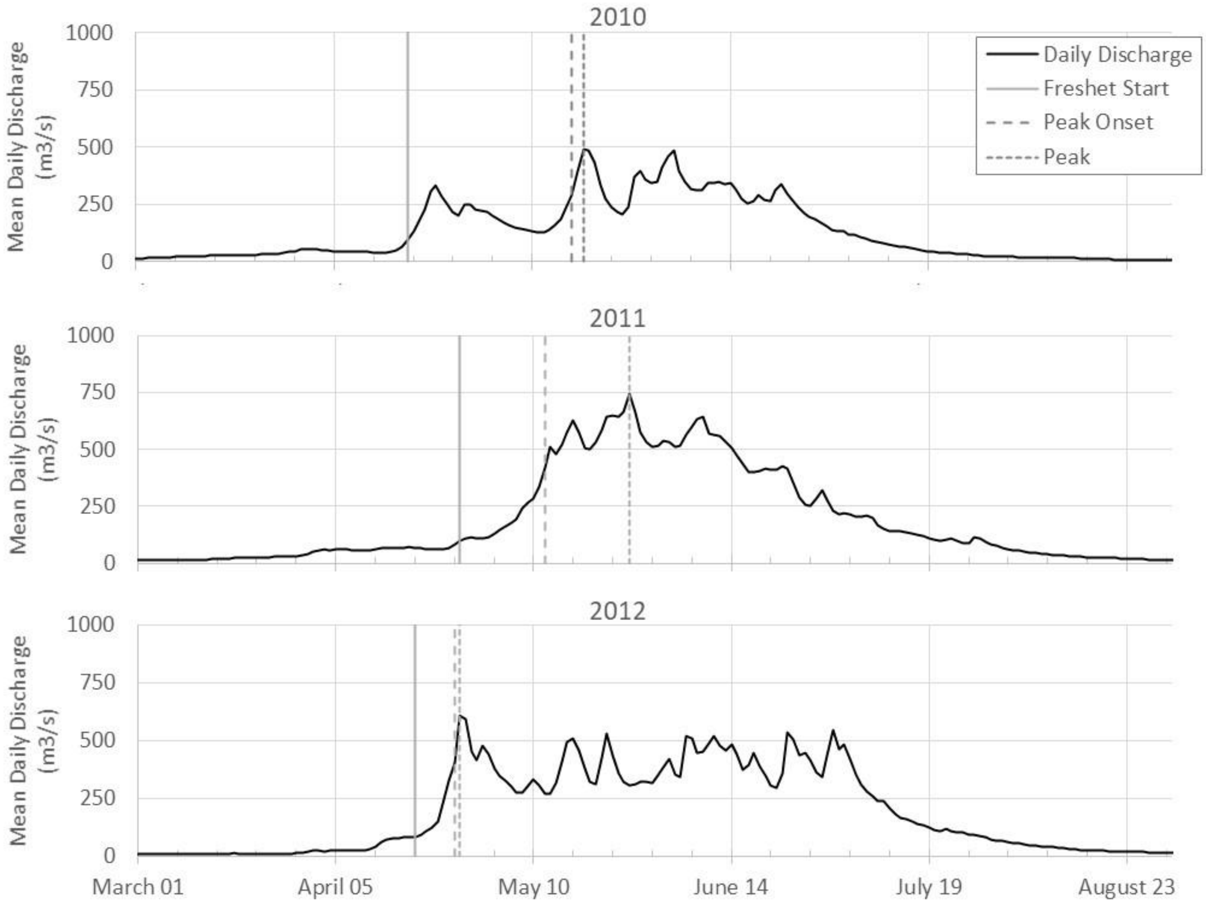


*Figure 5. Example freshet hydrographs for the Kettle River near Laurier, showing the effects of multiple snowmelt and rain events on streamflow. Onset dates for the freshet and peak flow periods and the date of peak flow for each year are shown.*

A comparison of dates between hydrometric stations showed patterns of synchronisation of the onset of peak flows across the Kettle River basin (Figure 6 and Table 9). Most stations in the Kettle River basin recorded the onset of the peak flow period near-synchronously during the 2010-2020 period, though deviations occurred (Figure 6). In the Granby River basin, the peak flow period began 0 to 1 days earlier at the Burrell Creek station relative to the downstream station near Grand Forks, except in 2010 and 2016 when it was 28 days earlier and 6 days later, respectively. The Granby River station was near-synchronous with the Kettle River near Ferry, except in 2018 and 2020 when the peak flow period in the Granby River began 6 days later than in the Kettle River. Aside from those two years, flow at the Laurier station was near-synchronous with both the Granby River and Kettle River near Ferry stations.

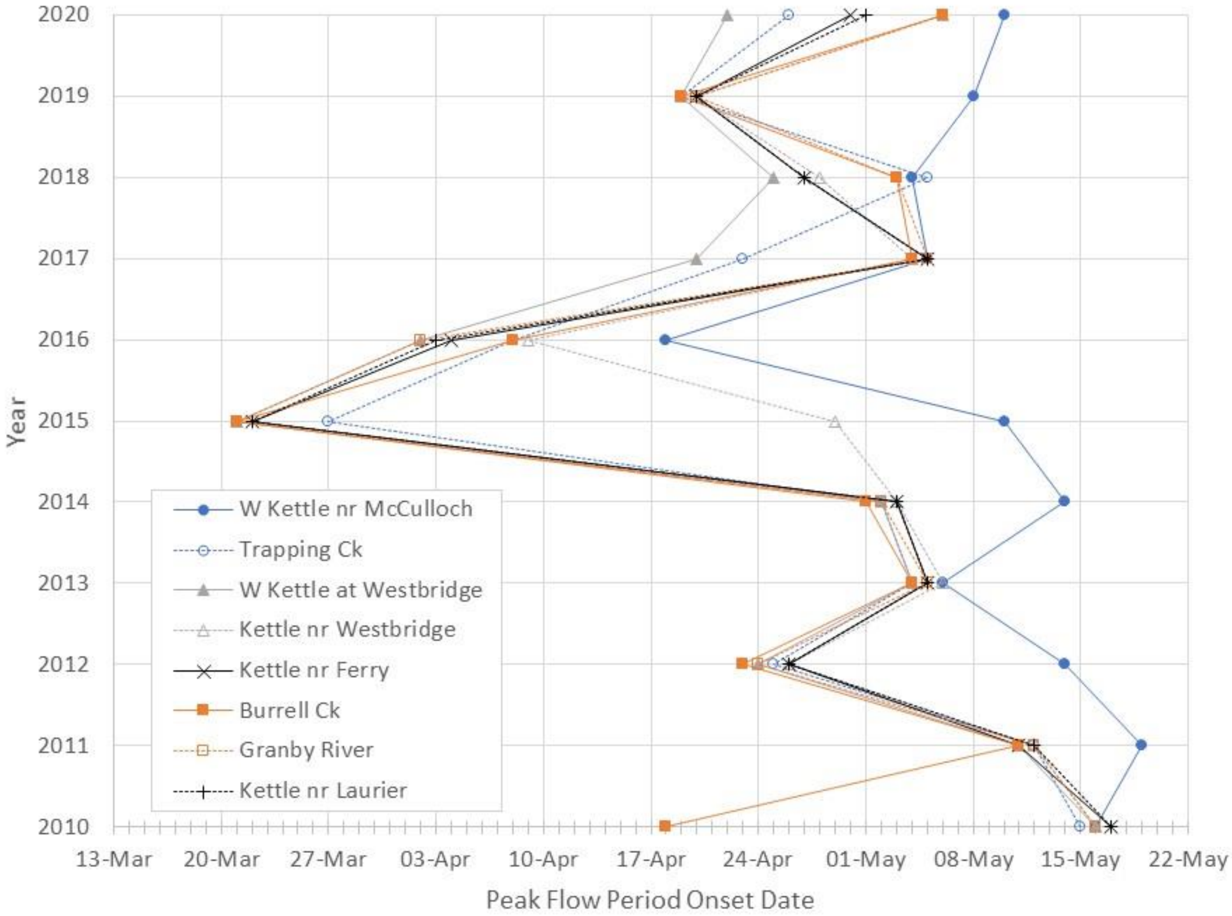


*Figure 6. Synchronisation patterns in the peak flow period onset date for stations in the Kettle River basin.*

*Table 9. Summary of dates for the onset of the peak flow period for catchments within the Kettle River watershed. Stations are organised according to synchronisation patterns (see text). Because of the small sample size, both mean and median dates are shown.*

| **Basin** | West Kettle River near McCulloch | Trapping Creek | West Kettle River at Westbridge | Kettle River near Westbridge | Kettle River near Ferry | Burrell Creek | Granby River | Kettle River near Laurier |
|---|---|---|---|---|---|---|---|---|
| **ID** | H | J | G | E | D | I | F | C |
| **Mean** | 8 May | 26 April | 23 April | 1 May | 24 April | 24 April | 27 April | 26 April |
| **Median** | 10 May | 27 April | 25 April | 3 May | 27 April | 1 May | 3 May | 2 May |

Dates derived for the station on West Kettle River near McCulloch, which was the highest elevation basin, indicated later onset of the peak flow period in most years. In the West Kettle River where it is measured at Westbridge, the onset of peak flow occurred shortly before the Trapping Creek basin, and often much earlier than in the West Kettle River headwaters (as measured near McCulloch). This indicated that snowmelt and/or rain at lower elevations of the West Kettle River basin can cause streamflow to increase before there are contributions from the higher elevation headwaters and mid-elevation catchments like Trapping Creek. The timing of the start of the peak flow period was near-synchronous between Trapping Creek and the West Kettle River at McCulloch in only three years (2010, 2013, and 2018) when there were sustained high temperatures (~10 days) at four nearby high elevation provincial Automated Snow Weather Stations early in the melt period (not shown). The peak flow period began near-synchronously in the Kettle and West Kettle tributaries near where they meet at Westbridge and further downstream near Ferry in 2010-2014 and 2018-2019. In 2015-2017 and 2020 the peak flow period began earlier in the West Kettle River drainage and was usually near-synchronous with the Kettle River station near Ferry.

On average, the peak flow period lasted 36—47 days for the Kettle River basins studied (Table 10). The shortest duration peak flow periods were observed for the headwaters of the West Kettle River, at the stations on Trapping Creek and where the West Kettle River is measured near McCulloch.

*Table 10. Summary of peak flow period duration (days) for hydrometric stations in the Kettle River basin. Because of the small sample size, both mean and median values are shown.*

| Basin | Mean | Median | Min | Max |
|---|---|---|---|---|
| Kettle River near Laurier | 47 | 44 | 33 | 78 |
| Kettle River near Ferry | 46 | 40 | 33 | 77 |
| Kettle River near Westbridge | 45 | 43 | 33 | 70 |
| Granby River | 47 | 40 | 26 | 79 |
| West Kettle River at Westbridge | 48 | 44 | 15 | 71 |
| West Kettle River near McCulloch | 36 | 35 | 25 | 51 |
| Burrell Creek | 42 | 36 | 26 | 77 |
| Trapping Creek | 37 | 36 | 21 | 55 |

### 3.2.2 *Snow Covered Area*

Basins that had significant areas at low elevation were never 100% snow covered at the start of the peak flow period (i.e., the end of April/start of May); only the higher elevation headwater catchments were completely snow covered (e.g., Figure 7). The slopes of the SCA curves generally increased with median basin elevation (Figure 8).

As expected in this mountainous basin, snow depletion patterns in the Kettle River basin were consistent from year to year (because elevation and aspect are the dominant control on snowmelt patterns) although the timing was different (because of the effect of weather). Figure 9 maps the changes in SCA during the 2010-2017 freshet periods for the Kettle River basin above Laurier. SCA is shown for the dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. There was a clear pattern of snow melting away earlier at low elevations in the catchment, and snow persistence in high elevation areas in the west and north part of the basin.

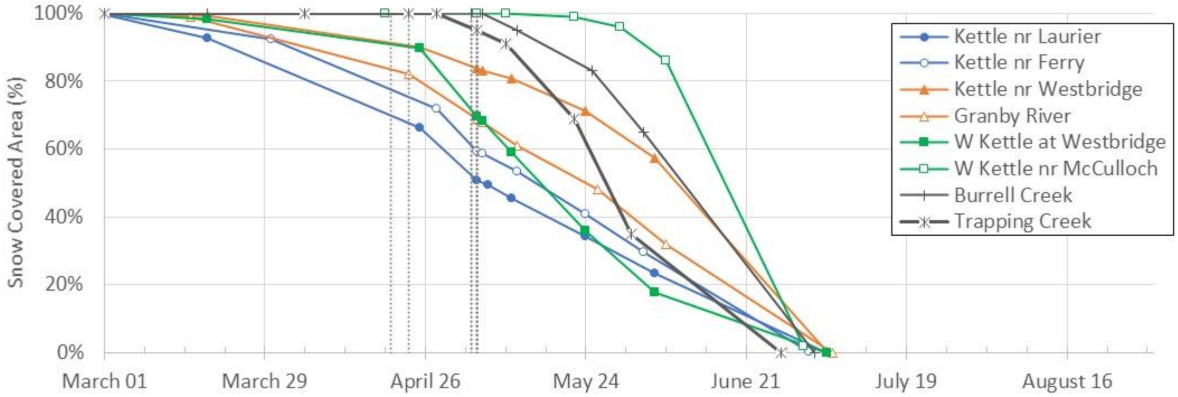


*Figure 7. Changes in snow covered area during the 2017 spring season for catchments in the Kettle River basin showing typical differences in timing and slope for 2010-2020. The dashed lines show the dates of onset of the peak flow period for each basin; the earliest dates occurred in (left to right) the West Kettle River at Westbridge and Trapping Creek basins.*

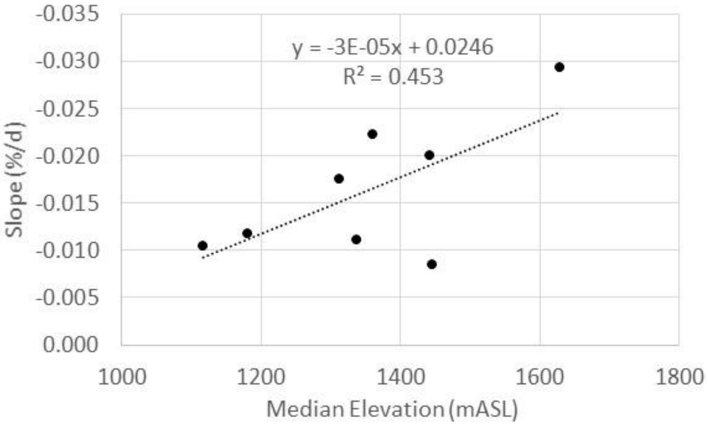


*Figure 8. Relationship between median elevation and slope of the snow covered area recession curve for watersheds in the Kettle River basin.*

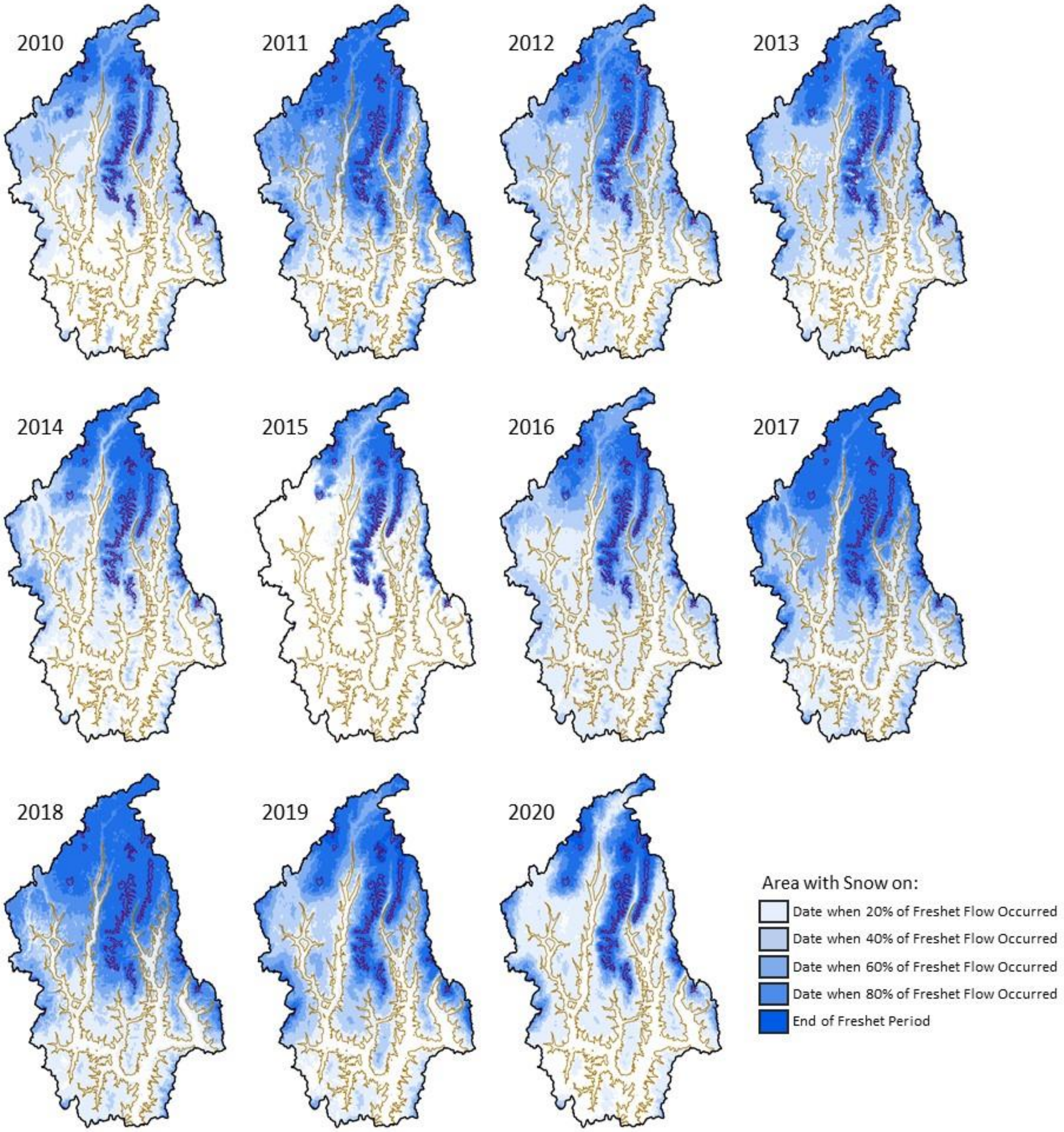


*Figure 9. The progression of snow covered area over the 2010-2020 spring freshet periods in the Kettle River basin above Laurier. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

SCA during the 2015 freshet flow period was inconsistent with other years because of winter and spring weather conditions. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in warmer than normal January, February and March temperatures (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow at low and middle elevations, which was noted to be much earlier than normal. These conditions explained the low SCA recorded at the start of the 2015 freshet period for all of the study catchments in the Kettle River basin. The effect was especially evident in the West Kettle River basin, where SCA was generally close to 100% at the start of the freshet period during the study period, but in 2015 was 4, 8 and 48% for Trapping Creek basin and the catchments above Westbridge and McCulloch, respectively. SCA remained low throughout the 2015 snowmelt period, and all basins became snow free much earlier (multi-year SCA depletion curves for the Kettle River basin above Laurier are shown as an example in Figure 10).

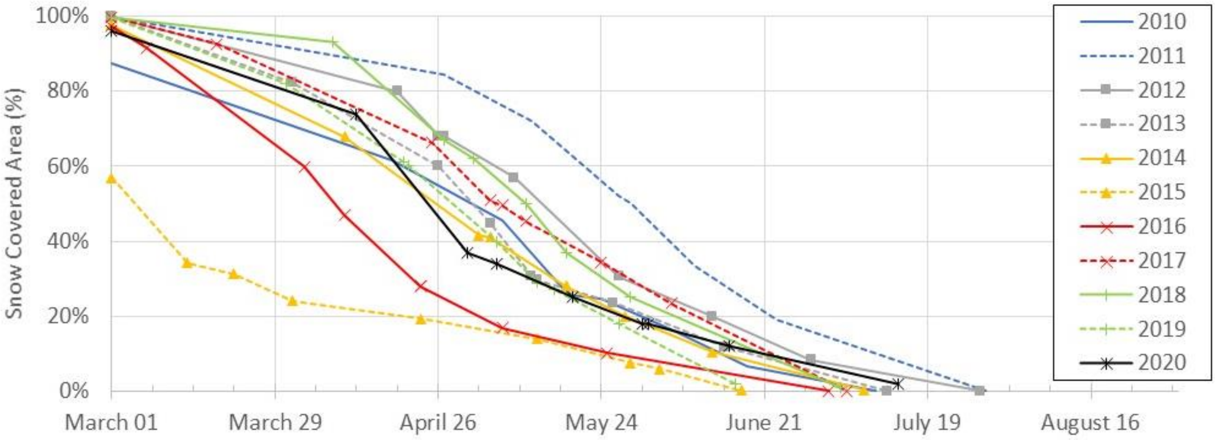


*Figure 10. Changes in snow covered area over the 2010-2020 freshet periods for the Kettle River basin above Laurier. Because of winter weather conditions, SCA in 2015 was much lower at the start of the freshet period than in other years.*

The degree of interannual variability in SCA at the onset of the peak flow period varied between the basins studied (Table 11). Coefficients of variation (CV) were lowest for Burrell Creek and the Kettle River above Westbridge, and highest for West Kettle River above Westbridge and Trapping Creek. There was a strong negative linear relationship between CV and median basin elevation ($R^2 = 0.97$ for the West Kettle River basins and 0.90 for the remaining basins), indicating that SCA at the onset of the peak flow period was more consistent from year to year as the median elevation increased (Figure 11, left). This is likely because lower elevations have shallower snowpacks that melt out faster in the early part of the peak flow period compared to higher elevations. This results in faster disappearance of snow cover at lower elevations and therefore more variability in SCA. The deviation of West Kettle River basins from the other study catchments may indicate that there are some unique aspects to snow accumulation and/or melt processes occurring in that catchment, though the slopes of the best-fit lines were similar.

*Table 11. Median, mean and interannual variability (represented using the coefficient of variation, CV) in snow covered area (%) derived for the date of onset of the peak flow period and the date of peak flow for the 2010-2020 period. Values in brackets are the means.*

| **Basin** | **Median (Mean)** | | **CV** | |
|---|---|---|---|---|
| | **Onset of Peak Flow Period** | **Peak Flow Date** | **Onset of Peak Flow Period** | **Peak Flow Date** |
| Kettle River near Laurier | 51 (51) | 29 (35) | 30 | 54 |
| Kettle River near Ferry | 64 (60) | 32 (41) | 31 | 53 |
| Kettle River near Westbridge | 80 (80) | 61 (62) | 13 | 21 |
| Granby River | 69 (68) | 43 (44) | 23 | 41 |
| West Kettle River at Westbridge | 74 (67) | 40 (48) | 44 | 64 |
| West Kettle River near McCulloch | 99 (90) | 91 (81) | 23 | 33 |
| Burrell Creek | 100 (94) | 73 (66) | 11 | 47 |
| Trapping Creek | 86 (74) | 34 (44) | 45 | 77 |

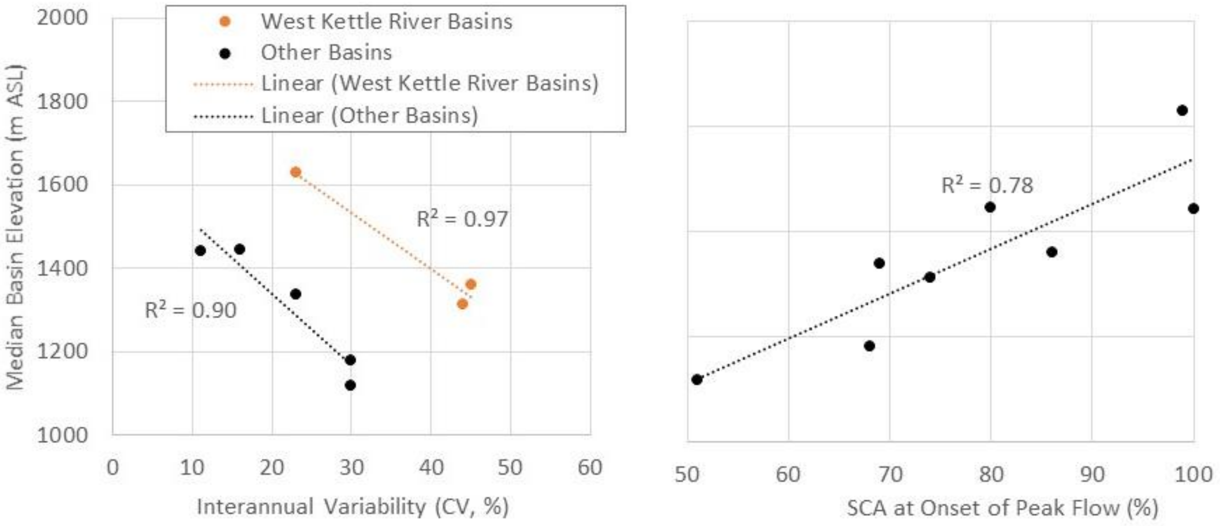


*Figure 11. Relationships between median catchment elevation and (left) interannual variability in snow covered area and (right) snow covered area (SCA) at the onset of the peak flow period.*

The median SCA for the Kettle River catchments at the onset of the peak flow period ranged between 51 and 100% (Table 11) and SCA values increased as median elevation increased (Figure 11, right). The smallest values were found for the largest basin areas which included considerable low elevation area. Using the date of peak flow, median SCA values were lower (range 29-91%) and there was greater interannual variability (21-77%). For all of the study catchments the interannual variability in SCA for the date of onset of the peak flow period was much less than for the date of peak flow. Figure 12 shows SCA for the Kettle River basin above Laurier at the onset of the peak flow period for 2010 to 2020 as an example of the year-to-year variability in SCA but consistency in snow cover patterns.

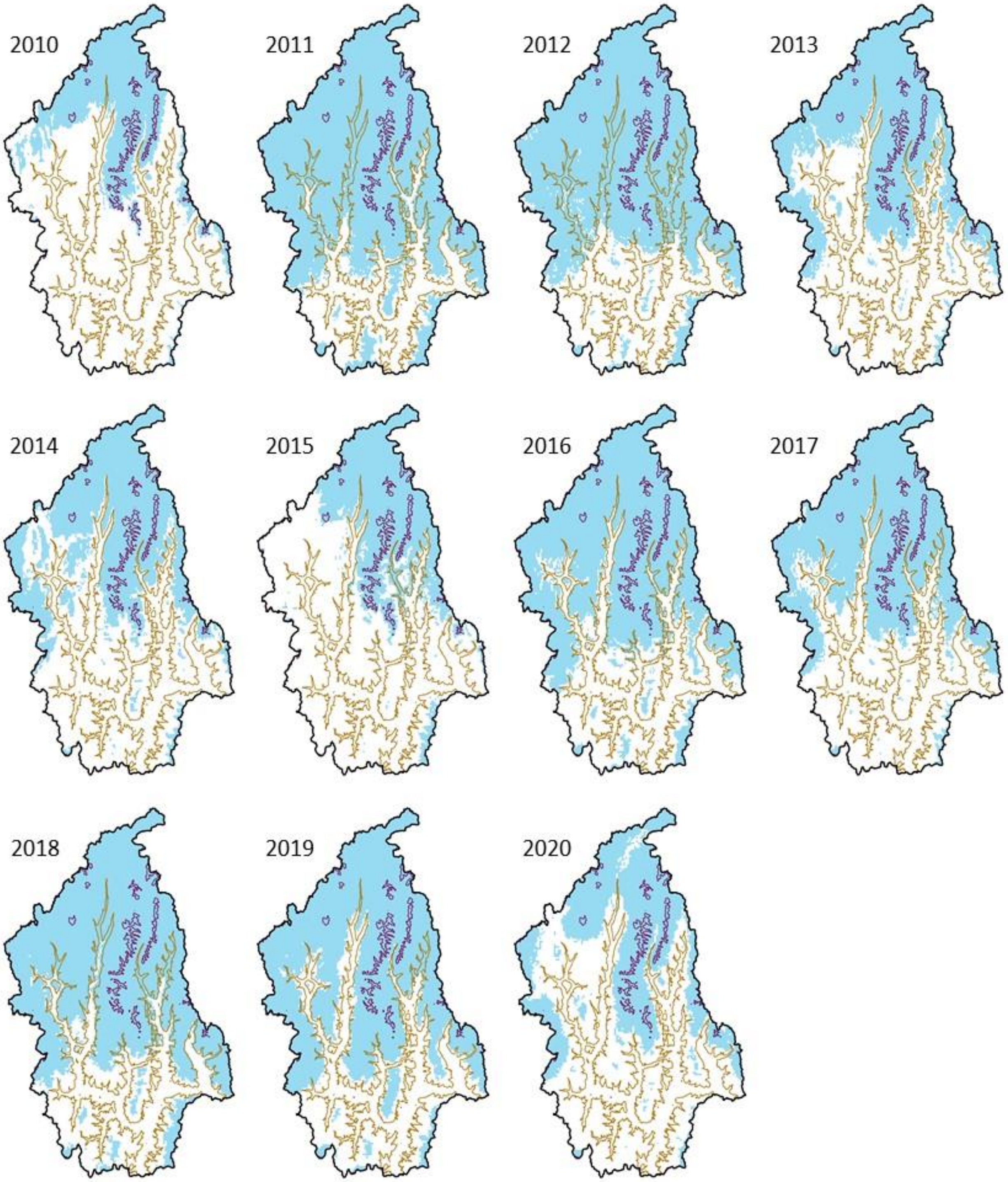


*Figure 12. Snow covered area in the Kettle River basin above Laurier on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m contours, respectively.*

### *3.2.3 Snow Sensitive Zone*

Elevation, topographic roughness and aspect control snow accumulation and melt in mountainous landscapes, resulting in similar snow depletion patterns from year to year (Erickson et al. 2005; Lehning et al 2011; Schirmer et al. 2011). The SSZ was therefore estimated using the median SCA for the onset of the peak flow period. The median SCA for the Kettle River basin above Laurier was 51%. SCA measured in 2017 was equal to the median, so this year was used to define the lower limit of the SSZ for this catchment (Figure 13). The same steps were repeated for each of the study catchments and results are reported in Appendices C to J.

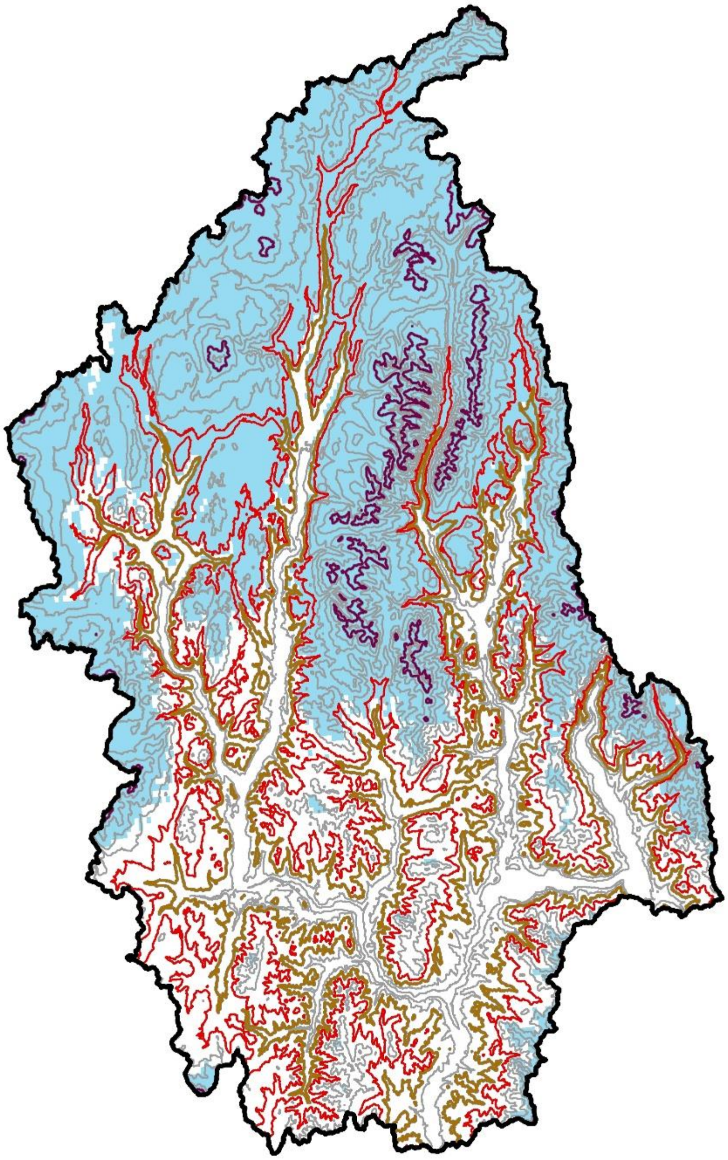


*Figure 13. The snow sensitive zone of the Kettle River basin above Laurier. Elevation contour interval is 200 m; the 1000 and 2000 m contours are brown and purple, respectively and the H60 elevation (1200 m) is red.*

### *3.2.4 Interannual and Spatial Variability*

The SSZ can be defined as the area that is typically snow covered at the time of peak flows, an average condition. However, in any given year the fraction of a basin that is snow covered at the time of peak flows will vary depending on winter precipitation amounts and timing, and spring weather conditions which affect melt rates and patterns. The SCA contributing meltwater to streamflow is generally larger in years with more winter snowfall (Seidel et al. 1997). Warm weather in late winter or at the start of the snowmelt period results in smaller snowmelt contributing area. Snowmelt is primarily controlled by the amount of solar radiation available for absorption by the snowpack, which follows predictable patterns every spring. Melt rates in the early spring are amplified by regional advection of warm air masses and the occurrence of rain-on-snow events, both of which are much more variable from year to year in terms of frequency, timing and intensity. When snowmelt in a watershed is primarily driven by radiation the streamflow hydrograph will likely have a single peak; in southeastern B.C. most hydrographs have multiple peaks, often of similar magnitude, indicating the importance of weather (primarily frontal weather patterns but also rain-on-snow events) on determining peak flow timing and magnitude and that some degree of interannual variability in SCA is to be expected.

To use the SNODAS data to calculate SCA, a SWE threshold of 25 mm was set to identify a pixel as snow covered or snow-free. Because of differences in spatial resolution, the definitions of snowline and interannual variability, it was difficult to identify an appropriate SWE threshold through comparison with previous studies. Instead, a sensitivity analysis was conducted for two basins (Redfish and Mission Creeks) using eighteen dates between 2010 and 2018 and using SWE thresholds ranging between 1 and 100 mm. It was found that SCA calculated for Mission Creek was more sensitive to the threshold than it was for Redfish Creek. This was largely attributed to topographic differences. In the less steep terrain of Mission Creek, neighbouring pixels were more likely to have similar snowpacks because of consistent snow accumulation and melt processes. More pixels would therefore be assigned a snow free status if the SWE threshold was raised, for example, from 25 to 50 mm. In steep terrain, snow accumulation and melt processes may be strongly controlled by elevation and aspect. As a result, snow cover properties in steep terrain may vary dramatically within a single 1 km$^2$ pixel. While the absolute differences in SCA calculated using the different thresholds was less than 9% (and less than 5% for Redfish Creek), 25 mm was identified as the threshold that would result in snowlines that were not considerably different from those derived using slightly lower or slightly higher thresholds; the 25 mm value was also consistent with the literature (Shamir and Georgakakos 2007).

Using SWE data and specifically the SNODAS SWE product to define the snowline avoids some of the problems encountered using air photos and satellite visible and near-infrared imagery, specifically the obscuring of the snowpack by forests and cloud cover, impacts of mid-spring light snowfall events that cover a large area with a thin layer of snow and the challenge of defining a snowline when the snow cover is patchy or discontinuous. The SNODAS products are validated using ground measurements and are continually improved to increase reliability, including representing snowpacks in different vegetation and terrain types. The SNODAS products use information from multiple sources as well as a snowpack model, which avoids problems when an area is obscured by clouds (Barrett 2003).

There is no standard method in hydrology for defining the peak flow period. The method of Smith et al. (2008) to identify the onset of the peak flow period using characteristics of the snowmelt hydrograph itself, specifically the mean discharge during the freshet period, provides a consistent and objective way to identify seasonal patterns. This is more hydrologically meaningful than using a fixed date each year, but there was considerable variability in the streamflow rate used to identify the peak flow period onset (for the station on Kettle River near Laurier, streamflow at the onset of the 2010-2020 peak flow periods was between 206 and 401 m$^3$/s (median = 334 m$^3$/s)). An alternative approach could be to identify a fixed streamflow threshold; the start of the peak flow period would be identified when flow in a river or creek exceeds its threshold. The primary difficulty of such an approach is in the definition of a 'peak flow threshold', which is not an easily identifiable hydrologic or ecological occurrence.

Using the date of onset of the peak flow period rather than the date of peak flow was considered more appropriate for hydrographs with multiple peaks, such as the streams and rivers used in this analysis. Using the peak flow onset date increased consistency in results from year to year compared to using the date of peak flow (lower coefficient of variation (CV) values in Table 11) and avoids including peak flow events caused by late spring rainfall in an analysis of snow-dominated processes.

Streamflow during the spring freshet period is not only influenced by snowmelt. Rainfall events can occur at any time and may occur widely or locally, depending on weather-generating processes. This additional water increases the total streamflow volume and therefore affects the date selected as the onset of the peak flow period. In years when there was a considerable volume of rain, the date identified as the onset of the peak flow period was delayed. For example, precipitation that fell as rain at low and mid-elevations during 2017 caused three of the four large peaks in the hydrograph (Figure 14) and increased the total streamflow volume over what it would have been from snowmelt alone. The date identified as the onset of the peak flow period for the station on the Kettle River near Laurier was 47 days after the beginning of the freshet period, much later than in other years (the median lag was 20 days). This demonstrates the value of including multiple years of measurements in assessing the SSZ. Rainfall during the freshet period occurred in every year between 2010 and 2020; these rain events varied in their impact on streamflow because of differences in total rainfall amount, the snow covered/snow free area, and the spatial extent of the rain.

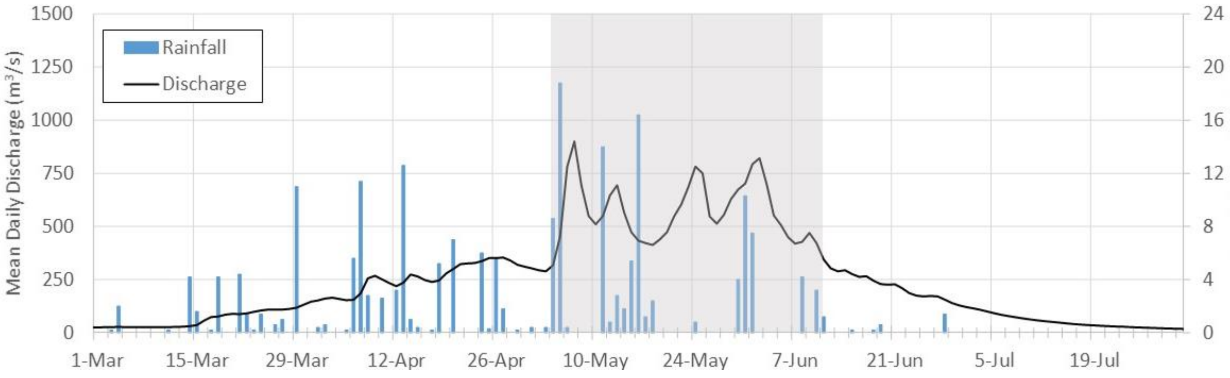


*Figure 14. Streamflow in the Kettle River near Laurier and rainfall measured at Penticton in 2017. The grey band shows the peak flow period.*

The degree of interannual variability in SCA derived for the onset of the peak flow period varied between study basins (Table 11). CV values were lowest for Burrell Creek and the Kettle River above Westbridge and highest for Trapping Creek and the West Kettle River above Westbridge. These differences may be understood through comparison of snow covered area depletion curves. SCA in Trapping Creek and the West Kettle River basin above Westbridge decreased rapidly over the early part of the peak flow period (Figure 7); although the slopes of the SCA depletion curves for Burrell Creek and the West Kettle River above McCulloch were similar, they occurred later in the season after the dates of onset of the peak flow period. This would suggest that SCA is more dynamic around the start of the peak flow period in the Trapping and West Kettle River basin above Westbridge than in the Burrell Creek and Kettle River basin above Westbridge. There was a strong negative linear relationship between CV and median basin elevation when the data for the West Kettle River basin was analysed separately ($R^2$ = 0.99 and 0.79 for the West Kettle River basin and the other stations, respectively), indicating that SCA at the onset of the peak flow period was more consistent from year to year as the median elevation increased (Figure 11, left). This was likely because lower elevations have shallower snowpacks that melt out faster at the start of the peak flow period compared to higher elevations, resulting in faster disappearance of snow cover at lower elevations and therefore more variability in SCA over short time periods (e.g., a week). The deviation of the West Kettle River basin relative to the other catchments in Figure 11 (left) may indicate that there are some unique aspects to snow accumulation and/or melt processes occurring in that catchment, although the slopes of the best fit lines were similar.

One of the objectives of this analysis was to evaluate the appropriate watershed scale for assessing the impacts of natural and anthropogenic disturbances and for managing forest harvest activities with regards to snowmelt-driven peak flows. The multiple basins within the Kettle River watershed provided a perspective that comparison of non-nested watersheds could not. Hypsometric curves were derived for each study basin and used to estimate the elevation of the SSZ lower limit (Figure 15 and Table 12). It should be emphasised that the hypsometric curves provide only an approximation of the snowline by showing the relationship between elevation and area; snowmelt patterns are strongly influenced by aspect, slope and wind exposure, so the actual lower limit of the SSZ at a specific location in a basin will deviate from the elevation estimated using a hypsometric curve. On broad south-facing slopes, for example, the actual snowline will occur at a higher elevation than on sheltered or north facing slopes.

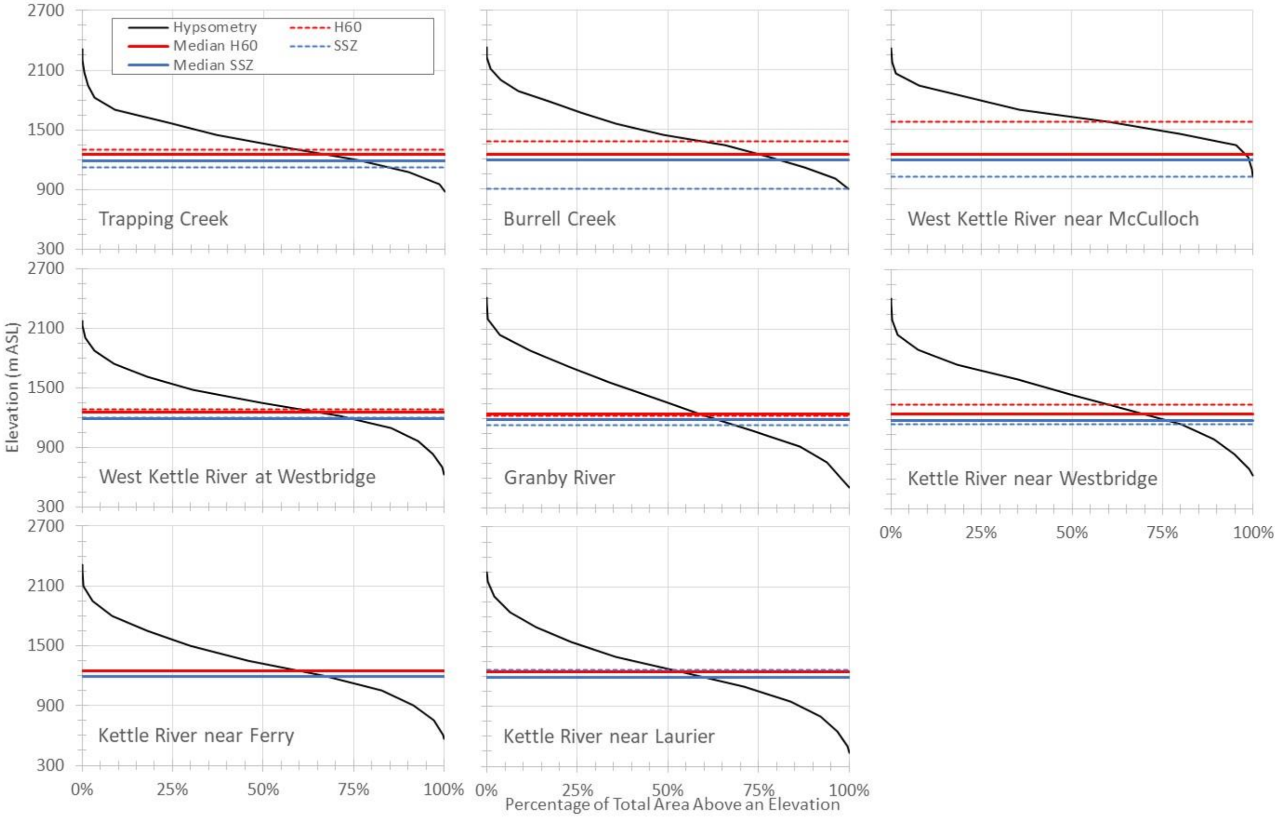


*Figure 15. Hypsometric curves for basins within the Kettle River watershed (black lines), with the estimated lower limit elevations of the snow sensitive zones (SSZ) and H60 elevations. The median values for basins larger than 1000 km² are indicated using thicker solid lines.*

The elevation of the SSZ lower limit for all of the basins in the Kettle River watershed ranged between 900 and 1270 m elevation (median = 1140 m), while the H60 elevations were generally higher and ranged between 1195 and 1580 m (median = 1290) (Table 12 and Figure 15). There was little variability in the estimated elevations for both the SSZ and H60 approaches; the range in elevations was less than 400 m and CV values were ≤10% (Table 12). The difference between the SSZ lower limit and H60 elevations varied between study basins and was greater for basins with a higher median basin elevation (Figure 16).

*Table 12. Summary of 2010-2020 snowline results from this analysis. Because of the small sample size, both mean and median values are shown. The lower limit elevations of the snow sensitive zone and the H60 elevations were estimated from hypsometric curves.*

| **Basin** | **Median SCA at Peak Flow Onset (%)** | **SSZ Lower Limit Elevation (m)** | **H60 Elevation (m)** | **Difference (m)** |
|---|---|---|---|---|
| Trapping Creek | 86 | 1120 | 1295 | -175 |
| Burrell Creek | 100 | 900 | 1380 | -480 |
| West Kettle River near McCulloch | 99 | 1030 | 1580 | -550 |
| West Kettle River at Westbridge | 74 | 1200 | 1285 | -85 |
| Granby River | 69 | 1130 | 1230 | -100 |
| Kettle River near Westbridge | 80 | 1150 | 1350 | -200 |
| Kettle River near Ferry | 64 | 1190 | 1250 | -60 |
| Kettle River near Laurier | 51 | 1270 | 1195 | 75 |
| **Mean** | **78** | **1124** | **1321** | **-197** |
| **Median** | **77** | **1140** | **1290** | **-150** |
| **Standard Deviation** | **17** | **114** | **121** | |
| **Coefficient of Variation** | **22%** | **10%** | **9%** | |

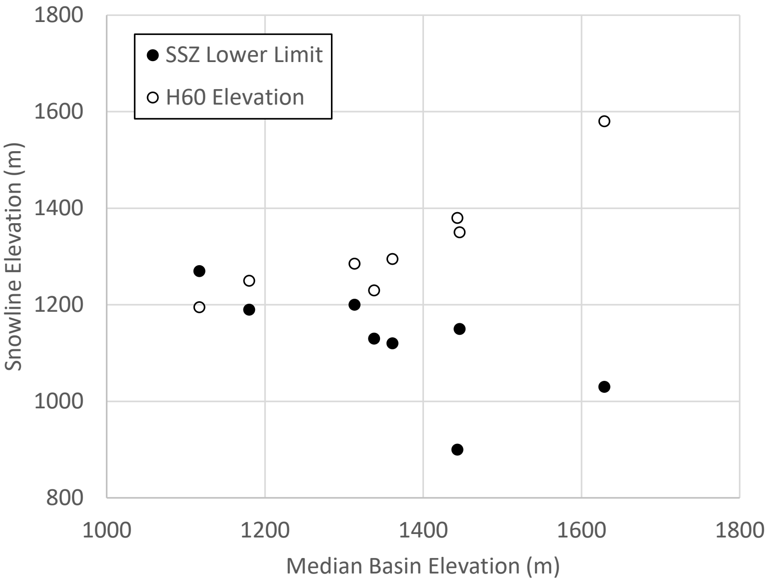


*Figure 16. SSZ lower limit and H60 elevations for the Kettle River study basins, plotted against median elevation.*

## 3.3 Climate Data Analysis

Relationships between elevation, precipitation and temperature were explored for the Kettle River basin area to help understand the snow sensitive zones. Specifically, the relationships were explored to verify the approximate elevation of the SSZ lower limit.

Plotting monthly average temperature for the ClimateNA points against elevation indicated above-freezing temperatures below an elevation of approximately 1900 m in April (Figure 17, left); all elevations had an average May temperature above freezing. Average values over the 2010-2020 study period were slightly warmer than during the 1991-2020 normal period, most noticeably in May.

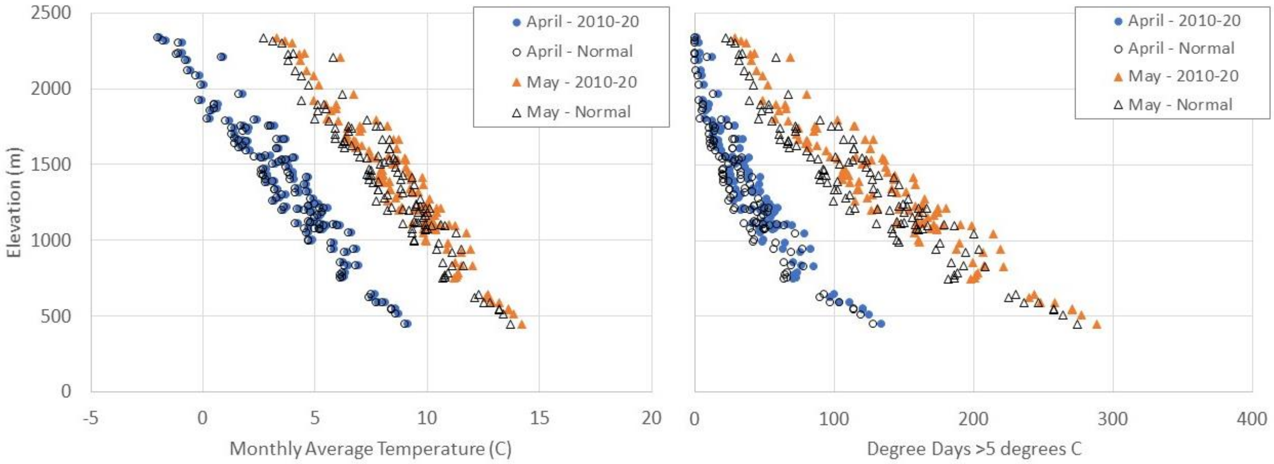


*Figure 17. April and May monthly average temperature (left) and monthly degree days greater than 5°C (right) for selected points in the Kettle River basin (data from ClimateNA desktop tool v. 7.01). Mean values for the 2010-2020 study period are shown (solid symbols) with the 1991-2020 climate normals (open symbols).*

Monthly degree days above 5 °C (DD>5) were used to provide more information on how air temperature may affect snowmelt. Degree days are units representing the combined effects of how much higher the air temperature is above some base value (in this case, 5 °C) and the duration of time that the air was warmer than the base temperature. The degree day calculation is done for each day, and then the daily values are summed for the month. Degree day variables take into account variability in air temperature through the day, which is not represented by the average temperature. For example, the daily mean air temperature may be 0 °C but over five hours the temperature may have warmed to 8 °C and snowmelt occurred. The DD>5 variable was developed to reflect the potential for plant growth; although the threshold temperature for snowmelt to occur is near 0 °C, the DD>5 values can be used as a proxy for the net radiation and sensible heat energy available for snowmelt. The larger the value of DD>5, the more energy that is available for melt. Monthly DD>5 values in April increased rapidly below approximately 1250 m elevation, suggesting that total snowmelt in April may have been limited at elevations above 1250 m (Figure 17, right).

Below 1250 m average annual snowfall was generally less than 250 mm and the percent of total annual precipitation that fell as snow (PAS) was less than 40% (Figure 18). Precipitation that fell in areas below this elevation, then, was predominantly in the form of rain. The amount of snowfall during the 2010-2020 period was slightly less than the 1991-2020 normal, with the difference increasing as elevation increased. In addition, the percent of total annual precipitation that fell as snow was reduced compared to the 1991-2020 normal, with the difference also increasing with elevation.

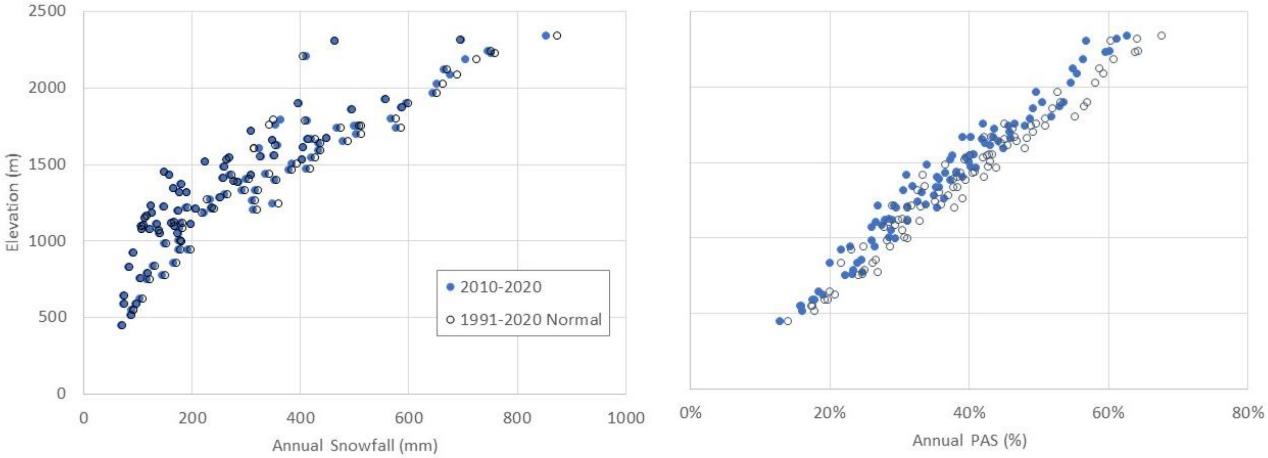


*Figure 18. Annual snowfall expressed in total water equivalent depth (left) and as a percent of total annual precipitation (right) for selected points in the Kettle River basin (data from ClimateNA desktop tool v. 7.01). Mean values for the 2010-2020 study period are shown (solid symbols) with the 1991-2020 climate normals (open symbols).*

All points in the rain dominated zone (i.e., below ~1250 m) received some snow, but in some years this snow may not have accumulated over the winter season. Melting due to periodic mid-winter warm weather or rain-on-snow events may have caused the snow to disappear or at least deplete. The Provincial Snow Survey and Water Supply Bulletins document variability in snowpack conditions at low elevations from year to year (Appendix K). On average, the amount of energy available in April to melt snow below 1250 m, as represented by the DD>5 value, may have been adequate to melt what snow accumulated there; above that elevation, the amount of melt occurring in April was small.

From this exploration of modeled temperature and precipitation data, 1250 m may be a useful elevation threshold to compare to the lower limits of SSZ polygons for the Kettle River basin. It should be noted that the ClimateNA data are interpolated between climate stations that are predominantly located at low elevations, so the values calculated for locations in mountainous terrain are affected by the lapse rates used in the interpolation. In addition, the data does not perfectly represent all components of the snowmelt energy balance; temperature is often used as an index for the amount of energy available for melt, but other drivers, especially the amount of solar radiation received on slopes with different aspects, are not perfectly represented.

## 3.4 Hydrologic Model

Modelled peak SWE and snowmelt rates from an existing hydrologic model (Chernos et al. 2020a, 2020b) were used to assess whether all elevations in the SSZ contributed meltwater at the onset of the peak flow period. The volume of meltwater contributed from different elevation bands depends on both the amount of snow that accumulates there and the total area of each band. In the Kettle River basin, the top 28% of the watershed (above 1500 m, Figure 19, left) was modelled to yield almost 50% of the total snow volume (Figure 19, right).

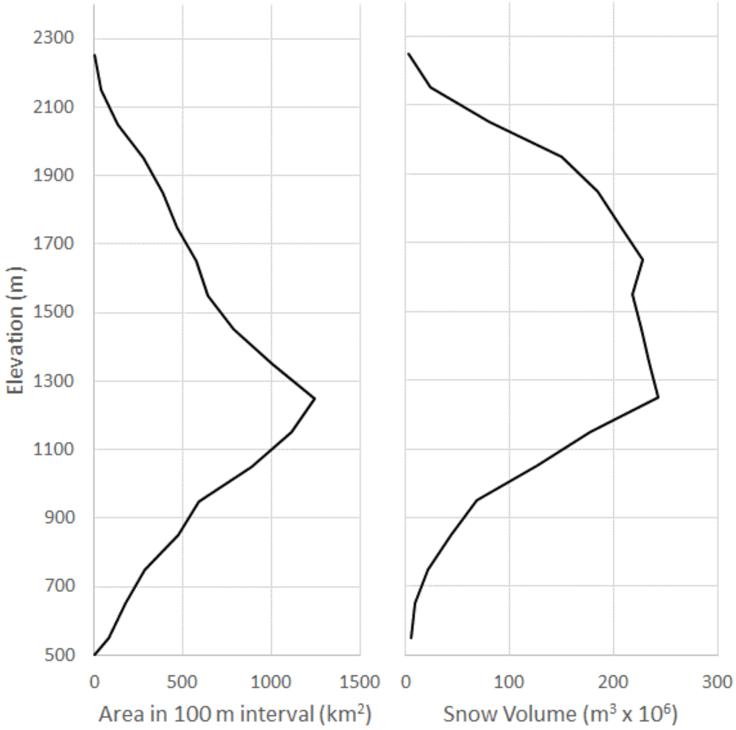


*Figure 19. Basin area in each 100 m elevation interval (left) and modeled average snow volume per 100 m elevation interval (right) for the Kettle River basin.*

Modelled average daily snowmelt volumes indicated that snowmelt was occurring at all elevations by the start of the peak flow period (except below 700 m where there was no snow remaining, on average) (Figure 20). Streamflow at the start of the peak flow period was primarily driven by melt above 1100 m elevation, and above 1400 m by mid-May. Peak meltwater contribution to streamflow from the 1100-1400 m band had occurred before the onset of the peak flow period. This indicated that the lower limit of the SSZ fell within the 1100-1400 m elevation zone, and that all elevations within the SSZ contributed meltwater to streamflow at the onset of the peak flow period.

Peak meltwater volumes for the 1100-1400 m and 1400-1700 m elevation bands were similar, and total volumes were equal for each of these two bands and for the >1700 m interval (~30% each).

Although the method used to calculate snowmelt in the model was a relatively simple one (a degree day method), it did consider spatial variations in air temperature, vegetation cover, slope and aspect and probably provided reasonable estimates of melt (Lindström et al. 1997; Jost et al. 2012; Bergström and Lindström 2015). The model developers concluded that model performance was good (Nash-Sutcliffe Efficiency scores >0.86) and that it generally represented streamflow-generating processes in the Kettle River basin (Chernos et al. 2020a).

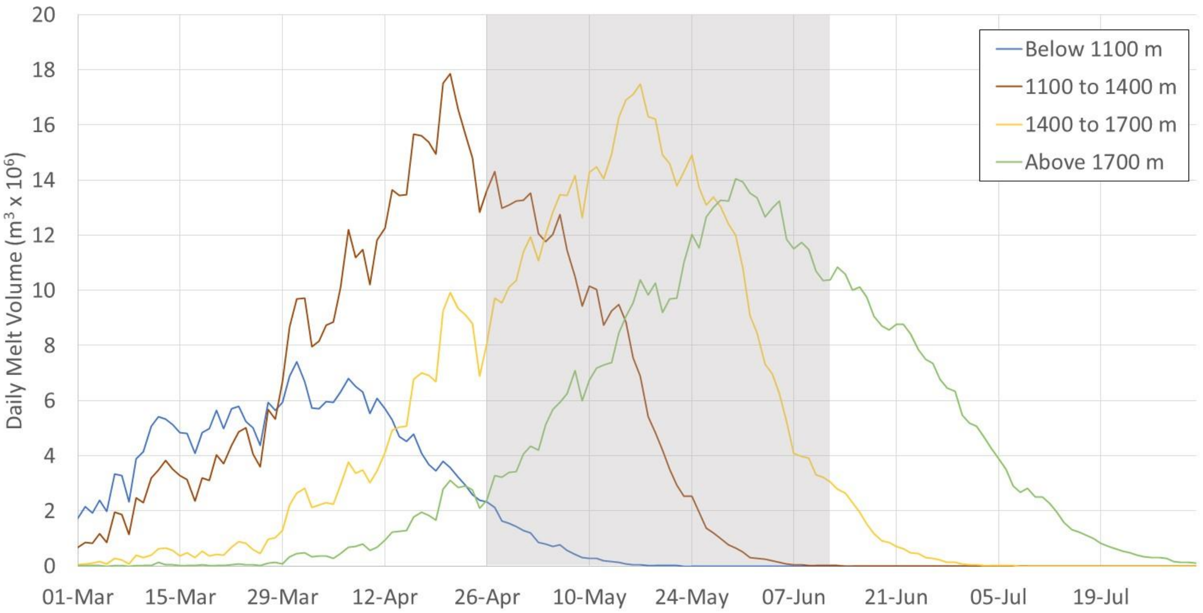


*Figure 20. Modeled daily snowmelt volumes for four elevation intervals. The grey band shows the average peak flow period for Kettle River near Laurier (2010-2020).*

## 4. DISCUSSION

The method adopted for this study used a combination of hydrograph and GIS analysis to identify the snow sensitive zone for eight drainage basins nested in the Kettle River watershed in southern B.C. SNODAS SWE data products with a 1 km$^2$ spatial resolution were retrieved for each basin on the date when the peak flow period began for each spring of 2010 to 2020, defined as the date when daily streamflow rose above the average value for each freshet period. The combination of GIS and streamflow data analysis used in this work provided an efficient and objective way to define the snow sensitive zone for mountainous watersheds in southern B.C. Importantly, the automated SWE-based identification of the snowline reduced subjectivity introduced in visual analysis of aerial photographs and errors in visual assessment due to shadows, forest cover and the angle of the aerial photography. SNODAS has the additional advantage of daily coverage.

Section 4.1 provides a more thorough comparison between results for the study basins and previous work, including the Redfish and Mission Creek watersheds. This is followed by discussions of management and operational applications and sources of uncertainty in Section 4.2, and suggestions for further work in Section 4.3.

### 4.1 Comparisons with Previous Studies

The SSZ results for Redfish Creek were compared to a previous study by Gluns (2000, 2001). While the similarities between results were promising, there were three significant differences in the methods used. First, in the study by Gluns (2000, 2001) the SSZ was defined as the area that was snow covered on the date of peak flow whereas this analysis used the onset of the peak flow period. The date of peak flow occurs later than the date of onset of peak flow, and the difference is not consistent from year to year. For example, for Redfish Creek the peak occurred between 4 and 44 days after the onset of the peak flow period. In addition, in this region of B.C. it is common to have multiple streamflow peaks during the freshet period, often of similar magnitude. Peaks in streamflow may be caused by snowmelt, rainfall or a combination (i.e., ROS events), whereas streamflow volumes at the start of the peak flow period are usually contributed by snowmelt. Because this study focussed on snow accumulation and melt processes, the date of onset of the peak flow period was considered a more appropriate and consistent variable to use.

Second, in the previous Redfish Creek study the snowline was defined as the boundary between areas that had equal coverage by snow and bare ground patches (as identified using oblique aerial photographs) whereas this analysis defined the snowline using spatial SWE data and a threshold of 25 mm. Lastly, the aerial photographs used in the previous study provided much finer spatial resolution than the 1 $km^2$ resolution SNODAS product, especially relative to the size of the Redfish Creek basin (27.3 $km^2$). In this study a single pixel could cover 3.7% of the total basin area, which was often larger than the differences in results between the various thresholds tested. The spatial resolution of the aerial photographs used by Gluns (2000, 2001) was unreported but estimated to be on the order of a few metres, so the similarity in results was surprising. In addition, the combination of the coarse resolution of the SNODAS data and the steep mountainous terrain of the Redfish Creek basin meant that a single pixel could cover a relatively wide range of elevations. This was significant because there is a strong relationship between snowline and elevation. For small catchments in steep terrain, a higher resolution spatial product would be more accurate (Hu et al. 2019a). However, it would be possible to estimate snow covered area using the SNODAS products to within ~10% for Redfish Creek.

Gluns (2001) reported that peak flow was generated when SCA was between 40 and 80%, and that the five-year average SCA at peak flow for both Redfish Creek and neighbouring Laird Creek was approximately 65%. That study, and subsequent modeling work, indicated that snowmelt in the middle third of the catchment was the primary source of water during the development of peak flows, but that melt in the upper portions of the catchment was also important during this period (Whitaker et al. 2002; Schnorbus and Alila 2004). The modeling study by Whitaker et al. (2002) also concluded that while the primary snowmelt contributing area was 65% for Redfish Creek, harvesting in the top 80% of the catchment increased annual maximum flows by up to 22% when harvested area (using clearcutting techniques) was 22.4% of the basin area. Harvesting in the lowest 20% of the basin caused little or no change in peak flows. The SNODAS-based results indicated that 88% of the basin area contributed meltwater at the start of the peak flow period, more than identified by Gluns (2001) but similar to the melt study by Whitaker et al. (2002). Some of the difference from Gluns (2001) can be attributed to the use of the peak flow date vs. the onset of the peak flow period; because it occurs later than the onset date, SCA will be smaller on the peak flow date. Some can also be attributed to the coarser spatial resolution of the SNODAS product compared to aerial photographs. Without more consistencies between the two studies, it is difficult to draw any firm conclusions from the comparison. A study is underway to assess snowlines in drainage basins near Redfish Creek to more concretely assess the SSZ in that region.

For Mission Creek, Smith et al. (2008) reported an average SCA of 38% at the onset of the peak flow period for 1999-2003 (range 29 to 53%). These results are lower than the median of 67% (mean 63%) found using SNODAS data and on the low end of the values measured between 2010 and 2018 (range 34-86%). Climatological assessments of the 1999-2003 and 2010-2018 periods for Mission Creek included comparisons of peak winter snow accumulation at mid- and high elevations, winter and spring conditions for the Oceanic Niño Index (ONI) and Pacific Decadal Oscillation (PDO) climate indices, peak streamflow and April mean air temperature (Table 8). Interannual variability in winter snow accumulation and spring air temperature in the B.C. Southern Interior have been found to be associated with El Niño/La Niña conditions and north Pacific Ocean sea surface temperatures (Moore et al. 2010). Data from the mid-elevation McCulloch snow survey station indicated that most years during the 2010-2018 period had higher than normal peak SWE, with the highest values associated with cool phases of the winter ONI and PDO. Most years during the 1999-2003 period had near-normal peak SWE despite three years of cold/negative winter ONI and PDO phases. The years with the lowest peak SWE values and peak daily streamflow (2003, 2010 and 2015) were associated with warm/positive winter ONI and PDO phases. Cold and neutral phases of the ONI and PDO were generally associated with normal and higher than normal SWE at the McCulloch and Graystoke Lake snow survey stations and elevated peak flows in Mission Creek, as well as higher SCA values at the onset of the peak flow period. Comparison between April temperature anomalies at Kelowna and the ONI and PDO climate indices indicated that the relationship between ONI, PDO and spring melt conditions may be less clear, likely because of the time lag between changes in ocean temperatures near the equator and impacts on weather at mid-latitudes. An in-depth statistical analysis of teleconnections was beyond the scope of this work.

From the ONI, PDO, SWE and air temperature comparisons, snowline analysis for the 2010-2018 period may result in larger SSZ estimates because of higher snow accumulation compared to the 1999-2003 period. More detailed comparison was not possible because the same analysis could not be applied to both time periods (i.e., there is no SNODAS data for 1999-2003). However, the 2010-2018 results may be a more conservative estimate of the SSZ. High peak flows often occur following winters with high snow accumulation, which were more prevalent during this period.

Climatological differences in winter snow accumulation and spring melt conditions between the 1999-2003 and 2010-2018 periods do not entirely explain the differences in results between this analysis and that of Smith et al. (2008). As with the Redfish Creek comparison, some may be due to differences in spatial resolution and methods. The aerial photographs used by Smith et al. (2008) had much finer resolution than the 1 km$^2$ resolution of the SNODAS products, as discussed for Redfish Creek. Another difference in methods between this and the earlier study of Mission Creek is that, while both used streamflow data from the same hydrometric station, the watershed area used was different. Smith et al. (2008) defined the drainage basin as the watershed upstream of a major water purveyor intake point, with an area of 601 km$^2$; in this analysis the catchment outlet was near the mouth, which defined an area of 791 km$^2$. Using the same definition for the date of onset of peak flow and a larger catchment area in this study should have resulted in lower SCA values. Instead, the higher mean SCA value for 2010-2018 was most likely the result of different definitions of the snowline. The previous study used the lowest elevation where the snowpack was continuous (no bare batches) whereas in this work the snowline was derived from SWE and probably included areas with some combination of bare and snow patches. Because the same analytical methods cannot be applied to both time periods, direct comparison is difficult.

The results for the Kettle River basin were also compared to previous studies on tributaries in the Okanagan and Thompson Rivers (Table 1). Most of these assessments were done following the same methods as Smith et al. (2008), with the exception of Horsefly Creek which was based on expert knowledge (Dobson Engineering, Ltd. 2007). The Okanagan River basin is adjacent to the Kettle River basins and the winter precipitation regime is similar to the west portion of the Kettle River basin. The Horsefly River and Chase Creek watersheds are north of the study area. Winter precipitation in the Chase Creek basins is similar to the Okanagan, while the large Horsefly River watershed has a climate more similar to the eastern part of the Kettle River basin.

The previous studies summarised in Table 1 span the period 1999-2004 (similar to that for the Mission Creek study), so there were some climatological differences from the 2010-2020 study period, as discussed above. SSZ results were reported as either elevations of the lower limit (m) or as snow covered area (%). The elevation of the lower limit of the SSZ for basins in the Kettle River catchment (range 900-

1270 m) was lower than reported for basins in the adjacent Okanagan River basin (range 1340-1660 m). When the SSZ was expressed as a percent of the total basin area (i.e., SCA), the value reported for the Horsefly River basin (60%) was in the low range of those calculated for the Kettle River basin (range 51-100%, Table 11). Throughout the Okanagan River basin and for Chase Creek, the SSZ (as a percent of the basin area) was considerably smaller than found for the Kettle River basin. The Okanagan measurements were conducted following the same methods as Smith et al. (2008) so the differences in these results were consistent with differences described in the Mission Creek comparison.

## 4.2 Watershed Management and Uncertainty

The primary use of the SSZ maps in forested watershed management is to inform the planning of harvest activities in ways that reduce the potential for snowmelt synchronization and resultant increases in peak flow. Snowmelt synchronisation within the SSZ can be reduced by considering differences in snow accumulation and melt with elevation, slope, aspect and harvesting method (e.g., clearcutting vs. selective harvesting). The spatial patterns in snow distribution and melt described in the results section can be informative when planning cutblock locations and sizes, and harvest methods. Balancing the potential for accelerated melt in one part of the basin with delayed melt in another can help reduce any potential impacts on peak flows, as well as on the subsequent transition to summer low flows. Appropriate use of the SSZ maps, however, requires thoughtful consideration of the sources of uncertainty. The lower limit elevations of the SSZ areas mapped in this analysis, while determined and analysed scientifically, are more appropriately described as guidance information rather than rigid thresholds.

Different definitions of the snowline are found in the published literature, leading to different calculations of SCA and difficulty comparing results between studies. Some studies map the actual snowline location, variously defined as where the ground area is 50% snow covered (Seidel et al. 1997; Gluns 2000, 2001; Wunderle et al. 2002) or where the snow cover is continuous (i.e., no bare ground patches) (Barnes and Bowley 1968; Smith et al. 2008), while others use snow persistence as a metric (Tennant et al. 2014; Moore et al. 2015). In this analysis the snowline was defined using a SWE threshold rather than visual analysis of the presence/absence of snow cover. Use of this snow volume metric provides a more hydrologically meaningful definition of the snowline, and avoids some problems associated with satellite imagery in the visible wavelength range such as erroneous mapping of high SCA when there is light snowfall during the melt period (Hu et al. 2019b), inaccuracies due to patchy snow covers (Hall et al. 2000) and obscuring of the snowpack in dense canopies. A threshold of 25 mm SWE was used to distinguish snow covered and snow free pixels in the SNODAS product. A previous study using 1 mm SWE as the threshold found a high rate of false snow presence detection during the melt period (Gan et al. 2021). The 25 mm SWE threshold used in this analysis was similar to that used by Shamir and Georgakakos (2007).

The multi-year SCA maps show the degree of interannual variability in SCA that can occur at the start of the peak flow season. This analysis used eleven years of data to overcome the effects of variability in snow accumulation and melt processes from year to year, but, as with any study, more years of data would increase confidence in the results. In addition, median SCA values were used to define the SSZ. In watersheds known to be more sensitive to disturbance, a more conservative approach may be to use the highest SCA value.

The SNODAS products combine satellite, airborne and ground observations with model output to estimate SWE, so the level of uncertainty of this dataset should be lower than for products that use only satellite- or ground-based information. However, this multi-platform approach also means that there are limited data that can be used to validate the SNODAS product, because the same data that would be used for validation was used to generate the maps. An intensive, multi-year field sampling campaign in the Kettle River basin would be needed to validate the SNODAS SWE data across different elevations, aspects and vegetation zones, which was outside the scope of this project. However, information can be derived from the published literature. A recent assessment of SNODAS SWE products found that they performed well in the western U.S. compared to passive microwave products (Gan et al. 2021). Comparisons with independent ground measurements indicate that SNODAS tends to overestimate SWE, with poorer performance in complex terrain, alpine areas, areas of deep snow and denser forest canopy, for ephemeral snow cover and with increasing distance away from ground observation stations (Clow et al. 2012; Boniface et al. 2015; Hedrick et al. 2015; Bair et al. 2016; Musselman et al. 2018; Gan et al. 2021), and that the product could be improved through better representation of wind redistribution of snow during the winter, sublimation and subcanopy melt processes (Lv et al. 2019). Spring SWE may be overestimated because the ground observations used in development are located in clearings at high elevations, where there is greater snow accumulation compared to adjacent forest stands (Dozier et al. 2016; Lv et al. 2019). In this analysis, the effects of SWE overestimation by SNODAS was ameliorated through use of a presence/absence threshold greater than 1 mm SWE.

There is some uncertainty in using the date of onset of the peak flow period in this analysis to identify the SSZ. There is no common standard for defining these types of hydrologically significant dates, but the definitions used by Smith et al. (2008) provided a consistent way to analyse the hydrometric data regardless if they were from low, high or extremely high flow years. The onset of the peak flow period is more appropriate than the date of peak flow, which in southern British Columbia can occur due to snowmelt, rainfall, or rain-on-snow processes. The start of the peak flow period is more consistent from year to year and occurs when streamflow is usually dominated by snowmelt inputs. The date of onset of the peak flow period was considered more appropriate in this study of snow accumulation and melt processes. Using the SCA at the start of the peak flow period was somewhat validated by the hydrologic model for the Kettle River basin above Grand Forks, which indicated that the majority of the snowmelt volume that contributes to peak flow occurs above 1100-1400 m elevation and was consistent with the lower limit elevations found for the Kettle River basin above Ferry and Laurier.

With regards to uncertainty in the hydrometric data, flow regulation by upstream dams and reservoirs would affect identification of the peak flow period onset date. If the selected date was off by one to three days then the effect on the resulting SCA would be small; if the date was off by five to seven days, however, then the error increases. In this analysis, four of the study basins in the Kettle River basins are categorised as regulated by WSC, meaning that a control structure affects flow in more than 5% of the watershed. This reflects the inter-basin transfer of water from the West Kettle River basin to Mission Creek watershed, a number of residential power generation licenses in the Kettle River basin above Westbridge, and small storage structures scattered around the study area. Overall, the effects of these structures on the flow regime were considered to be small, and that the peak flow period onset dates selected for the four study basins reasonably represented natural conditions.

While the timing of snow disappearance varies from year to year, spatial patterns in melt processes and snow cover disappearance in mountainous watersheds tend to be fairly consistent because of the control of topography on snowfall, the amount of snow that accumulates on the ground and the net radiation component of the snowmelt energy balance (Biggs and Whitaker 2012; Garvelmann et al. 2014). Because of the effects of aspect on snow accumulation and melt, the snowline does not follow a single elevation contour (Bagchi 1983). In the study basins, the snowline was higher on south-facing slopes than north-facing ones because of increased exposure to solar radiation (Figure 13). The elevation of a basin is also important; snowlines are lower in catchments with glaciers or significant alpine area (Seidel et al. 1997), and this study demonstrated that in the Kettle River basin they were also lower in watersheds with higher median elevations.

For basins within the Kettle River watershed, median SCA at the start of the peak flow period varied between 51 and 100% (Table 12), increasing as median elevation increased (Figure 11, right). These results suggested that using a fixed SCA value (e.g., the H60) when assessing the hydrologic impacts of forest harvesting or disturbance in the Kettle River watershed regardless of basin characteristics may not accurately reflect potential impacts on snow accumulation and melt patterns. This was consistent with previous studies that the snow sensitive zone could not always be estimated using the H60 concept (see the Section 4.1).

The SSZ maps provide important information for planning at multiple spatial scales on the landscape, specifically to conduct harvest, replanting and remediation activities in ways that reduce disturbance-driven hazards that may increase snowmelt-generated peak flow. Information about the SSZ can be used in watershed assessments, as well as by land and resource managers when evaluating cumulative effects of multiple disturbances on watershed processes. The results presented in this report are specific to the Kettle River basin; the applicability to adjacent or nearby catchments is uncertain at this time. When considering impacts on snow and snowmelt processes, forest management practices may be customised to the climate, topography, spatial heterogeneity and forest disturbance patterns of each catchment (Zhang and Wei 2014).

Uncertainty in the lower limit elevation of the SSZ likely has minimal consequences for planning to mitigate harvest effects on peak flow (Whitaker et al. 2002). However, earlier snowmelt in disturbed forests near the snowline has the potential to cause an earlier onset of the peak flow period and extension of the snow-free period (with subsequent impacts on soil evaporation and moisture, and implications for ecological drought and wildfires). These results can help inform consideration of all aspects of the hydrologic cycle and regime, to balance costs and benefits of forest harvesting for sustainable resource management as well as for public safety and the protection of infrastructure.

Cumulative effects theory purports that landscapes be managed at a scale most relevant to a point of value or interest. In the case of snowmelt-generated peak flows, the objective of watershed management can be to reduce the potential impacts of disturbance on downstream communities or infrastructure. Forest management in the Kettle River tributary of the Columbia River may conceptually have little impact on flow in the main river system which is managed through numerous dams and reservoirs upstream of the junction with Kettle River. However, landcover management could have significant impacts on communities, properties, infrastructure and ecosystems along the lower reaches of the Kettle River before it enters the Columbia River. Land use and landcover management may therefore need to consider the scale of the full Kettle River watershed when assessing potential effects on the timing and volume of peak streamflow, and the duration and timing of the transition to summer low flows.

The SSZ maps can be further refined by extracting snow distribution patterns. The SNODAS data allows estimation of the total snow volume in the SSZ and mapping of the distribution of snow (Figure 21). Within the SSZ of the largest study basin, the Kettle River above Laurier, 60% of the total snow volume is concentrated in the highest 39% of the SSZ area or approximately 20% of the total basin area. This information may be used in combination with slope, aspect, landcover and disturbance maps to plan forestry and other resource activities to make management decisions with consideration of impacts on snow accumulation and melt.

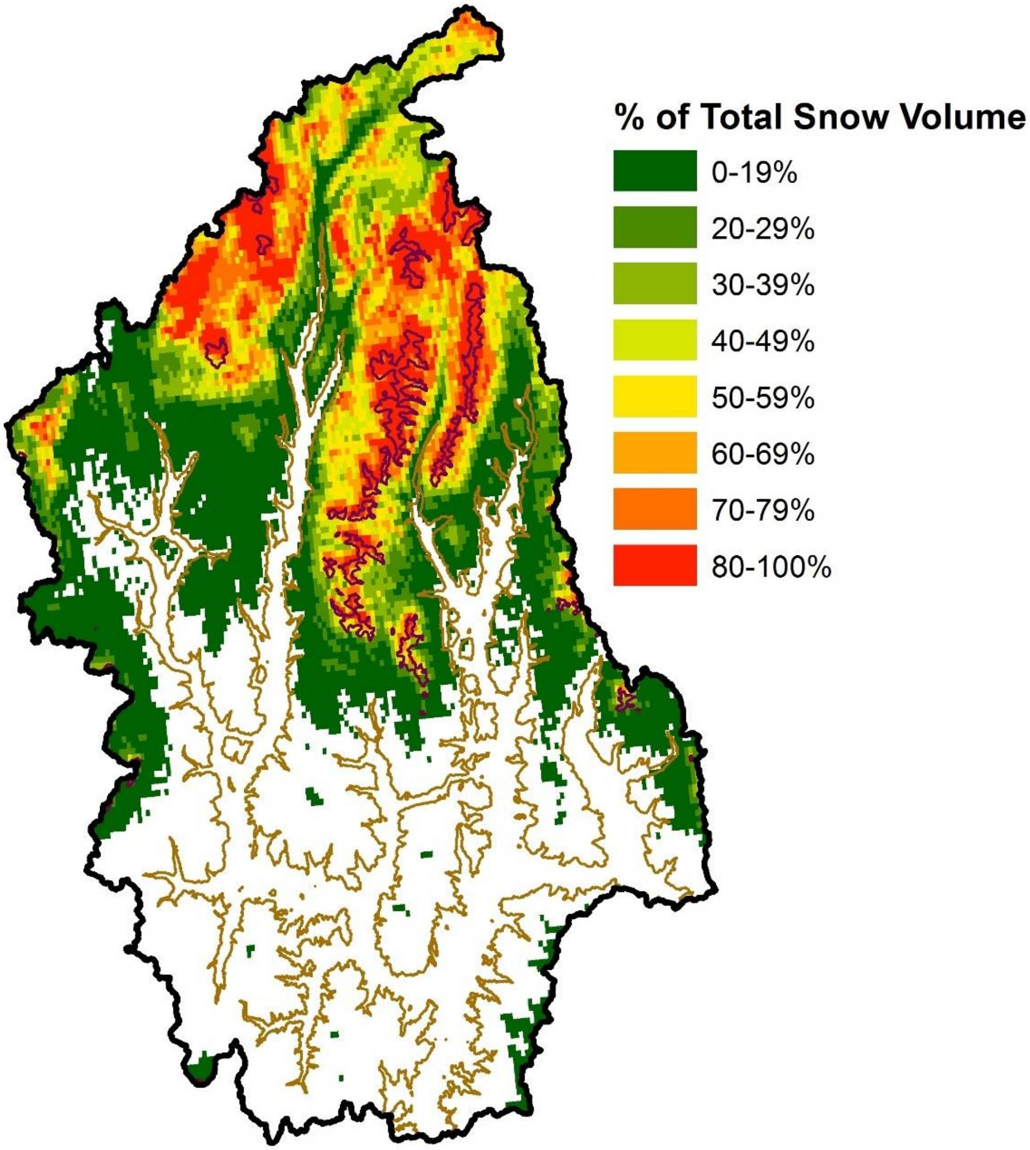


*Figure 21. Distribution of snow within the snow sensitive zone for the Kettle River basin above Laurier, by volume. The brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

## 4.3 Further Work

Several opportunities for further work have been identified from this study. First, methods described in this report will be applied to drainage basins across the upper Columbia River basin within Canada to gain more information on the SSZ across a wider range of climates and topographic conditions (elevation, steepness and aspects) in southeastern British Columbia. The same basins may also be used in complementary assessments of snow persistence (e.g., Kampf and Lefsky 2016; Bevington et al. 2020). Results from these studies may allow for identification of regional snow line elevations for forestry decision-making and cumulative effects analysis, and lead to improved understanding of potential climate change impacts on runoff characteristics and low flows (Moore et al. 2015; Kampf and Lefsky 2016; Parajka et al. 2019). Our understanding of the effects of forest disturbance within the SSZ areas could be further refined through modeling the distribution of snow and energy for snowmelt across different elevations to identify ‘critical zones’ where melt synchronisation could contribute substantially to peak flow (Biggs and Whitaker 2012).

A significant limitation of the SNODAS data products is their 1 km$^2$ spatial resolution, which may increase uncertainty in snowline mapping in steep terrain. The greatest advantage of the SNODAS products is their high temporal resolution (daily), which may be more important than fine spatial resolution (Sankey et al. 2015). The efficacy of different data sources could be further assessed (Masson et al. 2018; Bevington et al. 2019; Tsai et al. 2019; Salzano et al. 2019). These data sources could potentially also be used to validate the SNODAS products in the absence of intensive field sampling datasets for the study basins, or to extend the SCA analysis back in time to assess trends and the potential impacts of climate change. Because the size of the SSZ is expected to decrease over time but the rate of change is uncertain, the analysis should be updated in coming decades.

An avenue to support adoption of the SSZ areas in forestry operations and cumulative effects assessment would be to model the hydrologic impacts of forest disturbance and different forestry operations (e.g., selective harvesting vs. clearcutting) on snowmelt synchronisation. The existing HBV-EC hydrologic model for the Kettle River basin built within the Raven Hydrological Framework could be useful for this application.

The results presented in this report are specific to snowmelt-dominated peak flows, not flows generated predominantly by rainfall or ROS events. The differences in snowmelt rates between forested and non-forested land that lead to snowmelt synchronisation and enhanced peak flows are greatest under windy, clear sky conditions on south-facing slopes. Under these conditions, snowmelt rates in forest openings can be many times greater than in adjacent forest stands. During ROS events, however, the differences between forested and non-forested stands can be highly variable; studies have demonstrated that these differences have reversed, been reduced, remained the same or increased depending on characteristics of the storm, the snowpack and vegetation cover (Marks et al. 1998; Jones 2000; Garvelmann et al 2014; Wayand et al. 2015). With expected increases in ROS events in the future, the effects of forest disturbance on flood generation processes under these conditions requires further study in southern B.C. (Jeong and Sushama 2018; Musselman et al. 2018).

## 5. SUMMARY

The objective of this study was to develop a method using available spatial snow cover data to determine the snowmelt runoff contributing area or SSZ at the time of spring peak flow, and to compare results for multiple nested basins within the Kettle River watershed in southern B.C. The analysis focussed on eight nested watersheds in the Kettle River basin as well as two from previous snowline studies in the West Kootenays (Redfish Creek) and Okanagan (Mission Creek). For the Kettle River basin, annual hydrographs for the 2010-2020 period were retrieved from the Water Survey of Canada, and the date of onset of the peak flow period was identified for each year following Smith et al. 2008. SNODAS SWE products were used to derive snow covered area on those dates at a 1 km$^2$ resolution, and the median snow covered area was used to identify the snow sensitive zone.

Climate normal data and a hydrologic model were used to verify aspects of the SSZ in the basin. Elevation bands were identified where precipitation is dominated by rain, snow or mixed rain and snow. The lower limit of the SSZ, derived from the SNODAS products, occurred near the boundary between the rain dominated and mixed rain and snow zones. Results from a hydrologic model (Chernos et al. 2020a, 2020b) verified that snowmelt occurred at all elevations in the SSZ and that the lower limit of the SSZ fell between

1100 and 1400 m. Comparisons of results with previous studies were limited because of differences in methods and in climate conditions during the time periods studied, but the lower limit elevation of the Kettle River SSZ areas were generally lower than previously reported for adjacent areas.

The methods used in this analysis provide an objective, repeatable way to identify the SSZ for watersheds that have hydrometric data. The SWE threshold of 25 mm used in this study to distinguish “snow covered” from “snow-free” pixels in the SNODAS product was consistent with the research literature (Shamir and Georgakakos 2007). The use of the date of onset of the peak flow period instead of the date of peak flow was found to be better suited to streams in the southern interior of B.C. that have multiple peaks of similar magnitude rather than a single dominant peak (Gluns 2001) and provided more consistency in snow covered area results from year to year.

Maps of snow covered area over the 2010-2020 melt periods demonstrated variability in melt timing but consistent patterns in snow distribution and melt from year to year. Comparison of results for the eight nested basins within the Kettle River watershed indicated relationships with median elevation, and that the use of a single SCA value to identify the SSZ (such as the H60 concept) was not justified.

The SSZ maps can provide information for planning of forest management activities in ways that reduce the potential for snowmelt synchronization and resultant increases in peak flow in the Kettle River basin. Snowmelt synchronization can be reduced by considering differences in snow accumulation and melt with slope, aspect and harvest methods within the SSZ. Information in this report can also be used by land and resource managers when evaluating the potential cumulative effects of multiple disturbances on watershed processes. In terms of climate change, the amount and persistence of snow at low and mid-elevations is expected to decrease which would therefore cause the SSZ to decrease in area. SSZ mapping should be revisited occasionally in coming decades.

## REFERENCES

Associated Environmental. 2019. Streamflow datasets to support the application of the Okanagan Tennant methods in priority Okanagan streams: Final report. Report prepared for Okanagan Basin Water Board.

Arsenault, R.; F. Brissette; J.-L. Martel; M. Troin; G. Lévesque; J. Davidson-Chaput; M. Castañeda Gonzalez; A. Ameli; A. Poulin. 2020. A comprehensive, multisource database for hydrometeorological modeling of 14,425 North American watersheds. Scientific Data. 7: 243.

Artan, G.A.; J.P. Verdin; R. Lietzow. 2013. Large scale snow water equivalent status monitoring: Comparison of different snow water products in the upper Colorado basin. Hydrology and Earth Systems Sciences. 17: 5127-5139.

Bagchi, A.K. 1983. Generation of the snowline. Photogrammetric Engineering and Remote Sensing. 49(12): 1679-1689.

Bair, E.H.; R. Davis; K. Rittger; J. Dozier. 2013. Operational SWE forecasts using a hybrid approach. Proceedings of the International Snow Science Workshop (ISSW 2013), Grenoble Chamonix-Mont-Blanc, France. 7-11 October 2013. Pp. 1293-1297.

Bair, E.H.; K. Rittger; R.E. Davis; T.H. Painter; J. Dozier. 2016. Validating reconstruction of snow water equivalent in California’s Sierra Nevada using measurements from the NASA Airborne Snow Observatory. Water Resources Research.

Barnes, J.C.; C.J. Bowley. 1968. Snow cover distribution as mapped from satellite photography. Water Resources Research. 4(2): 257-272.

Barrett, A.P. 2003. National Operational Hydrologic Remote Sensing Center SNOw Data Assimilation System (SNODAS) products at NSIDC. NSIDC Special Report 11. National Snow and Ice Data Center: Boulder, Colorado.

Bergström, S.; G. Lindström. 2015. Interpretation of runoff processes in hydrological modelling – Experience from the HBV approach. Hydrological Processes. 29(16): 3535-3545.

Bevington, A.R.; H.E. Gleason; V.N. Foord; W.C. Floyd; H.P. Griesbauer. 2019. Regional influence of ocean-atmosphere teleconnections on the timing and duration of MODIS-derived snow cover in British Columbia, Canada. The Cryosphere. 13: 2693-2712.

Bevington, A.R.; H.E. Gleason; V.N. Foord. 2020. Snow cover timing from satellite imagery: Opportunities for near-real time mapping and seasonal forecasting. Technical Report 129. Province of British Columbia: Victoria.

Biggs, T.W.; T.M. Whitaker. 2012. Critical elevation zones of snowmelt during peak discharges in a mountain river basin. Journal of Hydrology. 438-439: 52-65.

Boniface, K.; J.J. Braun; J.L. McCreight; F.G. Nievinski. 2015. Comparison of Snow Data Assimilation System with GPS reflectometry snow depth in the western United States. Hydrological Processes. 29: 2425-2437.

Boon, S. 2012. Snow accumulation following forest disturbance. Ecohydrology. 5: 279-285.

B.C. Ministry of Forests. 2001. Watershed assessment procedure guidebook. 2nd edition. Forest Practices Branch, Ministry of Forests. Victoria, B.C. Forest Practices Code of British Columbia Guidebook.

Brown, R.; C. Derksen; L. Wang. 2007. Assessment of spring snow cover duration variability over northern Canada from satellite datasets. Remote Sensing of Environment. 111: 367-381.

Broxton, P.D.; N. Dawson; X. Zeng. 2016. Linking snowfall and snow accumulation to generate spatial maps of SWE and snow depth. Earth and Space Science. 3:246-256.

Carroll, T.; D. Cline; G. Fall; A. Nilsson; L. Li; A. Rost. 2001. NOHRSC operations and the simulation of snow cover properties for the coterminous U.S. Proceedings of the Western Snow Conference. 17-19 April 2001: Sun Valley, Idaho.

Chernos, M.; R.J. MacDonald; K. Green. 2020a. The hydrological effect of forest disturbance on the Kettle River watershed, B.C. Report prepared by MacDonald Hydrology Consultants Ltd. and Apex Geoscience Consultants Ltd. Report prepared for the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

Chernos, M.; R.J. MacDonald; K. Green. 2020b. Kettle River watershed hydrological model: Technical summary. Report prepared by MacDonald Hydrology Consultants Ltd. and Apex Geoscience Consultants Ltd. Report prepared for the B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

Clow, D.W.; L. Nanus; K.L. Verdin; J. Schmidt. 2012. Evaluation of SNODAS snow depth and snow water equivalent estimates for Colorado Rocky Mountains, USA. Hydrological Processes. 26: 2583-2591.

DeBeer, C.M.; J.W. Pomeroy. 2010. Simulation of the snowmelt runoff contributing area in a small alpine basin. Hydrology and Earth System Sciences. 14: 1205-1219.

Dietz, A.J.; C. Kuenzer; U. Gessner; S. Dech. 2012. Remote sensing of snow – A review of available methods. International Journal of Remote Sensing. 33(13): 4094-4134.

Dobson, D. 2013. Penticton Creek source assessment. Report prepared for the City of Penticton by Urban Systems.

Dobson Engineering Ltd. 2003a. Extent of snow cover during the 2002 spring freshet for the Mission Creek watershed (Second year of snowline data). Unpublished report.

Dobson Engineering Ltd. 2003b. Extent of snow cover during the 2002 spring freshet for the Peachland Creek watershed (Second year of snowline data). Unpublished report.

Dobson Engineering Ltd. 2003c. Extent of snow cover during the 2002 spring freshet for the Trout Creek watershed (Second year of snowline data). Unpublished report.

Dobson Engineering Ltd. 2004a. 2004 snowline survey in selected watersheds of the Central and South Okanagan (Year 2 of 5). Report prepared for Weyerhauser Company Limited.

Dobson Engineering Ltd. 2004b. Chase Creek hydrologic assessment: Impact of Mountain Pine Beetle infestations on peak flow (including application of the Ministry of Forest's Extension Note 67). Report prepared for Riverside Forest Products Ltd. and Tolko Industries Ltd.

Dobson Engineering Ltd. 2004c. Snowline data for the Trout Creek watershed: Extent of snow cover during the 2004 spring freshet. Report prepared for Riverside Forest Products Limited and Gorman Bros. Lumber Limited.

Dobson Engineering Ltd. 2005a. Snowline data for the Mission Creek watershed: Extent of snow cover during the 2004 spring freshet. Report prepared for Riverside Forest Products Limited and Gorman Bros. Lumber Limited.

Dobson Engineering Ltd. 2005b. Snowline data for the Peachland Creek watershed: Extent of snow cover during the 2004 spring freshet. Report prepared for Riverside Forest Products Limited and Gorman Bros. Lumber Limited.

Dobson Engineering Ltd. 2005c. Snowline data for the Shingle Creek watershed: Extent of snow cover during the 2004 spring freshet. Report prepared for Gorman Bros. Lumber Limited and Riverside Forest Products Limited.

Dobson Engineering Ltd. 2005d. Snowline data for the Trout Creek watershed: Extent of snow cover during the 2004 spring freshet. Report prepared for Riverside Forest Products Limited and Gorman Bros. Lumber Limited.

Dobson Engineering Ltd. 2007. 2006 hydrologic assessment for selected sub-basins in the Horsefly River watershed. Report prepared for Tolko Industries Limited.

Dozier, J.; E.H. Bair; R. E. Davis. 2016. Estimating the spatial distribution of snow water equivalent in the world's mountains. WIREs Water. 3: 461-474.

Driscoll, J.M.; L.E. Hay; A.R. Bock. 2017. Spatiotemporal variability of snow depletion curves derived from SNODAS for the coterminous United Stations, 2004-2013. Journal of the American Water Resource Association. 53(3): 655-666.

Erickson, T.A.; M.W. Williams; A. Winstral. 2005. Persistence of topographic controls on the spatial distribution of snow in rugged mountain terrain, Colorado, United States. Water Resources Research. 41: W04014.

Freudiger, D.; I. Kohn; K. Stahl; M. Weiler. 2014. Large scale analysis of changing frequencies of rain-on-snow events with flood-generation potential. Hydrology and Earth System Sciences. 18(7): 2695-2709.

Gan, Y.; Y. Zhang; C. Kongoli; C. Grassotti; Y. Liu; Y.-K. Lee; D.-J. Seo. 2021. Evaluation and blending of ATMS and AMSR2 snow water equivalent retrievals over the conterminous United States. Remote Sensing of Environment. 254:112280.

Gartska, W.U.; L.D. Love; B.C. Goodell; F.A. Bertle. 1958. Factors affecting snowmelt and streamflow: A report on the 1946-53 cooperative snow investigations at the Fraser Experimental Forest, Fraser, Colorado. U.S. Department of the Interior, Bureau of Land Management and U.S. Department of Agriculture, Forest Service.

Garvelmann, J.; S. Pohl; M. Weiler. 2014. Variability of observed energy fluxes during rain-on-snow and clear sky snowmelt in a midlatitude mountain environment. Journal of Hydrometeorology. 15: 1220-1237.

Garvelmann, J.; S. Pohl; M. Weiler. 2015. Spatio-temporal controls of snowmelt and runoff generation during rain-on-snow events in a mid-latitude mountain catchment. Hydrological Processes. 29: 3649-3664.

Gluns, D.R. 2000. Forest Renewal B.C. research program final report: Snowline evaluation for the Interior Watershed Assessment Procedure. FRBC Reference Number KB96063-RE.

Gluns, D.R. 2001. Snowline patterns during the melt season: Evaluation of the H60 concept. In Watershed Assessment in the Southern Interior of British Columbia: Workshop Proceedings. D.A.A. Toews and S. Chatwin (eds.). 9-10 March 2000: Penticton, B.C. Pp. 68-80.

Guan, B.; N.P. Molotch; D.E. Waliser; E.J. Fetzer; P.J. Neiman. 2013a. The 2010/2011 snow season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale variability. Water Resources Research. 49: 6731-6743.

Guan, B.; N.P. Molotch; D.E. Waliser; S.M. Jepsen; T.H. Painter; J. Dozier. 2013b. Snow water equivalent in the Sierra Nevada: Blending snow sensor observations with snowmelt model simulations. Water Resources Research. 49: 5029-5043.

Guan, B.; D.E. Waliser; F.M. Ralph; E.J. Fetzer; P.J. Neiman. 2016. Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers. Geophysical Research Letters. 43: 2964-2973.

Hall, D.K.; A.B. Tait; J.L. Foster; A.T.C. Chang; M. Allen. 2000. Intercomparison of satellite-derived snow-cover maps. Annals of Glaciology. 31: 369-376.

Hammond, J.C.; F.A. Saavedra; S.K. Kampf. 2018. How does snow persistence relate to annual streamflow in mountain watersheds of the western U.S. with wet maritime and dry continental climates? Water Resources Research. 54.

Harr, R.D. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: A new look at old studies. Water Resources Research. 22(7): 1095-1100.

Hedrick, A.; H.-P. Marshall; A. Winstral; K. Elder; S. Yueh; D. Cline. 2015. Independent evaluation of the SNODAS snow depth product using regional-scale lidar-derived measurements. The Cryosphere. 9: 13-23.

Hu, Z.; A. Dietz; C. Kuenzer. 2019a. Deriving regional snow line dynamics during the ablation seasons 1984-2018 in European Mountains. Remote Sensing. 11: 933. doi:10.3390/rs11080933.

Hu, Z.; A. Dietz; C. Kuenzer. 2019b. The potential of retrieving snow line dynamics from Landsat during the end of the ablation seasons between 1982 and 2017 in European mountains. International Journal of Applied Earth Observation and Geoinformation. 78: 138-148.

Jeong, D.I.; L. Sushama. 2018. Rain-on-snow events over North America based on two Canadian regional climate models. Climate Dynamics. 50: 303-316.

Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. Water Resources Research. 36(9): 2621-2642.

Jones, J.A.; R.M. Perkins. 2010. Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States. Water Resources Research. 46. W12512. Doi:10.1029/2009WR008632.

Jost, G.; R.D. Moore; R. Smith; D.R. Gluns. 2012. Distributed temperature-index snowmelt modelling for forested catchments. Journal of Hydrology. 420-421: 87-101.

Jost, G.; M. Weiler; D.R. Gluns; Y. Alila. 2007. The influence of forest and topography on snow accumulation and melt at the watershed-scale. Journal of Hydrology. 347: 101-115.

Kampf, S.K.; M.A. Lefsky. 2016. Transition of dominant peak flow sources from snowmelt to rainfall along the Colorado Front Range: Historical patterns, trends, and lessons from the 2013 Colorado Front Range floods. Water Resources Research. doi: 10.1002/2015WR017784.

Keum, J.; P. Coulibaly; T. Razavi; D. Tapsoba; A. Gobena; F. Weber; A. Pietroniro. 2018. Application of SNODAS and hydrologic models to enhance entropy-based snow monitoring network design. Journal of Hydrology. 561: 688-701.

Lea, J. 2007. The NOHRSC SNODAS snow water equivalent determination on Mount St. Helens, Washington. Proceedings of the Western Snow Conference. Pp. 175-178.

Lehning, M.; T. Grünewald; M. Schirmer. 2011. Mountain snow distribution governed by an altitudinal gradient and terrain roughness. Geophysical Research Letters. 38: L19504. Doi:10.1029/2011GL048927.

Lindström, G.; B. Johansson; M. Persson; M. Gardelin; S. Bergström. 1997. Development and test of the distributed HBV-96 hydrological model. Journal of Hydrology. 201: 272-288.

Liu, A.Q.; C. Mooney; K. Szeto; J.M. Thériault; B. Kochtubajda; R.E. Stewart; S. Boodoo; R. Goodson; Y. Li; J. Pomeroy. 2016. The June 2013 Alberta catastrophic flooding event: Part 1 – Climatological aspects and hydrometorological features. Hydrological Processes. 30: 4899-4916.

Liu, X.; L. Jiang; G. Wang; S. Hao. 2016. Improvement of long-term snow depth product accuracy from passive microwave satellite observations: A case study with SNODAS data. *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Pp. 4876-4879.

Liu, X.; L. Jiang; G. Wang; S. Wang. 2019. Deriving long-term snow depth datasets from passive microwave observations – A case study in the United States. *2019 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Pp. 4117-4120.

Lv, Z.; J.W. Pomeroy; X. Fang. 2019. Evaluation of SNODAS snow water equivalent in Western Canada and assimilation into a cold region hydrological model. Water Resources Research. 55: 11166-11187.

Marks, D.; J. Kimball; D. Tingey; T. Link. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. Hydrological Processes. 12: 1569-1587.

Marks, D.; T. Link; A. Winstral; D. Garen. 2001. Simulating snowmelt processes during rain-on-snow over a semi-arid mountain basin. Annals of Glaciology. 32: 195-202.

Massmann, C. 2019. Modelling snowmelt in ungauged catchments. Water. 11:301.

Masson, T.; M. Dumont; M. Dalla Mura; P. Sirguey; S. Gascoin; J.-P. Dedieu; J. Chanussot. 2018. An assessment of existing methodologies to retrieve snow cover fraction from MODIS data. Remote Sensing. 10: 619. Doi:10.3390/rs10040619.

McCabe, G.J.; M.P. Clark; L.E. Hay. 2007. Rain-on-snow events in the western United States. Bulletin of the American Meteorological Society. 88(3): 319-328.

Moore, C.; S. Kampf; B. Stone; E. Richer. 2015. A GIS-based method for defining snow zones: Application to the western United States. Geocarto International. 30(1): 62-81.

Moore, R.D.; D.L. Spittlehouse; P.H. Whitfield; K. Stahl. 2010. Weather and climate. In R.G. Pike, T.E. Redding, R.D. Moore, R.D. Winkler and K.D. Bladon (eds). Compendium of forest hydrology and geomorphology in British Columbia. B.C. Ministry of Forests and Range and FORREX Forum for Research and Extension in Natural Resources. B.C. Land Management Handbook 66. Pp. 47-84.

Musselman, K.N.; F. Lehner; K. Ikeda; M.P. Clark; A.F. Prein; C. Liu; M. Barlage; R. Rasmussen. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. Nature Climate Change. 8: 808-812.

National Operational Hydrologic Remote Sensing Center. 2004. Snow Data Assimilation System (SNODAS) Data Products at NSIDC, Version 1. 2010-2020 subset for southern British Columbia. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. https://doi.org/10.7265/N5TB14TC. Last accessed 16 June 2021.

Parajka, J.; N. Bezak; J. Burkhart; B. Hauksson; L. Holko; Y. Hundecha; M. Jenicek; P. Krajči; W. Mangini; P. Molnar; P. Riboust; J. Rizzi; A. Sensoy; G. Thirel; A. Viglione. 2019. MODIS snowline elevation changes during snowmelt runoff events in Europe. Journal of Hydrology and Hydromechanics. 67: 101-109.

Pomeroy, J.W.; R.E. Stewart; P.H. Whitfield. 2015. The 2013 flood event in the South Saskatchewan and Elk River basins: Causes, assessment and damages. Canadian Water Resources Journal.

Pomeroy, J.W.; X. Fang; D.G. Marks. 2016. The cold rain-on-snow event of June 2013 in the Canadian Rockies – Characteristics and diagnosis. Hydrological Processes. 30: 2899-2914.

Salzano, R.; R. Salvatori; M. Valt; G. Giuliani; B. Chatenoux; L. Ioppi. 2019. Automated classification of terrestrial images: The contribution to the remote sensing of snow cover. Geosciences. 9:97. Doi:10.3390/geosciences9020097.

Sankey, T.; J. Donald; J. McVay; M. Ashley; F. O'Donnell; S.M. Lopez; A. Springer. 2015. Multi-scale analysis of snow dynamics at the southern margin of the North American continental snow distribution. Remote Sensing of Environment. 169: 307-319.

Scherer, R. 2018. Watershed assessment of proposed forest development within the Peachland Creek community watershed: Revised final report. Report prepared for Tolko Industries Limited, B.C. Timber Sales and Ntityix Resource LP.

Schirmer, M.; V. Wirz; A. Clifton; M. Lehning. 2011. Persistence in intra-annual snow depth distribution: 1. Measurements and topographic control. Water Resources Research. 47: W09516.

Schneiderman, E.M.; A.H. Matonse; M.S. Zion; D.G. Lounsbury; R. Mukundan; S.M. Pradhanang; D.C. Pierson. 2013. Comparison of approaches for snowpack estimation in New York City watersheds. Hydrological Processes. 27: 3050-3060.

Schnorbus, M.; Y. Alila. 2004. Forest harvesting impacts on the peak flow regime in the Columbia Mountains of southeastern British Columbia: An investigation using long-term numerical modeling. Water Resources Research. 40. doi:10.1029/2003WR002918

Seidel, K.; C. Ehrler; J. Martinec; O. Turpin. 1997. Derivation of statistical snow line from high resolution snow cover mapping. Proceedings of the EARSeL Workshop on Land, Ice and Snow. 17-18 April 1997: Freiburg, Germany.

Shamir, E.; K.P. Georgakakos. 2007. Estimating snow depletion curves for American River basins using distributed snow modeling. Journal of Hydrology. 334: 162-173.

Siren, A.P.K.; M. Somos-Valenuela; C. Callahan; J.R. Kilborn; T. Duclos; C. Tragert; T.L. Morelli. 2018. Looking beyond wildlife: Using remote cameras to evaluate accuracy of gridded snow data. Remote Sensing in Ecology and Conservation. 4(4): 375-386.

Smith, R.S.; R.A. Scherer; D.A. Dobson. 2008. Snow cover extent during spring snowmelt in the south-central interior of British Columbia. B.C. Journal of Ecosystems and Management. 9(1): 57-70.

Tedesco, M.; P.S. Narvekar. 2010. Assessment of the NASA AMSR-E SWE product. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 3(1): 141-159.

Tennant, C.J.; B.T. Crosby; S.E. Godsey. 2014. Elevation-dependent responses of streamflow to climate warming. Hydrological Processes. 29: 991-1001.

Teti, P. 2003. Relations between peak snow accumulation and canopy density. The Forestry Chronicle. 79(2): 307-312.

Tsai, Y.-L.S.; A. Dietz; N. Oppelt; C. Kuenzer. 2019. Remote sensing of snow cover using spaceborne SAR: A review. Remote Sensing. 11: 1456. Doi:10.3390/rs11121456.

Varhola, A.; N.S. Coops; M. Weiler; R.D. Moore. 2010. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. Journal of Hydrology. 392: 219-233.

Vuyovich, C.M.; J.M. Jacobs; S.F. Daly. 2014. Comparison of passive microwave and modeled estimates of total watershed SWE in the continental United States. Water Resources Research. 50: 9088-9102.

Wang, T.; A. Hamann; D. Spittlehouse; C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS ONE. 11(6): e0156720. doi:10.1371/journal.pone.0156720.

Wayand, N.E.; J.D. Lundquist; M.P. Clark. 2015. Modeling the influence of hypsometry, vegetation, and storm energy on snowmelt contributions to basins during rain-on-snow floods. Water Resources Research. doi:10.1002/2014WR016576.

Whitaker, A.; Y. Alila; J. Beckers; D. Toews. 2002. Evaluating peak flow sensitivity to clear-cutting in different elevation bands of a snowmelt-dominated mountainous catchment. Water Resources Research. 38(9): 1172. doi:10.1029/2001WR000514

Winkler, R.; D. Gluns; D. Golding. 2004. Identifying snow indices for forest planning in southern British Columbia. Proceedings of the 72nd Annual Meeting of the Western Snow Conference. Pp. 53-61.

Winkler, R.; D. Spittlehouse; S. Boon; B. Zimonick. 2015. Forest disturbance effects on snow and water yield in interior British Columbia. Hydrology Research. 46(4): 521-532.

Wrzesien, M.L.; M.T. Durand; T.M. Pavelsky; I.M. Howat; S.A. Margulis; L.S. Huning. 2017. Comparison of methods to estimate snow water equivalent at the mountain range scale: A case study of the California Sierra Nevada. Journal of Hydrometeorology. 18: 1101-1119.

Wunderle, S.; M. Droz; H. Kleindienst. 2002. Spatial and temporal analysis of the snow line in the Alps based on NOAA-AVHRR data. Geographica Helvetica. 57(3): 170-183.

Würzer, S.; T. Jonas; N. Wever; M. Lehning. 2016. Influence of initial snowpack properties on runoff formation during rain-on-snow events. Journal of Hydrometeorology. 17: 1801-1815.

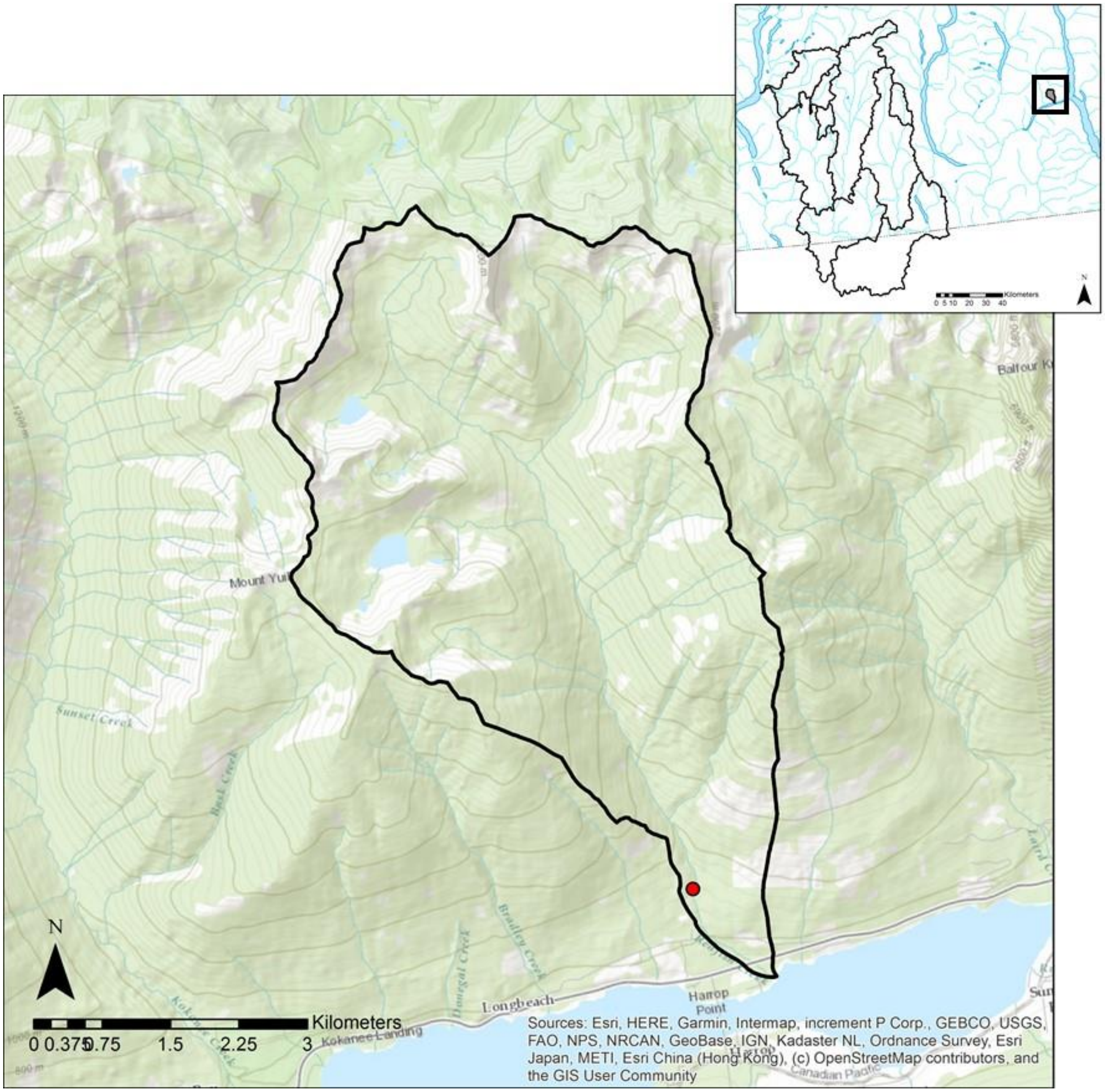
Würzer, S.; T. Jonas. 2018. Spatio-temporal aspects of snowpack runoff formation during rain on snow. Hydrological Processes. 32: 3434-3445.

Zahmatkesh, Z.; D. Tapsoba; J. Leach; P. Coulibaly. 2019. Evaluation and bias correction of SNODAS snow water equivalent (SWE) for streamflow simulation in eastern Canadian basins. Hydrological Sciences Journal. 64(13): 1541-1555.

Zhang, M.; X. Wei. 2014. Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: Implications for forest management and future forest hydrology studies. Hydrological Processes. 28: 6183-6195.

Zheng, Z.; N.P. Molotch; C.A. Oroza; M.H. Conklin; R.C. Bales. 2015. Spatial snow water equivalent estimation for mountainous areas using wireless-sensor networks and remote-sensing products. Remote Sensing of Environment. 215:44-56.

## APPENDIX A: REDFISH CREEK



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure A1. Map showing the drainage area for Redfish Creek, a tributary to the West Arm of Kootenay Lake. The basin is outlined in black and the location of the hydrometric station is shown with a red circle. Contour interval is 40 m.*

### A.1 Freshet Hydrographs

At Redfish Creek, the freshet flow period (the period when daily mean discharge was greater than the station's LTMAD) for 2010-2018 lasted 68 to 103 days (mean = 84 d), with the shortest in 2013 and the longest in 2015 (Table A1). On average, freshet began on 22 April and ended on 15 July; the earliest it began was 20 March in 2015, and the latest was 11 May in 2011.

The freshet period hydrographs for Redfish Creek between 2010 and 2018 rarely showed a single dominant peak (Figure A2), indicating that multiple melt events and potentially rain or rain-on-snow events occur during the freshet period. There are no large lakes or significant storage in wetlands so the hydrograph is responsive to melt and precipitation inputs.

*Table A1. Freshet and peak flow periods and dates of peak flow in 2010-2018 for Redfish Creek near Harrop (WSC station ID 08NJ061). Because of the small sample size, both mean and median dates are shown.*

| **Year** | **Freshet Period** | | | **Peak Flow Period** | | | **Peak Flow** |
|---|---|---|---|---|---|---|---|
| | **Start** | **End** | **Duration (# days)** | **Start** | **End** | **Duration (# days)** | |
| 2010 | 20 April | 14 July | 85 | 17 May | 1 July | 45 | 3 June |
| 2011 | 11 May | 5 August | 86 | 5 June | 15 July | 40 | 30 June |
| 2012 | 23 April | 28 July | 96 | 13 June | 12 July | 29 | 23 June |
| 2013 | 4 May | 11 July | 68 | 7 May | 22 June | 46 | 20 June |
| 2014 | 1 May | 16 July | 76 | 16 May | 29 June | 44 | 24 May |
| 2015 | 20 March | 1 July | 103 | 9 May | 13 June | 35 | 3 June |
| 2016 | 3 April | 6 July | 94 | 20 April | 11 June | 52 | 8 May |
| 2017 | 4 May | 15 July | 72 | 27 May | 18 June | 22 | 31 May |
| 2018 | 26 April | 10 July | 75 | 7 May | 1 June | 25 | 25 May |
| **Mean:** | **22 April** | **15 July** | **84** | **17 May** | **23 June** | **38** | **5 June** |
| **Median:** | **26 April** | **14 July** | **85** | **16 May** | **22 June** | **40** | **3 June** |

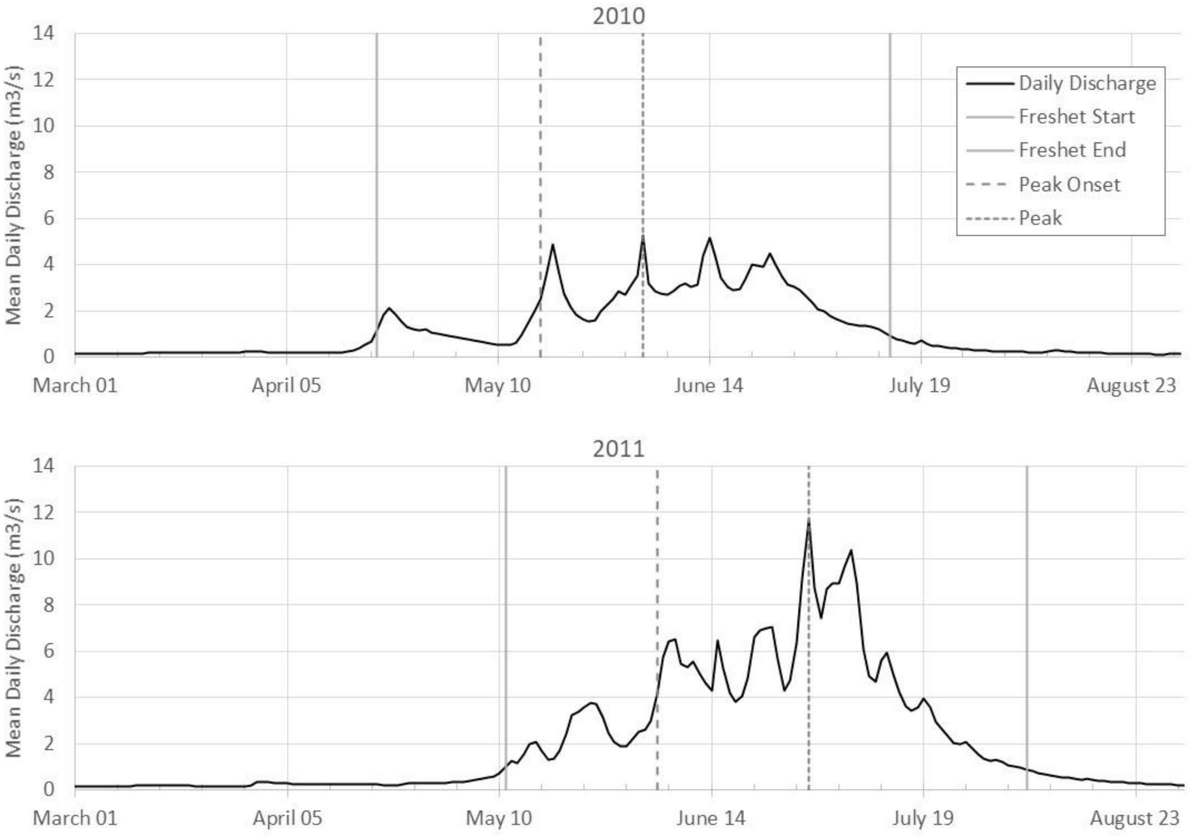


*Figure A2 (cont'd).*

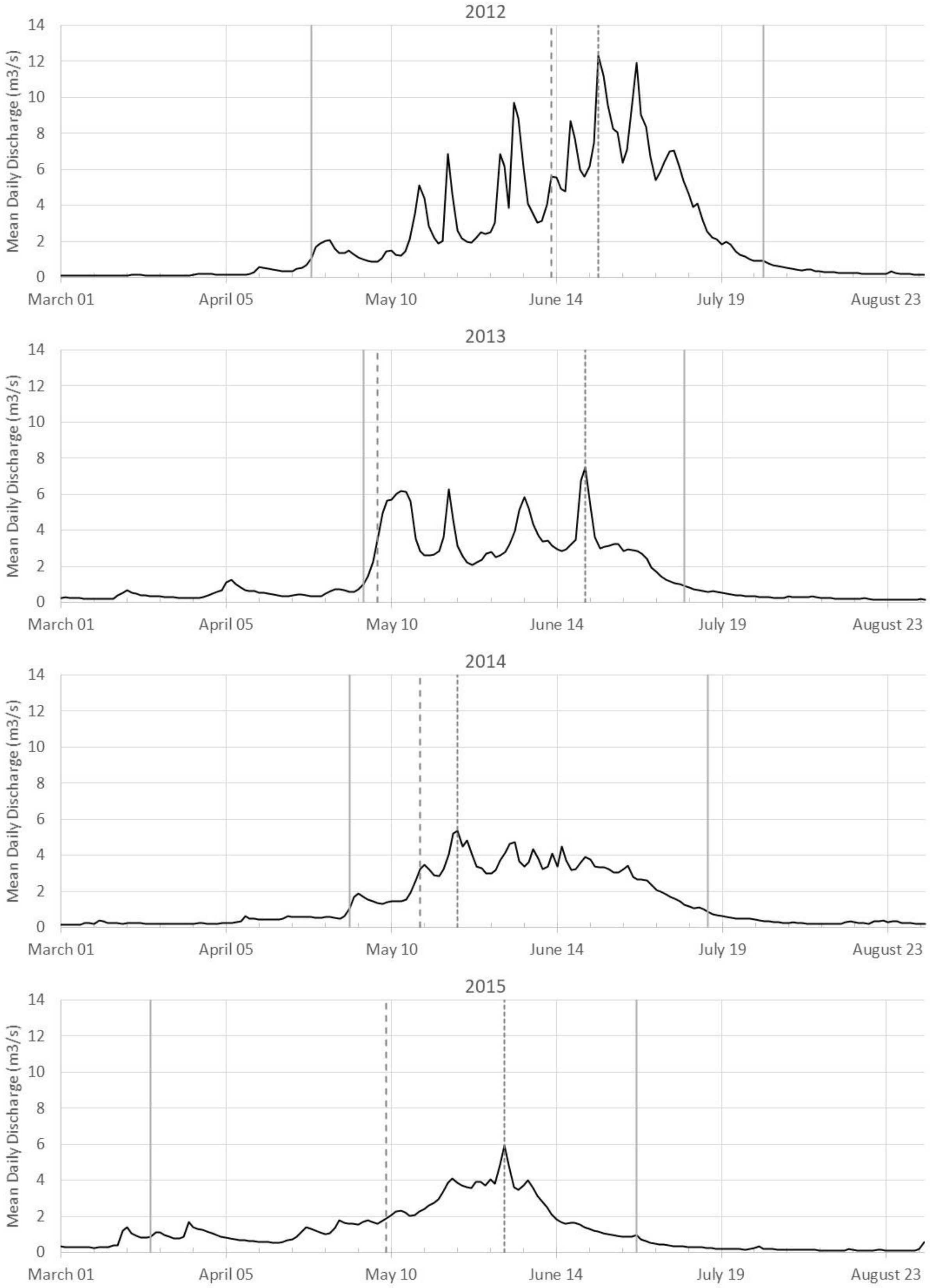


*Figure A2 (cont'd).*

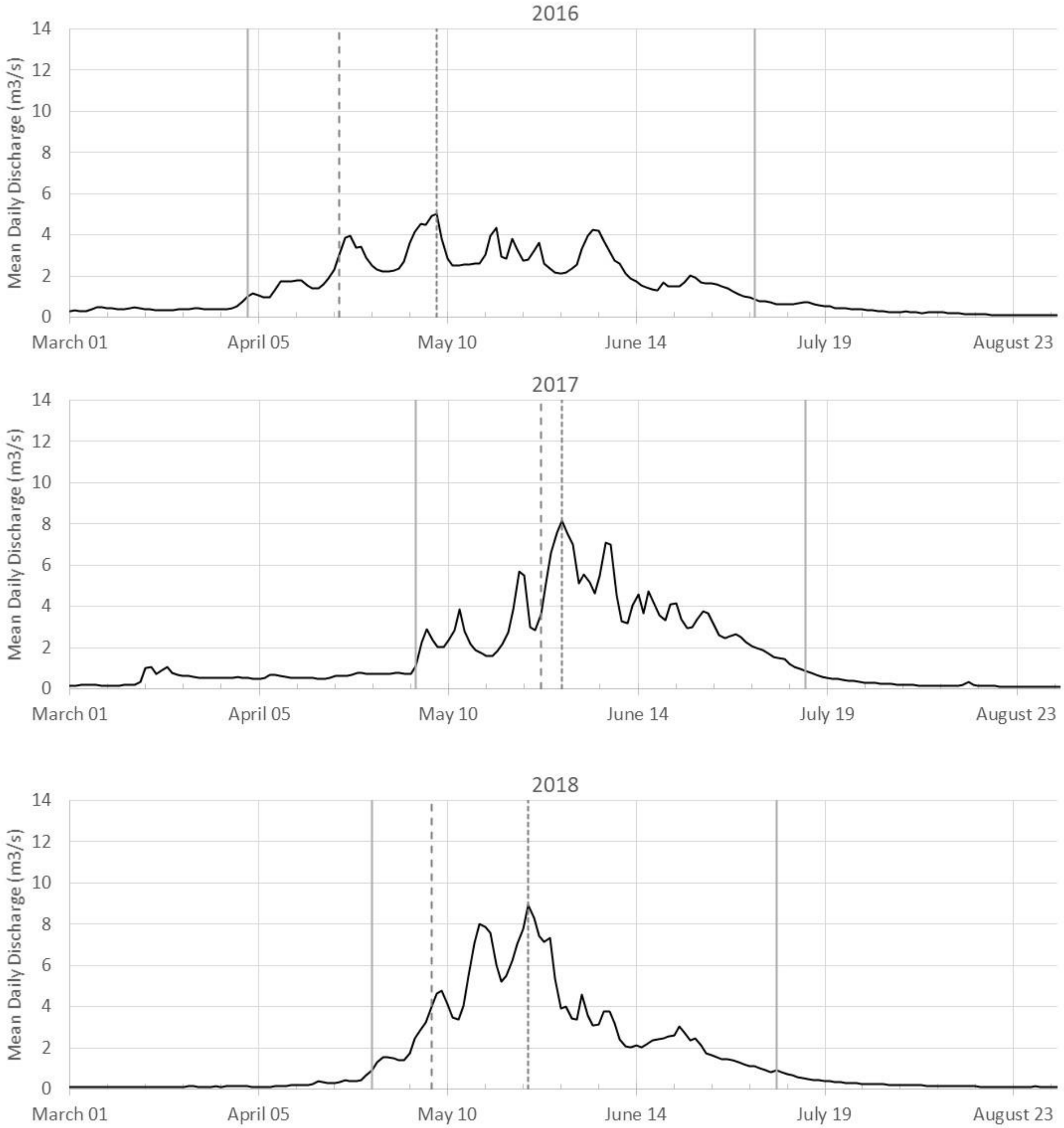


*Figure A2. Discharge in Redfish Creek (WSC station ID 08NJ061) during the 2010-2018 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable in Redfish Creek, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 23 and 75 d after the onset of the freshet period (mean = 43 d, median = 44 d), and when 26 to 78% of the cumulative freshet flow occurred (mean = 50%, median = 50%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 17% (median = 14%, range 4-38%), between 3 and 51 days since the beginning of the freshet flow period. On average, the peak flow period began on 17 May and ended on 23 June, lasting between 22 and 52 days (mean = 38 d, median = 40 d).

## A.2 Snow Covered Area

The combination of the coarse resolution of the SNODAS product and the small area of Redfish Creek basin (27.3 km$^2$) means that it is impossible to map the snowline in this catchment with a high degree of resolution, although the SCA values are reported here to the closest 1% (Table A2).

Median SCA at the onset of the peak flow period was 84% (mean = 83%, range = 61-95%). The snowline at the onset of the peak flow period was between approximately 1200 m and 1400 m (Figure A3). This indicated that these low elevation areas do not contribute snowmelt to peak flow. Most of the area below 1200 m has the same aspect (south) in Redfish Creek, so the snowline generally followed the elevation contours (because elevation is the dominant control on melt rate if aspect is not variable).

Air temperature measurements (not shown) from four climate stations in the Redfish Creek basin (elevation range 830 – 2045 m) indicated that in most years snow was melting at all stations by the onset of the peak flow period. If the snowpack across all elevations was melting, then meltwater was being contributed by all or nearly all areas of the catchment.

SCA on the date of peak flow ranged between 22 and 88% (mean = 66%, median = 75%) (Figure A4). These results were 0 to 58% lower than those for the start of the peak flow period.

*Table A2. Snow covered area (%) for hydrologically significant dates in the Redfish Creek basin. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Peak Flow Period | Peak Flow |
|---|---|---|
| 2010 | 89 | 82 |
| 2011 | 90 | 75 |
| 2012 | 61 | 22 |
| 2013 | 84 | 26 |
| 2014 | 84 | 84 |
| 2015 | 76 | 61 |
| 2016 | 86 | 73 |
| 2017 | 84 | 84 |
| 2018 | 95 | 88 |
| **Mean:** | **83** | **66** |
| **Median:** | **84** | **75** |

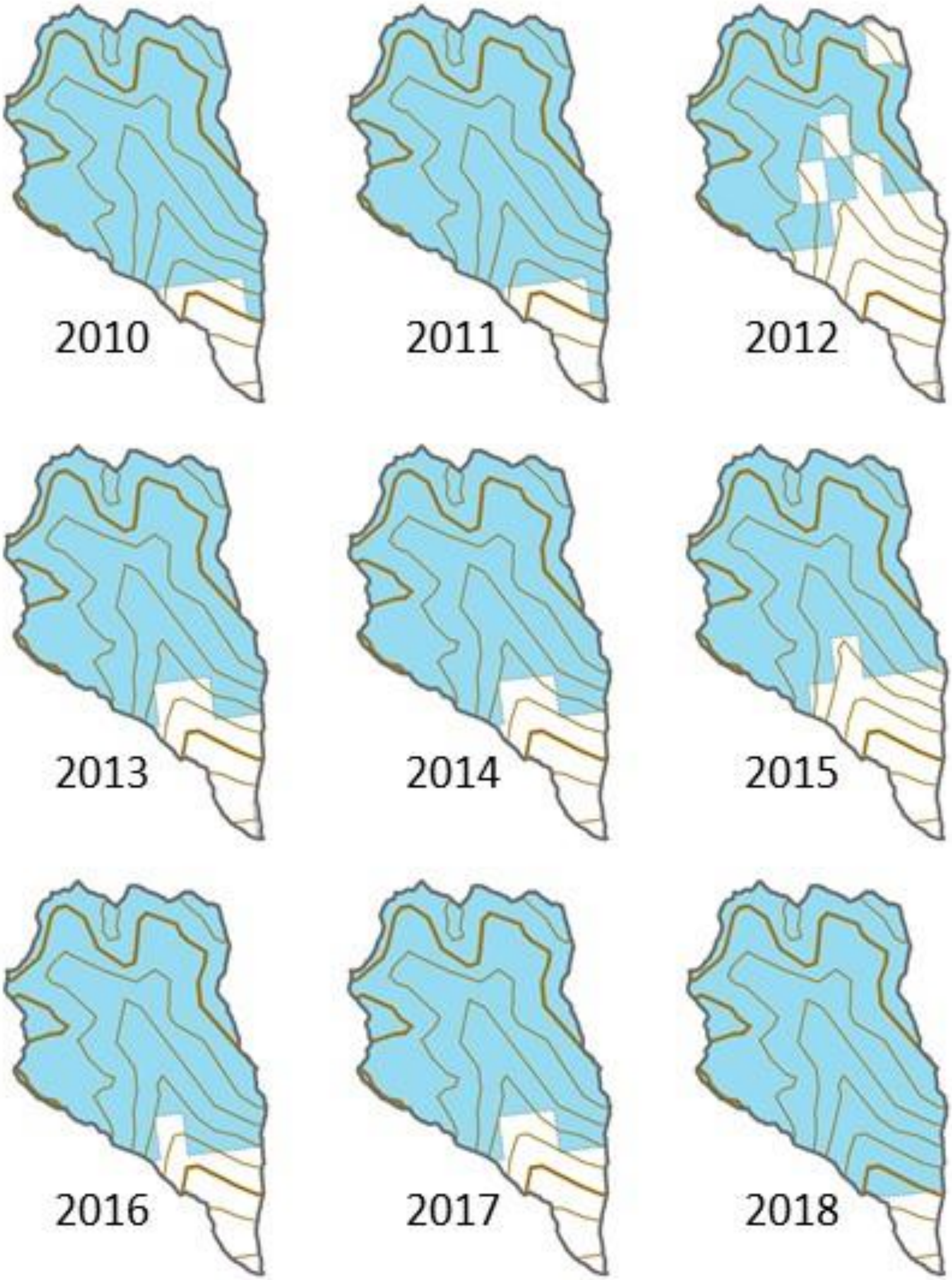


*Figure A3. Snow covered area in Redfish Creek basin on the date of onset of the peak flow period, 2010-2018. Brown lines are elevation contours (interval 200 m); the 1000 and 2000 m contours are bolded.*

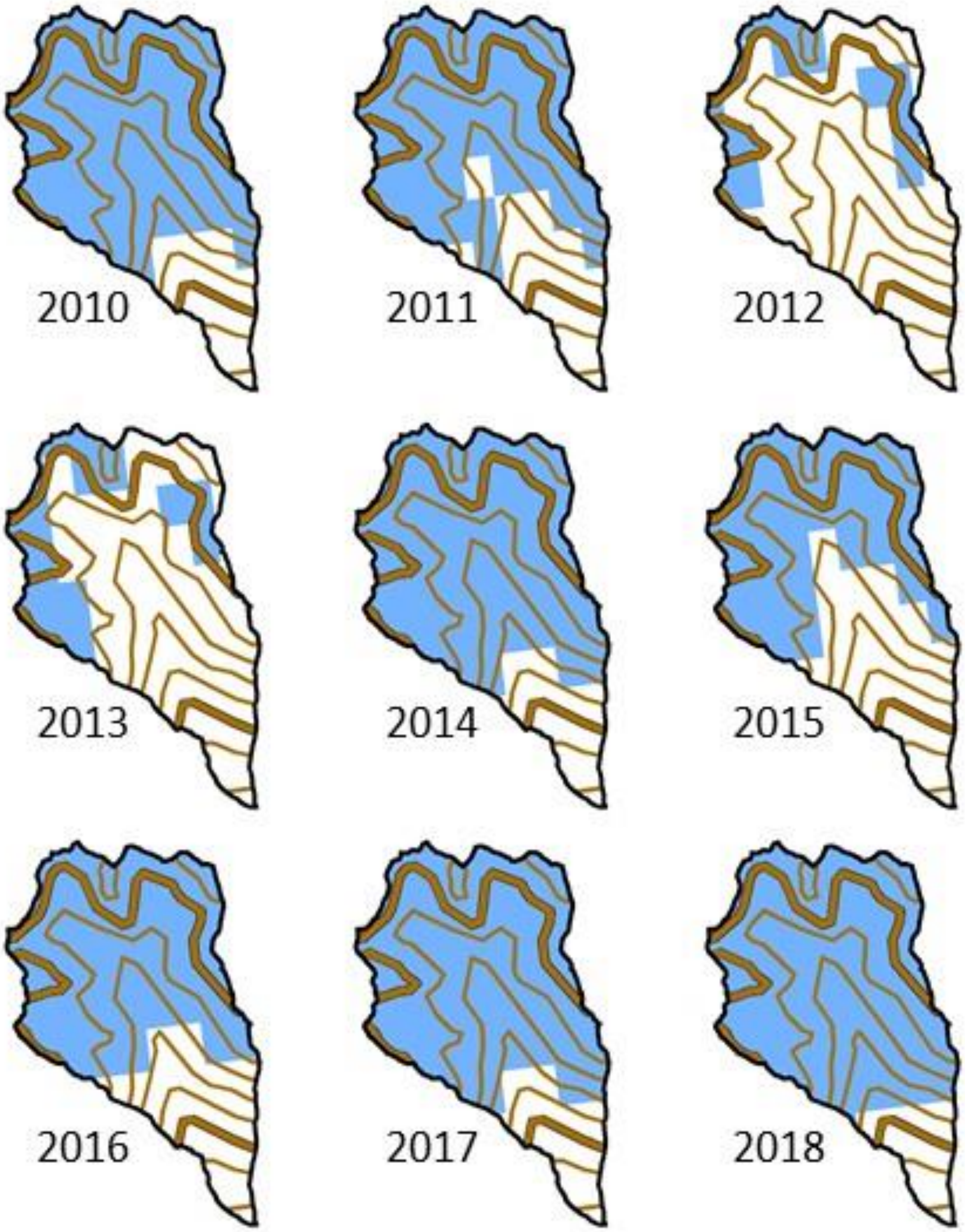
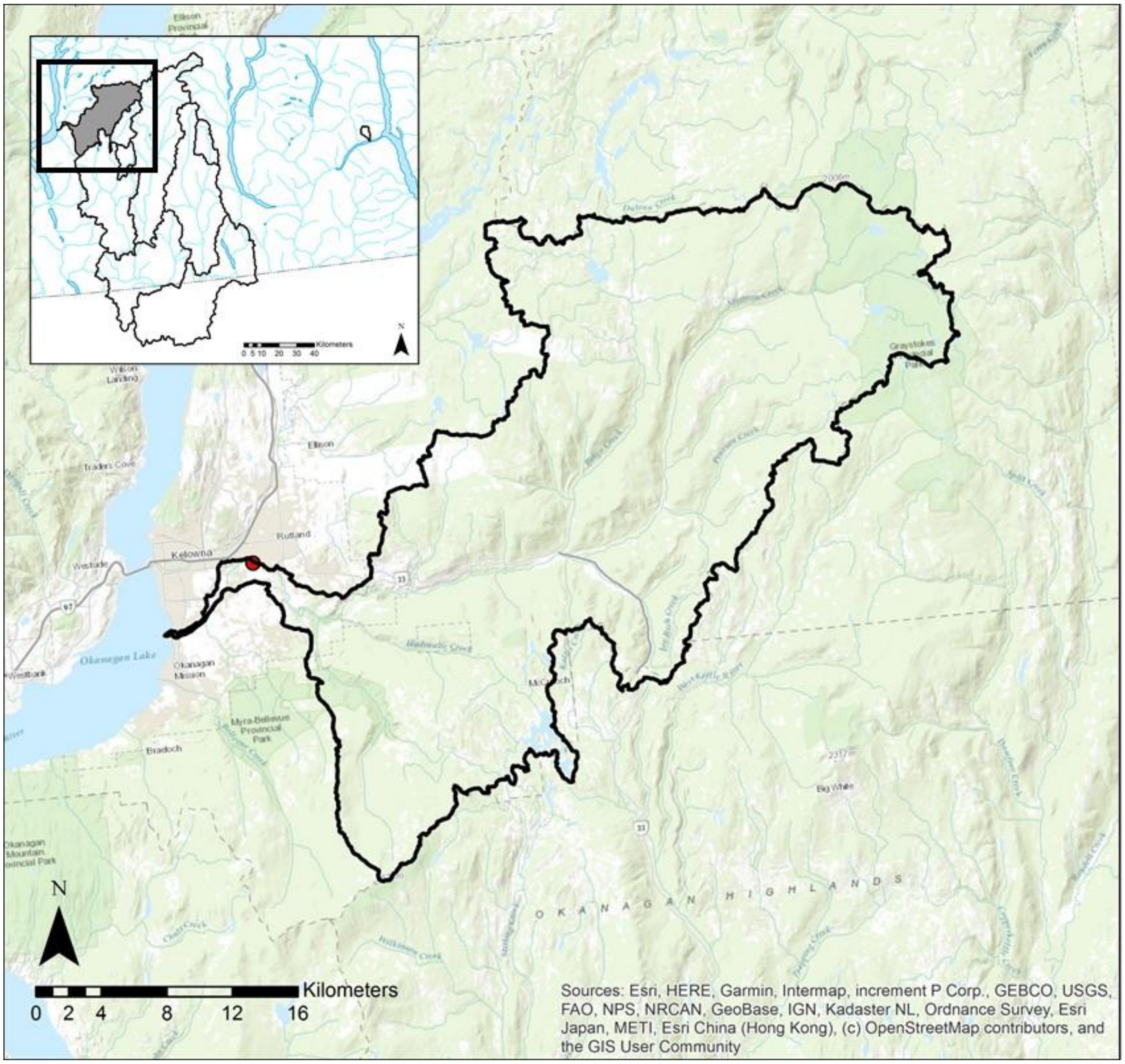


*Figure A4. Snow covered area in Redfish Creek basin on the date of peak flow, 2010-2018. Brown lines are elevation contours (interval 200 m); the 1000 and 2000 m contours are bolded.*

## APPENDIX B: MISSION CREEK



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure B1. Map showing the drainage area for Mission Creek, a tributary to Okanagan Lake. The basin is outlined in black and the locations of hydrometric stations are shown with red circles.*

### B.1 Freshet Hydrographs

The freshet flow period (when daily mean discharge was greater than the station's long term mean) for 2010-2018 lasted 73 to 95 days (mean = 82 d, median = 81 d), with the shortest in 2018 and the longest in 2013 (Table B1). On average, freshet began on 13 April and ended on 4 July; the earliest it began was 20 March on 2015, and the latest was 6 May in 2011.

Freshet period hydrographs for Mission Creek between 2010 and 2018 rarely showed a single dominant peak (Figure B2). This indicated that multiple melt events and potentially rain or rain-on-snow events throughout the freshet period. The large lakes, reservoirs and wetlands in the headwaters would provide some buffering of streamflow during the freshet period, primarily early in the melt period as the reservoirs and natural storage bodies filled. Once the water level had risen to the artificial or natural spillway, the flow pattern would be relatively natural.

*Table B1. Freshet flow period dates for Mission Creek near East Kelowna (WSC station ID 08NM116). Because of the small sample size, both mean and median dates are shown.*

| Year | Freshet Period | | | Peak Flow Period | | | Peak Flow |
|---|---|---|---|---|---|---|---|
| | **Start** | **End** | **Duration (# days)** | **Start** | **End** | **Duration (# days)** | |
| 2010 | 21 April | 7 July | 77 | 17 May | 24 June | 38 | 3 June |
| 2011 | 6 May | 22 July | 77 | 12 May | 24 June | 43 | 8 June |
| 2012 | 23 April | 16 July | 84 | 5 June | 4 July | 29 | 10 June |
| 2013 | 4 April | 8 July | 95 | 5 May | 28 June | 54 | 20 June |
| 2014 | 18 April | 4 July | 77 | 2 May | 17 June | 46 | 13 June |
| 2015 | 20 March | 9 June | 81 | 28 March | 5 June | 69 | 4 June |
| 2016 | 2 April | 30 June | 89 | 18 April | 26 May | 38 | 23 May |
| 2017 | 7 April | 29 June | 83 | 4 May | 9 June | 36 | 5 May |
| 2018 | 21 April | 3 July | 73 | 3 May | 29 May | 26 | 9 May |
| **Mean:** | **13 April** | **4 July** | **82** | **4 May** | **15 June** | **42** | **9 June** |
| **Median:** | **18 April** | **4 July** | **81** | **4 May** | **16 June** | **38** | **4 June** |

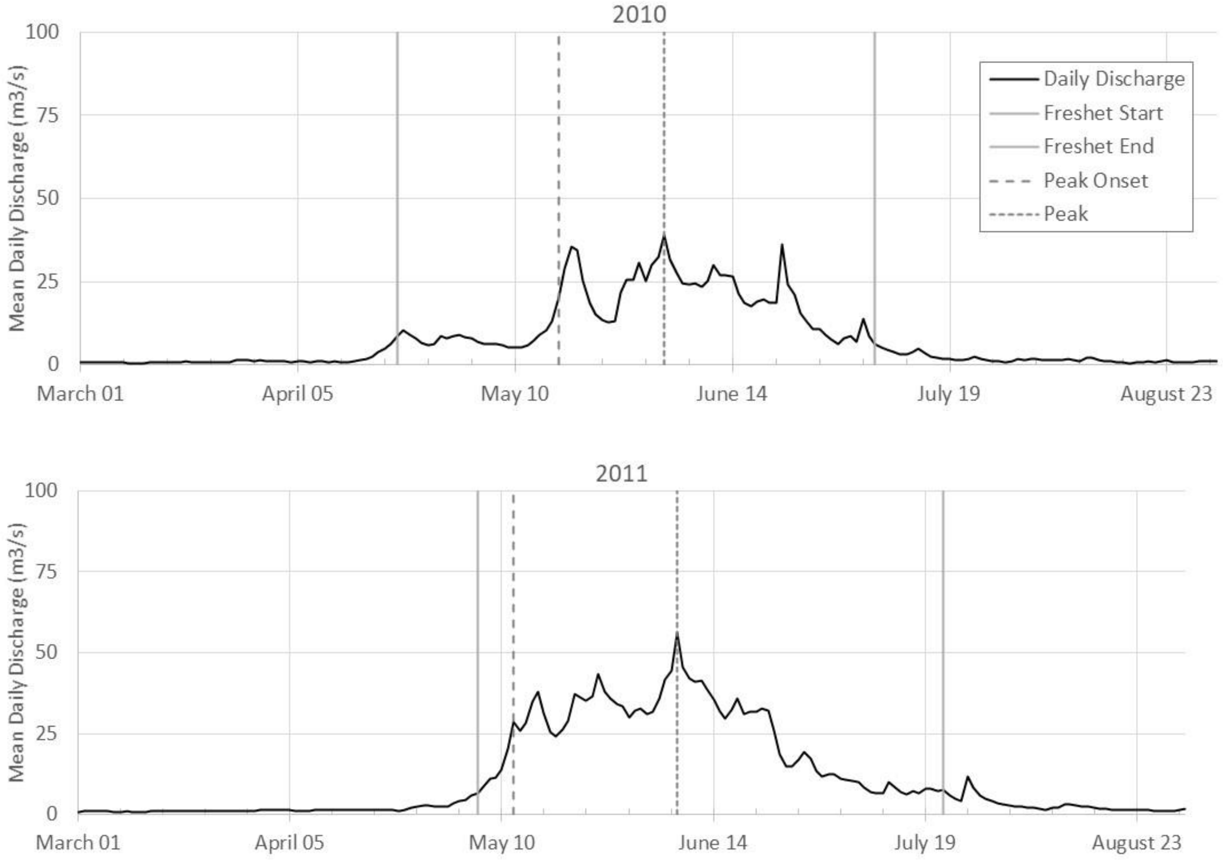


*Figure B2 (cont'd).*

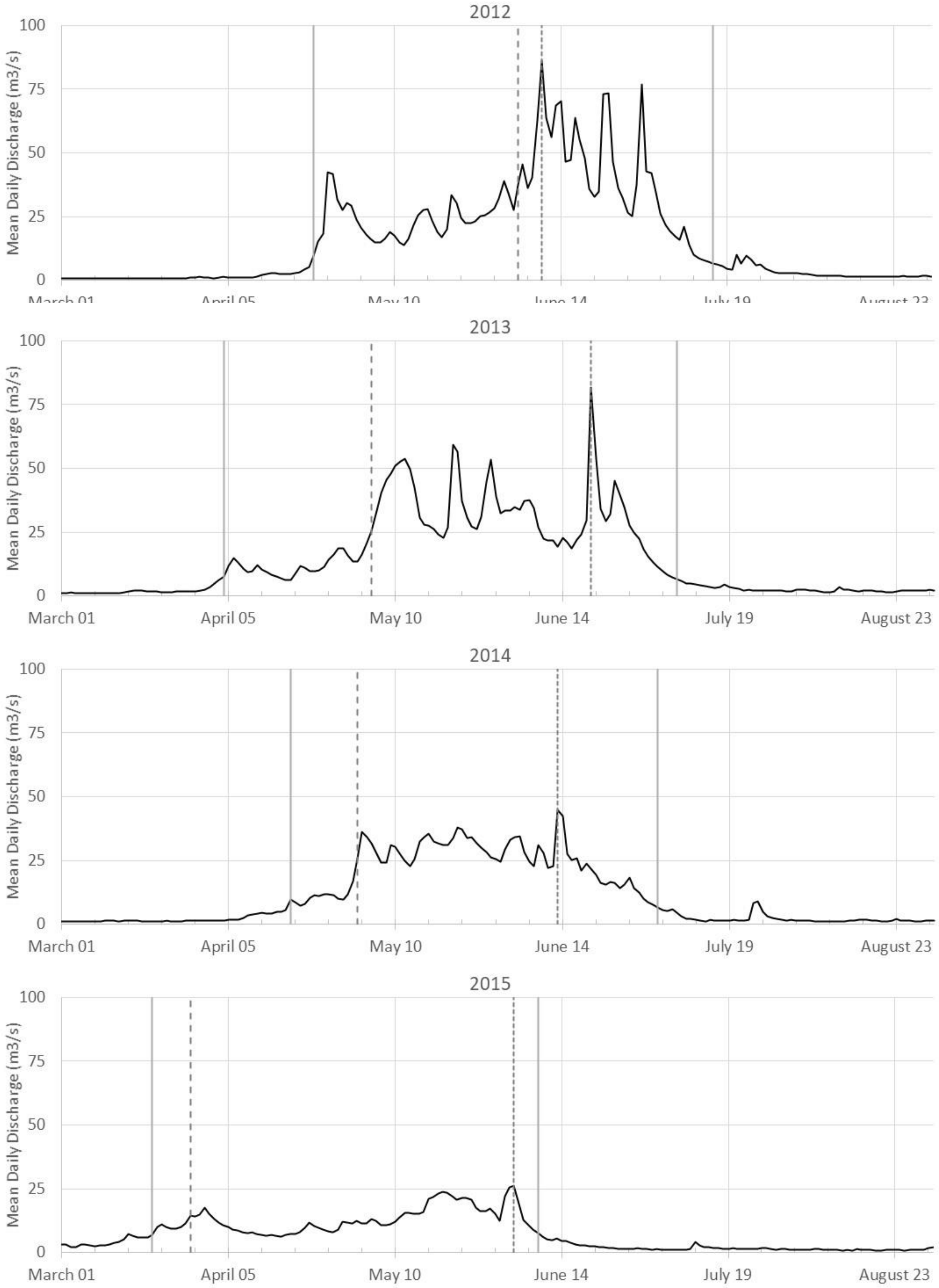


*Figure B2 (cont'd).*

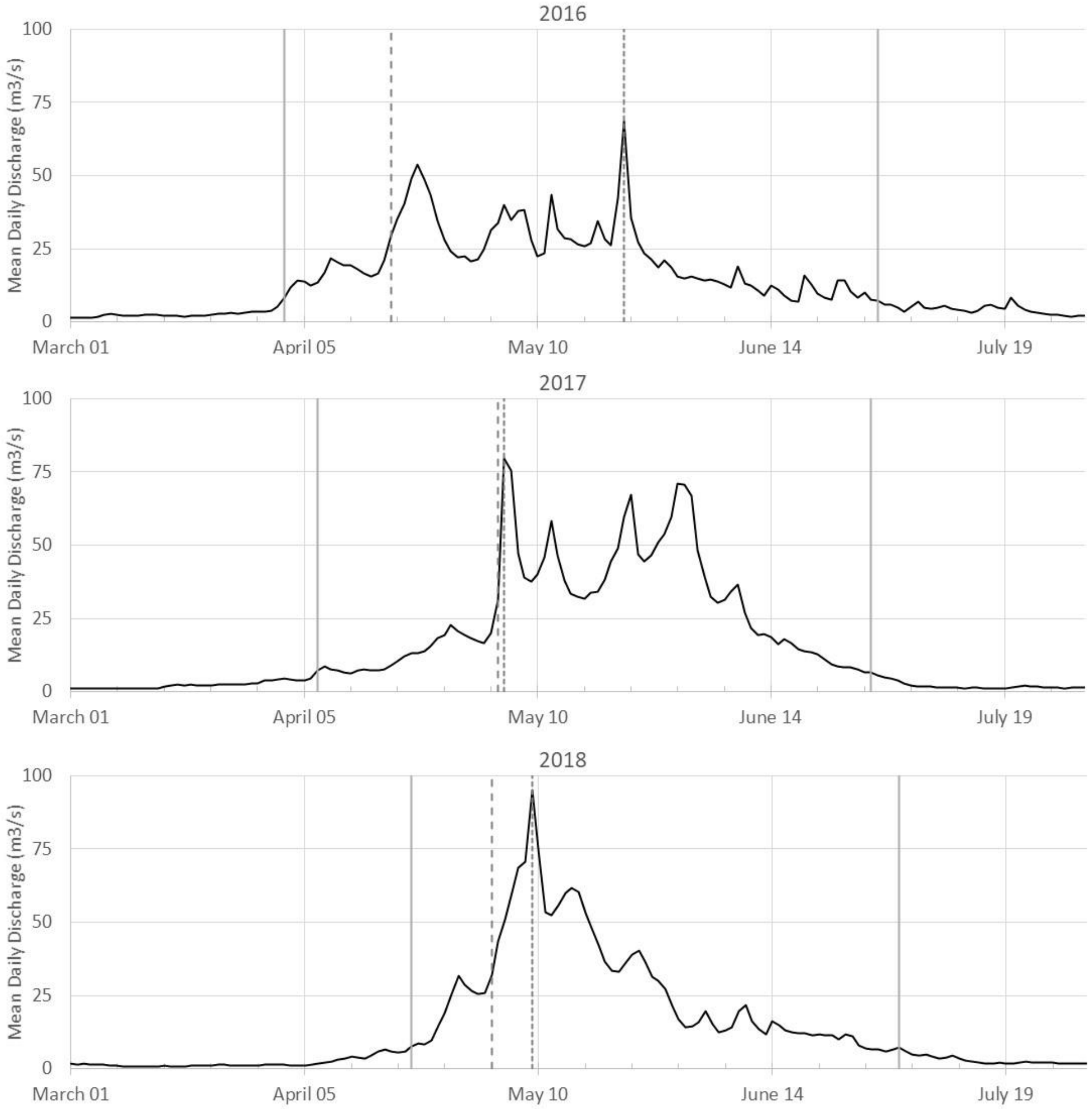


*Figure B2. Discharge in Mission Creek during the 2010-2018 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was variable in Mission Creek, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow (Figure B2). Peak flow occurred between 18 and 77 days after the onset of the freshet period (mean = 56 d, median = 48 d), and when 19 to 94% of the cumulative freshet flow occurred (mean = 68%, median = 55%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 15% (median = 14%, range 5-40%), between 6 and 31 days since the beginning of the freshet flow period. On average, the peak flow period began on 4 May and ended 15 June, lasting between 26 and 69 days (mean = 42 d, median = 38 d).

## B.2 Snow Covered Area

Snow covered area was calculated from the SNODAS data products for the Mission Creek basin (Table B2) and are reported to the neared 1%.

Median SCA at the onset of the peak flow period was 67% (mean = 63%, range = 34-86%) (Figure B3). These maps indicate that snowmelt patterns in Mission Creek basin are determined by both elevation and aspect. The average snowline elevation at the onset of the peak flow period was between 800 and 1400 m, depending on aspect.

*Table B2. Snow covered area (%) for selected dates in the Mission Creek basin. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Peak Flow Period | Peak Flow |
|---|---|---|
| 2010 | 53 | 35 |
| 2011 | 86 | 50 |
| 2012 | 34 | 34 |
| 2013 | 67 | 23 |
| 2014 | 78 | 24 |
| 2015 | 42 | 4 |
| 2016 | 48 | 17 |
| 2017 | 77 | 75 |
| 2018 | 79 | 70 |
| **Mean:** | **63** | **37** |
| **Median:** | **67** | **34** |

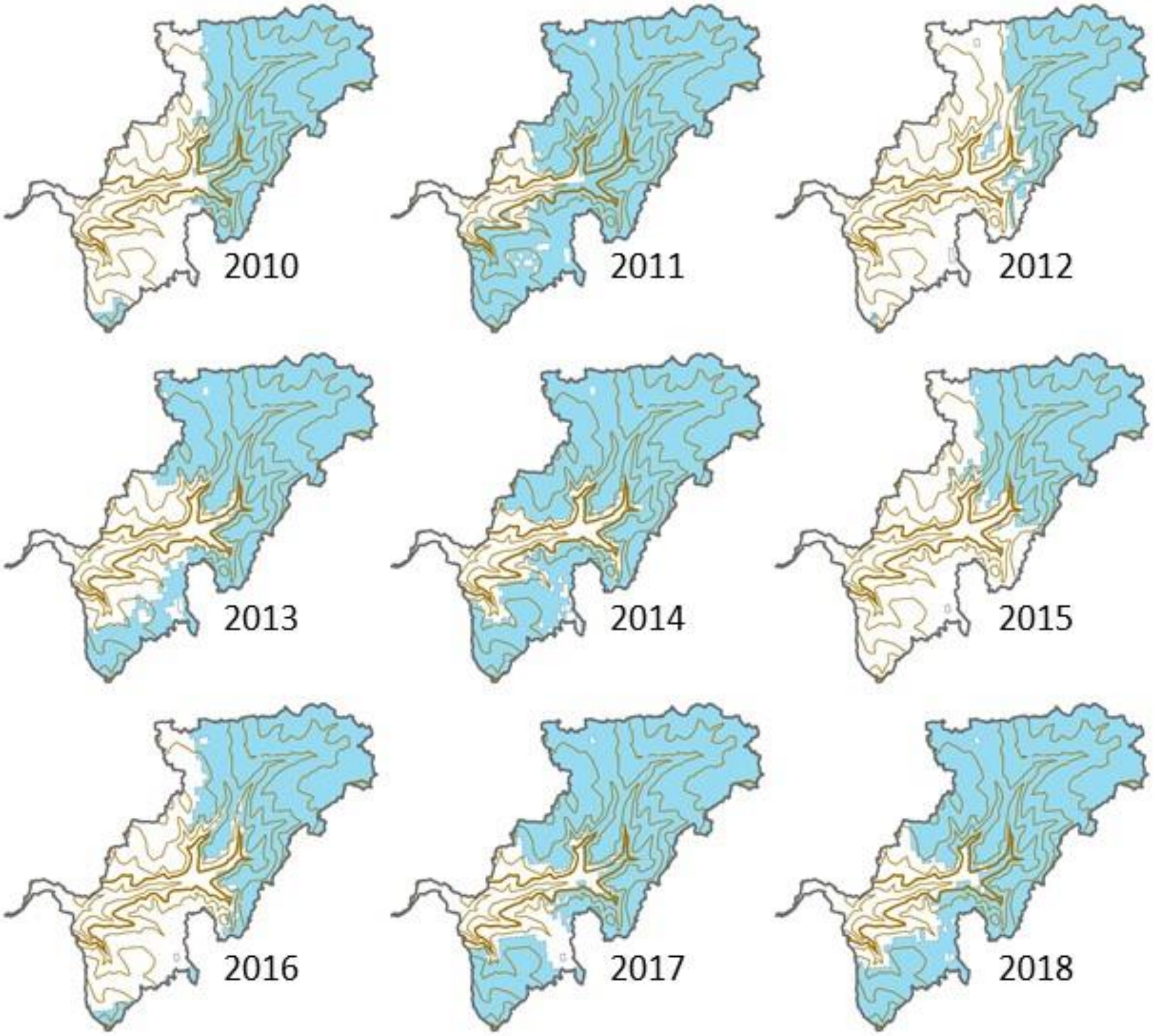
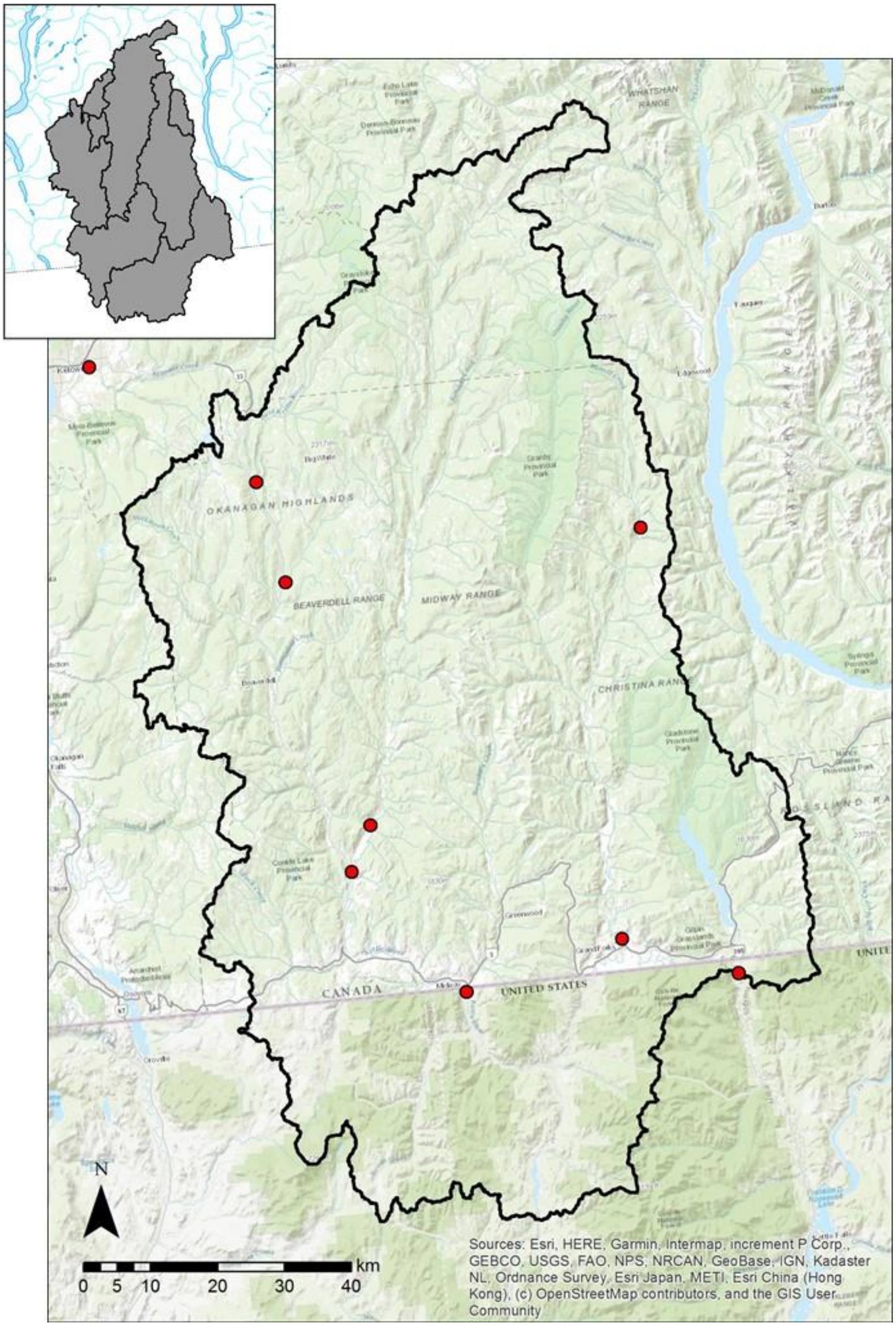


*Figure B3. Snow covered area in Mission Creek basin on the date of onset of the peak flow period, 2010-2018. Brown lines are elevation contours (interval 200 m); the 1000 and 2000 m contours are bolded.*

# APPENDIX C: KETTLE RIVER NEAR LAURIER



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure C1. Map showing the drainage area for the Kettle River near Laurier. The basin is outlined in black and the locations of hydrometric stations are shown with red circles. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

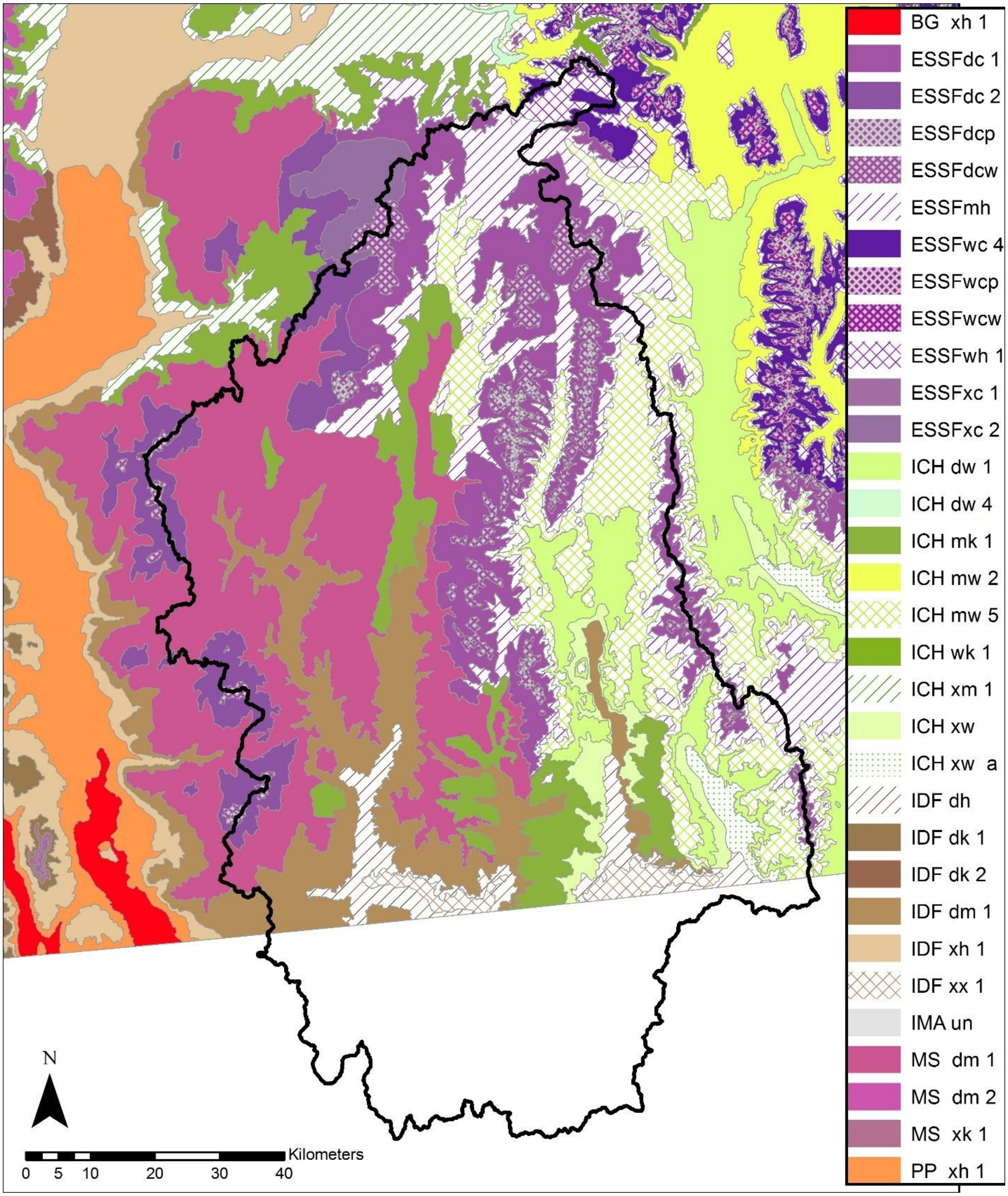


*Figure C2. Map of the drainage area for Kettle River near Laurier showing BEC subzones and elevation in the Canadian portion. The basin is outlined in black.*

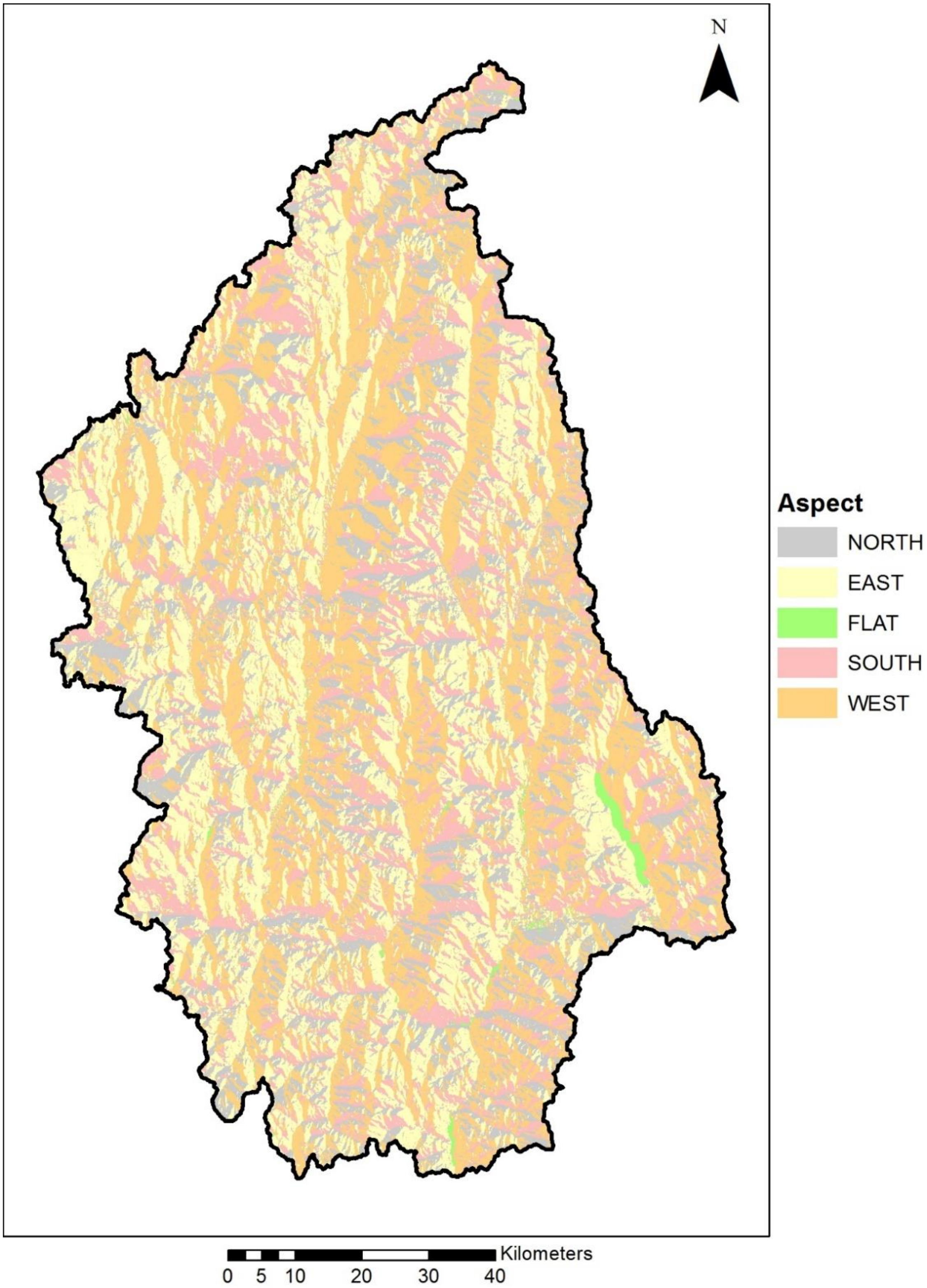


*Figure C3. Slope aspect map of the drainage area for Kettle River near Laurier. The basin is outlined in black.*

## C.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN012 Kettle River near Laurier for 2010-2018 were published and for 2019-2020 were provisional at the time of this analysis. The freshet flow period (when daily mean discharge was greater than the station's long term mean) for 2010-2020 lasted 77 to 117 days (mean = 95 d, median = 93 d), with the shortest in 2019 and the longest in 2016 (Table C1). On average, freshet began on 3 April and ended on 8 July; the earliest it began was 7 March in 2016, and the latest was 27 April in 2011.

The freshet hydrographs for Kettle River near Laurier between 2010 and 2020 rarely showed a single dominant peak (Figure C4), indicating that multiple melt events and potentially rain and rain-on-snow events occur through the freshet period. There is no significant attenuation by lakes or wetlands so the hydrograph is responsive to melt and precipitation inputs, with a lag reflecting the large basin area.

*Table C1. Freshet flow period dates for Kettle River near Laurier (WSC station ID 08NN012). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both mean and median dates are shown.*

| **Year** | **Freshet Period** | | | **Peak Flow Period** | | | **Peak Flow** |
|---|---|---|---|---|---|---|---|
| | **Start** | **End** | **Duration (# days)** | **Start** | **End** | **Duration (# days)** | |
| 2010 | 18 April | 10 July | 83 | 17 May | 25 June | 39 | 19 May |
| 2011 | 27 April | 29 July | 93 | 12 May | 25 June | 44 | 27 May |
| 2012 | 19 April | 28 July | 100 | 26 April | 6 July | 71 | 27 April |
| 2013 | 1 April | 12 July | 102 | 5 May | 9 June | 35 | 13 May |
| 2014 | 10 April | 8 July | 89 | 3 May | 7 June | 35 | 18 May |
| 2015 | 14 March | 17 June | 95 | 22 March | 8 June | 78 | 3 June |
| 2016 | 7 March | 2 July | 117 | 3 April | 27 May | 54 | 23 April |
| 2017 | 19 March | 6 July | 108 | 5 May | 11 June | 37 | 7 May |
| 2018 | 8 April | 4 July | 87 | 27 April | 30 May | 33 | 11 May |
| *2019* | *31 March* | *16 June* | *77* | *20 April* | *3 June* | *44* | *13 May* |
| *2020* | *12 April* | *14 July* | *93* | *1 May* | *17 June* | *47* | *1 June* |
| **Mean:** | **4 April** | **8 July** | **95** | **26 April** | **12 June** | **47** | **15 May** |
| **Median:** | **8 April** | **8 July** | **93** | **2 May** | **9 June** | **44** | **13 May** |

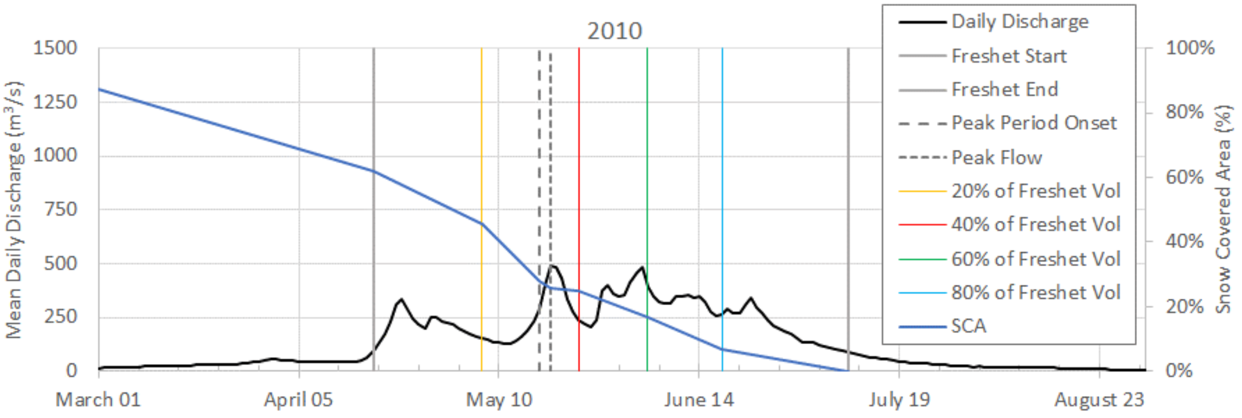


*Figure C4 (cont'd)*

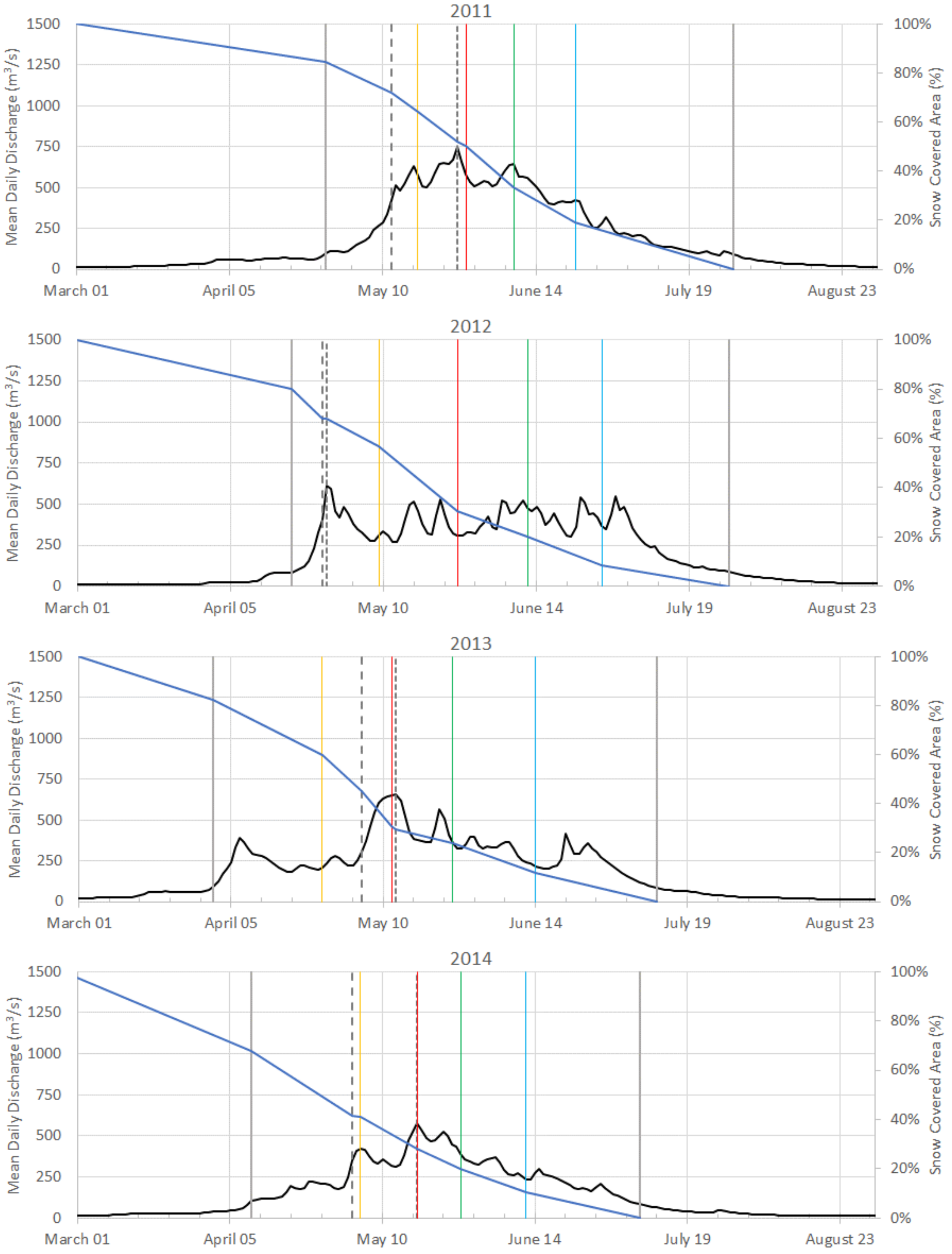


*Figure C4 (cont'd)*

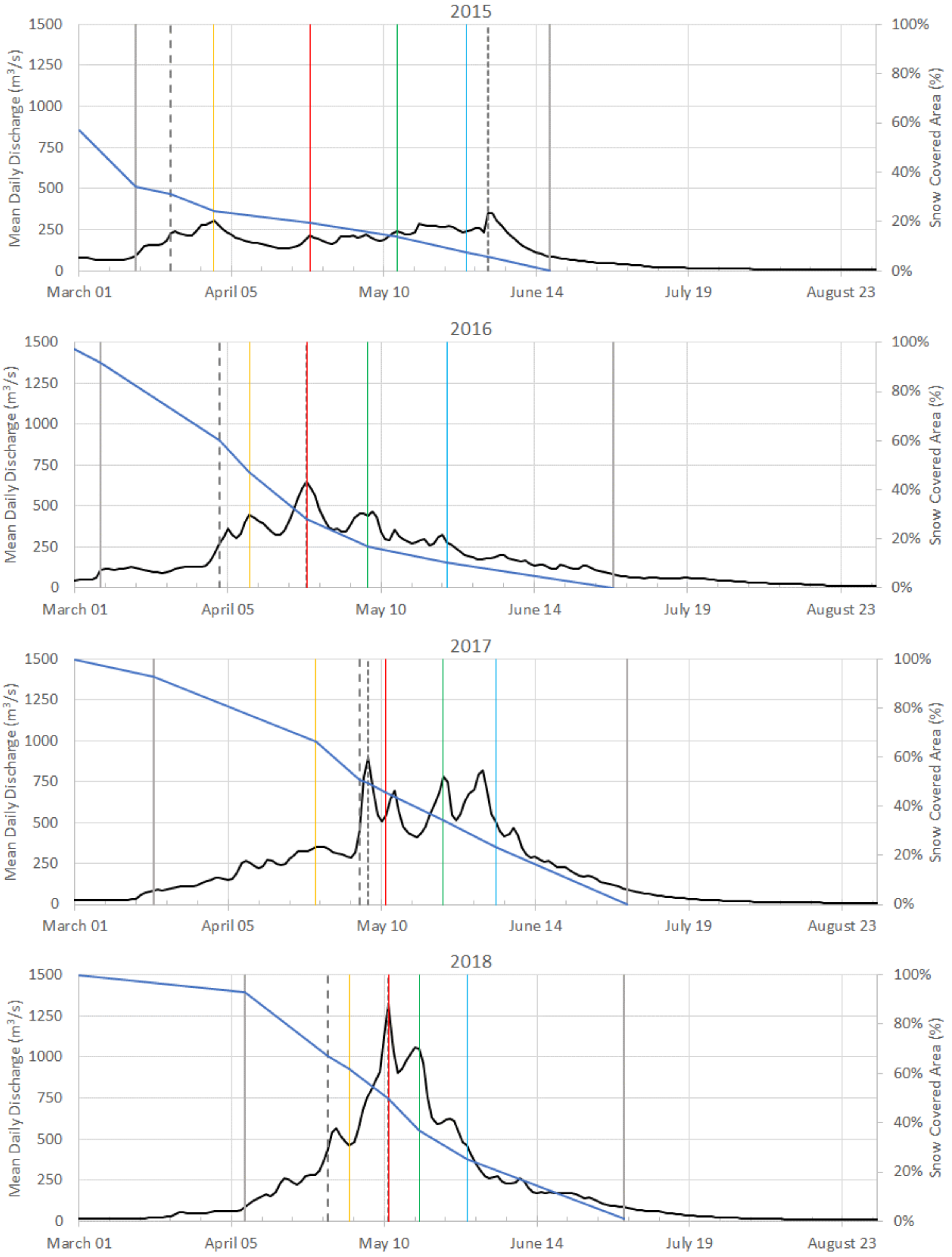


*Figure C4 (cont'd)*

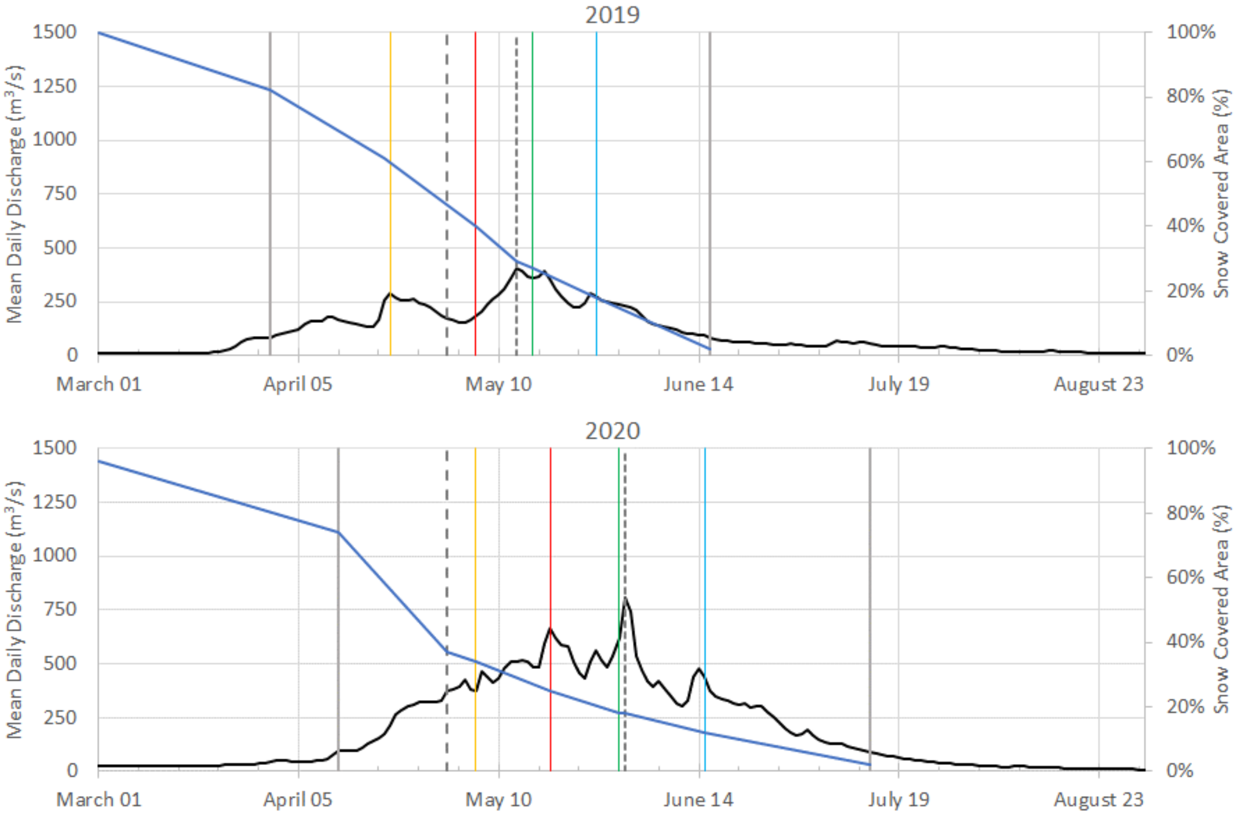


*Figure C4. Discharge measured in Kettle River near Laurier during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable for the Kettle River near Laurier, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 8 and 81 days after the onset of the freshet period (mean = 41 d, median = 42 d), when 6 to 87% of the cumulative freshet flow occurred (mean = 42%, median = 40%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 16% (median = 14%, range 5-29%), between 7 and 47 days after the onset of the freshet flow period. On average, the peak flow period began on 26 April and ended on 12 June, lasting between 33 and 78 days (mean = 47 d, median = 44 d).

## C.2 Snow Covered Area

SCA was always less than 100% at the start of the freshet period, and in all years there was very little or no snow in the basin at the end of the freshet flow period (Table C2). SCA depletion curves were plotted with the freshet hydrographs in Figure C4 and compared in Figure C5.

*Table C2. Snow covered area (%) for selected dates in the Kettle River basin above Laurier. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 62 | 46 | 25 | 16 | 7 | 0 | 28 | 26 |
| 2011 | 85 | 64 | 50 | 33 | 19 | 0 | 72 | 52 |
| 2012 | 80 | 57 | 31 | 20 | 8 | 0 | 68 | 68 |
| 2013 | 82 | 60 | 31 | 24 | 12 | 0 | 45 | 30 |
| 2014 | 68 | 41 | 28 | 20 | 11 | 0 | 42 | 28 |
| 2015 | 34 | 24 | 19 | 14 | 8 | 0 | 31 | 6 |
| 2016 | 92 | 47 | 28 | 17 | 10 | 0 | 60 | 28 |
| 2017 | 93 | 66 | 45 | 34 | 23 | 0 | 51 | 50 |
| 2018 | 93 | 62 | 50 | 37 | 25 | 1 | 67 | 50 |
| 2019 | 82 | 60 | 40 | 27 | 18 | 2 | 61 | 29 |
| 2020 | 74 | 34 | 25 | 18 | 12 | 2 | 37 | 18 |
| **Mean:** | **77** | **51** | **34** | **24** | **14** | **1** | **51** | **35** |
| **Median** | **82** | **57** | **31** | **20** | **12** | **0** | **51** | **29** |

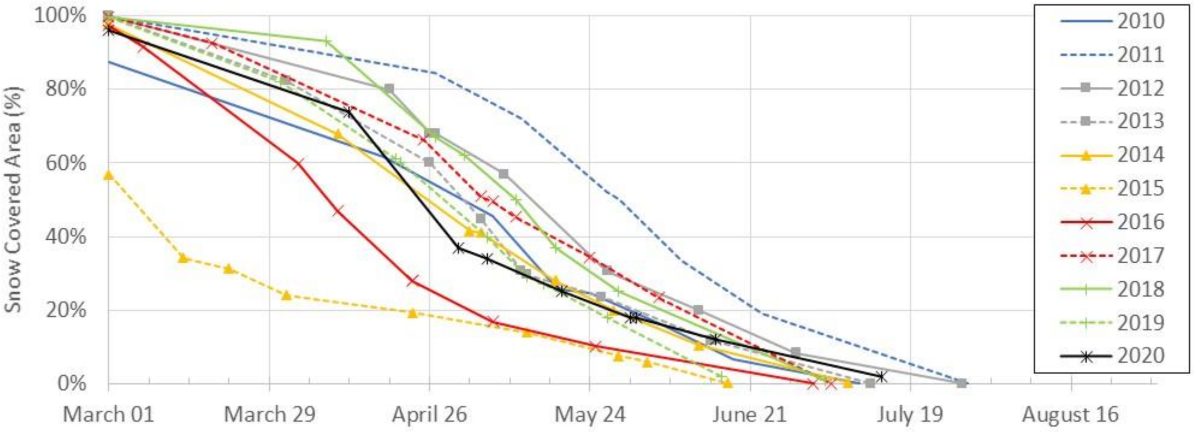


*Figure C5. Changes in snow covered area over the 2010-2020 freshet periods for the Kettle River basin above Laurier.*

Figure C6 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. There was a clear pattern of snow melting away earlier at low elevations in the catchment. Snow persisted longer in high elevation areas in the west and north part of the basin.

As was found for other catchments in the region, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in warmer than normal January, February and March air temperatures (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow recorded at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the low SCA recorded at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure C5).

The basin was 28-72% snow covered at the onset of the peak flow period, with a median of 51% (mean = 51%) (Figure C7). These results indicated that snowmelt over approximately half of the basin contributes to peak flow in the Kettle River near Laurier.

## C.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from SCA maps for the onset of the peak flow period. Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure C6). Median SCA was 51%. SCA measured in 2017 was equal to the median, so this year was used to define the SSZ (Figure C8).

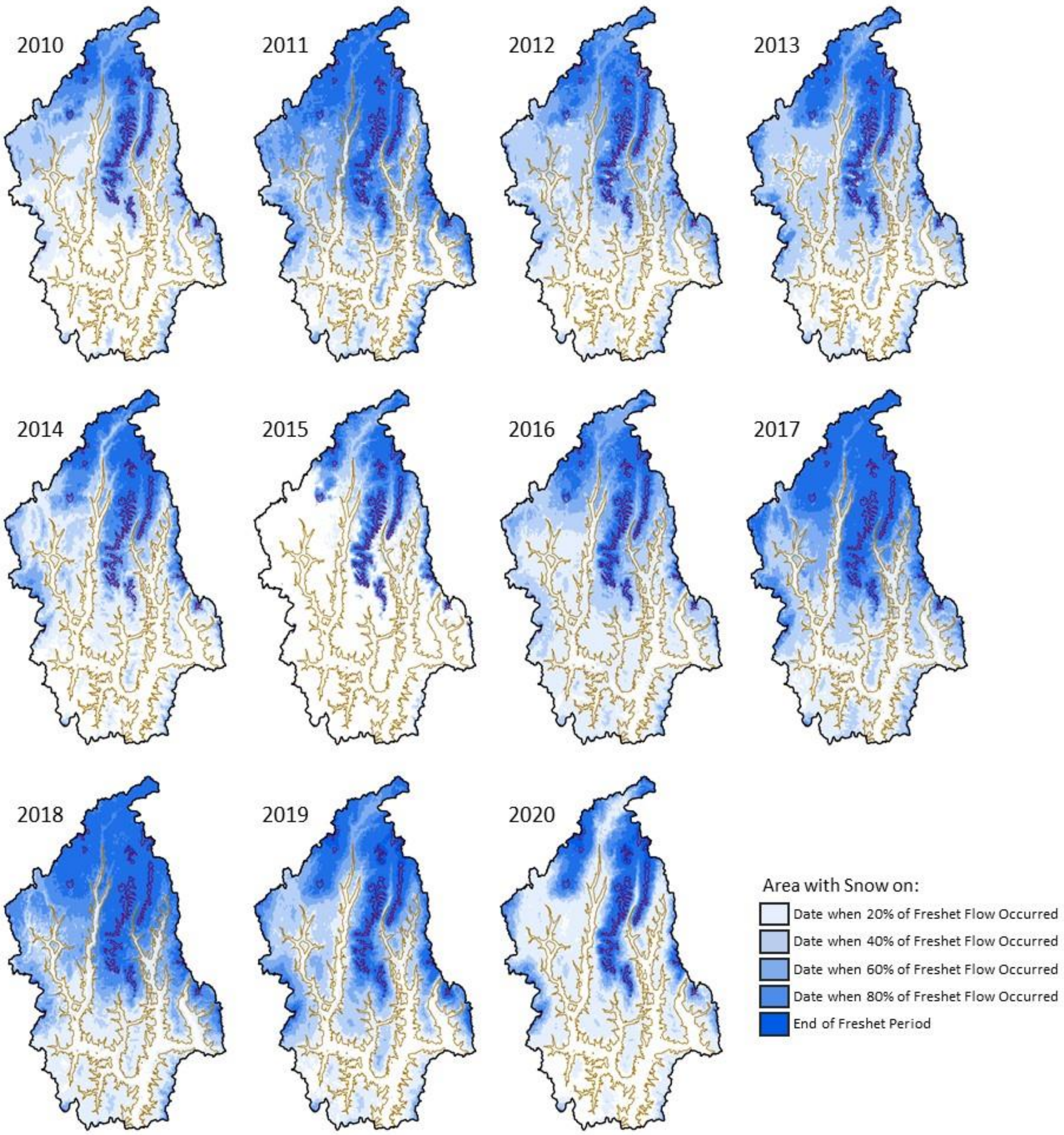


*Figure C6. The progression of snow covered area over the 2010-2020 spring freshet periods in the Kettle River basin above Laurier. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

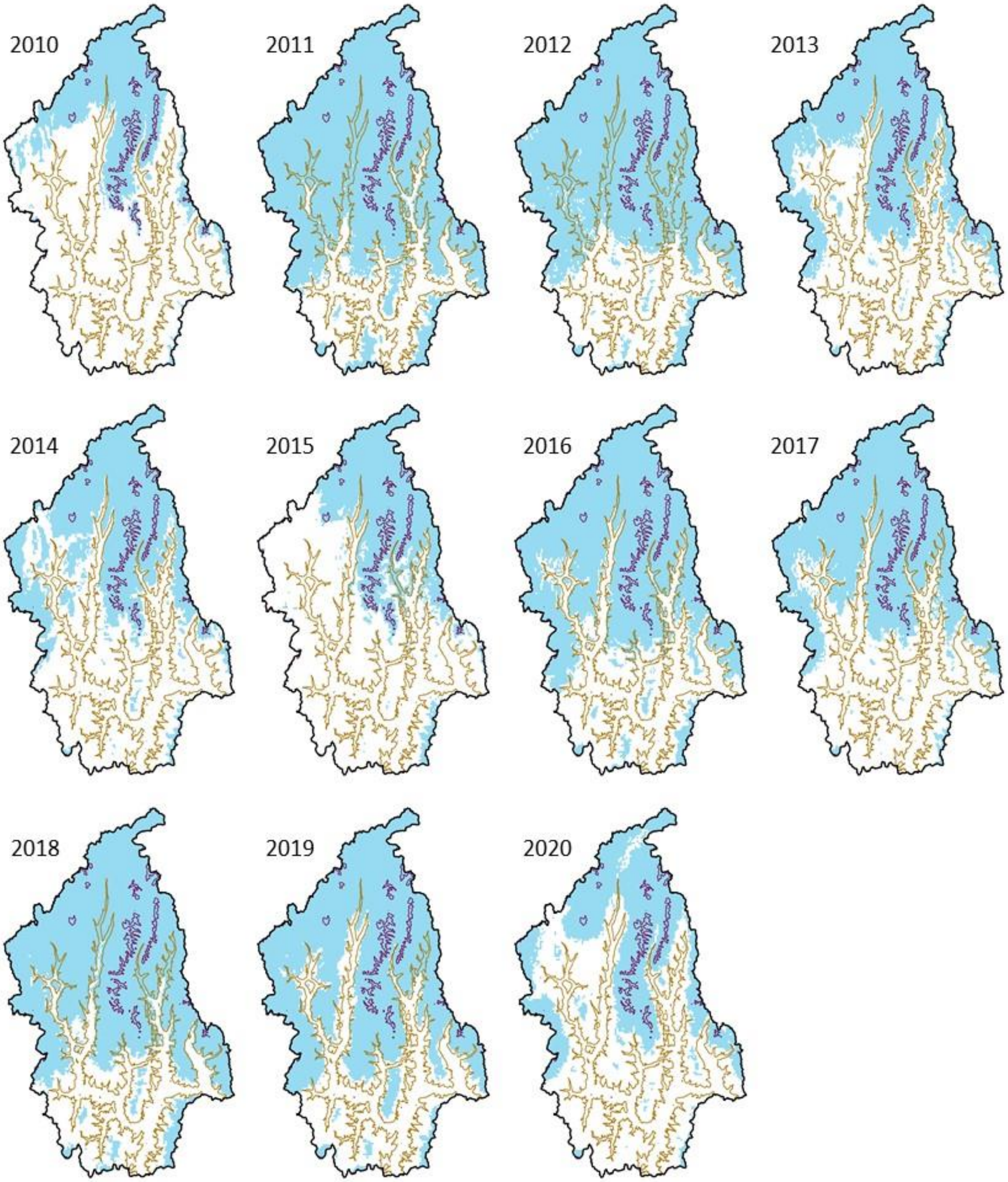


*Figure C7. Snow covered area in the Kettle River basin above Laurier on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

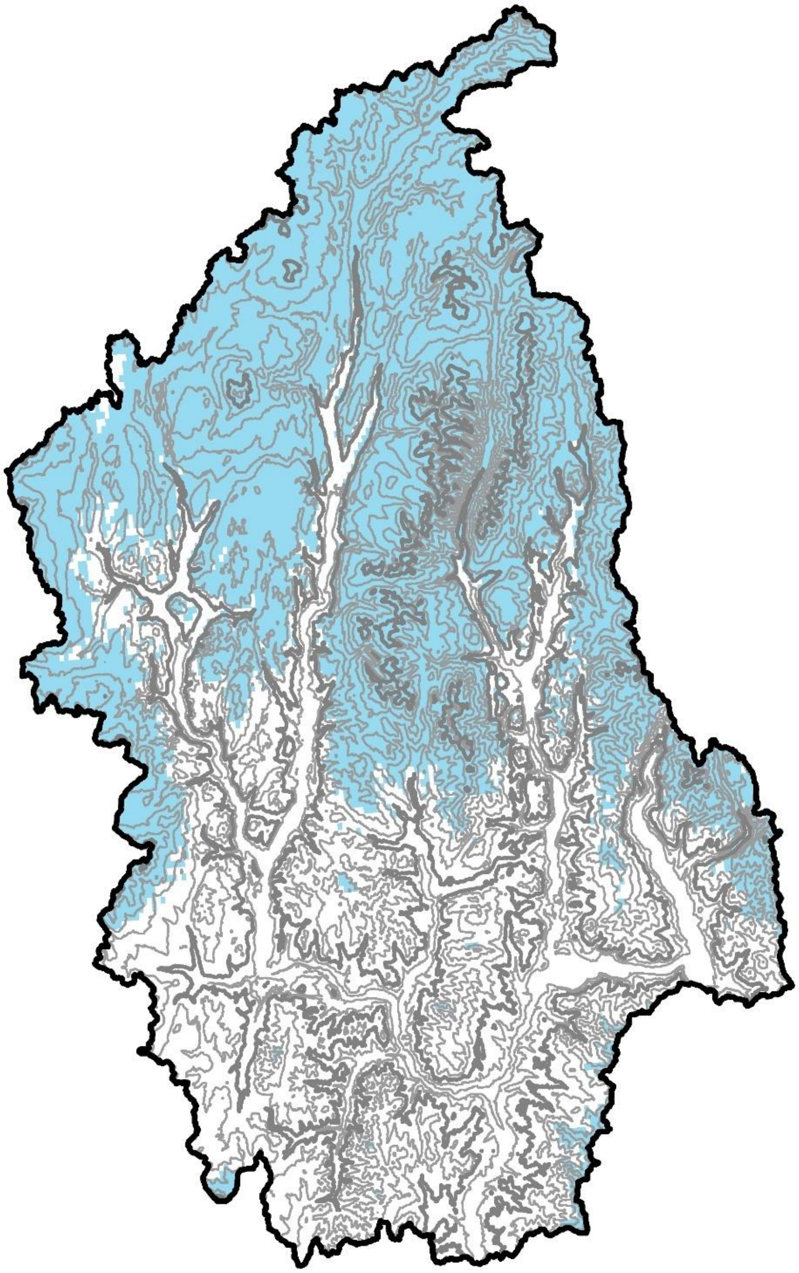
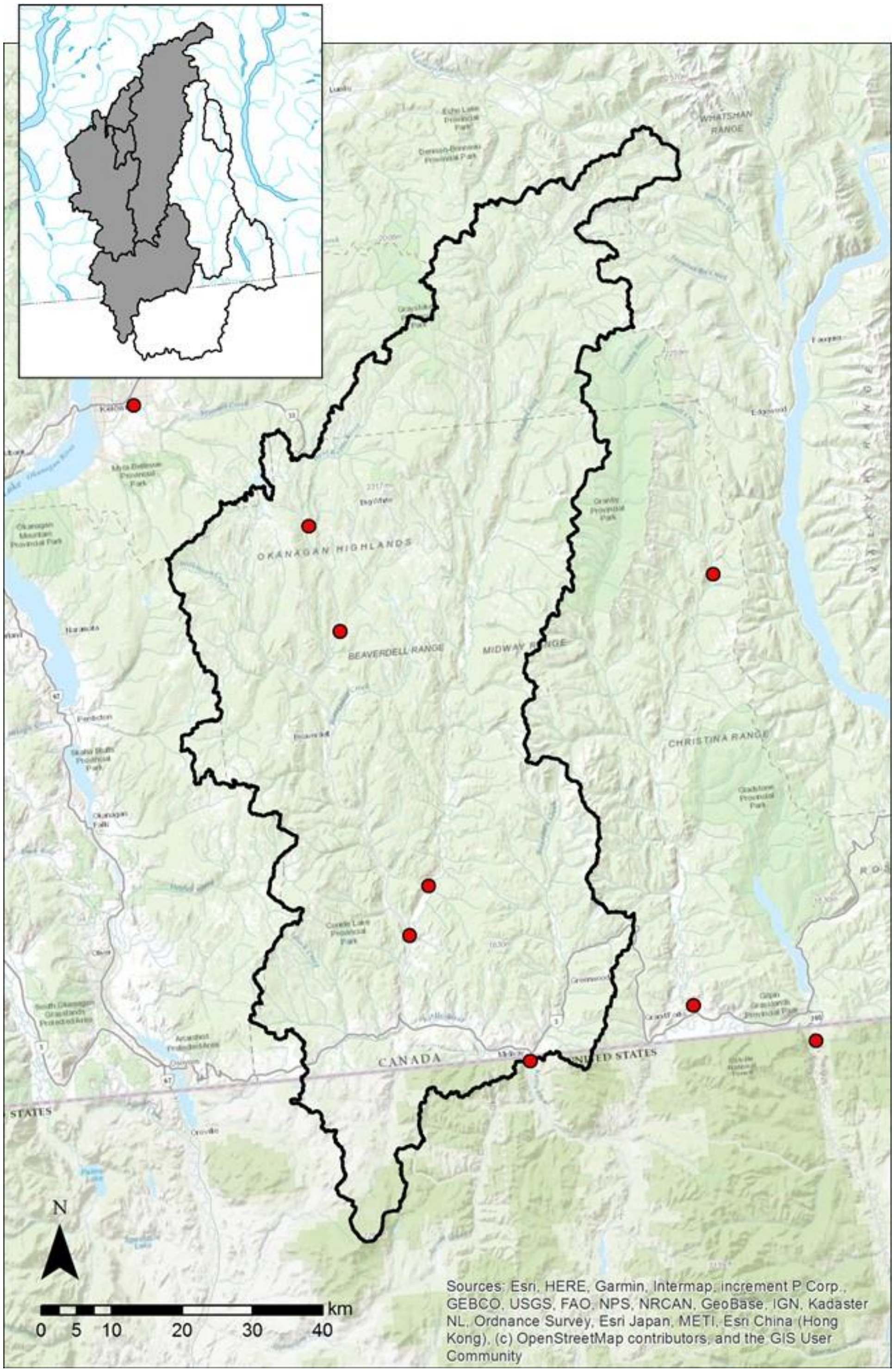


*Figure C8. The snow sensitive zone of the Kettle River basin above Laurier. Elevation contour interval is 200 m; the 1000 and 2000 m contours are bolded.*

## APPENDIX D: KETTLE RIVER NEAR FERRY



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure D1. Map showing the drainage area for the Kettle River near Ferry. The basin is outlined in black and the locations of hydrometric stations are shown with red circles. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

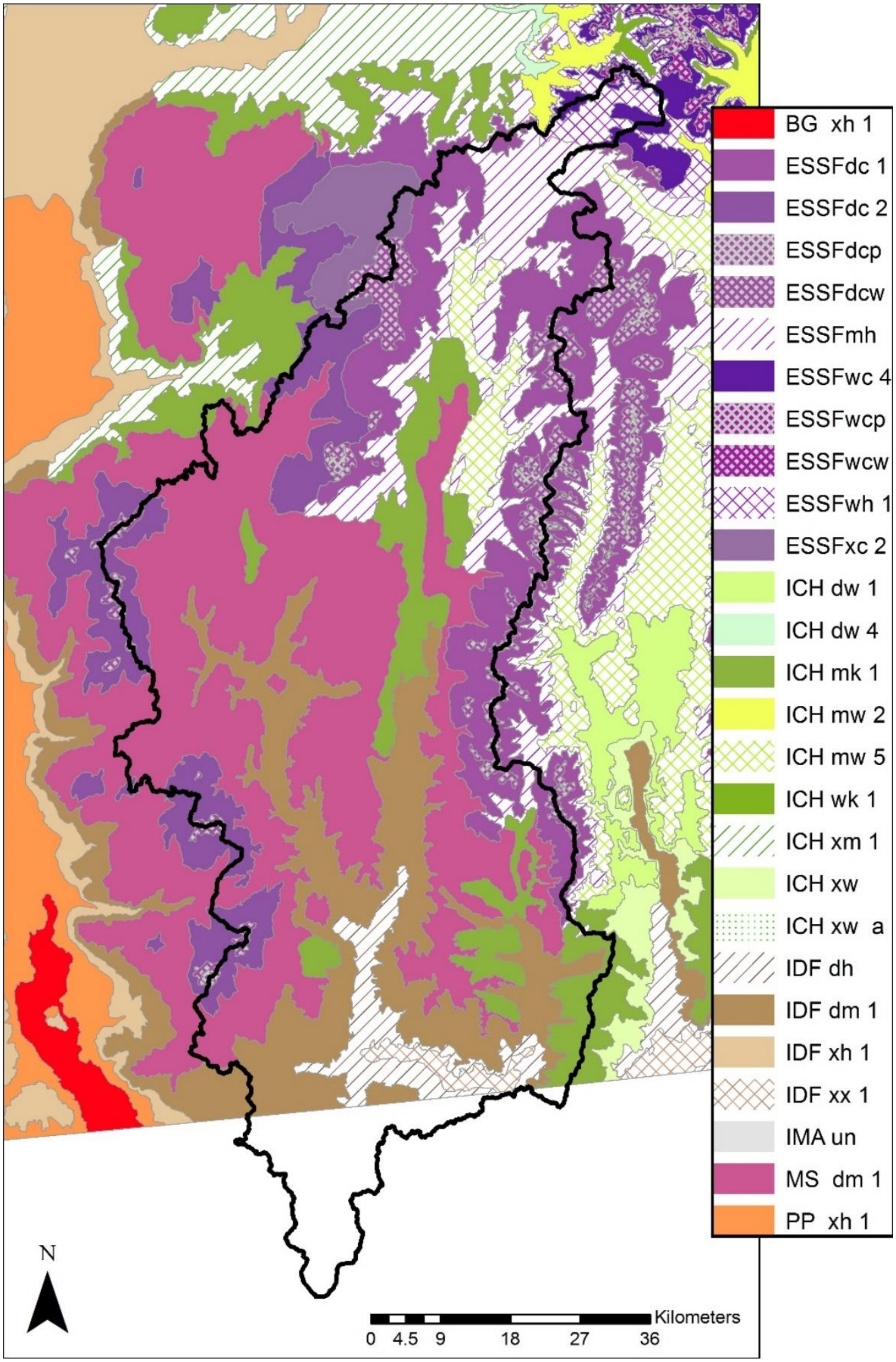


*Figure D2. Map of the drainage area for Kettle River near Ferry showing BEC subzones and elevation in the Canadian portion. The basin is outlined in black.*

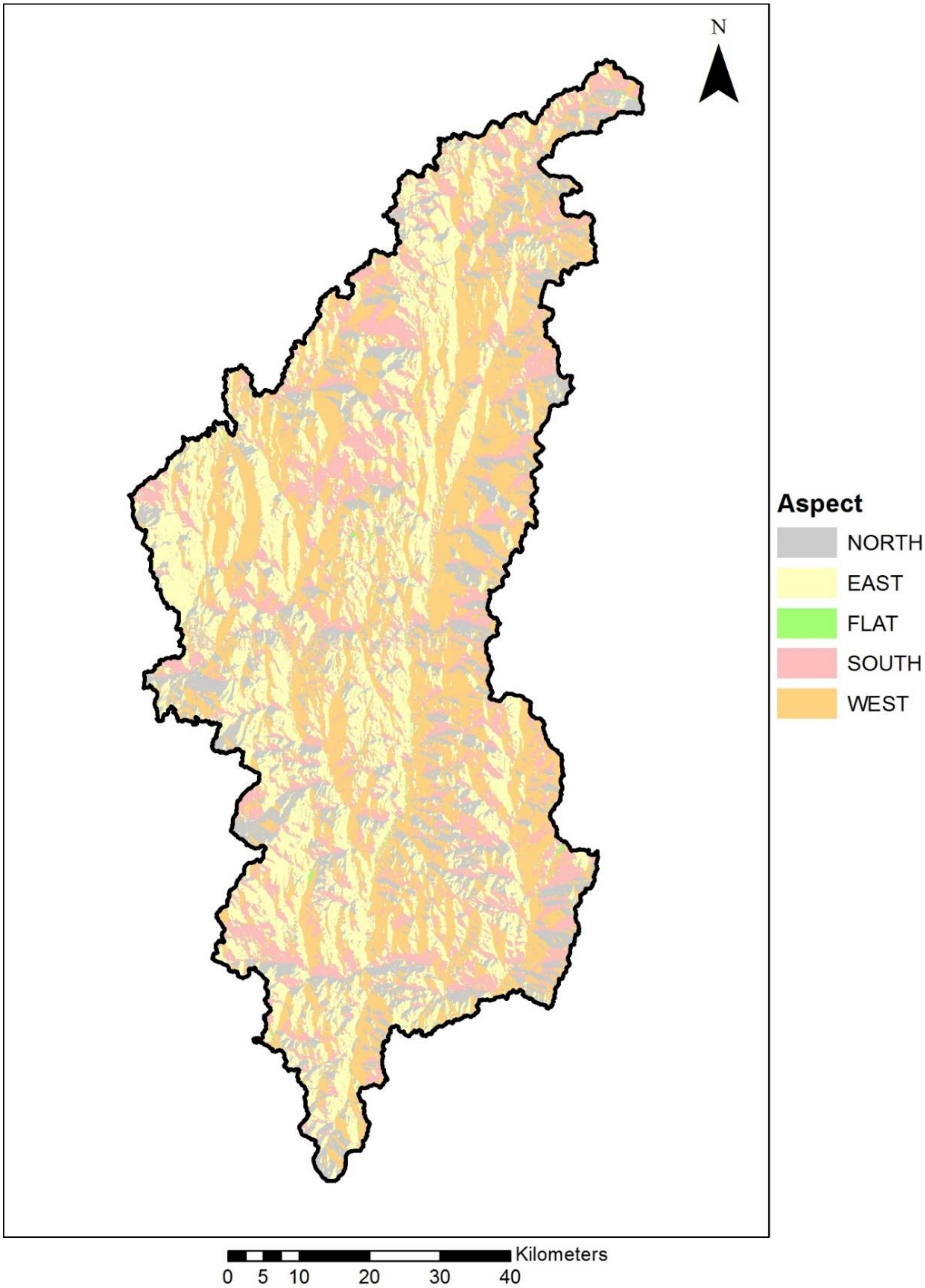


*Figure D3. Slope aspect map of the drainage area for Kettle River near Ferry. The basin is outlined in black.*

## D.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN013 Kettle River near Ferry for 2010-2018 were published and for 2019-2020 were provisional at the time of this analysis. The freshet flow period (when daily mean discharge was greater than the station's long term mean) for 2010-2020 lasted 72 to 99 days (mean = 90 d, median = 93 d), with the shortest in 2019 and the longest in 2013 and 2016 (Table D1). On average, freshet began on 7 April and ended on 6 July; the earliest it began was 14 March in 2015, and the latest was 27 April in 2011.

The freshet hydrographs for Kettle River near Ferry between 2010 and 2020 rarely showed a single dominant peak (Figure D4), indicating that multiple melt events and potentially rain and rain-on-snow events occur through the freshet period. There are no large lakes or significant storage in wetlands so the hydrograph is responsive to melt and precipitation inputs, with a lag reflecting the large basin area.

*Table D1. Freshet flow period dates for Kettle River near Ferry (WSC station ID 08NN013). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both the mean and median dates are shown.*

| Year | Freshet Period | | | Peak Flow Period | | | Peak Flow |
|---|---|---|---|---|---|---|---|
| | Start | End | Duration (# days) | Start | End | Duration (# days) | |
| 2010 | 19 April | 10 July | 82 | 17 May | 25 June | 39 | 19 May |
| 2011 | 27 April | 29 July | 93 | 11 May | 24 June | 44 | 27 May |
| 2012 | 21 April | 25 July | 95 | 26 April | 5 July | 70 | 27 April |
| 2013 | 2 April | 10 July | 99 | 5 May | 8 June | 34 | 11 May |
| 2014 | 12 April | 7 July | 86 | 3 May | 7 June | 35 | 18 May |
| 2015 | 14 March | 15 June | 93 | 22 March | 7 June | 77 | 3 June |
| 2016 | 24 March | 1 July | 99 | 4 April | 25 May | 51 | 23 April |
| 2017 | 30 March | 2 July | 94 | 5 May | 9 June | 35 | 6 May |
| 2018 | 9 April | 4 July | 86 | 26 April | 29 May | 33 | 10 May |
| *2019* | *3 April* | *14 June* | *72* | *20 April* | *30 May* | *40* | *13 May* |
| *2020* | *12 April* | *15 July* | *94* | *30 April* | *17 June* | *48* | *1 June* |
| **Mean:** | **7 April** | **6 July** | **90** | **26 April** | **11 June** | **46** | **14 May** |
| **Median:** | **9 April** | **7 July** | **93** | **1 May** | **8 June** | **40** | **13 May** |

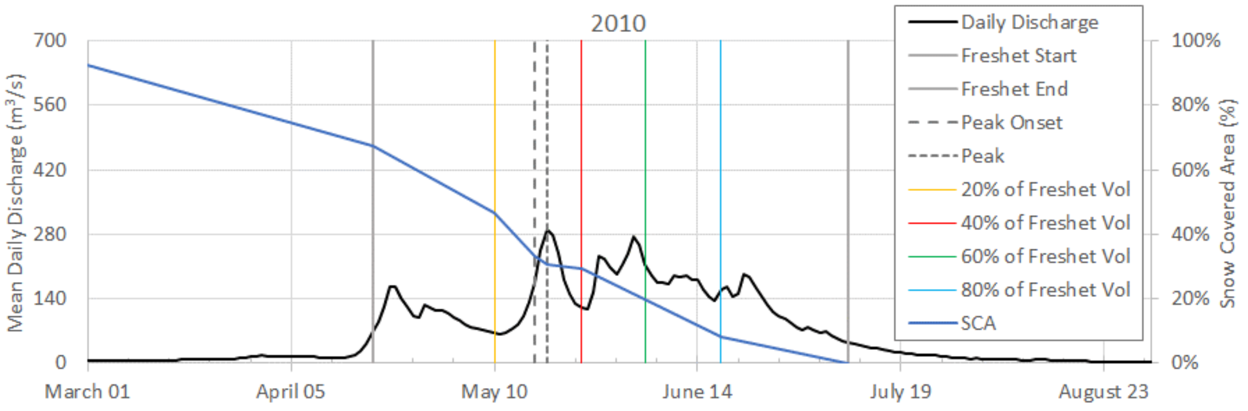


*Figure D4 (cont'd).*

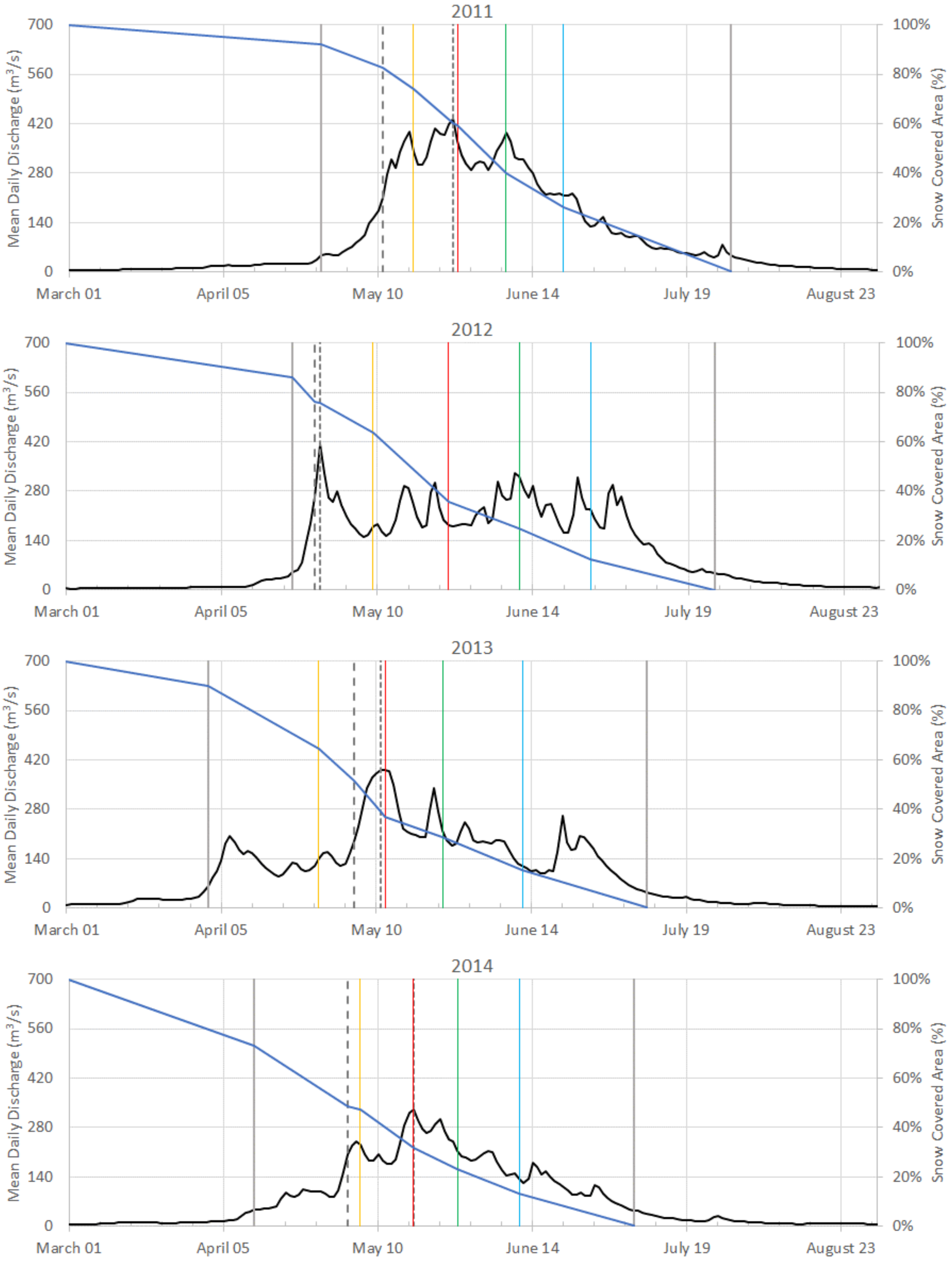


*Figure D4 (cont'd).*

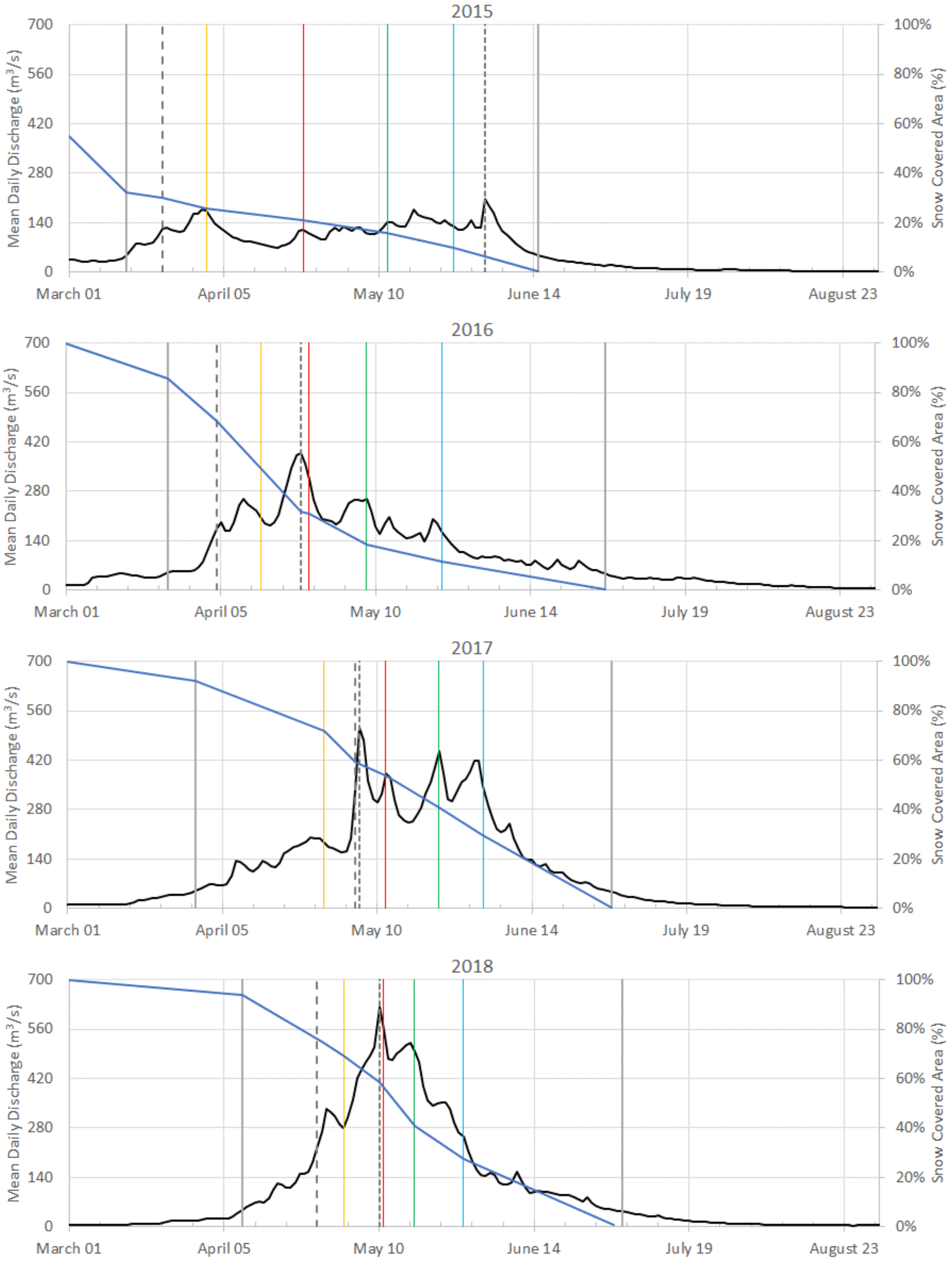


*Figure D4 (cont'd).*

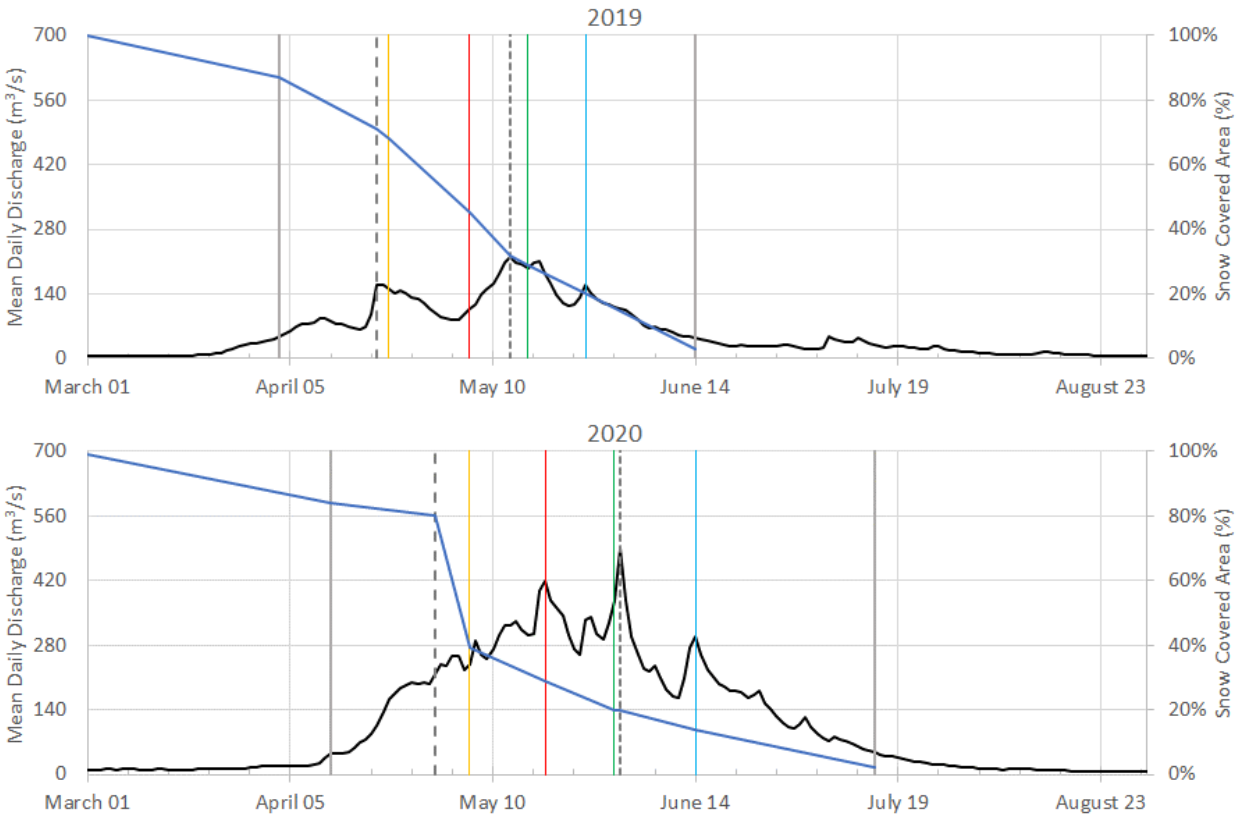


*Figure D4. Discharge measured in Kettle River near Ferry during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable in Kettle River near Ferry, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 6 and 81 days after the onset of the freshet period (mean = 37 d, median = 36 d), when 6 to 89% of the cumulative freshet flow occurred (mean = 42%, median = 39%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 14% (median = 12%, range 4-27%), between 5 and 36 days after the start of the freshet flow period. On average, the peak flow period began on 26 April and ended on 11 June, lasting between 33 and 77 days (mean = 46 d, median = 40 d).

## D.2 Snow Covered Area

SCA was always less than 100% at the start of the freshet period, and in all years there was almost no snow in the basin at the end of the freshet flow period (Table D2). SCA depletion curves were plotted with the freshet hydrographs in Figure D4 and compared in Figure D5.

*Table D2. Snow covered area (%) for selected dates in the Kettle River basin above Ferry. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 67 | 47 | 29 | 20 | 8 | 0 | 33 | 31 |
| 2011 | 92 | 74 | 59 | 40 | 26 | 0 | 83 | 60 |
| 2012 | 86 | 64 | 35 | 25 | 12 | 0 | 76 | 76 |
| 2013 | 90 | 65 | 37 | 29 | 15 | 0 | 52 | 39 |
| 2014 | 73 | 47 | 32 | 23 | 13 | 0 | 48 | 32 |
| 2015 | 32 | 26 | 21 | 16 | 10 | 0 | 30 | 6 |
| 2016 | 86 | 50 | 31 | 18 | 11 | 0 | 68 | 32 |
| 2017 | 92 | 72 | 54 | 41 | 30 | 0 | 59 | 59 |
| 2018 | 94 | 69 | 56 | 41 | 28 | 1 | 75 | 59 |
| 2019 | 87 | 68 | 45 | 29 | 20 | 3 | 71 | 32 |
| 2020 | 84 | 39 | 29 | 20 | 14 | 2 | 80 | 20 |
| **Mean:** | **80** | **56** | **39** | **27** | **17** | **1** | **61** | **41** |
| **Median:** | **86** | **64** | **35** | **25** | **14** | **0** | **68** | **32** |

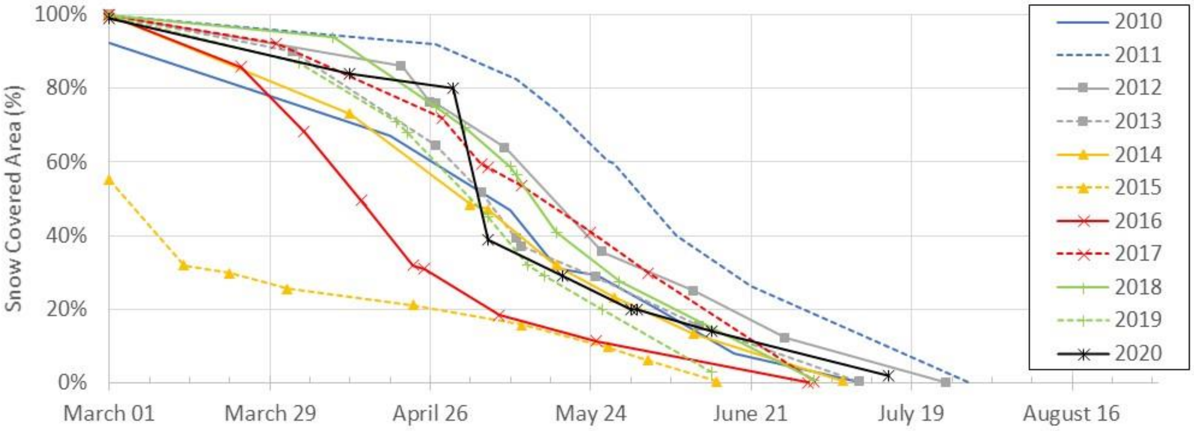


*Figure D5. Changes in snow covered area over the 2010-2020 freshet periods for the Kettle River basin above Ferry.*

Figure D6 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. There was a clear pattern of snow melting away earlier at low elevations in the catchment. Snow persisted longer in high elevation areas in the west and north part of the basin.

As was found for other catchments in the region, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in warmer than normal January, February and March air temperatures (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow recorded at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the low SCA recorded at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure D5).

The basin was 30-83% snow covered at the onset of the peak flow period, with a median value of 68% (mean = 61%) (Figure D7). These results indicated that snowmelt from approximately two thirds of the basin contributes to peak flow in the Kettle River near Ferry.

## D.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from SCA maps for the onset of the peak flow period (Figure D7). Visual assessment of the SCA maps showed similar patterns from year to year (Figure D7). Median SCA was 68%. SCA measured in 2016 was equal to the median, so this year was used to define the SSZ (Figure D8).

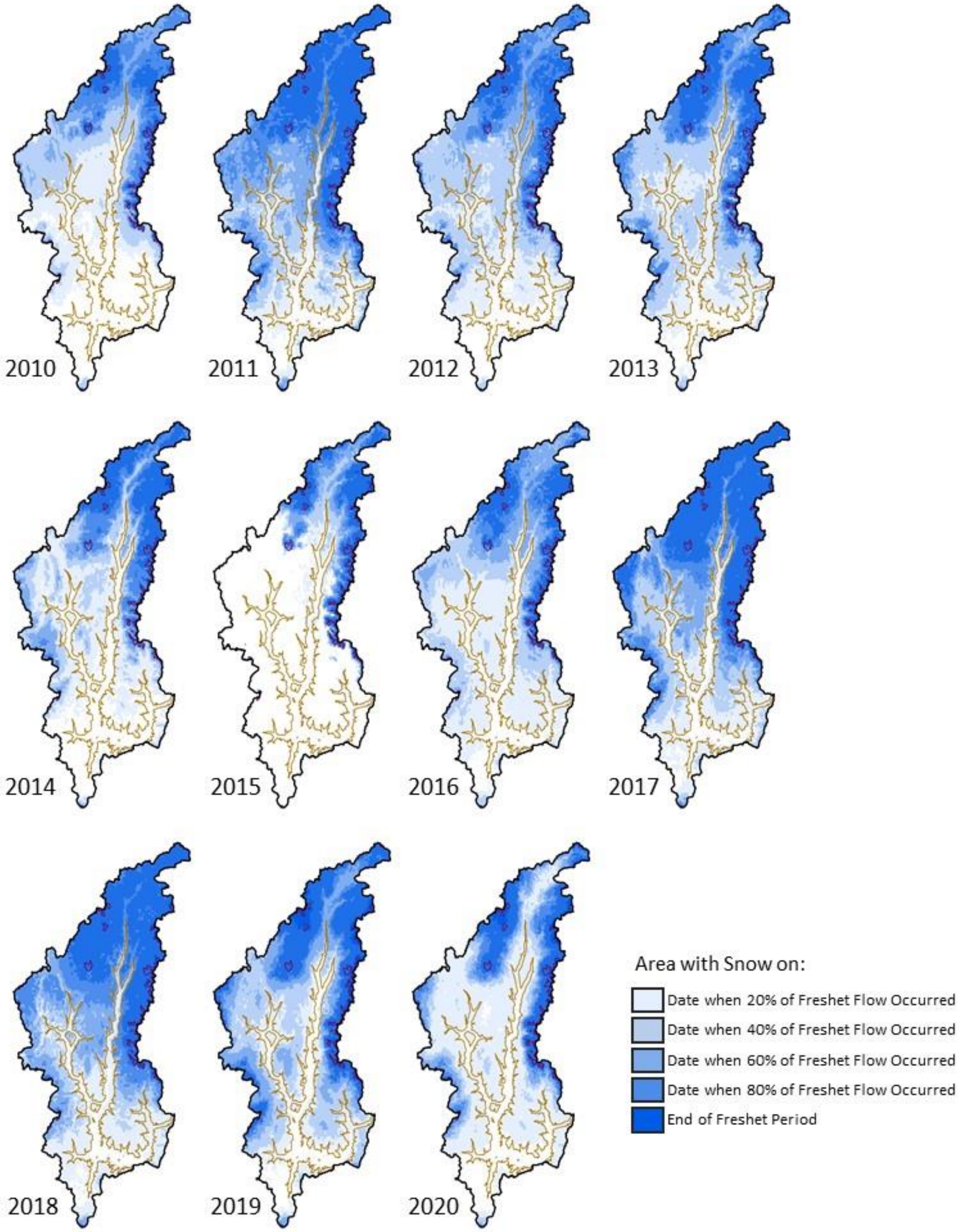


*Figure D6. The progression of snow covered area over the 2010-2020 spring freshet periods in the Kettle River basin above Ferry. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

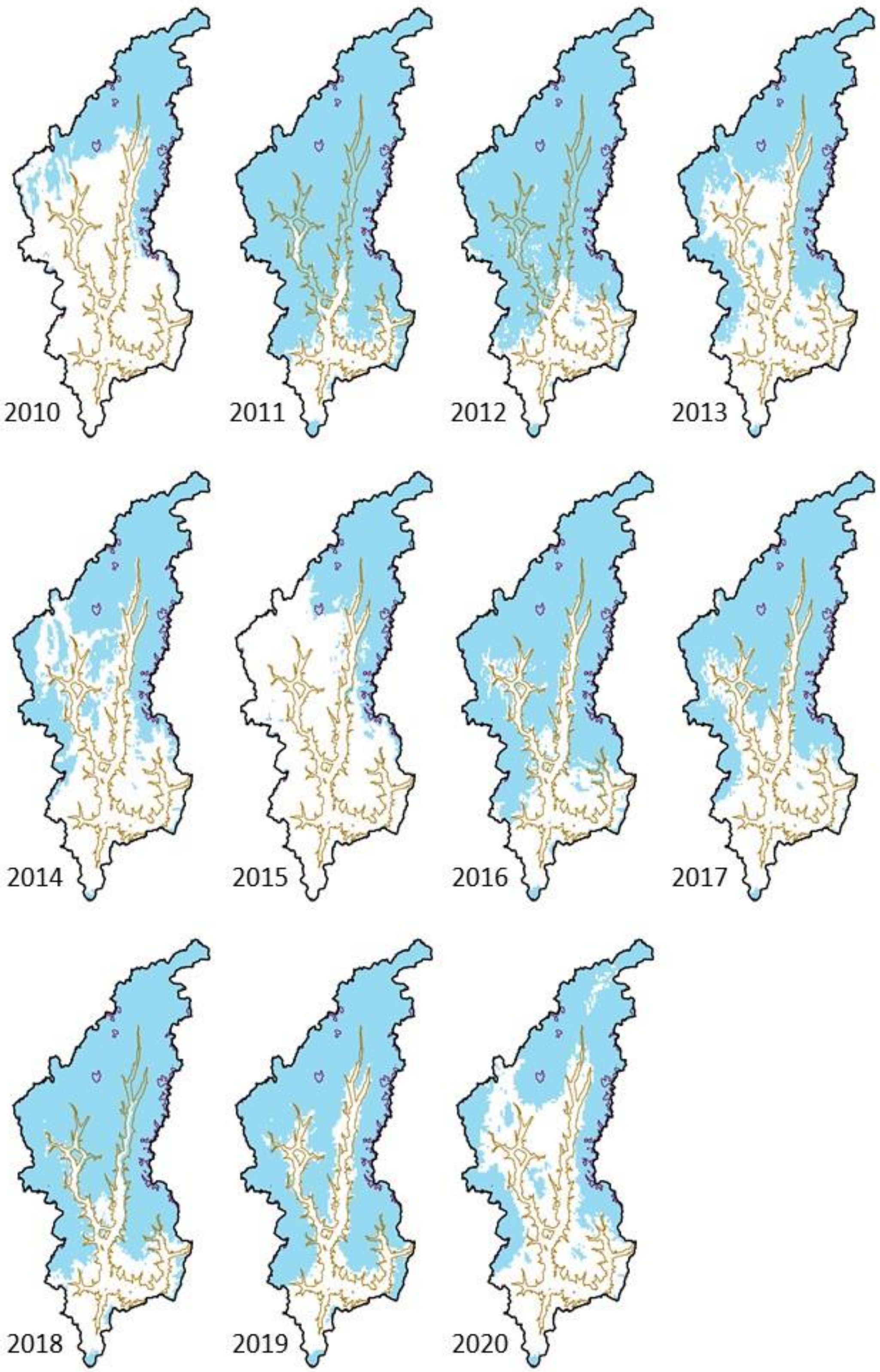


*Figure D7. Snow covered area in the Kettle River basin above Ferry on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

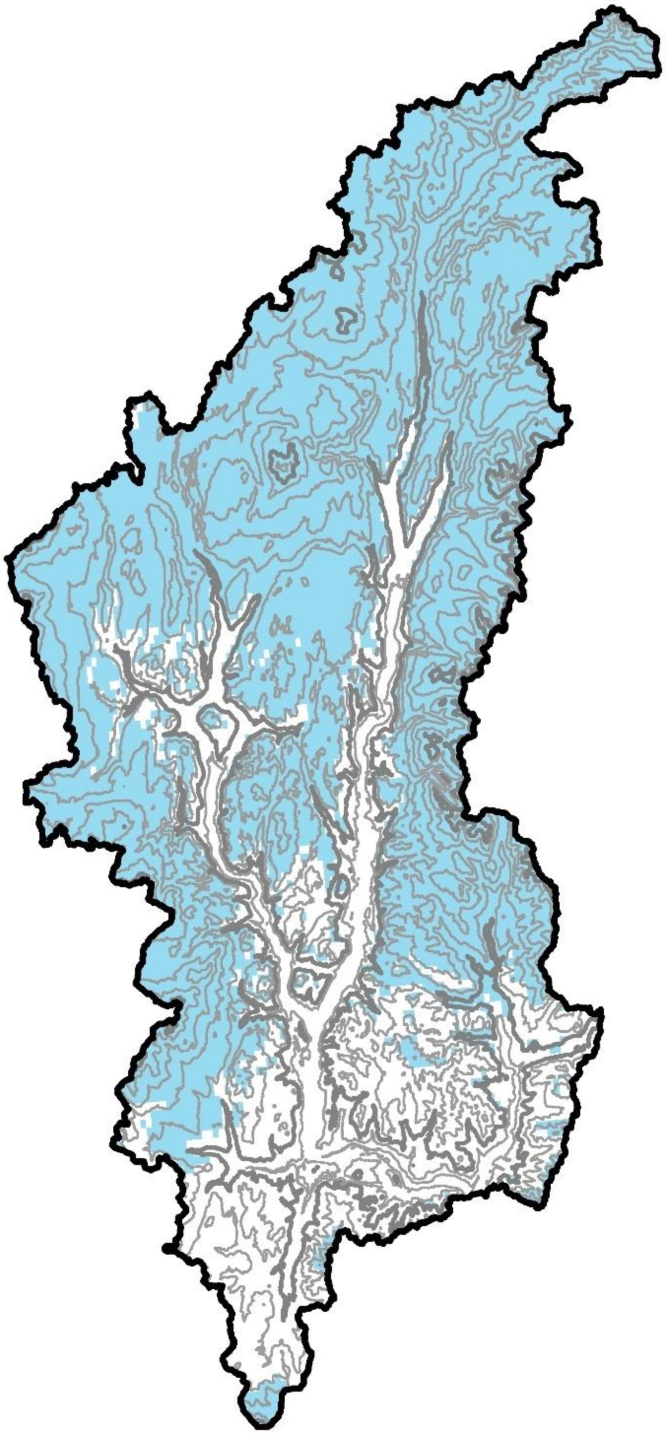
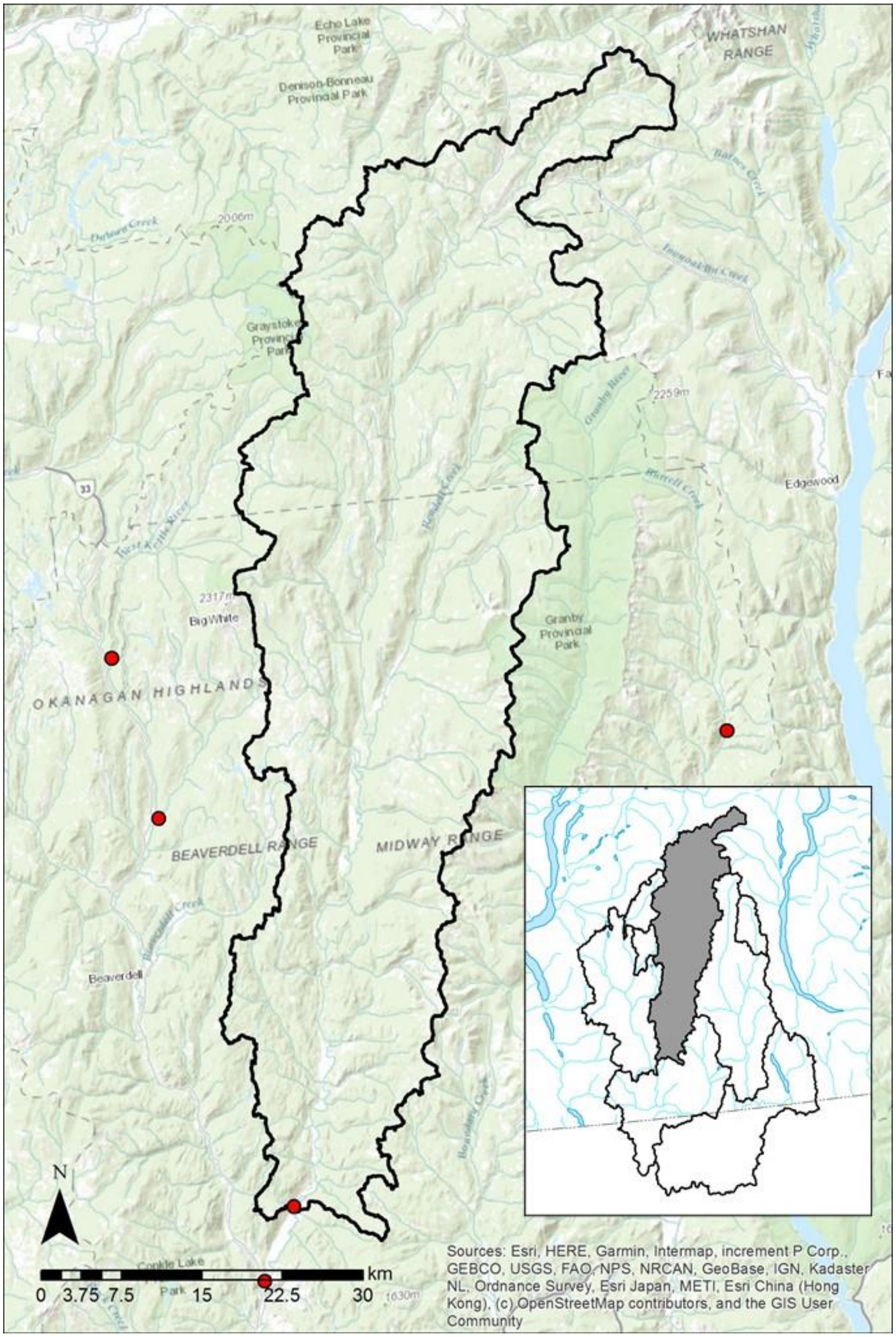


*Figure D8. The snow sensitive zone of the Kettle River basin above Ferry. Elevation contour interval is 200 m; the 1000 and 2000 m contours are bolded.*

## APPENDIX E: KETTLE RIVER NEAR WESTBRIDGE



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure E1. Map showing the drainage area for the Kettle River near Westbridge. The basin is outlined in black and the locations of hydrometric stations are shown with red circles. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

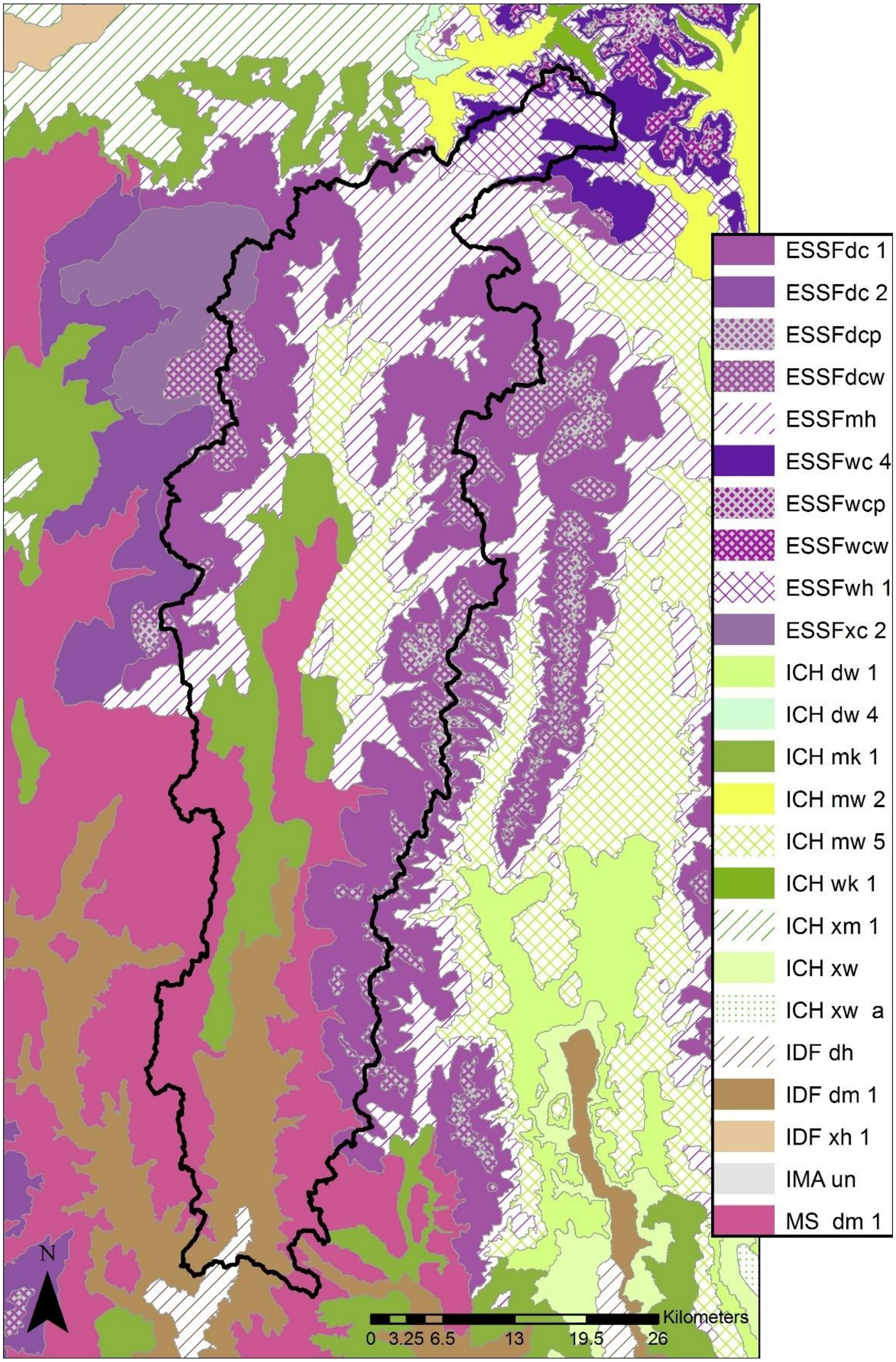


*Figure E2. Map of the drainage area for Kettle River near Westbridge showing BEC zones and elevation. The basin is outlined in black.*

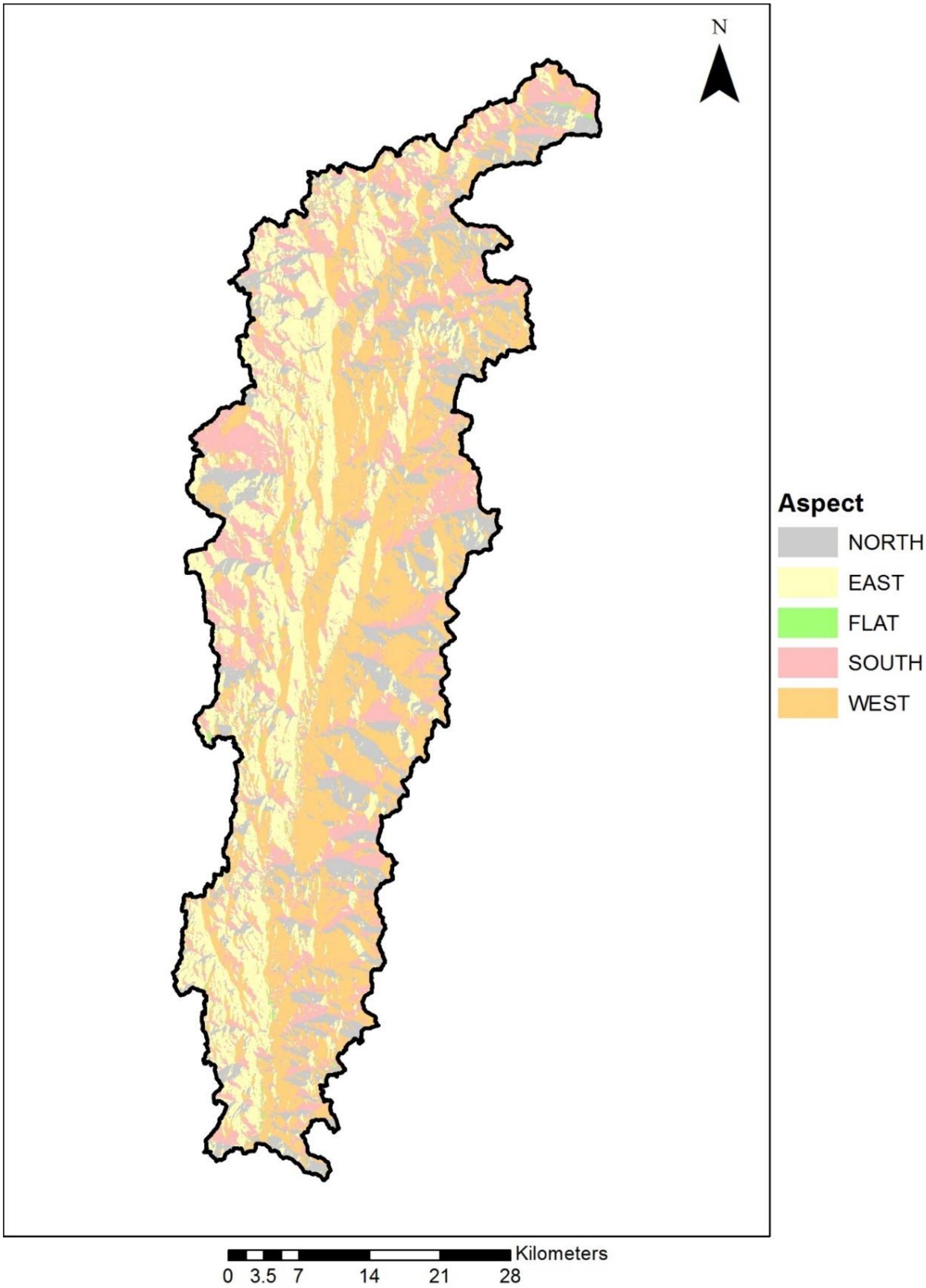


*Figure E3. Slope aspect map of the drainage area for Kettle River at Westbridge. The basin is outlined in black.*

## E.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN026 Kettle River near Westbridge for 2010-2019 were published and for 2020 were provisional at the time of this analysis.

Year-round hydrometric data were not available for the station on Kettle River near Westbridge until 2008, so the long term mean annual discharge (LTMAD) which is needed to identify the annual freshet period could not be calculated. Instead, the freshet start and end dates from another available station were used. To decide which station had the most similar flow regime and could be used as a proxy, cumulative discharge volumes for each year were compared. Using the freshet start and end dates identified for each of the other Kettle River stations, a time series of cumulative daily discharge volume was calculated for Kettle River near Westbridge over each of the 2010-2020 freshet periods. Plots indicated that the progression of freshet discharge for the Kettle River near Westbridge most closely matched that for the Kettle River near Laurier (Figure E4). In most years discharge at the downstream station increased more rapidly than at the headwater station near Westbridge, causing the curves to plot below the 1:1 line, but there was generally a good fit in the latter part of the freshet period. The freshet start and end dates for Kettle River near Laurier were used to analyse snow covered area for Kettle River near Westbridge (Table E1).

The Kettle River near Westbridge freshet hydrographs for 2010-2020 rarely showed a single dominant peak (Figure E5), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There are no large lakes or significant storage in wetlands, so the hydrograph is responsive to melt and rain inputs.

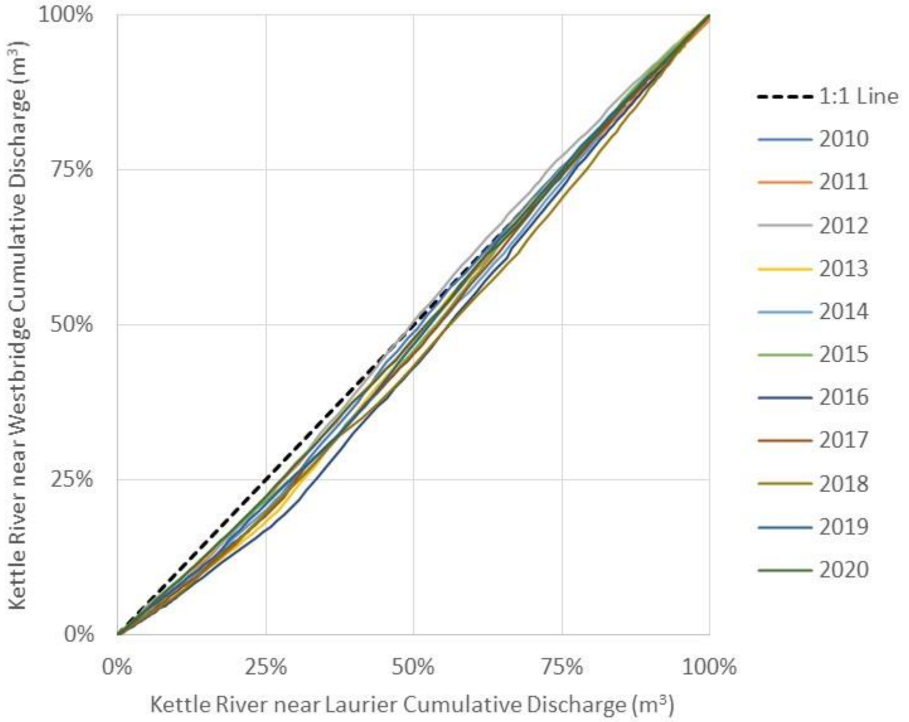


*Figure E4. Cumulative freshet period discharge for Kettle River near Westbridge (WSC station ID 08NN026) compared to Kettle River near Laurier (WSC station ID 08NN012), 2010-2020.*

*Table E1. Freshet flow period dates for Kettle River near Westbridge (WSC station ID 08NN026). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both mean and median dates are shown.*

| Year | Freshet Period* | | Peak Flow Period | | | Peak Flow |
|---|---|---|---|---|---|---|
| | Start | End | Start | End | Duration (# days) | |
| 2010 | 18 April | 10 July | 16 May | 25 June | 40 | 19 May |
| 2011 | 27 April | 29 July | 12 May | 24 June | 43 | 26 May |
| 2012 | 19 April | 28 July | 26 April | 5 July | 70 | 6 June |
| 2013 | 1 April | 12 July | 6 May | 27 June | 52 | 12 May |
| 2014 | 10 April | 8 July | 3 May | 17 June | 45 | 17 May |
| 2015 | 14 March | 17 June | 29 April | 7 June | 39 | 3 June |
| 2016 | 7 March | 2 July | 9 April | 27 May | 48 | 23 April |
| 2017 | 19 March | 5 July | 4 May | 11 June | 38 | 6 May |
| 2018 | 8 April | 4 July | 28 April | 31 May | 33 | 10 May |
| 2019 | 31 March | 16 June | 20 April | 2 June | 43 | 13 May |
| *2020* | *12 April* | *14 July* | *6 May* | *17 June* | *42* | *1 June* |
| **Mean:** | **4 April** | **8 July** | **1 May** | **14 June** | **45** | **18 May** |
| **Median:** | **8 April** | **8 July** | **3 May** | **17 June** | **43** | **16 May** |

** From the Kettle River near Laurier station.*

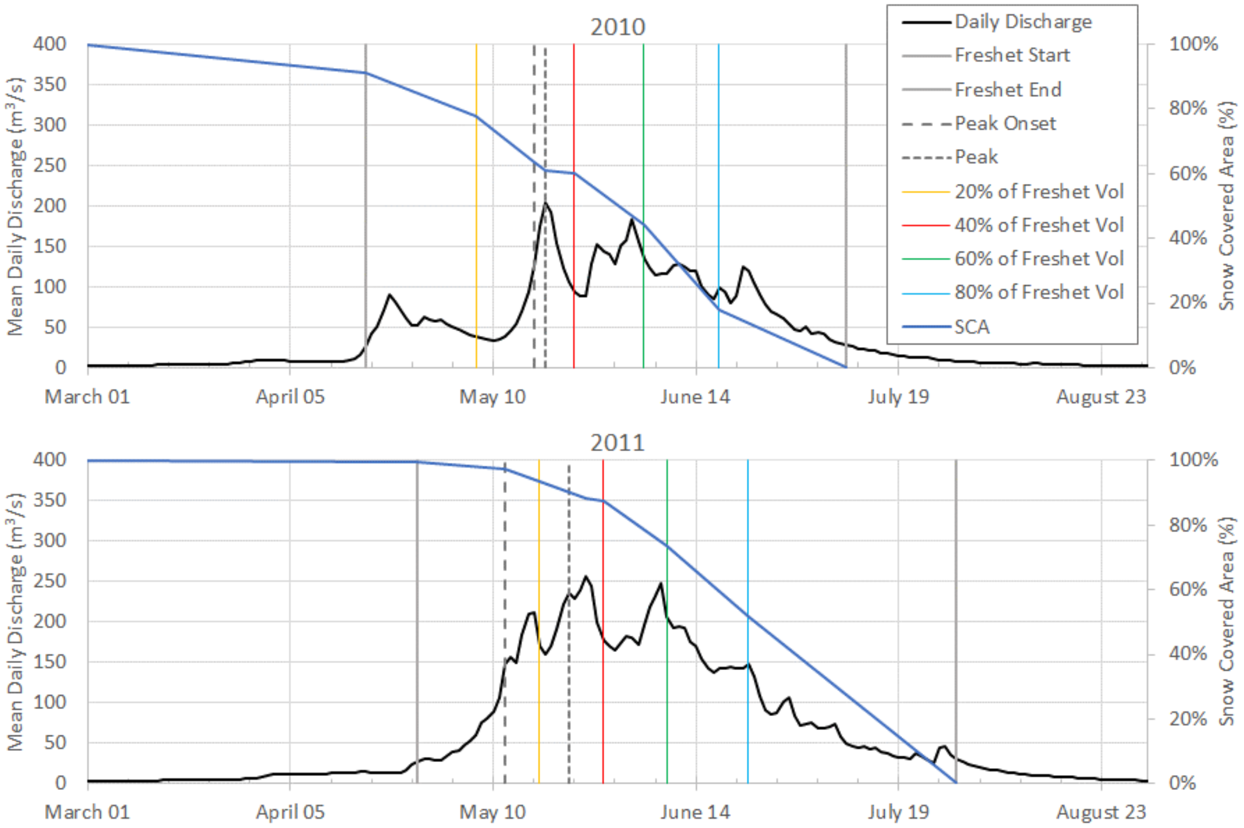


*Figure E6 (cont'd).*

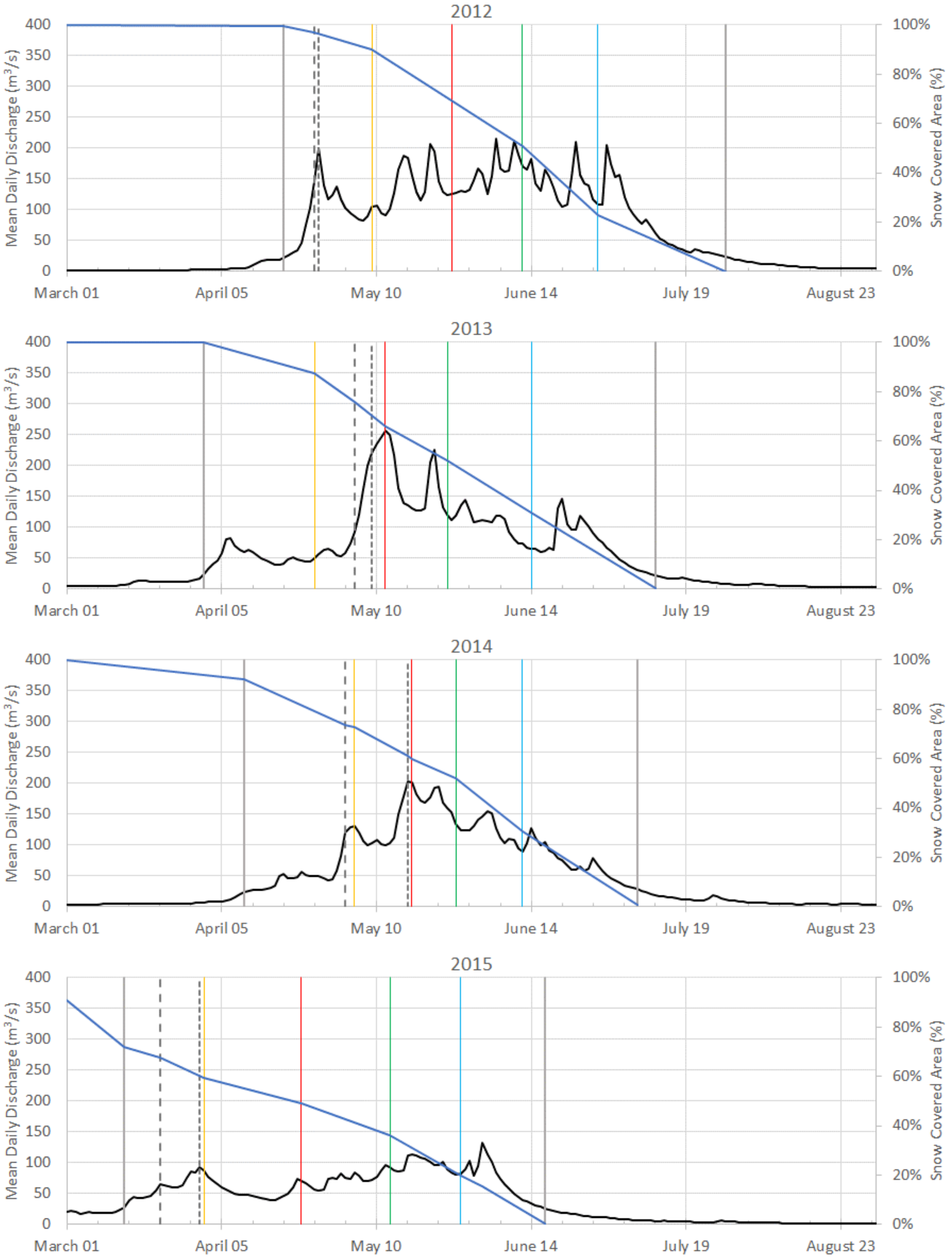


*Figure E6 (cont'd).*

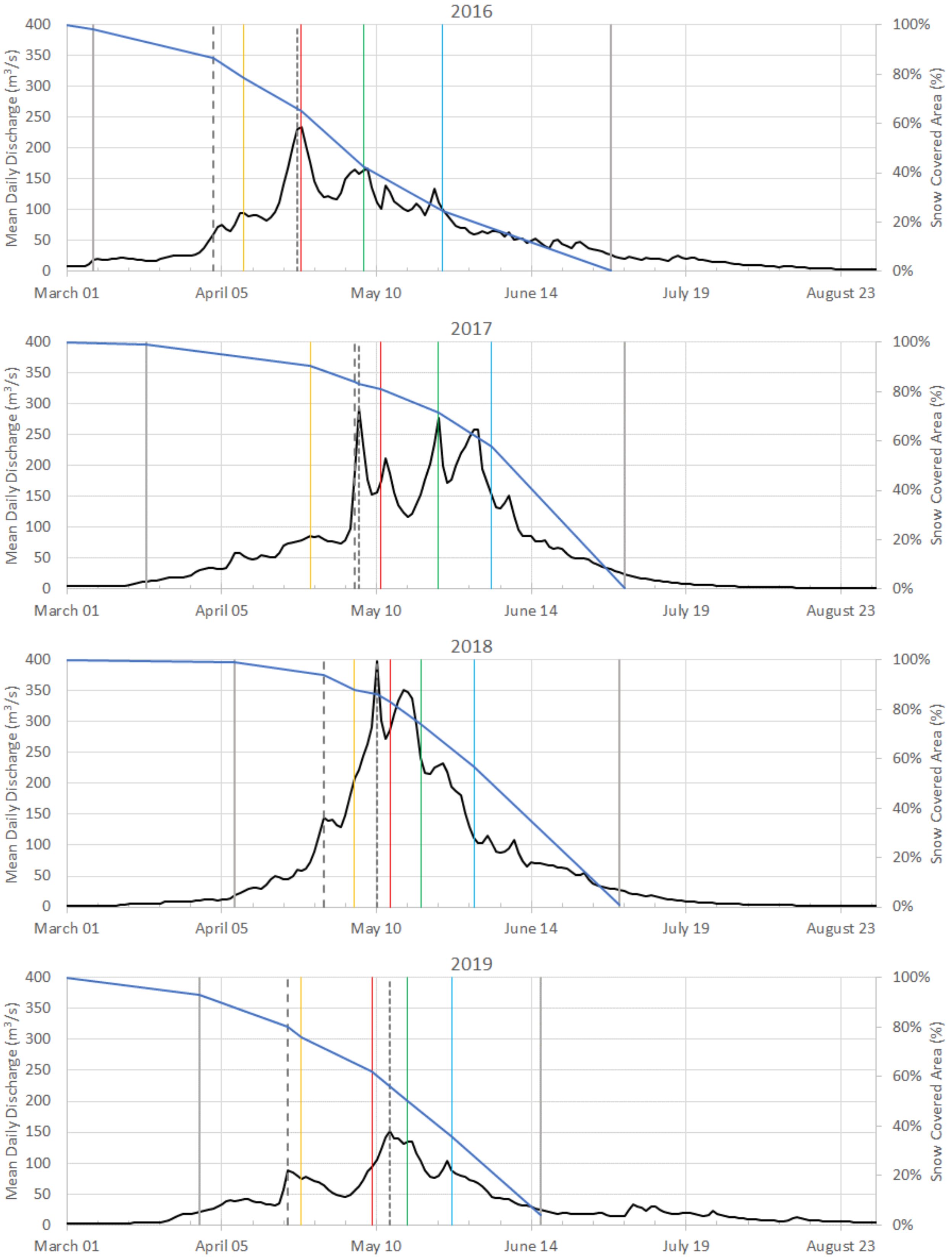


*Figure E6 (cont'd).*

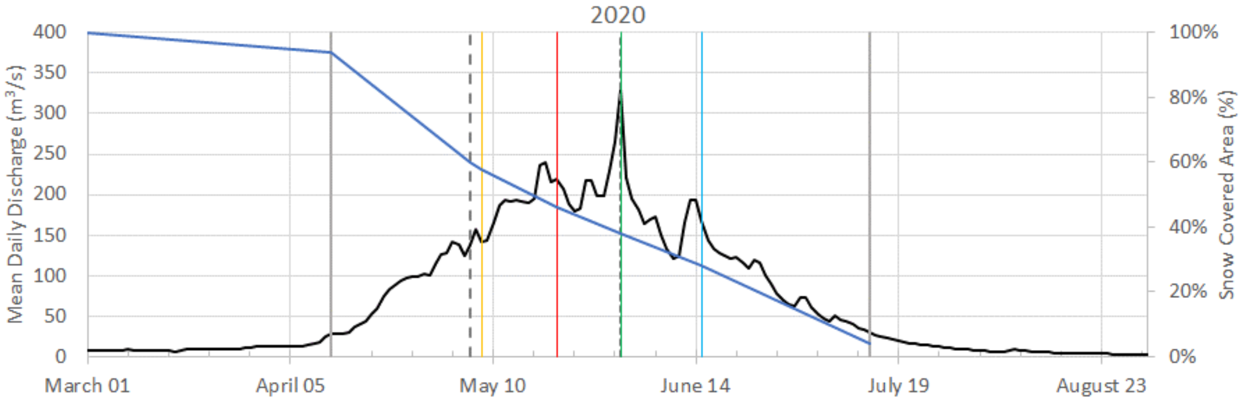


*Figure E6. Discharge measured in Kettle River near Westbridge during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable in Kettle River near Westbridge, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 22 and 87 days after the onset of the freshet period (mean = 46 d, median = 36 d), when 27 to 88% of the cumulative freshet flow occurred (mean = 43%, median = 34%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 17% (median = 15%, range 4-41%), between 7 and 46 days after the start of the freshet flow period. On average, the peak flow period began on 1 May and ended on 14 June, lasting between 33 and 70 days (mean = 45 d, median = 43 d).

## E.2 Snow Covered Area

SCA depletion curves are plotted with the freshet hydrographs in Figure E6 and compared in Figure E7. In most years the SCA was near 100% at the start of the freshet period, and in all years there was almost no snow in the basin at the end of the freshet flow period (Table E2).

Figure E8 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. There was a clear pattern of snow melting away earlier at low elevations in the catchment. Snow persisted longer in high elevation areas in the east and north part of the basin.

As was found for other catchments in the region, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in warmer than normal January, February and March (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the low SCA recorded at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure E7).

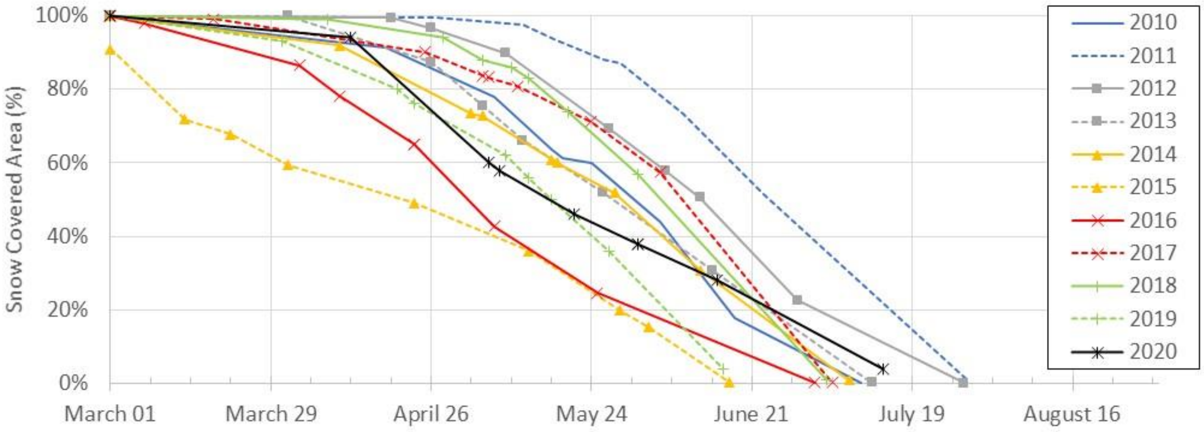


*Figure E7. Changes in snow covered area over the 2010-2020 freshet periods for the Kettle River basin above Westbridge.*

*Table E2. Snow covered area (%) for selected dates in the Kettle River above Westbridge. Because of the small samples size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 91 | 78 | 60 | 44 | 18 | 0 | 64 | 61 |
| 2011 | 100 | 93 | 87 | 73 | 52 | 1 | 97 | 88 |
| 2012 | 99 | 90 | 69 | 51 | 23 | 0 | 97 | 58 |
| 2013 | 100 | 87 | 66 | 52 | 31 | 0 | 76 | 66 |
| 2014 | 92 | 73 | 60 | 52 | 31 | 1 | 74 | 61 |
| 2015 | 72 | 59 | 49 | 36 | 20 | 0 | 68 | 15 |
| 2016 | 98 | 78 | 65 | 43 | 25 | 0 | 87 | 65 |
| 2017 | 99 | 90 | 81 | 71 | 58 | 0 | 84 | 83 |
| 2018 | 99 | 88 | 83 | 74 | 57 | 1 | 94 | 86 |
| 2019 | 93 | 76 | 62 | 50 | 36 | 4 | 80 | 56 |
| 2020 | 94 | 58 | 46 | 38 | 28 | 4 | 60 | 38 |
| **Mean:** | **94** | **79** | **66** | **53** | **34** | **1** | **80** | **62** |
| **Median:** | **98** | **78** | **65** | **51** | **31** | **0** | **80** | **61** |

The basin was 60-97% snow covered at the onset of the peak flow period, with a median value of 80% (mean = 80%) (Figure E9). These results indicated that snowmelt over more than three quarters of the basin contributed to peak flow in the West Kettle River near Westbridge.

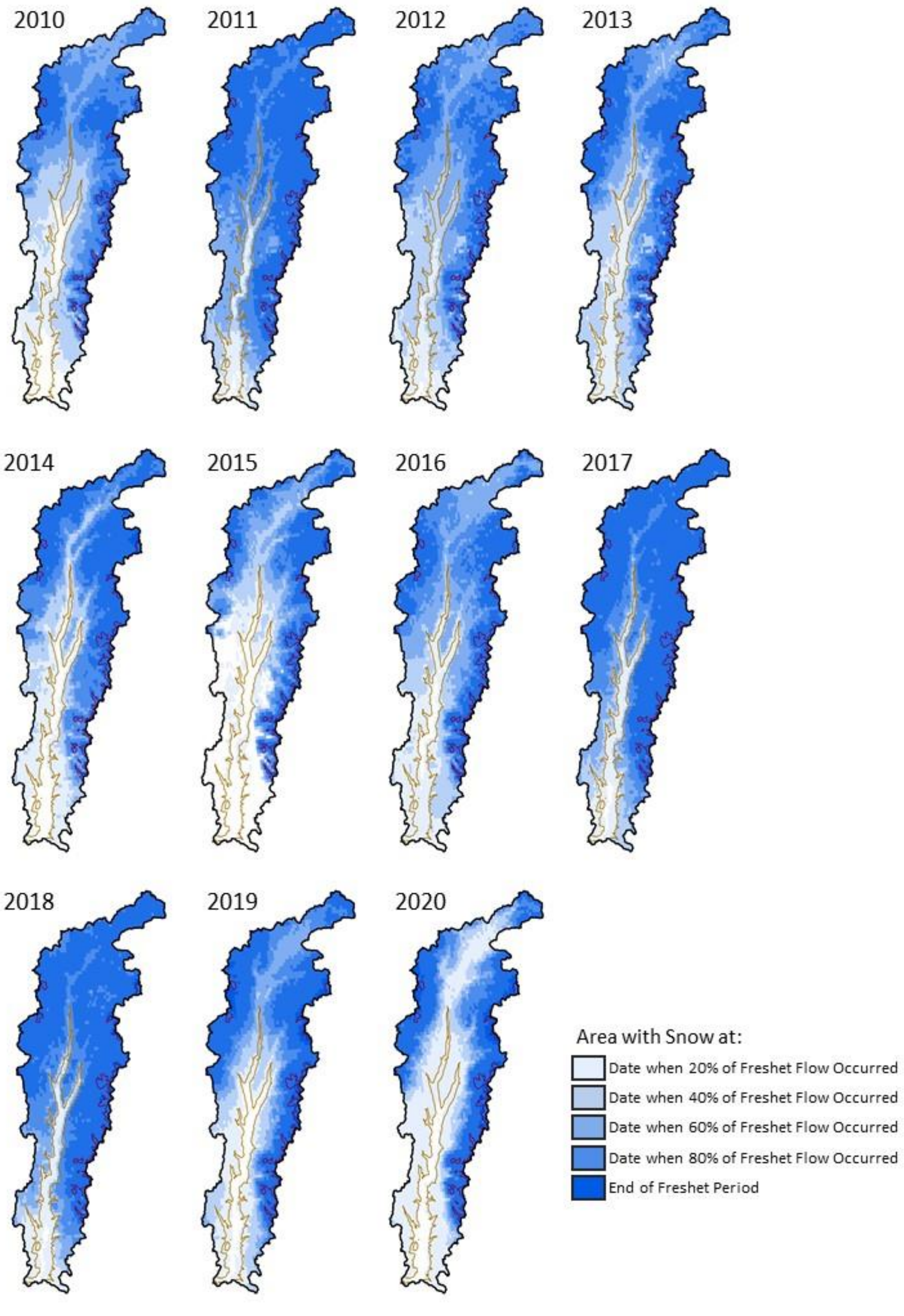


*Figure E8. The progression of snow covered area over the 2010-2020 spring freshet periods in the Kettle River basin above Westbridge. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

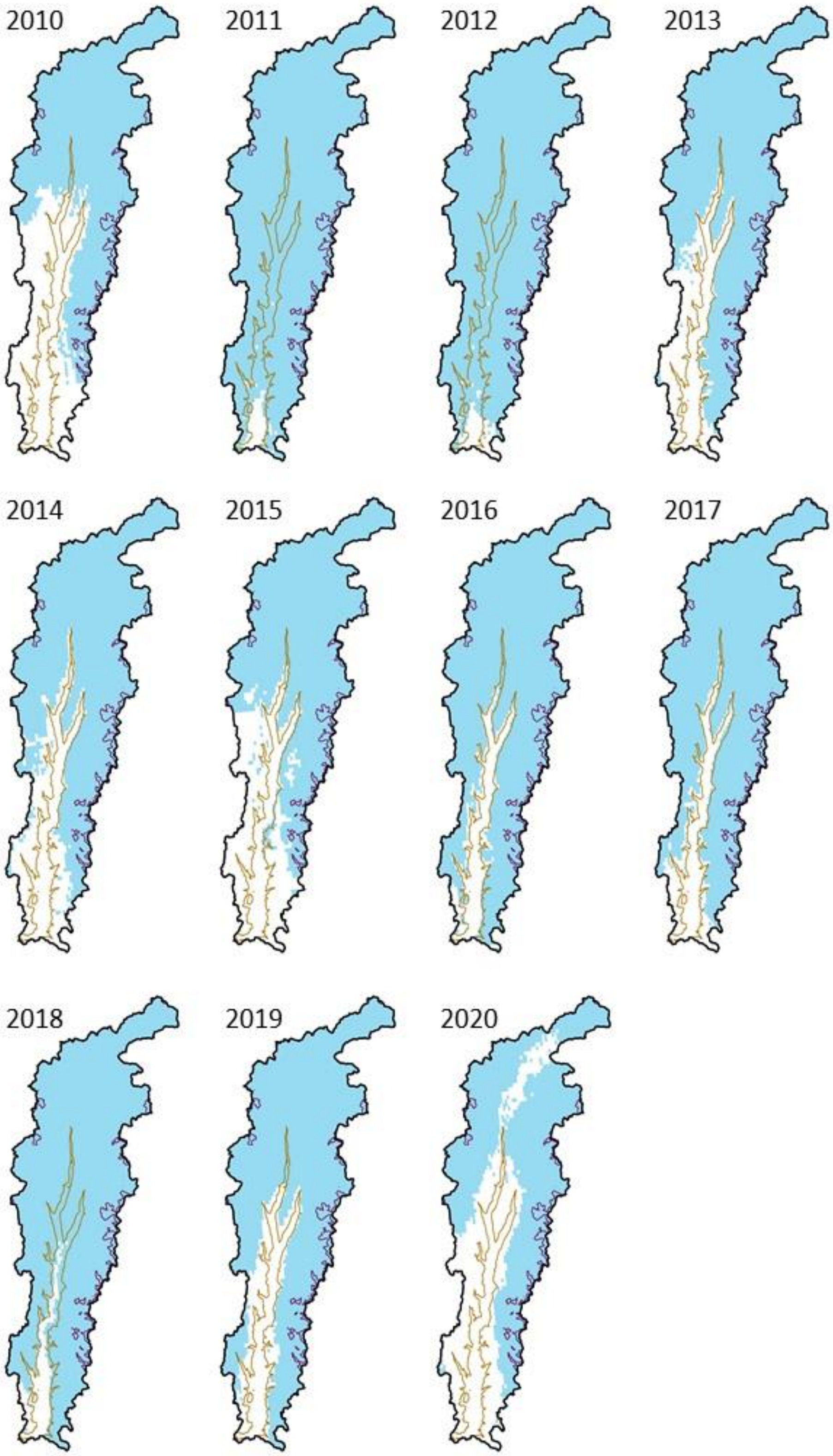


*Figure E9. Snow covered area in the Kettle River basin above Westbridge on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

## E.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from SCA maps for the onset of the peak flow period (Figure E9). Visual assessment of the SCA maps showed similar patterns from year to year (Figure E9). Median SCA was 80%. SCA measured in 2019 equal to the median, so this year was used to define the SSZ (Figure E10).

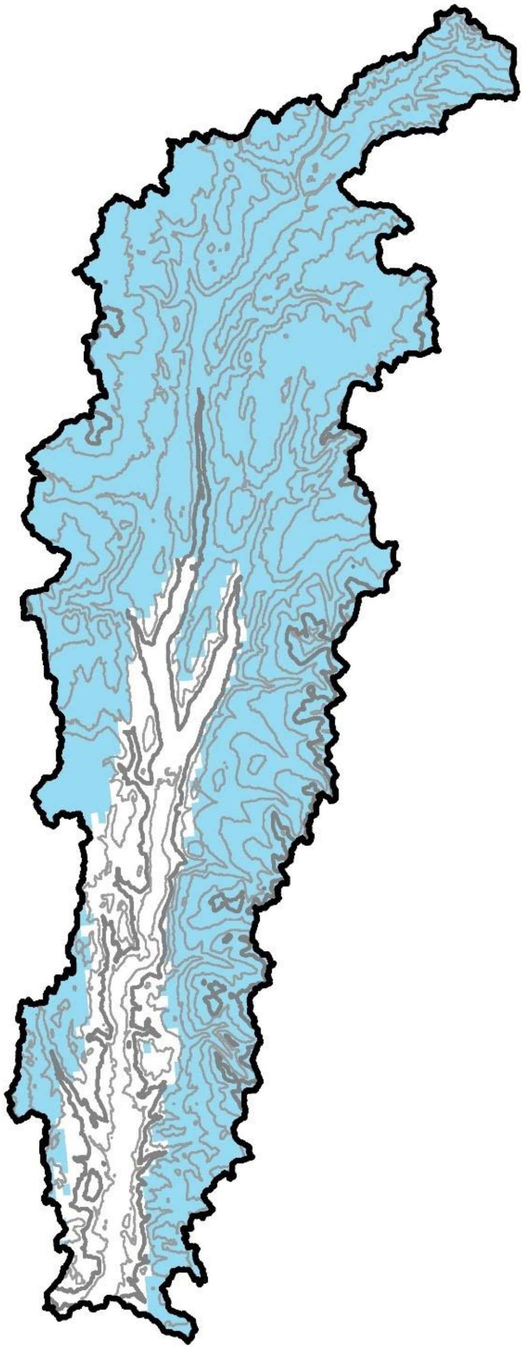
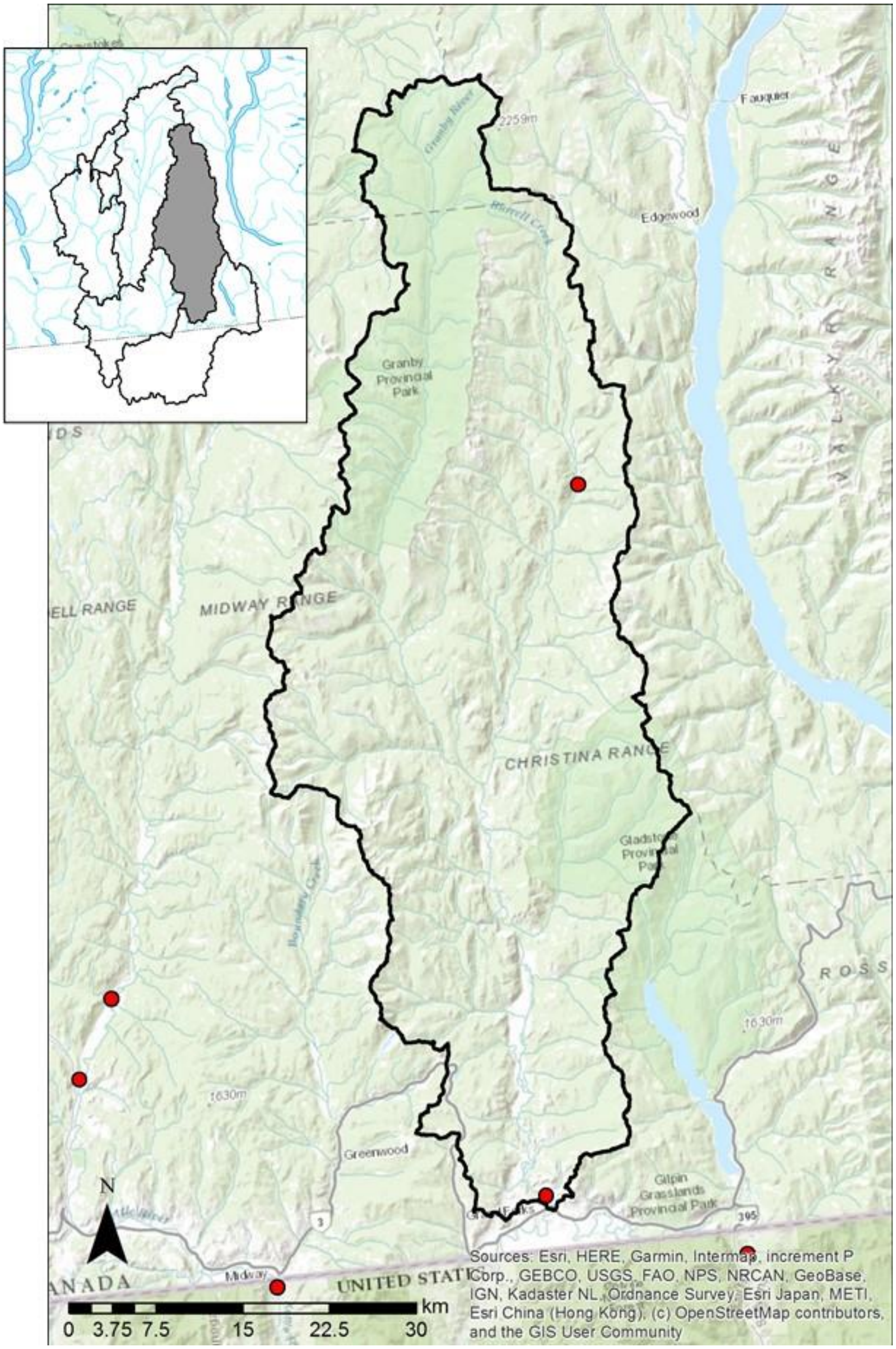


*Figure E10. The snow sensitive zone of the Kettle River basin above Westbridge. Elevation contour interval is 200 m; the 1000 and 2000 m contours are bolded.*

## APPENDIX F: GRANBY RIVER



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure F1. Map showing the drainage area for the Granby River at Grand Forks, a tributary of Kettle River. The basin is outlined in black and the locations of hydrometric stations are shown with red circles. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

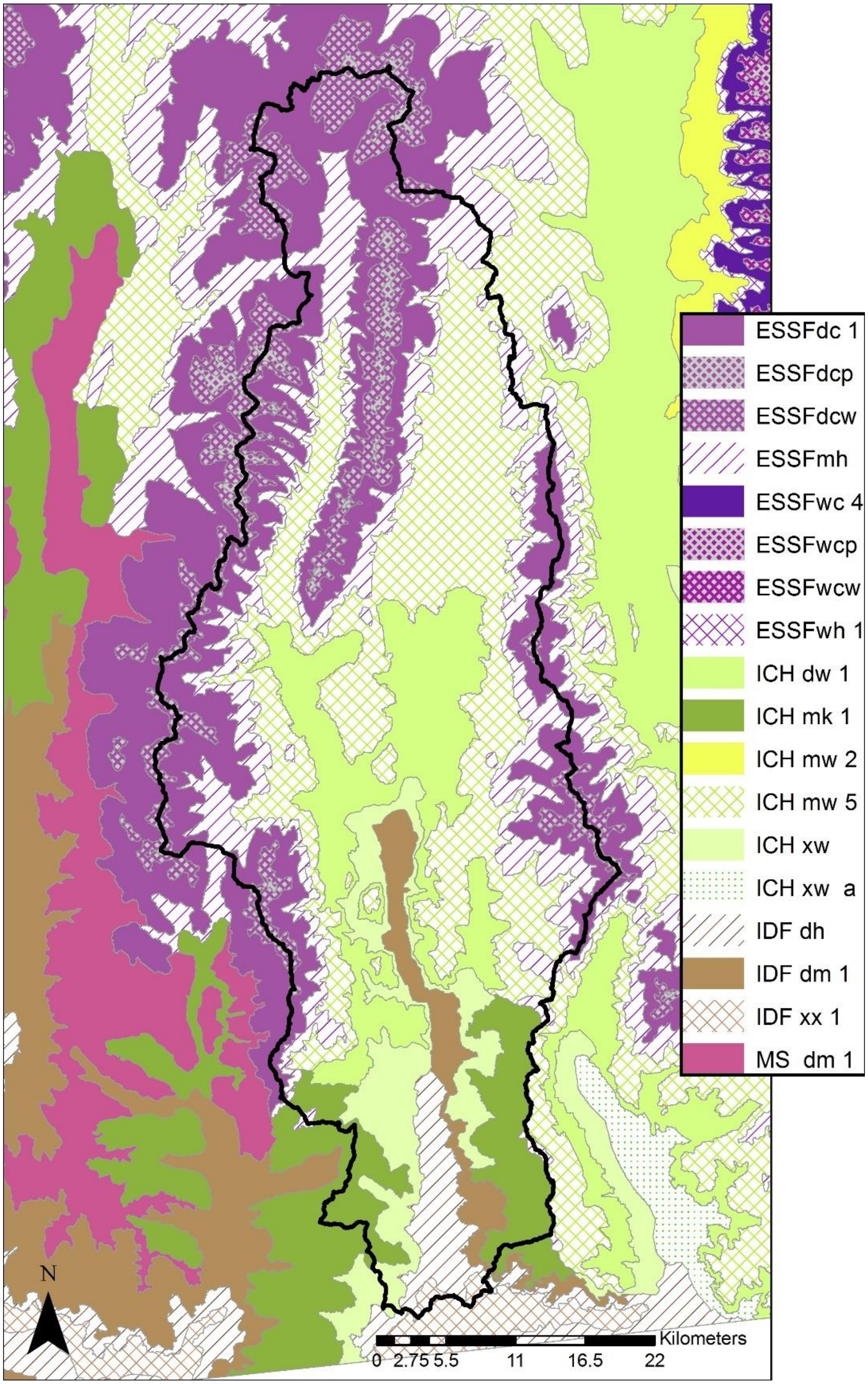


*Figure F2. Map of the Granby River basin showing BEC subzones and elevation. The basin is outlined in black.*

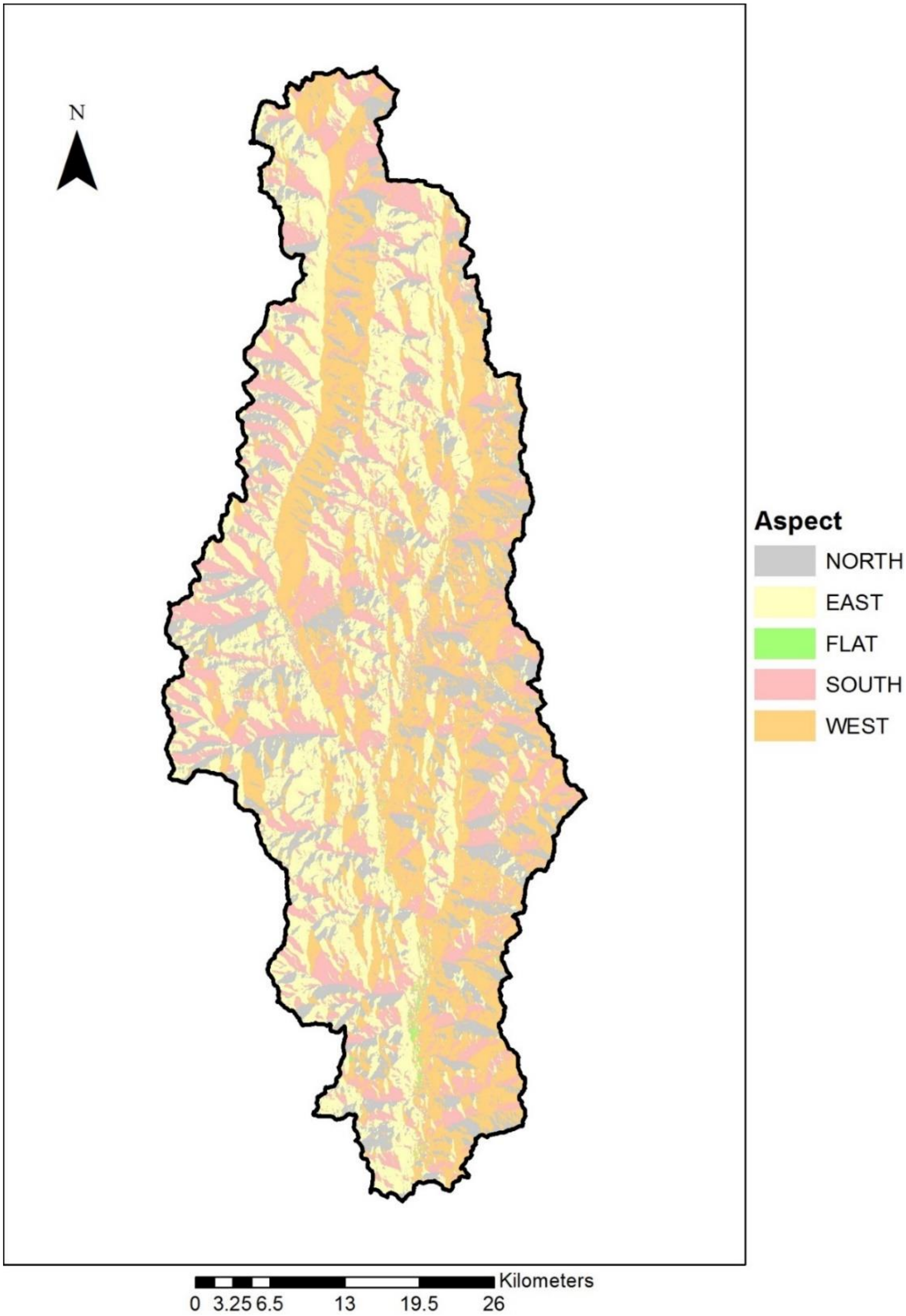


*Figure F3. Slope aspect map of the Granby River basin. The basin is outlined in black.*

## F.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN002 Granby River at Grand Forks for 2010-2019 were published and for 2020 were provisional at the time of this analysis. The freshet flow period (when daily mean discharge was greater than the station's long term mean annual discharge) for 2010-2020 lasted 82 to 117 days (mean = 94 d, median = 92 d), with the shortest in 2010, 2018 and 2019, and the longest in 2016 (Table F1). On average, freshet began on 1 April and ended on 5 July; the earliest it began was 6 March in 2016, and the latest was 26 April in 2011.

The Granby River freshet period hydrographs for 2010 to 2020 rarely showed a single dominant peak (Figure F4), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There are no large lakes or significant storage in wetlands so the hydrograph is responsive to melt and precipitation inputs.

*Table F1. Freshet flow period dates for Granby River at Grand Forks (08NN002). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both mean and median dates are shown.*

| **Year** | **Freshet Period** | | | **Peak Flow Period** | | | **Peak Flow Date** |
|---|---|---|---|---|---|---|---|
| | **Start** | **End** | **Duration (# days)** | **Start** | **End** | **Duration (# days)** | |
| 2010 | 17 April | 8 July | 82 | 16 May | 25 June | 40 | 19 May |
| 2011 | 26 April | 23 July | 88 | 12 May | 30 June | 49 | 27 May |
| 2012 | 13 April | 19 July | 97 | 24 April | 5 July | 72 | 6 June |
| 2013 | 31 March | 9 July | 100 | 5 May | 9 June | 35 | 12 May |
| 2014 | 7 April | 5 July | 89 | 2 May | 6 June | 35 | 18 May |
| 2015 | 13 March | 15 June | 94 | 21 March | 8 June | 79 | 3 June |
| 2016 | 6 March | 1 July | 117 | 2 April | 26 May | 54 | 23 April |
| 2017 | 16 March | 6 July | 112 | 5 May | 14 June | 40 | 6 May |
| 2018 | 8 April | 29 June | 83 | 3 May | 29 May | 26 | 10 May |
| 2019 | 26 March | 16 June | 82 | 20 April | 4 June | 45 | 13 May |
| *2020* | *10 April* | *11 July* | *92* | *6 May* | *15 June* | *40* | *1 June* |
| **Mean:** | **1 April** | **4 July** | **94** | **26 April** | **12 June** | **47** | **18 May** |

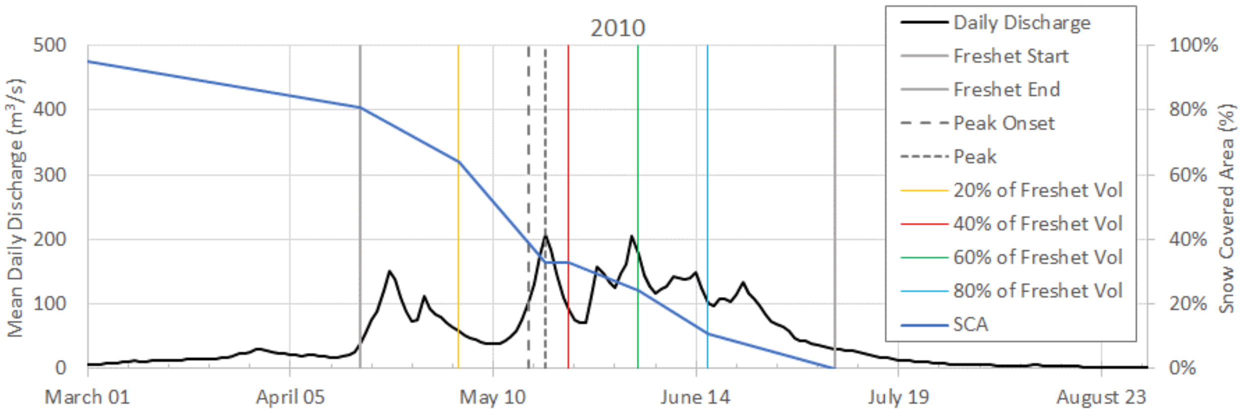


*Figure F4 (cont'd).*

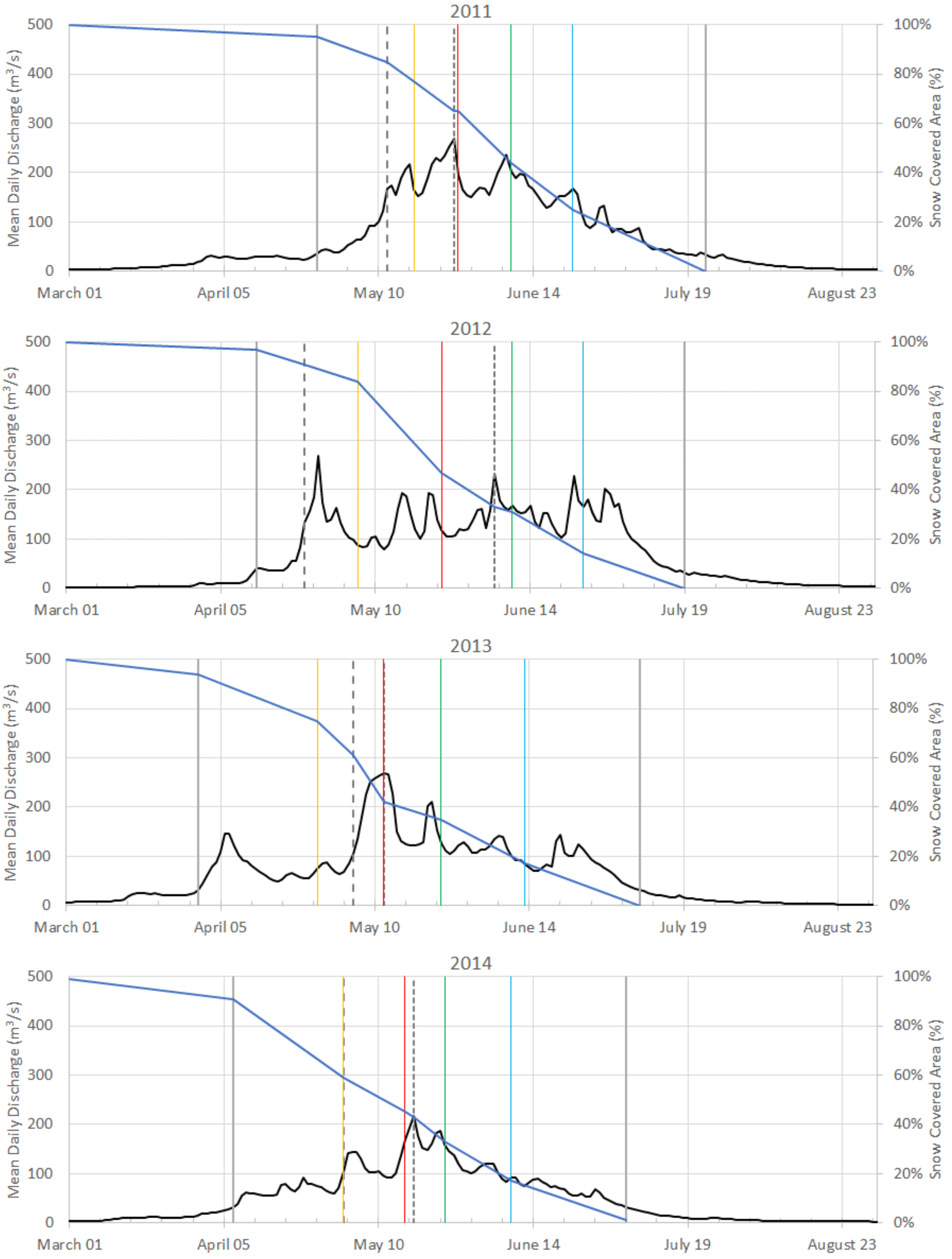


*Figure F4 (cont'd).*

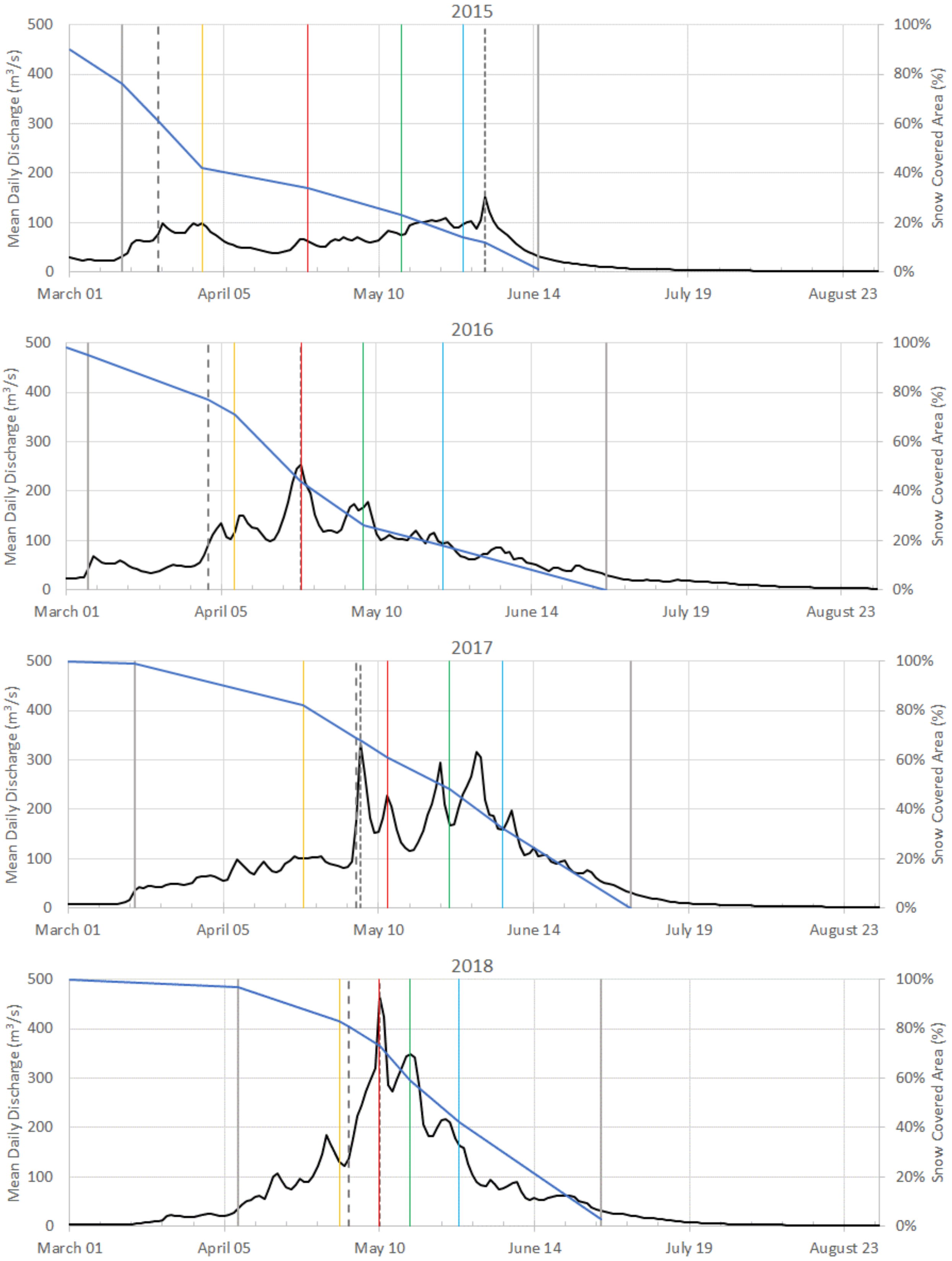


*Figure F4 (cont'd).*

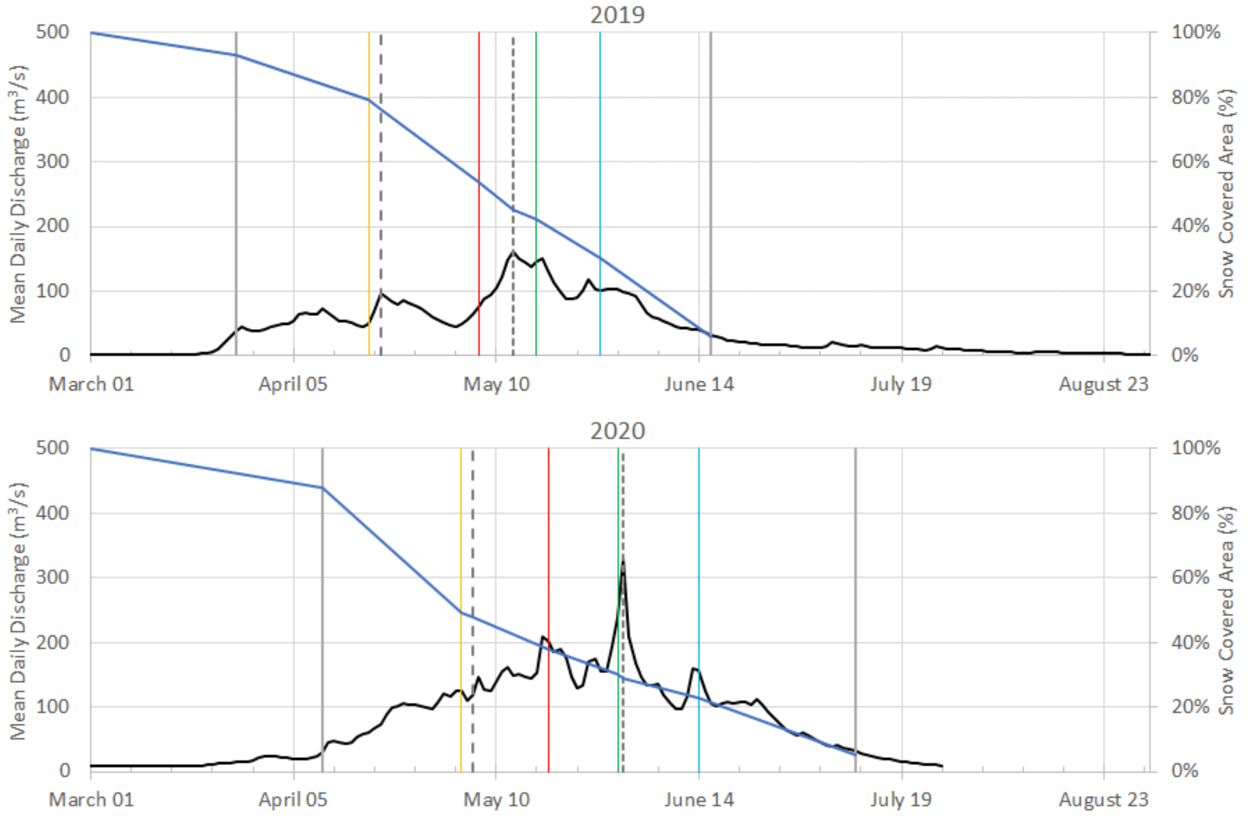


*Figure F4. Discharge measured in Granby River at Grand Forks during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable in Granby River, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 31 and 82 d after the onset of the freshet period (mean = 47 d, median = 48 d) when 34 to 88% of the cumulative freshet flow occurred (mean = 50%, median = 46%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 19% (median = 22%, range 5-29%), between 5 and 50 days after the start of the freshet flow period (mean = 25 d, median = 25 d). On average, the peak flow period began on 27 April and ended on 12 June, lasting between 26 and 79 days (mean = 47 d, median = 40 d).

## F.2 Snow Covered Area

SCA depletion curves were plotted with the freshet hydrographs in Figure F4 and together in Figure F5. In all years the SCA in the Granby River basin was less than 100% at the start of the freshet period, and in most there was no snow in the basin at the end of the freshet flow period (Table F2).

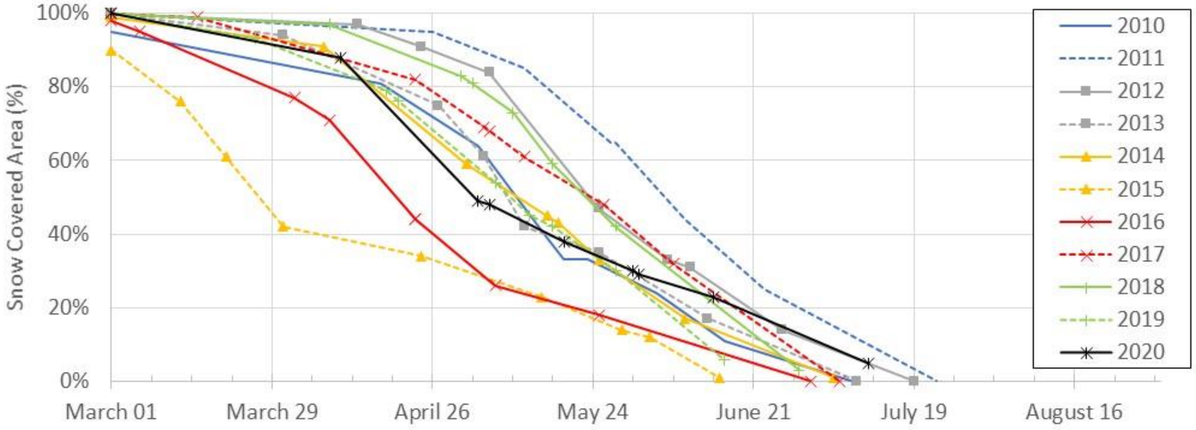


*Figure F5. Changes in snow covered area over the 2010-2020 freshet periods for the Granby River basin.*

*Table F2. Snow covered area (%) for selected dates in the Granby River basin. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 81 | 64 | 33 | 24 | 11 | 0 | 39 | 33 |
| 2011 | 95 | 77 | 65 | 44 | 25 | 0 | 85 | 65 |
| 2012 | 97 | 84 | 47 | 31 | 14 | 0 | 91 | 33 |
| 2013 | 94 | 75 | 42 | 35 | 17 | 0 | 61 | 42 |
| 2014 | 91 | 59 | 45 | 33 | 17 | 1 | 59 | 43 |
| 2015 | 76 | 42 | 34 | 23 | 14 | 1 | 61 | 12 |
| 2016 | 95 | 71 | 44 | 26 | 18 | 0 | 77 | 44 |
| 2017 | 99 | 82 | 61 | 48 | 32 | 0 | 69 | 68 |
| 2018 | 97 | 83 | 73 | 59 | 42 | 3 | 81 | 73 |
| 2019 | 93 | 79 | 54 | 42 | 30 | 6 | 76 | 45 |
| 2020 | 88 | 49 | 38 | 30 | 23 | 5 | 48 | 29 |
| **Mean:** | **91** | **70** | **49** | **36** | **22** | **2** | **68** | **44** |
| **Median:** | **94** | **75** | **45** | **33** | **18** | **0** | **69** | **43** |

Figure F6 maps the changes in SCA during each of the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow volume had occurred. A darker blue colour indicates that snow persisted longer during the freshet period, while lighter blue areas became snow-free sooner. There was a clear pattern of snow melting faster at low elevations in the catchment. Snow lingered longer in high elevation areas in the northwest of the basin, where east and west facing slopes dominate the landscape.

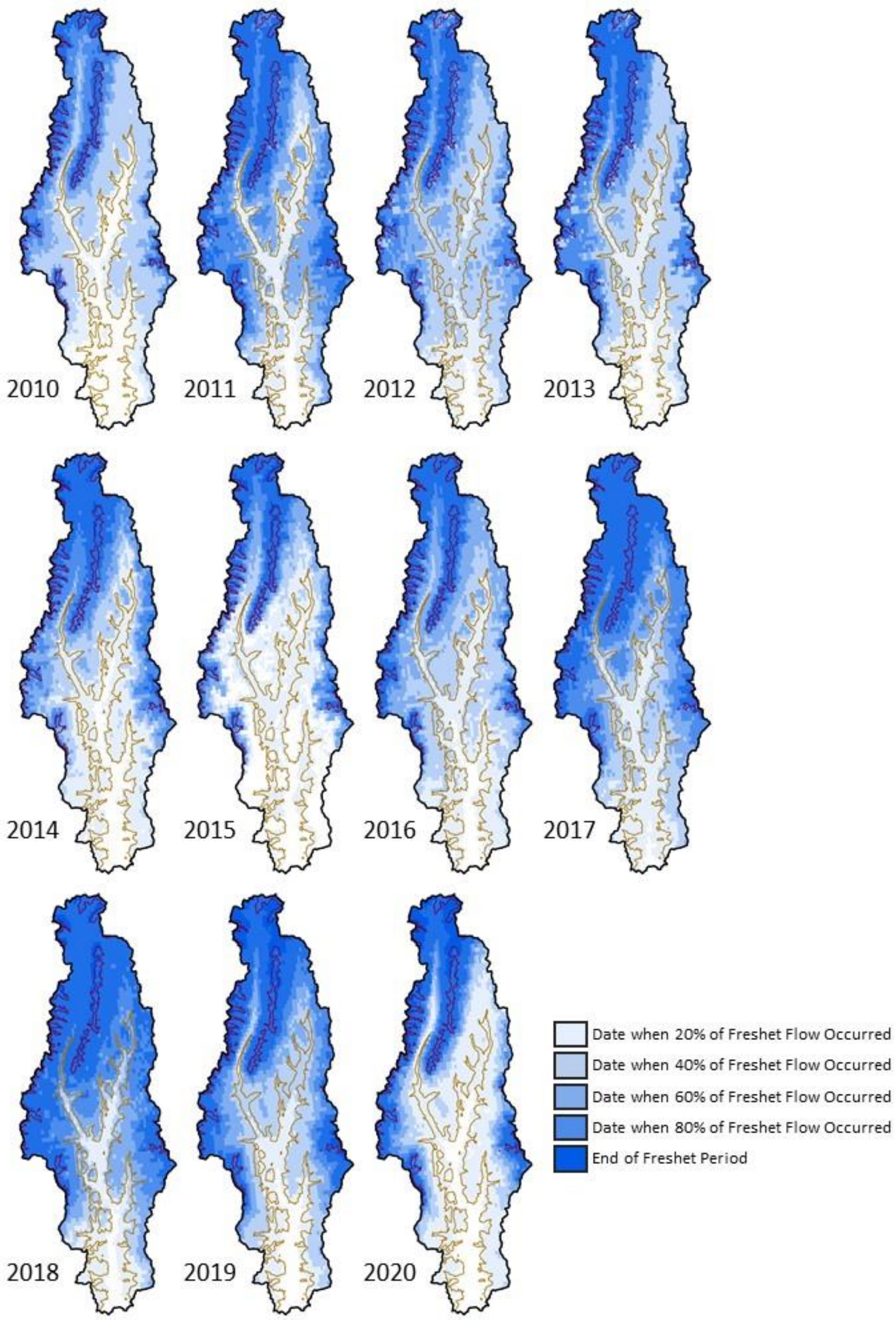


*Figure F6. The progression of snow covered area over the 2010-2020 spring freshet periods in the Granby River basin. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

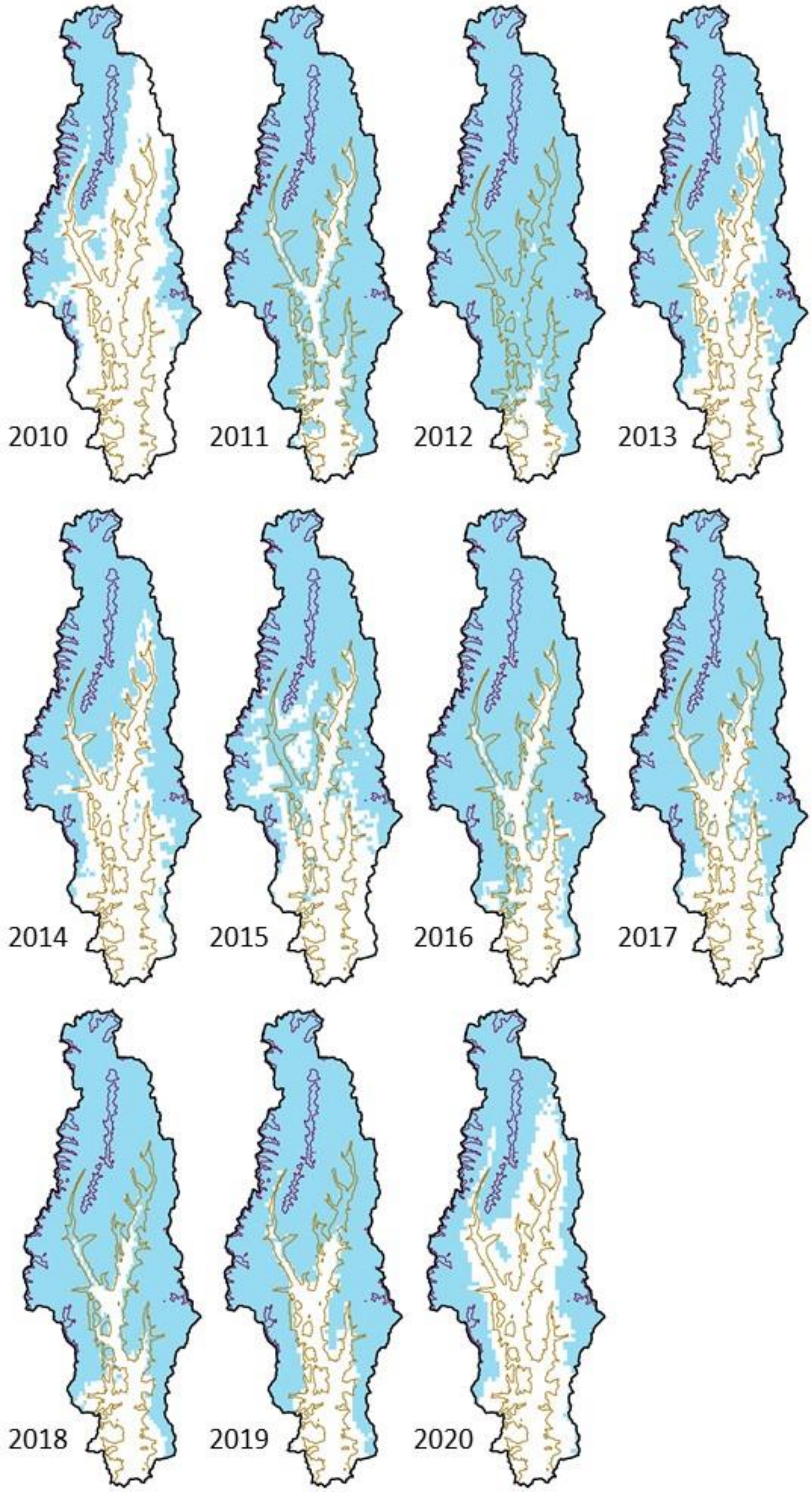


*Figure F7. Snow covered area in the Granby River basin on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

As was seen for other drainage basins in this analysis, the 2015 freshet period was unusual. The weather summary provided by the B.C. River Forecast Centre as part of the Snow Survey and Water Supply Bulletins noted the persistence of a ‘warm blob’ of ocean water off the coast of B.C. that resulted in warmer than normal temperatures in January, February and March (Appendix K). Precipitation during those months fell as rain at lower elevations instead of snow. In April, there was no snow at low and middle elevations, which was much earlier than normal. These conditions explain the low SCA recorded at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure F5).

The basin was 39-91% snow covered at the onset of the peak flow period, with a median of 69% (mean = 68%) (Figure F7). These results indicated that snowmelt over more than two thirds of the basin area contributes snowmelt to peak flow in the Granby River.

### F.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from the SCA maps for the onset of the peak flow period (Figure F7). Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure F6). Median SCA at the onset of the peak flow period was 69%. SCA measured in 2017 was equal to the multi-year median, so this year was selected to define the SSZ (Figure F8).

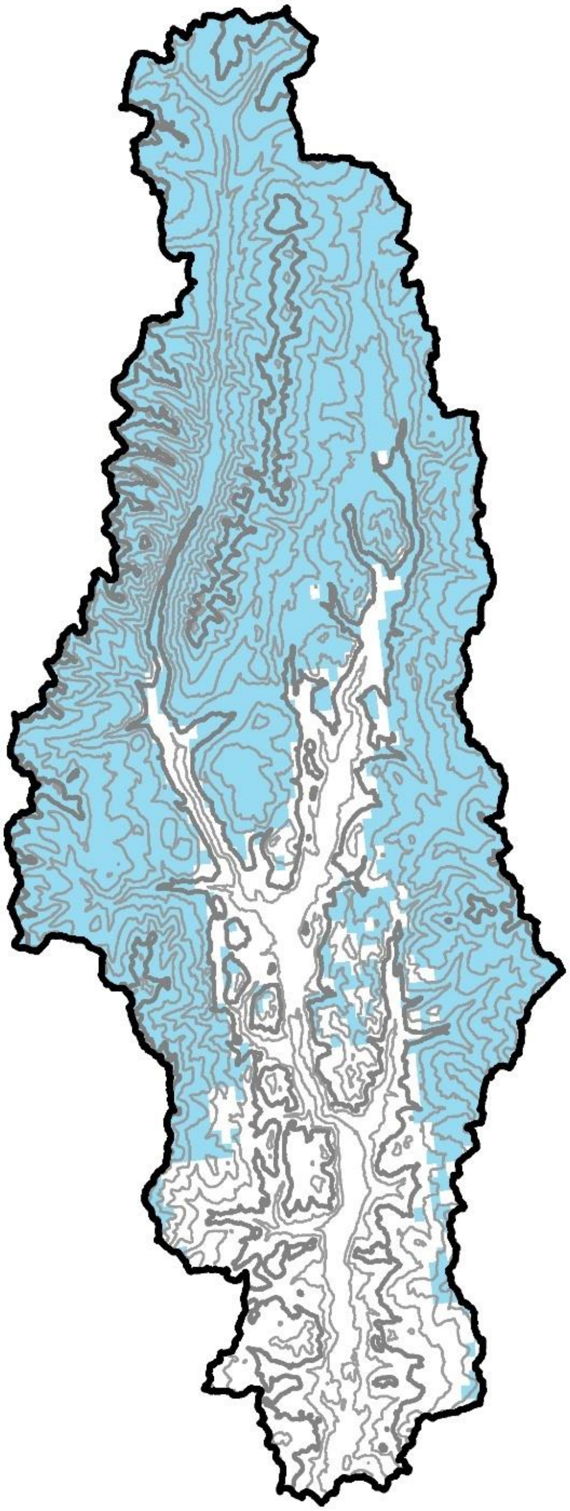
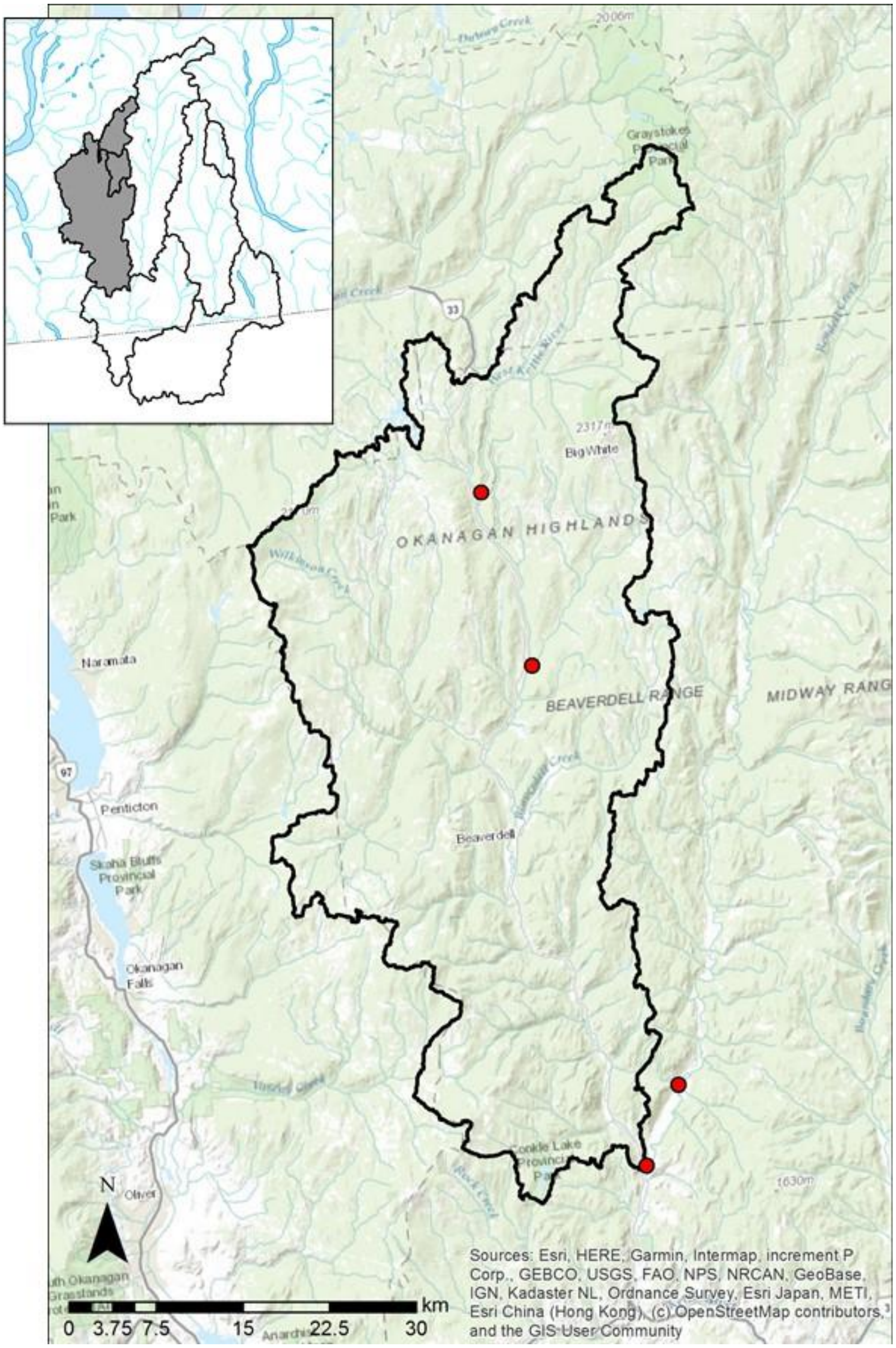


*Figure F8. The snow sensitive zone of the Granby River basin. Elevation contour interval is 200 m; the 1000 and 2000 m contours are bolded.*

# APPENDIX G: WEST KETTLE RIVER AT WESTBRIDGE



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure G1. Map showing the drainage area for the West Kettle River at Westbridge, a tributary to Kettle River. The basin is outlined in black and the locations of hydrometric stations are shown with red circles. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

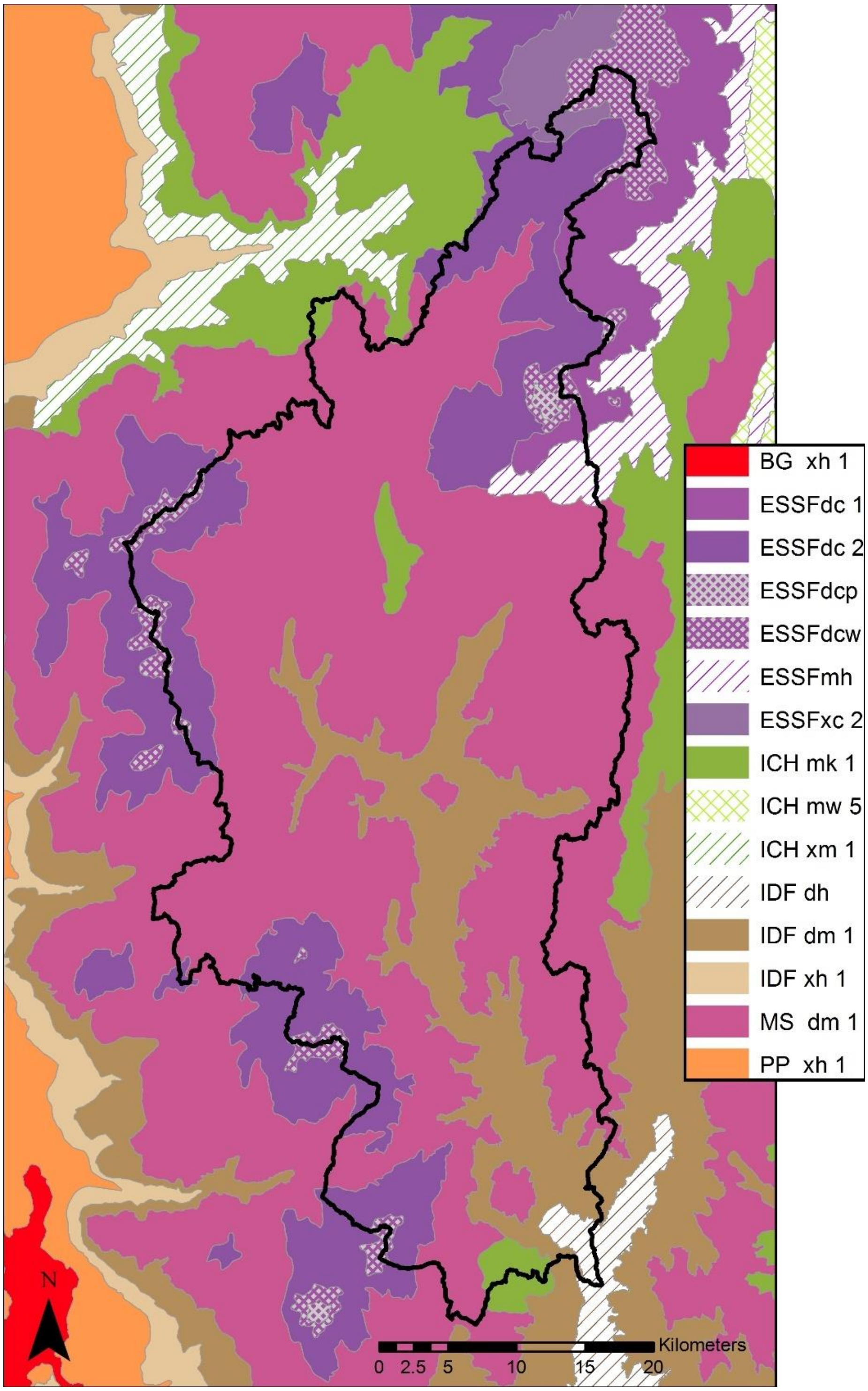


*Figure G2. Map of the drainage area for West Kettle River at Westbridge showing BEC subzones and elevation. The basin is outlined in black.*

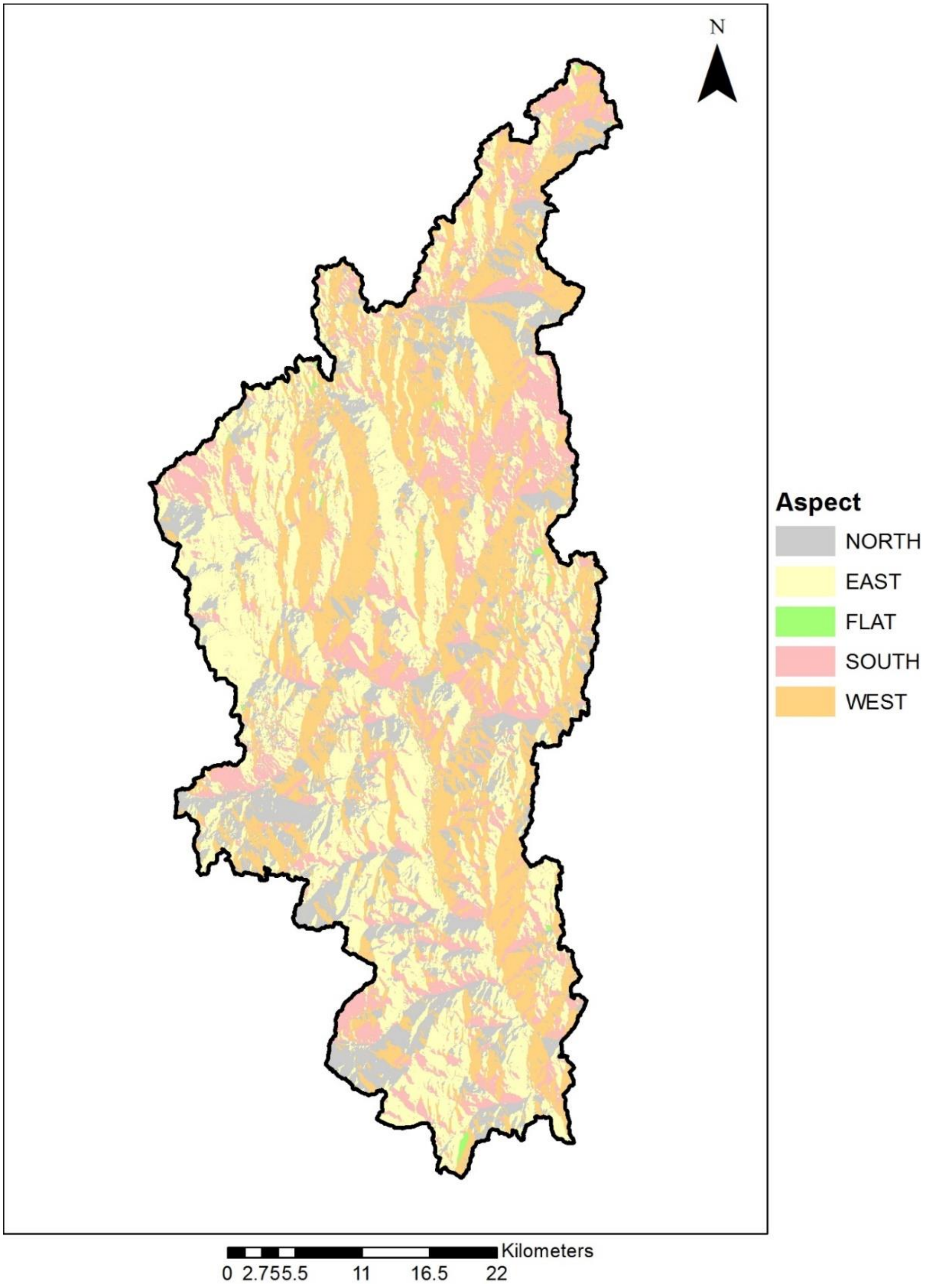


*Figure G3. Slope aspect map of the drainage area for West Kettle River at Westbridge. The basin is outlined in black.*

## G.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN003 West Kettle River at Westbridge for 2010-2019 were published and for 2020 were provisional at the time of this analysis.

Year-round hydrometric data was not available for the station on West Kettle River at Westbridge until 2008, so the long term mean annual discharge which is needed to identify the annual freshet period could not be calculated. Instead, the freshet start and end dates from another available station was used. To decide which station had the most similar flow regime and could be used as a proxy, cumulative discharge volumes for each year were compared. Using the freshet start and end dates identified for each of the other Kettle River stations, time series of cumulative daily discharge volume were calculated for West Kettle River at Westbridge over the 2010-2020 freshet periods. Plots indicated that the progression of freshet discharge for the West Kettle River tributary most closely matched that for the Kettle River near Laurier (Figure G4). In most years discharge at the West Kettle station increased more rapidly than at the downstream station, causing the curves to plot above the 1:1 line, but there was generally a good fit in the early part of the freshet period. The freshet start and end dates for Kettle River near Laurier were used to analyse snow covered area for West Kettle River at Westbridge (Table G1).

The West Kettle River freshet hydrographs for 2010-2020 rarely showed a single dominant peak (Figure G5), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There are no large lakes or significant storage in wetlands, so the hydrograph is relatively responsive to melt and precipitation inputs.

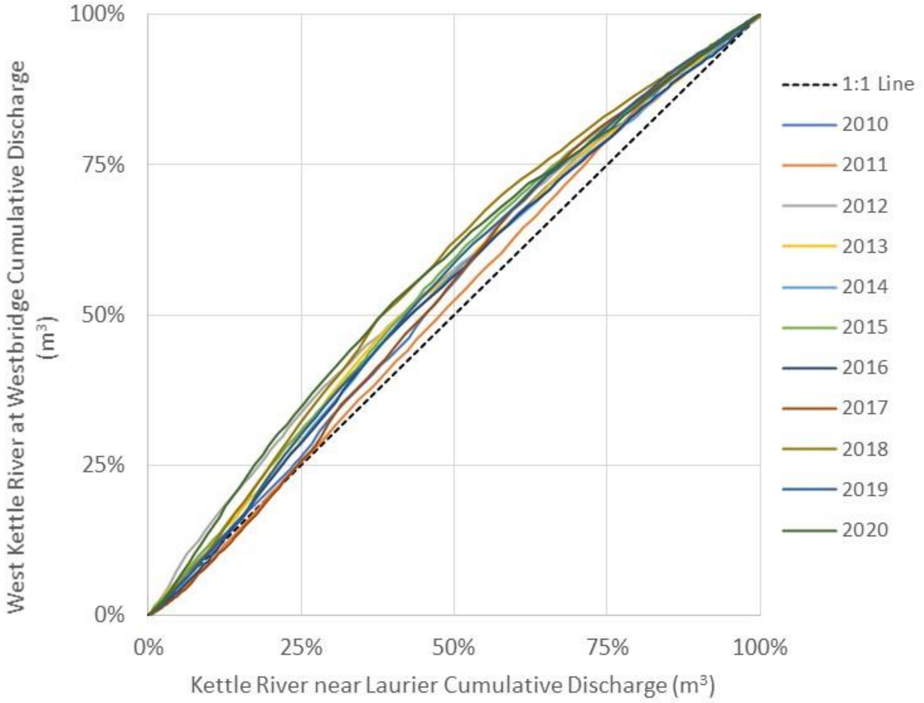


*Figure G4. Cumulative freshet period discharge for West Kettle River at Westbridge (WSC 08NN003) compared to Kettle River near Laurier (WSC 08NN012), 2010-2020.*

*Table G1. Freshet flow period dates for West Kettle River at Westbridge (WSC station ID 08NN003). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both the mean and median dates are shown.*

| **Year** | **Freshet Period*** | | **Peak Flow Period** | | | **Peak Flow Date** |
|---|---|---|---|---|---|---|
| | **Start** | **End** | **Start** | **End** | **Duration** | |
| 2010 | 18 April | 10 July | 16 May | 23 June | 38 | 19 May |
| 2011 | 27 April | 29 July | 11 May | 24 June | 44 | 23 May |
| 2012 | 19 April | 28 July | 24 April | 4 July | 71 | 27 April |
| 2013 | 1 April | 12 July | 4 May | 26 June | 53 | 9 May |
| 2014 | 10 April | 8 July | 2 May | 5 June | 34 | 17 May |
| 2015 | 14 March | 17 June | 21 Mar | 5 June | 76 | 31 March |
| 2016 | 7 March | 2 July | 2 April | 25 May | 53 | 22 April |
| 2017 | 19 March | 5 July | 20 April | 5 June | 46 | 6 May |
| 2018 | 8 April | 4 July | 25 April | 26 May | 31 | 10 May |
| 2019 | 31 March | 16 June | 19 April | 28 May | 39 | 20 April |
| *2020* | *12 April* | *14 July* | *22 April* | *3 June* | *42* | *18 May* |
| **Mean:** | **4 April** | **8 July** | **23 April** | **10 June** | **48** | **4 May** |
| **Median:** | **8 April** | **8 July** | **25 April** | **5 June** | **44** | **8 May** |

** From the Kettle River near Laurier station.*

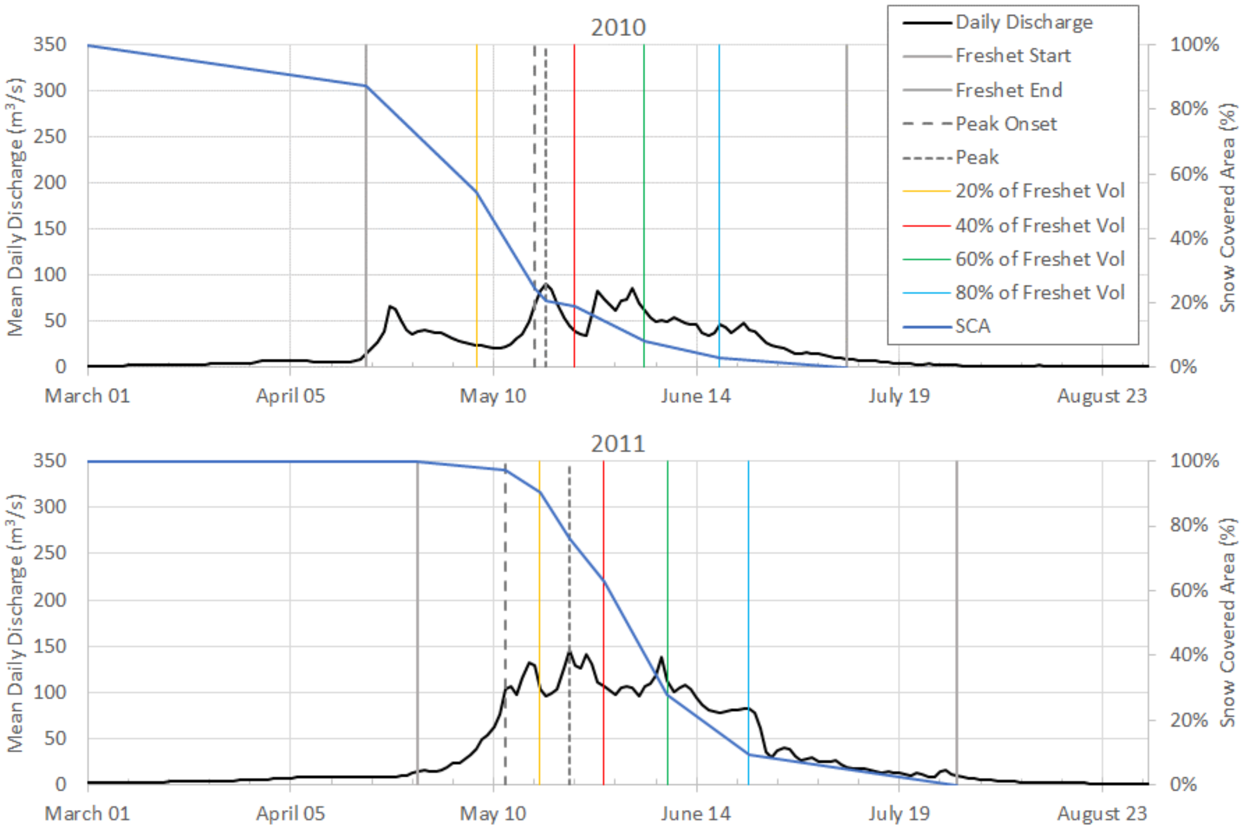


*Figure G5 (cont'd).*

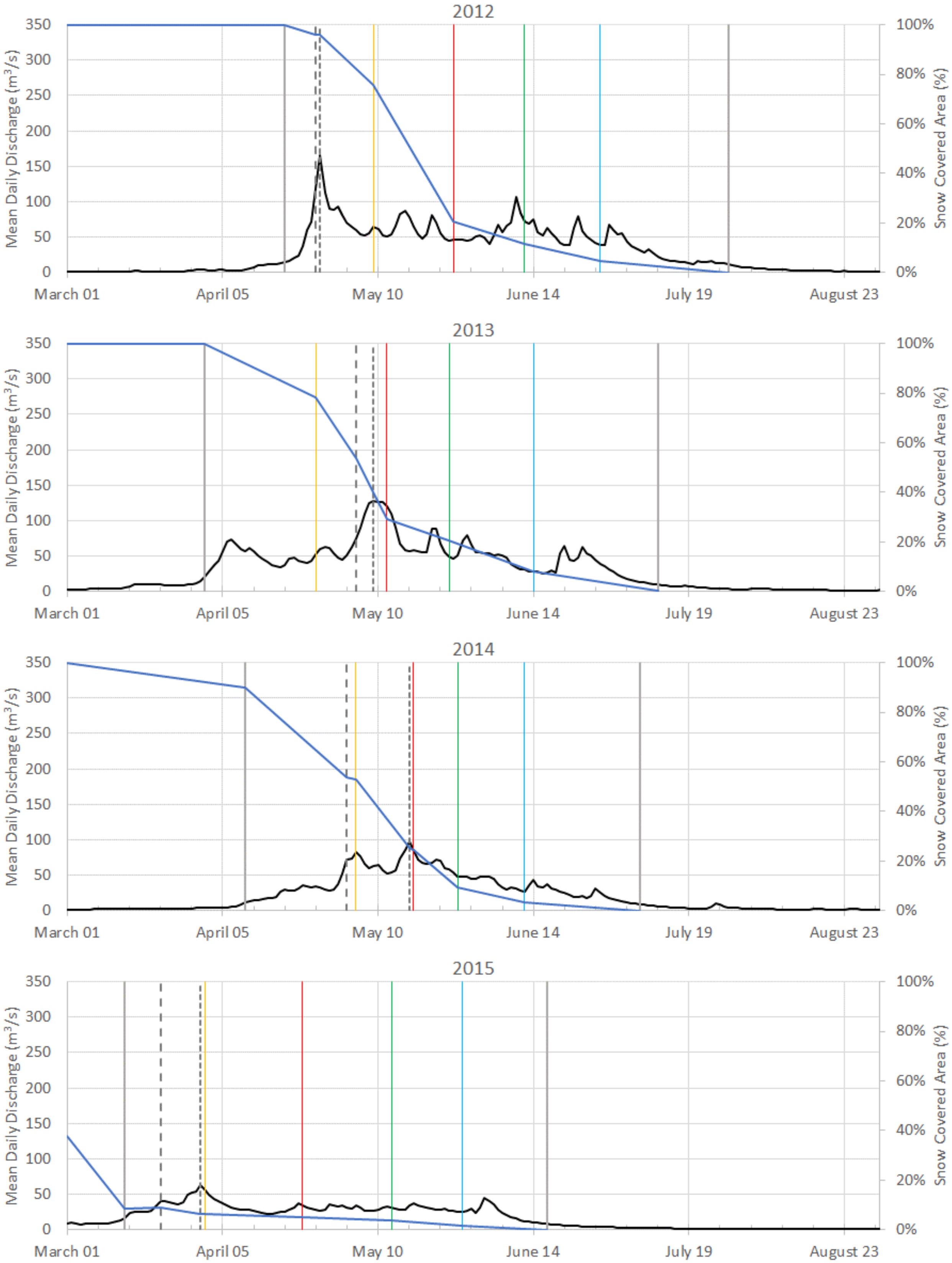


*Figure G5 (cont'd).*

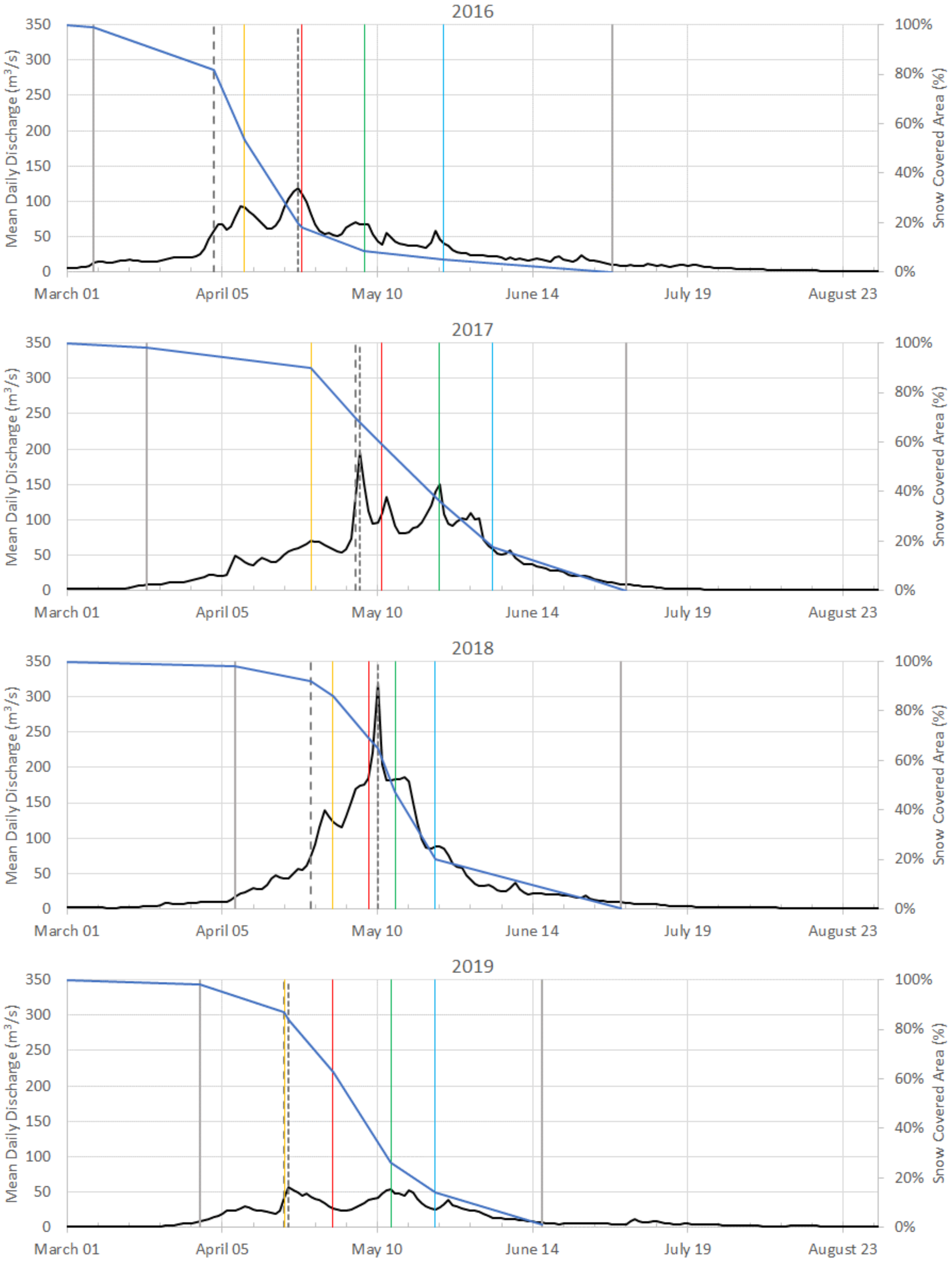


*Figure G5 (cont'd).*

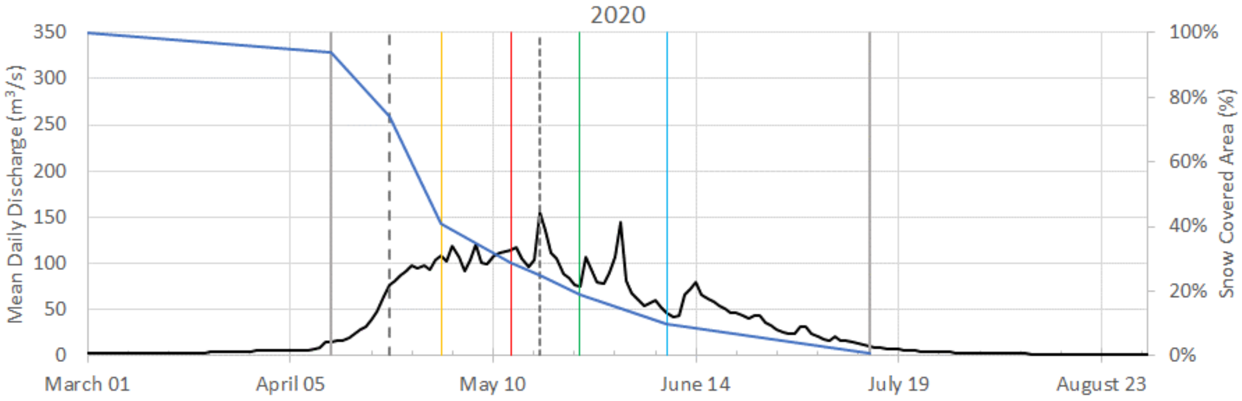


*Figure G5. Discharge measured in West Kettle River at Westbridge during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was variable in West Kettle River, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 8 and 48 d after the onset of the freshet period (mean = 31 d, median = 32 d), when 10 to 50% of the cumulative freshet flow occurred (mean = 35%, median = 36%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 15% (median = 12%, range 3-31%), between 5 and 33 days after the start of the freshet flow period. On average, the peak flow period began on 23 April and ended on 10 June, lasting between 31 and 76 days (mean = 48 d, median = 44 d).

## G.2 Snow Covered Area

SCA depletion curves are plotted with the freshet hydrographs in Figure G5, and together in Figure G6. In most years SCA was near 100% at the start of the freshet period, and in all years there was very little or no snow in the basin at the end of the freshet flow period (Table G2). SCA generally decreased rapidly after reaching 80%.

Figure G7 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. There was a clear pattern of snow melting away earlier at low elevations in the catchment. Snow lingered longer in high elevation areas in the west and north part of the basin.

As was found for other basins in the regions, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in warmer than normal January, February and March (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the very low SCA recorded at the start of the 2015 freshet period. SCA remained very low throughout the period, and the catchment became snow free much earlier (Figure G6).

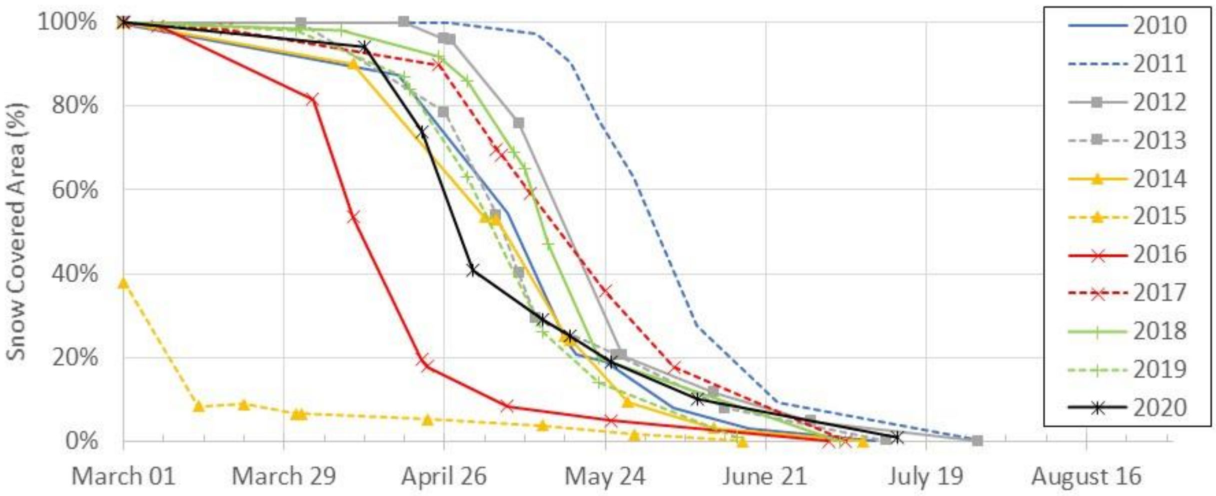


*Figure G6. Changes in snow covered area over the 2010-2020 freshet periods for the West Kettle River above Westbridge.*

*Table G2. Snow covered area (%) for selected dates in the West Kettle River basin. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 87 | 54 | 19 | 8 | 3 | 0 | 24 | 21 |
| 2011 | 100 | 90 | 63 | 28 | 9 | 0 | 97 | 76 |
| 2012 | 100 | 76 | 20 | 12 | 5 | 0 | 96 | 96 |
| 2013 | 100 | 79 | 29 | 21 | 8 | 0 | 54 | 40 |
| 2014 | 90 | 53 | 24 | 9 | 3 | 0 | 54 | 25 |
| 2015 | 8 | 7 | 5 | 4 | 2 | 0 | 9 | 7 |
| 2016 | 99 | 53 | 18 | 8 | 5 | 0 | 82 | 20 |
| 2017 | 98 | 90 | 59 | 36 | 18 | 0 | 70 | 68 |
| 2018 | 98 | 86 | 69 | 47 | 20 | 0 | 92 | 65 |
| 2019 | 98 | 87 | 63 | 26 | 14 | 1 | 87 | 84 |
| 2020 | 94 | 41 | 29 | 19 | 10 | 1 | 74 | 25 |
| **Mean:** | **87** | **65** | **34** | **19** | **8** | **0** | **67** | **48** |
| **Median:** | **98** | **76** | **29** | **19** | **8** | **0** | **74** | **40** |

This basin was 9-97% snow covered at the onset of the peak flow period, with a median value of 74% (mean = 67%) (Figure G8). These results indicated that snowmelt over more than two thirds of the basin contributes to peak flow in the West Kettle River.

## G.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from SCA maps for the onset of the peak flow period (Figure G8). Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure G8). Median SCA was 74%. SCA measured in 2020 was equal to the median value, so this year was used to define the SSZ (Figure G9).

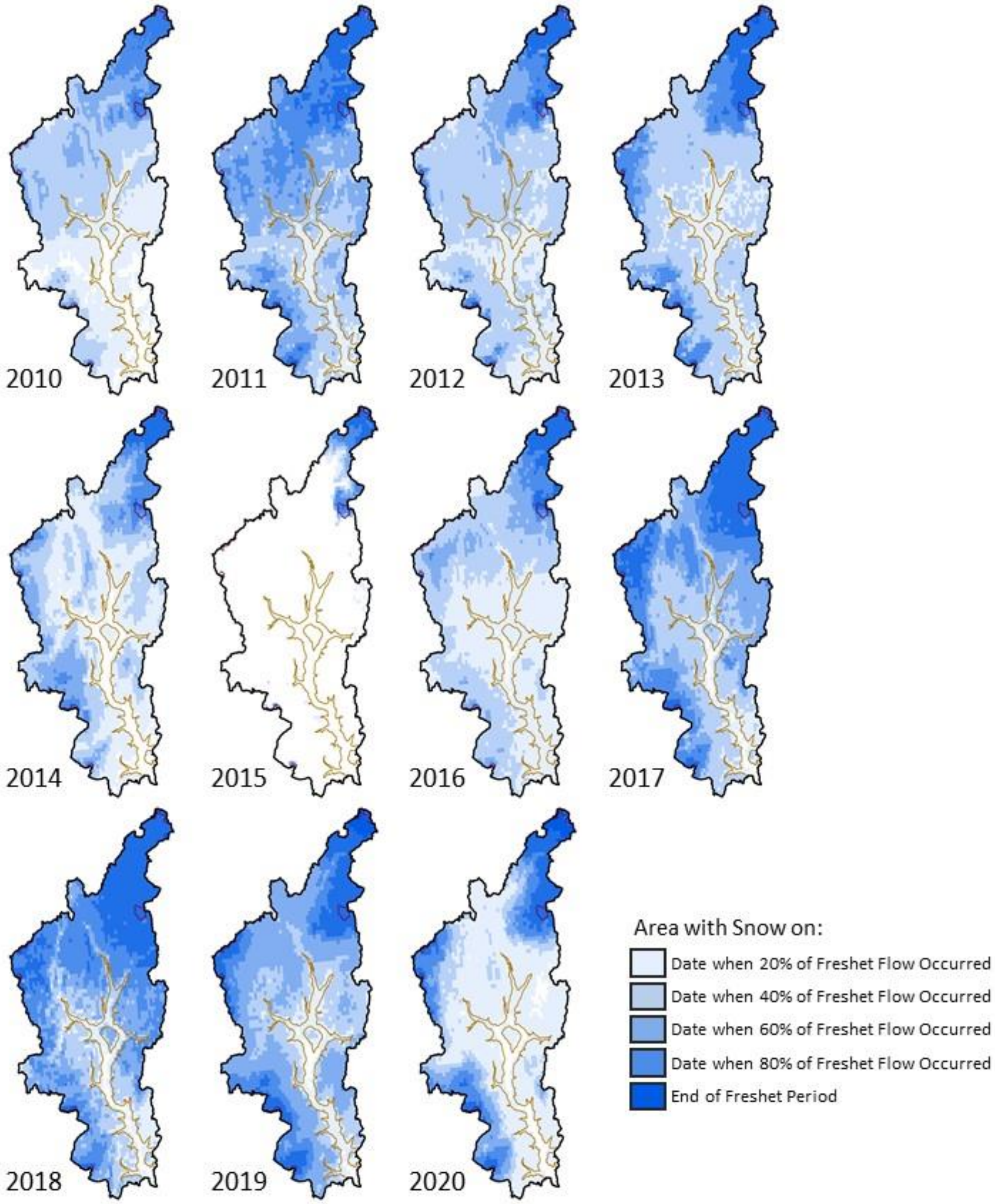


*Figure G7. The progression of snow covered area over the 2010-2020 spring freshet periods in the West Kettle River basin. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

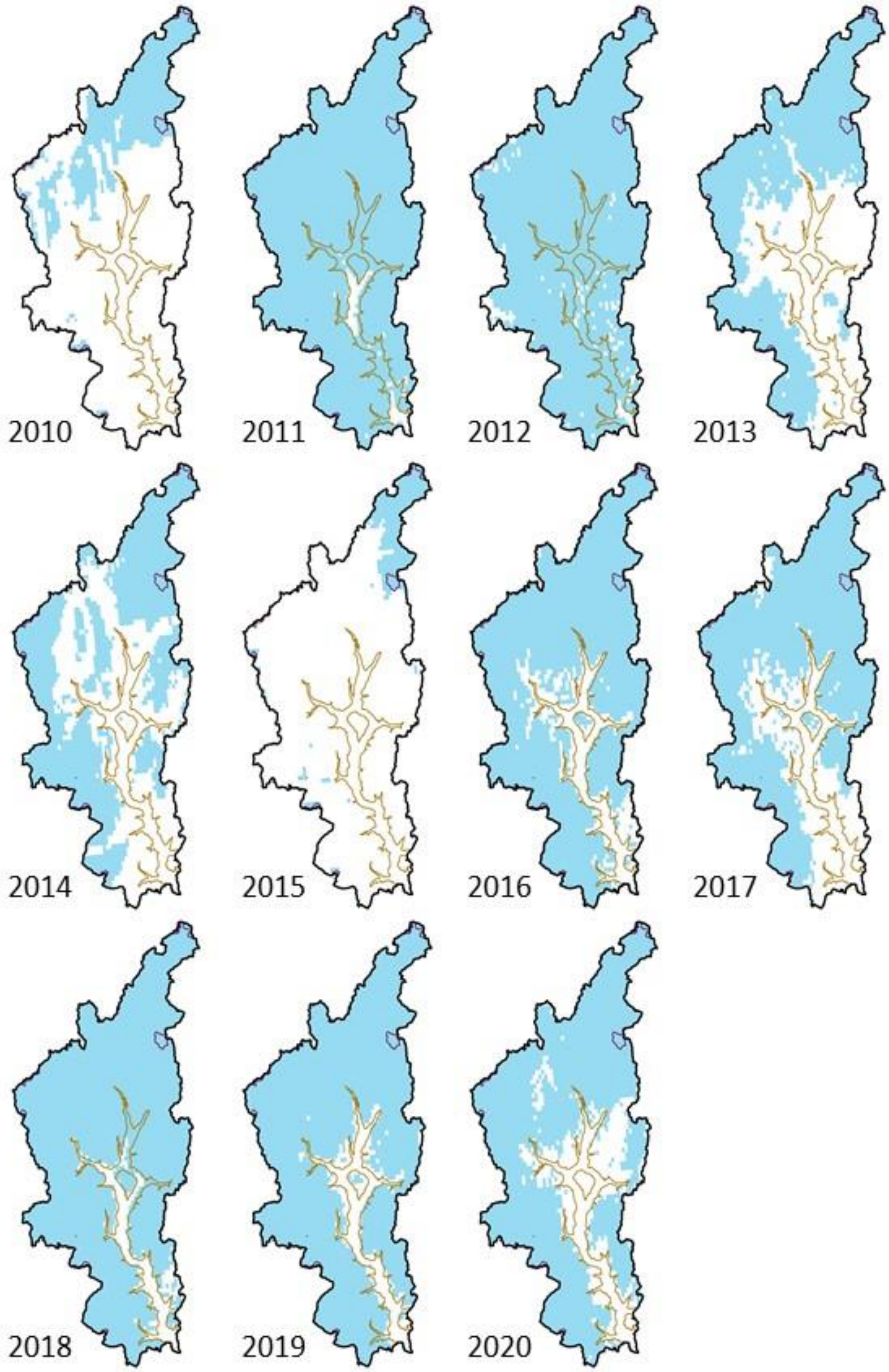


*Figure G8. Snow covered area in the West Kettle River basin on the date of onset of the peak flow period, 2010-2020. Brown and purple lines are the 1000 and 2000 m elevation contours, respectively.*

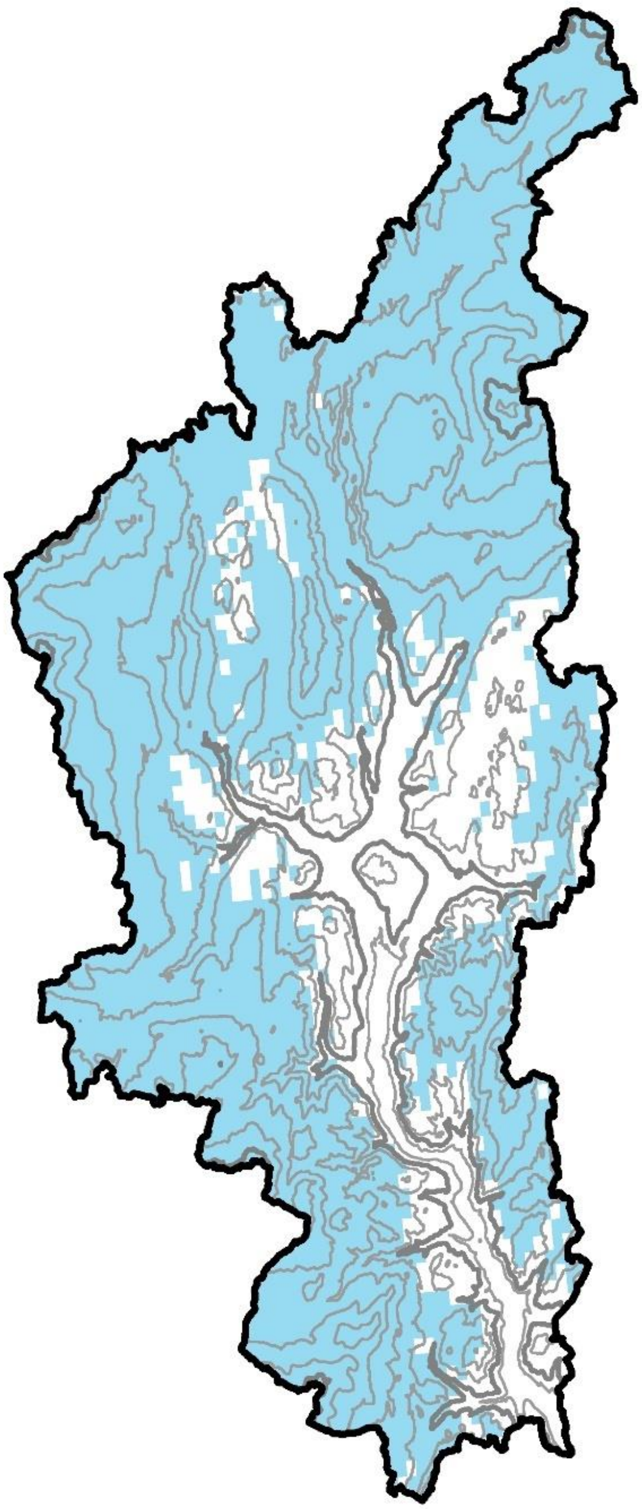
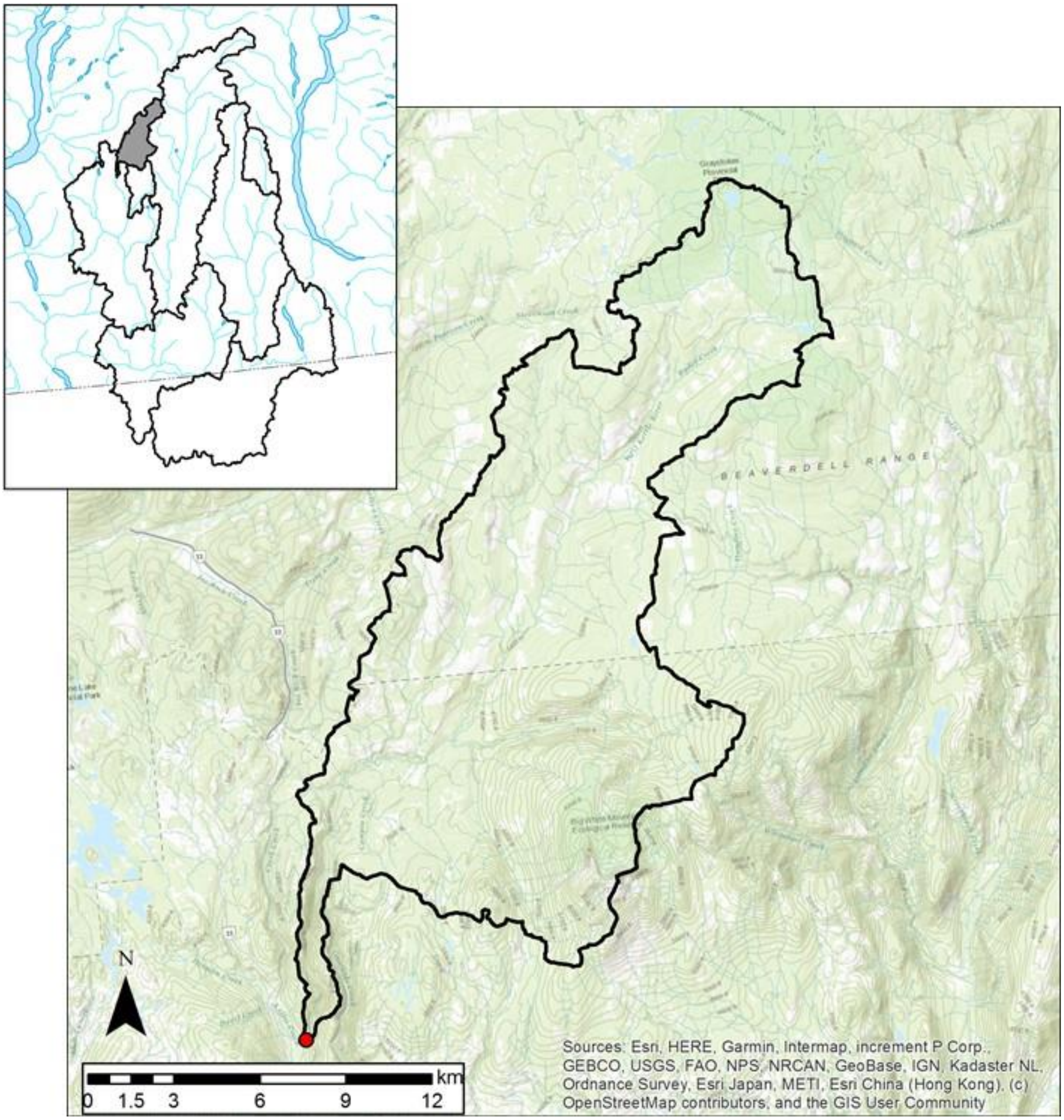


*Figure G9. The "snow sensitive zone" of the West Kettle River basin. Elevation contour interval is 200 m; the 1000 and 2000 m contours are bolded.*

## APPENDIX H: WEST KETTLE RIVER NEAR MCCULLOCH



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure H1. Map showing the drainage area for the West Kettle River near McCulloch. The basin is outlined in black and the location of the hydrometric station is shown with a red circle. The inset map shows this basin 9in grey) in the context of all of the Kettle River basins included in this study.*

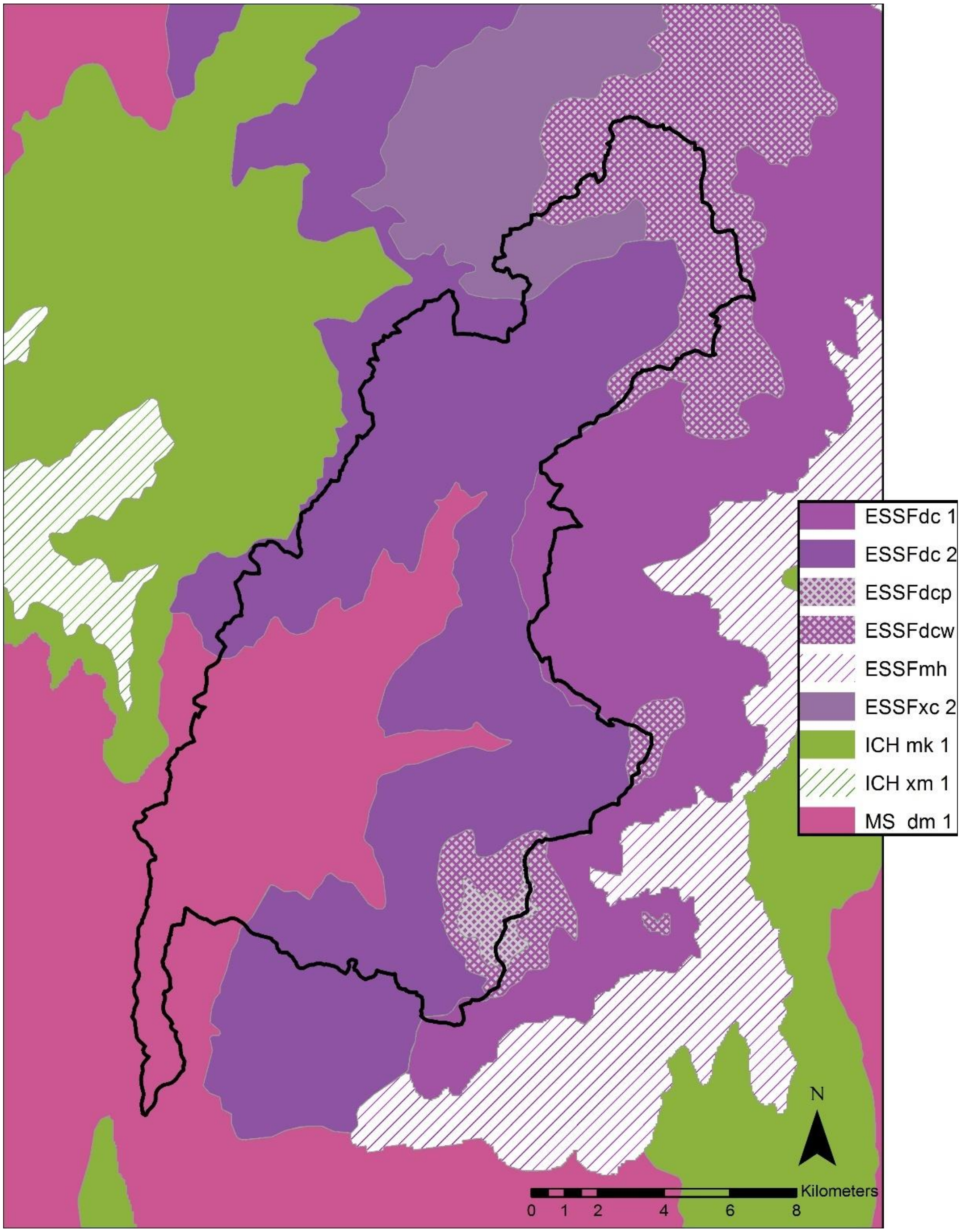


*Figure H2. Map of the drainage area for West Kettle River near McCulloch showing BEC subzones and elevation. The basin is outlined in black.*

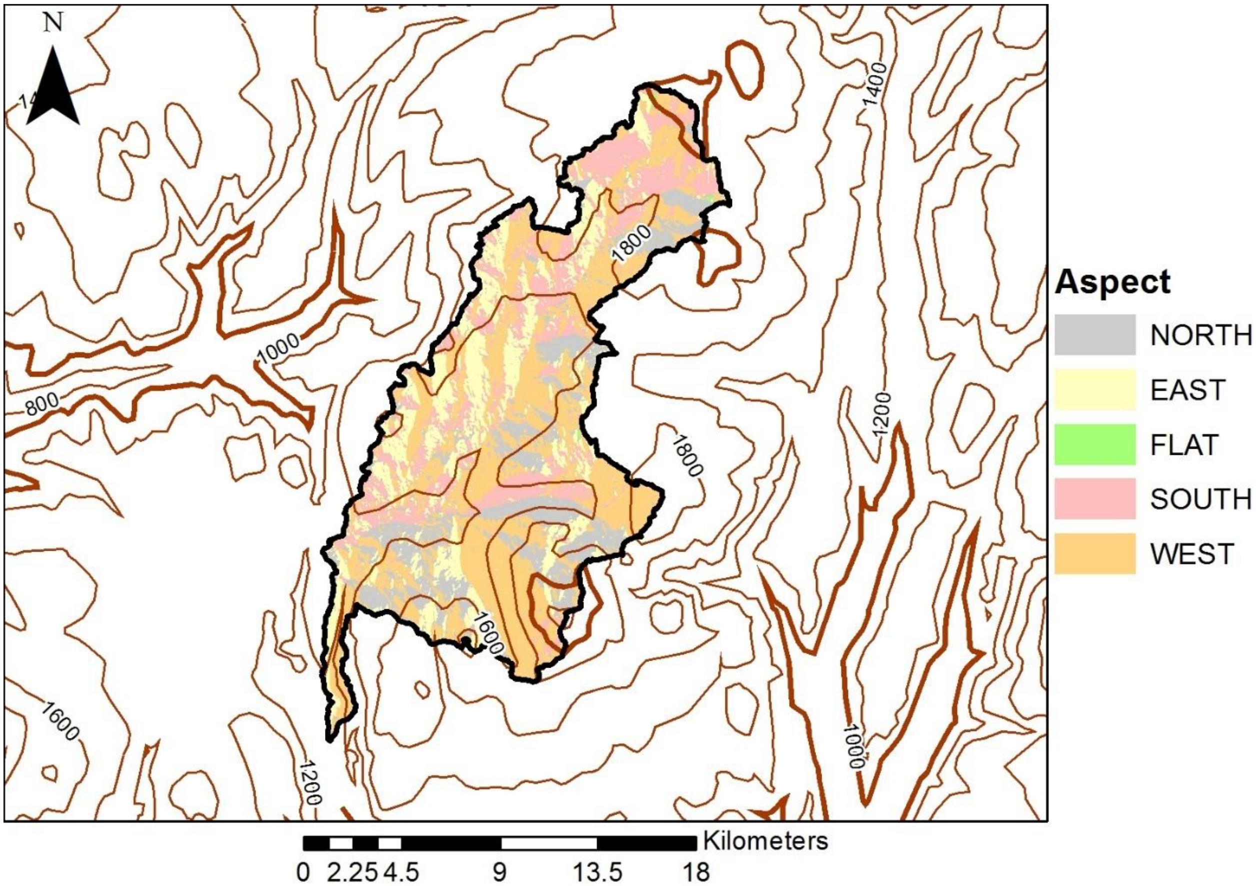


*Figure H3. Slope aspect map of the West Kettle River basin near McCulloch. The basin is outlined in black and elevation contours are brown (contour interval is 200 m).*

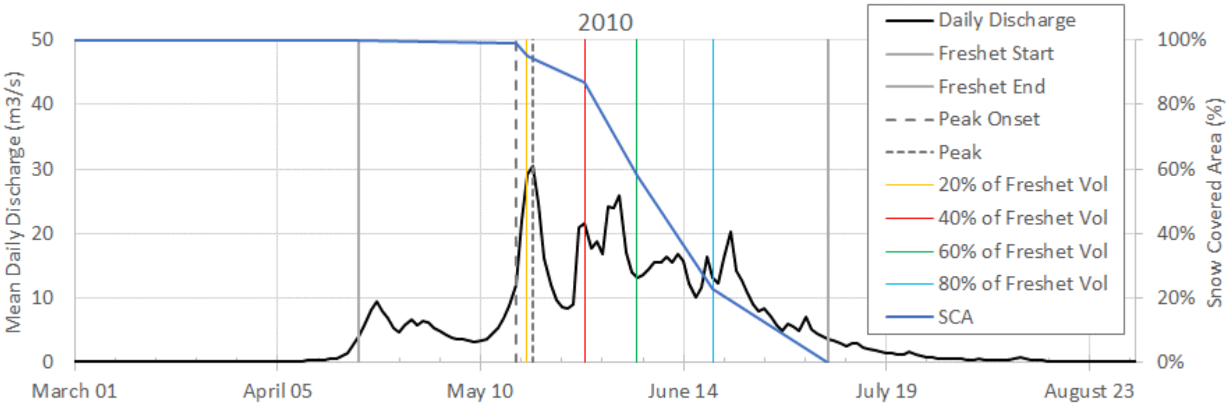
## H.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN015 West Kettle River near McCulloch for 2010-2019 were published and for 2020 were provisional at the time of this analysis. The freshet flow period (when daily mean discharge was greater than the station's long term mean) for 2010-2020 lasted between 56 and 109 days (mean = 77 d, median = 79 d), with the shortest in 2019 and the longest in 2016 (Table H1). On average, freshet began on 21 April and ended on 10 July; the earliest it began was 4 April in 2016, and the latest was 8 May in 2011.

The freshet hydrographs for West Kettle River near McCulloch between 2010 and 2020 rarely showed a single dominant peak (Figure H4), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There is no significant attenuation by lakes or wetlands so the hydrograph is responsive to melt and precipitation inputs.

*Table H1. Freshet flow period dates for West Kettle River near McCulloch (08NN015). Values in italics were derived from provisional hydrometric data. Because of the small sample size, mean and median dates are shown.*

| Year | Freshet Period | | | Peak Flow Period | | | Peak Flow Date |
|---|---|---|---|---|---|---|---|
| | Start | End | Duration (# days) | Start | End | Duration (# days) | |
| 2010 | 19 April | 9 July | 81 | 16 May | 24 June | 39 | 19 May |
| 2011 | 8 May | 28 July | 81 | 19 May | 24 June | 36 | 8 June |
| 2012 | 23 April | 27 July | 95 | 14 May | 4 July | 51 | 10 June |
| 2013 | 19 April | 7 July | 79 | 6 May | 8 June | 33 | 22 May |
| 2014 | 30 April | 7 July | 68 | 14 May | 17 June | 34 | 17 May |
| 2015 | 18 April | 14 June | 57 | 10 May | 6 June | 27 | 2 June |
| 2016 | 4 April | 22 July | 109 | 18 April | 6 June | 49 | 22 April |
| 2017 | 20 April | 1 July | 72 | 5 May | 9 June | 35 | 5 May |
| 2018 | 26 April | 5 July | 70 | 4 May | 29 May | 25 | 9 May |
| 2019 | 19 April | 14 June | 56 | 8 May | 3 June | 26 | 12 May |
| *2020* | *22 April* | *14 July* | *83* | *10 May* | *25 June* | *46* | *31 May* |
| **Mean:** | **21 April** | **10 July** | **77** | **8 May** | **14 June** | **36** | **20 May** |
| **Median:** | **19 April** | **7 July** | **79** | **10 May** | **9 June** | **35** | **19 May** |



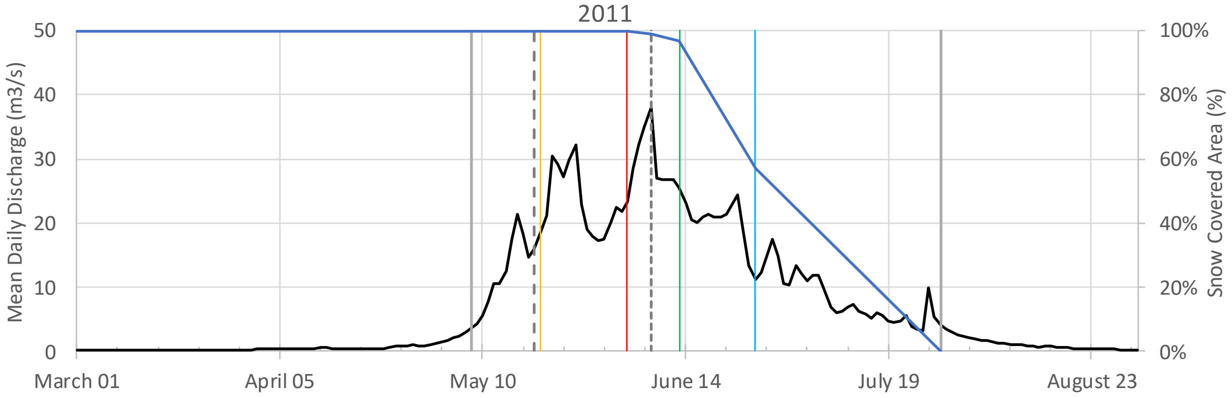


*Figure H4 (cont'd).*

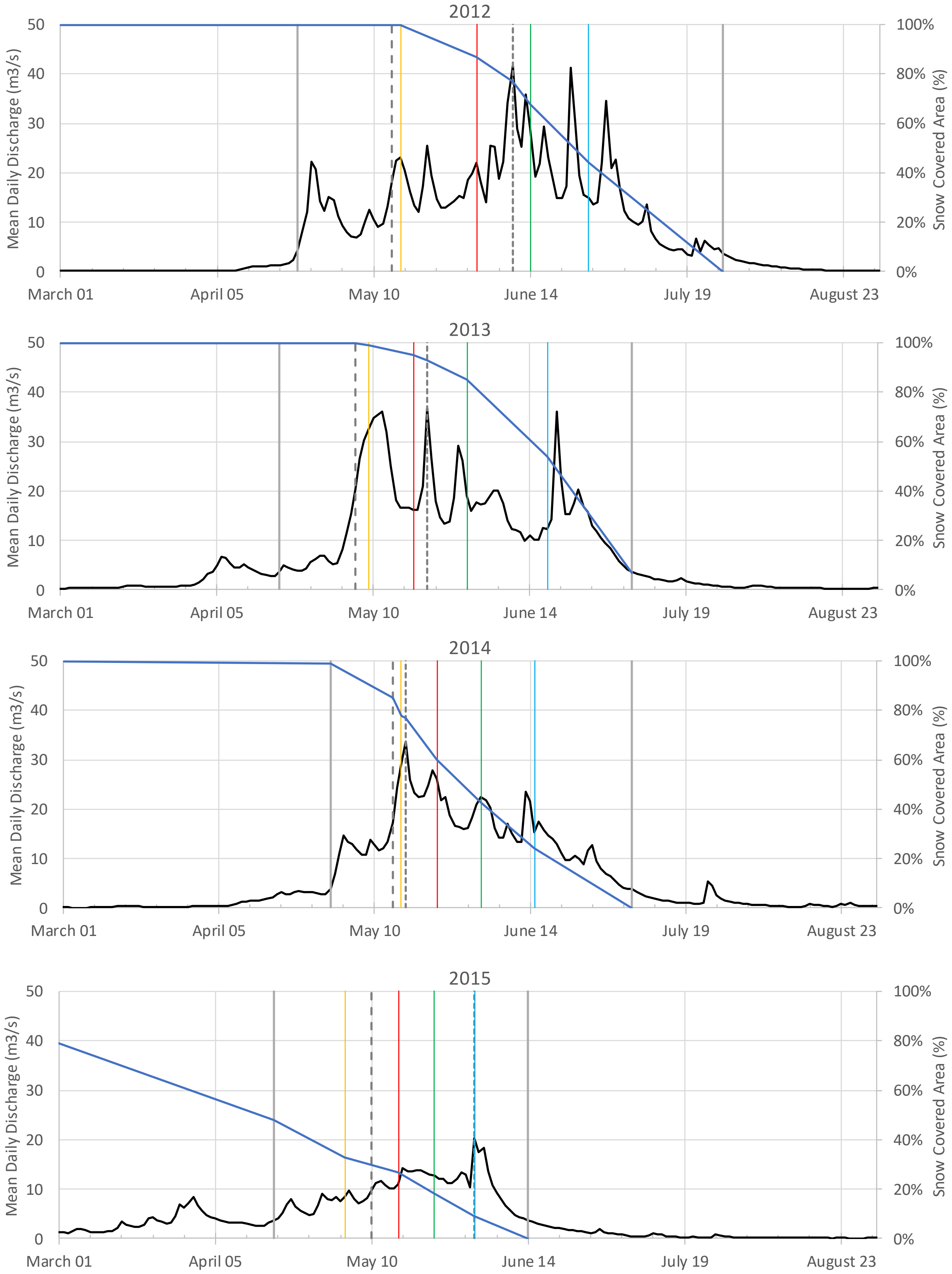


*Figure H4 (cont'd).*

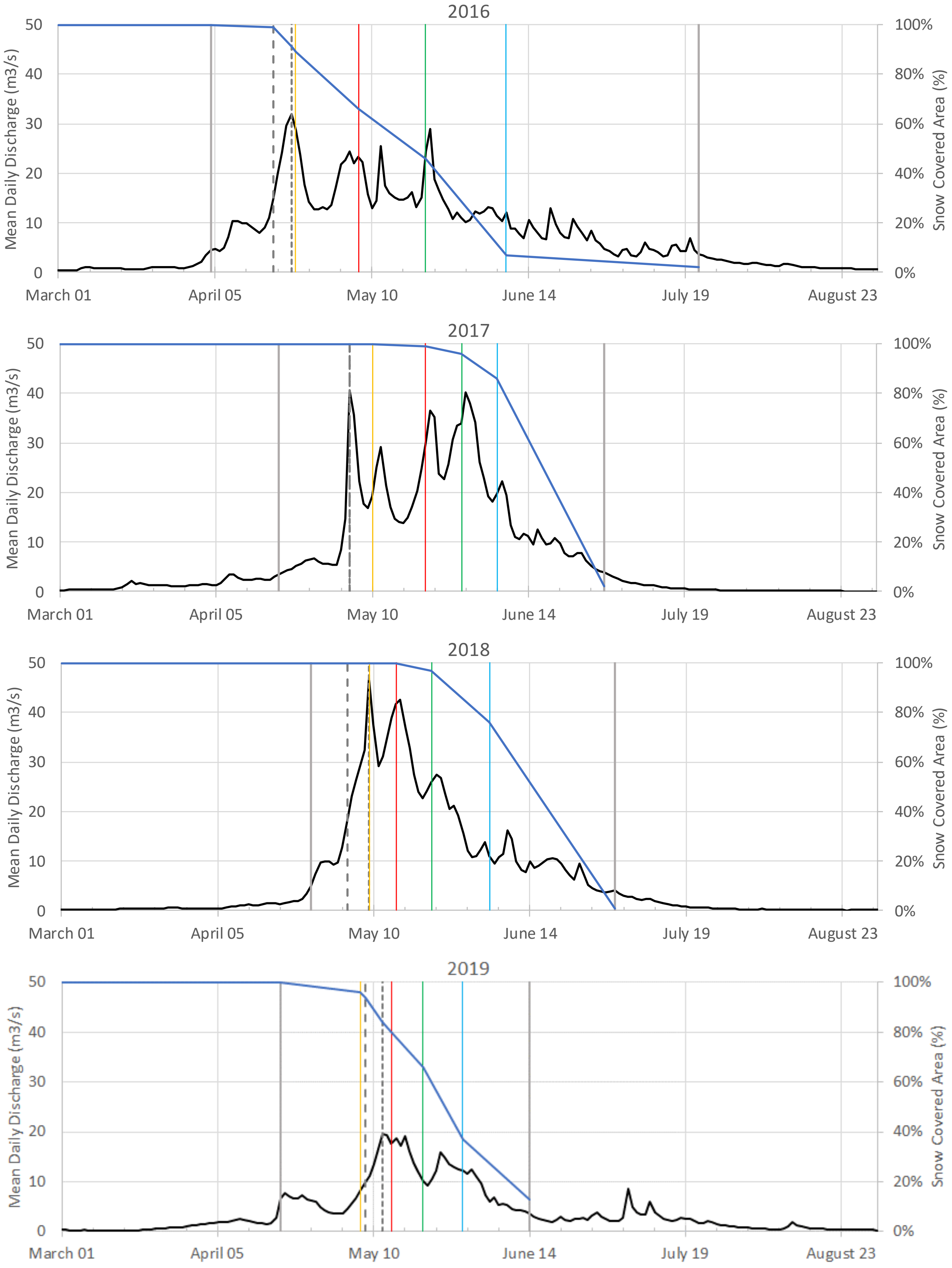


*Figure H4 (cont'd).*

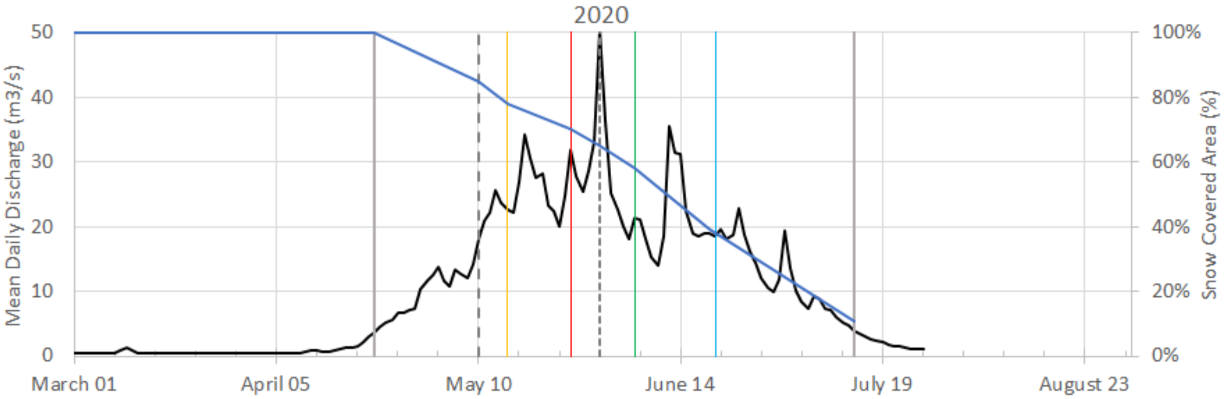


*Figure H4. Discharge in West Kettle River near McCulloch during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The date of peak flow was highly variable in West Kettle River near McCulloch, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed period of cumulative freshet flow. Peak flow occurred between 13 and 48 days after the onset of the freshet period (mean = 28 d, median = 30 d), when 11 to 81% of the cumulative freshet flow occurred (mean = 38%, median = 33%).

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 15% (median = 14%, range 8-29%), between 8 and 27 days after the start of the freshet flow period (mean = 17 d, median = 17 d). On average, the peak flow period began on 8 May and ended on 14 June, lasting between 25 and 51 days (mean 36 d, median = 35 d).

## H.2 Snow Covered Area

SCA depletion curves are plotted with the hydrographs in Figure H4 and together in Figure H5. In two of the eleven years studied the SCA at the end of the freshet period was more than 10% (Table H2).

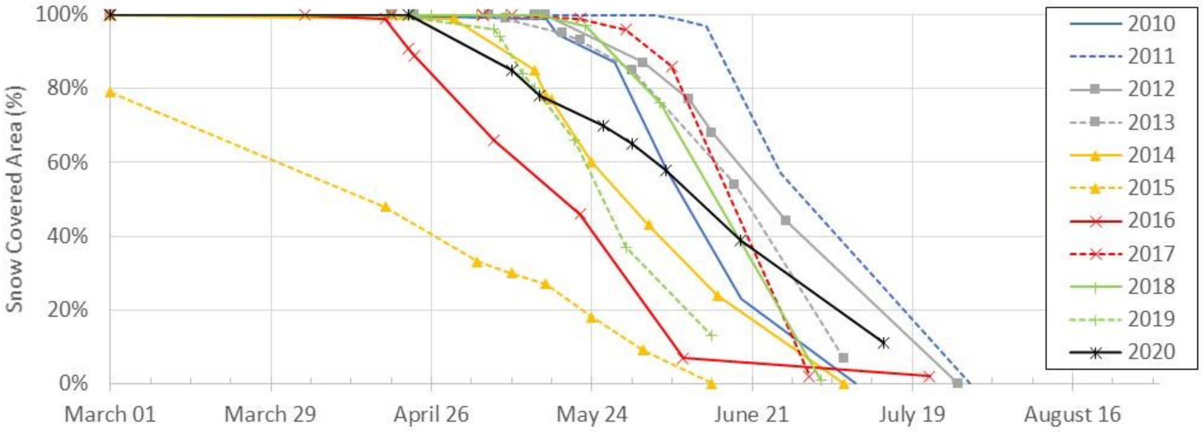


*Figure H5. Changes in snow covered area over the 2010-2020 freshet periods for the West Kettle near McCulloch basin.*

*Table H2. Snow covered area (%) for selected dates in the basin for West Kettle River near McCulloch. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 100 | 95 | 87 | 58 | 23 | 0 | 99 | 94 |
| 2011 | 100 | 100 | 100 | 97 | 57 | 0 | 100 | 99 |
| 2012 | 100 | 100 | 87 | 68 | 44 | 0 | 100 | 77 |
| 2013 | 100 | 99 | 95 | 85 | 54 | 7 | 100 | 93 |
| 2014 | 99 | 78 | 60 | 43 | 24 | 0 | 85 | 77 |
| 2015 | 48 | 33 | 27 | 18 | 9 | 0 | 30 | 9 |
| 2016 | 100 | 89 | 66 | 46 | 7 | 2 | 99 | 91 |
| 2017 | 100 | 100 | 99 | 96 | 86 | 2 | 100 | 100 |
| 2018 | 100 | 100 | 100 | 97 | 76 | 1 | 100 | 100 |
| 2019 | 100 | 96 | 80 | 66 | 37 | 13 | 94 | 84 |
| 2020 | 100 | 78 | 70 | 58 | 39 | 11 | 85 | 65 |
| **Mean:** | **95** | **88** | **79** | **67** | **41** | **3** | **90** | **82** |
| **Median:** | **100** | **96** | **87** | **66** | **39** | **1** | **99** | **91** |

Figure H6 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet volume had occurred. A darker blue colour indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. Lower elevation and west- and south-facing slopes tended to melt out earlier. Snow lingered in the north and east parts of the basin, at higher elevations.

As was found for other catchments in the regions, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean ‘warm blob’ off the coast of B.C. resulted in warmer than normal January, February and March temperatures (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow recorded at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the low SCA recorded at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure H5).

The basin was 30-100% snow covered at the onset of the peak flow period, with a median of 99% (mean = 90%) (Figure H7). These results indicated that snowmelt in all areas in the basin contributes to peak flow in the West Kettle River near McCulloch.

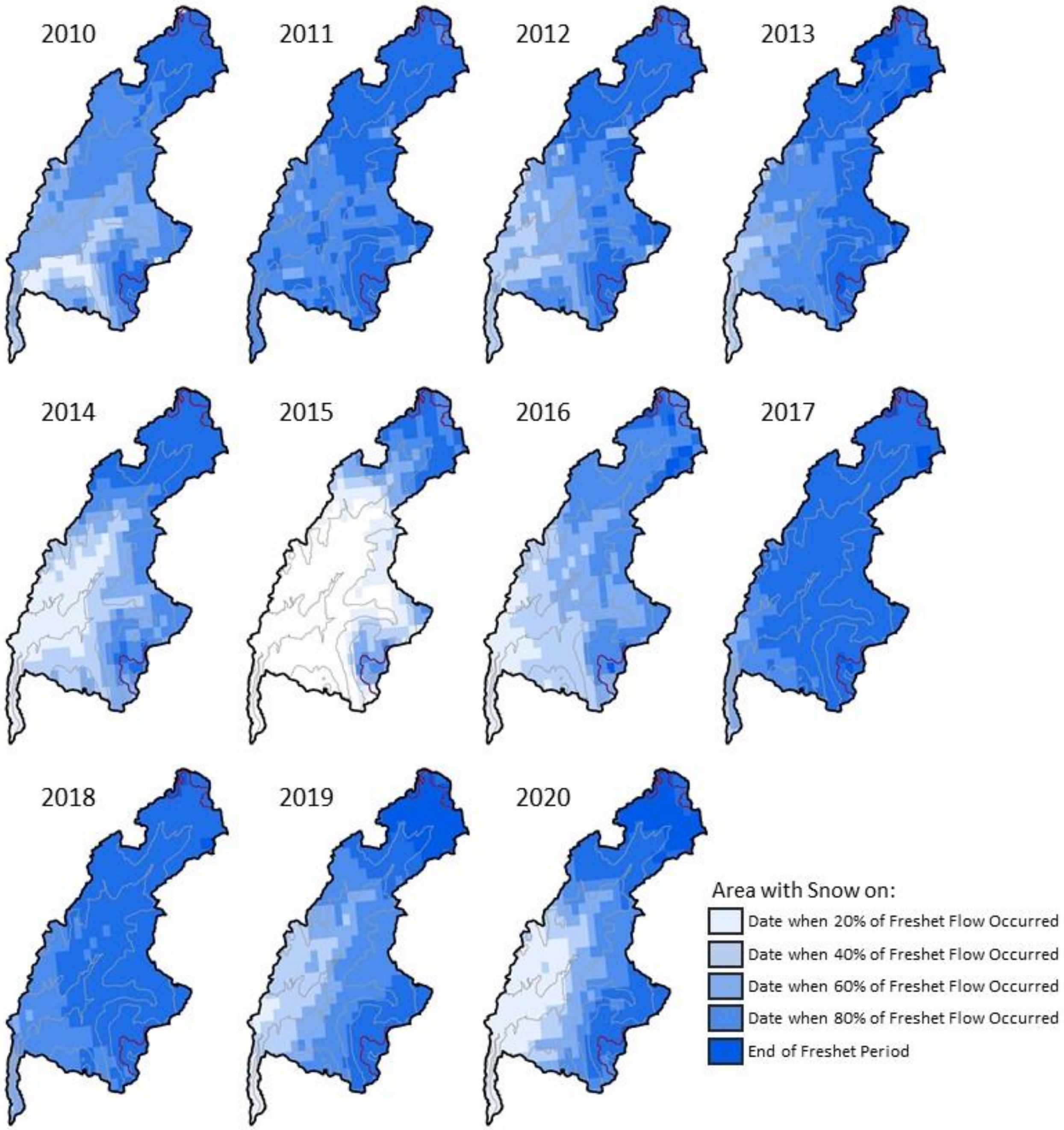


*Figure H6. The progression of snow covered area over the 2010-2020 spring freshet periods for the West Kettle River near McCulloch basin. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

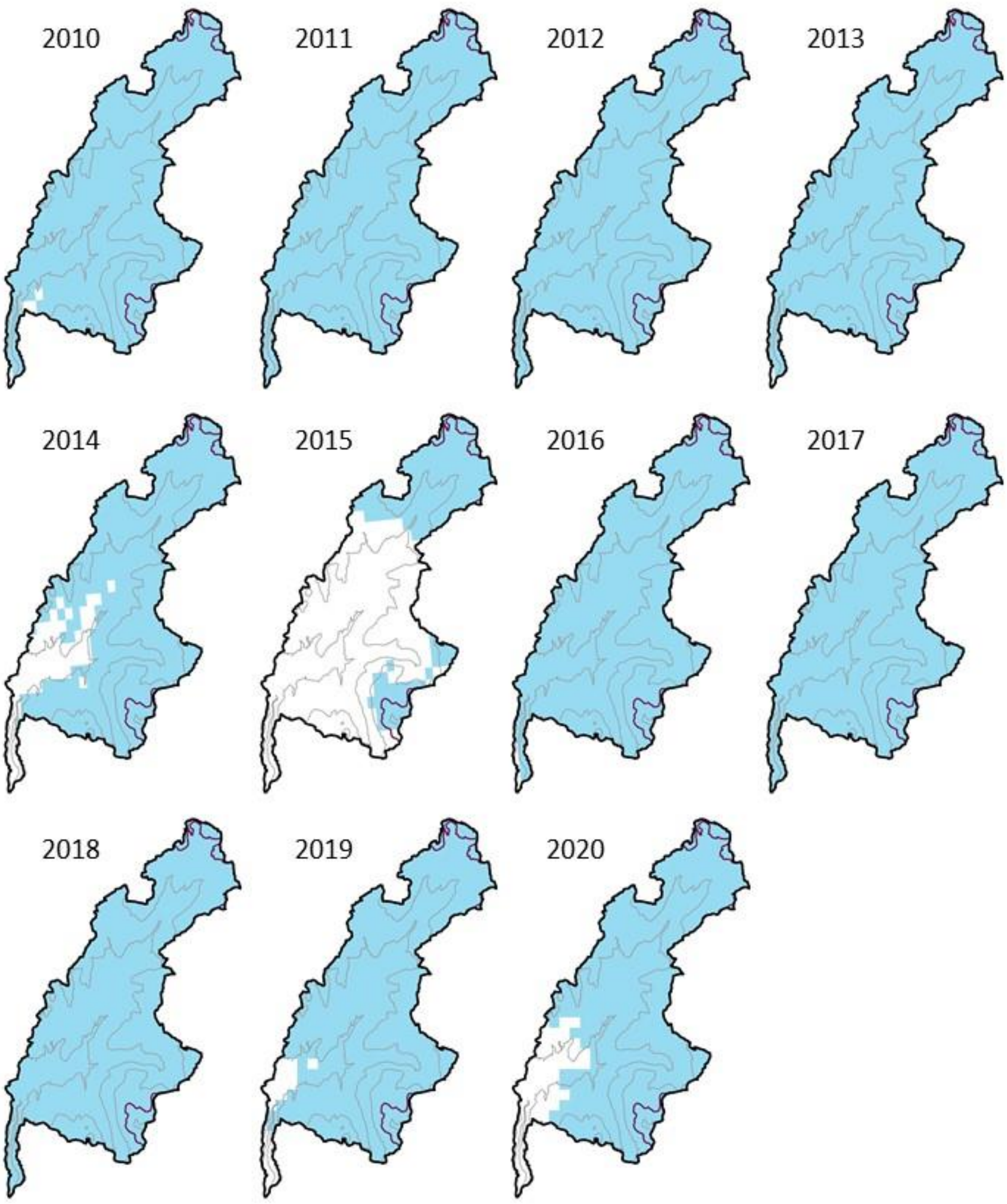


*Figure H7. Snow covered area in the West Kettle River near McCulloch basin on the date of onset of the peak flow period, 2010-2020. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

## H.3 The Snow Sensitive Zone

The lower limit of the SSZ for the basin was derived using the SCA maps for the onset of the peak flow period (Figure H7). Note that the coarse resolution of the SNODAS product means that the mapped snowlines are only approximations. Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure H6). Median SCA at the onset of the peak flow period was 99%. To be conservative, it was assumed that the snowmelt across the entire basin contributed to peak flow (i.e. the SSZ was 100% of the basin) (Figure H8).

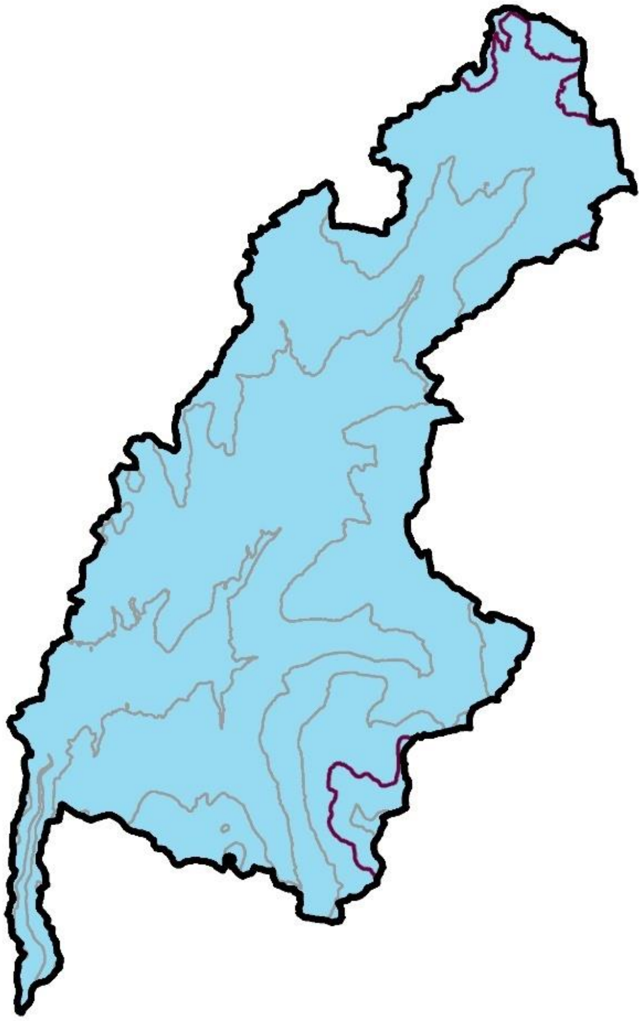
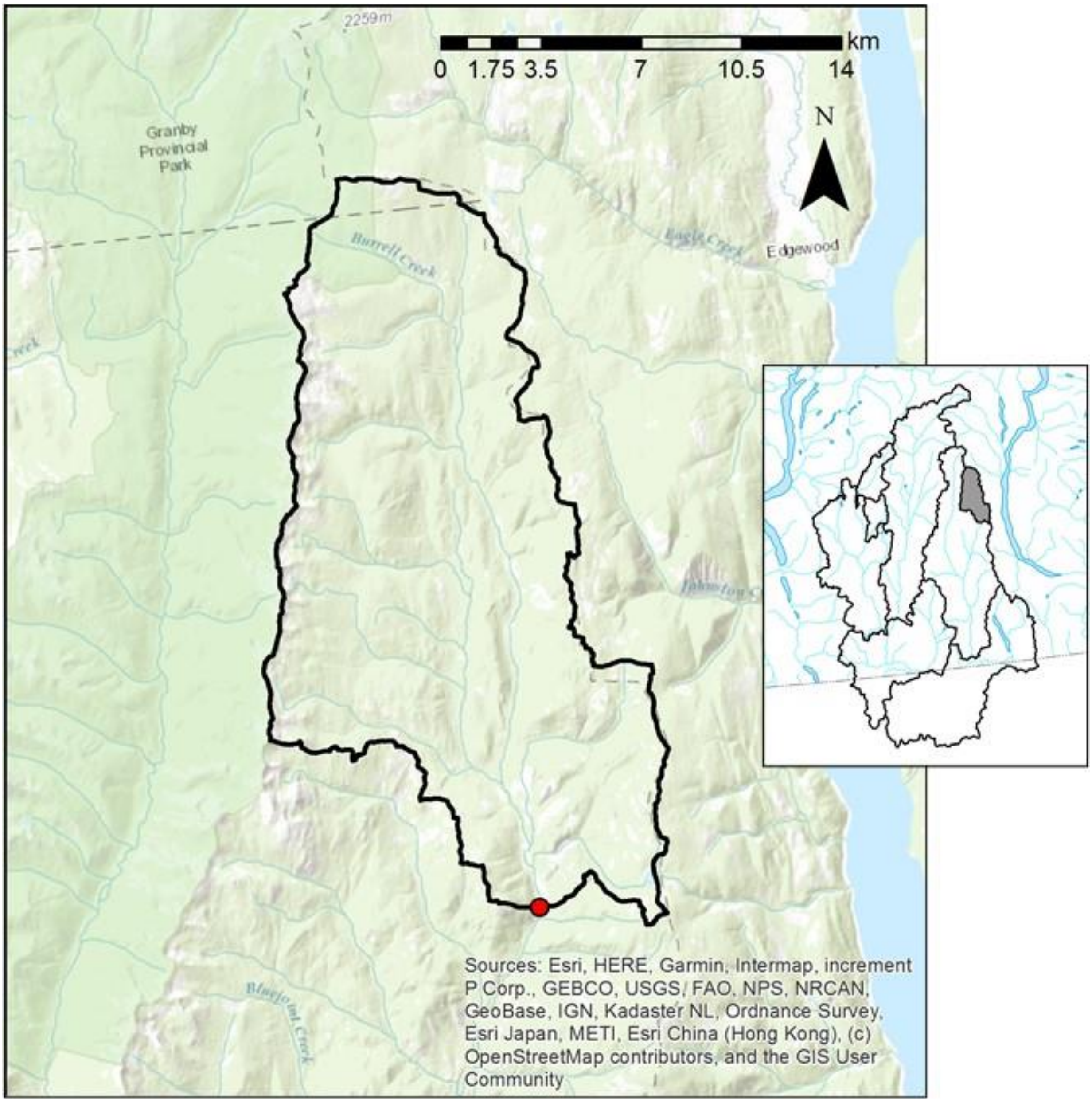


*Figure H8. The snow sensitive zone of the drainage basin for West Kettle River near McCulloch. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

## APPENDIX I: BURRELL CREEK



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure I1. Map showing the drainage area for Burrell Creek, a tributary to Granby River. The basin is outlined in black and the location of the hydrometric station is shown with a red circle. The inset map shows this basin (in grey) in the context of all of the Kettle River basins included in this study.*

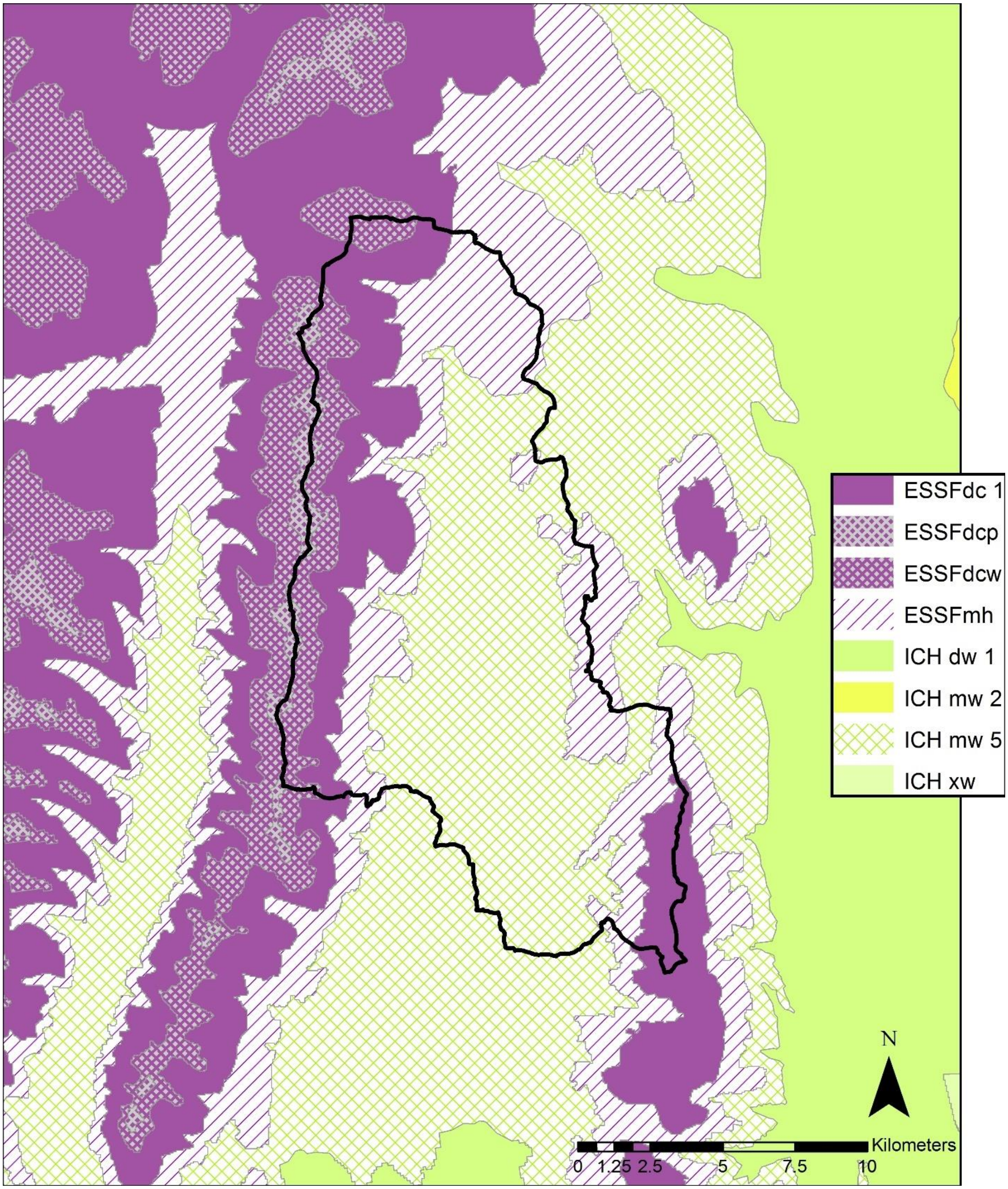


*Figure I2. Map of the Burrell Creek basin showing elevation and BEC subzones and variants. The basin is outlined in black.*

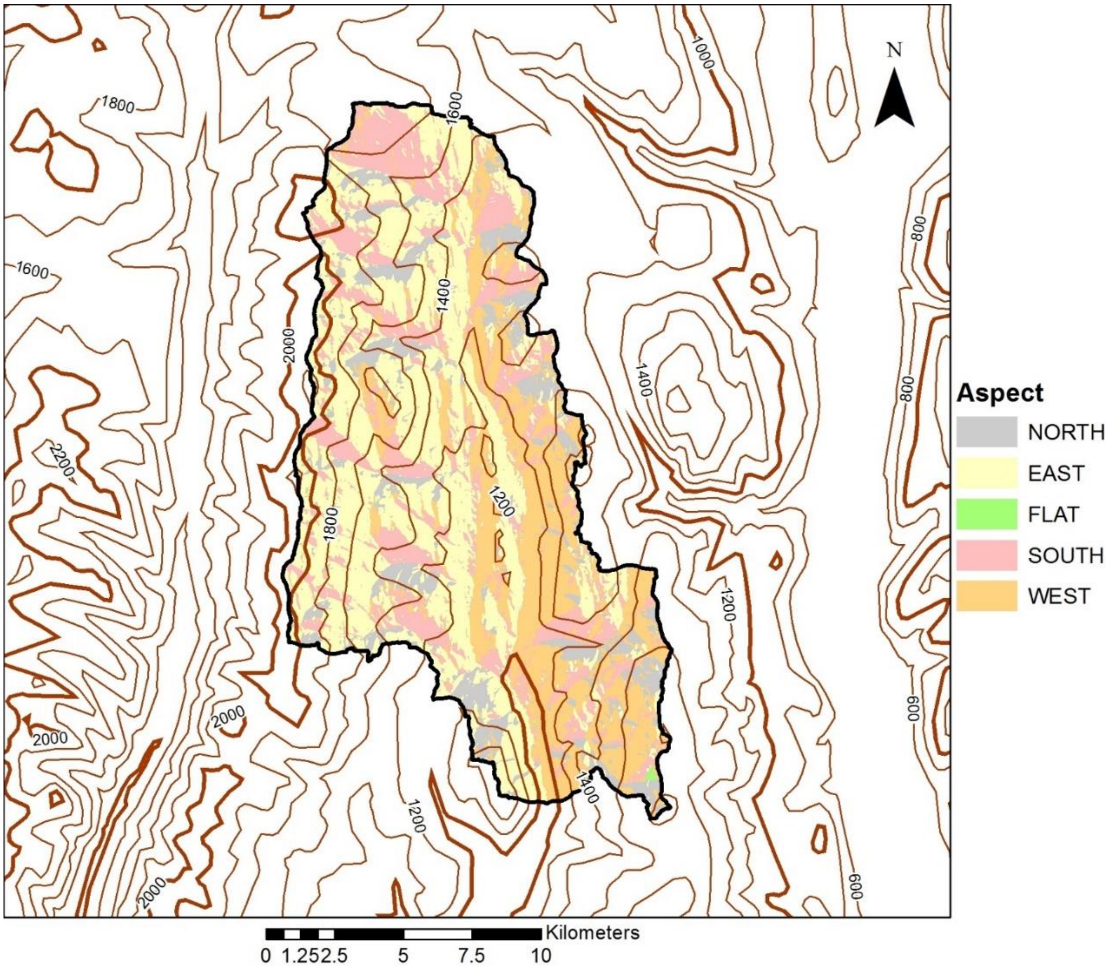


*Figure I3. Slope aspect map of the Burrell Creek basin. The basin is outlined in black and elevation contours are brown.*

## I.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN023 Burrell Creek above Gloucester Creek for 2010-2019 were published and for 2020 were provisional at the time of this analysis (Table I1). The freshet flow period (defined as when daily mean discharge was greater than the station's long term mean) for 2010-2020 lasted 72 to 106 days (mean = 86 d, median = 82 d). The freshet period was shortest in 2018 and the longest in 2017, both significant flood years. On average, freshet began on 5 April and ended on 2 July (median dates were 9 April and 2 July, respectively); the earliest it began was 13 March in 2015 and the latest was 26 April in 2011.

The Burrell Creek freshet period hydrographs for 2010 to 2020 rarely showed a single dominant peak (Figure I4), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There is no significant attenuation by lakes or wetlands, so the hydrograph is responsive to melt and precipitation inputs.

The date of peak flow was highly variable for Burrell Creek, and did not occur on a consistent date, elapsed period of time after the onset of freshet flow, or at a fixed percent of cumulative freshet flow. Peak flow occurred between 14 and 82 days after the onset of the freshet period (mean = 40 d, median = 38 d), when 11 to 91% of the cumulative freshet flow occurred (mean = 42%, median = 38%).

*Table I1. Freshet flow period dates for Burrell Creek above Gloucester Creek (08NN023). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both mean and median dates are shown.*

| Year | Freshet Period | | | Peak Flow Period | | | Peak Flow Date |
|---|---|---|---|---|---|---|---|
| | Start | End | Duration (# days) | Start | End | Duration (# days) | |
| 2010 | 16 April | 2 July | 77 | 18 April | 14 June | 57 | 18 May |
| 2011 | 26 April | 15 July | 80 | 11 May | 14 June | 34 | 26 May |
| 2012 | 12 April | 15 July | 94 | 23 April | 17 June | 55 | 26 April |
| 2013 | 1 April | 6 July | 96 | 4 May | 31 May | 27 | 22 May |
| 2014 | 9 April | 30 June | 82 | 1 May | 5 June | 35 | 17 May |
| 2015 | 13 March | 12 June | 91 | 21 March | 6 June | 77 | 3 June |
| 2016 | 30 March | 26 June | 88 | 8 April | 23 May | 45 | 22 April |
| 2017 | 19 March | 3 July | 106 | 4 May | 9 June | 36 | 6 May |
| 2018 | 16 April | 27 June | 72 | 3 May | 29 May | 26 | 10 May |
| 2019 | 25 March | 11 June | 79 | 19 April | 2 June | 44 | 12 May |
| *2020* | *16 April* | *2 July* | *77* | *6 May* | *3 June* | *28* | *31 May* |
| **Mean:** | **5 April** | **30 June** | **86** | **24 April** | **5 June** | **42** | **15 May** |
| **Median:** | **9 April** | **2 July** | **82** | **1 May** | **5 June** | **36** | **17 May** |

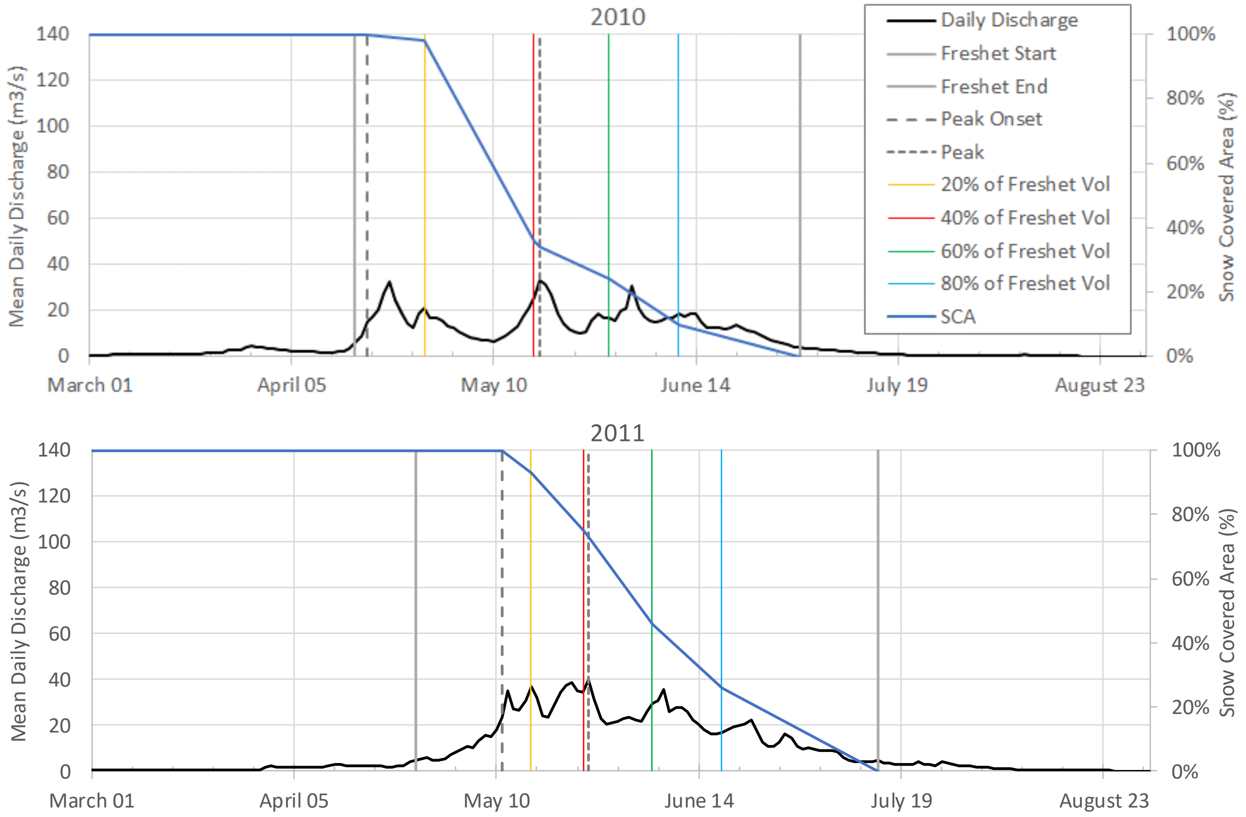


*Figure I4 (cont'd).*

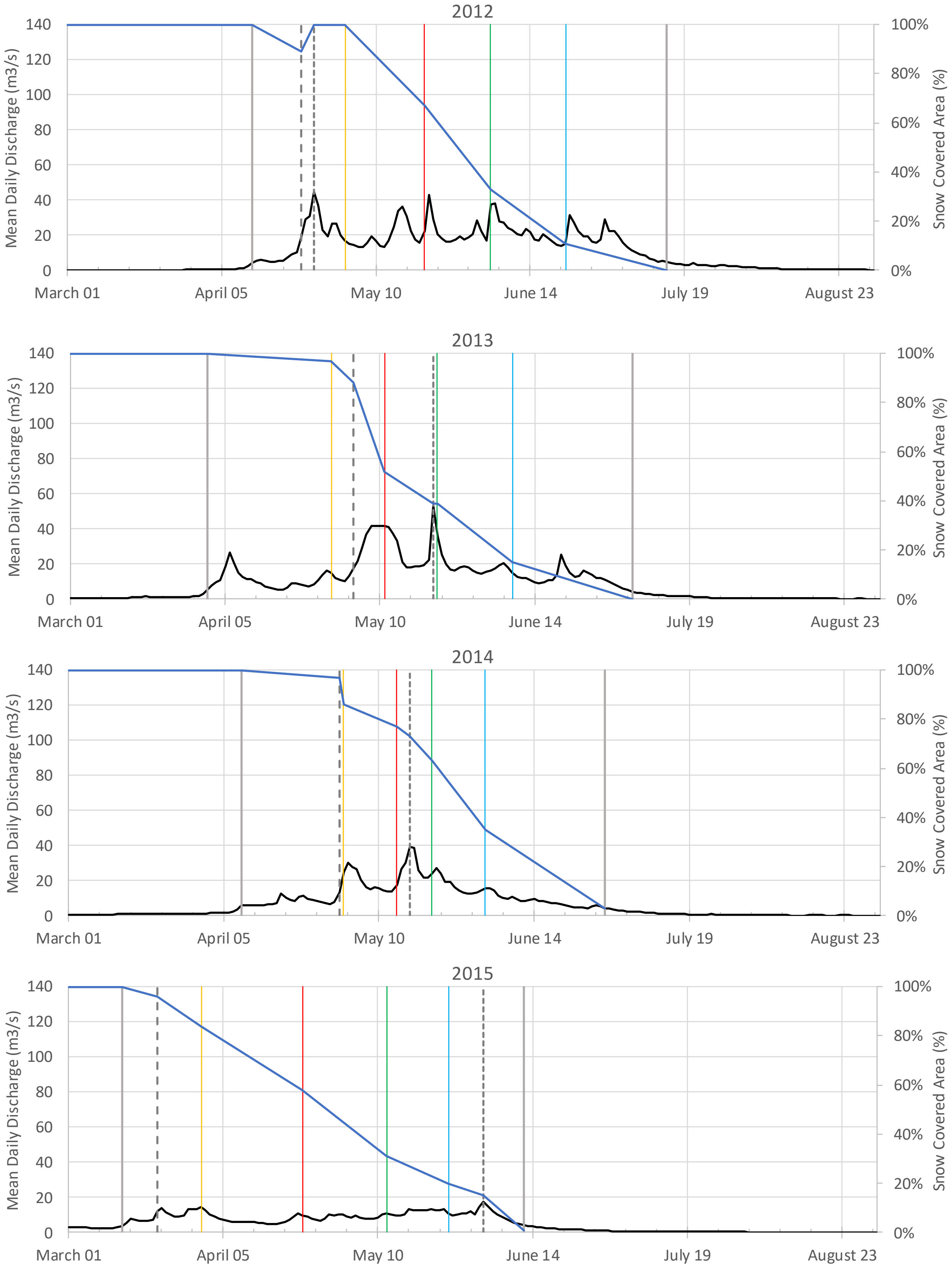


*Figure I4 (cont'd).*

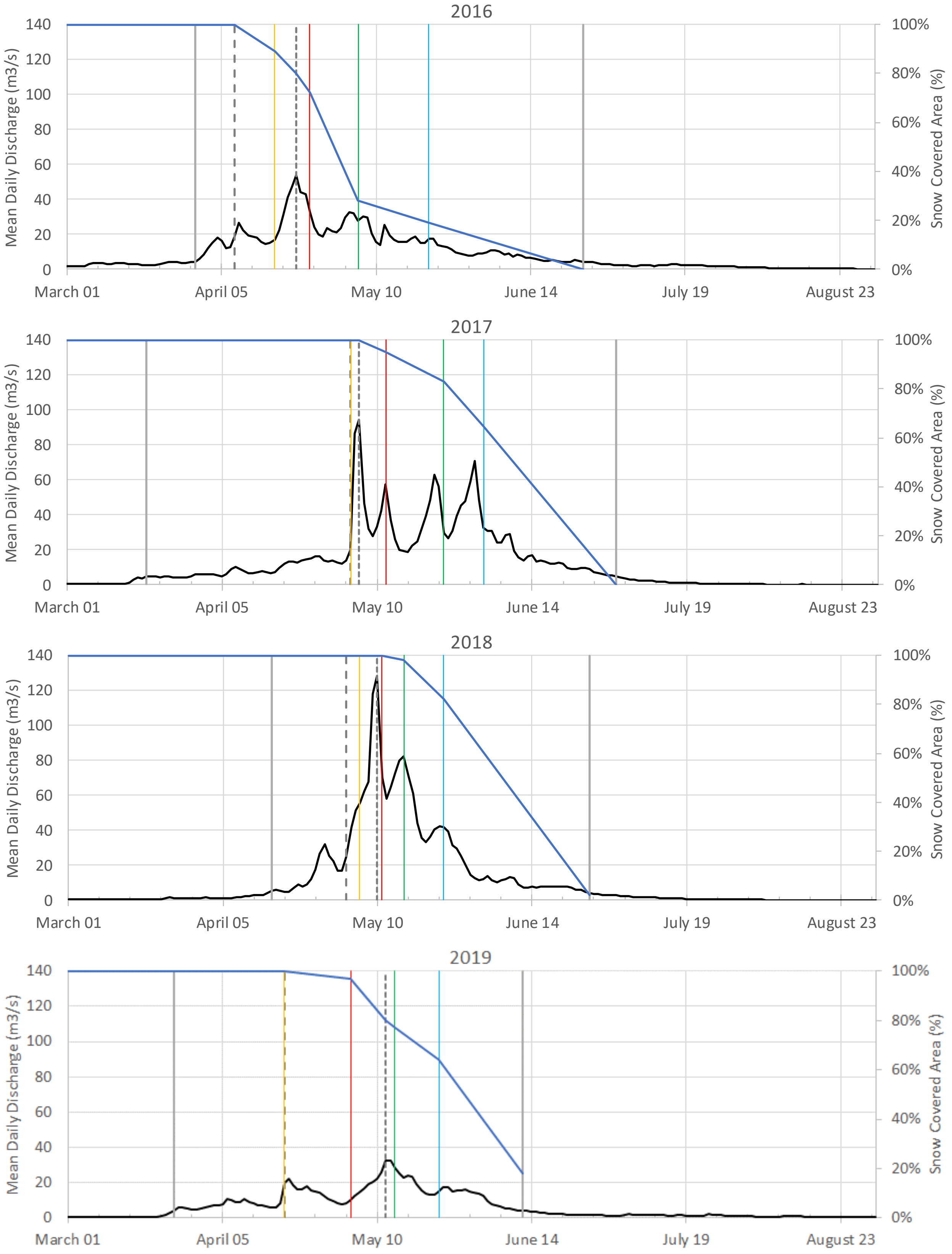


*Figure I4 (cont'd).*

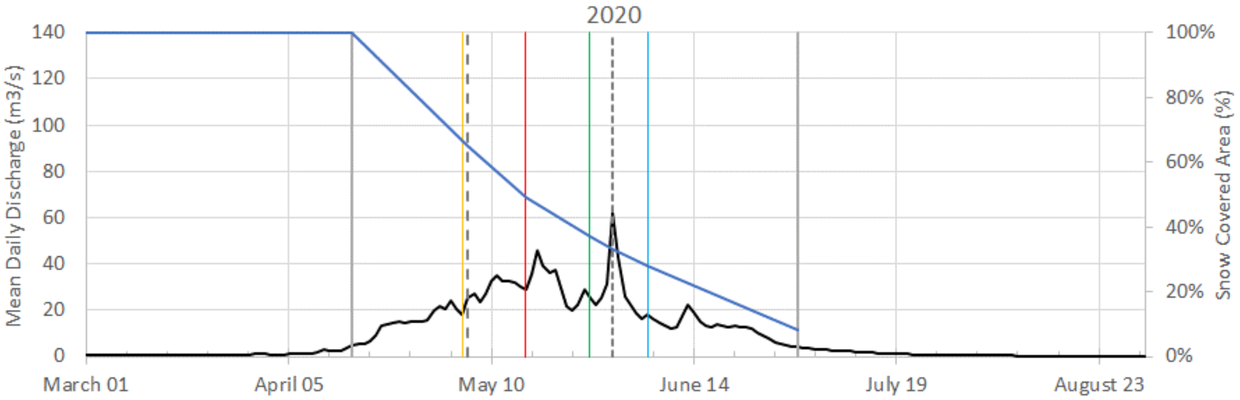


*Figure I4. Discharge in Burrell Creek during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis.*

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during that freshet period) on average occurred when the cumulative freshet flow was 11% (range 3-24%, median = 8%), between 2 and 46 days after the start of the freshet flow period (mean = 19, median = 17). On average, the peak flow period began on 24 April and ended on 5 June, lasting between 26 and 77 days (mean = 42, median = 36).

## I.2 Snow Covered Area

SCA depletion curves are plotted with the hydrographs in Figure I4 and together in Figure I5. In some year a small fraction of the basin still had snow at the end of the freshet period (Table I2), although in 2019 the SCA was 18% at the end of the freshet period. In 2012, SCA briefly increased near the end of April because of precipitation that fell as snow at these elevations (see Appendix K for snowmelt period weather conditions). In general, snow disappeared gradually in this catchment.

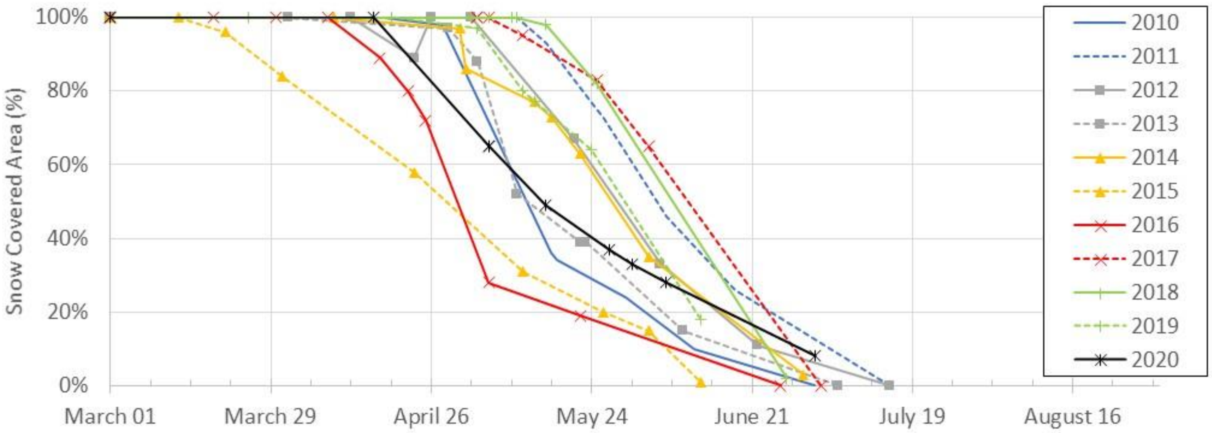


*Figure I5. Changes in snow covered area over the 2010-2020 freshet periods for Burrell Creek basin.*

*Table I2. Snow covered area (%) for selected dates in the Burrell Creek basin. Because of the small sample size, mean and median values are shown.*

| **Year** | **Onset of Freshet Period (0% Cum. Flow)** | **20% Cum. Flow** | **40% Cum. Flow** | **60% Cum. Flow** | **80% Cum. Flow** | **End of Freshet Period (100% Cum. Flow)** | **Onset of Peak Flow Period** | **Peak Flow** |
|---|---|---|---|---|---|---|---|---|
| 2010 | 100 | 98 | 36 | 24 | 10 | 0 | 100 | 34 |
| 2011 | 100 | 93 | 75 | 46 | 26 | 0 | 100 | 73 |
| 2012 | 100 | 100 | 67 | 33 | 11 | 0 | 100 | 100 |
| 2013 | 100 | 97 | 52 | 39 | 15 | 0 | 87 | 39 |
| 2014 | 100 | 86 | 77 | 63 | 35 | 3 | 88 | 73 |
| 2015 | 100 | 84 | 58 | 31 | 20 | 1 | 97 | 15 |
| 2016 | 100 | 89 | 72 | 28 | 19 | 0 | 96 | 80 |
| 2017 | 100 | 100 | 95 | 83 | 65 | 0 | 100 | 100 |
| 2018 | 100 | 100 | 100 | 98 | 82 | 2 | 100 | 100 |
| 2019 | 100 | 100 | 97 | 77 | 64 | 18 | 100 | 80 |
| 2020 | 100 | 65 | 49 | 37 | 28 | 8 | 65 | 33 |
| **Mean:** | **100** | **92** | **71** | **51** | **34** | **3** | **94** | **66** |
| **Median:** | **100** | **97** | **72** | **39** | **26** | **0** | **100** | **73** |

Figure I6 maps the changes in SCA during the 2010-2018 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow volume had occurred. A darker blue colour indicates that snow persisted longer during the freshet period, while light blue areas became snow free sooner. The coarse resolution of the SNODAS products is apparent in these maps. Low elevations and west-facing slopes in the Burrell Creek basin tended to melt out earlier. Snow lingered the longest at higher elevations in the west of the catchment, on east-facing slopes.

As was found for other catchments in the region, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean ‘warm blob’ off the coast of B.C. resulted in warmer than normal January, February and March temperatures (Appendix K). Precipitation during these months fell as rain at lower elevations. In April, there was no snow recorded at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the low SCA at the start of the 2015 freshet period. SCA remained low throughout the period, and the catchment became snow free much earlier (Figure I5).

The basin was 65-100% snow covered at the onset of the peak flow period, with a median of 100% (mean = 94%). These results indicated that snowmelt over nearly all of the basin contributes to peak flow in the Burrell Creek basin.

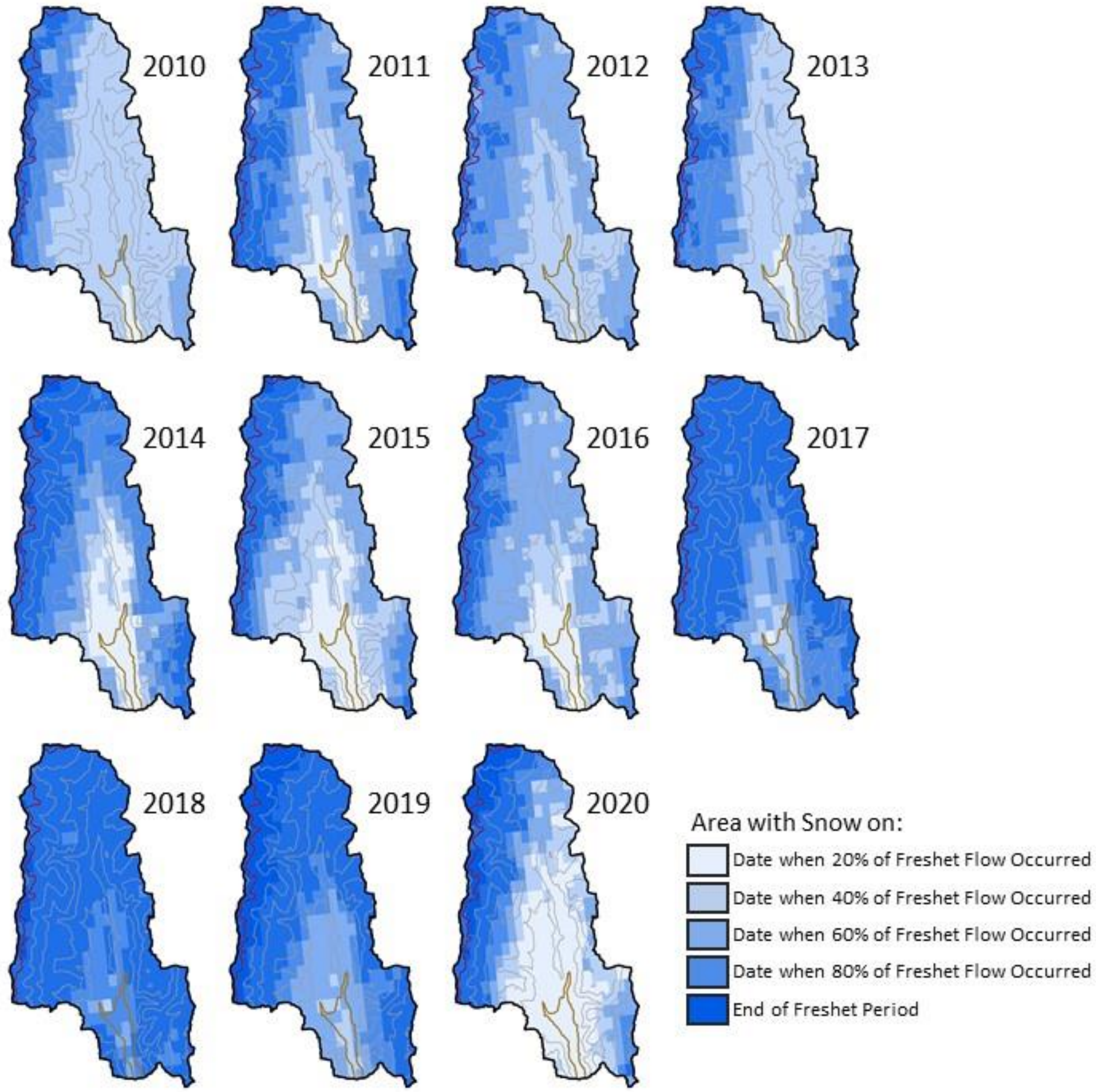


*Figure I7. The progression of snow covered area over the 2010-2020 spring freshet periods for Burrell Creek basin. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

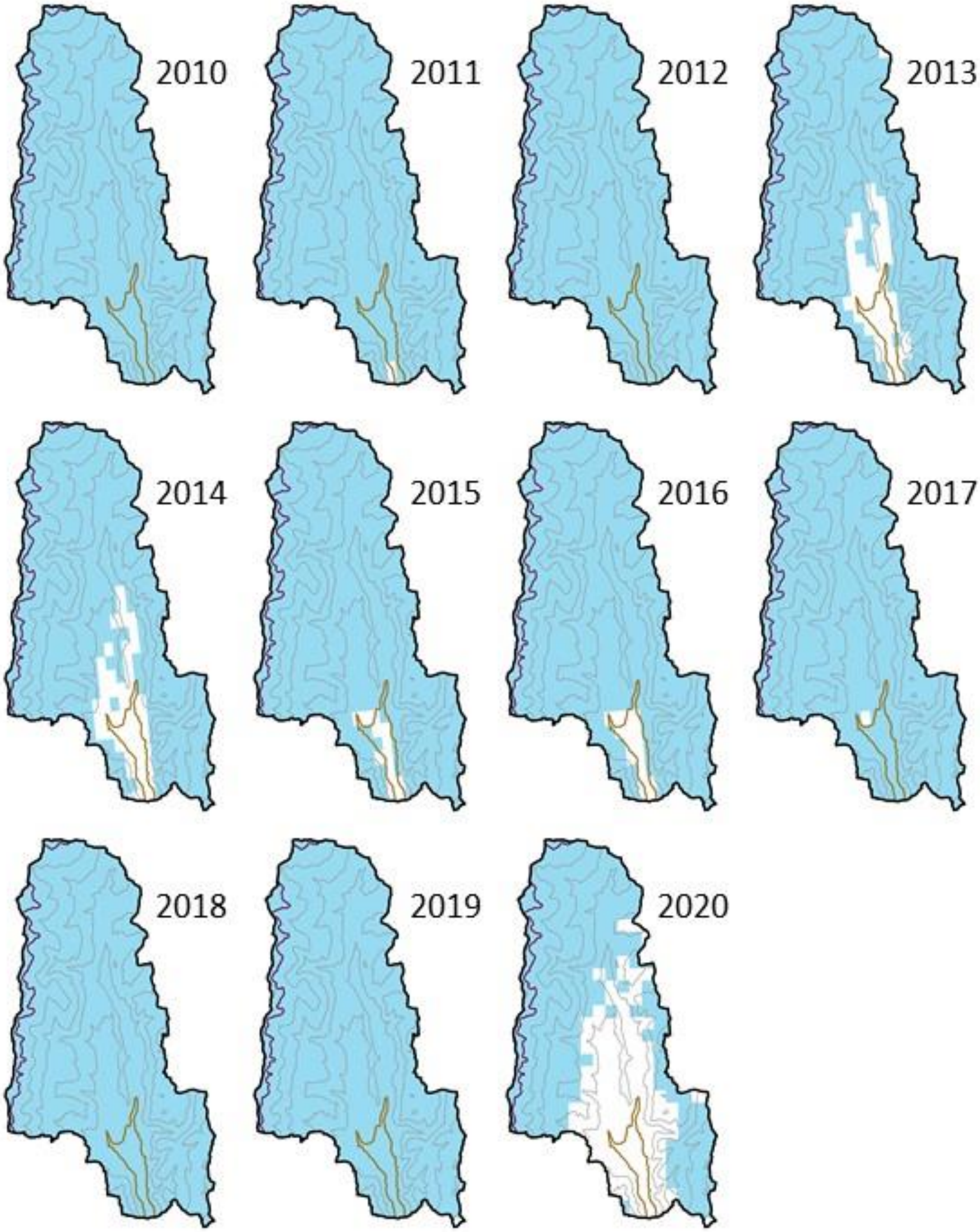


*Figure I8. Snow covered area in Burrell Creek basin on the date of onset of the peak flow period, 2010-2020. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

## I.3 The Snow Sensitive Zone

The lower limit of the SSZ basin was derived from the SCA maps for the onset of the peak flow period. Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure I6). Median SCA was 100% (Figure I7). The SSZ, then, was the entire basin (Figure I9).

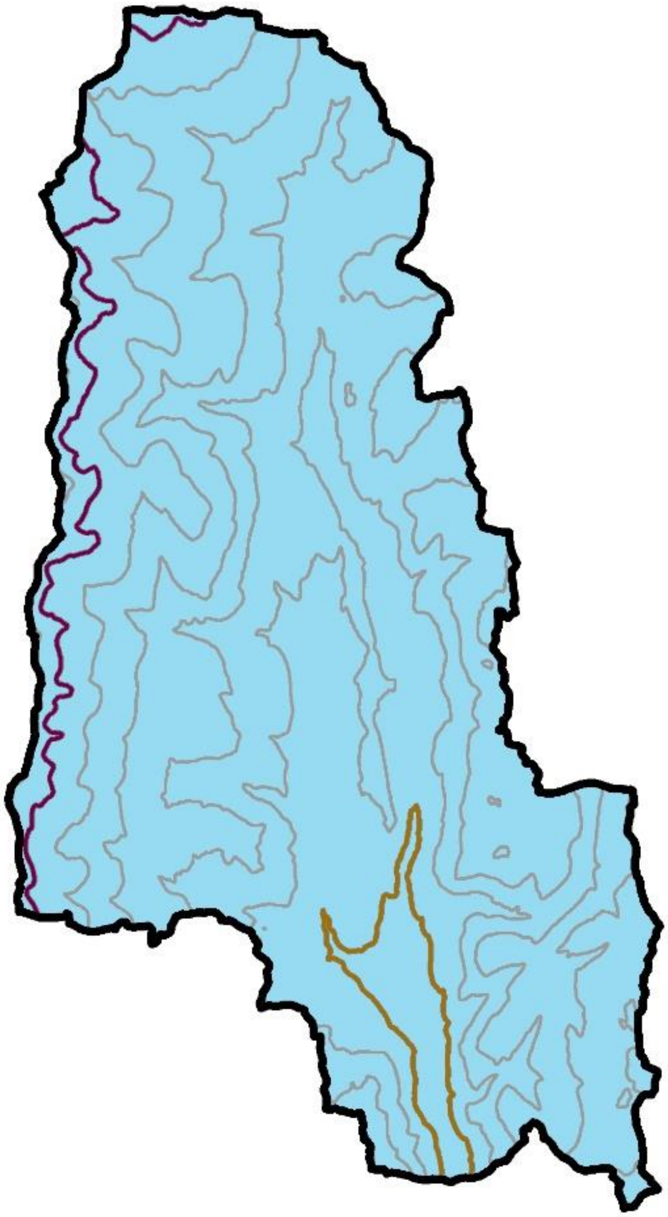
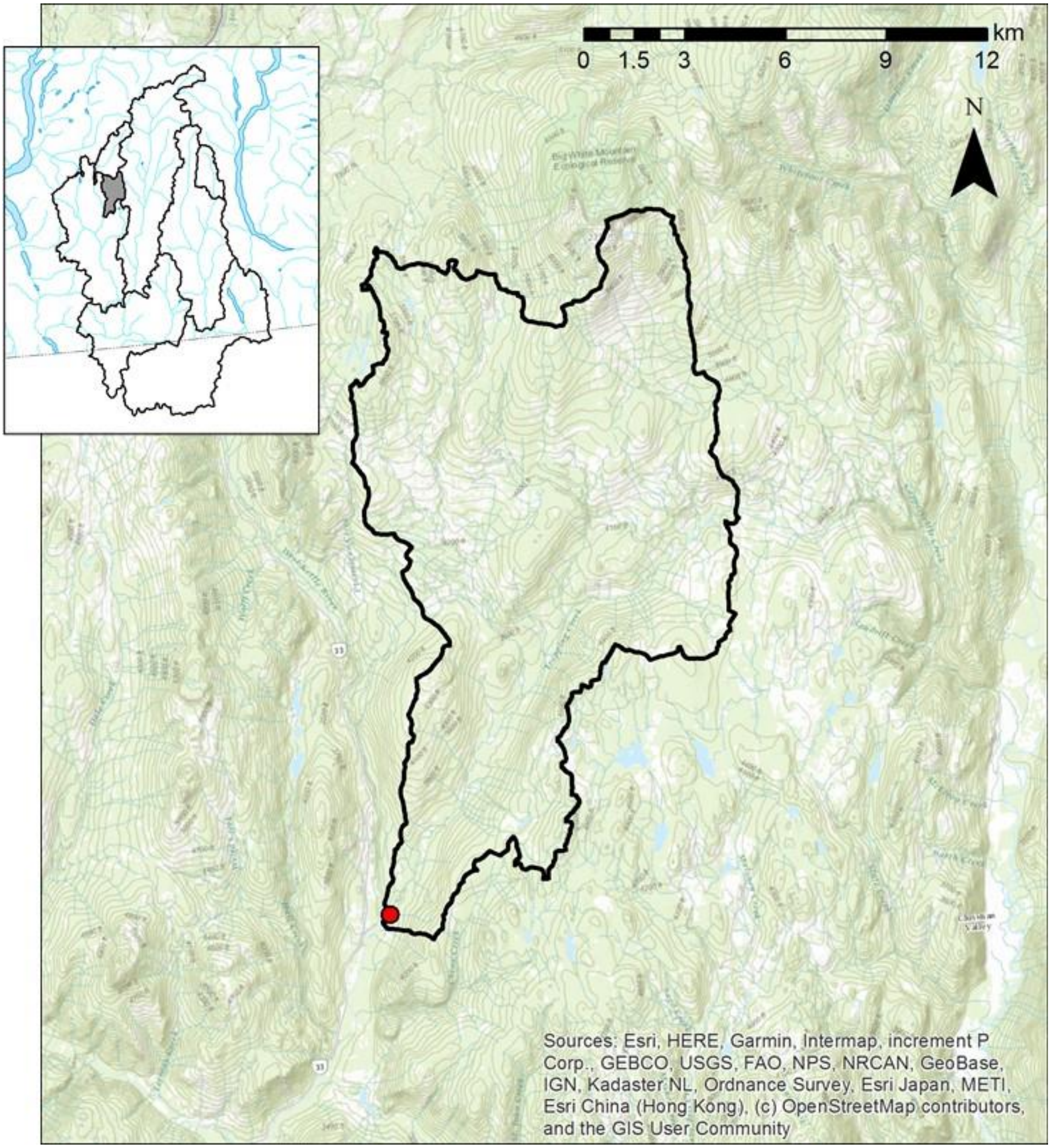


*Figure I9. The snow sensitive zone of Burrell Creek basin. Elevation contour interval is 200 m; the 2000 m contour is in purple.*

## APPENDIX J: TRAPPING CREEK



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Figure J1. Map showing the drainage area for the Trapping Creek basin, a tributary of West Kettle River. The basin is outlined in black and the location of the hydrometric station is shown with a red circle. The inset map shows this basin (in grey) in the context of all of the Kettle River basins used in this study.*

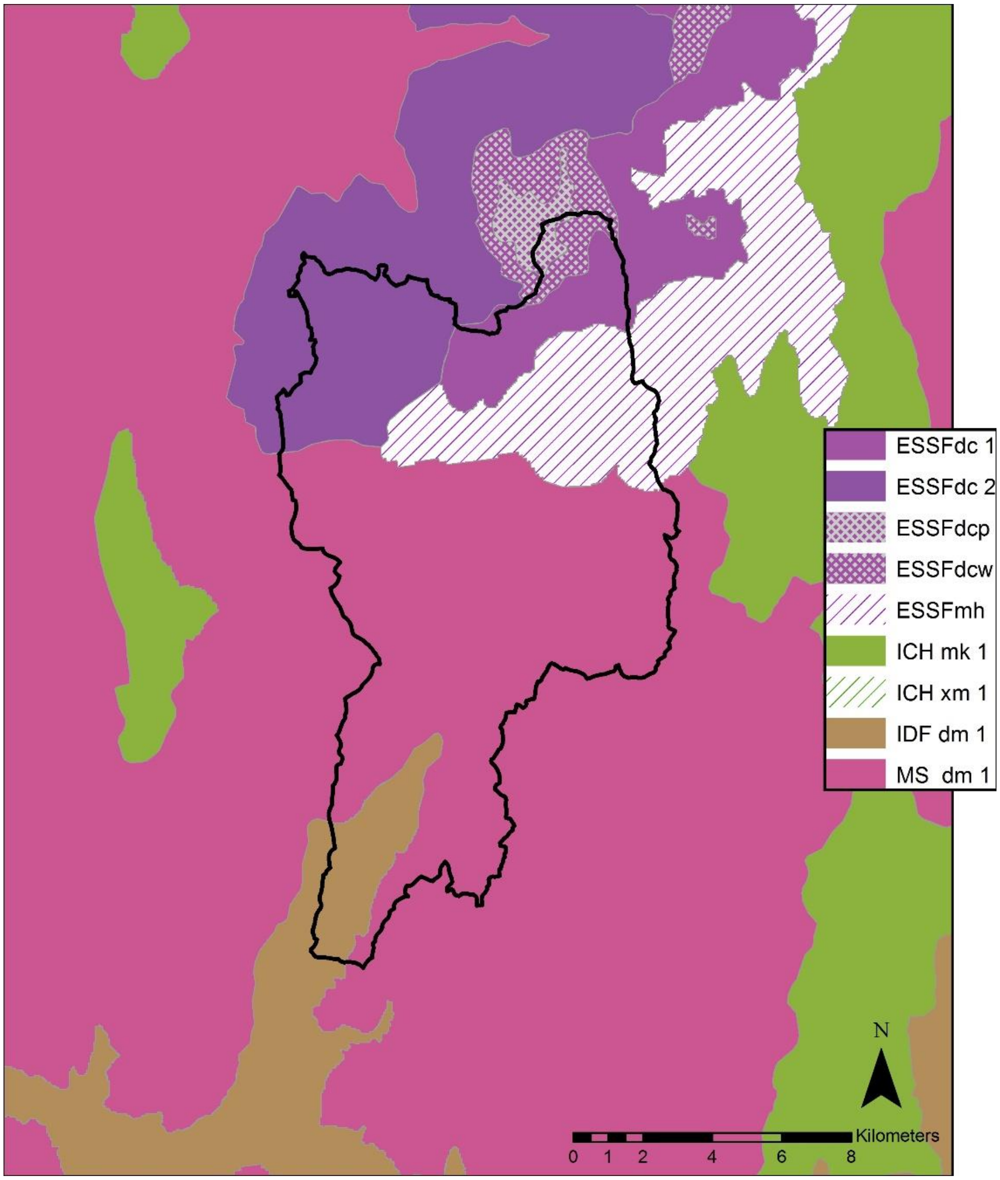


*Figure J2. Map of Trapping Creek basin showing BEC subzones and elevation. The basin is outlined in black.*

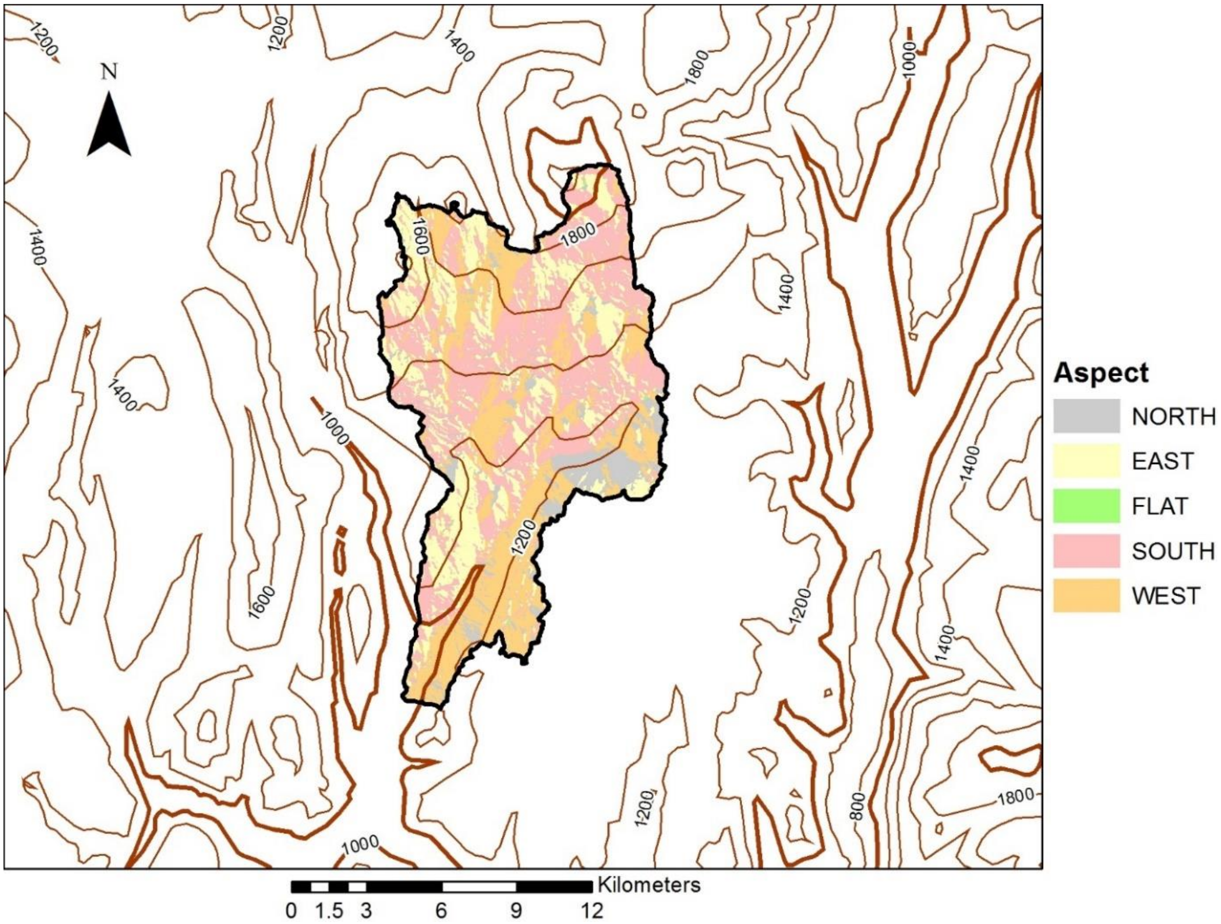


*Figure J3. Slope aspect map of the Trapping Creek basin. The basin is outlined in black and elevation contours are brown (contour interval is 200 m).*

## J.1 Freshet Hydrographs

Daily mean flow data for WSC station 08NN019 Trapping Creek near the Mouth for 2010-2018 were published and for 2019-2020 were provisional at the time of this analysis. The freshet flow period (when daily mean discharge was greater than the station's long term mean) for 2010-2020 lasted 65 to 94 days (mean = 79 d, median = 81 d), with the shortest in 2018 and the longest in 2013 (Table J1). On average, freshet began on 10 April and ended on 28 June; the earliest it began was 14 March in 2015, and the latest was 2 May in 2011.

The Trapping Creek freshet period hydrographs for 2010 to 2020 rarely showed a single dominant peak (Figure J4), indicating multiple melt events and potentially rain and rain-on-snow events during the freshet period. There are no large lakes or wetlands in the basin, so the hydrograph is responsive to snowmelt and rain inputs.

*Table J1. Freshet flow period dates for Trapping Creek near Mouth (08NN019). Values in italics were derived from provisional hydrometric data. Because of the small sample size, both mean and median dates are shown.*

| Year | Freshet Period | | | Peak Flow Period | | | Peak Flow Date |
|---|---|---|---|---|---|---|---|
| | Start | End | Duration (# days) | Start | End | Duration (# days) | |
| 2010 | 18 April | 2 July | 75 | 15 May | 13 June | 29 | 19 May |
| 2011 | 2 May | 9 July | 68 | 12 May | 14 June | 33 | 26 May |
| 2012 | 22 April | 12 July | 81 | 25 April | 17 June | 53 | 10 Jun |
| 2013 | 2 April | 5 July | 94 | 4 May | 4 June | 31 | 8 May |
| 2014 | 15 April | 3 July | 79 | 2 May | 5 June | 34 | 17 May |
| 2015 | 14 March | 9 June | 87 | 27 March | 21 May | 55 | 31 Mar |
| 2016 | 31 March | 26 June | 87 | 8 April | 14 May | 36 | 21 Apr |
| 2017 | 5 April | 27 June | 83 | 23 April | 5 June | 43 | 5 May |
| 2018 | 22 April | 26 June | 65 | 5 May | 26 May | 21 | 9 May |
| *2019* | *2 April* | *9 June* | *68* | *19 April* | *26 May* | *37* | *12 May* |
| *2020* | *16 April* | *8 July* | *83* | *26 April* | *2 June* | *37* | *18 May* |
| **Mean:** | **10 April** | **28 June** | **79** | **26 April** | **2 June** | **37** | **10 May** |

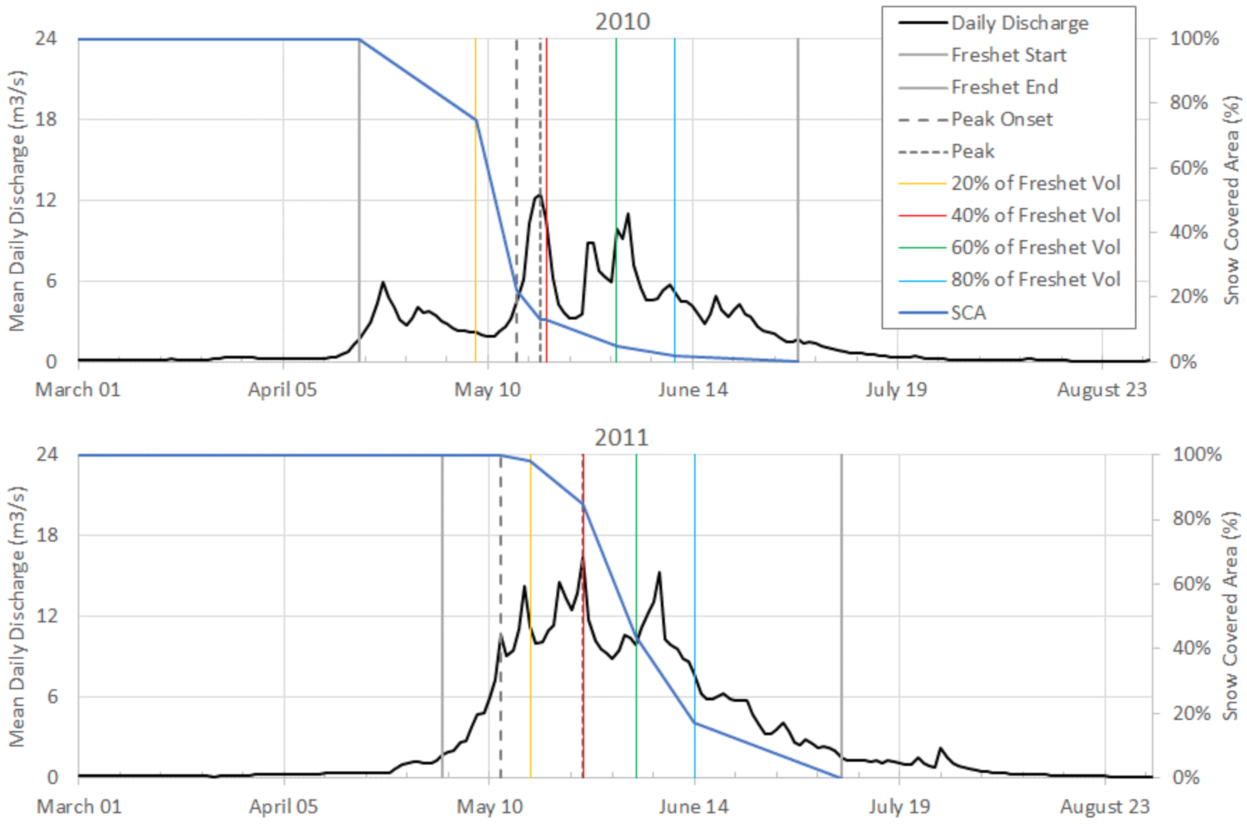


*Figure J4 (cont'd).*

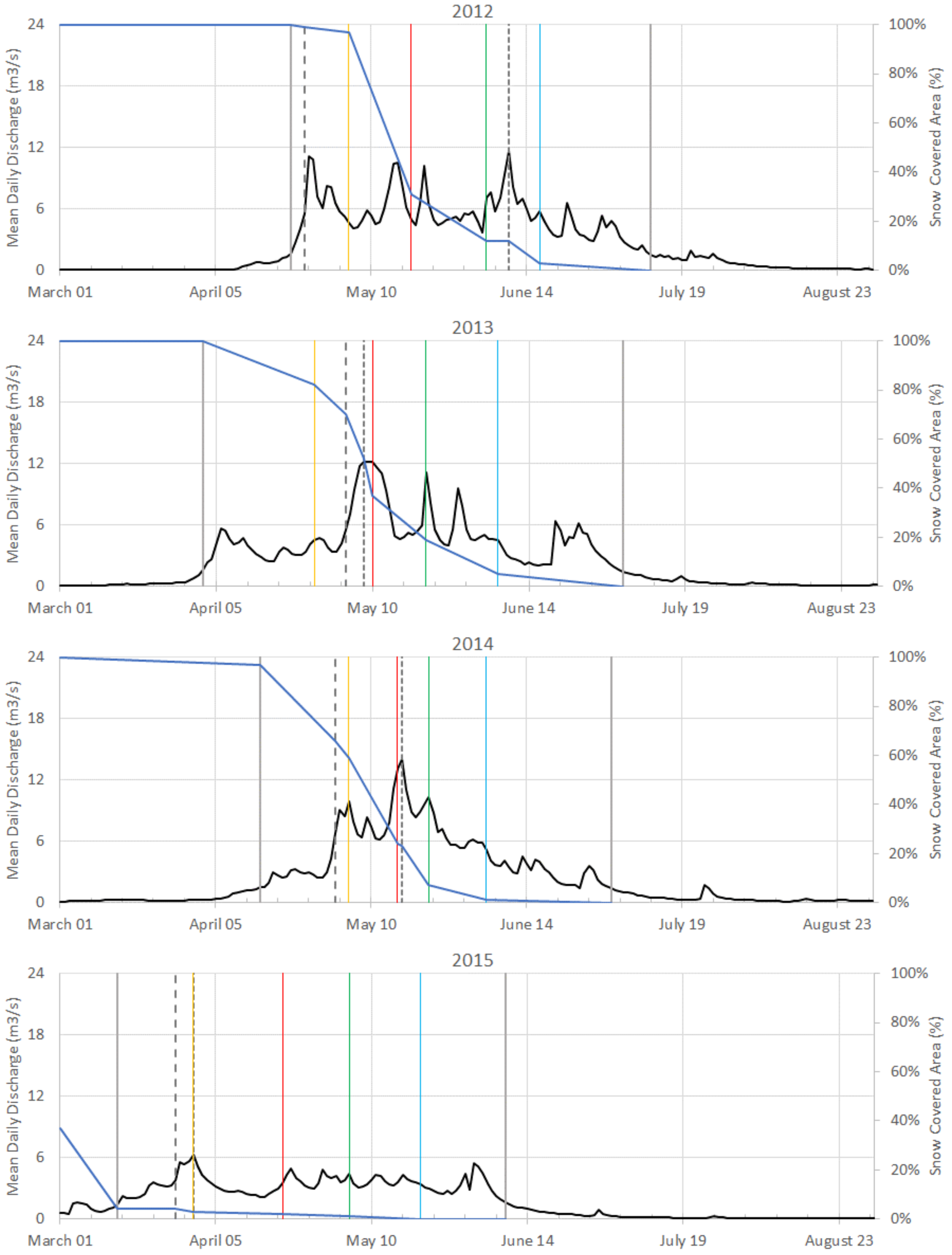


*Figure J4 (cont'd).*

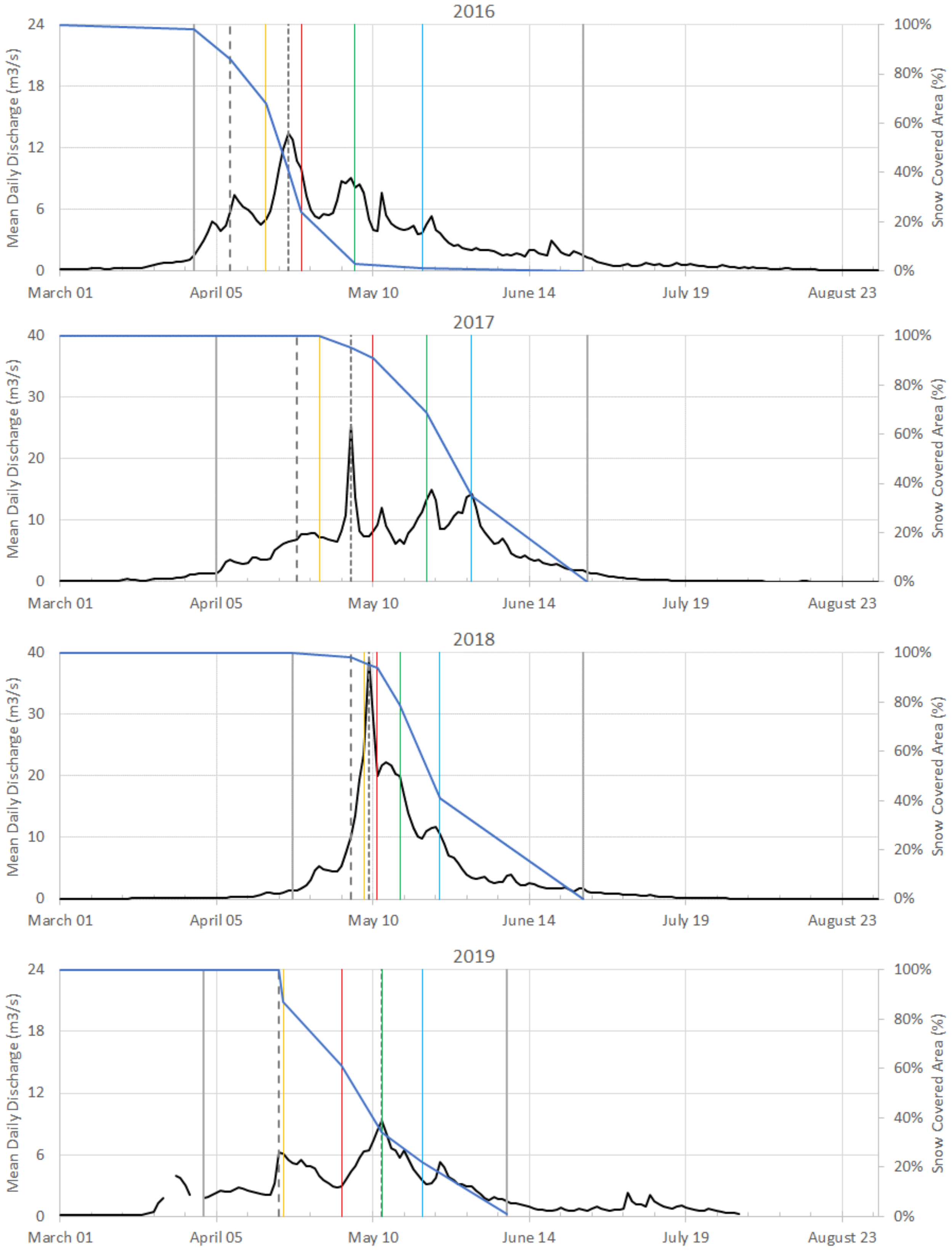


*Figure J4 (cont'd).*

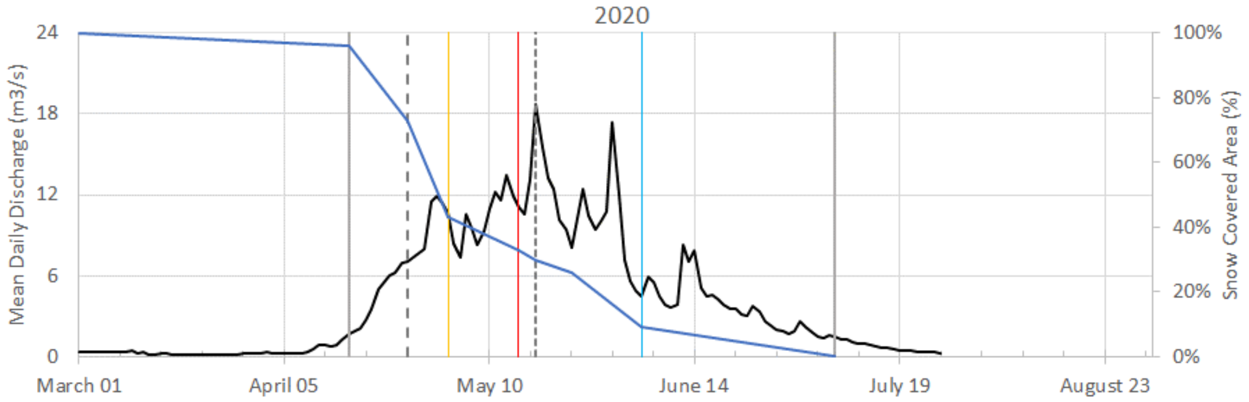


*Figure J4. Discharge in Trapping Creek during the 2010-2020 spring freshet periods, showing basin snow covered area and hydrologically significant dates used in this analysis. Note that a different vertical axis range was used for 2017 and 2018.*

The date of peak flow was highly variable in Trapping Creek and did not occur on a consistent date, elapsed period of time after the onset of freshet flow or after a consistent volume of flow had occurred. Peak flow occurred between 17 and 49 days after the onset of the freshet period (mean = 30 d, median = 31 d), and when 20-70% of the total freshet flow volume had occurred (mean = 41%, median = 38%). The latest date of peak flow, in 2012, occurred when 70% of the total freshet flow volume had already happened and was caused by a large rain event.

The onset of the peak flow period (when daily mean discharge was greater than the mean discharge during the freshet period) on average occurred when the cumulative freshet flow was 14% (range 3-27%, median = 13%), between 3 and 32 days after the onset of the freshet flow period (mean = 15 d, median = 13 d). On average, the peak flow period began on 26 April and ended on 2 June, lasting between 21 and 55 days (mean = 37 d, median = 36 d).

Note that the definition of the peak flow period depends on discharge due to snowmelt but also discharge resulting from rain events. For example, in 2012 heavy rains in mid-June caused large peaks in the hydrograph that were not due to snowmelt alone, and which increased the value of mean discharge during the freshet period. In the case of Trapping Creek, this extended the freshet flow period and the dates selected to represent 20, 40, 60, 80 and 100% cumulative freshet volume occurred later than if there had not been the rain events.

## J.2 Snow Covered Area

SCA values are reported to the neared 1% but their accuracy is affected by the relatively coarse resolution of the data (Table J2). SCA depletion curves were plotted with the hydrographs in Figure J4 and together in Figure J5. SCA in the Trapping Creek basin decreased rapidly after reaching 90%, and in all but one year the basin was completely snow-free at the end of the freshet period.

*Table J2. Snow covered area (%) for selected dates in the Trapping Creek basin. Because of the small sample size, both mean and median values are shown.*

| Year | Onset of Freshet Period (0% Cum. Flow) | 20% Cum. Flow | 40% Cum. Flow | 60% Cum. Flow | 80% Cum. Flow | End of Freshet Period (100% Cum. Flow) | Onset of Peak Flow Period | Peak Flow |
|---|---|---|---|---|---|---|---|---|
| 2010 | 100 | 75 | 13 | 5 | 2 | 0 | 22 | 13 |
| 2011 | 100 | 98 | 85 | 44 | 17 | 0 | 100 | 85 |
| 2012 | 100 | 97 | 31 | 12 | 3 | 0 | 99 | 12 |
| 2013 | 100 | 82 | 37 | 19 | 5 | 0 | 70 | 52 |
| 2014 | 97 | 59 | 24 | 7 | 1 | 0 | 66 | 23 |
| 2015 | 4 | 3 | 2 | 1 | 0 | 0 | 4 | 3 |
| 2016 | 98 | 68 | 24 | 3 | 1 | 0 | 86 | 41 |
| 2017 | 100 | 100 | 91 | 69 | 35 | 0 | 100 | 98 |
| 2018 | 100 | 96 | 94 | 79 | 41 | 0 | 98 | 98 |
| 2019 | 100 | 87 | 61 | 34 | 22 | 1 | 100 | 34 |
| 2020 | 96 | 43 | 33 | 26 | 9 | 0 | 73 | 30 |
| **Mean:** | **89** | **75** | **45** | **27** | **12** | **0** | **74** | **44** |
| **Median:** | **100** | **82** | **33** | **19** | **5** | **0** | **86** | **34** |

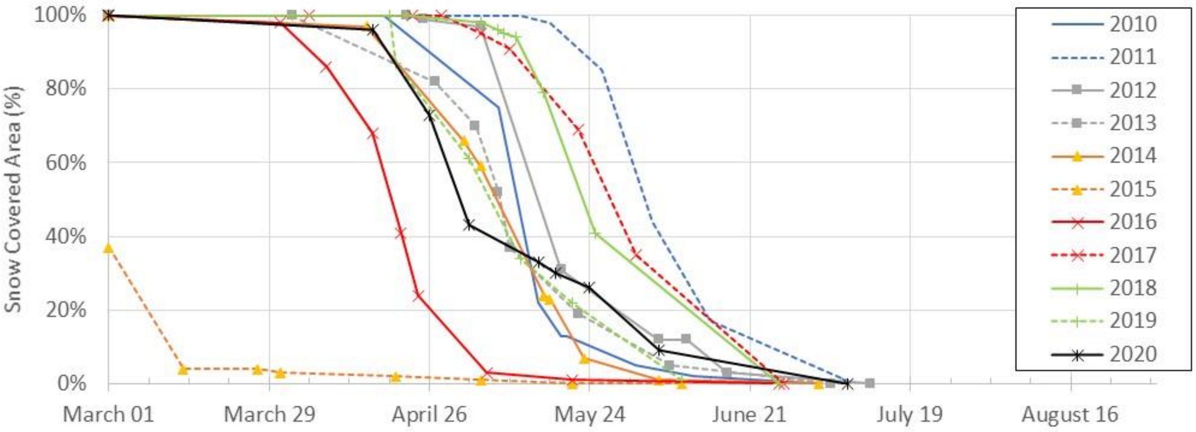


*Figure J5. Changes in snow covered area over the 2010-2018 freshet periods for Trapping Creek basin.*

Figure J6 maps the changes in SCA during the 2010-2020 freshet periods. SCA is shown for dates when 0, 20, 40, 60, 80 and 100% of the total freshet flow had occurred. A darker blue colour indicates that snow persisted longer during the freshet period, while light areas became snow-free sooner. Low elevation south and east facing slopes in the Trapping Creek basin tended to melt out earlier. Snow lingered at the highest elevations.

As was found for other catchments in the region, the 2015 freshet period was unusual. In the weather summary provided by the B.C. River Forecast Centre as part of their Snow Survey and Water Supply Bulletins, a Pacific Ocean 'warm blob' off the coast of B.C. resulted in a warmer than normal January, February and March (Appendix K). Precipitation during those months fell as rain at lower elevations. In April, there was no snow at low and middle elevations, which was noted to be much earlier than normal. These conditions explain the very low SCA recorded throughout the 2015 freshet period.

The basin was 4-100% snow covered at the onset of the peak flow period, with a median of 86% (mean = 74%). These results indicated that snowmelt over the majority of the basin contributes to peak flow in the Trapping Creek basin.

### J.3 The Snow Sensitive Zone

The lower limit of the SSZ was derived from the SCA maps for the onset of the peak flow period (Figure J7). Visual assessment of the SCA maps showed similar snowmelt patterns from year to year (Figure J6). Median SCA at the onset of the peak flow period was 86%. SCA at the onset of peak flow in 2016 was equal to the multi-year median, so this year was used to define the SSZ.

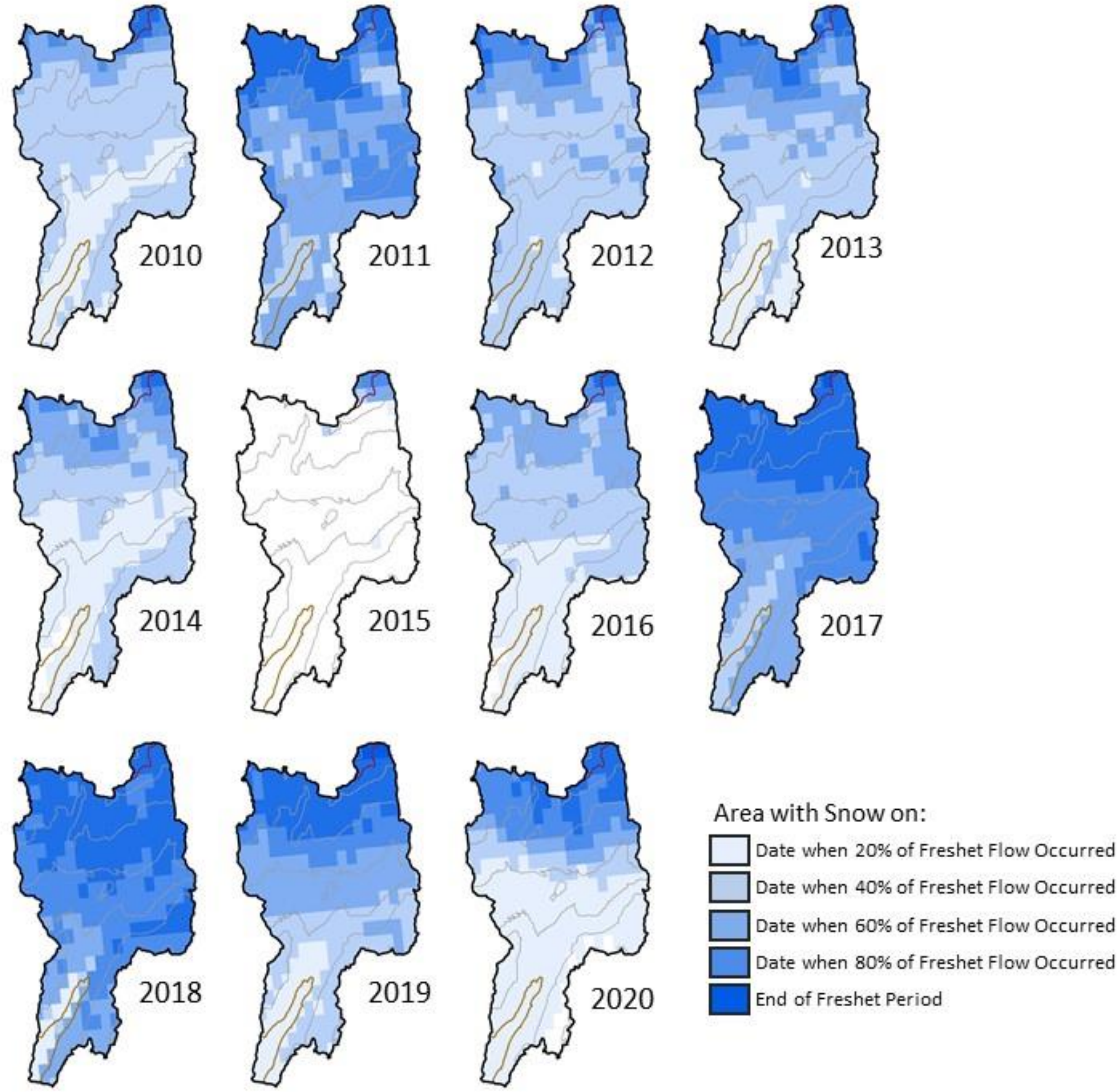


*Figure J6. The progression of snow covered area over the 2010-2020 spring freshet periods for Trapping Creek basin. Maps show SCA on the dates when 0, 20, 40, 60, 80 and 100% of the freshet flow volume occurred. Areas in white were snow-free at the start of the freshet flow period. Darker blue areas indicate longer snow persistence. Elevation contour interval is 200 m; the 2000 m contours is in purple.*

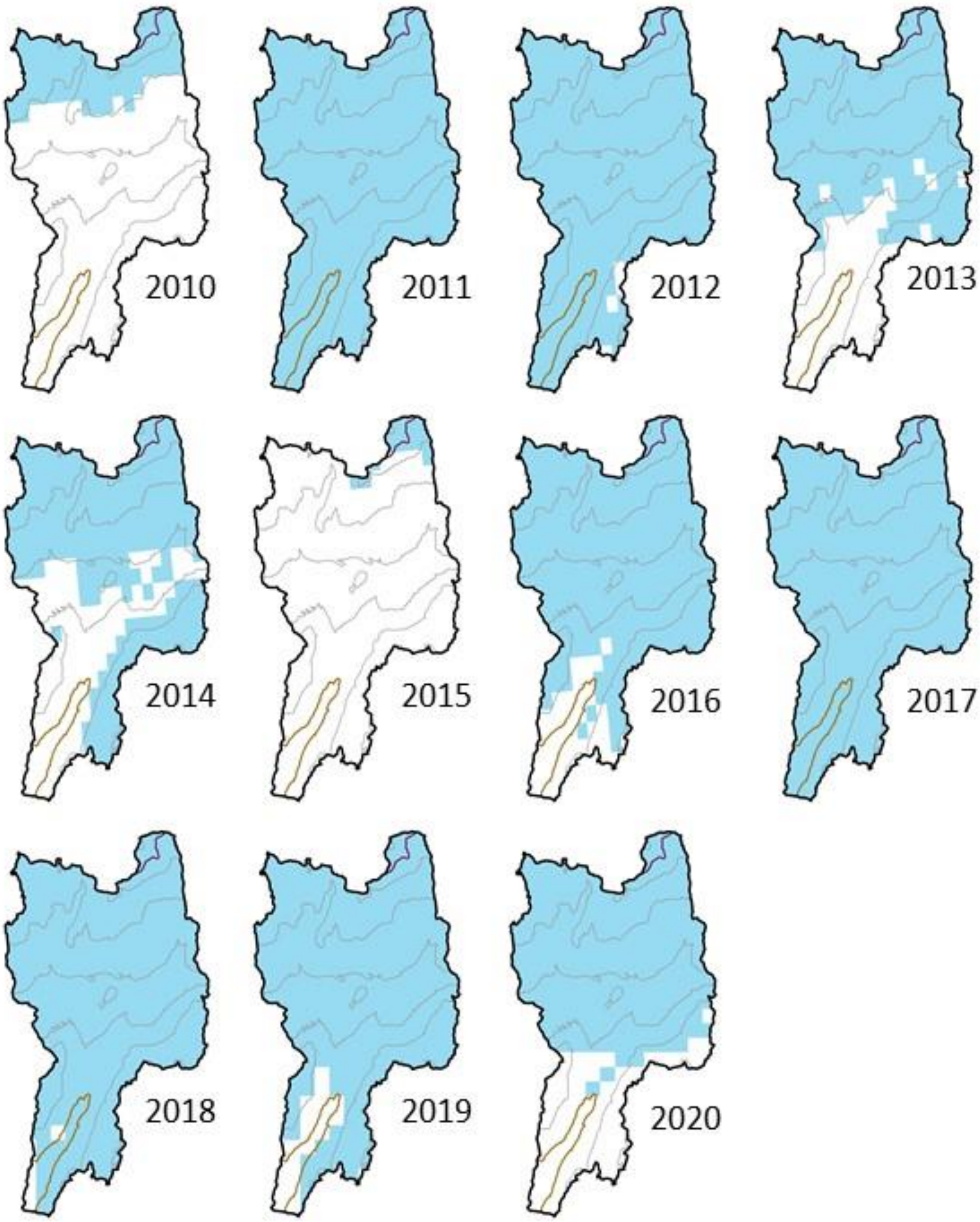


*Figure J7. Snow covered area in Trapping Creek basin on the date of onset of the peak flow period, 2010-2020. Elevation contour interval is 200 m; the 2000 m contours is in purple.*

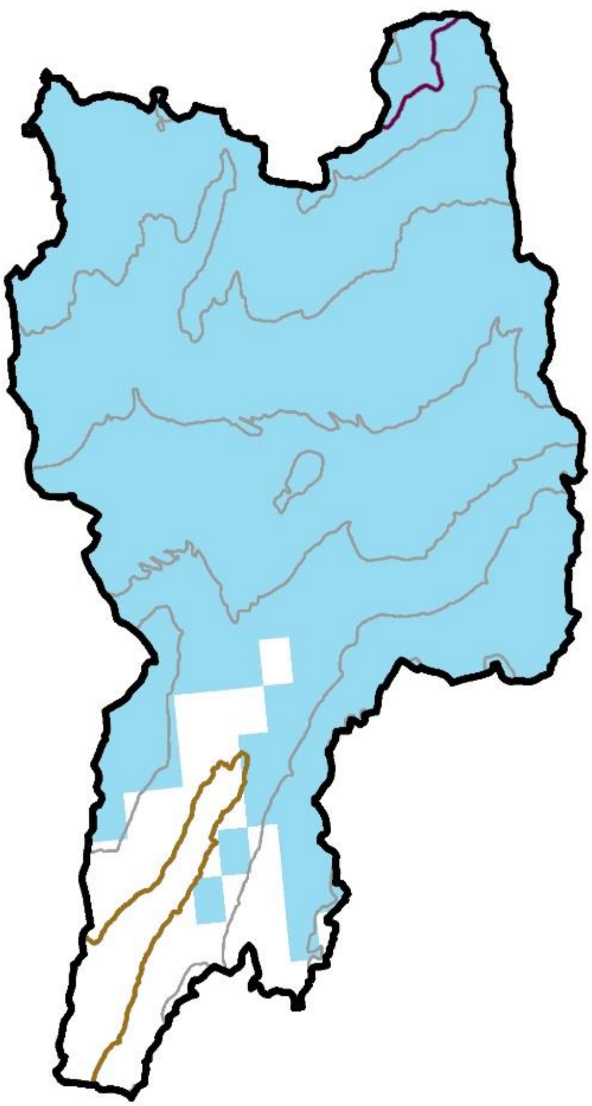


*Figure J8. The snow sensitive zone of Trapping Creek basin. Elevation contour interval is 200 m); the 2000 m contours is in purple.*

## APPENDIX K: SUMMARY OF ANNUAL SNOWMELT CONDITIONS

**(Summary of accumulation and melt conditions from Provincial Snow Survey and Water Supply Bulletins produced by B.C. River Forecast Centre)**

Between January and June each year, the B.C. River Forecast Centre sends out regular bulletins summarising snow cover conditions across 28 ‘snow basins’ in the province. Snow Indices are calculated for each snow basin using automated snow pillow and snow survey measurements and are reported as a % of historical normal of a specific day of the year (e.g. March 1st). Prior to 2015, the Kettle River basin was included in the Okanagan-Kettle snow basin and occasionally a separate index value was reported for the Kettle. In 2015 a new area named Boundary was defined. The 2010-2020 snow basin index values relevant to the Kettle River basin are shown in Table K1, including values for the Okanagan snow basin after 2015. The new Boundary region consistently had lower index values compared to those reported for the Okanagan (except in 2015).

*Table K1. Snow Basin Indices (% of normal) reported in River Forecast Centre Snow Survey and Water Supply Bulletins. Note: the Okanagan-Kettle snow basin was used until 2015, after which values were reported for the Boundary snow basin.*

| Year | 1 March | 1 April | 1 May | 15 May | 1 June |
|---|---|---|---|---|---|
| **2010** | 86 (75)[1] | 83 (69)[1] | 76 (69)[1] | n/a | n/a |
| **2011** | 88 | 107 | 145 | 173 | 274 |
| **2012** | 88 | 104 | 101 | 95 | 81 |
| **2013** | n/a | 107 | 115 | 64 | 76 |
| **2014** | 94 | 97 | 128 | 113 | 123 |
| **2015** | 75 (85)[2] | 61 (76)[2] | 58 (57)[2] | 70 (41)[2] | 1 (0)[2] |
| **2016** | 115 (123)[2] | 106 (131)[2] | 63 (75)[2] | 55 (35)[2] | 16 (26)[2] |
| **2017** | 59 (86)[2] | 86 (105)[2] | 121 (147)[2] | 139 (151)[2] | 178 (228)[2] |
| **2018** | 136 (141)[2] | 149 (152)[2] | 238 (206)[2] | 132 (126)[2] | 129 (51)[2] |
| **2019** | 68 (81)[2] | 65 (72)[2] | 71 (69)[2] | 58 (54)[2] | 3 (4)[2] |
| **2020** | 134 (115)[2] | 122 (116)[2] | 119 (110)[2] | 127 (99)[2] | 211 (193)[2] |

[1] *Values in brackets were reported for the Kettle snow basin.*

[2] *Values in brackets are for the Okanagan snow basin to allow comparison with years before 2015.*

The snow basin index reflects both (a) snow accumulation and (b) snowmelt, so it is very important to consider weather conditions when interpreting values. For example, a low value on 1 April may be due to low winter precipitation or to early melt of an average snowpack. The following paragraphs provide summaries of weather and melt conditions across B.C. as summarised in the B.C. Snow Survey and Water Supply Bulletins, including the phase of the El Niño-Southern Oscillation (ENSO). A warm ENSO phase, commonly referred to as an El Niño condition, is usually associated with warm and dry conditions in B.C. whereas the opposite (La Niña) tends to be cool and normal to wet in terms of precipitation.

**2010:** El Niño conditions. Although the fall started warm and wet, precipitation in November and December was lower than average. Warm temperatures in January, February and most of March resulted in melt at low elevations. It was noted that February was very dry in the Kettle region. Frontal storms brought precipitation at the end of March, but April was again warm and dry. May was very cool with high precipitation (e.g., precipitation in Castlegar was 118% of normal, Penticton was 203%), which slowed melt and brought some snow to high elevations. Only high elevations had snow on 1 June, and the month continued to be cool.

**2011:** Moderate La Niña conditions. The fall season was warm with below normal precipitation. While January had approximately average precipitation, February, March and April saw more that average.

February was cold, with alternating frontal storms and intrusions of cold Arctic air. March was also cold, and there was more snow at low and mid-elevations than normal. Cool and wet weather continued into April and May, delaying melt by 2-4 weeks. In June temperatures were close to normal with normal precipitation, and low to mid-elevations were mostly snow-free.

**2012:** Weak to moderate La Niña conditions, combined with a cool phase PDO (Pacific Decadal Oscillation) which tends to amplify La Niña conditions; transitioned to neutral ENSO by April. Precipitation and temperature during the fall season were near normal. A high pressure ridge caused dry and relatively warm conditions in December, and January saw alternating wet and dry periods with relatively warm temperatures. February, March and April were wetter than normal, and there was a brief hot spell in April followed by a big rain event. Most low elevation locations were snow free by late April and mid-elevations were actively melting. By the end of May there was limited snow at mid-elevations and there was more snow at high elevations than normal, where melt was delayed 3-4 weeks. There were heavy rains in early June, accelerating melt during this period.

**2013:** Neutral ENSO conditions. The fall season started warmer than normal until December when temperatures dropped. There was near normal precipitation during this period. January was drier than normal but inversions persisted in most areas, bringing warm temperatures to higher elevations. Despite two significant atmospheric river events in March bringing heavy precipitation, the month saw near-normal precipitation totals and normal temperatures. There were very hot temperatures at the beginning of April but the month ended wet and cool. Melt was generally delayed until hot and dry weather in May reversed this pattern and caused fast melt; low elevations were snow free and snow at mid-elevations was dwindling by the end of May.

**2014:** Neutral ENSO conditions. The fall period was generally dry, except for a warm and wet November. Warmer temperatures in January led to more precipitation falling as rain at low elevations. February was relatively cold, and near normal precipitation occurred in February and March. April saw mixed weather patterns; higher than normal precipitation was measured, occurring primarily at the end of the month. The onset of melt was delayed. Very hot temperatures at the beginning of May caused low elevations to become snow free and melt to commence at mid- and high elevations. The month ended drier than normal. June was wet with near normal temperatures.

**2015:** Neutral ENSO transitioned to weak El Niño; the ‘warm blob’ persisted in the Pacific Ocean off the coast of B.C. The fall season was relatively warm and dry. January, February and March were much warmer than normal with higher than normal precipitation that fell as rain at low elevations. April was not as warm as previous months but was still above normal and very dry. Snow was gone from low and mid-elevations by this time, which is much earlier than normal. Very warm temperatures in May were associated with convective storms, causing rapid melt. The very warm conditions continued into June.

**2016:** Strong El Niño conditions transitioned to neutral ENSO by June. There was considerable frontal storm activity in the fall, and October, November and December were wetter than normal. Temperatures were much warmer than normal in January through May. February and March saw more precipitation than normal, with more falling as rain at low elevations. Melt was occurring at mid-elevations in February, approximately 2-3 weeks early. Low and mid-elevations were mostly snow free by the end of March. April was much drier than normal and the very warm temperatures caused melt to occur 3-4 weeks early. May started very hot and dry, and ended cool and wet. Similarly, June started hot and ended cool.

**2017:** Weak La Niña transitioned to neutral ENSO by February. Highly variable conditions in the fall delayed snow accumulation and resulted in melt of any snow that fell early in the season. January started cold and dry, but an atmospheric river event brought warm and wet weather that caused melt at low elevations. February was cold and dry, allowing more snow to accumulate at low elevations than normal and less snow at high elevations. March and April were cool and very wet (this was the wettest April at many stations). Low and mid-elevations were mostly snow-free by the end of April though melt was delayed by approximately 2 weeks. May started hot with thunderstorms, causing rapid melt. This was followed by cold and wet weather that brought considerably more snow at high elevations. The month ended hot and sunny. Mid-elevations were mostly snow-free by mid-May but there was still a lot of snow at high elevations. June was warm and dry, and the rapid snowmelt continued.

**2018:** La Niña conditions. Temperatures in the fall were near normal until an arctic air mass moved in in December. The snow accumulation season started early, in November, and the cold temperatures in December resulted in more snow at low elevations. January was slightly warmer but very dry. February was very cold and wet, transitioning to near-normal temperatures and much higher than normal precipitation in March. April was cool and wet overall, but there was a significant warm period in the middle of the month that caused significant melt at low and mid-elevations. These elevations did not become snow-free, however, because considerable snow accumulated there. May was very hot with one heavy rainfall event, causing rapid melt; low elevations were snow free by the middle of the month, and most snow at mid-elevations disappeared by the end of the month. June started cool and wet but became dry and hot. Melt occurred 1-4 weeks early and only high elevation snowpacks remained by the end of June.

**2019:** El Niño conditions developed over winter. Fall temperatures were 1-2 degrees above normal in southern BC and snow accumulation on the ground was below normal. Elevated air temperatures in December and very high precipitation brought snowpack at high elevations closer to normal by the end of the month, but mixed rain and snow at low and mid-elevations resulted in less snow accumulation there. High precipitation in early January with elevated air temperatures meant more snow accumulation at high elevations but less at low and mid-elevations. Monthly mean air temperature in February was 6-9 degrees colder than normal due to persistence of an arctic air mass, which also brought little precipitation. March started cold but very warm temperatures occurred in southern BC at the end of the month, causing early melt at low and mid-elevations. This March was one of the driest on record. April was cool and unsettled; air temperature and precipitation were near-normal. The snowpack below ~1600 m in the Southern Interior disappeared in early May because of very warm temperatures (2-3 weeks ahead of normal) but there was limited melt at high elevations (where melt was 1-2 weeks later than normal). This created a sudden transition from snow-free to snow covered over a few hundred metres. Late May was also warm and very dry. The snowpack had nearly disappeared by the beginning of June. The Snow Survey Bulletin noted that "[t]his year's June 15th snowpack across the province is like conditions experienced in 2015 and 2016 – both years with early melt."

**2020:** Neutral ENSO. Fall weather was variable. October was cold with lower than normal precipitation, followed by near-normal air temperatures and slightly below normal precipitation in November. December was warm and wet; several frontal and atmospheric river systems after mid-December brought high precipitation and snow accumulation at mid and high elevations, with rain at lower elevations. Snow accumulation continued in January due to persistent wet weather, including snowfall at low elevations. February was warmer than normal in Southern Interior, and there was near to above normal precipitation. Monthly mean air temperature was colder than normal in March and there was little precipitation. Cooler weather meant little melt at lower elevations. A brief warm spell in the third week of April caused melt at low elevations. There was limited melt and some snow accumulation at high elevations in May while most low and mid-elevations were snow-free. A heavy rain event occurred on 30-31 May. A Snow Basin Index value of 211% on 1 June reflected persistent snowpack at high elevations because of delayed melt (low and mid-elevations were snow-free). Early June was wet, but melt was limited at high elevations.