Subject Matter Expert Report: Water Temperature and Ice. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population

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EXECUTIVE SUMMARY

Teck Coal Limited (Teck Coal) initiated an "Evaluation of Cause" (EoC) to assess factors that could be responsible for Reduced Recruitment of Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*; WCT) in the Harmer Creek population. Reduced Recruitment was observed for the 2017, 2018, and 2019 spawning -year cohorts, and Recruitment Failure was observed for the 2018 spawning -year cohort in Harmer Creek. In contrast, recruitment in the Grave Creek population appeared to remain at replacement levels, except in 2018, suggesting that conditions unique to Harmer Creek may have caused the Reduced Recruitment.

This stressor report evaluates whether water temperature or ice conditions (or both) may have caused or contributed to the Reduced Recruitment. Water temperature and ice conditions are both driven by a combination of atmospheric conditions, groundwater input, and physical features of streams, but each of the stressors causes fish mortality through a unique causal effect pathway. Warm water temperatures can inhibit fish physiological processes such as gas transfer across their gills. Cold water temperatures during the spawning and incubation period can limit recruitment by prolonging fish embryo development, and delaying emergence from the substrate, leaving inadequate rearing time before winter, which can result in high overwinter mortality. During the winter, severe ice conditions can cause direct mortality by freezing, injury, or isolation. Ice may also affect fish indirectly through injury, increased predation, or changes in habitat suitability.

Continuous water temperature data from several locations in the Grave Creek watershed were available for May 2017 to October 2019, and from end of May to beginning of October 2021, and allowed general characterization of the temperature regime during this time. The data were not sufficient to assess whether conditions at the time of Reduced Recruitment were anomalous compared to other years; however, the data allowed description of spatial and temporal trends in water temperature relative to WCT tolerances and allowed descriptions of differences of conditions in the Grave and Harmer population areas. Ice conditions were not directly recorded in the Grave Creek Watershed and were therefore inferred through other measures such as air and water temperature, snow cover, and streamflow. Air temperature and snow water equivalents (SWE) data extend back to the 1980s and provided context for whether recent years were unusual; however, the available data were insufficient to allow comparison of ice conditions in the two population areas.

The primary conclusions from evaluation of water temperature and ice conditions are summarized below.

Water Temperature

- Water temperature rarely exceeded BCWQG optima during spawning, incubation, or rearing periods.
- Water temperatures in Grave and Harmer creeks remained cold even during the summer and were below the WCT optimum for growth.

- Water temperatures were lower than the spawning and incubation optima in the uppermost reaches of Grave and Harmer creeks, as measured at temperature stations G3 and H3. However, data in 2021 from a new station, G4, in GRV-R4 suggest water temperatures in upper Grave Creek may be warmer, and therefore more suitable for spawning and incubation than previously assumed.
- Rapid changes in water temperature were generally of low magnitude and within BCWQG.
- Growing season degree days (GSDD) calculations indicated that the upper reaches of Grave and Harmer creeks had short growing seasons and low GSDD accumulation.
- Most or all of the Harmer Creek population area (depending on year) and the upper portion of the Grave Creek population area were assessed as GSDD-limited. The lower portions of the Grave Creek population area had sufficient GSDD.

Water temperatures in the Grave Creek Watershed never exceeded the WCT incipient lethal water temperature of 19ºC and were often cooler than the optimum range for spawning, incubation, and rearing. The growing season in the upper reaches of both Grave and Harmer creeks was less than 900 GSDD, which may not have allowed for sufficient time for growth prior to winter. Insufficient post-emergence growth can lead to poor survival through the winter (Coleman and Fausch 2007b). Lower elevation locations in the watershed (and in Dry Creek) appeared to be warmer than locations in the upper watershed but were still sometimes colder than WCT optima.

Ice Conditions

- Air temperatures were abnormally cold in February 2018 and February 2019 (average air temperatures were -10.6ºC and -13.6ºC, respectively, compared to a 2011--2020 average of -6.0ºC).
- A rapid air temperature transition from warm to cold occurred in February 2019. A rapid temperature transition of this magnitude was found to be rare and was estimated to occur on average once every ~25 years.
- Snow water equivalents (SWE) in February 2019 were the lowest in the historical data set of 1983-2020.
- Water temperature in winter appeared to be warmer in the upper reaches of both Grave and Harmer creeks relative to locations further downstream, indicating the influence of groundwater on ice conditions in the upper reaches.
- Streamflow records indicated that discharge in Harmer Creek in February 2019 was among the lowest in the period of record (1992-2020).

The low average winter air temperatures in the Grave Creek Watershed suggest that winters are typically long and ice is abundant. Ice conditions were likely particularly severe in February 2019, when cold air temperatures likely led to substantial ice formation; water temperature readings of 0ºC were common at all water temperature stations not influenced by groundwater. Furthermore, the low SWE and discharge in February 2019 may have compromised buffering of the stream to cold air temperatures. If abnormal ice conditions occurred in the watershed, fish may have suffered higher mortality from direct causes (e.g., crushing, freezing, isolation) or indirect causes (e.g., starvation, concentration leading to predation) and may have influenced recruitment patterns in the 2018 spawning year cohort. Unfortunately, no empirical data or photographic evidence were available to corroborate inferences of ice conditions in February 2019.

Conclusions

The evidence provided in this report supports conclusions that water temperature and ice conditions were not the sole cause of the WCT Reduced Recruitment in Harmer Creek but were likely to have been contributory. The available evidence indicates that conditions were broadly similar in both the Harmer and Grave population areas. Both population areas were perennially cold during the growing season and were likely affected similarly by ice each year. Nevertheless, there were some differences between Grave and Harmer creeks that were fairly small in absolute magnitude but are likely to have been biologically meaningful. The differences in water temperature regime indicate that recruitment was likely to have been more limiting in the Harmer Creek population area due to poor temperature conditions for emergence timing, growth, and survival of WCT fry, and therefore recruitment. Particular attention was drawn to measures of cold-water temperature and interactions with other stressors to result in Reduced Recruitment. The growing season, as described by GSDD, was generally shorter and cooler in the Harmer Creek population area than in the Grave Creek population area, which is expected to result in later emerging fry that have less time to grow and therefore begin the overwintering period at a smaller size. Small fry size has been linked to poor overwinter survival in other interior Cutthroat Trout populations. In addition, anomalous ice conditions in 2019 may be partly explanatory for the Recruitment Failure that occurred in the 2018 spawning-year cohort in the Harmer Creek population and Reduced Recruitment in the Grave Creek population.

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Appendix A. Summary of Climate Data

ACRONYMNS AND ABBREVIATIONS

ATU	Accumulated Thermal Units
BCWQG	BC Water Quality Guidelines
BRE	Baldy Ridge Expansion [Project]
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
EoC	Evaluation of Cause
GSDD	Growing Season Degree Days
MWMxT	Mean Weekly Maximum Temperature
SME	Subject Matter Expert
SWE	Snow Water Equivalent
UFR	Upper Fording River
WCT	Westslope Cutthroat Trout

READER'S NOTE

Background

The Elk Valley (Qukin ʔamaʔkis) is located in the southeast corner of British Columbia (BC), Canada. "Ktunaxa people have occupied Qukin ʔamaʔkis for over 10,000 years. . . . The value and significance of ʔa·kxamis ʼqapi qapsin (All Living Things) to the Ktunaxa Nation and in Qukin ʔamaʔkis must not be understated" (text provided by the Ktunaxa Nation Council [KNC]).

The Elk Valley contains the main stem of the Elk River, and one of the tributaries to the Elk River is Grave Creek. Grave Creek has tributaries of its own, including Harmer Creek. Harmer and Grave Creeks are upstream of a waterfall on Grave Creek, and they are home to isolated, genetically pure Westslope Cutthroat Trout (WCT; *Oncorhynchus clarkii lewisi*). This fish species is iconic, highly valued in the area and of special concern under federal and provincial legislation and policy.

In the Grave Creek watershed[1], the disturbance from logging, roads and other development is limited. The mine property belonging to Teck Coal Limited's Elkview Operations includes an area in the southwest of the Harmer Creek subwatershed. These operations influence Harmer Creek through its tributary Dry Creek, and they influence Grave Creek below its confluence with Harmer Creek (Harmer Creek Evaluation of Cause, 2023)[2]. Westslope Cutthroat Trout populations in both Harmer and Grave Creeks are part of Teck Coal's monitoring program.

[1] Including Grave and Harmer Creeks and their tributaries.

[2] Harmer Creek Evaluation of Cause Team. (2023*). Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited.

The Evaluation of Cause Process

The Process Was Initiated

Teck Coal undertakes aquatic monitoring programs in the Elk Valley, including fish population monitoring. Using data collected as part of Teck Coal's monitoring program, Cope & Cope (2020) reported low abundance of juvenile WCT in 2019, which appeared to be due to recruitment failure in Harmer Creek. Teck Coal initiated an Evaluation of Cause — a process to evaluate and report on what may have contributed to the apparent recruitment failure. Data were analyzed from annual monitoring programs in the Harmer and Grave Creek population areas[3] from 2017 to 2021 (Thorley et al. 2022; Chapter 4, Evaluation of Cause), and several patterns related to recruitment[4] were identified:

- *Reduced Recruitment*[5] occurred during the 2017, 2018 and 2019 spawn years[6] in the Harmer Creek population and in the 2018 spawn year in the Grave Creek population.
- The magnitude of Reduced Recruitment in the Harmer Creek population in the 2018 spawn year was significant enough to constitute *Recruitment Failure*[7].
- Recruitment was *Above Replacement*[8] for the 2020 spawn year in both the Harmer and Grave Creek populations.

[3] Grave Creek population area" includes Grave Creek upstream of the waterfall at river kilometer (rkm) 2.1 and Harmer Creek below Harmer Sedimentation Pond. "Harmer Creek population area" includes Harmer Creek and its tributaries (including Dry Creek) from Harmer Sedimentation Pond and upstream.

[4] Recruitment refers to the addition of new individuals to a population through reproduction.

[5] For the purposes of the Evaluation of Cause, Reduced Recruitment is defined as a probability of > 50% that annual recruitment is <100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2023).

[6] The spawn year is the year a fish egg was deposited, and fry emerged.

[7] For the purposes of the Evaluation of Cause, Recruitment Failure is defined as a probability of > 50% that annual recruitment is <10% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2023).

[8] For the purposes of the Evaluation of Cause, Above Replacement is defined as a probability of > 50% that annual recruitment is >100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2023).

The recruitment patterns from 2017, 2018 and 2019 in Harmer Creek are collectively referred to as Reduced Recruitment in this report. To the extent that there are specific nuances within 2017-2019 recruitment patterns that correlate with individual years, such as the 2018 Recruitment Failure, these are referenced as appropriate.

How the Evaluation of Cause Was Approached

When the Evaluation of Cause was initiated, an *Evaluation of Cause Team* (the Team) was established. It was composed of *Subject Matter Experts* (SMEs) who evaluated stressors with the potential to impact the WCT population. Further details about the Team are provided in the Evaluation of Cause report (Harmer Creek Evaluation of Cause Team, 2023).

During the Evaluation of Cause process, the Team had regularly scheduled meetings with representatives of the KNC and various agencies (the participants). These meetings included discussions about the overarching question that would be evaluated and about technical issues, such as identifying potential stressors, natural and anthropogenic, which had the potential to impact recruitment in the Harmer Creek WCT population. This was an iterative process driven largely by the Team's evolving understanding of key parameters of the WCT population, such as abundance, density, size, condition and patterns of recruitment over time. Once the approach was finalized and the data were compiled, SMEs presented methods and draft results for informal input from participants. Subject Matter Experts then revised their work to address feedback and, subsequently, participants reviewed and commented on the reports. Finally, results of the analysis of the population monitoring data and potential stressor assessments were integrated to determine the relative contribution of each potential stressor to the Reduced Recruitment in the Harmer Creek population.

The Overarching Question the Team Investigated

The Team investigated the overarching question identified for the Evaluation of Cause, which was:

> **What potential stressors can explain changes in the Harmer Creek Westslope Cutthroat Trout population over time, specifically with respect to Reduced Recruitment?**

The Team developed a systematic and objective approach to investigate the potential stressors that could have contributed to the Reduced Recruitment in the Harmer Creek population. This approach is illustrated in the figure that follows the list of deliverables, below. The approach included evaluating patterns and trends, over time, in data from fish monitoring and potential stressors within the Harmer Creek population area and comparing them with patterns and trends in the nearby Grave Creek population area, which was used as a reference. The SMEs used currently available data to investigate causal effect pathways for the stressors and to determine if the stressors were present at a magnitude and for a duration sufficient to have adversely impacted the WCT. The results of this investigation are provided in two types of deliverables:

1. Individual Subject Matter Expert reports (such as the one that follows this Note). Potential stressors were evaluated by SMEs and their co-authors using the available data. These evaluations were documented in a series of reports that describe spatial and temporal patterns associated with the potential stressors, and they focus on the period of Reduced Recruitment, including the Recruitment Failure of the 2018 spawn year where appropriate. The reports describe if and to what extent potential stressors may explain the Reduced Recruitment.

   The full list of Subject Matter Expert reports follows at the end of this Reader's Note.

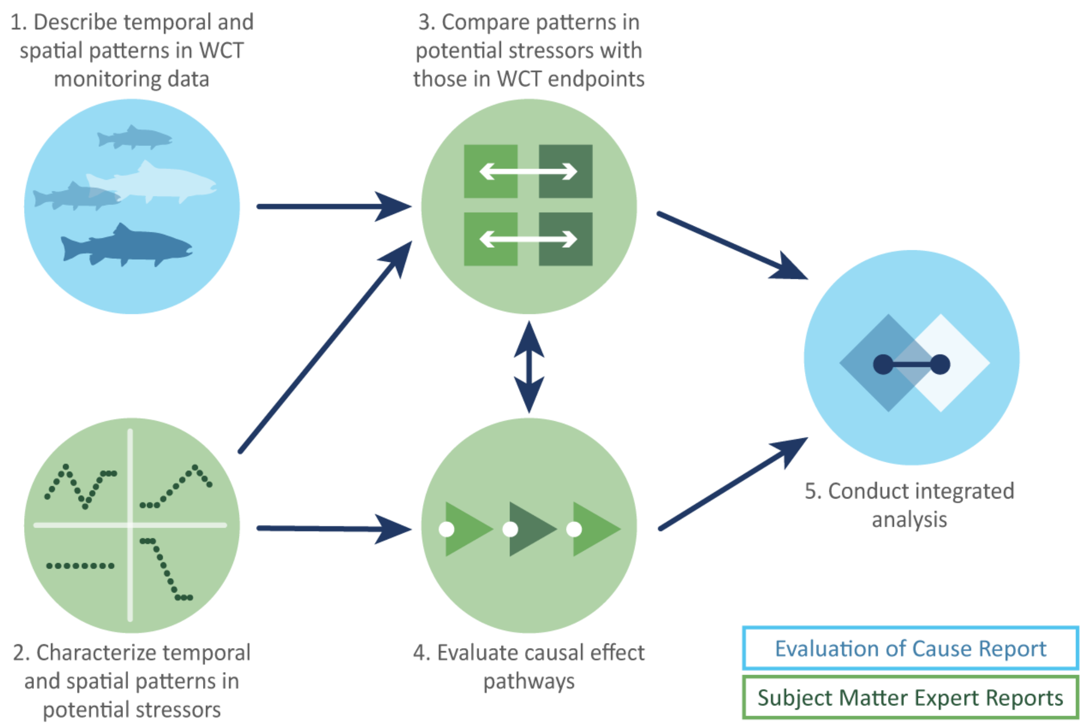
2. The Evaluation of Cause report. The SME reports provided the foundation for the Evaluation of Cause report, which was prepared by a subset of the Team and included input from SMEs.

   The Evaluation of Cause report:

   a. Provides readers with context for the SME reports and describes Harmer and Grave Creeks, the Grave Creek watershed, the history of development in the area and the natural history of WCT in these creeks

b. Presents fish monitoring data, which characterize the Harmer Creek and Grave Creek populations over time

c. Uses an integrated approach to assess the role of each potential stressor in contributing to Reduced Recruitment in the Harmer Creek population area.



Conceptual approach to the Evaluation of Cause for the Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout population.

Participation, Engagement & Transparency

To support transparency, the Team engaged frequently with participants throughout the Evaluation of Cause process. Participants in the Evaluation of Cause process, through various committees, included:

- Ktunaxa Nation Council
- BC Ministry of Forests,
- BC Ministry of Land, Water and Resource Stewardship

- BC Ministry Environment & Climate Change Strategy
- Ministry of Energy, Mines and Low Carbon Innovation
- Environmental Assessment Office

Citations for Evaluation of Cause Team Reports

Focus	Citation
Harmer Creek Evaluation of Cause report	Harmer Creek Evaluation of Cause Team. (2023). *Evaluation of Cause - Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited.
Calcite	Hocking, M. A., Cloutier, R. N., Braga, J., & Hatfield, T. (2022). *Subject Matter Expert Report: Calcite. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Dissolved oxygen	Abell, J., Yu, X., Braga, J., & Hatfield, T. (2022). *Subject Matter Expert Report: Dissolved Oxygen. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Energetic Status	Thorley, J.L. & Branton, M.A. (2023) *Subject Matter Expert Report: Energetic Status at the Onset of Winter Based on Fork Length and Wet Weight. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population*. Report prepared for Teck Coal Limited. Prepared by Poisson Consulting Ltd and Branton Environmental Consulting.

Focus	Citation
Food availability	Wiebe, A., Orr, P., & Ings, J. (2022). *Subject Matter Expert Report: Food Availability. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Minnow Environmental Inc.
Groundwater	Canham, E., & Humphries, S. (2022). *Evaluation of Groundwater as a Potential Stressor to Westslope Cutthroat Trout in the Harmer and Grave Creek Watersheds.* Memo prepared for Teck Coal Limited. Prepared by SNC-Lavalin Inc.
Habitat availability (instream flow)	Wright, N., Little, P., & Hatfield, T. (2022). *Subject Matter Expert Report: Streamflow and Inferred Habitat Availability. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Sediment quality	Wiebe, A., Orr, P., & Ings, J. (2022). Subject Matter Expert Report: Sediment Quality. *Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population*. Report prepared for Teck Coal Limited. Prepared by Minnow Environmental Inc.
Selenium	de Bruyn, A., Bollinger, T., & Luoma, S. (2022). *Subject Matter Expert Report: Selenium. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by ADEPT Environmental Sciences Ltd, TKB Ecosystem Health Services, and SNL PhD, LLC.
Small population size	Thorley, J. L., Hussein, N., Amish, S. J. (2022). *Subject Matter Expert Report: Small Population Size. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Poisson Consulting and Conservation Genomics Consulting, LLC.

Focus	Citation
Telemetry analysis	Akaoka, K., & Hatfield, T. (2022). *Harmer and Grave Creeks Telemetry Movement Analysis.* Memo prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Total suspended solids	Durston, D., & Hatfield, T. (2022). *Subject Matter Expert Report: Total Suspended Solids. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.
Water quality	Warner, K., & Lancaster, S. (2022). *Subject Matter Expert Report: Surface Water Quality. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by WSP-Golder.
Water temperature and ice	Hocking, M., Whelan, C. & Hatfield, T. (2022). *Subject Matter Expert Report: Water Temperature and Ice. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population.* Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.

1. INTRODUCTION

Teck Coal undertakes aquatic monitoring programs in the Elk Valley, including fish population monitoring. Using data collected from 2017 to 2019 in Harmer and Grave creeks, Cope and Cope (2020) reported low abundance of juvenile Westslope Cutthroat Trout (WCT; *Oncorhynchus clarkii lewisi*), which indicated apparent recruitment failure in Harmer Creek. Teck Coal initiated an Evaluation of Cause — a process to evaluate and report on what may have contributed to the apparent recruitment failure. Data were analyzed from annual monitoring programs in the Harmer and Grave Creek population areas[9] from 2017 to 2021 (Thorley *et al.* 2022; Chapter 4, Evaluation of Cause), and several patterns related to recruitment[10] were identified:

- *Reduced Recruitment*[11] occurred during the 2017, 2018 and 2019 spawn years[12] in the Harmer Creek population and in the 2018 spawn year in the Grave Creek population.
- The magnitude of Reduced Recruitment in the Harmer Creek population in the 2018 spawn year was significant enough to constitute *Recruitment Failure*[13].
- Recruitment was *Above Replacement*[14] for the 2020 spawn year in both the Harmer and Grave Creek populations.

The recruitment patterns from 2017, 2018, and 2019 in Harmer Creek are collectively referred to as Reduced Recruitment in this report. To the extent that there are specific nuances within 2017-2019 recruitment patterns that correlate with individual years, such as the 2018 Recruitment Failure, these are referenced as appropriate.

[9] "Grave Creek population area" includes Grave Creek upstream of the waterfall and Harmer Creek below Harmer Sedimentation Pond. "Harmer Creek population area" includes Harmer Creek and its tributaries (including Dry Creek) from Harmer Sedimentation Pond and upstream.

[10] Recruitment refers to the addition of new individuals to a population through reproduction.

[11] For the purposes of the Evaluation of Cause, Reduced Recruitment is defined as a probability of > 50% that annual recruitment was < 100% of that required for population replacement (See Chapter 4, Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

[12] The spawn year is the year a fish egg was deposited, and fry emerged.

[13] For the purposes of the Evaluation of Cause, Recruitment Failure is defined as a probability of > 50% that annual recruitment is < 10% of that required for population replacement (See Chapter 4 Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

[14] For the purposes of the Evaluation of Cause, recruitment Above Replacement is defined as a probability of > 50% that annual recruitment is > 100% of that required for population replacement (See Chapter 4 Evaluation of Cause, Harmer Creek Evaluation of Cause Team 2022).

The Evaluation of Cause Project Team investigated one overarching question: **What potential stressors can explain changes in the Harmer Creek Westslope Cutthroat Trout population over time, specifically with respect to patterns of Reduced Recruitment?** To investigate this question, the Team evaluated trends in WCT population parameters, including size, condition, and recruitment, and in the potential stressors[15] that could impact these parameters. They evaluated the trends in WCT population parameters based on monitoring data collected from 2017 to 2021 (reported in Thorley *et al.* 2022 and Chapter 4, Harmer Creek Evaluation of Cause Team 2022). The Grave Creek population area was used as a reference area for this evaluation.

The approach for analyzing potential stressors for the Evaluation of Cause was to: (1) characterize trends in each stressor for the Harmer and Grave Creek populations, (2) compare the trends between the two population areas, (3) identify changes in Harmer Creek during the period of Reduced Recruitment, including the 2018 Recruitment Failure of the 2018 spawn year where appropriate, and (4) evaluate how each stressor trended relative to the fish population parameters. The Team then identified mechanisms by which the potential stressors could impact WCT and determined if the stressors were present at a sufficient magnitude and duration to have an adverse effect on WCT during the period of Reduced Recruitment. Together, these analyses were used in the Evaluation of Cause report to support conclusions about the relative contribution of each potential stressor to the Reduced Recruitment observed in the Harmer Creek population area.

Ecofish Research Ltd. (Ecofish) was asked to provide support as a Subject Matter Expert (SME) for an evaluation of ice and water temperature as stressors. This report investigates water temperature and ice conditions in Grave and Harmer creeks and their tributaries. Exposure to severe ice conditions or water temperature outside of optima may have detrimental effects on fish; thus, it is possible that water temperature or ice may have caused or contributed to the observed WCT Reduced Recruitment. This document is one of a series of SME reports that supports the integrated Harmer Creek Westslope Cutthroat Trout Evaluation of Cause (Harmer Creek Evaluation of Cause Team 2022). For more information, see the preceding Reader's Note.

[15] The Evaluation of Cause process was initiated early in 2021 with currently available data. Although the process continued through mid-2022, data collected in 2021 were not included in the Evaluation of Cause because most stressor reports were already complete. Exceptions were made for the 2021 fish monitoring data and (1) selenium data because the selenium report was not complete and substantive new datasets were available and (2) water temperature data for 2021 in the temperature report because a new sampling location was added in upper Grave Creek that contributed to our understanding of the Grave Creek population area.

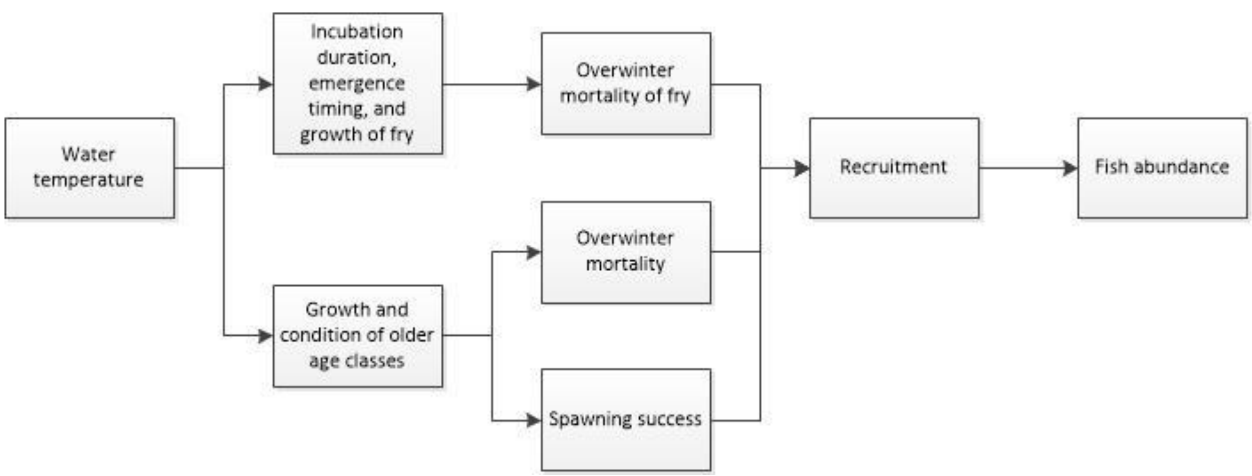
1.1. Background

1.1.1. Report-Specific Background

High-elevation streams present several unique challenges to fish survival. Streams at high elevation are often low-volume and high-gradient and receive less thermal energy input than nearby valley-bottom streams. High-elevation streams are generally tributaries to larger, valley-bottom rivers; fish in these smaller streams are more likely to be exposed to water temperature-related stressors than fish in larger rivers, since large volumes of water can buffer changes in temperature. Despite adverse environmental conditions, however, high-elevation streams can still support fish populations, though sometimes at lower densities.

This report assesses the effects of two stressors on WCT in the Grave Creek Watershed[16]: water temperature and ice conditions. Water temperature effects were assessed first. Cold water temperature can be a limiting factor for salmonids that can affect growth and survival of all age classes; however, effects on embryo (i.e., incubation) and fry life stages are especially noteworthy because of effects on recruitment (McCullough 1999, Bear *et al.* 2007, Coleman and Fausch 2007a, 2007b, Macnaughton *et al.* 2018; Mochnacz 2021). During the summer, low water temperature can prolong incubation and lead to late emergence of fry. Delayed emergence may leave inadequate time for growth of fry before the onset of winter, when fish are dependent primarily on stored energy reserves. Newly-emerged fish that do not accumulate enough fat stores prior to winter suffer high mortality and low recruitment into the next age class (Coleman and Fausch 2007b). Poor recruitment may lead to low densities and ultimately may limit the long-term viability of a population. Water temperature may also affect older juveniles and adults via lower physiological condition, growth, and survival. Figure 1 shows a causal effect pathway for the linkages between water temperature and fish abundance.

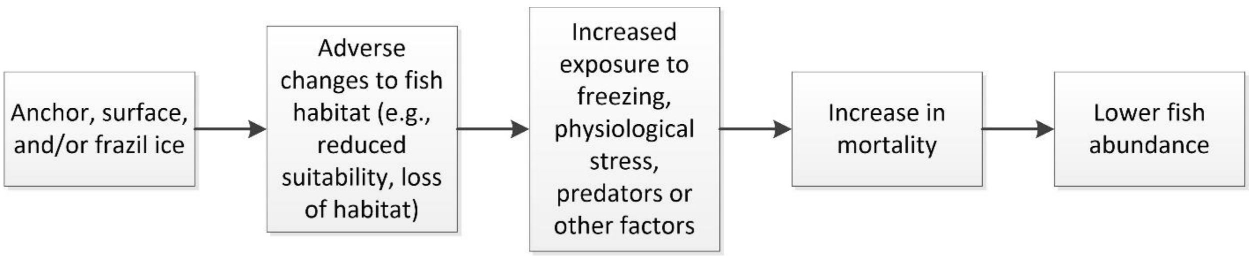
Figure 1. Causal effect pathway diagram linking water temperature to fish abundance.



[16] Throughout this report the term Grave Creek Watershed is used when referring to the entire catchment, which includes both Grave and Harmer creeks.

This report next assesses ice conditions in Grave and Harmer creeks. Fish in high-elevation streams are adapted to withstand cold winter stream temperatures, but severe ice conditions (entrained ice, anchor ice accumulation, ice dams, frazil ice) can nevertheless cause high mortality directly (via crushing or freezing) or indirectly (via displacement, isolation, increased vulnerability to predators, and starvation). The effect of ice conditions on fish can be influenced by the timing of ice and snow accumulation, ice type, and fish access to hydraulically and thermally suitable areas within the overwintering habitat. Groundwater inputs may provide temperature refuges but can also prevent surface ice from forming, thereby increasing water exposure to cold air. Figure 2 shows a causal effect pathway for the linkages between ice conditions and fish abundance.

Figure 2. Causal effect pathway diagram linking ice formation to fish abundance.



1.1.2. Author Qualifications

Todd Hatfield, Ph.D., R.P.Bio.

This project is being led by Todd Hatfield, Ph.D., a registered Professional Biologist and Principal at Ecofish Research Ltd. Todd has been a practicing biological consultant since 1996, and he has focused his professional career on three core areas: environmental impact assessment of aquatic resources, environmental assessment of flow regime changes in regulated rivers, and conservation biology of freshwater fishes. Since 2012, Todd has provided expertise to a wide array of projects for Teck Coal: third party review of reports and studies, instream flow studies, environmental flow needs assessments, aquatic technical input to structured decision making processes and other decision support, environmental impact assessments, water licensing support, fish community baseline studies, calcite effects studies, habitat offsetting review and prioritizations, aquatic habitat management plans, streamflow ramping assessments, development of effectiveness and biological response monitoring programs, population modelling, and environmental incident investigations.

Todd has facilitated technical committees as part of multi-stakeholder structured decision-making processes for water allocation in the Lower Athabasca, Campbell, Quinsam, Salmon, Peace, Capilano, Seymour and Fording rivers. He has been involved in detailed studies and evaluation of environmental flows needs and effects of river regulation for Lois River, China Creek, Tamihi Creek, Fording River, Duck Creek, Chemainus River, Sooke River, Nicola valley streams, Okanagan valley streams, and Dry Creek. Todd was the lead author or co-author on guidelines related to water diversion and allocation for the BC provincial government and industry, particularly as related to the determination of instream flow for the protection of valued ecosystem components in BC. He has worked on numerous projects related to water management, fisheries conservation, and impact assessments, and developed management plans and guidelines for industry and government related to many different development types. Todd was the subject matter expert for a series of stressor reports that Ecofish delivered for the Evaluation of Cause investigation into WCT decline in the upper Fording River. Todd recently completed his third 4-year term with COSEWIC (Committee on the Status of Endangered Wildlife in Canada) on the Freshwater Fishes Subcommittee.

Morgan Hocking, Ph.D., R.P.Bio.

Morgan is a Senior Environmental Scientist with Ecofish with over 20 years of experience conducting salmonid conservation and watershed resource management projects in British Columbia. For much of his career, he has studied how spawning Pacific salmon affect terrestrial biodiversity, and how this information can be used in ecosystem-based management. He uses a combination of field studies, experiments, watershed spatial data, quantitative modelling, and novel tools in ecology such as stable isotopes and environmental DNA to assess watershed status and the relationships between watershed developments and biodiversity and has published 25 peer-reviewed articles on his work. Morgan has extensive experience in designing and implementing large-scale monitoring programs and has over 15 years of experience working with First Nations, primarily related to fisheries management in the Great Bear Rainforest.

With Ecofish, Morgan works on technical project management, community engagement, experimental design, data analysis, reporting, and senior technical review on a diversity of projects such as the Cumulative Effects Monitoring Program in the Skeena watershed (Environmental Stewardship Initiative), the Fish and Wildlife Compensation Program (FWCP) Action Plan Update (FWCP Coastal and FWCP Peace), the Site C Tributary Mitigation Program (BC Hydro), and the Ecofish environmental DNA program. Morgan is the technical lead of the Calcite Biological Effects Program with Teck and the Teck Kilmarnock eDNA study. Morgan also holds a position as an Adjunct Professor in the School of Environmental Studies at the University of Victoria.

Colby Whelan, M.Sc., R.P.Bio.

Colby Whelan is a fisheries biologist who obtained his Bachelor of Science from the University of Victoria in 2012 and his Master of Science in Ecology at the University of Calgary in 2020. His graduate work focused on the risk of Whirling Disease infection to threatened populations of Westslope Cutthroat Trout in Banff National Park. His study examined how variation in fish habitats in Banff could lead to differential risk of Whirling Disease establishment, and how this information could be used to design protective measures for threatened fish populations.

Colby has worked for Ecofish since 2019 and prior to that worked for the aquatics department of Parks Canada in Banff National Park. Through these positions he has participated in several studies of factors that contribute to the decline of native trout populations, including Whirling Disease, climate change, invasive species, and habitat loss. Colby was a co-author on the Upper Fording River Evaluation of Cause – Ice and Fish Passage reports. He has also authored a number of reports that assess stressor effects on fish populations in various locations within BC. Colby has direct experience collecting data on WCT during winter and summer in the Canadian Rockies, including in conditions similar to those discussed in this report.

1.2. Objective

The objective of this report is to review the available information on water temperature and ice conditions, and to assess whether these stressors influenced WCT recruitment in the Harmer Creek population area.

The study question addressed was:

- Did unusual water temperature or ice conditions cause or contribute to Reduced Recruitment in the Harmer Creek WCT population?

1.3. Approach

Water temperature and ice stressors are ultimately driven by climatic factors, such as precipitation (rain and snow), solar radiation, air and ground temperature, and by intrinsic watershed characteristics, such as aspect, gradient, and riparian shading. However, the effect mechanisms of water temperature and ice are substantially different. Ice stressor mechanisms are primarily direct (i.e., physical) effects to habitat that influence the amount or suitability for fish, or direct effects to individuals that cause physical harm (e.g., entombment or injury). Water temperature stressor mechanisms are more indirect effects that influence the physiological state of fish, such as metabolic rate, energy budget, and growth rate, ultimately influencing survival and recruitment. There is also some overlap, in that ice effects to habitat can influence the characteristics of habitats that fish use and thereby the physiological costs of using those habitats (e.g., higher energy cost of using faster velocity habitat). Although the proximate mechanisms of water temperature and ice stressors are quite different, their evaluations in this report depend on analysis of similar types of data from nearby climate stations (air temperature, precipitation, snow) and *in situ* water temperature data from the Grave Watershed.

The effects of ice and water temperature as stressors on the Grave Creek Watershed WCT population were evaluated using several sources of information. A background literature review was conducted to provide background for understanding the mechanisms of water temperature effects on WCT, ice formation processes, and links between ice conditions and fish mortality. Multiple data sources were then used to infer whether water temperature, ice, and hydrological conditions were anomalous and potentially causal to Reduced Recruitment in Harmer Creek. The approach is similar to that used in the UFR EoC (Hatfield and Whelan 2021). To further understand the possible effects of water temperature on recruitment, a modelling exercise was undertaken to predict fry size relative to water temperatures observed at different locations in the watershed. The fry sizes were then applied to an overwintering survival function to determine whether differences in size could have contributed to the Reduced Recruitment.

Continuous water temperature data were available at several locations in the Grave Creek Watershed for a two-year period (May 2017 to October 2019; Cope and Cope 2020); these data provided partial coverage of the period of Reduced Recruitment (2017 – 2019; Thorley *et al.* 2021). Additional data were collected in 2021 to expand the temporal and spatial coverage of water temperature monitoring, and to provide an indicator of whether data recorded in 2017 – 2019 were anomalous; however, the 2021 data were incomplete since the record began partway through the year. Due to the limited data record, we were unable to compare water temperatures during the Reduced Recruitment period to prior years and thereby assess if temperatures were abnormal. Instead, the water temperature results were compared to WCT temperature optima derived from the literature. Growing season degree days (GSDD) were also calculated to assess the duration and strength of growing conditions. Conditions in the Harmer and Grave creek population areas were compared to determine whether water temperatures in different locations were suitable for WCT recruitment (including spawn timing, incubation duration, and fry rearing prior to overwinter).

Detailed and specific data for ice in the Grave Creek Watershed were not available, so a variety of related climate data (air and water temperature, snowpack, streamflow) were compiled and reviewed to infer ice conditions. Little information was available to corroborate whether the observed climate conditions led to anomalous ice conditions, so conclusions are necessarily inferential. Some degree of ice formation is expected in Grave and Harmer creeks each year, so determining the relative intensity of ice formation was a key component of this evaluation, because anomalous effects such as widespread WCT mortality would be expected only if unusually intense ice conditions occurred.

Results of the water temperature and ice analyses were compared to criteria for explanatory factors (Section 2.4) to determine whether these stressors could have caused or contributed to the Reduced Recruitment of the Harmer Creek population. Consideration was given to the intensity, duration, timing, location, and spatial extent of stressor exposure.

2. METHODS

Evaluation of water temperature and ice conditions in Grave Creek watershed relied on analyses of available climate and water temperature data and current understanding of effect mechanisms. The available data within Grave Creek watershed were limited in their temporal and spatial coverage. The analyses and results are nevertheless directly relevant to fish recruitment (i.e., water temperature, winter weather and winter flow conditions). Additional analyses of air temperature, precipitation, snow depth, and snow water equivalents are provided for context in Appendix A. Information on streamflow and inferred habitat availability is presented in Little *et al.* (2021), including analyses of historical data and whether conditions during the Reduced Recruitment were anomalous.

On occasion this report refers specifically to fish of a certain age class, in which case the terminology for ages classes is: age 0, age 1, age 2+, and adult (see Thorley *et al.* 2021). More often information was not available to allow reference to a specific age class, so instead the terms ‘fry’, ‘juvenile’ and ‘adult’ were used. Within this report fry refers to age 0 individuals (i.e., from emergence to the end of their first full summer), juvenile refers to age 1, and 2+ fish, and adult refers to ages ≥3+ and implies reproductive maturity. No fish lengths are presented within this report; however, for the Evaluation of Cause, fish ≥150 mm at the start of the spawning period in spring are classified as adult in the Grave Creek watershed.

The species periodicity used for the analysis is provided in Table 1. An early and late incubation period were defined to describe temperature conditions for redds created during early spawning versus late spawning. Additional information on WCT periodicity in the Grave Creek watershed is provided in Harmer Creek Evaluation of Cause Team (2022).

Table 1. WCT life history periodicity table for the Grave Creek Watershed. For Incubation, two scenarios are provided to indicate incubation periodicity based on WCT spawning early in the spawning period (dark grey) and incubation for eggs spawned late in the period (light grey).

Life History Activity	Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Spawning																																																
Incubation (egg and alevin)																																																
Summer Rearing (>5ºC)																																																
Over-wintering																																																

2.1. Literature Review

To better understand how water temperature and ice influence recruitment, a literature review was undertaken. The objectives of the literature review were to understand:

- Water temperature interactions with fish growth and survival;
- Ice formation processes;
- Mechanisms via which ice influences survival of fish; and
- The distribution of fish in the Grave Creek watershed.

Information on the above topics was drawn from the primary literature, experience and observations in the field, and results from other monitoring programs in the Elk Valley.

2.2. Water Temperature

2.2.1. Data Collection

Water temperature data were collected for the Harmer and Grave Creek Westslope Cutthroat Trout Habitat and Population Assessment (Cope and Cope 2020). Temperature loggers were deployed at stations in the Grave Creek Watershed from May 2017 to October 2019 (Map 1; see Table 2 for station details). A logger was also installed in Dry Creek (D3) from May 2018 to October 2019. In response to the finding of Reduced Recruitment, additional data collection was implemented in 2021 at most of the stations monitored for 2017-2019 and at four additional stations (Map 1; Table 2). All loggers collected water temperature data at 15-minute intervals.

The locations of water temperature stations were selected to capture water temperature variation in the watershed. The sensors were placed at locations where water temperature in a stream was expected to shift (e.g., downstream of major confluences, sedimentation ponds, and groundwater sources). The loggers were installed in deep sections of creek that were unlikely to dewater or freeze to bottom. Further details on water temperature sensors, deployment locations, methods for securing the loggers, and the download frequency are provided in Cope and Cope (2020).

Table 2. Metadata for Grave Creek Watershed temperature loggers used in water temperature analysis. All monitoring stations had duplicate loggers installed and recorded on a 15-minute interval.

Creek/Reach	Site	Reach	Elevation (masl)[1]	Period of Record 1			Period of Record 2		
				Start Date	End Date	% Complete	Start Date	End Date	% Complete
Grave Creek	EV_G4	GRV-R4	1587	-	-	-	26-May-2021	7-Oct-2021	88
	EV_G3	GRV-R3	1489	17-May-2017	15-Oct-2019	97	26-May-2021	7-Oct-2021	55
	EV_G2	GRV-R3	1303	17-May-2017	15-Oct-2019	96	27-May-2021	7-Oct-2021	99
	EV_G1	GRV-R1	1241	17-May-2017	15-Oct-2019	100	27-May-2021	7-Oct-2021	74
Dry Creek	EV_D3	DC-R2	1466	28-May-2018	15-Oct-2019	100	-	-	-
Balzy Creek	EV_BAL	BL-R1	1417	-	-	-	8-Jul-2021	29-Oct-2021	91
Harmer Creek	EV_HG	HRM-R6	1536	17-May-2017	15-Oct-2019	100	26-May-2021	7-Oct-2021	100
	EV_H3	HRM-R5	1473	17-May-2017	15-Oct-2019	100	-	-	-
	EV_H2	HRM-R2	1325	17-May-2017	15-Oct-2019	100	27-May-2021	7-Oct-2021	77
	EV_H1	HRM-R1	1316	17-May-2017	15-Oct-2019	100	27-May-2021	7-Oct-2021	100
	EV_LH	HRM-R5	1437	-	-	-	8-Jul-2021	28-Oct-2021	100
	EV_UH	HRM-R4	1385	-	-	-	8-Jul-2021	29-Oct-2021	100

[1] Meters above sea level

"-" denotes no water temperature available for the period

2.2.2. Water Temperature Metrics

Temperature optima provided in Oliver and Fidler (2001)[17] were refined for this report, based on the primary literature for closely related interior Cutthroat Trout subspecies (Greenback Cutthroat Trout *O. c. stomias* and Colorado River Cutthroat Trout *O. c. pleuriticus*; Coleman and Fausch 2007a) and site-specific information for Grave and Harmer creeks (e.g., Cope and Cope 2020, water temperature records, redd observations). The temperature optima used for the analysis are provided in Table 3.

Table 3. Water temperature criteria in the BC Water Quality Guidelines for the protection of aquatic life (Oliver and Fidler 2001), with adjustments based on information for WCT in Cope *et al.* (2016) and other observations.

Activity Period	Criterion	Source
All Periods (January 1 - December 31)	the rate of temperature change in natural water bodies should not exceed 1ºC/hr	Oliver and Fidler (2001)
Spawning (June 12 - July 11)	mean weekly temperature should not exceed ±1ºC beyond 7 - 10ºC	Oliver and Fidler (2001); Cope *et al.* 2016; Cope and Cope 2020
Incubation (June 12 - October 31)	mean weekly temperature should not exceed ±1ºC beyond 7 - 12ºC	Oliver and Fidler (2001); Cope *et al.* 2016; Cope and Cope 2020
Summer Rearing (May 28 - October 10)	mean weekly temperature should not exceed ±1ºC beyond 7 - 16ºC	Oliver and Fidler (2001); Cope *et al.* 2016; Cope and Cope 2020

The following summary statistics were calculated as data availability permitted: monthly mean and monthly instantaneous minimum and maximum water temperatures for each month of the record, hourly rate of change of temperature, number of days with mean daily water temperature >18ºC, >20ºC, and <1ºC, and mean weekly maximum water temperature (MWMxT) (Table 4). Mean weekly temperature was compared to species-specific water temperature optima (Table 4). Mean weekly water temperature was also compared to the WCT upper optimum, which is based on the upper incipient lethal temperature for WCT (19.6ºC; Bear *et al.* 2007). Hourly rates of change in water temperature were compared to the BC WQG, which specify that the hourly rate of water temperature change should not exceed ±1.0°C/hr. Extremes in MWMxT were compared to optimum temperature ranges for WCT life stages as described in Table 4. Each analysis above was completed for all years with available data.

GSDD were calculated as a measure of thermal energy accrued at each water temperature station during the growing season. The growing season was defined as starting when the average weekly water temperature exceeded 5ºC and ending when the average weekly water temperature declined below 4ºC (Coleman and Fausch 2007b). GSDD was calculated by summing the average water temperature on each day in the growing season. GSDD at each station were compared to thresholds developed by

[17] The temperature optima provided in Oliver and Fidler (2001) are general to Cutthroat Trout and appear to be specific to temperate coastal waters occupied by Coastal Cutthroat Trout (*Oncorhynchus clarkii clarkii*).

Coleman and Fausch (2007b) to describe the growing seasons for Cutthroat Trout recruitment in high-elevation Colorado streams. Coleman and Fausch (200a,b) considered GSDD <800 to be unsuitable for recruitment, 800-900 to be marginally suitable, and >900 to be suitable for recruitment.

Using Coleman and Fausch's three levels of GSDD suitability, recruitment suitability by stream reach was displayed in map format. For visualization purposes, GSDD was linearly interpolated using 10 segments of equal stream length between temperature stations. GSDD was extended upstream of the HG, G3, and D3 stations and downstream of G1 based on the GSDD value of the closest station. Separate maps were generated for GSDD in 2018 (Map 2) and 2019 (Map 3). A map was not generated for 2017 because data were insufficient at some stations; likewise, data were insufficient to complete maps for water temperature in 2021. Results at stations with sufficient data in 2017 were similar to results at those stations in 2018 and 2019.

Table 4. Description of water temperature metrics and methods of calculation.

Parameter	Description	Method of Calculation
Monthly water-temperature statistics	Mean, minimum, and maximum temperatures on a monthly basis	Calculated from 15 minute data and presented in tabular format.
Rate of change in water temperature	Change in water temperature over hourly intervals	Calculated from 15 minute data, presented in graphical form.
Number of days with extreme daily-mean temperature	Total number of days with daily-mean water temperature >18°C , >20°C , and <1°C	Calculated from daily-mean temperatures.
Number of days with optimal daily-mean temperature	Total number of days with daily-mean water temperature between 15°C and 13°C	Calculated from daily-mean temperatures.
MWMxT	Mean Weekly Maximum Temperature	A 1-week moving-average filter was applied to the record of daily-maximum water temperatures inferred from hourly data; e.g., if MWMxT = 18°C on August 1, 2008, this was the average of the daily-maximum water temperatures for the 7 days from July 29 to August 4. MWMxT is calculated for every day of the year.
Growing Season Degree Days (GSDD)	The beginning of the growing season is defined as the beginning of the first week that average stream temperatures exceed and remain above 5°C; the end of the growing season is defined as the last day of the first week that average stream temperature dropped below 4°C (modified from Coleman and Fausch 2007b).	Daily average water temperatures were summed over this period (i.e., from the first day of the first week when weekly average temperatures reached and remained above 5°C until the last day of the first week when weekly average temperature dropped below 4°C).

2.2.3. Recruitment Scenario Testing with GSDD

To further evaluate how spatial and temporal patterns of GSDD in the Grave Creek watershed could affect WCT fry growth and survival from the time of emergence through to the following spring, several additional explorations were undertaken as part of a detailed scenario evaluation. The GSDD values for temperature stations were integrated into functions developed by Coleman and Fausch (2007a,b) to allow predictions of fry size and survival (i.e., recruitment) in relation to GSDD at each station. Detailed methods of the scenario testing are presented along with results (see Section 3.2.6.2) because the scenario test has multiple steps, each of which depends on previous steps.

2.2.4. Air Temperature as a Proxy Measure

Continuous water temperature data in the Grave Creek watershed have a short period of record, so we examined air temperature records to provide an indication of whether temperature during the Reduced Recruitment period was anomalous. Air temperature values at EC Sparwood CS were used to fill gaps in the data series at EC Sparwood, and this data series is referred to herein as "EC Sparwood – Extended". To fill gaps, air temperature values at EC Sparwood were regressed against Sparwood CS using a linear model. The resulting model parameters were then used to fill in the Sparwood data series. The original Sparwood data series covered 1980 to 2020, and was 95% complete; whereas the Sparwood CS covered 1992 to 2020, and was 97% complete. The gap-filled EC Sparwood extended dataset is 99.8% complete over a period of 41 years (1980-2020).

The results presented in this report include average monthly air temperature for 2011 to 2020 from EC Sparwood. Average by month for the period of record (1980 – 2020) is also presented for context. Air temperature was further summarized by plotting the average daily temperature for the winter period (October - March) for the last four winters (2016/17, 2017/18, 2018/19 and 2019/20). A GSDD proxy measure was calculated using air temperature degree days >5°C and compared to water temperature GSDD to evaluate whether the short water temperature data record was representative of a longer period.

2.3. <u>Ice</u>

Air temperature, water temperature, snowpack, and streamflow data were compiled and reviewed to infer ice conditions in the Grave Creek watershed.

2.3.1. Air Temperature

Most of the methods for analysis of air temperature are presented in Section 2.2.4, and the results were used to help infer ice conditions during Reduced Recruitment. In addition, to understand the severity of the temperature shift in February 2019, an additional analysis was carried out specific to the Ice stressor. To detect the magnitude and rarity of temperature transitions (i.e., shifts from warm to cold air temperature) in the air temperature data, we identified the 10 largest-magnitude transitions in temperature since 1980. A probability distribution of temperature transitions was calculated, and the probability of occurrence, or return period, for the 10 largest-magnitude transitions was computed using a Weibull plotting position formula.

2.3.2. Water Temperature

Most of the methods for analysis of water temperature are presented in Section 2.2, and the results were used to help infer ice conditions during Reduced Recruitment. In addition, plots were generated that focused on water temperatures during winter months (October – March) to allow for comparisons among years.

2.3.3. Snow Water Equivalents

Snow Water Equivalents (SWE) are a measure of the snowpack based on weight of accumulated snow. SWE is a more consistent measure of the amount of snow than a simple snow depth measurement. A plot was generated for the Morrissey Ridge SWE measuring station that summarizes SWE for the last four winters (2016/17, 2017/18, 2018/19 and 2019/20). Further results for other snow depth stations can be found in Appendix A.

2.3.4. Discharge and Stage

Streamflow data were collected by both Water Survey Canada (WSC) and Teck Coal. No statistical analyses were conducted, but panel plots illustrating stage, discharge, and historical norms (November – March) were generated for relevant stations with sufficiently complete data. Two stations were selected for inclusion: WSC NK002 Elk River at Fernie and HC1 located below the Harmer Creek Sedimentation Pond (Map 1). These stations were considered representative of regional and local conditions.

Transformation of stage data to discharge estimates can be error-prone when ice is present (RISC 2018). Because discharge at continuous hydrometric stations is calculated from measured stage and is often adjusted or removed during the hydrometric QA processes, we closely examined the uncorrected stage time series with a particular focus on variation of stage with the understanding that high variation in stage is often an indication of ice.

Streamflow data were analyzed by standard temporal periods (months, years) to identify temporal trends in the available data. Data gaps that existed in the HC1 discharge record influenced the calculation of some statistics. For example, instantaneous flow measurements at EV_HC1 were collected on approximately a weekly basis during the open water period and a monthly basis during the winter. For this station and others, gaps between measurements were filled using linear interpolation prior to calculating median and daily percentiles of flow. Only gaps less than or equal to 45 days were filled.

2.3.5. Direct Observations of Ice

To evaluate whether ice conditions directly or indirectly influenced the observed WCT Reduced Recruitment, we searched for records of direct observations of ice conditions. There were few direct observations of ice conditions within the Grave Creek watershed, and no direct observations were available during periods of extreme cold; therefore, weather, water temperature, hydrology data and other ancillary information were used to infer ice conditions.

2.4. Evaluation of Explanatory Factors

Five explanatory factors were used to assess effects of water temperature and ice conditions on WCT recruitment: exposure intensity, duration, spatial extent, location, and timing. Criteria for each of these factors (Table 5) were used to determine whether water temperature and ice conditions caused or contributed to the Reduced Recruitment. For water temperature and ice conditions to be considered a primary cause of the Reduced Recruitment, conditions for all five explanatory factors would need to be met. For example, the stressor must have been of moderate-to-high intensity, been widespread in the watershed (i.e., in multiple reaches), and occurred coincident with the Reduced Recruitment and acted for sufficient duration. For a stressor to be assessed as contributing to reduced WCT recruitment, all explanatory factors did not need to be met.

Table 5. Conditions for explanatory factors that were used to determine whether water temperature and ice conditions were a cause of or contributor to Reduced Recruitment.

Explanatory Factor	Condition
Intensity	Ice or water temperature conditions were sufficiently severe to be detrimental to WCT survival or reproduction
Spatial Extent	Detrimental ice or water temperature conditions occurred over an area sufficient to affect a large proportion of the fish population
Location	Harmer Creek was most strongly affected by detrimental ice or water temperature conditions
Timing	Detrimental ice or water temperature conditions were temporally consistent with the observed recruitment failure
Duration	Detrimental ice or water temperature were of sufficient duration to result in fish mortality

3. RESULTS

3.1. Literature Review

3.1.1. Westslope Cutthroat Thermal Tolerances

3.1.1.1. Warm Limitations

Within the salmonid family, thermal tolerances can differ among species, subspecies, and populations (Drinan *et al.* 2012). The natural range of salmonids reaches as far south as California with a few small populations of Rainbow Trout existing in Northern Mexico; however, it is hypothesized that the southern range boundary is limited by warm water temperature (MacCrimmon 1971). When water temperature exceeds an individual fish's tolerance there can be physiological breakdown, such that oxygen can no longer be moved from its gills into the bloodstream, resulting in death (McCullough

1999). Water temperature can also have various negative effects on spawning, fertilization, incubation, and rearing (Coleman and Fausch 2007a, 2007b). The ability to withstand high temperature can vary by life stage; larger-bodied adults tend to suffer the highest mortality at high temperature (Bear *et al.* 2007).

Westslope Cutthroat Trout tend to reside in high elevation, snowmelt or glacier fed streams in the Rocky Mountains, where water temperature is generally cold. In laboratory experiments, the incipient lethal temperature (the temperature at which mortality starts to occur) of WCT was 19.6ºC (95% CI = 19.1 – 19.9ºC), whereas for Rainbow Trout it was 24.3ºC (95% CI = 24.0 – 24.7ºC; Bear *et al.* 2007). In a separate experiment, it was identified that WCT may inhabit warmer temperatures (as high as 26ºC) if acclimatized over several days, and if a cold-water refuge is also accessible, which can be the case in streams with deep pools, cold tributaries, or groundwater input (Macnaughton *et al.* 2018).

In some locations, distribution of WCT may be undergoing a range contraction from lower elevations due to increasingly warm water temperatures (DFO 2014). Water temperatures in Grave and Harmer creeks and nearby areas have previously been found to not exceed the upper water temperature thresholds of WCT (Cope *et al.* 2016; Cope and Cope 2020). An examination of water temperature trends in Grave and Harmer creeks is provided in Section 3.2 below.

3.1.1.2. Cold Limitations

Water temperature during the growing season influences the timing of nearly all developmental milestones that trout must reach to reproduce and sustain recruitment (Heggenes *et al.* 2021). WCT inhabit high-elevation rivers that often remain <15ºC throughout the open water period, which leads to several challenges. Though air temperature begins to warm in April and can remain warm as late as October, cold water can persist through freshet when streamflow and water temperature is driven mostly by snowmelt. In northern temperate interior streams, water temperature generally begins to rise after freshet, and peaks in late July or early August, before beginning to cool in September and reaching winter conditions by late October or November (Whelan *et al.* 2021).

Cold water can influence the entire reproductive cycle including spawning date, rate of embryonic development, and rearing conditions. Trout in the genus *Oncorhynchus* spawn in the spring, but spawning can be delayed until freshet ends and streams begin to warm (Todd *et al.* 2008). Water temperatures of 7-10ºC are considered optimal for spawning, but in high-elevation streams in the Elk Valley water may not reach this temperature until early July (Whelan *et al.* 2021), after which spawning will occur. Water temperature directly influences the duration of incubation and timing of fry emergence from the spawning gravel; water temperature of 7–12ºC is considered optimal for incubation (Oliver and Fidler 2001), and temperatures below 7ºC extend the time from spawning to emergence. Low abundance of Cutthroat Trout was common in Colorado and New Mexico streams with July mean temperature ≤7.8ºC, while study streams with a July mean temperature ≥10.1ºC had high abundance (Harig and Fausch 2002). Low abundance at low stream temperatures may be influenced by slow growth; the optimum temperature for WCT growth was found to be 13.6ºC

(Bear *et al.* 2007). Slow growth can contribute to delayed maturity, lower fecundity, and lower overwinter survival. Recent work by Macnaughton *et al.* (2021) suggested a similar optimum temperature of ~14.5ºC and confirmed that WCT do not perform as well in cold water (≤10 °C). Moreover, in behavioural experiments WCT preferred water temperature of 19.9ºC, indicating this species can occupy a warmer thermal niche than previously thought, at least over relatively short periods.

Late spawning and delayed fry emergence shorten the amount of time available to fry for rearing prior to onset of winter, and limit growth prior to overwintering (Coleman and Fausch 2007a). In a lab experiment, insufficient degree days during a simulated short summer meant that most individuals failed to develop sufficient energy reserves to survive winter (Coleman and Fausch 2007a). Cold water during the rearing period can also be detrimental because it can affect exothermic fish by reducing their activity level and swimming ability. Coleman and Fausch (2007a) suggest that a short growing season can fail to prepare age 0 fish for winter, and that size achieved during the period immediately after emergence is correlated with overwintering survival. Results presented by Coleman and Fausch (2007a, b) indicated a total length of 30-35 mm was a minimum size for overwinter survival of Cutthroat Trout in Colorado. If poor rearing conditions affect a large portion of a cohort, recruitment failure can result.

The duration and strength of the growing period as it relates to the growth of all trout life stages can be gauged by GSDD, which measures the intensity of the growing season and is a cumulative count of the average daily water temperature between the start and end of the growing season. Less than 800 GSDD is unsuitable for recruitment, 800-900 GSDD is marginally suitable, and >900 GSDD tends to be sufficient for recruitment to support high-abundance populations (Coleman and Fausch 2007b).

Reduced Recruitment due to a too-cold or too-short growing season is poorly researched in WCT specifically, but fairly well understood in salmonids in general. GSDD limitations have been documented in other high-elevation trout such as Greenback Cutthroat Trout, Colorado River Cutthroat Trout (Coleman and Fausch 2007a, 2007b) and Bull Trout (Mochnacz 2021). Studies documented that failure to reach sufficient GSDD led to poor incubation and hatch success. In the high elevation streams studied it was found that overwinter Cutthroat Trout survival was 28 - 50% in age 0 fish, in part due to poor growing conditions prior to winter (Coleman and Fausch 2007b). Since WCT inhabit cold water streams with similar thermal regimes to these species, we assume that WCT are limited by similar GSDD constraints. However, in streams with insufficient GSDD, population growth or maintenance may be achieved in other ways, such as immigration from more productive reaches (Coleman and Fausch 2007b).

3.1.1.3. Temperature Stability

Stable temperatures are more suitable for trout growth and survival than variable water temperature. Growth and survival decreased in Lahontan Cutthroat Trout (a subspecies that inhabits the Great Basin in Northern Nevada) as daily temperature variation increased (Meeuwig *et al.* 2004). Similarly, in

Rainbow Trout the incipient lethal temperature decreased as temperature variation increased (Hokanson *et al.* 1977).

Swift, high-magnitude warming, or cooling can result in lethal or sublethal effects to fish. Survival of fertilized Yellowstone Cutthroat eggs was found to be significantly lower when they were exposed to a temperature drop from 7ºC to 3ºC in the first 11 days after spawning; however, after 11 days of incubation, there were fewer effects of rapid temperature shifts (Hubert and Gern 1995). With the recognition that rapid temperature change may affect fish, guidance is provided within the BC Water Quality Guidelines that states water temperature should not vary by more than ±1ºC per hour (Oliver and Fidler 2001). This guidance was based primarily on water temperature observations in unregulated watercourses rather than on physiological tolerances determined from experimental trials.

3.1.1.4. Influences on Water Temperature

In order to understand water temperature in mountainous regions, meteorological and hydrological processes must be considered. During the open water period, solar radiation is the largest contributor to stream warming, along with contribution from air temperature (Leach and Moore 2011). Shading, aspect and substrate type can also influence warming by solar radiation. During the summer, sub-surface water contribution can cool the stream and moderate peak summer temperatures (MacDonald *et al.* 2014). Contributions to catchment scale moisture content through snowmelt and rainfall may also contribute to cooling in the summer and counteract solar radiation-driven warming.

During the winter, water temperature in high elevation streams within the Canadian Rockies may decline to near 0°C, due to very low solar input, low air temperatures, and the absence of moisture inputs from rain or snowmelt. The cold temperatures can persist from November until March or even April, depending on the year (see Section 3.2.2). Depending on flow conditions, water temperature near 0°C can lead to ice formation, which is covered in more detail in Section 3.1.2. Sub-surface water input may contribute to warmer stream temperatures in the winter. Sub-surface water input may also provide maintenance flow during the winter when surface inputs (precipitation, meltwater) tend to remain frozen (Power *et al.* 1999).

3.1.2. Ice Formation in Streams

3.1.2.1. Influences on Ice Conditions

Many factors influence the formation of stream ice in winter. Key factors include weather conditions, flow characteristics (e.g., velocity and turbulence), and channel characteristics (e.g., size and shape). Once a layer of surface ice has formed, snow accumulation can insulate the water below and slow or prevent further ice accumulation (Needham and Jones 1959). Water depth and volume are also important factors; ice formation is expected to occur faster when flows are comparatively low.

The velocity and turbulence of flow is a critical factor in the freezing process. Low stream velocity is associated with surface ice formation (Ashton 1986). A surface velocity of <0.6 m/s (Ashton 1986) is generally accepted as the threshold for static ice formation (Stickler *et al.* 2010). When velocity is below this threshold, ice will stay on the surface because vertical turbulence is insufficient to overcome the rise velocity (due to buoyancy) of an ice particle.

High velocities and turbulent flows can lead to super-cooling conditions (water temperatures less than 0ºC) and frazil or anchor ice formation processes (Tesaker 1994; Stickler and Alfredsen 2009). When sub-zero air cools open water, but turbulence prevents surface ice formation, a uniform water temperature forms within the stream; and ice crystals are able to form within the water column, rather than rising to the surface (Brown *et al.* 2011). The ice crystals can eventually agglomerate to form frazil ice (suspended in the water column), or anchor ice (attached to bottom substrate). Under certain conditions agglomerations may occupy the majority of the stream (Figure 3; Figure 4).

Figure 3. A schematic illustration of ice formation in rivers from Huusko *et al.* (2007).

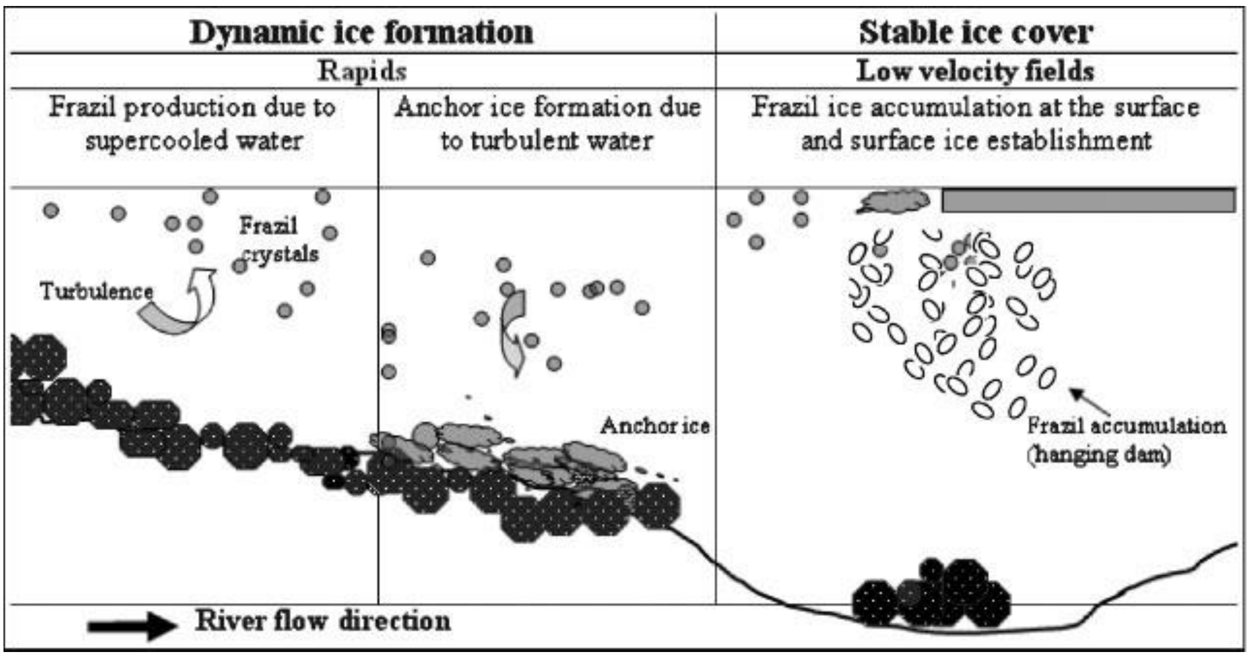


Figure 4. Examples of anchor ice (top; from Brown *et al.* 2011) and an extreme frazil ice event (bottom; from http://www.lifeinyosemite.com/2009/04/15/frazil-ice-in-yosemite-creek/).

Frazil and anchor ice can form large accumulations that act as obstructions or dams within streams (Huusko *et al.* 2007, Brown *et al.* 2000, Brown *et al.* 2011), which may cause flow to become constricted in some areas (e.g., increased velocities through pools; Cunjak and Caissie 1994; Brown *et al.* 2000). Although ice production in small, steep rivers is typically dynamic due to higher water velocities and turbulent flow (Huusko *et al.* 2007; Table 6), both dynamic and static ice can form in mesohabitats depending on flow and channel conditions.

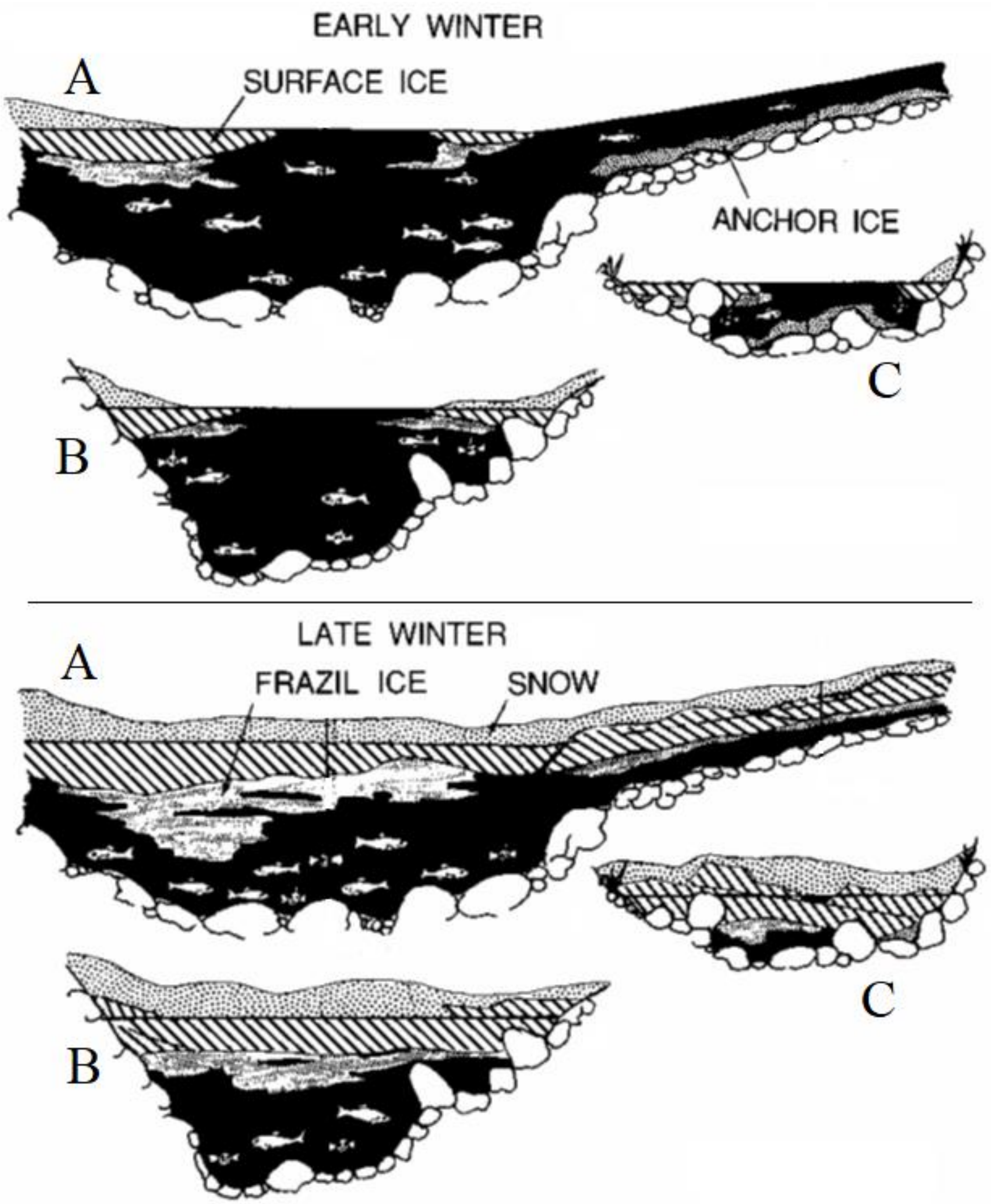
Table 6. Generalized ice processes over the course of winter in three types of rivers (from Huusko *et al.* 2007).

Ice regimes	River Type		
	Small, steep rivers	**Large rivers**	**Regulated rivers**
Early Winter Freeze-up	Border and skim ice Dynamic ice formation	Border and skim ice Ice over formation	Border ice Dynamic ice formation
Mid-Winter	Extended dynamic ice formation Anchor ice dams Local ice runs	Stable ice cover Dynamic ice formation in open riffles	Less surface ice Local ice runs Increased dynamic ice formation
Late Winter Ice break-up	Thermal ice break-up	Thermal ice break-up	Repeated mechanical ice break-ups throughout winter

3.1.2.2. Seasonal Differences in Ice Conditions

Ice formation in interior streams typically begins in late fall when low air temperatures cool water to the freezing point. At this time, border ice forms along the stream margins and skim ice forms in areas with low velocity (Huusko *et al.* 2007). In high gradient streams and river sections, dynamic ice formation occurs due to super-cooling and turbulence; thus, frazil ice, anchor ice, and frazil slush are common (Brown *et al.* 2011; Figure 5). As winter progresses, small, high-gradient streams may undergo an extended period of dynamic ice formation before reaching stable winter conditions (Huusko *et al.* 2007). Generally, streams in cold regions undergo continual discharge reduction from fall until early spring, and these low flows generally make the stream less resistant to severe ice formation during cold weather. With warmer air temperature in the spring ice break-up begins; it can be categorized as thermal or mechanical, but typically, both processes occur to some extent (Huusko *et al.* 2007; Brown *et al.* 2011). During thermal break-up, ice cover deteriorates with increasing temperatures and melts in place, and there may be no notable increase in discharge and little or no movement of ice. During mechanical break-up, an increase in stream discharge fragments the ice cover, which is then transported downstream by the current.

Figure 5. **Representation of the change in habitat availability in a temperate A) large stream, B) small stream pool, and C) small stream riffle as a standard winter progresses and ice accumulates (from Cunjak 1996).**

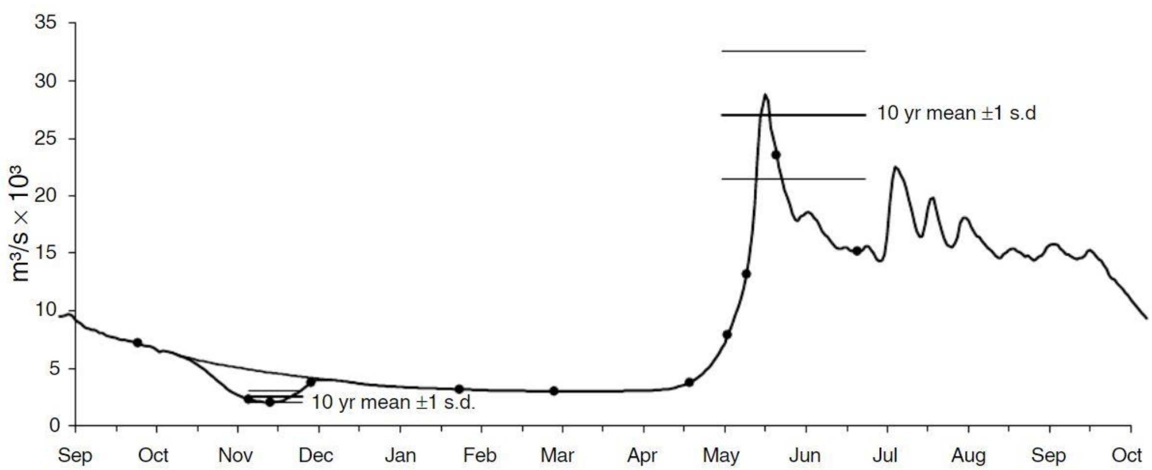


3.1.2.3. Hydrological Response to Ice Formation

A dynamic relationship exists between ice and stream hydrology. One well-documented relationship between ice and discharge is the discharge reduction (or "discharge depression") that can result downstream of areas where ice is forming (Hamilton and Moore 1996; Prowse 2001; Moore *et al.* 2002; Morse and Hicks 2005). The formation of ice puts water into hydraulic storage, which means that as water is transformed to ice it is removed from the river's net discharge (Figure 6). Conversely, ice build-up and related constrictions in the channel can increase resistance to flow (i.e., friction), which can alter streamflow characteristics (Prowse and Carter 2002; Morse and Hicks 2005).

Fluctuations in discharge may also occur due to the dynamic nature of ice formation processes, such as backwatering and release of water behind ice dams (Moore *et al.* 2002). Discharge may vary dramatically during ice break-up; the release of water from hydrologic storage, and the break-up of ice concurrently reduces resistance to flow, though at times the loose ice may form dams that may reduce flow (Morse and Hicks 2005).

Figure 6. Mackenzie River at Arctic Red, 1995-1996 hydrograph with data from Environment Canada, 1996 (from Prowse *et al.* 2007). Mean annual fall low flow and spring high flow periods are indicated. Circles indicate the date of discharge measurements. The discharge depression in November is attributed to ice formation storing water locally, an effect similar to withdrawal of water.



If a discharge depression occurs at the same time as a stream's natural low flow period it can result in a very low stream level (Conly and Prowse 1995). Extreme low flow events tend to be relatively short-lived: once ice cover is formed normal flow tends to resume.

Despite short durations, discharge depressions can have substantial effects on the aquatic environment and may have implications for water diversion or use (e.g., effective effluent dilution; Prowse 2001). For example, Maciolek and Needham (1952) observed diurnal isolation of side channels of a high-elevation stream during exceptionally cold conditions that caused hydrological responses from ice formation at night. Short-lived extreme low-flow events are rarely documented due to difficulties in reliable data collection during dynamic flow periods and because the interpolation of infrequently measured (e.g., once a week or less is a common measurement interval in winter conditions) flows can mask extreme values (Prowse 1994).

3.1.3. Salmonid Overwinter Habitat Preferences

The use of specific habitats during winter is an adaptation that salmonids in cold climates have developed to mitigate the negative effects of ice conditions and the need to conserve energy during winter. Salmonids, including WCT, tend to move to deeper pools that provide cover and lower water velocities (Cunjak 1996; Hiscock *et al.* 2002; Huusko *et al.* 2007; Brown *et al.* 2011). These types of habitats are often somewhat scarce in streams and rivers, so it is common for fish to be found in groups or aggregations where these habitats do occur (Huusko *et al.* 2007). Although fish generally move to lower velocity areas in winter, small individuals may seek cover in interstitial spaces in the stream substrate (McMahon and Hartman 1989; Lindstrom and Hubert 2004). Mean water column velocity and depth used by *Oncorhynchus* spp. in winter is <0.3 m/s, and >0.4 m, respectively (Baltz *et al.* 1991; Harper and Farag 2004; Huusko *et al.* 2007).

Movement of fish in winter has been found to be greater in the presence of frazil and anchor ice than stable ice (Brown *et al.* 1993, Jakober *et al.* 1998, Brown *et al.* 2000, Simpkins *et al.* 2000), and more extensive movements occur in streams with frequent freezing and thawing events (Jakober *et al.* 1998). However, even static ice formation can cause channel constrictions that increase velocities, which may also reduce habitat suitability and lead to movements and redistributions of individuals (Whalen *et al.* 1999).

3.1.4. Effects of Ice on Overwintering Fish

The availability and quality of overwintering habitat is often limited in streams occupied by WCT and, therefore, is disproportionately important habitat (Cleator *et al.* 2009). Existing studies indicate that mortality during winter in streams is a substantial source of total mortality (Simpkins *et al.* 2000, Hoffsten 2003, Alexiades *et al.* 2012, Cope *et al.* 2016).

Winter mortality in stream habitat may be exacerbated by dynamic ice conditions, which may cause increased flow velocity and displacement from, or loss of, optimal habitat or habitat features. Frazil or anchor ice accumulation can create constrictions and increase local water velocity to levels that are unsuitable for fish (Brown and Mackay 1995; Jakober *et al.* 1998; Whalen *et al.* 1999; Prowse *et al.* 2007). Frazil, anchor, or entrained pieces of surface ice can accumulate in fish habitat resulting in occlusion (Brown and Mackay 1995; Jakober *et al.* 1998; Lindstrom and Hubert 2004). Frazil ice can also displace fish from their habitat by forming hanging dams or other accumulations (Brown *et al.* 2011). The formation of anchor ice can be extensive enough to limit access to important interstitial cover in coarse substrate and woody debris (Huusko *et al.* 2007; Brown *et al.* 2011).

Fish mortality coincident with ice conditions may be due to one or many mechanisms and determining cause can be difficult, not least because observations are difficult in winter. In addition to effects on fish habitat and physiology discussed above, fish may be killed by ice directly through freezing, crushing, or entrapment. Fish may also be killed indirectly if ice increases their vulnerability to predators (potentially because they aggregate within a reduced habitat area or are physiologically stressed) or places unsustainable demands on energy reserves. Fish mortalities have been attributed to frazil ice (Maciolek and Needham 1952; Simpkins *et al.* 2000; Cope *et al.* 2016); however, this is poorly documented in the literature despite widespread acceptance of the effect. Fish populations are generally not regularly monitored, especially during winter, so there can be considerable uncertainty with respect to specific effects of winter conditions.

3.1.5. WCT in Grave and Harmer Creeks

Detailed observations of adult fish movements and habitat use are available from telemetry tracking and direct observations that took place during monitoring for Cope and Cope (2020). WCT monitored with telemetry in Grave and Harmer creeks had small home ranges (Cope and Cope 2020). The average WCT home range in Grave Creek was less than 0.5 km (n=33), and in Harmer Creek less than 1 km (n=30). The maximum movement measured for either population was 4.19 km; however, this amount of movement was rare. The small home range size indicates that fish within Grave and Harmer creeks use the same stream reaches for overwinter and summer rearing, and have little movement over the course of a year.

Fish in Grave and Harmer creeks are divided into two isolated sub-populations (Cope and Cope 2020). One sub-population inhabits the 11.6 km or habitat within Grave Creek between its headwaters downstream to a waterfall barrier near the confluence with the Elk River. Harmer Creek downstream of the Harmer Creek Sedimentation Pond (an additional 0.6 km of habitat) is also accessible to this sub-population. The other sub-population inhabits an approximately 9.0 km stretch of Harmer and Dry creeks that extends from the headwaters of Dry Creek to Harmer Creek Sedimentation Pond. Harmer Creek above the Dry Creek confluence has a groundwater source that is approximately 4ºC year-round and may be too cold to be consistently occupied by fish (Cope and Cope 2020).

Overwintering was studied using telemetry observations of radio-tagged WCT. Data were only available for a single winter (2017). The observations showed that tagged WCT undertook small movements during winter, though overall they remained near certain areas. In the Grave Creek population area (Map 1), overwintering was concentrated in three locations: in the downstream section near the barrier, around the confluence with Harmer Creek immediately downstream of Harmer Creek Sedimentation Pond, and around G3. Overwintering areas in the Harmer Creek population area were more evenly distributed between the Harmer Creek Sedimentation Pond and the confluence with Dry Creek. There are few deep pools in the Grave Creek watershed and the telemetry data indicated that fish were likely overwintering in interstitial spaces (Cope and Cope 2020).

Spawning and redd observations were studied during the spawning period in 2018 and 2019 using direct observations and were summarized in Cope and Cope (2020). Redds were broadly distributed in the watershed. In both Grave and Harmer creeks, redds were not found in the upstream-most portions of stream accessible to fish. Grave Creek had redds distributed from the barrier near the

Elk River upstream until roughly G3. Redds were found throughout Harmer Creek mainstem (with the exception of HRM-R6) and a small number was observed in the lower portion of Dry Creek.

Rearing was monitored using telemetry tracking of tagged fish through two periods (2017 and 2018; Cope and Cope 2020). The distribution of fish during the rearing period roughly mirrored that during the spawning and overwintering periods.

3.2. Water Temperature

3.2.1. Overview

The water temperature record in Grave and Harmer creeks was compiled from 8 data loggers[18] that were in place from May 2017 until October 2019 to support the reporting in Cope and Cope (2020). Data presented here are grouped into Harmer Creek (includes HG, D1, H3, H2 and H1; see Map 1) and Grave Creek (G3, G2 and G1)[19]. Where relevant, H1 was grouped with the Grave Creek stations to reflect the distribution of the two WCT sub-population (Grave Creek population area and Harmer Creek population area), which are separated by a barrier below the Harmer Creek Sedimentation Pond.

The top and bottom panels of Figure 7 illustrate water temperature time series by location; temperature variability was most pronounced during the growing season. The loggers at G1, G2 and H1 indicate a similar temperature pattern, and reached considerably warmer temperatures than G3. In all years with data, these three stations (G1, G2, H1) began to warm earlier in the year and began to cool later in the year than G3 (G3 spent nearly 2 more months below 2ºC in each year). By late September all stations began a rapid decline and remained consistently cold until warming began again in April. The onset of temperature decline was particularly abrupt in 2019, and this pattern occurred at all temperature stations.

The water temperature loggers within the Harmer Creek population area (D3, H3 and H2) also showed water temperature variability, with the exception of HG, which was in the groundwater reach of Harmer Creek and remained near 4°C throughout most of the year. During the growing season, D3 was far warmer than H2, which was warmer than H3. During the single winter of data at D3, indications of ice occurred from December until April, followed by rapidly increasing temperature. H2 and H3 had similar values except H3 is roughly 1ºC warmer in the winter and 1ºC colder in the summer. This temperature moderation was consistent with H3's proximity to the groundwater source of HRM-R6.

[18] The logger at Grave Lake outlet was excluded from the analysis because it does not influence the Grave Creek population area.

[19] Water temperatures are presented as results from individual water temperature monitoring stations, and due to the spatially variable inputs of groundwater and other inflows, few inferences are made to the reach scale. The reach locations of water temperature stations are presented in Table 2.

Figure 7. Daily mean water temperature (2017 – 2019) from water temperature loggers located in the Grave Creek population area.

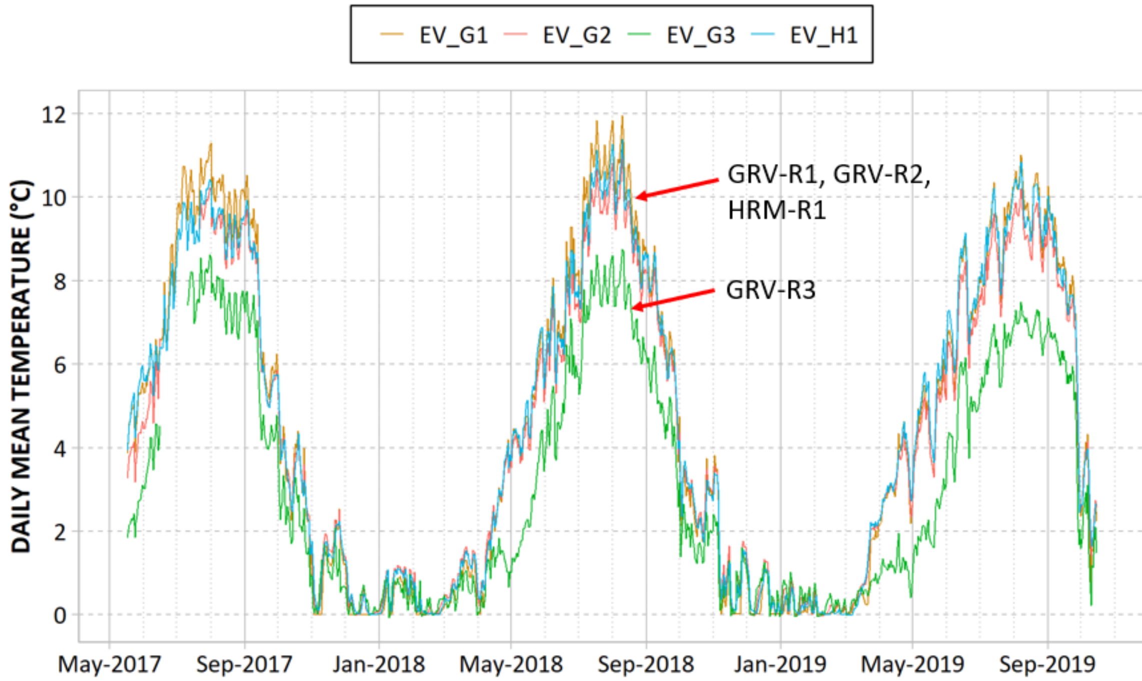
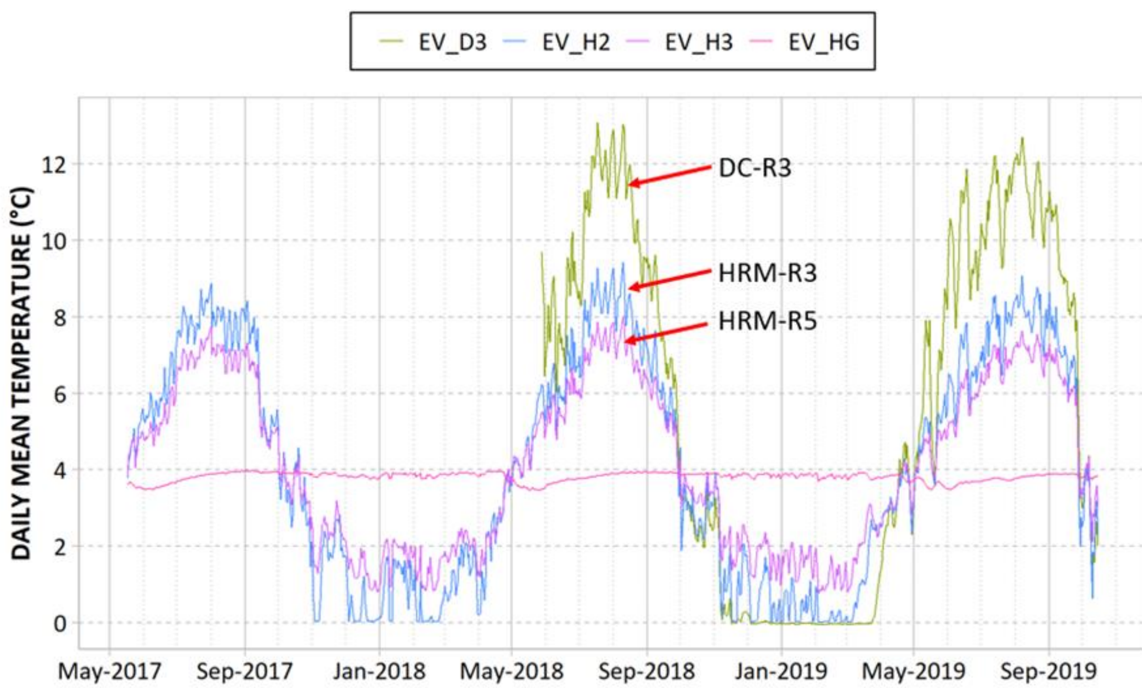


Figure 8. Daily mean water temperature (2017 – 2019) from water temperature loggers located in the Harmer Creek population area.



3.2.2. Monthly Statistics

Monthly average, and monthly instantaneous minimum and maximum water temperature for each station are presented in Table 7. As previously noted, the HG site monitored the groundwater-fed headwaters of Harmer Creek and remained near 4ºC year-round. The table illustrates that temperatures during the open water period were lower at higher elevation stations (G3, H3, H2) apart from Dry Creek, which was the warmest station in the summer. As the streams decreased in elevation (G3 → G2 → G1 and HG → H3 → H2 → H1 → G1; see Map 1), water temperature tended to increase. At all stations (except HG) June was warmer than September, and temperatures quickly declined through the fall.

In winter, most stations other than HG and H3 had minimum temperatures at or near 0ºC from November until April. H3 was moderated by warmer inflows from HRM-R6, and was not quite as cold as other stations, though average temperature was usually within 1ºC of H2. Downstream of H3, Harmer Creek cooled and by the time the stream reached H2 it had minimum winter temperatures similar to those in Grave Creek.

Overall, water temperature trends were similar in the three open water periods with complete data (2017, 2018 and 2019); water temperatures peaked in July or August at all stations (except HG, which has little variation). The different station locations had similar temperature regimes, but where exceptions occurred, they were at the highest elevation stations in Harmer (H3) and Grave (G3) creeks. H3 and G3 were the coldest stations; H3 reached 7.1ºC in July 2018, and August 2019, and G3 reached 7.5ºC in July 2018, and 6.9ºC in August 2019. The station just above the Harmer Sedimentation Pond (H2) was also cold, with a peak average water temperature of 8.2ºC in both 2018 and 2019. The remainder of the stations had warmer peak mean water temperatures that ranged from 9.3ºC to 11.4ºC over the three years of data. A unique feature present at all stations was the sharp decline in temperatures near the end of September 2019. This trend occurred to some degree each fall, but the decline in 2019 was more pronounced than in other years.

Table 7. Monthly statistics for water temperature at monitoring stations in Grave, Harmer and Dry creeks (2017 – 2019).

Year	Month	Water Temperature (°C)																															
		Grave Population Area																Harmer Population Area															
		EV_G3				EV_G2				EV_G1				EV_H1				EV_HG				EV_D3				EV_H3				EV_H2			
		Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD
2017	Jan	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	May	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jun	-	-	-	-	-	-	-	-	6.7	4.1	10.9	1.4	6.6	4.4	9.9	1.1	3.6	3.5	3.7	0.1	-	-	-	-	5.3	4.1	7.9	0.7	5.9	4.2	9.5	1.0
	Jul	-	-	-	-	-	-	-	-	10.2	7.3	13.6	1.4	9.5	7.3	12.2	1.0	3.8	3.7	4.0	0.1	-	-	-	-	7.0	5.4	9.5	0.9	8.0	5.3	11.2	1.4
	Aug	7.5	5.1	10.4	1.1	9.2	7.1	11.6	0.8	9.9	7.0	13.4	1.3	9.3	7.6	12.2	0.8	3.9	3.8	4.2	0.0	-	-	-	-	7.0	5.3	9.2	0.8	7.9	5.1	10.7	1.2
	Sep	5.6	3.0	9.2	1.6	7.1	4.3	10.9	1.7	7.5	3.9	12.5	2.1	7.1	4.3	11.2	1.8	3.9	3.9	4.1	0.0	-	-	-	-	5.8	3.9	8.5	1.1	6.3	3.3	10.0	1.5
	Oct	2.3	0.2	4.7	0.8	3.4	0.8	6.2	0.9	3.4	0.2	7.0	1.1	3.3	0.7	6.3	1.0	3.9	3.8	4.0	0.0	-	-	-	-	3.6	2.0	5.4	0.6	3.4	0.9	6.2	0.9
	Nov	0.9	0.0	2.4	0.6	1.4	0.0	2.7	0.7	1.1	0.0	2.8	0.8	1.3	0.1	2.4	0.6	3.9	3.7	4.0	0.0	-	-	-	-	2.3	1.2	3.5	0.5	1.6	0.0	3.0	0.9
	Dec	0.2	0.0	1.0	0.2	0.3	0.0	1.6	0.4	0.1	0.0	1.7	0.3	0.3	0.0	1.4	0.4	3.8	3.6	3.9	0.0	-	-	-	-	1.3	0.7	2.3	0.4	0.3	0.0	2.1	0.5
2018	Jan	0.6	-0.1	1.3	0.3	0.8	0.0	1.4	0.4	0.5	0.0	1.2	0.4	0.7	0.0	1.2	0.4	3.9	3.7	4.0	0.0	-	-	-	-	1.8	0.6	2.3	0.4	1.1	0.0	2.1	0.6
	Feb	0.2	-0.1	0.9	0.2	0.2	0.0	1.2	0.3	0.1	0.0	1.0	0.2	0.2	0.0	0.9	0.2	3.8	3.7	3.9	0.1	-	-	-	-	1.3	0.7	2.2	0.4	0.3	0.0	1.7	0.4
	Mar	0.6	-0.1	1.7	0.4	1.0	0.0	2.2	0.5	0.7	0.0	2.5	0.5	0.9	0.2	2.0	0.4	3.9	3.8	4.0	0.0	-	-	-	-	2.0	0.9	3.1	0.4	1.3	0.0	3.2	0.7
	Apr	1.0	-0.1	3.5	0.7	2.2	0.0	5.0	1.2	2.1	0.0	5.5	1.4	2.2	0.2	5.2	1.2	3.9	3.5	4.1	0.1	-	-	-	-	2.6	0.9	4.8	0.9	2.4	0.0	5.7	1.3
	May	2.4	0.7	6.5	1.1	4.7	2.9	8.0	1.0	4.9	2.8	8.7	1.2	5.0	3.0	8.5	1.2	3.5	3.4	3.8	0.1	-	-	-	-	4.6	3.1	6.7	0.8	4.8	2.8	8.2	1.1
	Jun	5.2	2.5	9.5	1.3	6.8	4.6	10.3	1.1	7.4	4.6	11.4	1.4	7.2	4.9	10.9	1.1	3.7	3.5	3.9	0.1	8.2	5.0	12.2	1.4	5.7	4.1	8.3	0.8	6.3	4.0	10.3	1.2
	Jul	7.5	4.7	10.6	1.3	9.4	6.4	12.2	1.3	10.4	6.9	14.5	1.7	9.8	6.9	13.1	1.4	3.8	3.7	4.0	0.1	11.3	7.7	15.1	1.6	7.1	5.3	9.7	1.0	8.2	5.5	12.3	1.5
	Aug	7.4	4.8	10.7	1.2	9.3	6.8	12.5	1.2	10.0	6.6	14.6	1.6	9.6	7.1	13.3	1.2	3.9	3.8	4.1	0.0	11.0	7.7	14.8	1.5	7.1	5.3	9.6	0.9	8.0	5.2	12.1	1.3
	Sep	5.0	1.9	7.6	1.1	6.6	3.6	9.5	1.2	6.9	2.9	10.8	1.6	6.9	3.7	10.3	1.3	3.9	3.8	4.1	0.0	7.5	3.5	10.8	1.6	5.5	3.3	7.6	0.8	5.9	2.7	9.8	1.3
	Oct	1.9	-0.1	3.7	0.6	2.9	1.4	5.0	0.6	2.7	0.0	6.0	0.8	2.8	1.3	5.1	0.7	3.9	3.7	4.0	0.0	2.7	1.5	4.8	0.6	3.4	2.5	4.5	0.4	2.9	0.3	5.7	0.8
	Nov	0.9	-0.1	3.1	0.8	1.3	0.0	4.0	1.1	1.0	0.0	4.5	1.2	1.2	0.1	3.7	1.0	3.9	3.6	4.0	0.0	0.6	-0.1	3.7	1.0	2.3	1.2	4.1	0.7	1.4	0.0	4.6	1.2
	Dec	0.5	-0.1	1.5	0.4	0.5	0.0	1.5	0.5	0.3	0.0	1.5	0.4	0.5	0.0	1.3	0.4	3.9	3.6	4.0	0.1	0.0	0.0	0.4	0.1	1.7	0.9	2.4	0.4	0.6	0.0	1.9	0.6
2019	Jan	0.4	-0.1	1.2	0.3	0.3	0.0	1.1	0.3	0.2	0.0	0.9	0.2	0.2	0.0	0.7	0.2	3.9	3.6	4.0	0.0	0.0	0.0	0.0	0.0	1.6	0.9	2.4	0.4	0.4	0.0	1.6	0.4
	Feb	0.2	0.0	1.0	0.2	0.1	0.0	0.9	0.2	0.1	0.0	0.8	0.1	0.1	0.0	0.5	0.1	3.8	3.7	4.0	0.1	0.0	0.0	0.0	0.0	1.2	0.7	2.2	0.4	0.1	0.0	1.5	0.2
	Mar	0.5	0.0	1.6	0.3	1.0	0.0	2.7	0.8	0.7	0.0	3.1	0.8	0.9	0.0	2.9	0.9	3.8	3.7	4.1	0.1	0.1	0.0	1.8	0.3	2.1	0.6	3.6	0.7	1.3	0.0	4.3	1.1
	Apr	1.1	0.0	3.0	0.6	3.2	1.4	5.3	0.7	3.2	0.8	6.2	1.0	3.3	1.7	5.8	0.8	3.8	3.6	4.2	0.1	3.1	0.9	6.4	1.1	3.3	2.0	5.2	0.7	3.2	0.9	6.2	1.0
	May	2.1	0.2	5.8	0.9	4.5	2.0	7.5	1.0	4.7	1.7	8.4	1.2	5.0	2.3	8.0	1.0	3.6	3.5	4.1	0.1	6.0	1.8	11.3	1.8	4.5	2.5	6.8	0.6	4.7	1.8	8.8	1.2
	Jun	4.8	2.1	8.2	1.2	6.9	4.3	9.7	1.2	7.2	4.2	10.9	1.4	7.5	5.1	10.6	1.1	3.6	3.4	4.1	0.1	9.8	6.8	14.0	1.5	5.7	4.2	8.4	0.8	6.5	3.8	10.8	1.4
	Jul	6.2	4.2	8.6	0.9	8.5	5.9	11.2	1.0	9.1	6.0	12.7	1.4	9.0	6.3	11.9	1.0	3.7	3.7	3.9	0.0	11.0	7.4	14.1	1.3	6.8	5.2	9.0	0.8	7.7	4.9	11.4	1.4
	Aug	6.9	5.4	8.5	0.6	9.3	7.0	12.0	0.9	9.9	6.7	13.5	1.3	9.8	7.7	13.0	0.9	3.8	3.7	3.9	0.0	11.4	8.5	14.7	1.2	7.1	5.4	9.3	0.8	8.2	4.9	11.7	1.3
	Sep	5.7	1.5	7.8	1.4	7.4	2.2	10.9	1.7	7.8	2.1	12.1	2.0	7.8	1.8	11.9	1.7	3.9	3.8	3.9	0.0	8.7	2.9	12.4	2.1	6.1	3.1	8.3	1.1	6.6	1.8	10.5	1.8
	Oct	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Nov	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Dec	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Results based on months with more than three weeks of data.

"-" = Less than three weeks data available

Shaded values denote minimum and maximum for each station (only completed for 2018 due to imcomplete data in other years).

Recognizing the importance of water temperature data within the Grave Creek watershed, additional water temperature data were collected the same locations monitored in 2017 – 2019 (with the exception of the stations at D3 and H3). The data collected in 2021 indicated slightly warmer peak temperatures than in previous years. Where data were present to allow comparison, the new stations (EV_UH and EV_LH) between H3 and H2 supported the finding that Harmer Creek increases in temperature as it flows downstream. The temperature station in Balzy Creek had a higher July peak in 2021 than all stations but H1.

The additional water temperature data from monitoring in 2021 extended the spatial extent of monitoring in Grave Creek to GRV-R4. Figure 9 provides a plot of the 15-minute records of G2, G3, and G4 for May through October 2021. The figure illustrates that through June the highest temperatures occur at G2 and the lowest at G4. Near the end of June, G4 began to exceed G3, and by the end of July through mid-August, G4 exceeded G2. After mid-August, water temperature declined by several degrees at all stations and converged to similar values until the end of observations in October. Temperature recording at G3 ceased in early August so could not be compared through the latter portion of the period. For the roughly two-week period of late July and early August, G4 was consistently the warmest of the three stations, indicating that water temperature did not decrease consistently in an upstream direction. Further data collection and analysis is warranted to better characterize water temperature trends within Grave Creek upstream of its confluence with Harmer Creek.

Table 8. Monthly statistics for water temperature at monitoring stations in the Harmer Creek population area (including one station in lower Balzy Creek) (2021).

Year	Month	EV_HG				EV_UH				EV_LH				EV_BAL				EV_H2			
		Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD
2021	Jan	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	May	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jun	3.7	3.5	4.3	0.1	-	-	-	-	-	-	-	-	-	-	-	-	5.3	2.5	12.3	1.9
	Jul	3.9	3.7	4.5	0.1	7.9	6.0	10.7	1.1	8.0	5.8	10.5	1.1	10.5	6.6	14.5	1.4	-	-	-	-
	Aug	4.0	3.9	4.1	0.0	7.3	5.0	10.3	1.0	7.4	4.8	10.0	1.0	9.9	5.1	14.5	2.0	8.2	4.7	12.8	1.5
	Sep	4.0	3.9	4.1	0.0	6.0	4.2	8.0	0.8	6.0	3.9	8.1	0.9	6.9	2.2	11.0	1.8	6.5	3.5	10.1	1.2
	Oct	-	-	-	-	4.0	2.0	6.2	0.8	4.0	1.7	6.2	0.9	-	-	-	-	-	-	-	-

Results based on months with more than three weeks of data.

"-" = Less than three weeks data available

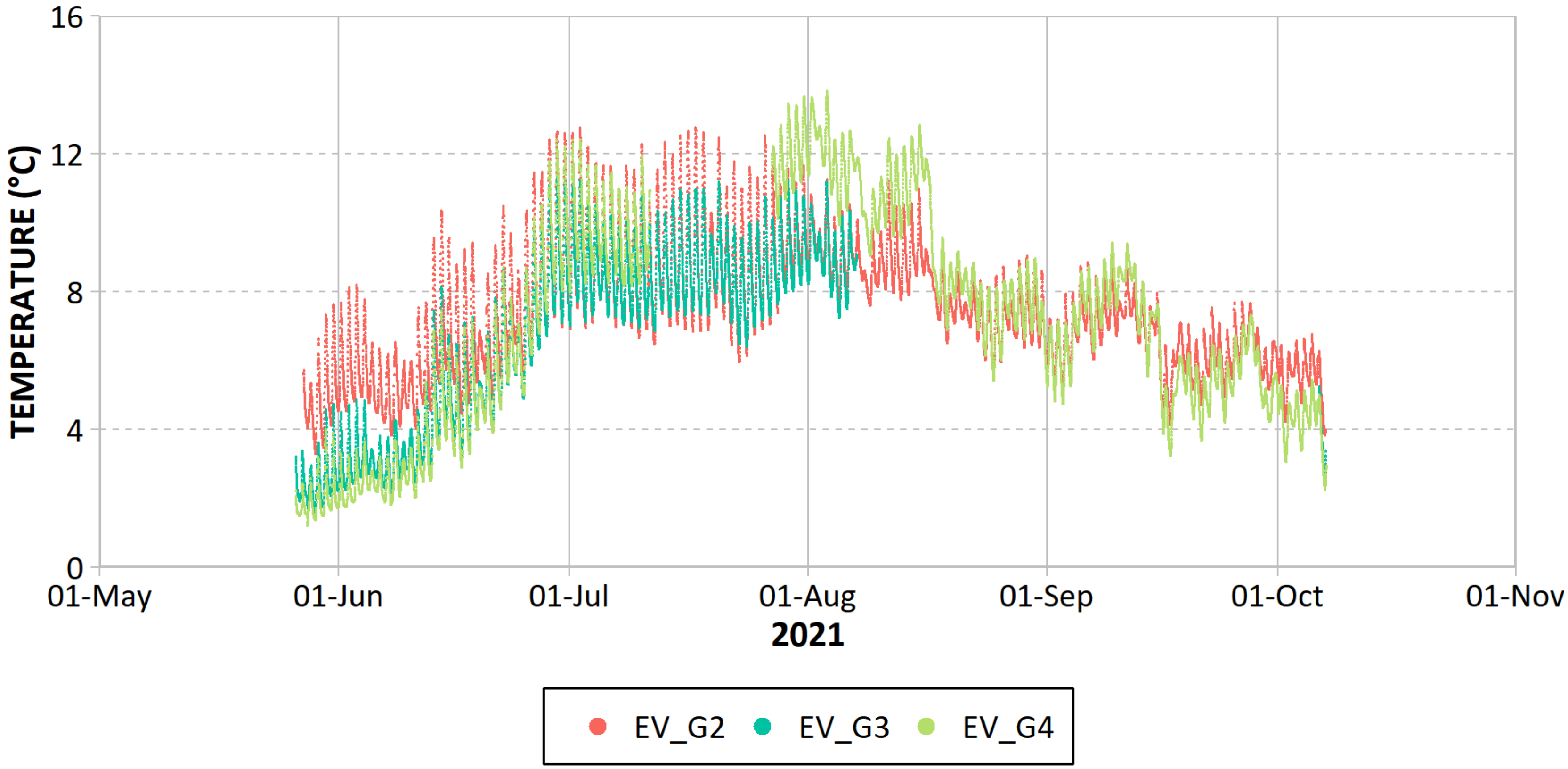
Table 9. Monthly statistics for water temperature at monitoring stations in the Grave Creek population area (2021).

Year	Month	Water Temperature (°C)																			
		EV_G4				EV_G3				EV_G2				EV_G1				EV_H1			
		Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD	Avg	Min	Max	SD
2021	Jan	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Feb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Apr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	May	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Jun	4.8	1.7	12.4	2.5	5.0	2.1	11.3	2.1	6.7	3.8	12.6	1.9	6.8	4.3	11.2	1.5	7.4	3.9	13.9	2.4
	Jul	-	-	-	-	8.6	6.4	11.2	1.1	9.0	5.9	12.7	1.6	-	-	-	-	11.4	8.5	15.0	1.4
	Aug	9.7	5.4	13.8	2.0	-	-	-	-	8.3	5.5	11.3	1.1	10.3	6.4	15.4	1.8	9.7	7.1	13.8	1.5
	Sep	6.4	3.2	9.4	1.4	-	-	-	-	6.6	4.1	9.1	0.9	7.7	4.3	11.4	1.4	7.5	5.8	11.0	1.0
	Oct	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Results based on months with more than three weeks of data.

"-" = Less than three weeks data available

Figure 9. Water temperature measured at 15-minute intervals for select Grave Creek monitoring stations from May through October 2021.



3.2.3. Mean Weekly Maximum Temperature

Mean Weekly Maximum Water Temperature (MWMxT) is an important indicator of prolonged periods of cold and warm water temperatures. The BC guideline for the protection of aquatic life states "Where fish distribution information is available, then mean weekly maximum water temperatures should only vary by ±1ºC beyond the optimum temperature range of each life history phase (incubation, rearing, and spawning) for the most sensitive salmonid species present" (Oliver and Fidler 2001), though natural conditions may exceed these guidelines in some regions (McCullough 1999). The results indicated small differences among years, but there was no indication that one year was notably better than another, so further comparisons between years were not conducted.

3.2.3.1. Spawning (May 15 – July 15)

MWMxT during the spawning period was often within the bounds of optima at most stations, with some exceptions. At G3 and H3, the two highest elevation stations in Grave and Harmer creeks, MWMxT were commonly less than the lower bound of optimum for spawning (i.e., <7ºC), sometimes by more than 1ºC. The spawning period at G3 appeared to be the only location where the majority of the year (76.7%) is below the lower bound of optimum (7ºC).

In some instances, at G1 and D1, and to a lesser extent H1, MWMxT during spawning exceeded the upper optimum temperature. Most often the exceedances were within 1ºC above optimum and therefore within BCWQG, but on some occasions (most commonly at G1) MWMxT was >1ºC above optimum.

3.2.3.2. Early Incubation (June 12 to August 11)

At most stations, MWMxT during the early incubation period remained within the bounds of optimum. Exceptions occurred at H3 and G3 where at times MWMxT was colder than optimum, and at G1 and D1 where MWMxT exceeded the optimum for much of the period.

3.2.3.3. Late Incubation (July 11 to October 31)

The period of late incubation was strongly influenced by cold temperatures that begin to occur in September. All stations were colder than optimum for some of the period, though this was most common at G3 and H3. Stations G1 and D1 were warmer than optimum for a portion of the period, and became colder than optimum for the latter portion of the period. Overall, the results indicate that earlier spawning resulted in incubation MWMxT that were more often within the optimal range.

3.2.3.4. Summer Rearing

The summer rearing period (May 28 to October 10) refers to the period when WCT most actively feed and grow. The trends for the summer rearing period were similar to those of late incubation, although no station exceeded the optimum rearing temperature at any time. G3 and H3 were often below optimal, whereas the other stations were more often within the bounds of optimal. D1 is the station with the most time within the optimal bounds of rearing, followed by G1 and H1.

Table 10. Comparison of 2017 – 2019 MWMxT to WCT water temperature optima by life stage for stations in the Grave Creek population area.

Station	Life Stage Periodicity	Optimum Temperature Range (°C)	Duration (days)	Year	Percent Complete	MWT (°C) Min.	MWT (°C) Max.	% of MWT Below Lower Bound by >1°C	% of MWT Below Lower Bound	% of MWT Between Bounds	% of MWT Above Upper Bound	% of MWT Above Upper Bound by >1°C
EV_G3	Spawning (June 12 to July 11)	7-10	30	2017	16.67	-	-	-	-	-	-	-
	Early Incubation (June 12 to Aug. 11)	7-12	61		59.02	5.3	10.5	13.9	16.7	83.3	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.2	10.5	38.9	42.5	57.5	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		81.62	3.2	10.5	37.8	41.4	58.6	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	5.5	9.1	20.0	46.7	53.3	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	5.5	10.2	9.8	23.0	77.0	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	1.9	10.2	40.7	45.1	54.9	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-10	136		100.00	2.7	10.2	30.1	43.4	56.6	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	5.8	7.8	3.3	76.7	23.3	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	5.8	8.2	1.6	44.3	55.7	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	2.7	8.2	22.8	52.9	47.1	0.0	0.0
EV_G2	Spawning (June 12 to July 11)	7-10	30	2017	13.33	-	-	-	-	-	-	-
	Early Incubation (June 12 to Aug. 11)	7-12	61		42.62	-	-	-	-	-	-	-
	Late Incubation (July 11 to Oct. 31)	7-12	113		91.15	3.0	11.5	32.0	40.8	59.2	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		74.26	4.5	11.5	21.8	39.6	60.4	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	6.8	10.5	0.0	10.0	80.0	10.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	6.8	11.9	0.0	4.9	95.1	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.8	11.9	28.3	36.3	63.7	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.7	11.9	8.1	21.3	78.7	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	7.2	9.6	0.0	0.0	100.0	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.2	11.4	0.0	0.0	100.0	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.8	11.4	8.1	14.7	85.3	0.0	0.0
EV_G1	Spawning (June 12 to July 11)	7-10	30	2017	100.00	7.1	12.3	0.0	0.0	60.0	40.0	23.3
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.1	13.4	0.0	0.0	45.9	54.1	11.5
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	3.2	13.4	23.9	31.9	35.4	32.7	6.2
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.9	13.4	4.4	19.1	80.9	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	7.8	12.0	0.0	0.0	56.7	43.3	10.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.8	13.9	0.0	0.0	47.5	52.5	39.3
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.8	13.9	26.5	29.2	35.4	35.4	24.8
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.9	13.9	6.6	8.8	91.2	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	8.2	10.9	0.0	0.0	73.3	26.7	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	8.2	13.1	0.0	0.0	80.3	19.7	1.6
	Late Incubation (July 11 to Oct. 31)	7-12	113		84.96	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.1	13.1	7.4	9.6	90.4	0.0	0.0
EV_H1	Spawning (June 12 to July 11)	7-10	30	2017	100.00	7.0	11.2	0.0	10.0	66.7	23.3	13.3
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.0	11.9	0.0	4.9	95.1	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.8	11.9	28.3	37.2	62.8	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.5	11.9	8.1	26.5	73.5	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	7.1	11.1	0.0	0.0	86.7	13.3	3.3
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.1	12.5	0.0	0.0	73.8	26.2	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.6	12.5	27.4	31.0	53.1	15.9	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.9	12.5	7.4	10.3	89.7	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	7.7	10.1	0.0	0.0	90.0	10.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.7	12.2	0.0	0.0	95.1	4.9	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.8	12.2	7.4	10.3	89.7	0.0	0.0

Blue shading indicates provincial guideline exceedance of the lower bound of the optimum temperature range by more than 1°C
Red shading indicates provincial guideline exceedance of the upper bound of the optimum temperature range by more than 1°C

Table 11. Comparison of 2017 – 2019 MWMxT to WCT water temperature optima by life stage for stations in the Harmer Creek population area. EV_HG is not shown because it consistently maintained ~4°C and was below the lower temperature optima by >1°C for 100% of the record.

Station	Life Stage Periodicity	Optimum Temperature Range (°C)	Duration (days)	Year	Percent Complete	MWT (°C) Min.	MWT (°C) Max.	% of MWT: Below Lower Bound by >1°C	Below Lower Bound	Between Bounds	Above Upper Bound	Above Upper Bound by >1°C
EV_D3	Spawning (June 12 to July 11)	7-10	30	2018	100.00	8.2	12.7	0.0	0.0	56.7	43.3	13.3
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	8.2	14.6	0.0	0.0	45.9	54.1	49.2
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	2.9	14.6	27.4	29.2	32.7	38.1	31.9
	Rearing (May 28 to Oct. 10)	7-16	136		95.59	3.7	14.6	7.7	9.2	90.8	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	10.3	13.0	0.0	0.0	0.0	100.0	73.3
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	10.3	14.1	0.0	0.0	45.9	54.1	34.4
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	3.9	14.1	7.4	8.1	91.9	0.0	0.0
EV_H3	Spawning (June 12 to July 11)	7-10	30	2017	100.00	5.6	8.6	26.7	60.0	40.0	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	5.6	9.3	13.1	29.5	70.5	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	3.6	9.3	37.2	40.7	59.3	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.4	9.3	32.4	42.6	57.4	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	6.1	8.4	0.0	50.0	50.0	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	6.1	9.4	0.0	24.6	75.4	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	3.7	9.4	36.3	44.2	55.8	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.0	9.4	14.7	43.4	56.6	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	6.5	7.9	0.0	30.0	70.0	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	6.5	9.0	0.0	14.8	85.2	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.1	9.0	12.5	34.6	65.4	0.0	0.0
EV_H2	Spawning (June 12 to July 11)	7-10	30	2017	100.00	6.7	10.2	0.0	20.0	66.7	13.3	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	6.7	10.8	0.0	9.8	90.2	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	3.3	10.8	30.1	38.1	61.9	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.6	10.8	11.0	31.6	68.4	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2018	100.00	7.2	10.3	0.0	0.0	93.3	6.7	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.2	11.7	0.0	0.0	100.0	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		100.00	3.2	11.7	28.3	36.3	63.7	0.0	0.0
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.0	11.7	8.1	14.7	85.3	0.0	0.0
	Spawning (June 12 to July 11)	7-10	30	2019	100.00	7.7	9.9	0.0	0.0	100.0	0.0	0.0
	Early Incubation (June 12 to Aug. 11)	7-12	61		100.00	7.7	11.3	0.0	0.0	100.0	0.0	0.0
	Late Incubation (July 11 to Oct. 31)	7-12	113		85.84	-	-	-	-	-	-	-
	Rearing (May 28 to Oct. 10)	7-16	136		100.00	4.0	11.3	8.8	9.6	90.4	0.0	0.0

Blue shading indicates provincial guideline exceedance of the lower bound of the optimum temperature range by more than 1°C
Red shading indicates provincial guideline exceedance of the upper bound of the optimum temperature range by more than 1°C

3.2.4. Daily Average Temperature Extremes

The calculated daily average extreme temperatures (Table 12) (see parameter description in Table 4) demonstrated that Grave and Harmer creeks are cold systems in which water temperatures did not approach the incipient lethal water temperature for WCT (19.6ºC; Bear *et al.* 2007) on any occasion within the period of record.

All stations within Grave had more than 100 days per year with average daily water temperatures <1ºC. There was some variation between years and stations; for example, G3 was colder for longer than G2 or G1. The number of days <1ºC was similar in the two winters during which water temperature was monitored (Table 12).

In Harmer Creek groundwater appeared to play a large role in the timing, location, and duration of water temperatures <1ºC. The groundwater source remained at ~4ºC all year, while nearby, Dry Creek (D1) was cold for a long duration in the single winter it was measured. These two stream segments meet, and their mixed water temperature was measured at H3, which rarely was <1ºC. The number of days of average water temperature <1ºC increased at each successive station (H3<H2<H1<G1), suggesting the influence of subsurface water input moderates upper Harmer in the winter. There was no obvious difference in water temperatures between the two winters with monitoring.

Table 12. Number of days with extreme daily-mean water temperature (i.e., <1ºC, and >18ºC). A year was defined as 1 October to 30 September so that a single winter was not split in two.

Population Area	Station	Monitoring Year[1]	Days T_{water} < 1°C	Days T_{water} > 18°C
Grave	EV_G3	2017/2018	145	0
		2018/2019	137	0
	EV_G2	2017/2018	104	0
		2018/2019	118	0
	EV_G1	2017/2018	126	0
		2018/2019	125	0
	EV_H1	2017/2018	109	0
		2018/2019	122	0
Harmer	EV_HG	2017/2018	0	0
		2018/2019	0	0
	EV_D3	2017/2018	-	0
		2018/2019	143	0
	EV_H3	2017/2018	19	0
		2018/2019	17	0
	EV_H2	2017/2018	88	0
		2018/2019	102	0

[1] Monitoring Year extends from 1 Oct to 30 Sep of the following year.

3.2.5. Hourly Rates of Water Temperature Change

Hourly rates of change in water temperature were compared to the BCWQG, which states that hourly rates of change that exceed ±1.0ºC/hr may have negative effects on fish (Oliver and Fidler 2001). Hourly rates of change in water temperature are summarized in Table 13.

G1 was the station with by far the highest occurrence of temperature change in excess of ±1ºC, in all years. The exceedances made up <2% of the total record but occurred nearly daily from June to August each year. The exceedances were possibly due to the station's location below the confluence with the outlet creek from Grave Lake. During the summer, radiative heating may heat the surface of the lake rapidly during the day, and then the warm surface water would flow downstream to G1. A similar effect, though smaller, was apparent in the H1 data, which was likely attributable to its location immediately below the Harmer Creek Sedimentation Pond.

The remainder of the water temperature stations did not feature notable within-day variations in water temperature. The 99th percentile of warming temperature changes were below 1ºC for all but G1. The 1st percentile of cooling temperature changes was less than or equal to -0.5ºC, which indicated that rapid heating was more likely than rapid cooling.

Table 13. **Hourly rate of change in water temperature in the Grave Creek Watershed from 2017 - 2019. Shown is the frequency of temperature changes exceeding 1.0°C/hr, maximum rates of temperature increase (positive rates) and decrease (negative rates), and the rates of temperature changes corresponding to the 1st, 5th, 95th, and 99th percentiles.**

Population Area	Site	Year	Start Date	End Date	Percent dataset complete	Occurrence of rates >1°C/hr		Max negative	Percentile				Max positive
						#	% of record		1st	5th	95th	99th	
Grave	EV_G3	2017	17-May-2017	31-Dec-2017	88.96	5	0.03	-3.3	-0.4	-0.3	0.4	0.7	0.9
		2018	1-Jan-2018	31-Dec-2018	100.00	5	0.01	-1.6	-0.4	-0.3	0.3	0.7	1.0
		2019	1-Jan-2019	15-Oct-2019	99.69	7	0.03	-1.2	-0.4	-0.2	0.3	0.5	1.0
	EV_G2	2017	17-May-2017	31-Dec-2017	84.56	10	0.05	-1.1	-0.4	-0.2	0.3	0.5	1.3
		2018	1-Jan-2018	31-Dec-2018	100.00	22	0.06	-1.3	-0.4	-0.2	0.3	0.5	1.3
		2019	1-Jan-2019	15-Oct-2019	99.74	5	0.02	-1.4	-0.3	-0.2	0.3	0.5	1.1
	EV_G1	2017	17-May-2017	31-Dec-2017	99.80	344	1.57	-1.0	-0.4	-0.3	0.6	1.1	1.5
		2018	1-Jan-2018	31-Dec-2018	99.99	428	1.22	-2.1	-0.5	-0.3	0.4	1.1	1.6
		2019	1-Jan-2019	15-Oct-2019	99.75	367	1.33	-2.3	-0.4	-0.3	0.5	1.1	1.5
	EV_H1	2017	17-May-2017	31-Dec-2017	99.86	74	0.34	-1.4	-0.5	-0.3	0.4	0.7	1.7
		2018	1-Jan-2018	31-Dec-2018	100.00	163	0.47	-1.4	-0.5	-0.3	0.3	0.8	1.9
		2019	1-Jan-2019	15-Oct-2019	99.74	82	0.30	-1.3	-0.5	-0.3	0.4	0.7	1.8
Harmer	EV_HG	2017	17-May-2017	31-Dec-2017	99.92	0	0.00	-0.2	0.0	0.0	0.0	0.1	0.3
		2018	1-Jan-2018	31-Dec-2018	99.92	0	0.00	-0.3	0.0	0.0	0.0	0.1	0.2
		2019	1-Jan-2019	15-Oct-2019	99.78	0	0.00	-0.4	-0.1	0.0	0.0	0.1	0.3
	EV_D3	2018	28-May-2018	31-Dec-2018	99.84	60	0.29	-0.7	-0.3	-0.2	0.4	0.8	1.5
		2019	1-Jan-2019	15-Oct-2019	99.72	17	0.06	-1.1	-0.3	-0.2	0.4	0.8	1.1
	EV_H3	2017	17-May-2017	31-Dec-2017	99.90	16	0.07	-0.7	-0.3	-0.2	0.4	0.7	1.2
		2018	1-Jan-2018	31-Dec-2018	100.00	34	0.10	-0.7	-0.3	-0.2	0.3	0.6	1.2
		2019	1-Jan-2019	15-Oct-2019	99.71	4	0.01	-0.8	-0.3	-0.2	0.3	0.6	1.1
	EV_H2	2017	17-May-2017	31-Dec-2017	99.87	72	0.33	-1.1	-0.4	-0.3	0.6	0.9	1.6
		2018	1-Jan-2018	31-Dec-2018	100.00	65	0.19	-1.1	-0.4	-0.3	0.5	0.9	1.4
		2019	1-Jan-2019	15-Oct-2019	99.74	114	0.41	-1.4	-0.5	-0.4	0.6	0.9	1.6

3.2.6. Growing Season Degree Days

3.2.6.1. GSDD Variation within the Grave Creek Watershed

Growing Season Degree Days (GSDD) is a measure of the length and intensity of the growing season, from the date that MWMxT exceeds 5ºC in the spring until MWMxT declines below 4ºC in the fall. GSDD was calculated for each station except HG[20] (Figure 10; Table 14). Variation occurred among reaches for the beginning and the end date of the growing season. Accordingly, there was also variation in the length of the growing season at each station. In nearly all cases, the length of the growing season was between 130 and 135 days, except at the two highest-elevation stations. The growing season at G3 was 103 days in 2018 and 92 days in 2019. At H3 the growing season varied between 114 and 123 days across the three growing seasons with data. The accumulation of thermal energy within the growing season determines its suitability for recruitment and varied considerably among stations.

GSDD differences within the Grave Creek watershed indicated that some stations present poor growing conditions for WCT eggs, alevin, and fry. Some locations in the watershed had GSDD values of <900, which is predicted to result in poor to moderate survival of fry through the winter (Coleman and Fausch 2007b) and thereby poor to moderate recruitment. GSDD at G3 was 673 in 2018 and 583 in 2019, all well below the threshold of 900. At H3, GSDD ranged from 723 to 819 from 2017 to 2019, also well below the threshold of 900. At H2, GSDD was near the threshold of 900, varying from 894 to 926 during the same period. Stations H1, G2, G1 and D1 had GSDD >1,000 for all years, which indicated reasonable water temperature conditions for recruitment.

When considering the effects of GSDD on Cutthroat Trout recruitment, of note is the amount of time for adequate feeding and growth between the time of fry emergence and the onset of winter. Coleman and Fausch (2007b) suggest that GSDD <900 shortens this crucial period, and GSDD <800 may eliminate this period altogether. Low GSDD occurred in the Grave Creek watershed, particularly at the higher-elevation stations (i.e., at H3 and G3; Table 14). The results for these higher-elevation locations indicated that slow GSDD accumulation would likely have led to fry emerging with little time for feeding and growth before the onset of winter. We speculate that such water temperature conditions would make these stream segments comparable to those described in Coleman and Fausch (2007b) with low predicted survival (between 28 – 50%) relative to stream segments with GSDD >900 and higher predicted survival (71-74%).

Maps of GSDD in the Grave Creek watershed provide visualization of estimated recruitment suitability in the Grave Creek watershed. The maps show that in both 2018 (Map 2) and 2019 (Map 3), the headwaters of Grave Creek (GRV-R3 and GRV-R4) had water temperature conditions that were unsuitable for recruitment. Downstream portions of Grave Creek (downstream of roughly midway between G2 and G3) appear to have been suitable for recruitment. Most of Harmer Creek (most of HRM-R3, plus HRM-R4, HRM-R5 and HRM-R6) had marginally suitable or unsuitable conditions

[20] Growing season begins when water temperature reaches 5ºC for a 7-day running average; however, water temperature at HG (located in HRM-R6) did not reach 5ºC so the GSDD were calculated as zero.

for recruitment in 2018 (Map 2) and 2019 (Map 3). Water temperature conditions in the lower portion of HRM-R3 and downstream were likely sufficient to support adequate fry emergence and fry rearing. Water temperature conditions in Dry Creek were suitable; however, other conditions such as high calcite concretion impact spawning habitat suitability such that fry are unlikely to occur in this stream segment.

Additional data from monitoring in 2021 extended the spatial coverage within Grave Creek to areas upstream of G3. Data from the new station in GRV-R4 (station G4) indicated that summer water temperature upstream of G3 is warmer than previously assumed. In fact, August mean at G4 in 2021 exceeded that at G2. Unfortunately, the G4 station was not initiated in time to allow calculation of GSDD for 2021. However, the available data for G4 cast some doubt on the representativeness of temperature data at G3, suggesting that temperature conditions at G3 may be localized (e.g., possibly affected by local groundwater intrusion or other factors). In any case, the data from G3 are not representative of the temperature regime in GRV-R4. The data also imply that the water temperature regime in Grave Creek upstream of G2 as a whole is warmer in the open water period than previously reported. Until more data are available, a better characterization of the GRV-R4 temperature regime, including calculation of GSDD, is not possible. The visualizations provided in Map 2 and Map 3 therefore used a dashed line type and blue colour to flag the uncertainty of GSDD in this portion of the watershed.

Figure 10. GSDD accumulation by month, blank panels indicate insufficient data were available. Station plots above the blue line are part of the Grave Creek population area, and plots below are part of the Harmer Creek population area. GSDD levels of 800 and 900 are indicated by the horizontal dashed lines.

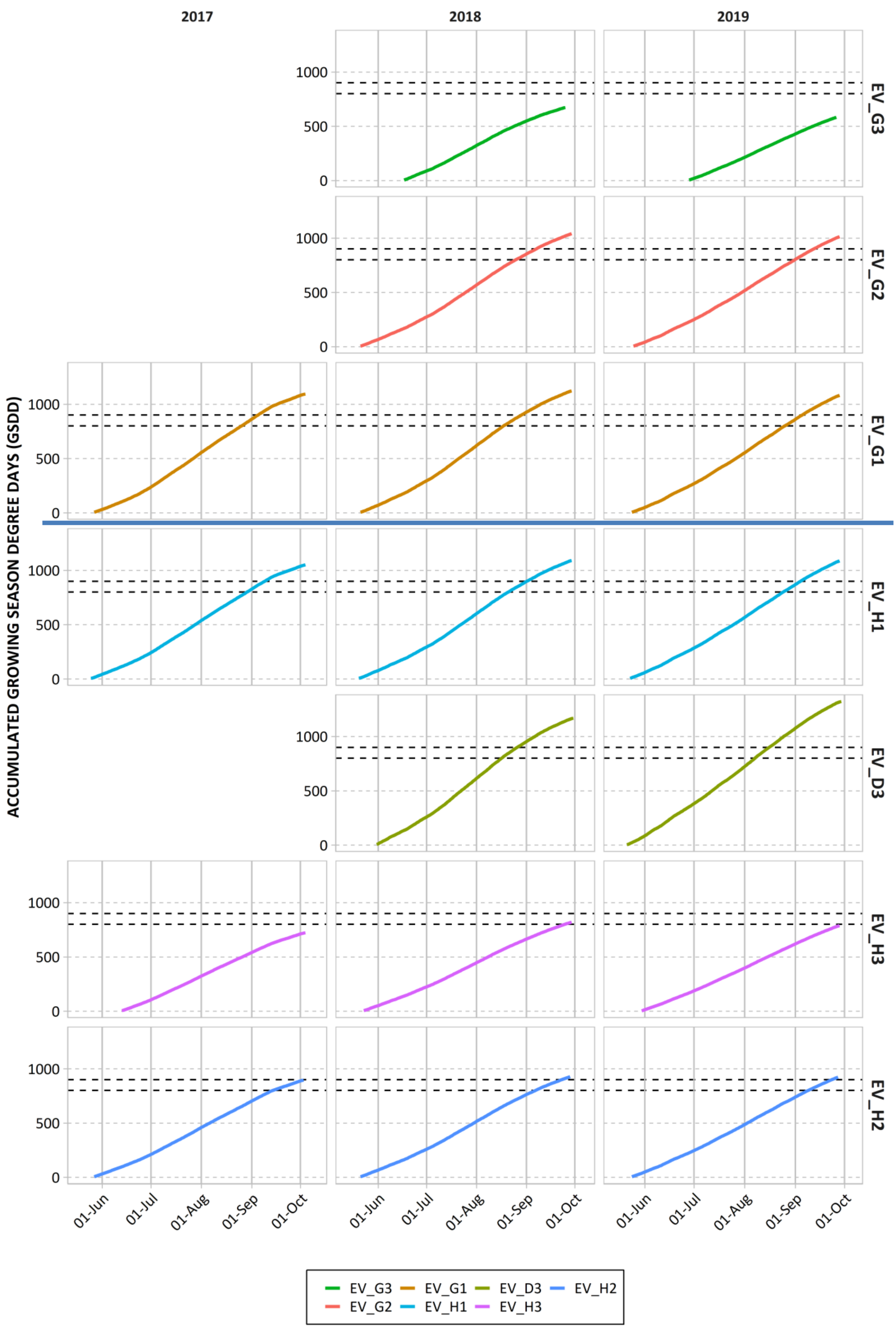


Table 14. Summary of Growing Season Degree Days showing the duration of the growing season and the GSDD accumulated.

Population Area	Site	Year	Number of days with valid data[1]	Growing Season Data Summary			
				Start Date	End Date	Length (days)	GSDD
Grave	EV_G3	2017	202	-	-	-	-
		2018	365	17-Jun	26-Sep	103	673.3
		2019	286	28-Jun	27-Sep	92	582.6
	EV_G2	2017	192	-	-	-	-
		2018	365	21-May	30-Sep	133	1039.9
		2019	286	25-May	29-Sep	128	1011.4
	EV_G1	2017	228	27-May	5-Oct	131	1093.6
		2018	365	21-May	30-Sep	133	1121.3
		2019	286	24-May	29-Sep	129	1079.3
	EV_H1	2017	228	25-May	5-Oct	135	1050.9
		2018	365	20-May	30-Sep	135	1090.5
		2019	286	23-May	29-Sep	131	1085.3
Harmer	EV_D3	2018	217	31-May	1-Oct	123	1166.9
		2019	286	21-May	30-Sep	133	1321.2
	EV_H3	2017	228	13-Jun	5-Oct	114	722.7
		2018	365	23-May	30-Sep	131	819.3
		2019	286	30-May	29-Sep	123	787.4
	EV_H2	2017	228	27-May	4-Oct	131	893.8
		2018	365	21-May	29-Sep	133	925.5
		2019	286	24-May	28-Sep	128	920.0

[1] The number of days that have observations for 21 hours or more.

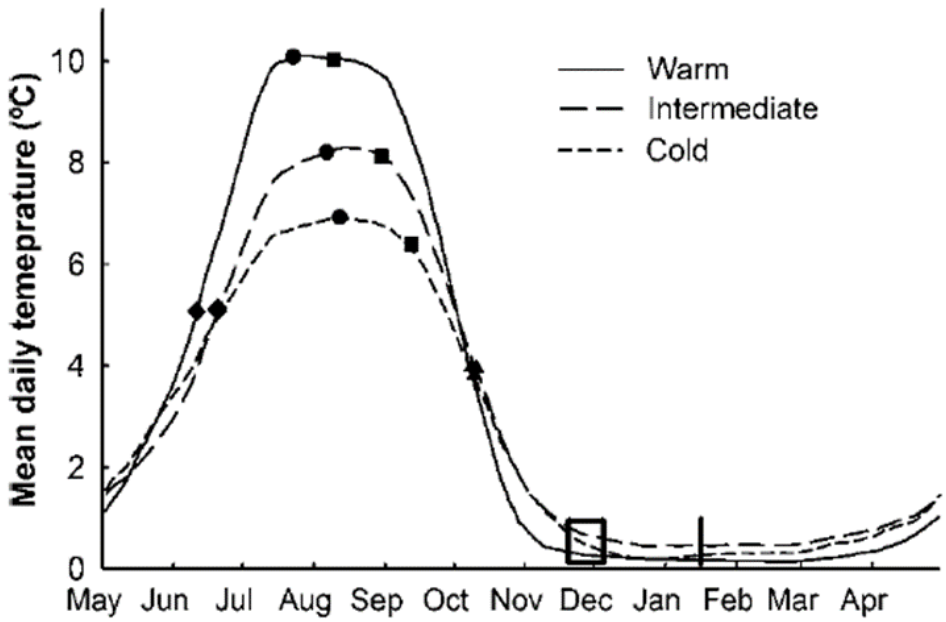
"_" No data available.

Note: Green shading indicates GSDD are suitable for recruitment, yellow indicates marginally suitable, and red indicates unsuitable

3.2.6.2. Recruitment Scenario Testing with GSDD

Coleman and Fausch (2007a) conducted lab-based rearing experiments of Cutthroat Trout fry exposed to what they referred to as "warm", "intermediate", and "cold" growing season temperature regimes as shown in Figure 11. The "warm" growing season temperature regime is similar to the temperature regime experienced by WCT in reaches GRV-R1, GRV-R2, and HRM-R1 in the growing season (Figure 7 and Figure 8). In comparison, the temperature stations in Harmer Creek reaches HRM-R3 and HRM-R5, and the station in upper Grave in reach GRV-R3, are similar to the "intermediate" lab-based temperature regime. Dry Creek is warmer than the "warm" regime and HMR-R6 is colder than the "cold" regime. The experimental temperature regimes were designed to mimic high-elevation streams in Colorado where translocations for species conservation had resulted in no Cutthroat Trout ("cold" temperature regime), low abundance ("intermediate" temperature regime), or high abundance ("warm" temperature regime) (Coleman and Fausch 2007a).

Figure 11. Cold, intermediate, and warm temperature regimes tested in the lab-based assessment of temperature on growth and survival of Cutthroat Trout fry (Coleman and Fausch 2007a).



Predicted Fry Size from GSDD— The relationship between GSDD and fry length from Coleman and Fausch (2007b) was used to estimate fry fork length at each water temperature station in the Grave watershed in 2017, 2018, and 2019. Coleman and Fausch (2007b) used fry total length as a measure of body size; we adjusted their relationship to provide predictions for fork length, since this metric is more commonly used in Elk Valley fish surveys. Fry fork length was obtained from fry total length using the standardization (Mayhood 2012):

$$\textbf{Total Length (mm)} = 1.040 \times \textbf{Fork Length (mm)} + 1.697$$

Then a regression equation between GSDD and fry fork length (Coleman and Fausch 2007b; Figure 12):

$$\textbf{Fry Fork Length (mm)} = (18.983 + 0.17e^{0.046 \times GSDD}) / 1.04$$

was applied to data from each water temperature station for each year with sufficient data.

The predicted fry fork length (mm) at onset of winter differed by temperature station (and therefore stream reach) more so than by year of measurement, as shown by clustering of fry size by water temperature stations (Figure 13). GSDD was lowest at G3 in GRV-R3, ranging from 583 to 673 and producing fry estimated to be 20 to 22 mm fork length at the onset of winter. This is smaller than observed for upper Grave Creek (Thorley *et al.* 2022), which may be because the temperature at G3 is not representative of upper Grave Creek as a whole. For example, the G4 temperature station was warmer than G3 in July and August of 2021 (Figure 9). For most of the Harmer Creek population area (reaches HRM-R3 to HRM-R5), GSDD was also low and ranged from 723 to 926 across all years. This temperature regime is predicted to produce WCT fry that range in fork length from 22 to 30 mm at the onset of winter. In contrast, for the remainder of the Grave Creek population area in reaches HRM-R1, GRV-R1, and GRV-R2, the temperature regime was >1,000 GSDD at each station in each year and produced fry estimated to be >35mm fork length. Dry Creek (DC-R3) had the highest GSDD (>1,150 GSDD), which would be predicted to produce fry >50mm in fork length each year in the absence of non-temperature related stressors.

The GSDD and estimated fork lengths presented here predicted larger fry at the onset of winter in the lower reaches of the Grave Creek population area than in the upper portion of Grave Creek or the Harmer Creek population areas. This difference is consistent with the limited field measurements of WCT fry (Figure 14), which indicate that fry tend to be smaller in the Harmer Creek population than in the Grave Creek population (Thorley *et al.* 2021, Thorley *et al.* 2022). Fry in Harmer Creek were ~15% smaller by length, which equates to a mass difference of ~39% (assuming fry shape remains unchanged) (Thorley, pers. comm. 2022).

Figure 12. Field and lab-based relationship between accumulated growing season degree days and total length of Cutthroat Trout fry (Coleman and Fausch 2007b).

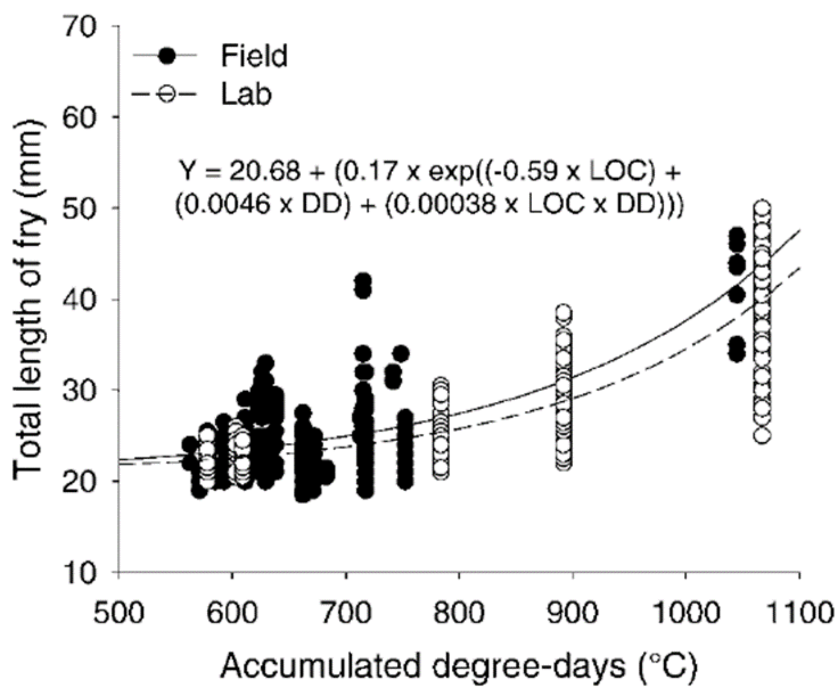


Figure 13. Estimated fork length (mm) of WCT fry reared at each temperature station in the Grave Creek and Harmer Creek population areas in 2017, 2018, and 2019. Each station has a point for each growing season with complete data.

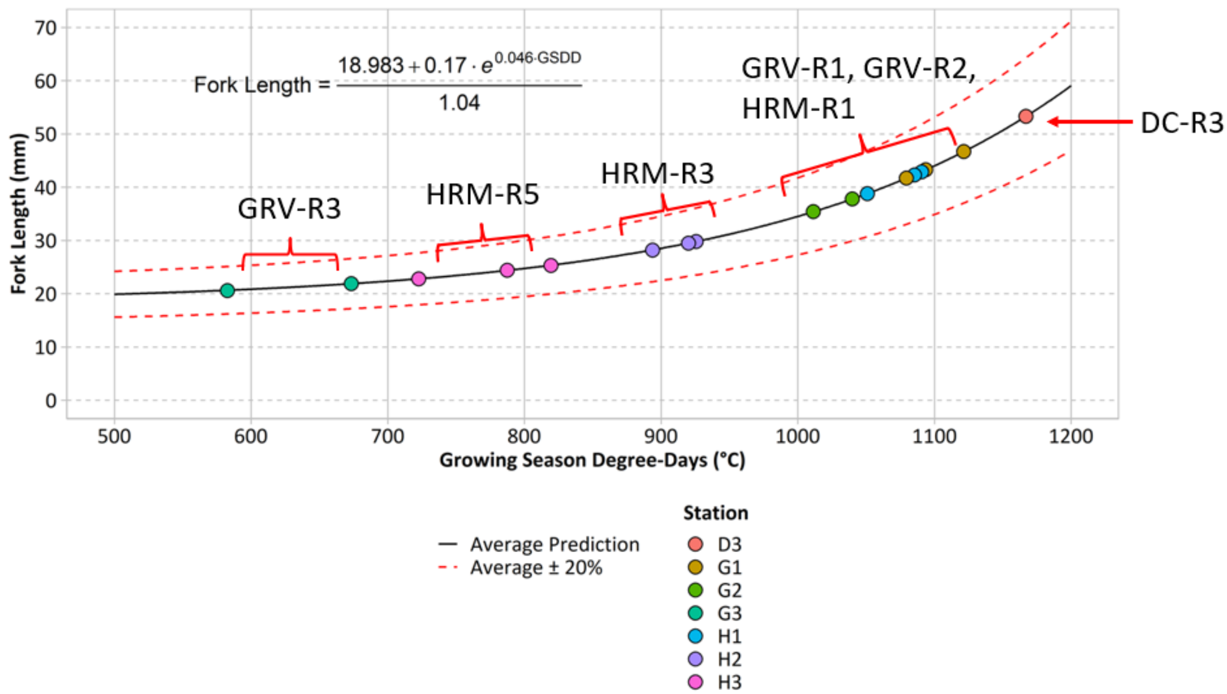
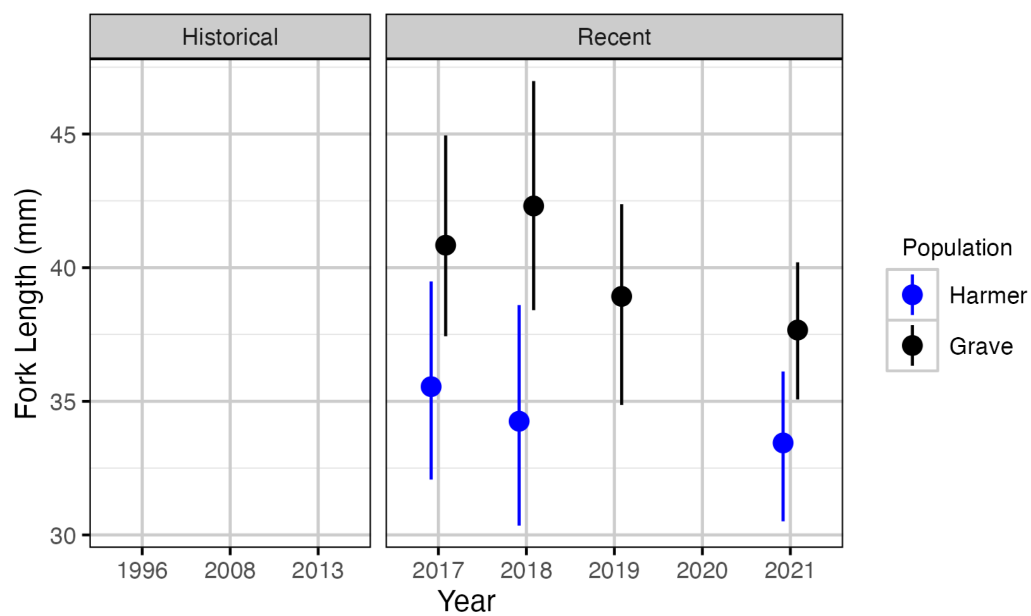


Figure 14. The observed fork length for fry on October 1 by year, period and population (with 95% CIs); figure from Thorley *et al.* (2022).



Fry Survival to Onset of Winter— In addition to influencing fry body size, stream temperature regime during the growing season can also influence fry survival prior to the onset of winter. In field assessments conducted by Coleman and Fausch (2007b), they observed a strong positive relationship between Cutthroat Trout fry density per 100 m of stream length as a function of GSDD in high elevation streams in Colorado (Figure 15). Streams and years with <800 GSDD had few fry at the onset of winter, implying mortality during the growing season. Coleman and Fausch (2007a) supplemented the field observations by conducting lab-based trials in "warm", "intermediate", and "cold" temperature regimes, as shown in Figure 11, to evaluate fry survival prior to and during the overwintering period. They estimated the following positive response between GSDD and fry survival to the onset of winter (Figure 16):

$$\textbf{Fry survival to onset of winter} = e^{-3.71 + 0.0048 \times GSDD} / (1 + e^{-3.71 + 0.0048 \times GSDD})$$

This relationship between GSDD and fry survival to the onset of winter was used to estimate fry survival in the Grave and Harmer Creek population areas at each temperature station (Figure 17).

Predicted fry survival was lowest in GRV-R3 at 29-38% survival. Predicted fry survival to the onset of winter in HRM-R3 and HRM-R5 of the mainstem Harmer Creek population area ranged from 44% to 68%. In contrast, fry survival was estimated to be higher in the warmer temperature regimes present in HRM-R1, GRV-R1, and GRV-R2 in the lower Grave Creek population area, with estimated survival ranging from 78% to 84%. These predictions suggest that the entirety of the Harmer Creek population area (with the exception of Dry Creek) is exposed to a water temperature regime that limits growth of fry prior to onset of winter, and therefore limits overwinter survival. In contrast, only a portion of the Grave Creek population area (i.e., GRV-R3) is similarly limited. (see also the discussion in Section 3.2.6.1 regarding relatively warm temperature observations in GRV-R4, which indicates that portions of upper Grave Creek have a temperature regime that is suitable for recruitment. This interpretation is reinforced by observations of relatively high densities of multiple age classes of fish in GRV-R4.) The remainder of the Grave Creek population area appears to have a temperature regime that supports more growth and higher survival.

Figure 15. Observed Cutthroat Trout fry density per 100 m in the fall from multiple high elevation streams in Colorado that vary in GSDD (Coleman and Fausch 2007b).

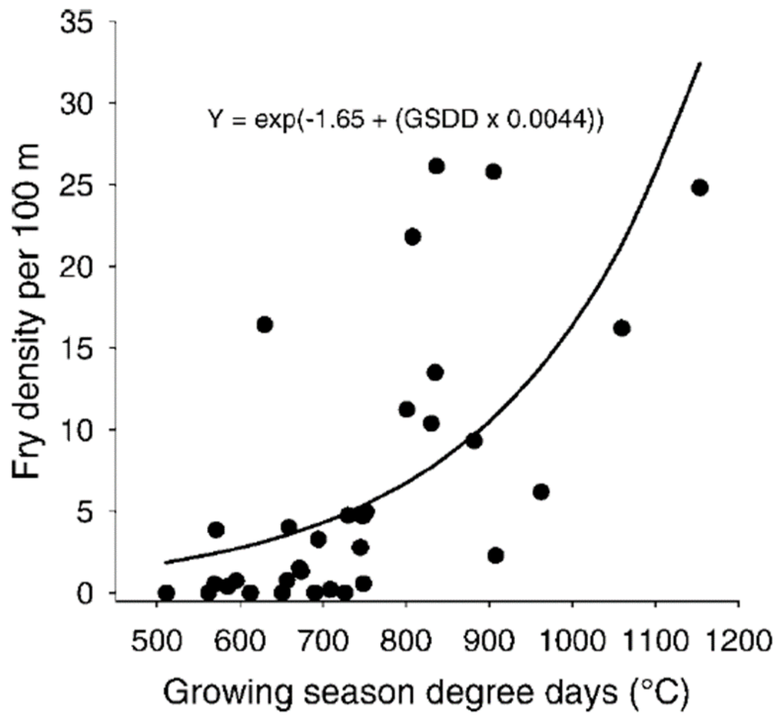


Figure 16. Proportion of Cutthroat Trout fry surviving to the onset of winter in lab-based trials (Coleman and Fausch 2007a).

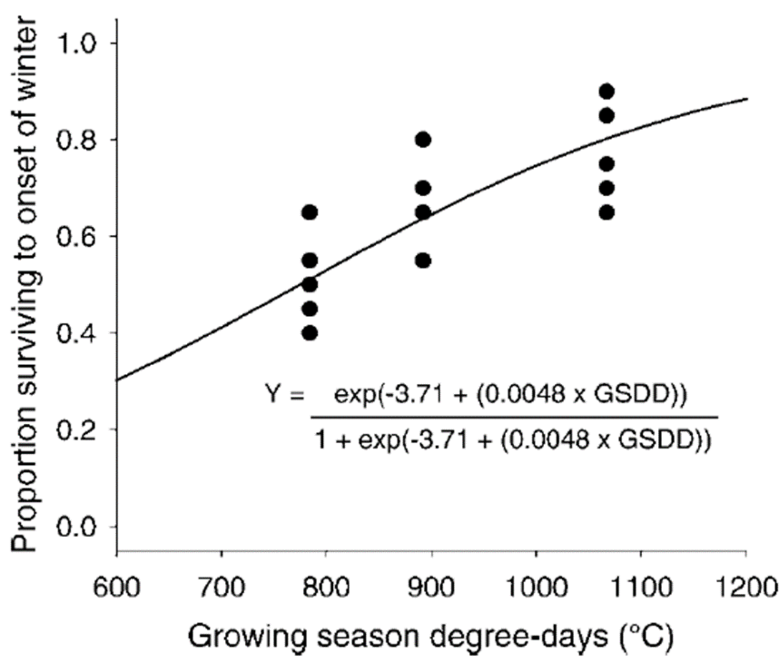
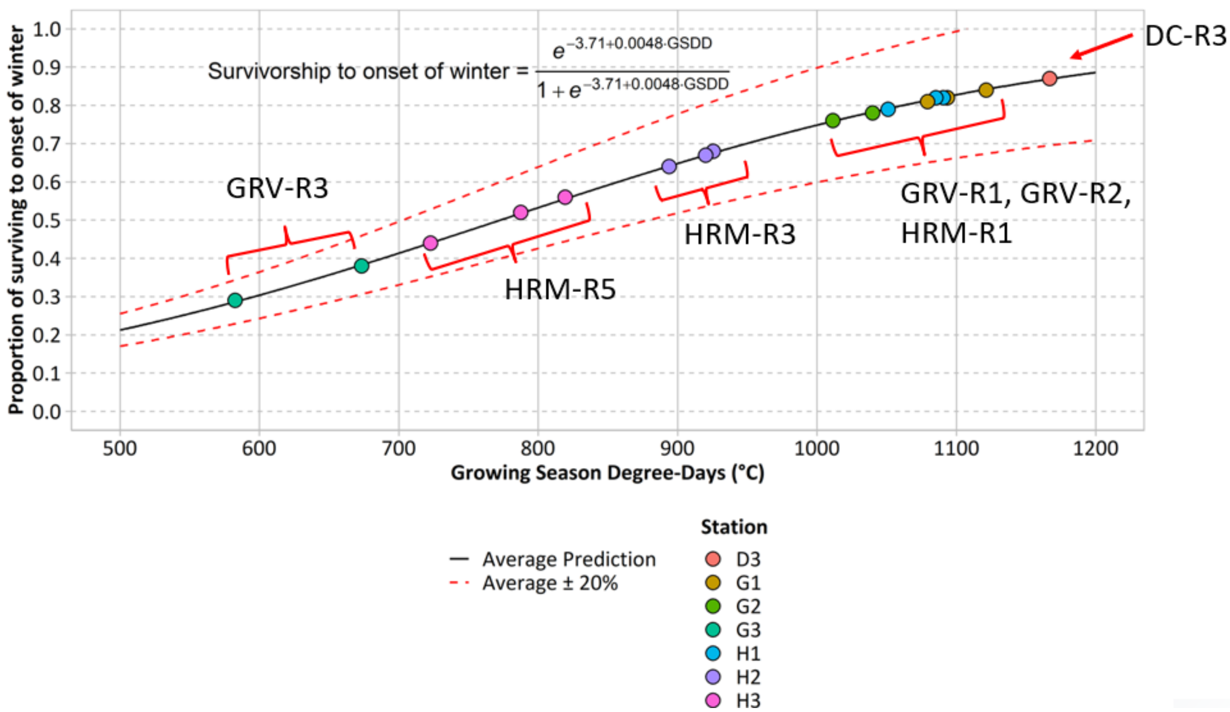


Figure 17. Estimated proportion of WCT fry surviving to the onset of winter at each temperature station in the Grave Creek and Harmer Creek population areas in 2017, 2018, and 2019.



Fry Size and Overwinter Survival— The Coleman and Fausch (2007a) lab-based experiments were used to provide an estimate of mortality of WCT fry as a function of fry size at the onset of winter for the Grave and Harmer Creek population areas. The proportion of fry surviving in the lab-based experiments under the warm, intermediate, and cold temperature regimes are shown in Figure 18 for the growing season and overwintering periods. There is a period of high mortality at the end of the growing season during the transition to winter and extending into the overwintering period, particularly in the cold treatment (Figure 18).

We used the mortality observed during the full overwintering period from the lab-based experiment (Figure 18) to develop a functional relationship between overwintering mortality and fry fork length. There are three data points, representing the average overwinter survival and average fork lengths of fry at the onset of winter in the three lab treatments. The points were fitted with a logistic regression model, yielding a functional relationship shown in Figure 19. The model predicts that under controlled lab-based conditions overwinter survival of Cutthroat Trout fry is high (>90%) at a fork length greater than ~30 mm. Below 30 mm, survival decreases sharply, and at a fork length of ~20 mm survival is predicted to be only 40%.

Potential overwinter survival of WCT fry in the Grave watershed was estimated using fry fork length. The model was fitted using the *glm* function from the "stats" R package and using a "binomial" distribution (logit link function; R Core Team, 2021).

The functional equation of:

$$\textbf{Lab-based Overwinter Survival} = e^{-5.21+0.239 \times \text{Fork Length}} / (1 + e^{-5.21+0.239 \times \text{Fork Length}})$$

was used to estimate survival at each temperature station in the Grave and Harmer Creek population areas. An assumption of the modelling exercise was that fry in the system truly attain the sizes predicted by the GSDD and fry fork length model above in Figure 13. The results of this scenario are shown below in Figure 19 and Figure 20.

Figure 18. Proportion of fry surviving from swim-up in the Coleman and Fausch (2007a) lab-based experiments under the warm, intermediate, and cold temperature regimes through the growing season (white area) and the winter (shaded area).

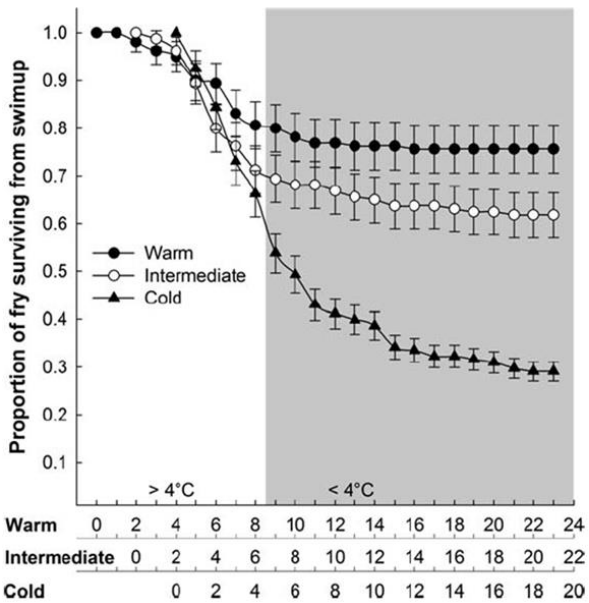


FIGURE 3.—Proportion of age-0 Colorado River cutthroat trout surviving from swim-up to each week during phase 2 of the 2003 experiment. The survival curves have been shifted along the horizontal axis to synchronize them based on the timing of the onset of winter temperatures. Bars show Kaplan–Meier 95% confidence intervals.

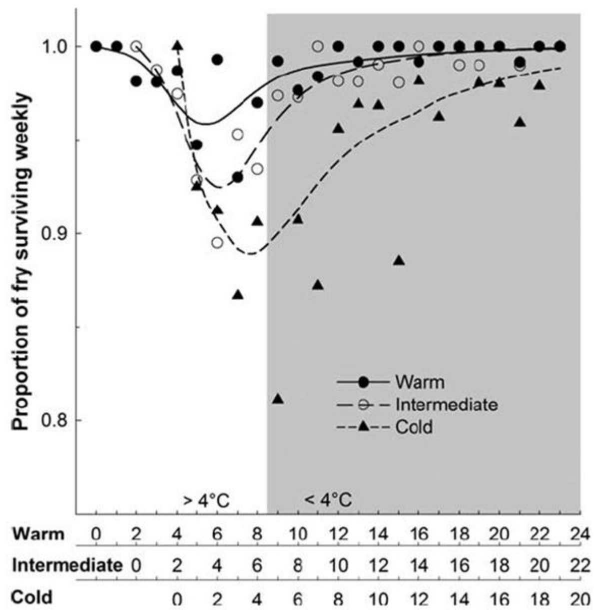
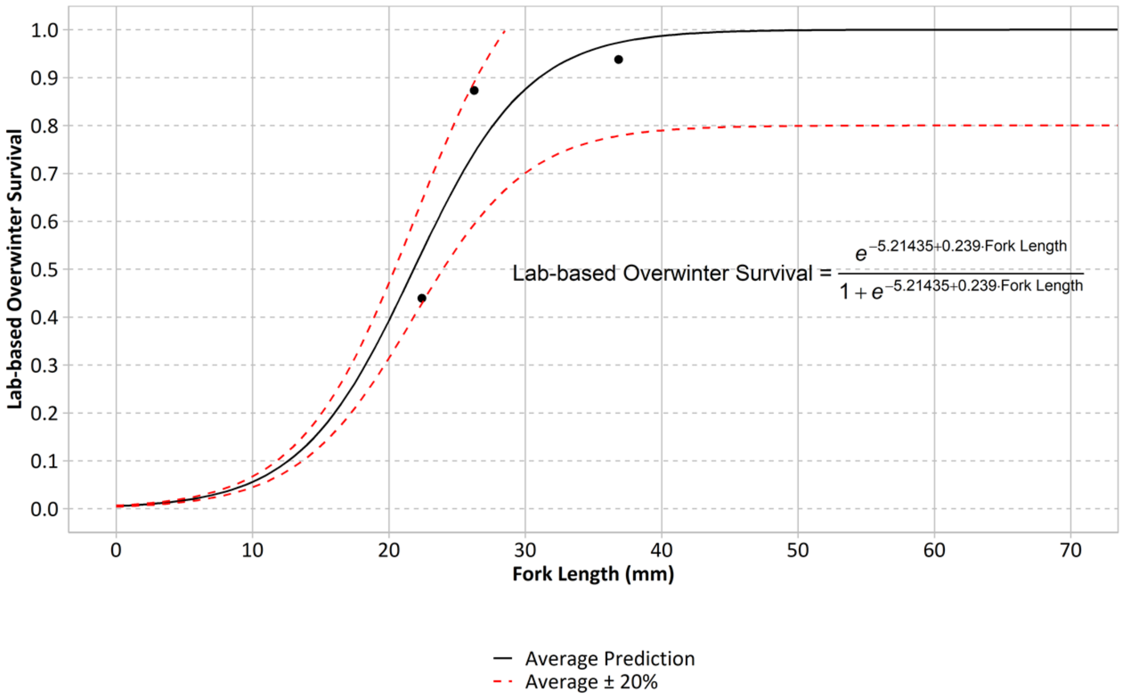


FIGURE 4.—Hazard plots showing the survival of age-0 Colorado River cutthroat trout fry each week during phase 2 of the 2003 experiment for the three temperature regimes. Logistic regression curves from the best-fitting model are given in Table 2. The curves have been shifted along the horizontal axis as in Figure 3.

Figure 19. Lab-based overwinter survival as a function of fry fork length estimated from Coleman and Fausch (2007a). The three points represent the average overwinter survival from the warm, intermediate, and cold growing season temperature regimes. Note that predictions extrapolated below ~18 mm are not realistic as WCT fry emerge around this size.



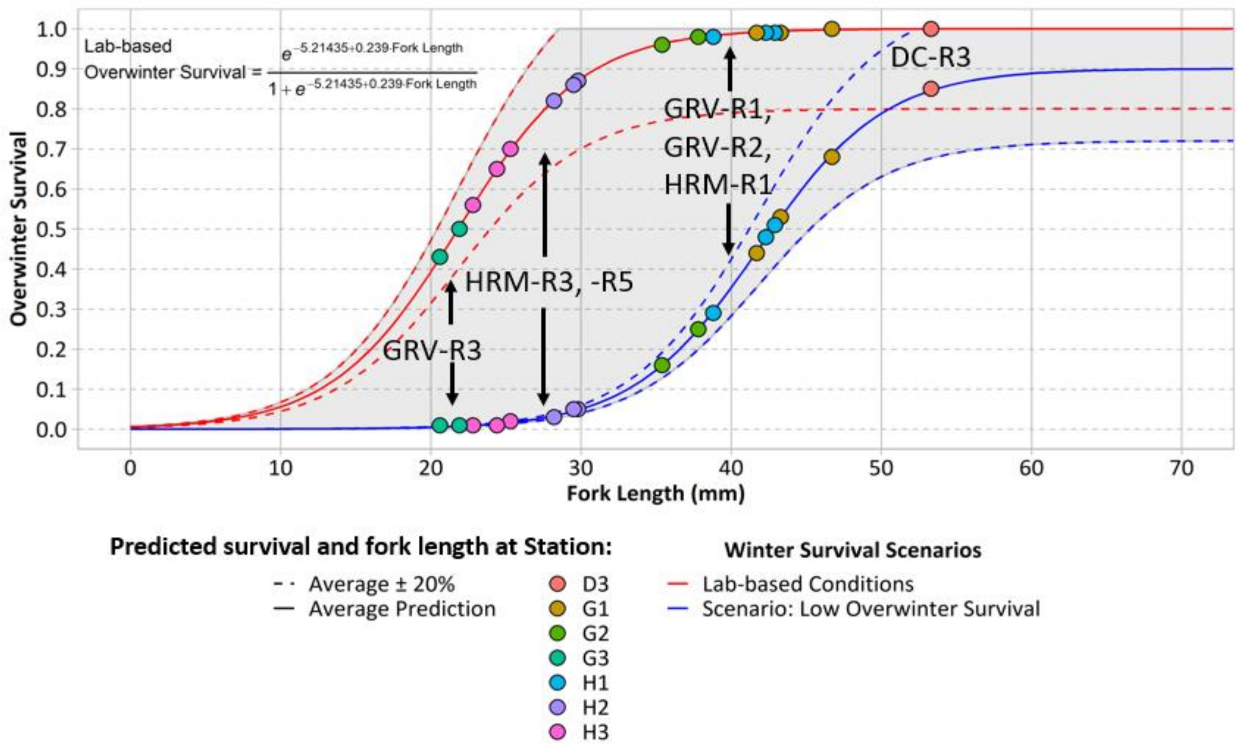
Potential Effects on Survival from Interactions with Other Factors— In Section 3.3 it was noted that conditions in winter 2018/2019 were particularly severe and included a sharp and significant drop in temperature in February 2019, abnormally low flows, and a low snowpack, which may have combined to create severe conditions such as abnormal ice extent. These conditions would have likely occurred in both the Grave and Harmer Creek population areas. However, the response to such conditions may have differed in each population area. We explored alternate scenarios to the lab-based overwinter survival versus fry size relationship developed in Figure 19 to include a general low overwinter survival-based scenario (Figure 20). Coleman and Fausch's (2007a) lab-based estimates of fry overwintering mortality in relation to fry size are likely higher than would occur in the wild. For example, the estimates do not include coincident effects of ice, predators, rapid temperature transitions, or water quality. The lab-based relationship thus likely represents an overly conservative estimate of mortality in relation to fry size; conditions outside the lab are likely more challenging for Cutthroat Trout fry. Conceptually, these factors would lower the asymptote and shift the curve to the right. Shifting the curve to the right would account for higher mortality across all size classes. A similar form to response relationship (i.e., an S-shaped function) seems likely if overwinter survival is related to fry size, but conceivably the slope of the function may also shift if the size-dependency changes through time, or differs among locations. A reduction in the asymptote would allow for mortality to a greater proportion of a cohort due to predation or other factors, as has been shown in various studies (Lindstrom and Hubert 2004; Cope *et al.* 2016).

The estimated overwinter survival at each temperature station in the Grave and Harmer Creek population areas is shown for the lab-based overwinter survival scenario and the lower overwinter survival scenario in Figure 20. There are several key takeaways from this analysis. First, in the simple lab-based scenario, overwinter survival is likely to be lower in the Harmer Creek population area (HRM-R3, HRM-R5) than in the lower portion of the Grave Creek population area (HRM-R1, GRV-R1, GRV-R2) based on temperature effects alone. These predictions of overwinter survival based on fry size, coupled with the estimates of mortality prior to the onset of winter as a function of GSDD (Figure 17), suggest that based on temperature effects alone, age-1 WCT population density is likely to be lower in the Harmer Creek population area than in the lower portion of the Grave Creek population area. Observations of age-1 WCT density suggest that recent age-1 abundance in Grave Creek has been higher than in Harmer Creek during the period of Reduced Recruitment (Thorley *et al.* 2022).

The second main takeaway is that under a more severe overwinter mortality scenario it is possible to produce a recruitment failure in the Harmer Creek population but not the Grave Creek population based on the combined effects of reduced GSDD in Harmer Creek and a severe winter with high overwinter mortality. Fundamentally, this exploration indicates that it is conceivable to have interacting effects between the temperature regime at a location (and the resulting fry size) and other factors that influence the functional relationship between survival and fry size. The low overwinter survival conceptual scenario estimated very low (<5%) overwinter survival in Harmer Creek reaches HRM-R3 and HRM-R5 across all years, whereas overwinter survival was considerably higher (20-70% depending on the year and reach) in the lower portion of the Grave Creek population area (i.e., GRV-R1, GRV-R2, and HRM-R1).

The critical assumption here is the size basis to the magnitude of effects of environmental conditions on fry survival. If the effects of ice and winter conditions are equally severe across all size classes of age-0 fry (i.e., no size dependency) then recruitment failures would be predicted in both the Grave Creek and Harmer Creek population areas. Conversely, if there is a size-basis to survival and only a moderate shift of the curve to the right (Figure 20), then it is plausible that a recruitment failure could occur in the Harmer Creek population area while only reduced recruitment occurs in the Grave Creek population area. Likewise, if the curve shifts sufficiently far to the right in Figure 20, fry of all sizes will be affected, and a recruitment failure may occur in all locations.

Figure 20. Lab-based and low overwinter survival scenarios depicting overwinter survival of fry as a function of fry fork length (mm) at the onset of winter for each temperature station in the Grave and Harmer Creek population areas. The lab-based relationship (red line) shown in Figure 13 is shifted to the right with a reduced asymptote (blue line). The grey shaded area indicates a range of potential overwinter survival scenarios depending on winter conditions.



3.2.7. Air Temperature as a Proxy Measure

The empirical water temperature data for Grave and Harmer creeks have a short period of record and were therefore compared to air temperature records to understand if the short record was representative of typical conditions. The best empirical air temperature records were from Sparwood; however, it is reasonable to expect that conditions in Grave and Harmer creeks were colder due to their higher elevations.

The months with the coldest average air temperature during the recent period of record[21] (2011-2020) were December and January, which averaged -6.9 and -6.7°C respectively (Table 15). The single coldest month in the 2011-2020 period was February 2019, with an average air temperature of -13.5°C. February 2019 was substantially colder than the February average, but the winter months that preceded it (October 2018 through January 2019) were all warmer than average. This resulted in an unusual shift from abnormally warm to abnormally cold temperatures. Among other recent years, the winter of 2017-2018 also had a particularly cold December (-10.4°C) and February (-10.6°C); both months were colder than the average for the recent period of record (2011 – 2020).

[21] A recent average is provided because in recent years a general trend towards warmer temperatures exists, and the average from the last ten years deviated from the average of the last 40 years.

Table 15. Monthly average air temperatures using the dataset 'EC Sparwood Extended' from 2011-2020, and at the bottom, the average for the recent period of record (2011-2020). See Section 2.3.1 for description of data time series extension.

	Air Temperature (°C)												Yearly
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Average**
2011	-6.4	-8.6	-0.6	1.8	8.1	12.2	15.4	16.8	13.0	5.0	-2.6	-4.2	**4.2**
2012	-5.8	-5.0	0.4	5.8	8.6	12.1	17.8	16.4	12.1	4.2	0.7	-5.7	**5.1**
2013	-5.5	-1.8	-0.1	3.6	10.5	13.1	18.0	17.1	12.6	4.4	-3.3	-7.1	**5.1**
2014	-4.9	-10.2	-2.1	4.7	9.2	12.7	**18.8**	16.8	11.0	8.1	-4.4	-5.4	**4.5**
2015	-4.8	-0.4	3.3	5.3	9.4	15.9	17.2	16.5	10.4	7.5	-2.5	-4.9	**6.1**
2016	-4.8	0.4	3.0	8.8	9.8	13.6	16.1	16.1	10.8	4.9	2.7	-10.8	**5.9**
2017	-11.0	-6.6	0.1	4.6	10.2	14.2	18.7	17.4	11.8	4.4	-1.3	-10.4	**4.4**
2018	-4.2	-10.6	-1.1	3.3	12.8	13.1	17.6	16.3	9.7	3.6	-1.3	-4.6	**4.5**
2019	-4.4	**-13.5**	-1.5	5.0	9.6	13.4	15.1	16.1	10.7	1.2	-2.8	-2.4	**3.9**
2020	-4.8	-3.3	-1.8	3.0	8.9	12.8	15.6	17.1	13.1	0.0	0.1	-4.5	**4.7**
2011-2020	-5.6	-6.0	0.0	4.6	9.7	13.3	17.0	16.7	11.5	4.3	-1.5	-6.0	**4.8**

Notes:

Values are shaded from coldest (most blue) to warmest (most red) within each year

Minima and maxima for the entire period (2011 to 2020) are bolded for each monitorig station

A recent and longer-term pattern can be gleaned from the air temperature GSDD time series shown in Figure 21. First, air temperature GSDD from 2013 to 2017 — the years immediately prior to the Reduced Recruitment — were hotter and/or longer than most of the years on record for EC Sparwood. GSDD exceeded 2,400 in all five years. In the growing seasons of 2018 and 2019, air temperature GSDD regressed to ~2,200 GSDD, which is below the longer-term moving average. An initial analysis demonstrated a high correlation between weekly mean air temperature at EC Sparwood and the weekly mean water temperatures at each temperature station in the Grave and Harmer Creek population areas (Figure 22), which indicated that air temperature GSDD at Sparwood is a reasonable predictor of water temperature in Grave and Harmer creeks. A longer-term trend indicated that the length and magnitude of air temperature GSDD at Sparwood increased by roughly 10% over the most recent 40-year time period (Figure 21).

Figure 21. Time series of air temperature (growing season degree days > 5°C) at EC Sparwood from 1980-2020.

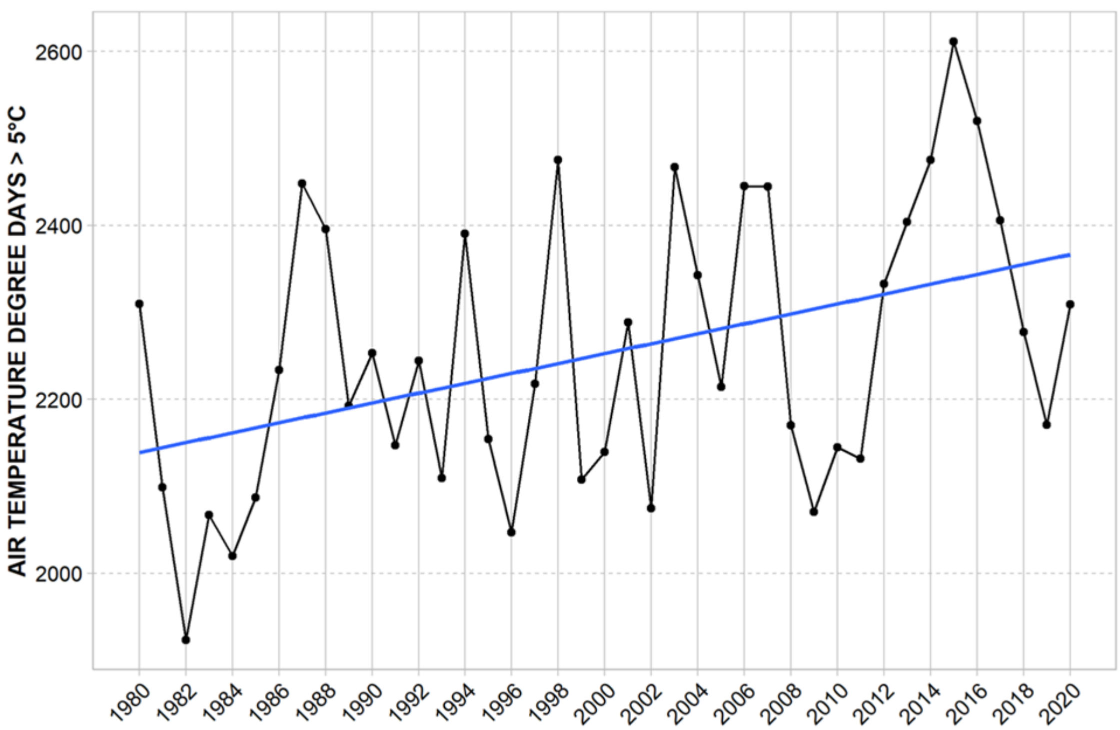
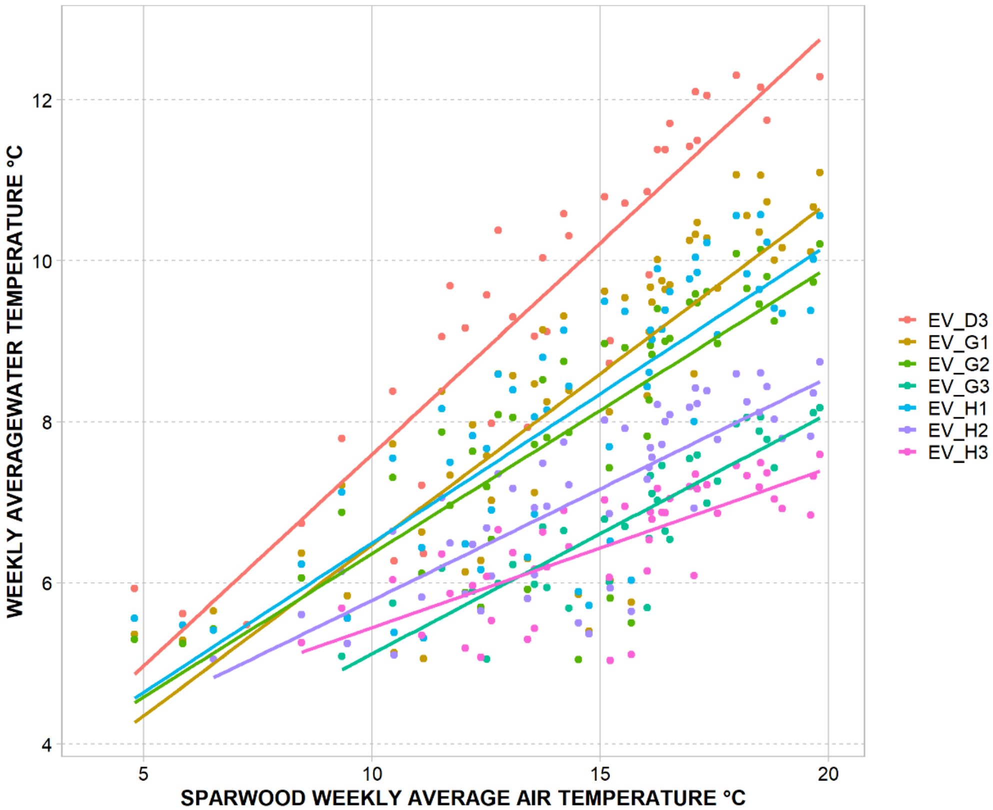


Figure 22. Correlation between weekly average water temperature at each Grave and Harmer Creek temperature station and weekly average air temperature at EC Sparwood.



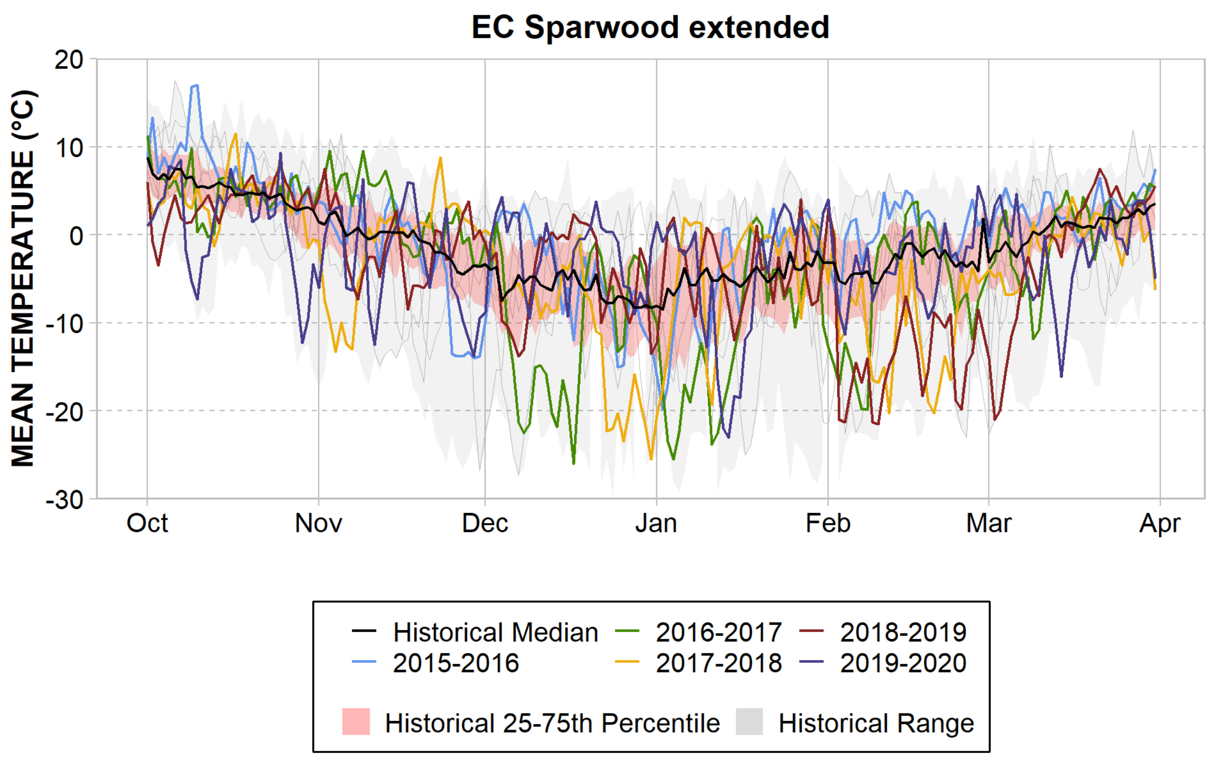
3.3. <u>Ice</u>

3.3.1. Air Temperature

Air temperature in the Canadian Rockies can be highly variable. Average daily temperatures of -20ºC are not uncommon in winter, but may also exceed 0ºC for short periods (Figure 23). There have been periods over the last several years when cold snaps have occurred that resulted in severe ice conditions in the Elk Valley. The winters of 2016/17, 2017/18, 2018/19 and 2019/20 each had a period when daily average air temperature dropped below -20ºC (Figure 23). In February 2019, air temperature remained below -10ºC for the longest period in recent years. At times, this period exceeded the historical range of air temperatures for February and was preceded by a day when the temperature was higher than the historical range.

Attention should also be drawn to two other cold periods in the recent past. The first occurred from late December 2016 to early January 2017. This period was split across two calendar months so is not well displayed by the monthly averages (can be seen in green in Figure 23), but it was also notable for its magnitude and duration and approached the lower limit of the historical range. The second cold period of note was two weeks of cold in December 2017 and had among the coldest temperatures ever recorded at EC Sparwood-Extended.

Figure 23. Average daily air temperatures at the EC Sparwood-Extended for the years of 1980-2020 (Elevation 1,138 m).



A unique feature of the cold period in February 2019 was that it began with a rapid temperature transition from near 0°C to below -20°C (-20.7°C drop). This was the second largest temperature decline in the 1980-2020 period. The probability of the February 2019 temperature decline was estimated as a one in 22-year event (Table 16). A temperature shift that occurred in January 2018 was also among the ten largest in the record (-17.1°C drop), with a return period of one in five years.

Table 16. Return period calculation for rapid temperature declines at EC Sparwood – Extended (1980-2020).

Event Date	Daily Temperature Drop (°C)	Rank	Return Period[1] (Years)
31-Jan-1989	-30.5	1	43
3-Feb-2019	-20.7	2	22
28-Jan-2008	-19.3	3	14
15-Jan-1982	-18.9	4	11
2-Jan-1998	-18.3	5	9
27-Dec-1992	-18.2	6	7
16-Jan-1994	-17.1	7	6
10-Jan-2018	-17.1	8	5
30-Jan-1988	-16.9	9	5
28-Dec-1990	-15.5	10	4

[1.] Calculated using the Weibull plotting position formula

3.3.2. Winter Water Temperature

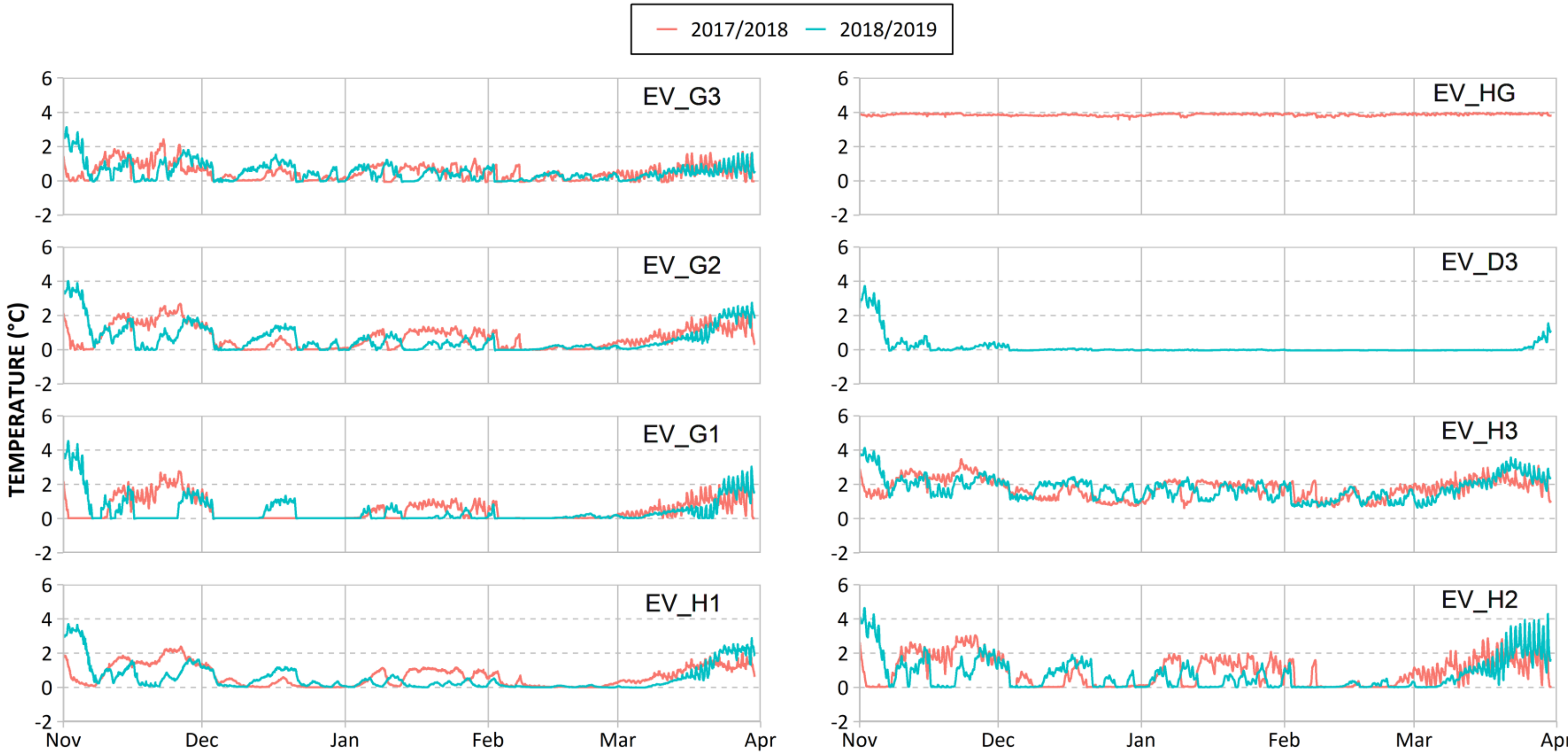
Eight water temperature loggers[22] were operated from May 2017 to May 2019 in the Grave Creek Watershed (Dry Creek (D3) was installed in May 2018). When inferring ice processes from water temperature data, caution is required when extrapolating from the single point location of the sensor to a broader spatial area. For example, water temperature loggers are typically installed in locations selected to be ice-free (e.g., deeper water).

For the Grave Creek population area, Figure 24 illustrates that during the winter, station G3 (upper Grave Creek) spent the least time at 0ºC, and Grave Creek water temperature was progressively colder the further downstream it was measured. This trend is visible in both winters with available data (2017/18 and 2018/19). At G2 and G1 water temperature data are represented by a flat line at 0ºC, which we interpret as an indication of ice at or near the gauge, in February of both years. The indication of ice is more pronounced at G1 and occurred in December and February for both years. January 2019 appeared to have slightly colder water temperature than in 2018, and the first three weeks of March of 2019 were colder than in 2018.

[22] A ninth temperature logger was available for the outlet creek of Grave Lake but was not utilized for this analysis because it does not influence the sections of the watershed under study.

For the Harmer Creek population area, the temperature loggers indicate a pattern that is similar to that in the Grave Creek population area. The station within Dry Creek (D3) appears to be iced from December 2018 through April 2019, the only winter data available. Below the confluence of Harmer and Dry creeks the combination of relatively warm groundwater from upper Harmer and cold water from Dry Creek appear to keep water temperature at H3 (Harmer below the confluence of upper Harmer and Dry Creek) between 2ºC and >0ºC from December to mid-March after which the temperature begins to rise. Similar to Grave Creek, Harmer Creek cools in a downstream direction during winter and appears to show increased indication of ice in December and February for both of the winters with available data. Overall, despite notable differences in air temperature patterns in the winters of 2017/18 (cold earlier in winter, than average) and 2018/19 (warm earlier in winter, then very cold), the water temperature records for the two winters appear to be similar throughout most of the winter, which indicates the streams may be buffered from short term variation in air temperature.

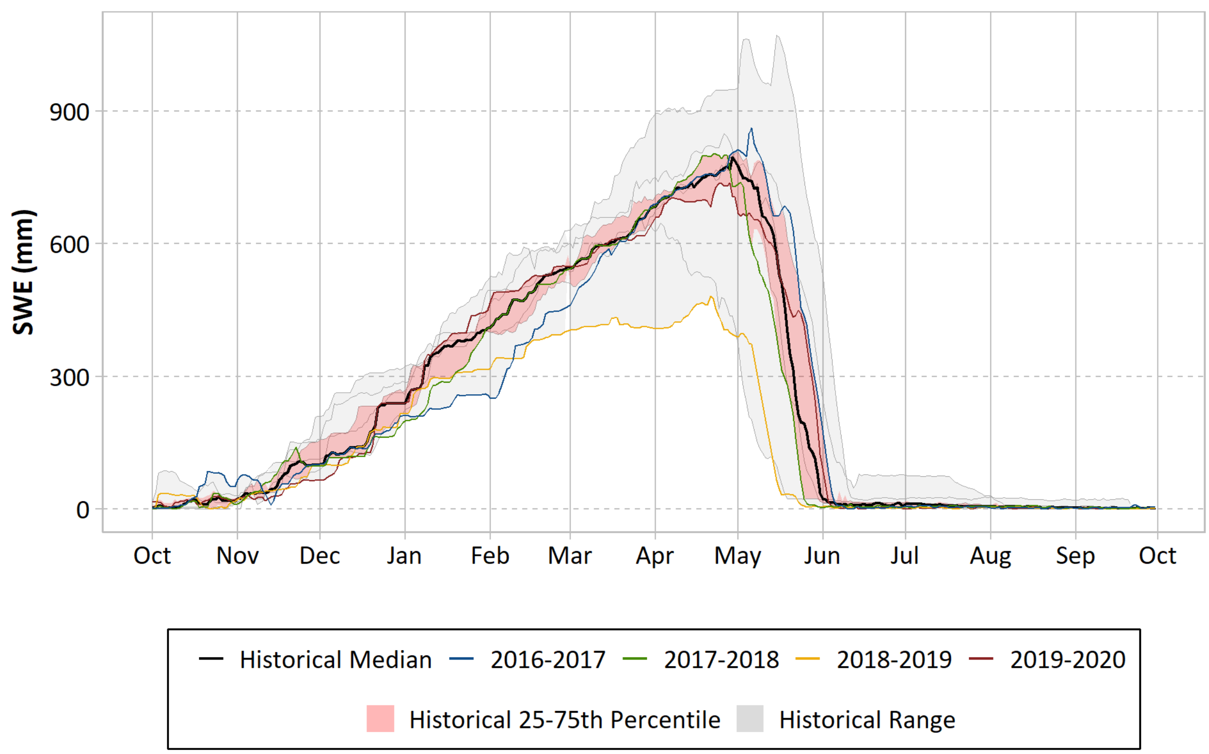
Figure 24. **Water temperature records during winter (November – March) of 2017/18 and 2018/19. Stations in the Grave Creek population area are shown in the left column, and stations from the Harmer Creek population area are in the right column.**



3.3.3. Snow Water Equivalents

Snow can occur year-round in the Grave Creek Watershed, although accumulation on the ground typically occurs between November and April. The nearest weather station with comparable elevation to the upper reaches of Grave and Harmer was the Morrissey Ridge snow-water equivalent (SWE) station[23]. From February onward the winter of 2018/19 had the lowest SWE of any year on record (1983-2020). Other recent years were within the 25-75% percentile range, although for a period in January and February 2017 there was also an unusually low SWE. The onset of the abnormally low SWE conditions at Morrissey Ridge occurred during on the same dates as the abnormally cold air temperature that was recorded at the nearby EC Sparwood weather station. This suggests that there was little snow cover on the stream to act as a buffer between cold air and open water or surface ice. Less snow cover would allow for more rapid cooling of stream water during periods of especially cold weather.

Figure 25. Winter (November-March) snow water equivalents at the Morrissey Ridge weather station (elev. 1,860 m; 1983-2020).



[23] Snow-water equivalents are a measure of the accumulated water in a snowpack and can be used as an indicator for how insulative the snowpack is throughout the year.

3.3.4. Discharge and Stage

Streams in the Canadian Rockies follow a seasonal discharge pattern. Low flows occur in the winter when precipitation is stored as snowpack, followed by peak flows as snowmelt occurs in the late spring and early summer, and then a lengthy flow recession from late summer through winter. We examined winter hydrologic data to determine: 1) whether Grave and Harmer creeks had abnormally low discharge during any of the winters in the last ten years; 2) the magnitude and timing of hydrologic depletion effects, if detectable; and 3) whether periods of highly variable stage exist in the record as an indication of dynamic ice.

Discharge/stage data are quite limited for Grave and Harmer creeks during winter months. Hydrometric monitoring consists of manual monthly measurements at DC1 and HC1; these data can support a general understanding of whether discharge was normal or anomalous; however, these data are not sufficient to detect events like ice-induced discharge depressions, though there is some indication, in some years, of stage fluctuations that could be attributed to ice conditions.

Among recent winters it appears that the winter of 2018/19 had a discharge that was lower than normal, and lower than most winters in the last 10 years (Figure 26). The measurement points (blue dots in Figure 26) suggest that discharge was highly variable through January 2019, but by February it stabilized at low levels that were below the 25th percentile (outlined in blue in Figure 26). These low discharge measurements coincide with the period of extreme cold air temperatures that occurred in February 2019.

To determine if a discharge depression or extreme stage fluctuations may have been occurring generally in the region, the Elk River at Natal gauge, near the Elk and Grave confluence, was examined (Figure 27). The variation visible in the stage record suggests that water level at the station can vary substantially in a short period of time. During the winter months the record is suggestive of ice dams retaining and releasing water rather than precipitation or melt-induced discharge increases, which tend to result in smoother changes in stage. Rapid stage change events occur in most years, but a sustained event occurred in the winter of 2018/2019 that dramatically increased the stage reading from early February until mid-March (Figure 27). This event occurred while air temperature in the region transitioned from generally warm to cold, and during the period that low insulative cover was available from the snowpack.

Figure 26. **Streamflow measurements at HC1 (elevation 1,324 masl) for the winter months (November – March) of 2011/12 through 2019/20, including the historical median and 25th/75th percentiles. All data are from non-continuous manual discharge measurements; linear interpolation was used to infill data gaps to allow calculation of median and percentiles. The historical median is calculated from the period of record (1992-2020). Blue points indicate manual discharge measurements.**

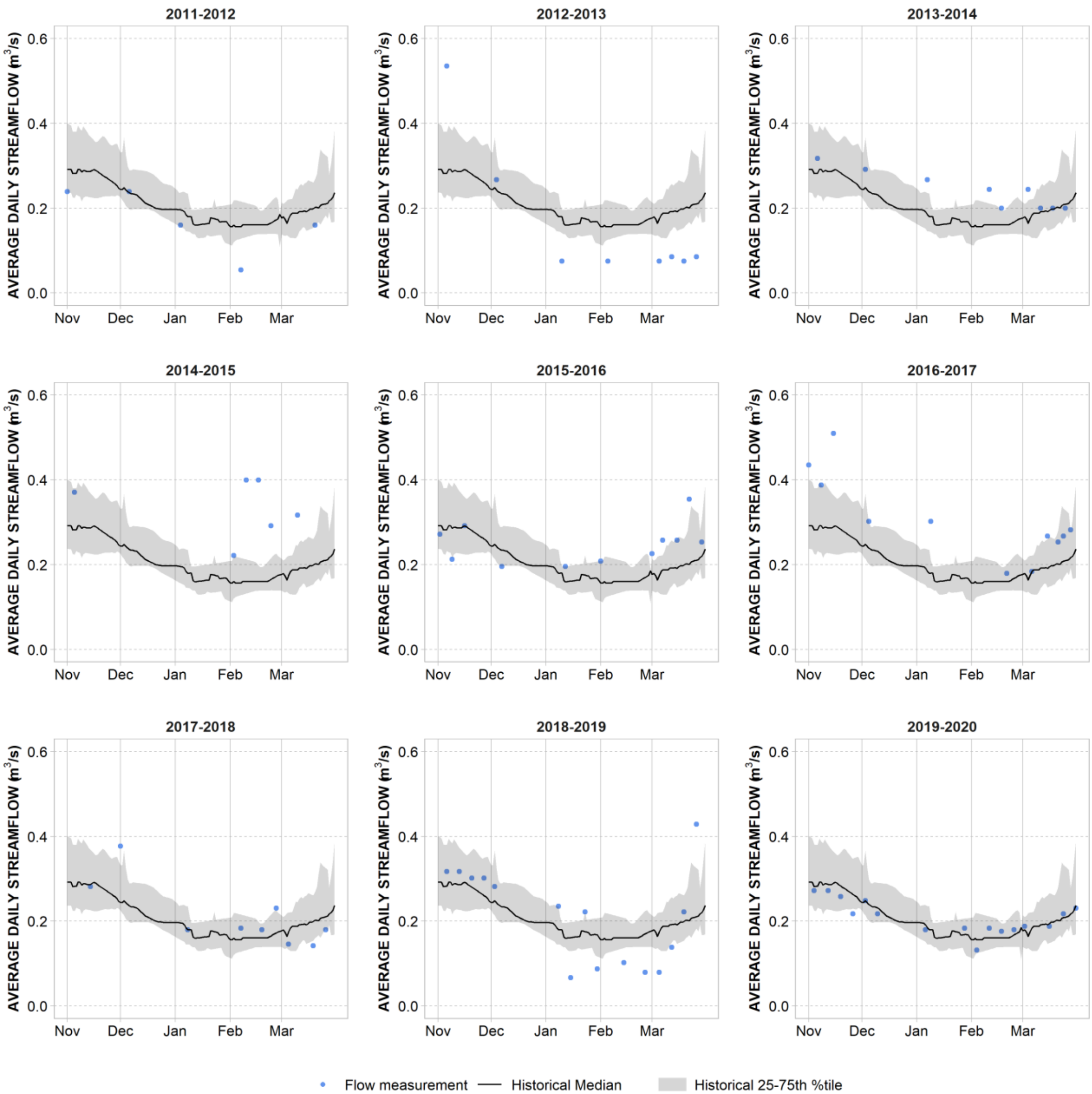
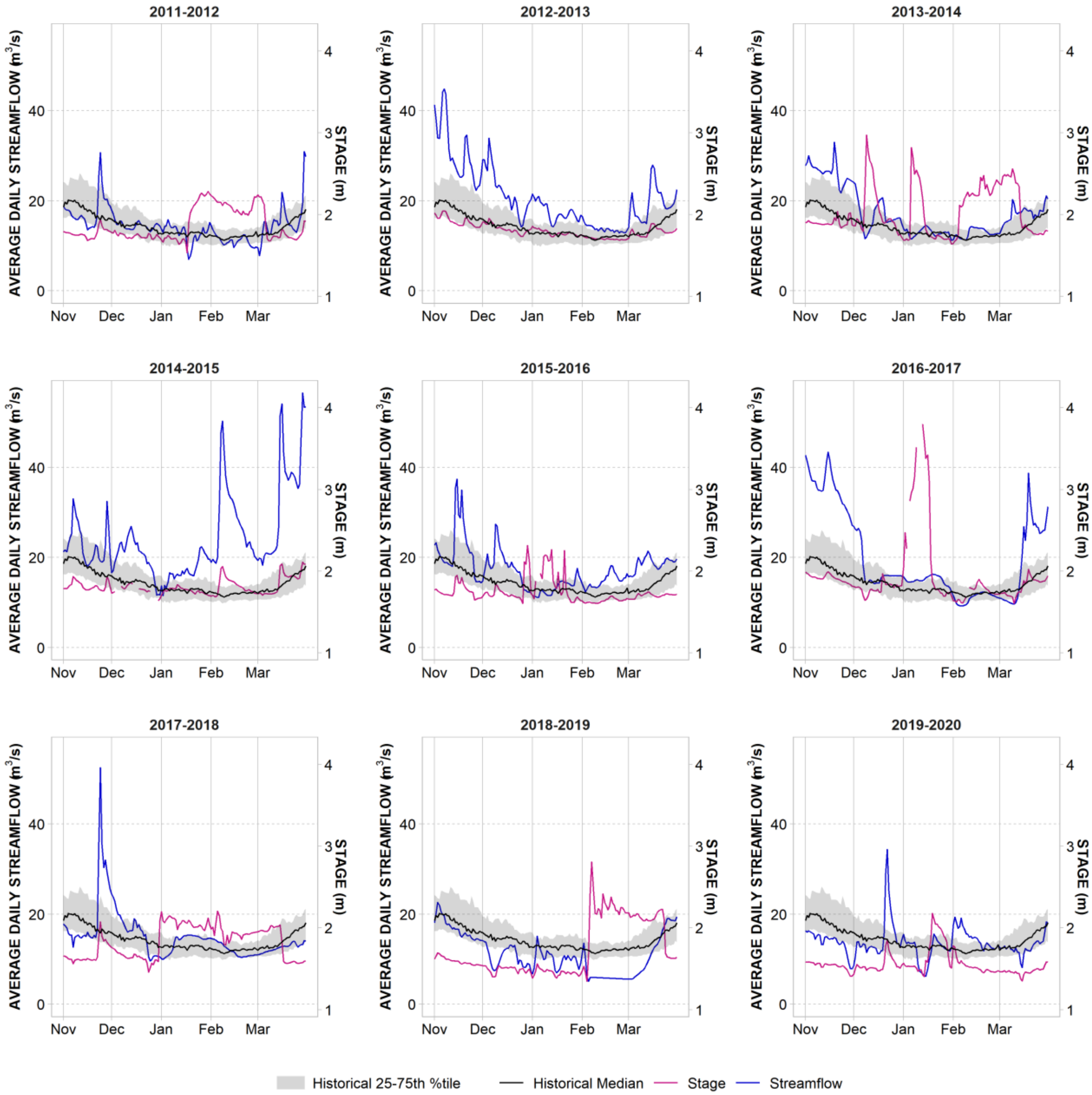


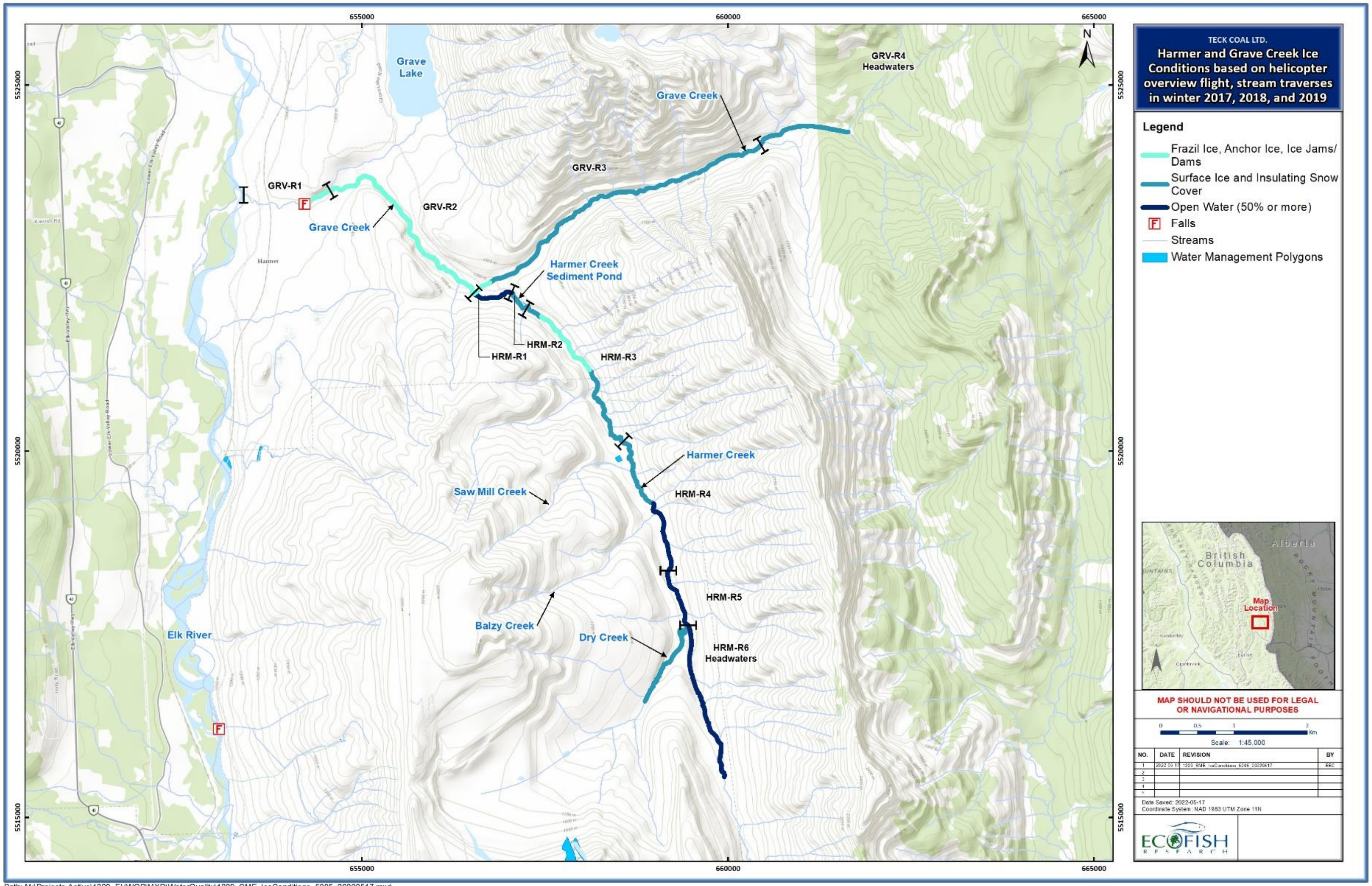
Figure 27. Maximum daily discharge and stage from the WSC gauge NK002 (Elk River at Fernie, elevation 974 masl) for November - March 2011/12 through 2019/20.



3.3.5. Direct Observations of Ice

Figure 3.14 in Cope and Cope (2020), summarizes observations of ice conditions in the Grave Creek Watershed (Figure 28). The figure shows Harmer Creek upstream of the Balzy Creek confluence as open water, whereas downstream it transitions through stable ice cover and into entrained ice. The open water upstream of Balzy Creek (HRM-R5 and HRM-R6; Figure 28) can likely be attributed to groundwater input providing water that remains approximately 4ºC throughout the year. Grave Creek above the confluence with Harmer (GRV-R3 and GRV-R4) had stable ice cover before it transitioned to frazil and anchor ice from the confluence with Harmer Creek down to the barrier near the Elk River. The weather conditions at the time of observations for the ice map were not noted in the Cope and Cope (2020) report; it is therefore unknown whether the observations represent average or extreme winter conditions.

Figure 28. Map representation of observed ice conditions in Grave and Harmer creeks illustrated from observations collected during telemetry monitoring in 2017-2019 (reproduced from Cope and Cope 2020).



Path: M:\Projects-Active\1229_EVWQP\MXD\WaterQuality\1229_SME_IceConditions_5005_20220517.mxd

4. DISCUSSION

4.1. Interpretation of Findings

4.1.1. Water Temperature

Several measures of water temperature related to fish survival are presented in Section 3.2. The data span May 2017 – October 2019, with some additional observations in 2021. Although the record is short, the analyses allow evaluation of the suitability of water temperatures for WCT activity periods of spawning, incubation, and rearing. The results clearly indicated that Grave and Harmer creeks are cold systems, with few warm exceedances of water temperature optima. The rarity and small magnitude of warm exceedances indicate that it is unlikely that too-warm conditions in Harmer Creek could have led to the Reduced Recruitment.

Both Grave and Harmer creeks have reaches with cold water temperatures in the open-water period (April to October) that are often sub-optimal for spawning, incubation, and rearing. During this period, water temperature in both Harmer and Grave creeks tended to warm in a downstream direction. In Harmer Creek, the input of relatively warm water from Dry Creek moderated the cold water that flowed from the groundwater-fed headwaters of Harmer Creek (HRM-R6), though water temperature just downstream of the confluence of Harmer and Dry creeks (H3) remained cold through the summer. Water temperatures in the lower watershed, near and below the confluence of Grave and Harmer Creeks (G2 and H1) were mostly within optima for spawning, incubation, and rearing periods.

GSDD calculations indicated that Grave and Harmer creeks have reaches with poor temperature conditions for fish growth and survival and other reaches that have adequate temperature conditions. Upper Grave (G3) and upper Harmer (H3) had GSDD values comparable with streams in Colorado that had low fish abundance (Coleman and Fausch 2007b), poor predicted overwinter survival of fry, and poor recruitment. G3 had lower GSDD than H3 but both were cold enough through the growing season (<900 GSDD) to have poor predicted recruitment. Grave and Harmer creeks also have lower reaches with temperature conditions that are adequate for recruitment (>900 GSDD). For example, GSDD accumulation was calculated to begin earlier and end later at stations D3, H1, G2, and G1 than at stations G3 and H3. An earlier start to growing season and higher GSDD accumulation would allow for earlier spawning, earlier fry emergence, a longer fry rearing period, and larger fry with a greater probability of overwinter survival.

The upper portion of the Grave population area did not experience a major decline in recruitment, despite the cold-water temperature regime recorded at G3. This may be due to immigration from with the warmer portions of lower Grave Creek. Alternatively, recent 2021 data from G4 (upstream of G3) indicate warmer conditions during the growing season than at G3, suggesting that cold temperatures in upper Grave Creek may be more localized than previously assumed, and therefore the temperature regime at G3 does not appear to be representative of the entire upper portion of Grave Creek.

Recruitment Scenario Testing with GSDD— Section 3.2.6.2 provides descriptions of detailed explorations of the predicted influence of GSDD on fry size and survival. The detailed explorations provide strong support for temperature regime as a key driver of fry size at onset of winter, fry survival prior to and during winter, and therefore a link between water temperature and recruitment. Further, the explorations indicate that differences in temperature regime within the Grave Creek watershed may be explanatory for differences in recruitment observed among years and among locations within the watershed. Also key from the explorations is the support for interactions between water temperature regime and other factors co-occurring in the watershed, such as effects of ice, rapid temperature transitions, or water quality. Conceptually, such factors would influence the relationship between survival and fry size, by lowering the asymptote and/or shifting the curve to the right. Variation in these factors through time or space may account for differences in recruitment observed at different locations in the watershed. At this time, there is insufficient data to understand the relative influence of each factor, but the possibility of such interactions is considered to be potentially important and worthy of further attention. The relation between fry size and overwinter survival suggests a mechanism related to starvation or general physiological health (because smaller fish have smaller energy stores for their size) and therefore a long winter duration may exacerbate the size-dependent survival effect. Since data were available for only two winters, additional exploration was not possible, although initial calculations did not indicate notable differences in winter duration (measured as non-growing season days).

It is important to note that these results are conceptual and should be interpreted with respect to the broad patterns predicted rather than interpreted as estimating a specific "true" recruitment to age-1 in a given location and year. The predictions rely heavily on field and lab studies in high elevation Cutthroat Trout in Colorado (Coleman and Fausch 2007a, 2007b), and while the broad patterns (e.g., fry size as a function of GSDD) are likely to hold, the response relationships with GSDD have not been specifically determined for WCT in the Elk Valley. The low overwinter survival scenario in particular has the greatest uncertainty given that the response relationships between factors like ice and temperature transitions during winter on trout survival are not well understood (Hatfield and Whelan 2021). Overwinter survival is likely to vary year to year depending on temperature conditions and other factors (shaded area in Figure 20).

4.1.2. Air Temperature as a Proxy Measure

The short-term trend in air temperature GSDD (2013 - 2019) predicts that recruitment conditions during the growing season may have been better in the Grave and Harmer Creek population areas in the years leading up to the Reduced Recruitment than in the years when the reduction occurred. While this does not provide sufficient evidence for temperature being the cause of the Reduced Recruitment, it does reinforce that water temperature during the open water period may have contributed to low recruitment in the Harmer Creek population area based on a shorter growing season length than the Grave Creek population area.

4.1.3. Ice

Weather data were used to infer that, in the winters of 2017/18 and 2018/19, ice conditions in the Grave Creek Watershed were likely similar to those described for the upper Fording River (Hatfield and Whelan 2021). While several cold periods were observed in the record, the conditions for ice formation during February 2019 were severe and rare. Such conditions could cause mortality to fish in the area through direct pathways such as freezing or crushing, or indirect pathways such as displacement, starvation, or predation. Weather during winter 2018/19 may have created severe ice conditions within the Grave Creek Watershed. The air temperature record for this period shows that until February, air temperatures were relatively warm (Figure 23). Early cold weather with a gradual onset is considered ideal for surface ice formation that would create stable aquatic conditions for the rest of winter, particularly if early formation of surface ice was accompanied by snow accumulation. This pattern did not occur in 2018/19. The drop in temperature that occurred in February 2019 was remarkable for its magnitude and suddenness. The transition recorded at EC Sparwood - Extended was the second most sudden and severe transition to have occurred since 1980 (Table 16). Following the temperature drop in February 2019, there was a period of sustained cold that lasted until early March. This period was notable for the consistent very cold air temperatures and daily maximum temperatures did not exceed 0°C until mid-March. SWE accumulation in the winter of 2018/19 was well below average and therefore snow cover may have failed to buffer streams from effects of the sudden drop in cold air temperature. The onset of sudden cold air temperature, which allowed little previous surface ice formation, combined with low SWE and abnormally low streamflow, suggest that ice conditions may have been severe. Plots of water temperature records from February 2019 illustrate that this was a period when most water temperature stations recorded near or at 0°C, but with only two winters of data it is unclear whether these trends are anomalous.

Evaluating the effect of ice conditions is hampered by information on overwintering habitat quantity and quality. Table 3.15 in Cope and Cope (2020) indicates that in the Harmer Creek population 75% of fish overwinter in riffles, whereas use of riffles was lower in the Grave population . However, Cope and Cope's findings represent adult overwintering habitat use, and may not reflect juvenile habitat use. Given that juveniles are expected to primarily overwinter within coarse substrates, differences in pool habitat availability between Grave and Harmer creeks may be unimportant for this life stage.

4.2. Evaluation of Explanatory Factors

The evidence provided in this report supports conclusions that water temperature and ice conditions were contributory to the WCT Reduced Recruitment in Harmer Creek. Since only some of the conditions described for the five explanatory factors (Section 2.4) were met, the evidence does not indicate that either water temperature or ice conditions were the sole cause of the Reduced Recruitment. However, some of the conditions were met, which suggests that water temperature and ice conditions were contributors to the Reduced Recruitment; we acknowledge that other factors have also been brought forward as partially explanatory (Harmer Creek Evaluation of Cause Team 2022), so winter conditions should be considered as part of an integrated explanation for the observed recruitment patterns. The rationale for these conclusions is elaborated below, and potential uncertainties are described.

4.2.1. Water Temperature

To be identified as a sole cause of the Reduced Recruitment, water temperature conditions would need to have been anomalous or noteworthy in relation to all five of the explanatory factors (Section 2.4). To be identified as a contributor to the Reduced Recruitment one or more of the conditions needed to be met.

Grave and Harmer creeks are coldwater systems. There were very few warm exceedances in any part of the Grave Creek watershed. Thus, conditions were not met for any of the five explanatory factors, so we conclude that effects of too-warm water were not sufficient to be a notable contribution to the Reduced Recruitment.

In contrast, cool water temperature appeared to pose ongoing challenges to recruitment and survival of WCT in the Grave Creek watershed. The upper reaches of both Grave and Harmer creeks had low summer peak temperatures, short cool growing seasons (as measured by GSDD), and low July mean water temperatures. When a threshold of 900 GSDD was used to define conditions adequate for recruitment, the colder stations in the watershed (G3 and H3) were found to be unsuitable for recruitment, and conditions at H2 were only slightly above this threshold. July mean water temperatures at the same stations (G3, H2, H3) were cooler than the optimum temperature for WCT growth and were comparable to streams in Colorado with low fish abundance (Coleman and Fausch 2007a). Conversely, locations elsewhere in the watershed (H1, G2, G1 and D1) had temperature conditions that were appropriate for spawning, incubation, and fry rearing. Additional monitoring during May through October 2021 indicated that water temperature in GRV-R4 at station G4, upstream of GRV-R3 at station G3, appeared to be warmer than previously assumed. The record was too short to allow calculation of GSDD; however, this new information in upper Grave Creek suggests that water temperature at G3 may represent localized conditions, such that the water temperature regime in Grave Creek above its confluence with Harmer Creek may be warmer overall than previously assumed and therefore more suitable for recruitment, or that the water temperature regime in GRV-R3 and GRV-R4 may be more complex (e.g., patchy) than previously thought.

Given the general trends in water temperature, and specifically the similarity in temperature regimes between Harmer Creek and Grave Creek, the cause of the Harmer Creek Reduced Recruitment was not attributed solely to water temperature. The differences in water temperature between Grave and Harmer creeks were fairly small in absolute magnitude but the differences are biologically meaningful if the threshold of 900 GSDD is applicable to the WCT in the Grave Creek watershed (Table 14). The differences in water temperature regime indicate that recruitment was likely to have been more limiting in the Harmer Creek population area due to poor temperature conditions for emergence timing, growth, and survival of WCT fry, and therefore recruitment. Despite these differences, there was not clear support for water temperature being the sole cause of Reduced Recruitment. Conditions for the five explanatory factors were each met to some extent, but there did not seem to be sufficient intensity difference between Harmer and Grave (Table 14) or between the period of Reduced Recruitment and prior (Figure 21) to warrant concluding that water temperature was a sole cause.

Nevertheless, there was strong evidence that water temperature contributed to the Reduced Recruitment in Harmer Creek. Overall, water temperatures in Grave and Harmer creeks are cold. Incubation and fry rearing conditions were challenging in the growing season of 2018 and 2019 (and to a lesser degree in 2017), especially within the Harmer Creek population area. Modelling exercises (Section 3.2.6.2) demonstrated that conditions in Harmer Creek may have led to Reduced Recruitment, including the potential for interactions with severe winter conditions in 2018/2019 leading to recruitment failure in the 2018 spawn year in Harmer Creek. Large differences in conditions among years were not apparent; thus, there was no strong indication that water temperature alone was responsible for the Recruitment Failure in 2018; however, overall a role in both Reduced Recruitment and Recruitment Failure are plausible, particularly if there were interactions with other stressors such as the severe winter in 2018/2019, water quality, or other factors. The primary prerequisite for an interaction effect is size-dependent mortality (i.e., smaller individuals suffer greater mortality than larger individuals). An alternative (though not mutually exclusive) explanation is that Grave and Harmer population areas both had substantially lower recruitment from the 2017 to 2019 spawn years, but that immigration from reaches with suitable GSDD conditions was greater in the Grave Creek population area than the Harmer Creek population area. Thus, recruitment in the warmer portions of Grave Creek may help seed other areas in the stream. Current data are insufficient to test this hypothesis.

4.2.2. Ice

To be identified as a sole cause of the Reduced Recruitment, ice conditions would need to have been anomalous or noteworthy in relation to all five of the explanatory factors (Section 2.4). To be identified as a contributor to the Reduced Recruitment one or more of the conditions needed to be met.

Ice conditions did not meet the condition for Location for the full period of Reduced Recruitment, suggesting that Ice could not be the sole (or primary) cause of the Reduced Recruitment. Data suggest that severe ice conditions occurred in both Grave and Harmer creeks in February 2019 (and to a lesser degree during other winters). This timing was coincident with Recruitment Failure of the 2018 spawn year in the Harmer Creek population and Reduced Recruitment of the 2018 spawn year in the Grave Creek population. Intensity, Duration and Spatial Extent conditions were also likely met at this time. There is evidence that the winter of 2018-2019 would have been one of the most challenging on record. Air temperature, water temperature, SWE, and streamflow all suggest that conditions would have caused substantial ice formation. There were no observations of fish or ice conditions within specific habitats in the Grave Creek watershed during this period, but inferences from available data indicate that conditions may have caused fish mortality and may have reduced individuals' ability to cope with other natural or anthropogenic stressors. Thus, we suggest that ice conditions may have directly caused mortality or interacted with other stressors and thereby contributed to the Reduced

Recruitment. The contribution was notable especially for the 2018 spawn year, but the effect in other years was less discernable.

4.3. Key Uncertainties

Key uncertainties that limit confidence in the conclusions of this assessment are:

- The available water temperature data spanned only three years, and part of a fourth growing season in 2021, which was insufficient to determine whether the observed conditions were anomalous relative to historical conditions. This uncertainty was partially addressed through exploration of air temperature as a proxy measure.
- The addition of 2021 data from GRV-R4 indicated higher peak temperatures than those observed downstream in GRV-R3. These data suggested that data from GRV-R3 may not be representative of conditions over a broader spatial scale. This uncertainty is being addressed through collection of additional water temperature data in the Grave Creek watershed.
- Ice conditions were not directly observed, rather they were inferred from air temperature, SWE, water temperature, and stream discharge data. Likewise, there were no field observations of fish during the period of assumed ice effects.
- The recruitment scenario testing analyses were conceptual and should be interpreted with respect to the broad patterns predicted rather than interpreted as estimating a specific "true" recruitment to age-1 in a given location and year. The predictions rely on field and lab studies in high elevation Cutthroat Trout in Colorado (Coleman and Fausch 2007a, 2007b), and while the broad patterns (e.g., fry size as a function of GSDD) are likely to hold, the response relationships with GSDD have not been specifically determined for WCT in the Elk Valley. For example, observed fry sizes in the Grave Creek and Harmer Creek population areas were similar to but slightly larger than predicted by the Coleman and Fausch models.
- The recruitment scenario testing analyses related to overwinter survival have significant uncertainty given that the response relationships between factors like ice and temperature transitions during winter survival are not well understood. A key assumption of these models was size-dependent mortality (i.e., smaller individuals suffer greater overwinter mortality than larger individuals).

5. CONCLUSION

The evidence provided in this report supports conclusions that water temperature and ice conditions were not the sole cause of the WCT Reduced Recruitment in Harmer Creek but were likely to have been contributory. The available evidence indicates that conditions were broadly similar in both the Harmer and Grave population areas. Both population areas were perennially cold during the growing season and were likely affected similarly by ice each year. Nevertheless, there were some differences between Grave and Harmer creeks that were fairly small in absolute magnitude but are likely to have been biologically meaningful. The differences in water temperature regime indicate that recruitment was likely to have been more limiting in the Harmer Creek population area due to poor temperature conditions for emergence timing, growth, and survival of WCT fry, and therefore recruitment.

Cold water temperature may have interacted with other stressors to result in Reduced Recruitment. The growing season, as described by GSDD, was generally shorter and cooler in the Harmer Creek population area than in the Grave Creek population area, which is expected to result in later emerging fry that have less time to grow and therefore begin the overwintering period at a smaller size. Small fry size has been linked to poor overwinter survival in other interior Cutthroat Trout populations.

The Recruitment Failure observed in the cohort from the 2018 spawn year may have been related to anomalous ice conditions in winter 2019. Based on weather and hydrological records, ice conditions were inferred to have been a widespread and annual occurrence, but conditions are likely to have been especially severe in February 2019, when a high-magnitude transition occurred from warm to cold air temperature, followed by prolonged low daily average air temperatures through most of February and early March. Low SWE suggested that Harmer Creek would also have been more exposed to the atmosphere than normal, and low discharge at the time means the stream would have had less buffer against temperature changes. These changes in the physical setting may have caused rapid freezing and potentially higher WCT mortality, either due to physiological challenges from the rapid temperature shift or from physical effects such as rapid changes in habitat suitability. Ice conditions were likely similar in both population areas and therefore may have played a role in Reduced Recruitment in the Grave Creek population and Recruitment Failure in the Harmer Creek population. More normal ice conditions occurred in other years, suggesting that ice had stronger effects on the 2018 spawn year than on other cohorts.

REFERENCES

Alexiades, A.V., M.M. Peacock, R. Al-Chokhachy. 2012. Movement patterns, habitat use, and survival of Lahontan Cutthroat Trout in the Truckee River. North American Journal of Fisheries Management 32: 974-983.

Ashton, G. (editor). 1986. River and lake ice engineering. Water Resources Publications, Highlands Ranch, Colorado.

Baltz, D.M., B. Vondracek, L.R. Brown, and P.B. Moyle. 1991. Seasonal changes in microhabitat selection by rainbow trout in a small stream. Transactions of the American Fisheries Society 120: 166–176.

Bear, E.A., T.E. McMahon, and A.V. Zale, 2007. Comparative thermal requirements of Westslope cutthroat trout and rainbow trout: implications for species interactions and development of thermal protection standards. Transactions of the American Fisheries Society, 136: 1113-1121.

Brown, R.S. and W.C. Mackay. 1995. Fall and winter movements of and habitat use by cutthroat trout in the Ram River, Alberta. Transactions of the American Fisheries Society 124: 873-885.

Brown, R.S., S.S. Stanislawski, and W.C. Mackay. 1993. Effects of frazil ice on fish. Proceedings of the Workshop on Environmental Aspects of River (Editor), National Hydrology Research Institute. Saskatoon, SK. NHRI Symposium Series 12: 261-278.

Brown, R.S., G. Power, S. Beltaos, and T.A. Beddow. 2000. Effects of hanging ice dams on winter movements and swimming activity of fish. Journal of Fish Biology. 57: 1150-1159.

Brown, R.S., W.A. Hubert, and S.F. Daly. 2011. A primer on winter, ice, and fish: what fisheries biologists should know about winter ice processes and stream-dwelling fish. Fisheries 36:1, 8-26.

Cleator, H., J. Earle, L. Fitch, S. Humphries, M. Koops, K. Martin, D. Mayhood, S. Petry, C. Pacas, J. Stelfox, and D. Wig. 2009. Information relevant to a recovery potential assessment of pure native Westslope Cutthroat Trout, Alberta population. Canadian Science Advisory Secretariat: 1–26.

Coleman, M.A. and K.D. Fausch. 2007a. Cold summer temperature regimes cause a recruitment bottleneck in age-0 Colorado River cutthroat trout reared in laboratory streams. Transactions of the American Fisheries Society, 136: 639-654.

Coleman, M.A. and K.D. Fausch. 2007b. Cold summer temperature limits recruitment of age-0 cutthroat trout in high-elevation Colorado streams. Transactions of the American Fisheries Society, 136: 1231-1244.

Conly, F.M., and T.D. Prowse. 1995. Hydrologic response to freeze-up on large northern rivers (Case Study). Pages 23–42 Winter Environments of Regulated Rivers, Proceedings of the 8th Workshop on the Hydraulics of Ice Covered Rivers.

Cope, S. and A. Cope. 2020. Harmer and Grave Creek Westslope Cutthroat Trout Habitat and Population Assessment: Final Report. Report Prepared for Teck Coal Limited2, Sparwood, B.C. Report Prepared by Westslope Fisheries Ltd., Cranbrook, B.C. 121 p. + 2 app.

Cope, S., C.J. Schwarz, A. Prince, and J. Bisset. 2016. Upper Fording River Westslope Cutthroat Trout Population Assessment and Telemetry Project: Final Report. Report Prepared for Teck Coal Limited, Sparwood, BC. Report Prepared by Westslope Fisheries Ltd., Cranbrook, BC. 266 p.

Cunjak, R.A., and D. Caissie. 1994. Frazil ice accumulation in a large salmon pool in the Miramachi River, New Brunswick: ecological implications for overwintering fish. Pages 279-295 in Ford, J. E., and D. G. Lonzarich. 2000. Over-winter survival and habitat use by juvenile coho salmon (*Oncorhynchus kisutch*) in two Lake Superior tributaries. Journal of Great Lakes Research 26:94-101.

Cunjak, R.A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Canadian Journal of Fisheries and Aquatic Science 53: 267-282.

DFO (Fisheries and Oceans Canada). 2014. Recovery Strategy for the Alberta populations of Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) in Canada [Final]. Species at Risk Act Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa. iv + 28 pp + Appendices.

Drinan, D.P., A.V. Zale, M.A. Webb, M.L. Taper, B.B. Shepard, and S.T. Kalinowski. 2012. Evidence of local adaptation in westslope cutthroat trout. Transactions of the American Fisheries Society, 141:872-880.

Dugdale, S.J., I.A. Malcolm, K. Kantola, D.M. Hannah. 2018. Stream temperature under contrasting riparian forest cover: Understanding thermal dynamics and heat exchange processes. Science of The Total Environment, 610: 1375-1389.

Hamilton, A.S., and R.D. Moore. 1996. Winter streamflow variability in two groundwater-fed sub-Arctic rivers, Yukon Territory, Canada. Canadian Journal of Civil Engineering 1996: 1249–1259.

Harig, A.L. and K.D. Fausch. 2002. Minimum habitat requirements for establishing translocated cutthroat trout populations. Ecological Applications, 12:535-551.

Harmer Creek Evaluation of Cause Team. 2022. Evaluation of Cause – Reduced Recruitment in the Harmer Creek Westslope Cutthroat Trout Population. Report prepared for Teck Coal Limited.

Harper D.D., and A.M. Farag. 2004. Winter habitat use by cutthroat trout in the Snake River near Jackson, Wyoming. Transactions of the American Fisheries Society 133: 15–25.

Hatfield T. and C. Whelan. 2021. Subject Matter Expert Report: Ice. Evaluation of Cause – Decline in Upper Fording River Westslope Cutthroat Trout Population. Report prepared for Teck Coal Ltd. Report Prepared by Ecofish Research Ltd. March 15, 2021.

Heggenes, J., M. Stickler, K. Alfredsen, J.E. Brittain, A. Adeva-Bustos, and A. Huusko. 2021. Hydropower-driven thermal changes, biological responses and mitigating measures in northern river systems. River Research and Applications. 37:743–765.

Hiscock, M.J., D.A. Scruton, J.A. Brown, and K.D. Clarke. 2002. Winter movement of radio-tagged juvenile Atlantic Salmon in northeast Brook, Newfoundland. Transactions of the American Fisheries Society 131: 577-581.

Hoffsten, P.O. 2003. Effects of an extraordinarily harsh winter on macroinvertebrates and fish in boreal streams. Archiv fur Hydrobiologia 157: 505:523.

Hokanson, K.E., C.F. Kleiner, and T.W. Thorslund. 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth and mortality rates and yield of juvenile rainbow trout, *Salmo gairdneri*. Journal of the Fisheries Board of Canada, 34: 639-648.

Hubert, W.A. and W.A. Gern. 1995. Influence of embryonic stage on survival of cutthroat trout exposed to temperature reduction. The Progressive Fish-Culturist, 57: 326-328.

Huusko, A., L. Greenberg, M. Stickler, T. Linnansaari, M. Nykänen, T. Vehanen, S. Koljonen, P. Louhi, and K. Alfredsen. 2007. Life in the ice lane: the winter ecology of stream salmonids. River Research and Applications 23: 469-491.

Jakober, M.J., T.E. McMahon, and R.F. Thurow, and C.G. Clancy. 1998. Role of stream ice on fall and winter movements and habitat use by bull trout and cutthroat trout in Montana headwater streams. Transactions of the American Fisheries Society 127: 223-235.

Lindstrom, J.W. and W.A. Hubert. 2004. Ice processes affect habitat use and movements of adult cutthroat trout and brook trout in a Wyoming foothills stream. North American Journal of Fisheries Management 24: 1341-1352.

Little, P., N. Wright, and T. Hatfield. 2021. Subject Matter Expert Report: Streamflow and Habitat Availability. Evaluation of Cause – Recruitment Failure in the Harmer Creek Decline in Grave and Harmer Westslope Cutthroat Trout Population. Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd.

MacCrimmon, H.R. 1971. World Distribution of Rainbow Trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada. 28: 663-704.

Maciolek, J. A., and P. R. Needham. 1952. Ecological effects of winter conditions on trout and trout foods in Convict Creek, California, 1951. Transactions of the American Fisheries Society 81: 202-217.

Macnaughton, C.J., C. Kovachik, C. Charles, and E.C. Enders. 2018. Using the shuttlebox experimental design to determine temperature preference for juvenile Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*). Conservation Physiology. 6: 0-18.

Macnaughton, C.J., T.C. Durhack, N.J. Mochnacz, and E.C. Enders. 2021. Metabolic performance and thermal preference of westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) and non-native trout across an ecologically relevant range of temperatures. Canadian Journal of Fisheries and Aquatic Sciences, 78(9), 1247–1256. https://doi.org/10.1139/cjfas-2020-0173.

Mayhood, D.W. 2012. Cutthroat Trout Length Conversion Regressions. A Freshwater Research Limited Report, Fisheries and Oceans Canada and Alberta Sustainable Resource Development, Lethbridge, AB.

McCullough, D.A., 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. US Environmental Protection Agency, Region 10. pp. 1-291.

McMahon T.E., and G.F. Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences 46: 1551–1557.

Meeuwig, M.H., Dunham, J.B., Hayes, J.P. and Vinyard, G.L., 2004. Effects of constant and cyclical thermal regimes on growth and feeding of juvenile cutthroat trout of variable sizes. *Ecology of Freshwater Fish*, *13*(3), pp.208-216.

Mochnacz, N.J. 2021. Thermal ecology of bull trout (*Salvelinus confluentus*) and potential consequences of climate warming in montane watersheds. Ph.D. Thesis. University of Manitoba. pp. 1-222.

Moore, R. D., A. S. Hamilton, and J. Scibek. 2002. Winter streamflow variability, Yukon Territory, Canada. Hydrological Processes 16:763-778.

Morse, B., and F. Hicks. 2005. Advances in river ice hydrology 1999 – 2003. Hydrological Processes 263:247–263.

Myers, R. A. 1998. When do environment–recruitment correlations work?. Reviews in Fish Biology and Fisheries. 8: 285-305.

Needham, P.R. and A.C. Jones, 1959. Flow, temperature, solar radiation, and ice in relation to activities of fishes in Sagehen Creek, California. Ecology, 40: 465-474.

Oliver, G.G. and L.E. Fidler. 2001. Towards a water quality guideline for temperature in the Province of British Columbia. Prepared for Ministry of Environment, Lands and Parks, Water Management Branch, Water Quality Section, Victoria, B.C. Prepared by Aspen Applied Sciences Ltd., Cranbrook, B.C., 53 pp + appendices. Available online at: https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-quality. Accessed on July 30, 2021.

Prowse T.D. 1994. Environmental significance of ice to streamflow in cold regions. Freshwater Biology 32: 241–259.

Prowse, T.D. 2001. River-ice ecology I: Hydrologic, geomorphic and water quality aspects. Journal of Cold Regions Engineering 15:1–16.

Prowse, T.D., and T. Carter. 2002. Significance of ice-induced storage to spring runoff: A case study of the Mackenzie River. Hydrological Processes 16:779–788.

Prowse, T.D, B.R. Bonsal, C.R. Duguay, and M.P. Lacroix. 2007. River-ice break-up/freeze-up: A review of climatic drivers, historical trends and future predictions. Annals of Glaciology 46:443–451.

RISC (Resources Information Standards Committee). 2018. Manual of British Columbia Hydrometric Standards, Version 2.0, December 2018. Knowledge Management Branch, B.C. Ministry of Environment and Climate Change Strategy, Victoria, BC.

Simpkins, D.G., W.A. Hubert, and T.A. Wesche. 2000. Effects of fall-to-winter changes in habitat and frazil ice on the movements and habitat use of juvenile rainbow trout in a Wyoming tailwater. Transactions of the American Fisheries Society 129: 101–118.

Sloat, M.R., B.B. Shepard, R.G. White, and S. Carson. 2005. Influence of stream temperature on the spatial distribution of westslope cutthroat trout growth potential within the Madison River basin, Montana. North American Journal of Fisheries Management, 25: 225-237.

Stickler, M., and K. Alfredsen. 2009. Anchor ice formation in streams: a field study. Hydrological Processes 23:2307–2315.

Stickler, M., K.T. Alfredsen, T. Linnansaari, and H.P. Fjeldstad. 2010. The influence of dynamic ice formation on hydraulic heterogeneity in steep streams. River research and Applications, 26:1187-1197.

Tesaker, E. 1994. Ice formation in steep rivers. In Proceedings of the 12th International Ice Symposium, vol. 2. 630–638.

Thorley, J.L. 2022. Grave Westslope Cutthroat Trout Population 2021. A Poisson Consulting Analysis Appendix. URL: https://www.poissonconsulting.ca/f/839299341.

Thorley, J.L., Kortello, A.K., and M. Robinson. 2021. Grave and Harmer Creek Westslope Cutthroat Trout Population Monitoring 2020. A Poisson Consulting report prepared by Poisson Consulting, Grylloblatta and Lotic Environmental for Teck Coal Ltd., Sparwood, BC.

Thorley, J.L., Kortello, A.K., Brooks, J. & M. Robinson. 2022. Grave and Harmer Creek Westslope Cutthroat Trout Population Monitoring 2021. A Poisson Consulting, Grylloblatta and Lotic Environmental report prepared for Teck Coal Ltd., Sparwood, BC.

Todd, A.S., M.A. Coleman, A.M. Konowal, M.K. May, S. Johnson, N.K. Vieira, and J.F. Saunders. 2008. Development of new water temperature criteria to protect Colorado's fisheries. Fisheries, 33: 433-443.

Velsen, F.P.J. 1987. Temperature and Incubation in Pacific Salmon and Rainbow Trout: Compilation of Data on Median Hatching Time, Mortality and Embryonic Staging. Canadian Data Report of Fisheries and Aquatic Sciences. Pacific Biological Station, Nanaimo BC. 626: 1-67.

Whalen K.G., D.L. Parrish, and M.E. Mather. 1999. Effect of ice formation on selection of habitats and winter distribution of post-young-of-the-year Atlantic salmon parr. Canadian Journal of Fisheries and Aquatic Sciences 56: 87–96.

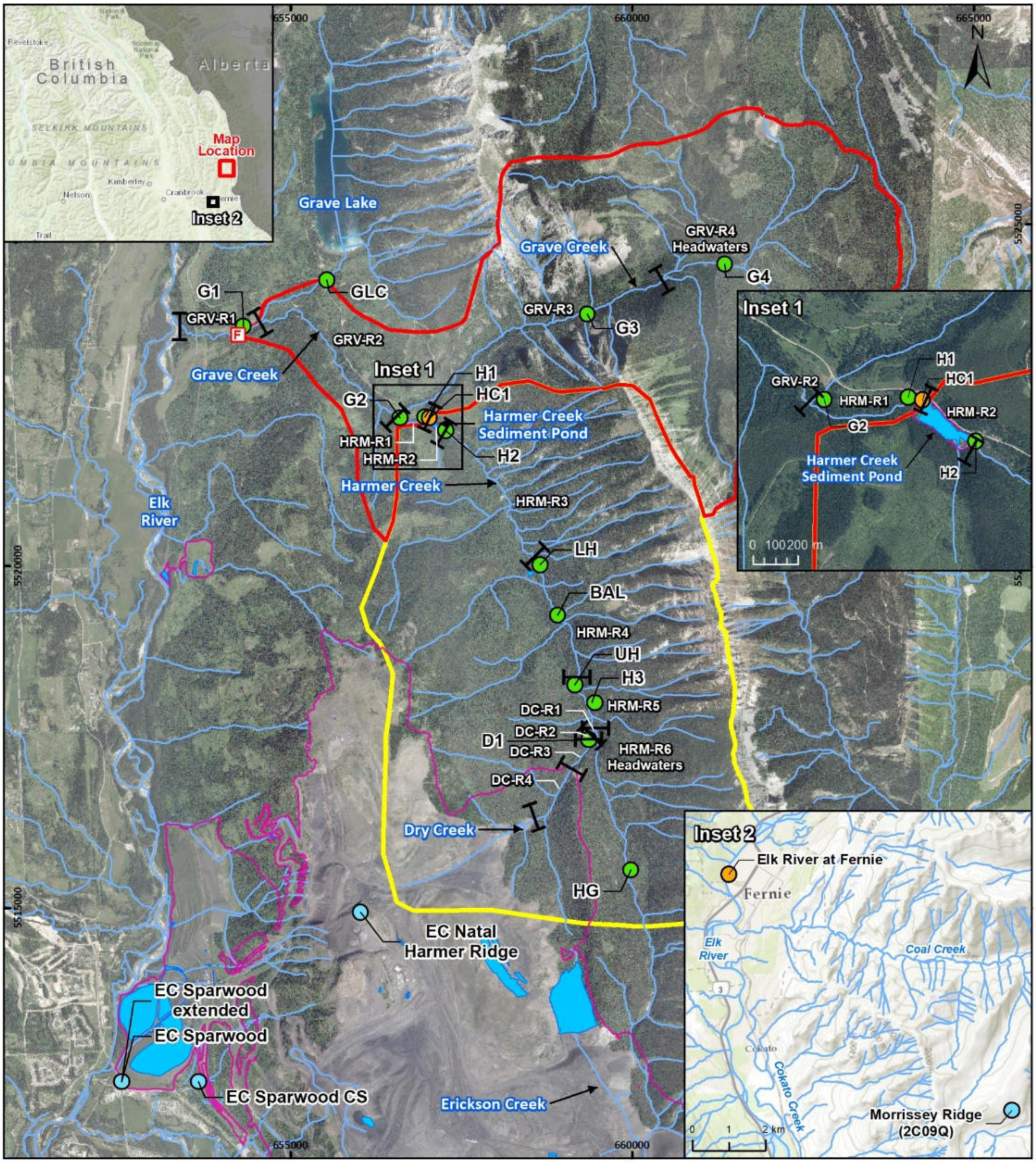
Whelan, C., S. Nicholl, C. Suzanne, K. Akaoka, D. Greenacre, K. Healey, J. Ammerlaan, N. Wright, S. Faulkner, A. Harwood, and T. Hatfield. 2021. Fording River Operational Environmental Monitoring Plan 2020 – Annual Report Year 3. Consultant's report prepared for Teck Coal Limited Fording River Operations by Ecofish Research Ltd. April 30, 2021.

Personal Communications

Thorley J. (Senior Computational Biologist, Poisson Consulting Ltd.). 2022. Microsoft Teams call to Todd Hatfield on April 12, 2022.

PROJECT MAPS

SME Report: Ice and Water Temperature. Overview Map



Legend

- Air Temperature Stations
- Water Temperature Stations
- Hydrometric Stations
- Falls
- Reach Break
- Streams
- Water Management Polygons

Permit Regions

- EVO

Population Area

- Grave Creek Population Area
- Harmer Creek Population Area

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 1 2 km

Scale: 1:80,000

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3			
4			
5			

Date Saved: 2022-03-21
Coordinate System: NAD 1983 UTM Zone 11N

ECOFISH RESEARCH

Map 1

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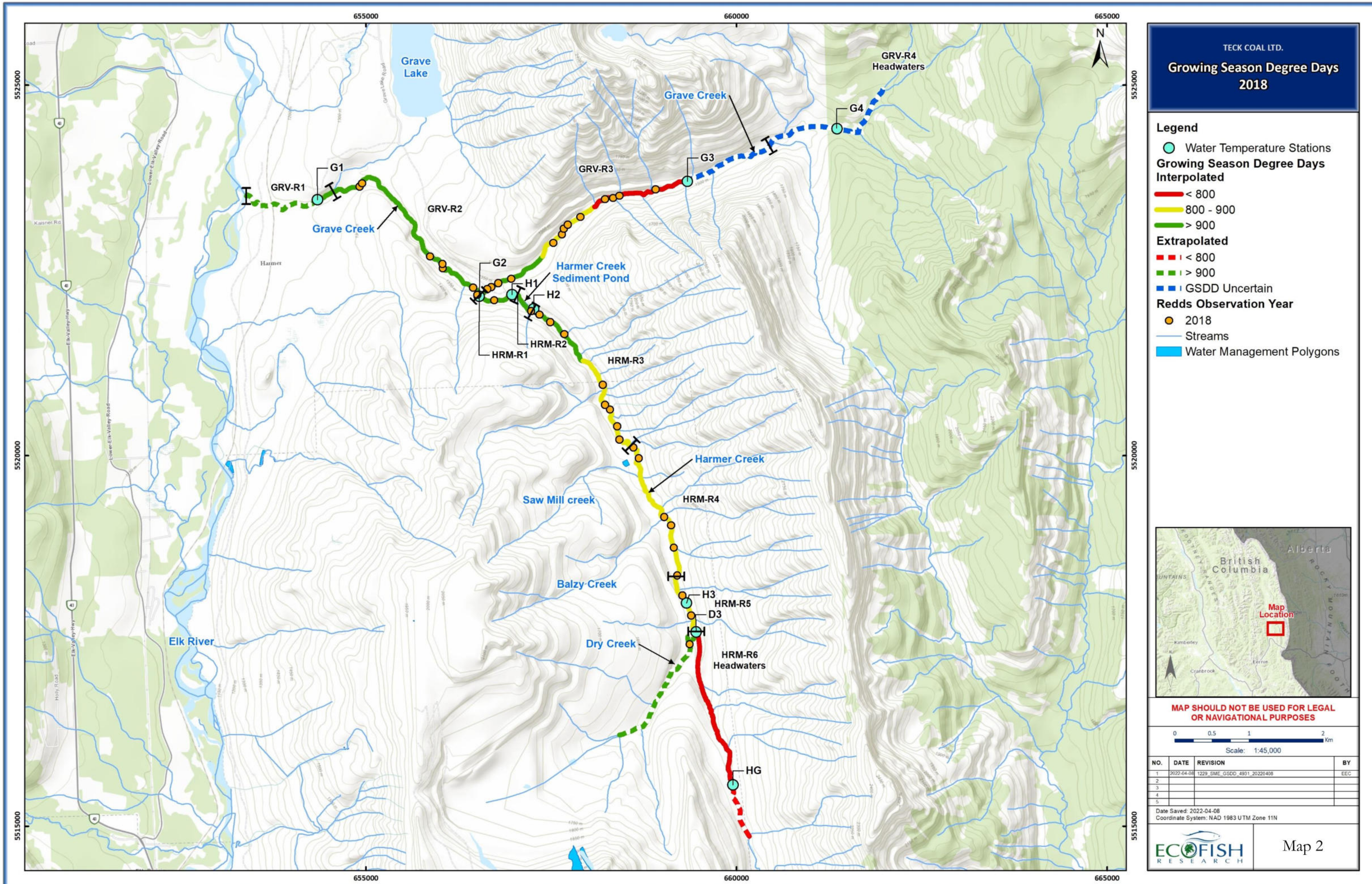

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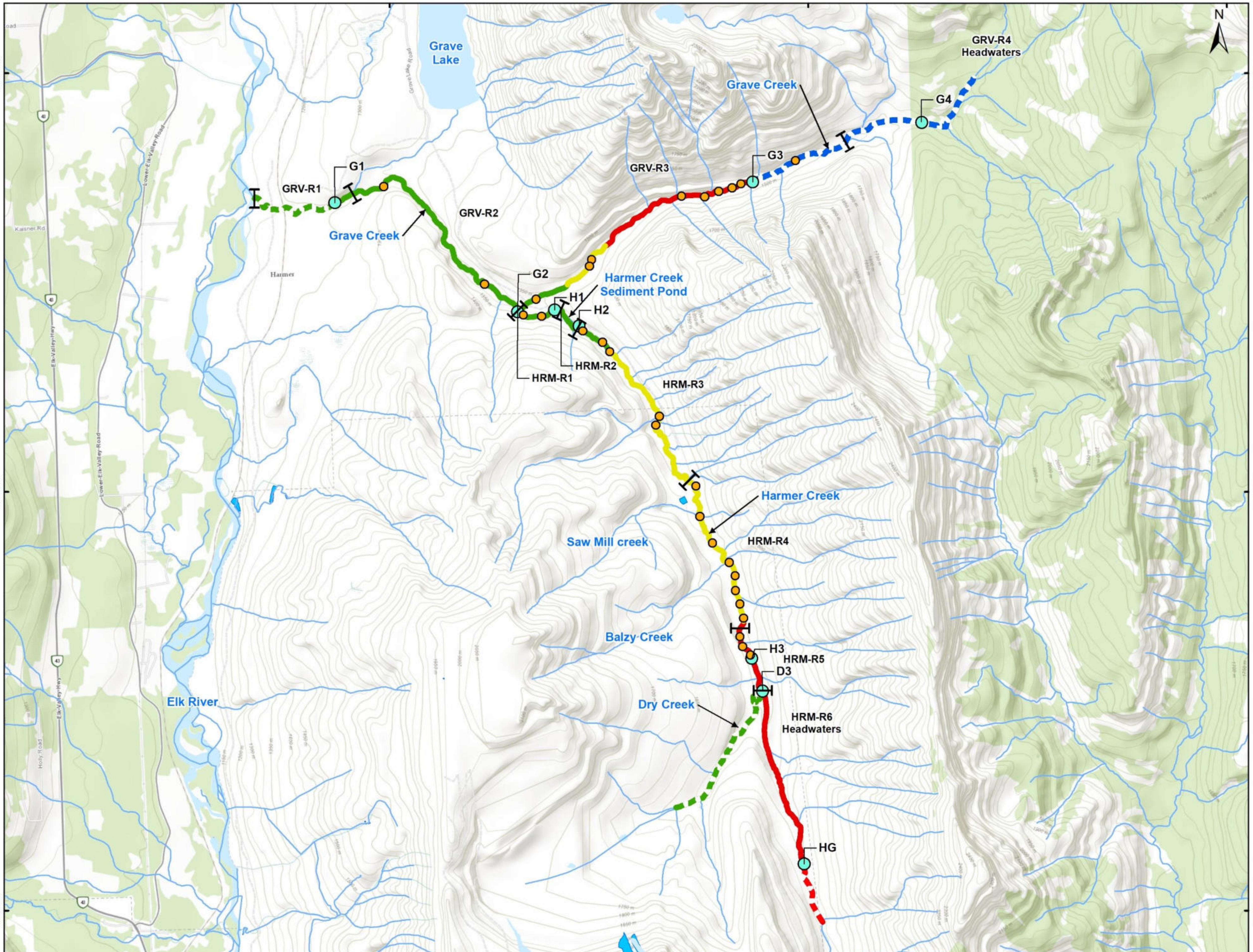

TECK COAL LTD.

Growing Season Degree Days 2019

Legend

- Water Temperature Stations

Growing Season Degree Days Interpolated

- < 800
- 800 - 900
- > 900

Extrapolated

- < 800
- > 900
- GSDD Uncertain

Redds Observation Year

- 2019
- Streams
- Water Management Polygons

MAP SHOULD NOT BE USED FOR LEGAL OR NAVIGATIONAL PURPOSES

0 0.5 1 2 Km

Scale: 1:45,000

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ECOFISH RESEARCH

Map 3

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1. INTRODUCTION

The objective of this appendix is to compile and review available information to characterize trends and anomalies in climatic factors in support of the Harmer Creek Evaluation of Cause. Climatic factors, including air temperature, precipitation, and snow depth are evaluated here to inform investigations presented in other reports that address stressors directly.

Air temperature, precipitation, and snowpack can directly and indirectly affect fish survival and productivity. Precipitation amounts and types (e.g., rain or snow), as well as the timing of precipitation events directly influence streamflow by changing water inputs, which, in turn, affect stream habitat for fish. Similarly, air temperature affects streamflow (e.g., warm temperatures and freeze-up conditions can both cause changes in flow), and air temperature will also affect water temperature, which affects the suitability of stream habitat and fish biological processes (e.g., spawning, incubation optimal temperature ranges). Climatic factors may, in extreme cases, directly cause mortality of fish, but in most cases play an influencing role, interacting with other potential WCT stressors.

2. METHODS

2.1. Trends and Anomalies

Trends and anomalies in the data were analysed by standard temporal periods (months, years) and water temperature was also examined separately for each WCT activity period (Table 1). In general, trends and anomalies were identified in the context of specific variables and their relevance to WCT activity periods by comparing data for recent years (2016-2019) to data for preceding years. Where possible, a station with a long-term record was used to corroborate trends found at stations with shorter data records. Specific methods and data sources are described in the following sections.

Table 1. Periodicity of Westslope Cutthroat Trout in the Harmer-Grave Creek watershed.

Life History Activity	Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Spawning																																																
Incubation (egg and alevin)[1]																																																
Rearing (>5ºC)[2]																																																
Over-wintering																																																

[1] Computed for two periods: 1) assuming early spawning (June 12 – August 15); and 2) assuming late spawning (July 11 – October 31).

2.2. Air Temperature

Air temperature data were obtained from six weather stations near the Harmer Creek watershed (Table 2, Map 1). Data for the Harmer Weather Study Plot and EV_MET1 stations were provided by Teck Coal. Data for the Environment Canada (EC) stations (Sparwood, Sparwood CS and Natal Harmer Ridge) were downloaded from Environment Canada using the weathercan package in R. Data for the Morrissey Ridge station, which is managed by B.C. Hydro, was downloaded from the Pacific Climate Impacts Consortium (PCIC) web portal.

Air temperature values at EC Sparwood CS were used to fill gaps in the data series at EC Sparwood, and this data series is referred to herein as EC Sparwood – extended. To fill gaps, air temperature values at EC Sparwood were regressed against Sparwood CS using a linear model. The resulting model parameters were then used to fill in the Sparwood data series. The original Sparwood data series covered 1980 to 2020 and was 95% complete; whereas the Sparwood CS covered 1992 to 2020 and was 97% complete. The gap-filled EC Sparwood extended dataset is 99.8% complete over a period of 41 years (1980-2020).

Air temperature data were reviewed to identify trends and anomalies relative to historical data. Analysis of air temperature data involved computing the following summary statistics for each station: mean, minimum, and maximum air temperatures for each month of the record, and number of days with mean daily temperature >18ºC and number of days with mean daily temperature <1°C and < -10ºC (representing thresholds for "warm", "cold", and "very cold" temperatures based on mean annual temperatures). The summary statistics were computed from daily averages.

Table 2. Location, elevation, period of record, data source, and data gaps for the weather stations near the Grave-Harmer watershed.

Type	Station	Data Source	UTM Coordinates		Elevation (masl)	Period of Record		Parameters						Years on Record	Total Days Missing	% Complete	Data Gaps
			Northing	Easting		Start	End	Air Temp.	Precip	Rain	Snow	Snow Depth	SWE				
Primary	EC Sparwood (1157630) - extended[1,2]	EC	5512461	652528	1,138	3/3/80	12/31/20	x	x	x	x	-	-	41	29	99.8	Oct. 13-27, 2020; Intermittent periods <7 days duration: 2008 (3); 2009 (1); 2020 (3)
	Morrissey Ridge (2C09Q)[3] snow pillow	BC Hydro	5479469	647374	1,860	9/30/03	12/31/20	x	-	-	-	-	x	16	192	96.9	Jun. 6 - Sep. 20, 2005; Aug 2-14, 2007; Nov. 14, 2012-Jan 11, 2013; May 7-14, 2019; 11 additional intermittent gaps of <5 days duration occurred between 2005-2019
	EV_MET1 at Brodie Rock	RWDI	5510423	656162	1,370	12/1/11	10/28/20	x	-	x	-	x	-	9	109	96.5	Dec 1, 2011; Jun. 13 - Oct 1, 2014; Oct. 28, 2020
Supporting	EC Sparwood (1157630)	EC	5512461	652528	1,138	3/3/80	2/22/20	x	x	x	x	-	-	38	694	95.0	May 1-31, 1995; Aug 1-31 1995; Nov 1- Dec 31, 1997; Feb 28, 2008 to Sep 27, 2009; every 1-4 days every few months since January 2010
	EC Natal Harmer Ridge (1155402)	EC	5514941	656023	1,890	7/28/71	12/30/91	x	x	x	x	-	-	16	778	88.2	Intermittent periods <7 days duration: 1971 (12 gaps); 1975 (1 gap); 1976 (8 periods); 1977 (1); period of 1-4 days every few months from 1980-1991. Longer duration gaps of 10-122 days each year in 1977, 1981-1984, and 1986-1991
	EC Sparwood CS (1157631)	EC	5512462	653650	1,137	11/1/92	12/31/20	x	x	x	x	x	-	26	347	96.5	July 1-31, 1993; Oct 61-17, 1996; Aug 1-Nov 19,1998; Feb 2-17, 2002; June 30-Jul.12, 2004; Aug 23-Nov 1, 2007; Oct 13-27, 2020. Intermittent periods <of 1-7 days 1993, 1994, 1996, 1998, 2001, 2002, 2004, 2006, 2007, 2009-2020.
	Harmer Weather Study	Teck	5531575	661592	1,535	5/17/13	12/31/20	x	x	x	x	x	-	7	21	99.2	Mar. 13-Apr. 25, 2016; Apr. 26 to May 3, 2017

[1] EC = Environment Canada; data obtained from Pacific Climate Information Consortium; https://data.pacificclimate.org/portal/pcds/map/

[2] Air temperature data gaps were interpolated based on strong correlations with air temperatures measured at Sparwood CS climate (R^2 = 0.993) station

[3] Snow pillow station. Data obtained from the BC River Forecast Centre; https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-data-tools/snow-survey-data/automated-snow-weather-station-data

[4] Data for Harmer Weather Study Plot are excluded from analysis due to uncertain data quality assurance

2.3. Precipitation

Precipitation data were obtained from five weather stations located near the Harmer Creek watershed (Table 2, Map 1). All data were reviewed for gaps: Sparwood precipitation data series covering the period from 1980 to 2020 and was 95% complete; whereas the Natal Harmer Ridge data series covered 1971-1991, and Sparwood CS covered 1992 to 2020 but excludes winter months. Data for Harmer Weather Study Plot cover from May 2013 to December 2020, while EV_MET1 data cover from 2012-2020. Only data from EC Sparwood were used in this summary years because data for other stations were either not recently available (Natal Harmer Ridge), had substantial data gaps (Sparwood CS), were affected by data quality concerns (Harmer Weather Study Plot), or included rainfall only (EV_MET1). Note that local undercatch[1] factors are unknown and were therefore not considered in this analysis.

Precipitation data for the Sparwood climate station were provided as daily values for total precipitation, rainfall, and snowfall. These precipitation data were reviewed to identify trends and anomalies that may have occurred over recent years (2011-2020) by computing total precipitation for each month on record, and corresponding total, minimum and maxim monthly precipitation for each year.

2.4. Snow Depth and Snow Water Equivalent

Snow depth data were obtained from the EC Sparwood, EV_MET1, and Harmer Weather Study Plot stations (Table 2, Map 1). Only snow depth data for EC Sparwood were used in this summary because data from other stations were affected by data gaps (EV_MET1) or had quality concerns (Harmer Weather Study Plot).

In addition to snow depth, snow water equivalent (SWE)[2] data were obtained from a snow pillow station at Morrissey Ridge, which is located outside of the Harmer Creek watershed but provides the nearest continuous dataset (Map 1). All data were provided as daily snow depth (cm) or water equivalent (mm).

Snow depth and water equivalent data were reviewed to identify trends and anomalies over recent years. Analysis of these data involved computing the average, minimum and maximum snow depth for each month of the record, along with the maximum SWE and timing when it occurred in each year (annual peak snowpack).

[1] "Undercatch" is the difference between the rainfall recorded by a rain gauge and the amount reaching the ground surface. Undercatch is often higher for rain gauges with rims above the ground surface and is affected by wind speed and vegetation cover.

[2] The amount of liquid water contained in the snowpack.

3. RESULTS

3.1. Air Temperature

3.1.1. Temperature Trends

Figure 1 presents air temperature as a seven-day running average at all stations over the past decade and presents average daily temperature with emphasis on recent years of interest (2016-2019) to compare to historical data. At EC Sparwood (the station with the longest record) the historical median of mean daily temperature peaks at the beginning of August at ~18ºC and reaches a low of nearly -10ºC at the beginning of January (Figure 2). This pattern is seen at the other gauges but with slightly lower temperatures at Morrissey ridge and more variability in temperature at EV_MET1 (likely a feature of a shorter dataset). Figure 3 shows average daily temperatures during the winter. The historical median of mean daily temperature is below 0ºC from November to March with slight differences at each gauge (Figure 3). A summary table of monthly averages is provided in Table 3 and a comparison of mean, minimum, and maximum air temperatures between the last decade (2011-2020) and the historical period (pre-2011) at each site is presented in Table 4.

Key anomalies in the air temperature records during the period of interest from 2016-2019 are summarized below.

- The coldest monthly average air temperature over the past decade occurred in February 2019 (Table 3). Wright *et al.* (2021)[3] reported that monthly average air temperature recorded at nearby EC Cominco station in February 2019 was a 1-in-50-year event.
- Monthly average air temperature in July 2017 was the warmest in the past decade at EV_MET1. This month was warmer than the 2011-2020 July average but was not record breaking at the other stations (Table 3).
- April 2016 was the warmest April in the past decade by several degrees (Table 3) and was record breaking on several days (Figure 2).
- At EV_MET1, the annual average temperature during 2019 was the coldest in the past decade. At Morrissey Ridge and EC Sparwood, this year was colder than average but not the coldest on record (Table 4).
- At EV_MET1 and Morrissey Ridge, the maximum daily temperature occurred in 2018 but at EC Sparwood, maximum daily temperature during this year was not unusually high (Table 4).
- 2016 was cooler than average at all three stations through every life history stage, and 2019 was cooler than average through most life history stages at most stations. During the 2019 late

[3] Wright, N., D. Greenacre, and T. Hatfield. 2021. Subject Matter Expert Report: Climate, Temperature, Streamflow, and Water Use Trends. Evaluation of Cause – Decline in Upper Fording River Westslope Cutthroat Trout Population. Report prepared for Teck Coal Limited. Prepared by Ecofish Research Ltd. 2021.

incubation and rearing periods, average temperatures were the coldest in the past decade at all three stations, while temperatures during 2019 spawning were the coldest on record at EV_MET1 only (Table 5).

- 2017 was warmer than average at all three stations during all life history stages except over-wintering. Temperatures during the 2017 rearing period were the warmest in the past decade at all three stations and temperatures during early incubation were the warmest in the past decade at EV_MET1 and EC Sparwood (and the second warmest on record at Morrissey Ridge) (Table 5).

Figure 1. Seven-day running average air temperature at EV_MET1, Environment Canada (EC) Sparwood, and at Morrisey Ridge (2C09Q) snow pillow. Vertical reference lines indicate the start of the calendar year.

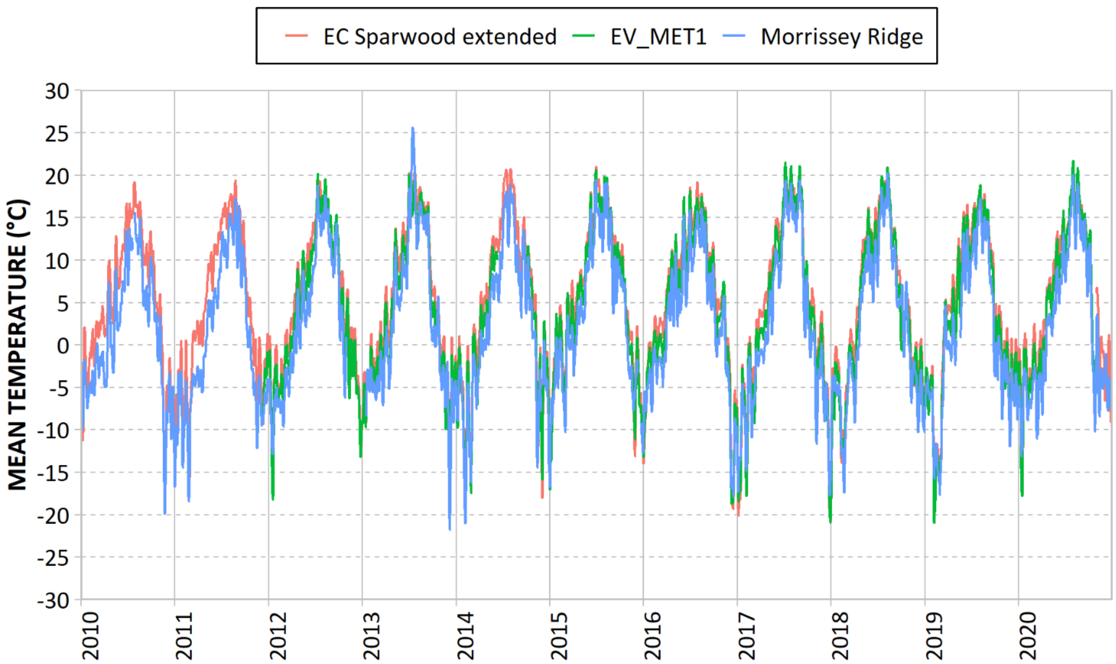

Figure 2. Average daily air temperature at a) EV_MET1, b) Morrissey Ridge, and c) EC Sparwood extended. Vertical lines indicate the start of each month.

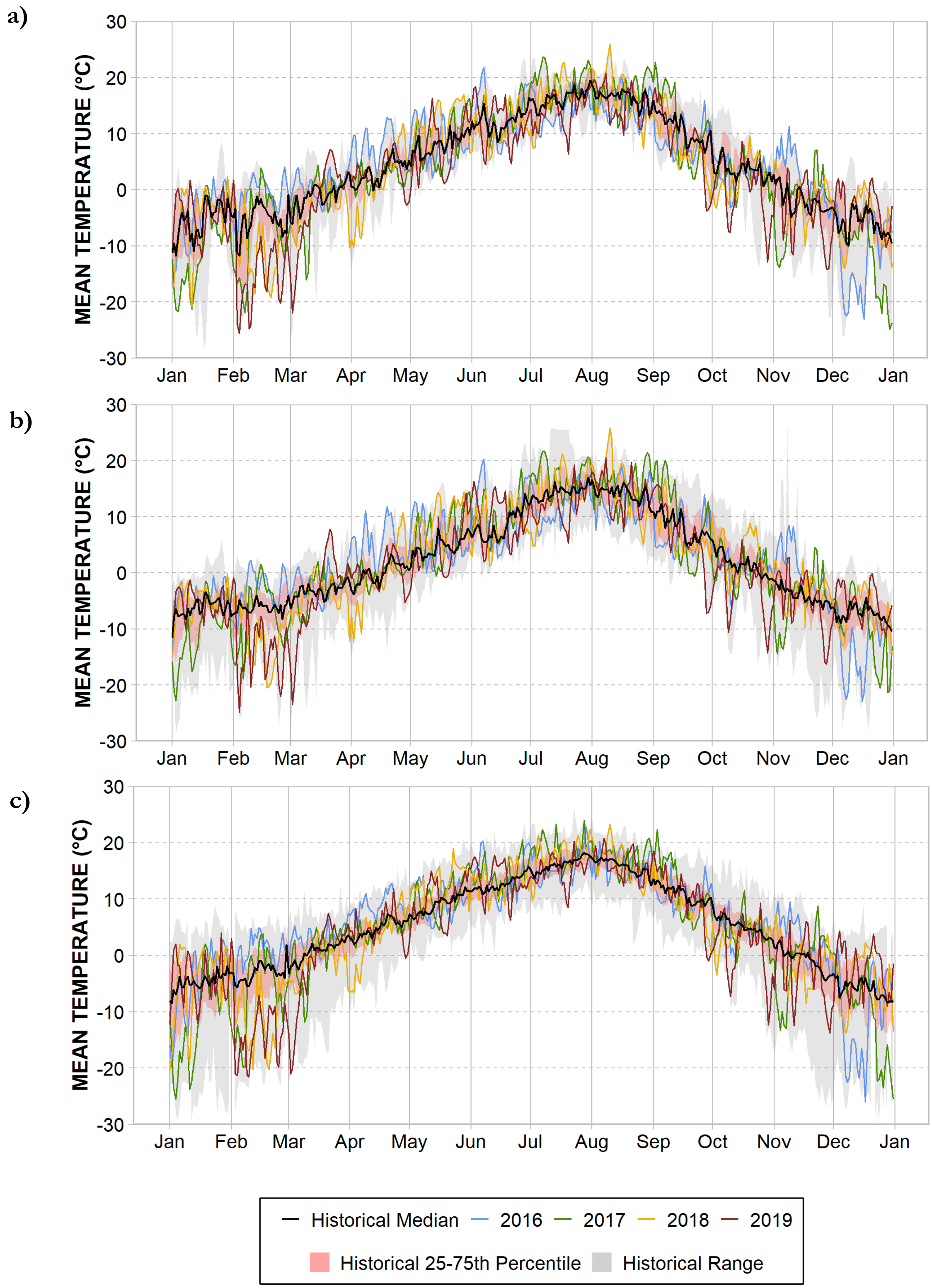

Figure 3. Average daily winter air temperature at a) EV_MET1, b) Morrissey ridge, and c) EC Sparwood. Vertical lines indicate the start of each month.

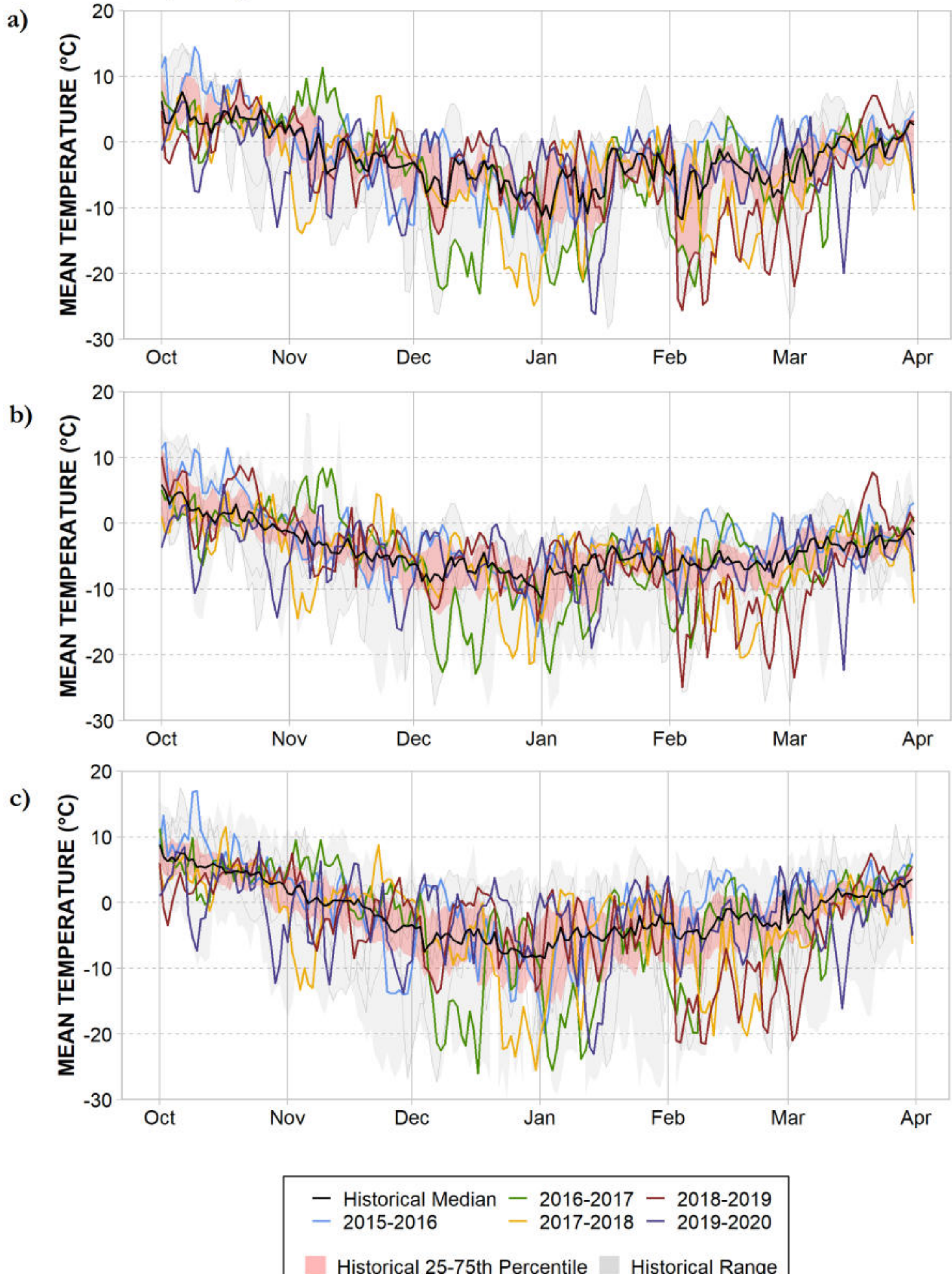

Table 3. Monthly average air temperature at EV_MET1, Morrisey Ridge (2C09Q) snow pillow, and at EC Sparwood.

Climate Station	Year	Air Temperature (°C)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EV_MET1	2011	-	-	-	-	-	-	-	-	-	-	-	-4.7
	2012	-6.8	-5.8	-1.3	3.8	7.0	10.1	16.7	16.4	12.7	2.4	-0.8	-6.8
	2013	-5.9	-3.1	-1.7	1.1	8.8	11.5	17.2	15.8	11.2	2.8	-4.0	-8.1
	2014	-5.6	-11.2	-3.8	2.7	7.3	-	-	-	-	7.2	-5.3	-5.5
	2015	-5.4	-1.7	2.0	3.8	8.2	14.9	16.2	16.1	9.3	6.9	-3.3	-6.0
	2016	-4.9	-0.9	0.6	7.3	8.5	12.8	14.4	15.1	9.3	3.1	2.0	-11.6
	2017	-10.8	-7.7	-1.8	2.2	8.8	12.8	**19.3**	17.4	11.5	3.0	-2.8	-11.1
	2018	-5.3	-10.8	-2.4	1.5	11.7	11.5	16.8	16.5	8.0	2.5	-2.2	-5.5
	2019	-4.8	**-15.0**	-2.6	2.9	7.5	11.9	14.2	15.6	9.4	-0.2	-3.8	-3.6
	2020	-5.8	-4.3	-3.6	1.4	7.2	11.2	15.6	17.6	12.8	2.4	0.0	0.0
	2011-2020	-6.2	-6.7	-1.6	3.0	8.3	12.1	16.3	16.3	10.5	3.3	-2.2	-6.5
Morrissey Ridge	2011	-8.6	-11.2	-4.4	-3.5	3.1	6.8	11.7	14.5	10.6	1.3	-6.4	-7.1
	2012	-7.6	-7.4	-3.8	1.0	3.9	6.9	14.5	14.5	10.9	0.5	0.0	0.0
	2013	0.0	-4.9	-3.6	-0.5	6.3	9.3	**19.4**	14.4	9.6	1.2	-4.2	-9.8
	2014	-6.2	-12.5	-4.7	0.1	4.9	8.1	16.0	13.8	8.4	5.0	-6.5	-6.0
	2015	-5.7	-3.5	-0.3	1.1	5.9	13.2	14.6	14.8	7.5	5.4	-4.4	-7.1
	2016	-5.4	-3.0	-1.9	4.9	5.9	10.3	12.1	13.3	7.0	1.1	0.0	-12.3
	2017	-10.6	-8.0	-3.0	-0.2	6.4	10.0	17.3	15.7	9.5	0.7	-4.8	-10.3
	2018	-5.4	-11.3	-4.0	-0.5	9.1	8.8	14.8	14.9	6.8	3.5	-3.2	-7.3
	2019	-5.7	**-13.6**	-4.2	0.1	4.6	9.6	12.4	14.0	7.0	-2.5	-4.8	-5.6
	2020	-6.4	-6.5	-5.3	-0.9	4.3	8.5	13.2	15.2	11.2	0.8	-3.5	-5.1
	2011-2020	-6.1	-8.2	-3.5	0.1	5.4	9.1	14.6	14.5	8.8	1.7	-3.8	-7.1
EC Sparwood - extended	2011	-6.4	-8.6	-0.6	1.8	8.1	12.2	15.4	16.8	13.0	5.0	-2.6	-4.2
	2012	-5.8	-5.0	0.4	5.8	8.6	12.1	17.8	16.4	12.1	4.2	0.7	-5.7
	2013	-5.5	-1.8	-0.1	3.6	10.5	13.1	18.0	17.1	12.6	4.4	-3.3	-7.1
	2014	-4.9	-10.2	-2.1	4.7	9.2	12.7	**18.8**	16.8	11.0	8.1	-4.4	-5.4
	2015	-4.8	-0.4	3.3	5.3	9.4	15.9	17.2	16.5	10.4	7.5	-2.5	-4.9
	2016	-4.8	0.4	3.0	8.8	9.8	13.6	16.1	16.1	10.8	4.9	2.7	-10.8
	2017	-11.0	-6.6	0.1	4.6	10.2	14.2	18.7	17.4	11.8	4.4	-1.3	-10.4
	2018	-4.2	-10.6	-1.1	3.3	12.8	13.1	17.6	16.3	9.7	3.6	-1.3	-4.6
	2019	-4.4	**-13.5**	-1.5	5.0	9.6	13.4	15.1	16.1	10.7	1.2	-2.8	-2.4
	2020	-4.8	-3.3	-1.8	3.0	8.9	12.8	15.6	17.1	13.1	0.0	0.1	-4.5
	2011-2020	-5.6	-6.0	0.0	4.6	9.7	13.3	17.0	16.7	11.5	4.3	-1.5	-6.0

Red shades show years that were warmer than median, while blue shades show years that were colder than median, for each month.
Minima and maxima for the entire period (2011 to 2020) are bolded for each monitoring station

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Table 4. Annual mean, minimum, and maximum air temperature for the historic (pre-2011) and recent periods (2011-2020), where data are available. Note, table continues over next two pages.

Station	Year	Air Temperature (°C)		
		Annual Average	Minimum Daily	Maximum Daily
EV_MET1[1]	2011	-	-	-
	2012	4.0	**-28.3**	21.3
	2013	3.8	-26.1	23.7
	2014	-	-26.9	-
	2015	5.1	**-19.4**	23.4
	2016	4.6	-23.1	21.7
	2017	3.5	-24.8	23.7
	2018	3.6	-21.0	**25.9**
	2019	**2.7**	-25.6	**20.8**
	2020	**5.5**	-26.2	23.4
	2012-2020	4.1	-24.6	23.0
Morrissey Ridge	2003	-	-	-
	2004	2.0	**-28.5**	20.4
	2005	-	-22.1	-
	2006	2.3	-24.3	22.8
	2007	1.4	-22.1	23.0
	2008	1.1	-28.0	22.1
	2009	0.9	-24.2	19.3
	2010	1.3	-26.1	20.0
	2011	**0.7**	-27.2	**19.1**
	2012	3.6	-17.5	25.7
	2013	3.0	-27.7	25.8
	2014	1.8	-27.5	21.0
	2015	**3.7**	**-17.2**	23.3
	2016	2.7	-22.9	20.3
	2017	2.0	-22.8	21.7
	2018	2.3	-20.4	**25.9**
	2019	0.9	-24.9	20.5
	2020	2.2	-22.3	22.2
	2002-2010	0.5	-28.5	13.6
	2011-2020	2.3	-27.7	19.1

Table 4. Continued (2 of 2).

Station	Year	Air Temperature (°C)		
		Annual Average	Minimum Daily	Maximum Daily
EC Sparwood extended[2]	1980	-	-26.3	21.0
	1981	4.8	-23.3	22.2
	1982	2.8	-24.0	19.8
	1983	4.4	-29.8	21.5
	1984	4.0	-24.8	22.9
	1985	2.9	-26.6	21.1
	1986	5.1	-23.0	20.9
	1987	5.7	-19.6	23.3
	1988	5.1	-22.8	20.4
	1989	4.0	-31.6	21.2
	1990	4.3	**-31.8**	21.0
	1991	4.3	-25.9	20.2
	1992	5.1	-28.3	21.2
	1993	3.4	-24.9	**18.1**
	1994	5.1	-22.7	22.1
	1995	4.3	-26.5	20.0
	1996	**2.5**	-28.1	20.4
	1997	4.6	-28.0	21.7
	1998	5.8	-30.1	22.5
	1999	5.2	-16.9	21.7
	2000	4.0	-23.1	21.8
	2001	5.0	-19.8	20.9
	2002	4.1	-19.0	23.0
	2003	5.1	-19.8	22.5
	2004	5.3	-29.2	22.0
	2005	4.5	-27.0	21.0
	2006	5.5	-23.4	**26.4**
	2007	5.2	-21.4	23.7
	2008	4.1	-27.1	22.9
	2009	3.6	-23.5	19.9
	2010	4.8	-25.8	21.3
	2011	4.2	-23.0	21.8
	2012	5.2	-25.0	22.0
	2013	5.2	-27.3	23.5
	2014	4.6	-26.8	22.0
	2015	**6.1**	**-16.8**	23.3
	2016	5.9	-26.0	22.8
	2017	4.4	-25.5	24.0
	2018	4.7	-20.5	23.3
	2019	4.0	-21.5	20.8
	2020	5.3	-23.0	24.5
	1971-2010	4.2	-31.8	18.1
	2011-2020	5.0	-27.3	20.8

[1] 2011 not reported due to incomplete year. Summer temperature extremes not reported due to data gap from June 11, 2014 to October 2, 2014.

[2] Data from intermittent data gaps since 1995 were interpolated based on strong correlations with air temperatures measured at Sparwood CS climate station. 1980 average temperature not reported due to incomplete year.

Red shades show years that are warmer than median, while blue shades show years colder than median

Bolded values denote overall minima and maxima at each station.

Table 5. Mean air temperature during WCT life history periods (2011-2020).

Station	Year	Spawning June 12 to July 11		Early Incubation June 12 to August 12		Late Incubation July 11 to October 31		Rearing May 28 to October 10		Over-wintering[1] October 11 to May 27	
		Mean Temperature (°C)	% Complete	Mean Temperature (°C)	% Complete	Mean Temperature (°C)	% Complete	Mean Temperature (°C)	% Complete	Mean Temperature (°C)	% Complete
EV_MET1	2011	-	0%	-	0%	-	0%	-	0%	0.00	77%
	2012	13.04	100%	15.19	100%	11.72	100%	13.08	100%	-1.02	100%
	2013	13.77	100%	14.96	100%	11.26	100%	13.08	100%	**-2.80**	100%
	2014	-	3%	-	2%	-	27%	-	18%	-0.06	100%
	2015	**15.92**	100%	16.24	100%	11.63	100%	13.73	100%	**0.63**	100%
	2016	12.30	100%	**13.61**	100%	10.21	100%	12.10	100%	-2.41	100%
	2017	15.76	100%	**17.01**	100%	12.11	100%	**14.46**	100%	-2.32	100%
	2018	12.62	100%	15.78	100%	10.74	100%	12.25	100%	-2.28	100%
	2019	**12.25**	100%	13.99	100%	**9.50**	100%	**11.92**	100%	-1.90	100%
	2020	12.40	100%	14.95	100%	**12.45**	96%	14.18	100%	-	8%
Morrissey Ridge	2011	**9.02**	100%	**10.88**	100%	9.30	100%	10.25	100%	-3.63	100%
	2012	10.34	100%	12.78	100%	9.78	100%	10.84	100%	**0.00**	71%
	2013	12.19	100%	**15.19**	100%	**10.75**	100%	12.13	100%	**-4.13**	100%
	2014	11.01	100%	13.82	100%	10.32	100%	11.16	100%	-1.67	100%
	2015	**14.44**	100%	14.67	100%	10.07	100%	12.15	100%	-0.94	98%
	2016	9.52	100%	11.14	100%	8.17	100%	9.90	100%	-3.76	100%
	2017	13.41	100%	14.96	100%	10.10	100%	**12.35**	100%	-3.55	100%
	2018	10.20	100%	13.77	100%	9.87	100%	10.81	100%	-3.91	97%
	2019	10.33	100%	12.14	100%	**7.38**	100%	**9.84**	100%	-3.73	100%
	2020	9.89	100%	12.52	100%	10.16	100%	11.96	100%	-	36%
EC Sparwood extended	2011	**13.44**	100%	**14.91**	100%	12.34	100%	13.63	100%	-0.07	100%
	2012	14.37	100%	16.28	100%	12.30	100%	13.84	100%	0.45	100%
	2013	15.13	100%	16.41	100%	12.56	100%	14.48	100%	**-1.50**	100%
	2014	15.21	100%	17.12	100%	13.25	100%	14.38	100%	0.96	100%
	2015	**17.18**	100%	17.09	100%	12.38	100%	14.68	100%	**1.75**	100%
	2016	13.58	100%	15.03	100%	11.71	100%	13.46	100%	-1.21	100%
	2017	16.08	100%	**17.23**	100%	12.54	100%	**14.78**	100%	-1.16	100%
	2018	14.34	100%	16.55	100%	11.44	100%	13.26	100%	-1.03	100%
	2019	13.89	100%	14.99	100%	**10.47**	100%	**13.01**	100%	-0.58	100%
	2020	13.64	93%	15.45	97%	**14.61**	87%	14.51	99%	-	29%
EV_MET1	2011-2020	13.51		15.22		11.20		13.10		-1.35	
Morrissey Ridge	2011-2020	11.26		13.44		9.62		11.24		-2.71	
EC Sparwood extended	2011-2020	14.82		16.24		12.36		14.04		-0.29	

Red shades show years that are warmer than median, while blue shades show years that are colder than median, for each life stage.

Bolded values are maxima and minima during period shown for each station, during each life stage.

[1] Overwintering period starts on October 11 of the stated year and goes to May 27 of the following year.

[2] Mean temperature reported only for years with greater than 50% complete record.

3.1.2. Extreme Daily Temperature Analysis

The number of days with extreme daily air temperatures are provided in Table 6 for EV_MET1, Morrissey Ridge, and EC Sparwood extended. Averages during the past decade (2011-2020) and during prior periods (if available) are included so that individual years can be compared.

- Over the past decade, days with average air temperature <10°C occurred most frequently in 2017 at all stations, whereas air temperatures <1°C occurred the most frequently in 2018 at EC Sparwood extended and EV_METI.
- Over the past decade, days with average air temperature >18°C occurred most frequently in 2017 at all stations. 2019 had very few days with temperature >18°C.

Table 6. Summary of the number of days with mean daily air temperatures >18°C <1°C, and <-10°C.

Station	Year	Record Length (days)[1]	Days T_{air} < -10°C	Days T_{air} < 1°C	Days T_{air} > 18°C
EV_MET1	2011	30	-	-	-
	2012	366	**19**	152	25
	2013	365	21	155	20
	2014	254	-	-	-
	2015	365	21	114	31
	2016	366	22	**112**	**15**
	2017	365	**48**	151	**43**
	2018	365	31	**160**	23
	2019	365	38	152	16
	2020	301	-	-	-
	Average	2012-2019	29	142	25
Morrissey Ridge	2003	93	-	-	-
	2004	366	16	173	8
	2005	272	-	-	-
	2006	360	29	182	19
	2007	352	41	182	18
	2008	361	36	190	10
	2009	365	43	**202**	5
	2010	363	19	187	**3**
	2011	365	39	201	4
	2012	311	-	-	-
	2013	354	18	174	22
	2014	364	41	175	13
	2015	360	**16**	**146**	20
	2016	366	21	157	5
	2017	365	**47**	195	**27**
	2018	365	27	178	18
	2019	357	39	196	4
	2020	366	22	187	14
	Average	2004-2010	31	186	11
		2011-2020	30	179	14

Table 6. Continued (2 of 2).

Station	Year	Record Length (days)[1]	Days T_{air} < -10°C	Days T_{air} < 1°C	Days T_{air} > 18°C
EC Sparwood extended[1]	1980	304	-	-	-
	1981	365	16	110	9
	1982	365	45	**146**	6
	1983	365	25	100	11
	1984	366	28	117	18
	1985	365	42	145	18
	1986	365	19	101	16
	1987	365	21	101	16
	1988	366	28	115	21
	1989	365	40	126	15
	1990	365	32	122	19
	1991	365	30	121	16
	1992	366	19	104	15
	1993	365	39	127	**1**
	1994	365	29	115	22
	1995	365	33	109	5
	1996	366	**56**	140	17
	1997	365	21	123	10
	1998	365	18	103	36
	1999	365	**7**	112	12
	2000	366	26	133	21
	2001	365	20	124	18
	2002	365	28	133	20
	2003	365	25	125	37
	2004	366	17	113	23
	2005	365	31	104	14
	2006	365	18	116	22
	2007	362	28	108	34
	2008	366	27	132	20
	2009	357	38	137	17
	2010	365	20	103	14
	2011	365	31	123	18
	2012	366	19	117	23
	2013	365	20	130	25
	2014	365	38	120	35
	2015	365	17	95	33
	2016	366	23	**89**	16
	2017	365	41	116	**40**
	2018	365	26	135	25
	2019	365	30	131	9
	2020	348	16	125	24
	Average	1981-2010	28	119	17
		2011-2020	26	118	25

[1]Intermittent data gaps since 1995 were interpolated based on strong correlations with air temperatures measured at the Sparwood CS climate station

Red shades show years that are warmer than median, while blue shades show years that are colder than med:

Bolded values denote overall maxima and minima at each station

Note that years with <330 days of data were excluded

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3.2. Precipitation

3.2.1. Total Precipitation

Of the three stations examined for this study, EC Sparwood has the most complete record of precipitation. Total monthly precipitation at this location is presented in Figure 4 and monthly and annual totals are provided in Table 7. Precipitation was variable across years, with annual precipitation ranging from 556 mm (2012) to 319 mm (2018) over the past decade (Table 7). Timing of maximum or minimum monthly precipitation is inconsistent across years, (i.e., the highest and lowest precipitation occurred in different months), although generally there is less recorded precipitation during winter and summer months than during fall or spring. On average August had the lowest average precipitation and November had the highest (Table 7). For historical context, cumulative precipitation during recent years is plotted relative to historical data (1980-2019) at the EC Sparwood station in Figure 5.

Key anomalies during the period of interest (2016-2019) are summarized below:

- Annual precipitation during 2015-2019 was lower than every year during 2011-2014.
- Monthly precipitation in 2016-2019 was more often lower than median (n=26 out of 48 months) than during 2011-2015 (n=21 out of 60 months).
- During 2017, precipitation was lower than average from May through September, with record low (over the past decade) monthly precipitation occurring in July, August, and September.
- Cumulative precipitation during 2018-2019 was lower than the 25th percentile from the beginning of December through October; 2016-2017 was higher than the 25th percentile from October to end of November and March to June (Figure 5).

Figure 4. Total monthly precipitation recorded at the EC Sparwood climate station (2011-2020).

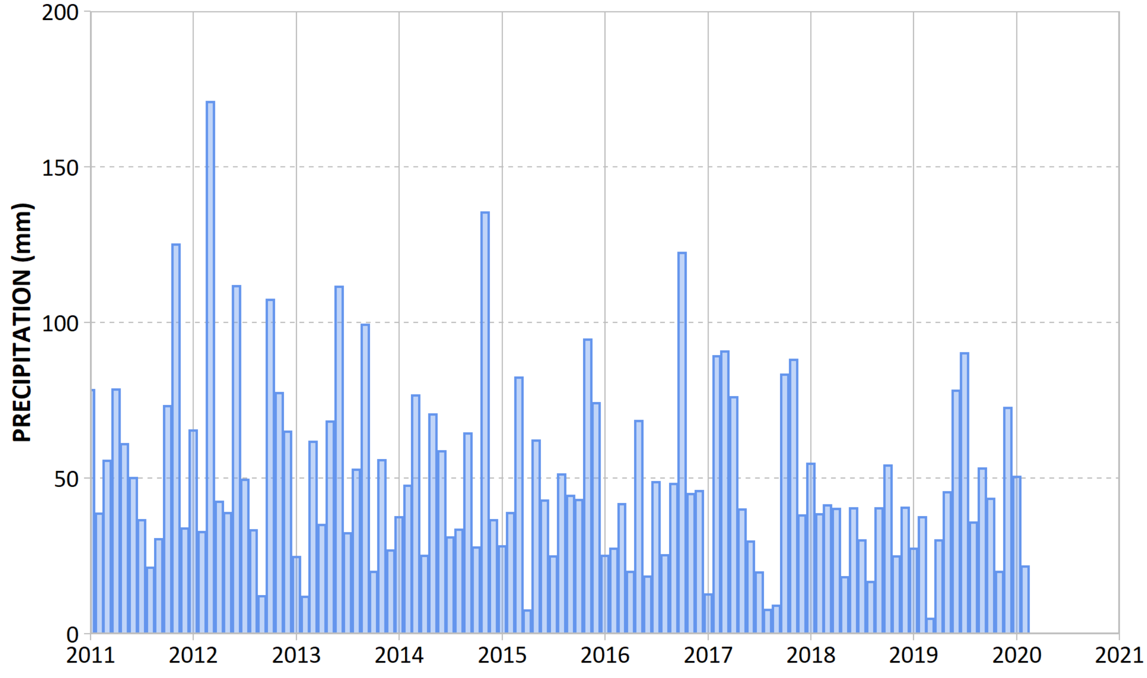


Table 7. Total monthly and annual precipitation at the EC Sparwood climate station (2011-2020).

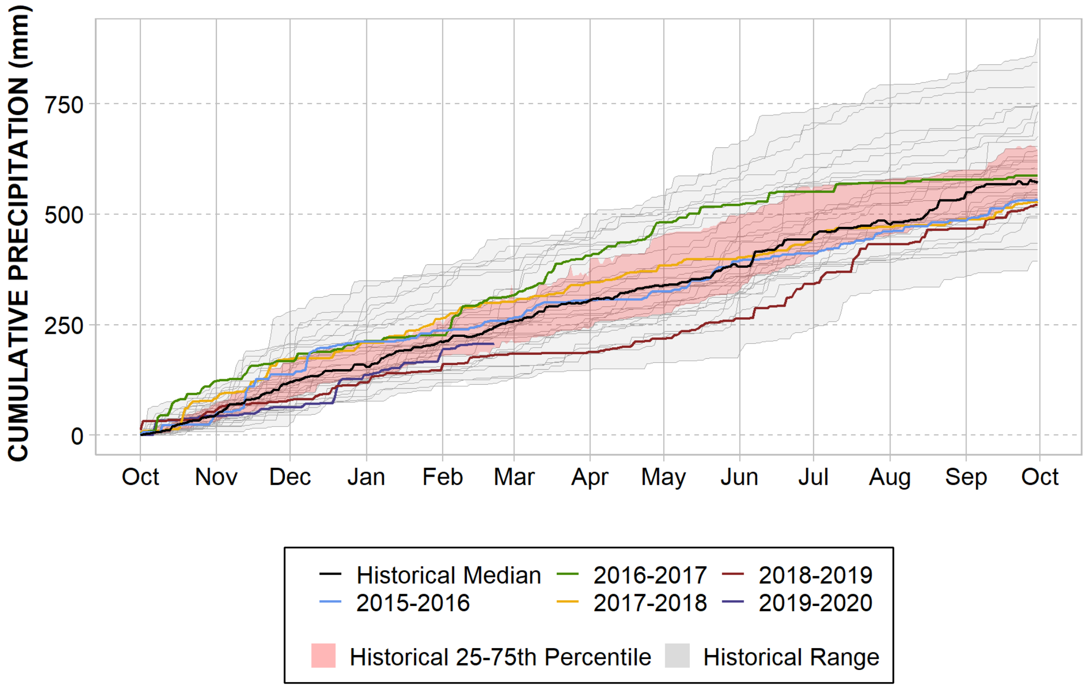
Year	Total Precipitation (mm)												Jan-Dec
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2011	**78.3**	38.5	55.5	**78.4**	60.8	49.9	36.4	21.2	30.4	73.1	125.1	33.8	449.4
2012	65.2	32.7	**170.8**	42.3	38.8	**111.6**	49.4	33.2	12.0	107.2	77.3	64.9	**556.0**
2013	24.7	**11.8**	61.6	35.0	68.2	111.4	32.3	**52.6**	**99.2**	**19.8**	55.8	**26.8**	496.8
2014	37.4	47.6	76.6	25.0	**70.4**	58.6	31.0	33.4	64.4	27.6	**135.3**	36.4	444.4
2015	28.0	38.8	82.2	**7.5**	62.0	42.8	24.8	51.2	44.2	43.0	94.4	**74.0**	381.5
2016	25.0	27.2	41.6	19.8	68.4	**18.4**	48.6	25.2	48.0	**122.4**	44.8	45.8	322.2
2017	**12.6**	**89.2**	90.6	76.0	39.8	29.6	**19.6**	**7.6**	**9.0**	83.2	88.0	38.0	374.0
2018	54.6	38.4	41.2	40.0	**18.2**	40.2	29.9	16.6	40.3	54.0	24.8	40.4	319.4
2019	27.2	37.4	**4.8**	30.0	45.4	78.0	**90.0**	35.6	53.0	43.4	**19.8**	72.6	401.4
2020	50.4	21.6	-	-	-	-	-	-	-	-	-	-	-
2011-2019	39.2	40.2	69.4	39.3	52.4	60.1	40.2	**30.7**	44.5	63.7	**73.9**	48.1	416.1

Notes:

Red shades show years that are lower than median, while blue shades show years that are higher than median, for each month.

Minima and maxima for each month are bolded

Figure 5. Cumulative precipitation recorded at the EC Sparwood climate station during recent years relative to historical (1980-2019) data.



3.2.2. Snowfall

Total monthly snowfall recorded at EC Sparwood is shown in Figure 6 and summarized in Table 8. For historical context, cumulative snowfall at the EC Sparwood station during recent years is plotted with historical data (1980-2019) in Figure 7.

- Total snowfall at EC Sparwood was unusually high in 2016-2017 and unusually low in 2015-2016 and 2018-2019 (Table 8).
- Cumulative snowfall during 2018-2019 was within a normal range but by March was below the 25th percentile.

Figure 6. Total monthly snowfall at EC Sparwood.

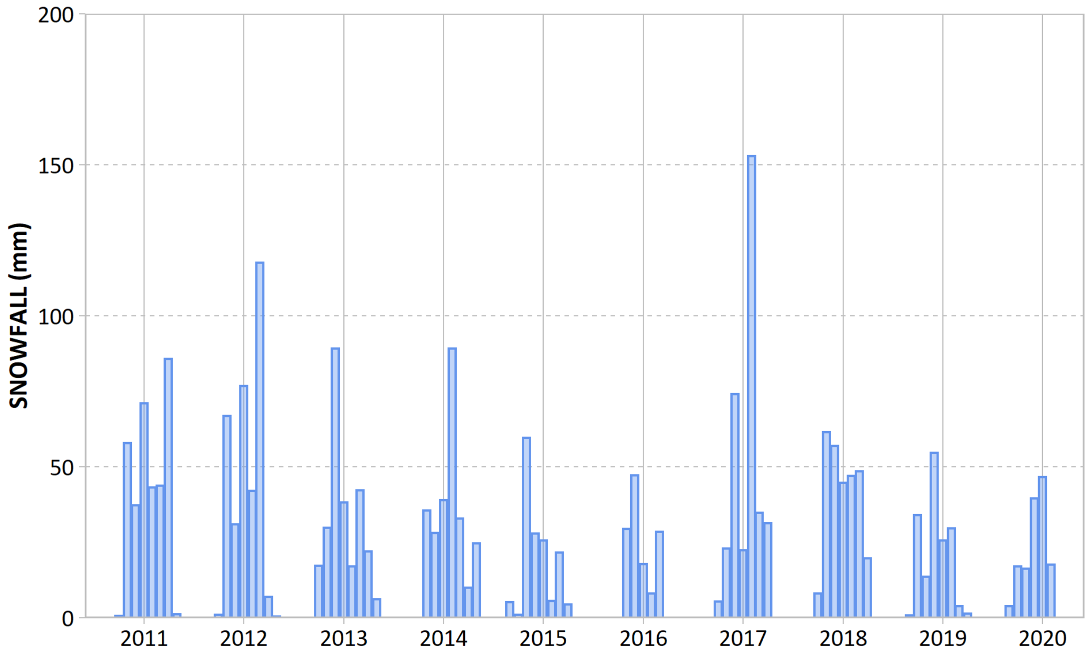


Table 8. Total monthly and winter (November to March) snowfall at EC Sparwood.

Year	Total Snowfall (mm H_2O)					Nov-Mar
	Nov	Dec	Jan	Feb	Mar	Total
2011-2012	66.8	30.9	76.8	41.9	117.5	**333.9**
2012-2013	29.8	89.1	38.1	17.0	42.1	216.1
2013-2014	35.4	28.0	39.0	89.1	32.9	224.4
2014-2015	59.6	27.9	25.6	5.6	21.6	140.3
2015-2016	29.4	47.2	17.8	8.0	28.4	130.8
2016-2017	22.8	74.0	22.4	**152.8**	34.8	306.8
2017-2018	61.4	56.8	44.6	47.0	48.4	258.2
2018-2019	13.6	54.6	25.6	29.6	**3.8**	**127.2**
2019-2020	16.2	39.4	46.6	17.6	-	-
2011-2019	37.2	49.8	37.4	45.4	41.2	211.0

Notes:

Red shades show years that are lower than median, while blue shades show years that are higher than median, for each month.

Minima and maxima for the entire period are bolded

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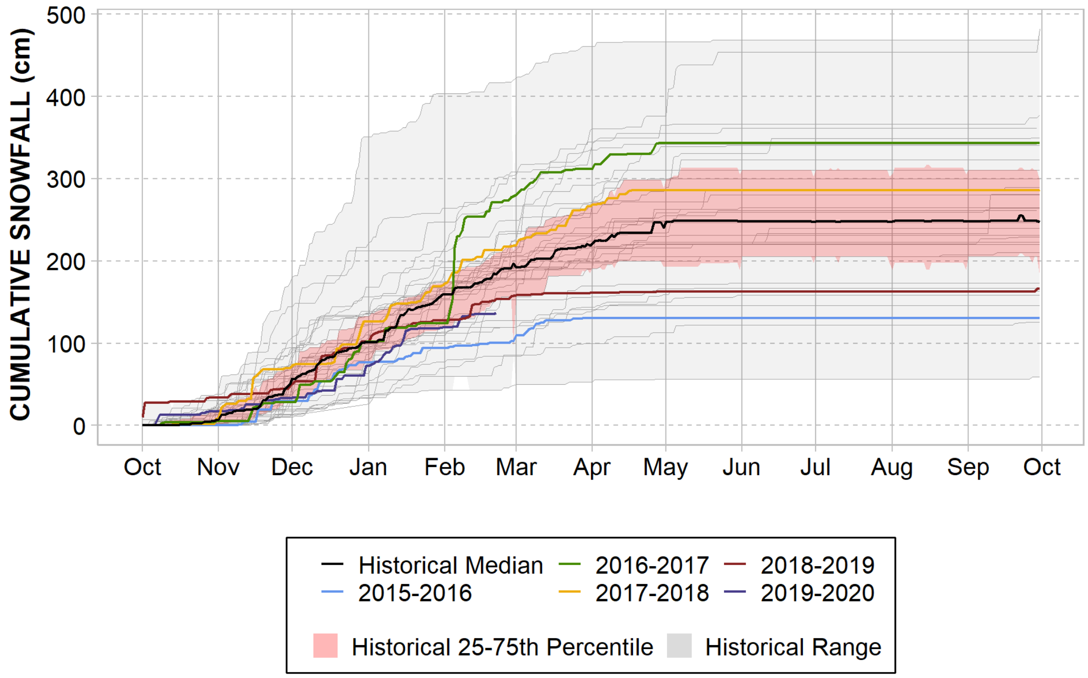
Figure 7. **Cumulative snowfall recorded at the EC Sparwood climate station during recent years relative to historical (1980-2019) data.**



3.3. Snowpack

Monthly snow depth at EC Sparwood is presented in Figure 8 and monthly and annual statistics are reported in Table 9. Maximum snow depth at EC Sparwood typically occurred in January or February (Table 9). Snow water equivalent (SWE) at Morrissey Ridge is presented in Figure 9. SWE at Morrissey Ridge typically peaked during late April or early May (Figure 9).

- Average snow depth at EC Sparwood during 2016-2017 was the deepest in the past decade and maximum snow depth over the past decade occurred in February of 2017 (Table 9).
- Snow depth at EC Sparwood was below average during most months of 2018-2019. Average and maximum snow depth was the 4th lowest within the past decade over that winter.
- SWE at Morrissey Ridge during 2018-2019 was the lowest on record from mid-February to April (Figure 9).
- SWE at Morrissey Ridge peaked earlier than most years in April 2016 and rapid melt resulted in record low SWE from mid-April to mid-May.

Figure 8. Mean monthly snow depth at EC Sparwood (2010/2011 to 2019/2020).

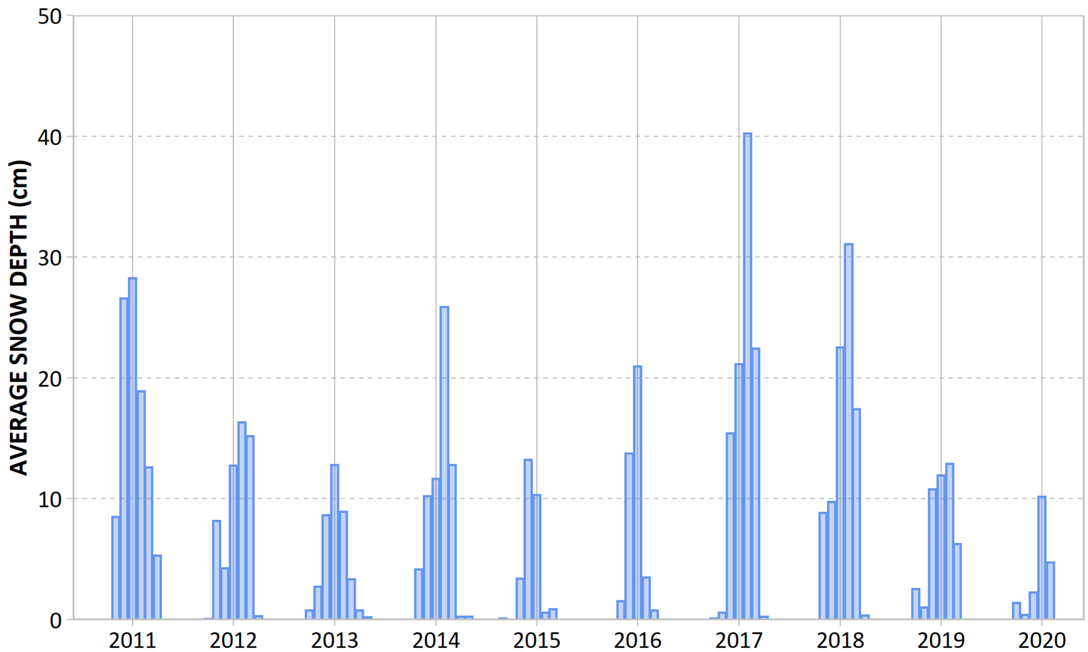


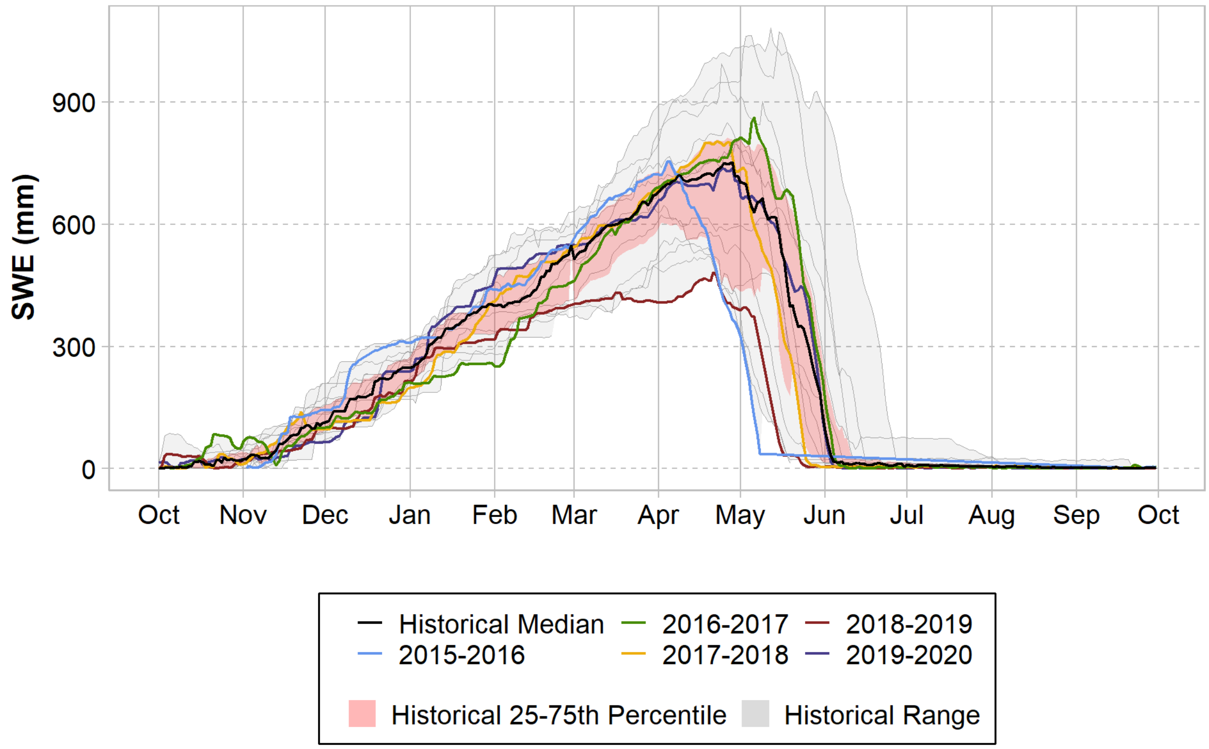
Table 9. Monthly snow depth statistics for EC Sparwood (2010/2011 to 2019/2020).

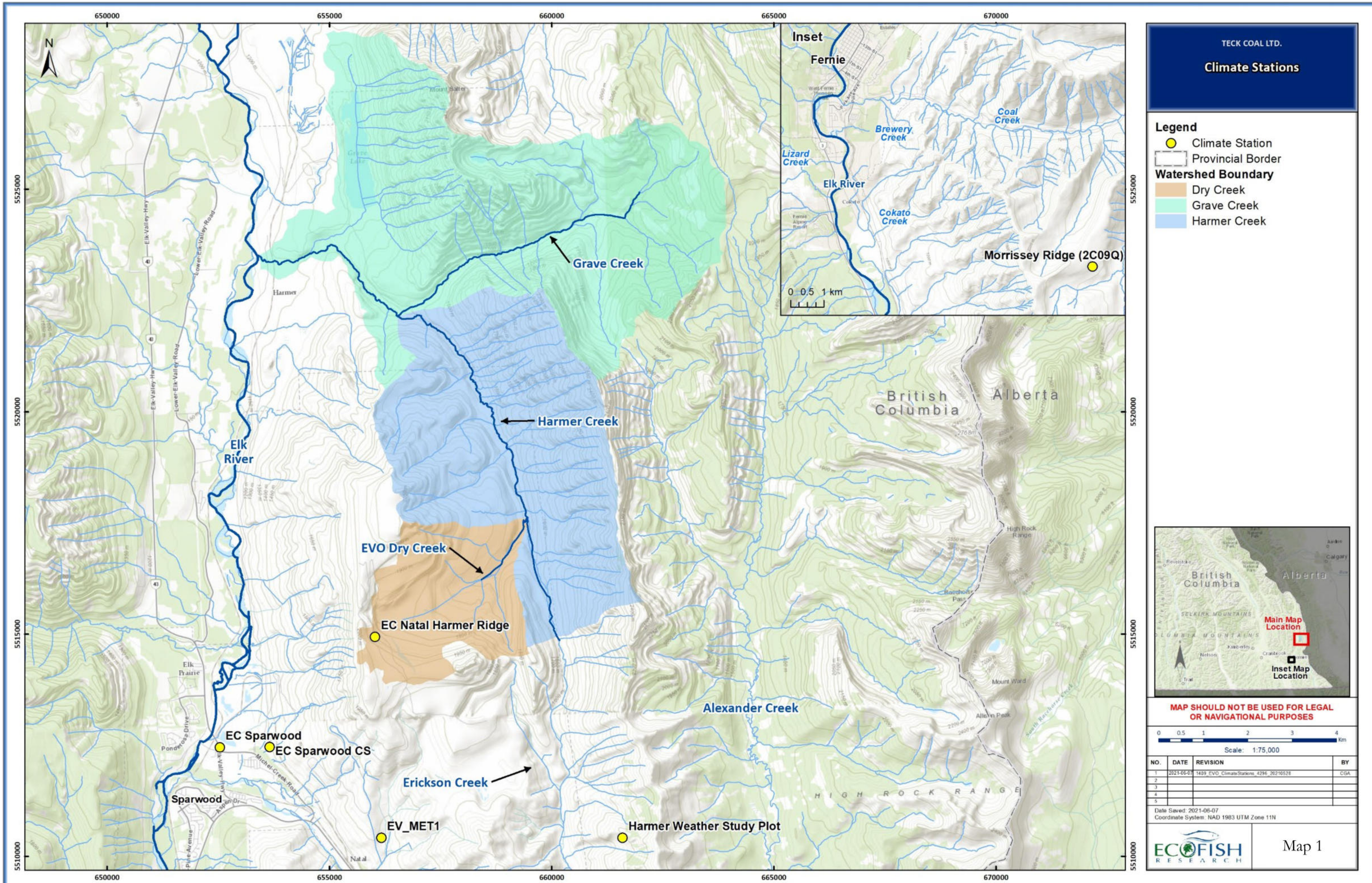
Year	Average Monthly Snow Depth (cm)					Nov-Mar Average	Annual Maximum
	Nov	Dec	Jan	Feb	Mar		
2010-2011	8.5	26.6	28.2	18.9	12.6	19.0	28.2
2011-2012	8.1	4.3	12.7	16.3	15.2	11.3	16.3
2012-2013	2.7	8.6	12.8	8.9	3.4	7.3	12.8
2013-2014	4.2	10.2	11.6	25.9	12.8	12.9	25.9
2014-2015	3.4	13.2	10.3	0.6	0.9	5.7	13.2
2015-2016	1.5	13.7	20.9	3.5	0.8	8.1	20.9
2016-2017	0.6	15.4	21.1	40.2	22.4	19.9	40.2
2017-2018	8.8	9.7	22.5	31.1	17.4	17.9	31.1
2018-2019	1.0	10.8	11.9	12.9	6.3	8.6	12.9
2019-2020	0.4	2.3	10.2	4.7	-	-	10.2
2010 - 2020	3.9	11.5	16.2	16.3	10.2	12.3	40.2

Notes:

Red shades show years that are lower than median, while blue shades show years that are higher than median, for each month.

Figure 9. Snow water equivalent (SWE) during recent years relative to the historical period of record (2003 to 2020) at Morrissey Ridge.





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