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Madison River Drainage 2188 Project Monitoring Report 2023

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Introduction

Montana Fish, Wildlife & Parks (FWP) monitors the fisheries in the Madison River Drainage to determine potential effects from operations at Hebgen and Madison dams. This work is funded through an agreement with NorthWestern Energy (NWE), the owner and operator of the dams. The agreement between FWP and NWE is designed to assist NWE in meeting the terms and conditions of the Federal Energy Regulatory Commission (FERC) license issued to NWE in 2000 to operate hydropower systems on the Madison and Missouri rivers (FERC 2000). This license includes Hebgen and Madison dams (Figure 1) and seven dams on the Missouri River collectively referred to by FERC as the 2188 Project. The 2188 license details requirements NWE must follow to operate the dam and hydropower facilities on the Madison and Missouri Rivers.

NWE entered a 10-year Memorandum of Understanding (MOU) with state and federal resource management agencies to provide annual funding to implement 2188 license requirements for the protection, mitigation, and enhancement (PM&E) of fisheries, recreation, and wildlife resources. The MOU established Technical Advisory Committees to collectively allocate annual funding to implement PM&E programs and the provisions of the 5-year fisheries and wildlife PM&E plans using adaptive principles. The Madison Fisheries Technical Advisory Committee (MadTAC) comprised of representatives from NWE, FWP, the U.S. Fish & Wildlife Service (USFWS), the U.S. Forest Service (USFS), and the U.S. Bureau of Land Management (BLM) is responsible for the allocation of funds to address fisheries issues related to operations of the Hebgen and Madison Dams under the 2188 license.

This report summarizes work completed by FWP in 2023 with funding provided by the MadTAC to address requirements of the 2188 license, specifically Articles 403, 408, 409, 412, and 419 that pertain to the Madison River fishery. Work included 1) fish abundance estimates in the Madison River, 2) assessment of fish populations in Hebgen and Ennis reservoirs, 3) evaluation of the effects of the 2021 Hebgen gate failure to upper Madison River fisheries 3) conservation and restoration of Arctic Grayling populations, 4) conservation and restoration of Westslope Cutthroat Trout populations, 5) evaluation of opportunities for the enhancement of mainstem and tributary habitats, and 6) evaluation of the effects of high-water on riparian regeneration and side-channel habitat.

Study Area

The Madison River originates in Yellowstone National Park at the confluence of the Gibbon and Firehole rivers and flows north for 180 miles through Southwest Montana to its confluence with the Missouri River near Three Forks. The Madison transitions from a narrow, forested river valley in the headwaters to a broad valley bounded by the Madison and Gravelly mountain ranges south of Ennis. North of Ennis the river flows through a steep canyon for 11 miles before it transitions into a broad alluvial valley bottom where it joins the Jefferson and Gallatin rivers, forming the Missouri River (Figure 1).

Two dams impound the Madison River; Hebgen Dam forms Hebgen Reservoir and the Madison Dam forms Ennis Reservoir (Figure 1). Hebgen Reservoir is operated as a water storage facility to control inflow to the downstream Madison Dam, which is a power generating facility. Madison and Hebgen dam operations are coordinated to provide year-round flows at or above required minimum instream flows and below required maximum rates of flow change while also mitigating thermal issues in the Madison River below Madison Dam by delivering pulsed flows (Figure 1).

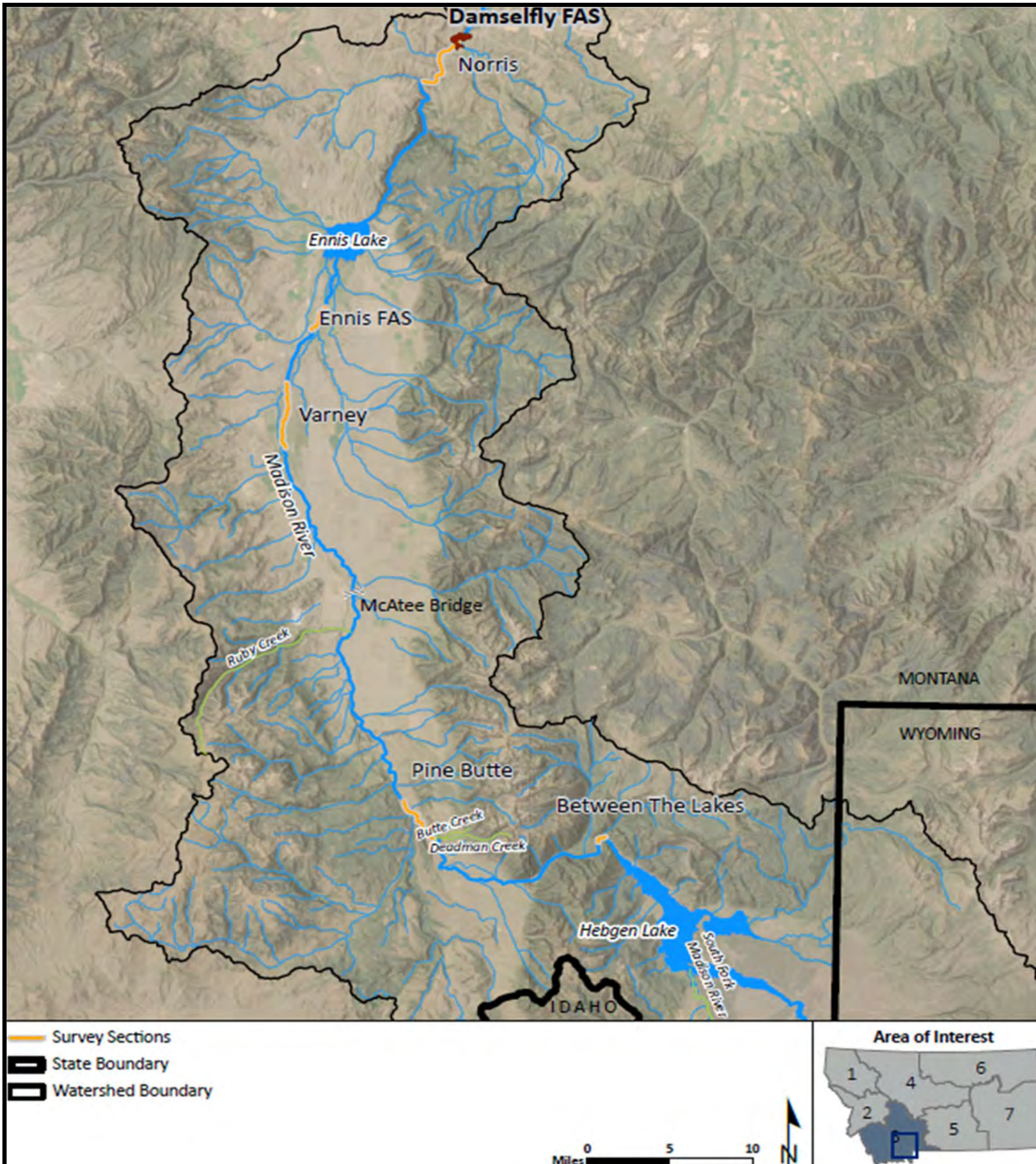

Figure 1. Locations of NWE dams on the Madison River (FERC Project 2188), FWP annual abundance estimate sections, Ennis and Hebgen Lakes, and project areas discussed in this report.

Monitoring and Projects

Article 403-River Discharge:

Article 403 of the 2188 Project FERC license specifies operational conditions, including minimum and maximum instream flows in various sections of the Madison River. NWE must maintain a minimum flow of at least 150 cfs in the Madison River below Hebgen Dam (gage no. 6-385) and limit the change in the outflow from Hebgen to no more than 10% per day. Additionally, a minimum flow of 600 cfs at Kirby Ranch (USGS gage no. 6-388) and 1100 cfs at USGS gage no. 6-410 below the Madison Dam must be maintained. Flows at Kirby Ranch are limited to a maximum of 3500 cfs under normal conditions to minimize erosion of the Quake Lake outlet. These License requirements necessitated the establishment of the permanent flow gage at Kirby Ranch. FWP and NWE monitor river flow to avoid deviations from operational conditions.

Deviations from Article 403 occurred below Hebgen Dam and at Kirby Ranch on November 30, 2021. The deviations resulted from a broken component on the Hebgen Dam gate which resulted in a 43% change in Madison River discharge between Hebgen and Quake lakes and reduced flows at Kirby Ranch to 395 cfs for approximately 48 hours. To assess the potential impacts of the Hebgen Dam gate failure on the Madison River fishery, a monitoring plan developed by MadTAC and the preparation of a literature review to evaluate the potential effects of low flows were approved by FERC on August 18, 2022. Monitoring completed by FWP and NWE in 2023 is summarized in Appendix A.

Article 408-1) Effects of Project Operations on Hebgen Reservoir Fish Populations:

FWP monitors the Hebgen Reservoir fish assemblage with annual spring gill netting surveys to assess the effects of project operations (Figure 1). Significant changes in the fish assemblage would warrant a review of project operations to address identified issues.

The mean catch-per-unit-effort (CPUE) of total trout in Hebgen Reservoir appears to remain stable or is slightly increasing. Standardized gill netting shows an increase in CPUE from 20 trout/net in 2022 to 23 trout/net in 2023 and remains above the long-term average of 19 trout (Figure 2). The CPUE of Brown Trout increased from 14.8 trout/net in 2022 to 17.3 trout/net in 2023, exceeding the management goal of 15.5 Brown Trout/net. Rainbow Trout CPUE increased from 5.2 trout/net in 2022 to 6 trout/net in 2023 which remains below the management goal of 7.5 Rainbow Trout/net. The mean length of Brown Trout decreased from 459 mm in 2022 to 456 mm in 2023, remaining above than long-term average (Figure 3). The mean length of Rainbow Trout decreased from 433 mm in 2022 to 404 mm in 2023, which is slightly above the long-term average of 403 mm (Figure 3). Ninety percent of the Brown Trout captured in gill nets were ≥ 406 mm, and 61 % of the Rainbow Trout captured were ≥ 406 mm.

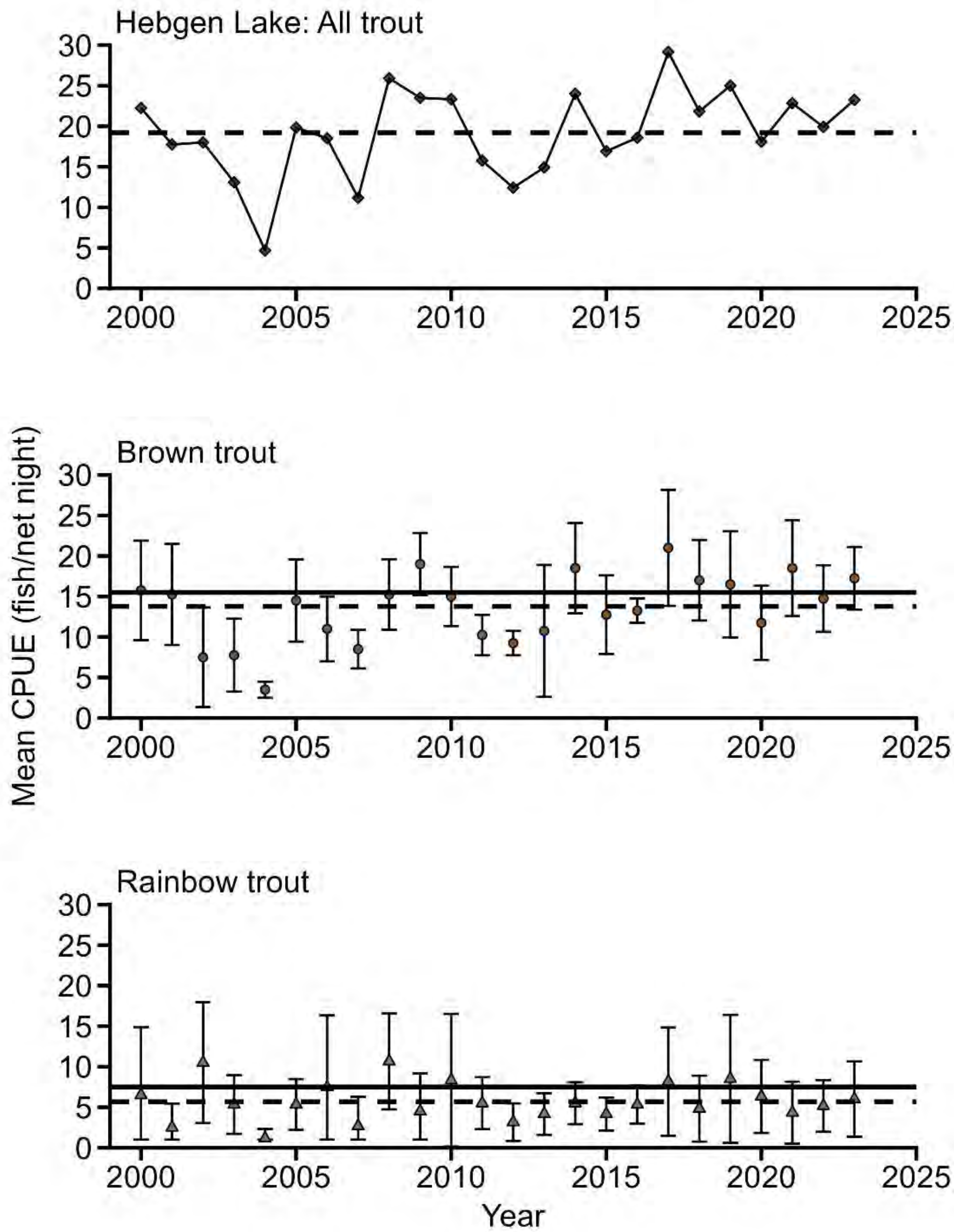

Figure 2. Mean catch-per-unit-effort (CPUE) of all trout combined (black diamonds), Brown (brown circles) and Rainbow Trout (green triangles) captured in Hebgen Reservoir from 2000 to 2023. Catch-per-unit-effort was calculated using catches from both floating and sinking nets. Brown Trout CPUE was calculated from sinking gill nets, and Rainbow Trout CPUE was calculated from floating gill nets to account for behavioral differences of each species. Solid lines represent management goals, dashed lines represent the long-term average CPUE from 2000 to 2023, and error bars represent standard deviations for each year.

Article 412–1) Effects of Project Operations on Ennis Reservoir Fish Populations:

FWP historically monitored the Ennis Reservoir fish assemblage with biannual fall gill netting surveys on odd years. New gill net locations were established in 2021 to provide better coverage of the reservoir while eliminating gill net sets in shallow habitats that had poor capture efficiencies. The third year of consecutive sampling occurred in 2023, and FWP is currently analyzing data to establish management goals for the Brown and Rainbow Trout fisheries. Although FWP will assess long-term trends using data collected with the new sampling approach, much uncertainty will exist with such comparisons until additional data using the new gill net sets are available. Considering that, the mean catch-per-unit-effort (CPUE) of total trout, Brown Trout, and Rainbow Trout were near the long-term averages (Figure 3). The mean total length of Brown Trout increased from 402 to 430 mm, exceeding the long-term average of 399 mm. The mean total length of Rainbow Trout increased from 356 to 390 mm, also exceeding the long-term average of 375 mm (Figure 4).

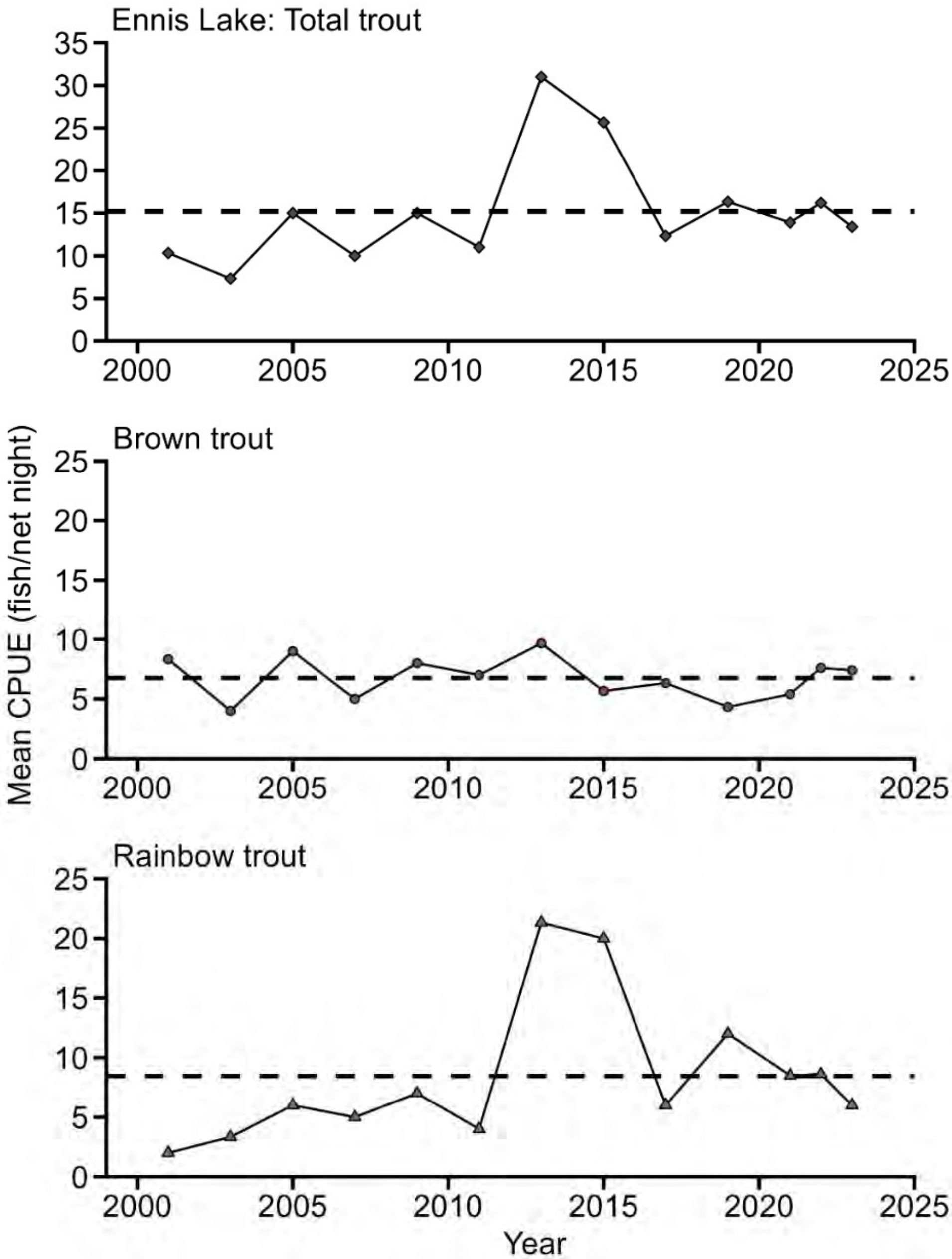

Figure 3. Mean catch-per-unit-effort (CPUE) of total (black diamonds), Brown (brown circles) and Rainbow Trout (green triangles) captured in gill nets set in Ennis Reservoir from 2001 to 2023. Brown and Rainbow Trout mean CPUE and were calculated using all nets set from each year.

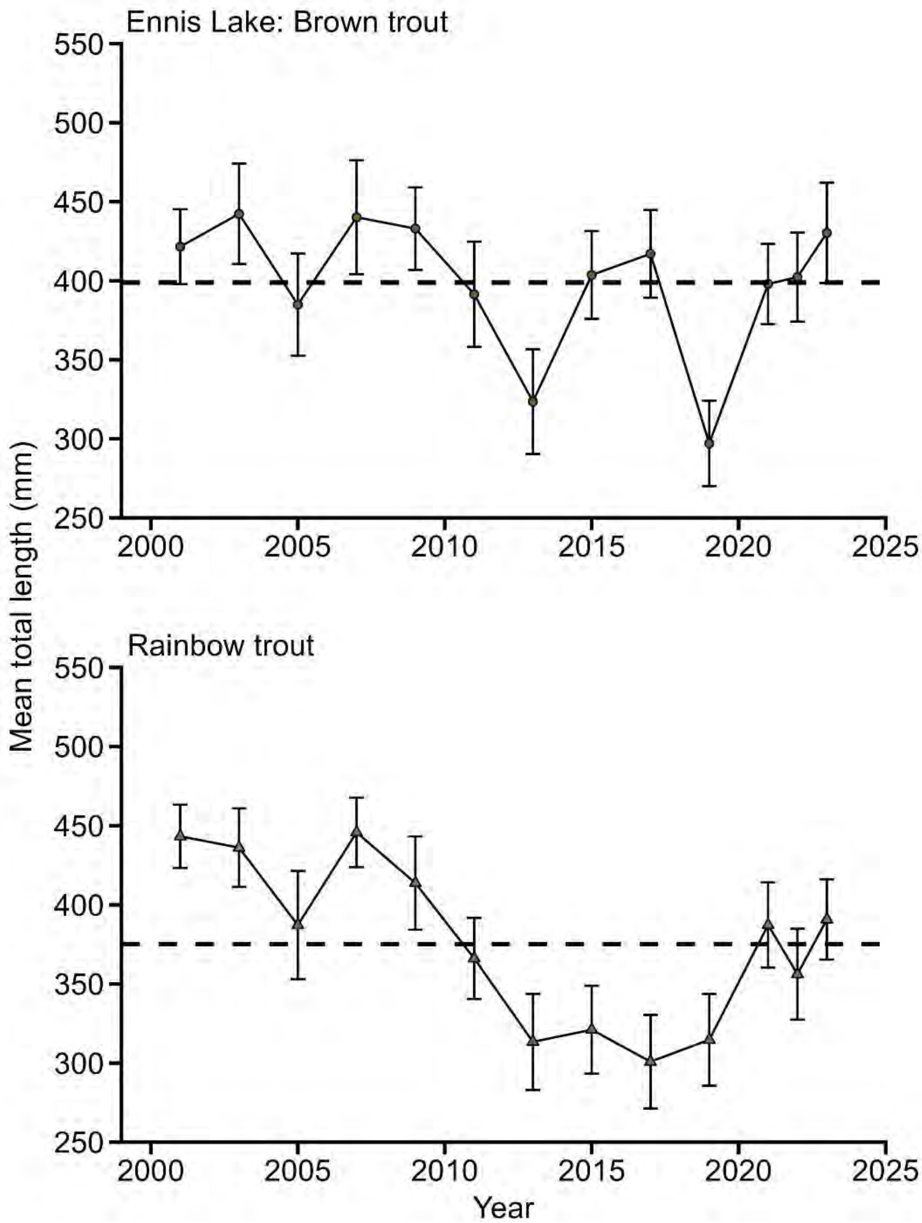

Figure 4. Mean total lengths (mm) of Brown (brown circles) and Rainbow Trout (green triangles) in Ennis Lake from 1999 to 2023. Dashed black lines represent the long-term average total lengths of each species and vertical bars represent the 95% confidence intervals for mean lengths each year.

408-3) Reservoir Draw Down Effects on Fish:

The interactions between Hebgen Reservoir elevation and operations, trophic status, and the trout populations had been assessed annually by FWP from 2006-2020. Sampling occurred in June, July, and August, because these months correspond with the emigration of juvenile trout from natal tributaries to Hebgen Reservoir and their recruitment to the fishery, may be influenced by reservoir conditions at the time of emigration (Watschke 2006, Clancey and Lohrenz 2007, Clancey and Lohrenz 2008, Clancey and Lohrenz 2009). Reservoir elevation may influence juvenile trout growth and recruitment by altering the amount of shoreline habitat and zooplankton abundances. Fluctuating reservoir elevations can impoverish the plankton assemblage through the loss of nutrients, which could limit forage for juvenile trout until they can switch to macroinvertebrates or piscivory (Axelson 1961, Haddix and Budy 2005). Hebgen Reservoir has a full pool elevation of 6534.87 feet (msl) and license article 403 requires NWE to maintain reservoir elevations between 6530.26 feet and 6534.87 feet from June 20 through October 1 and reach full pool elevation by late June or early July. Given the narrow operational range and similarity in reservoir conditions among years, limnological sampling was moved to a biannual schedule in 2020 or when reservoir elevations are outside of normal operational ranges.

FWP did not conduct limnological sampling on Hebgen reservoir in 2023. However, limnological sampling is scheduled for 2024 per FWP'S recommendation to continue limnological sampling every other year and in years when departures from normal operations occur.

408-4) Monitor the Effects of Modified Project Operations on Upper Madison River Fish Populations-Madison River Fisheries Assessment:

FWP monitors Rainbow and Brown Trout abundances in three long-term monitoring sections of the Madison River (Figure 1) to evaluate the influence of modified project operations at Hebgen and Madison dams on the trout fisheries. This report is limited to a discussion of potential influences of project operations; however, other potential population drivers (e.g., angling pressure, disease) are hypothesized to be influential and thus are evaluated independently by FWP. Crews conducted mark-recapture surveys to estimate trout abundance. Trout were collected by electrofishing from a drift-boat mounted, mobile anode system. Fish captured in the initial sampling event (marking run) were weighed (g) and measured to total length (mm), marked with a fin clip, and released. Crews conducted a second sampling event (recapture run) about a week later. Trout captured on the recapture run were measured, weighed, and examined for an existing fin clip. Length-specific, log-likelihood closed population abundance estimates were generated and standardized to stream mile for Brown and Rainbow Trout using an R-based, proprietary FWP fisheries database and analysis tool.

FWP developed management goals for combined species, trout abundances (trout ≥ 252 mm [≈ 10"]), and size structure (percentages of trout ≥ 252 mm that are also ≥ 402 mm (≈ [16"]) for each of the long-term sampling sections using the approximate 66th percentiles of data collected over the past 20 years (Table 1). Abundance goals are 2300 trout per mile in the Pine Butte section, 1200 in the Varney section, and 2500 in the Norris section. The proportional size structure goals for each section are 25% for Pine Butte, 35% for Varney, and 15% for Norris (Table 1). Evaluating PM&E (Protection, Mitigation, and Enhancement) activities and management actions (e.g., flushing flows) in the context of these goals provides a better understanding of how they influence the Madison River trout fishery relative to other potential population drivers.

Abundance management goals were not met for any section in 2023. Abundances of trout per mile ≥ 252 mm increased slightly in Varney, were stable in Norris, and decreased in Pine Butte (Figure 5). Pine Butte was the only section where the size-structure goal was achieved (Figure 6); 30% of stock-length (≥252 mm) trout were ≥ 406 mm.

The estimated abundance of Rainbow Trout ≥ 152 mm ([≈6.0"]) in Pine Butte decreased from 2,937 trout/mile in 2022 to 1340 trout/mile in 2023 (Figure 7). Smaller age classes were less represented in 2023, indicated by the reduced frequency of Rainbow Trout ≤ 252 in our catch (Figure 8). These abundance estimates indicate near historic, 20-year lows for Rainbow Trout ≥ 152 mm in Pine Butte. The abundance of Brown Trout ≥ 152 mm in Pine Butte increased from 1159 trout/mile in 2022 to 1257 trout/mile in 2023 but remained near the historic 20-year lows. However, high frequencies of trout ≥ 252 mm indicate a strong year class was recruited to the sampling gear (Figure 8), which may result in large trout contributing to the Madison fishery in subsequent years.

Abundances of trout ≥ 252 mm have been relatively low in Varney since 2015 with great variability in the size structure over the past several years. However, estimated abundances of Rainbow Trout ≥ 152 mm remain above the long-term average at 1574 trout/mile in the Varney Section, despite a decrease from 1950 trout/mile in 2022 (Figure 9). A decline in the frequencies of Rainbow Trout ≤ 252 mm from 2022 to 2023 indicates reduced recruitment or poor survival of younger age classes in recent years. However, the overall increase in abundance of total trout ≥ 252 mm, and bimodal length-frequency histograms, indicate good survival of previous year classes. Brown Trout abundances increased to the historic, 20-year average of 1610 trout/mile in 2023.

Abundances of trout ≥ 252 mm remain at historic lows in Norris (Figure 5). The estimated abundances of Rainbow Trout ≥ 152 mm remained below the long-term averages in the Norris Section with 1248 trout/mile in 2023. Brown Trout abundance increased from 523 trout/mile in 2022 to 680 trout/mile in 2023 but remains below the 20-year historic average (Figure 7).

The truncated length-frequency histograms of Rainbow Trout in recent years (Figure 10) indicate reduced survival of adult Rainbow Trout to population from that observed in the 2000s and 2010s. The high frequency of Brown Trout ≥ 252 mm indicates strong recruitment in recent years, but abundance estimates indicate an overall decline in the population compared to the 20-year historic averages (Figures 7 and 10). Overall reduced abundances of adult trout in Norris may indicate why recent recruitment was strong, resulting in reduced competition for younger year classes. Capture probabilities for Westslope Cutthroat Trout were too low in 2023 to accurately estimate abundance.

Table 1. FWP management goals for trout abundances and size structures in three long-term monitoring sections of the Madison River.

Site	Management objectives
Pine Butte	2,300 trout ≥ 252 mm per mile with 25% of those fish being ≥ 402 mm
Varney	1,200 trout ≥ 252 mm per mile with 35% ≥ 402 mm
Norris	2,500 trout ≥ 252 mm per mile with 15% ≥ 402 mm

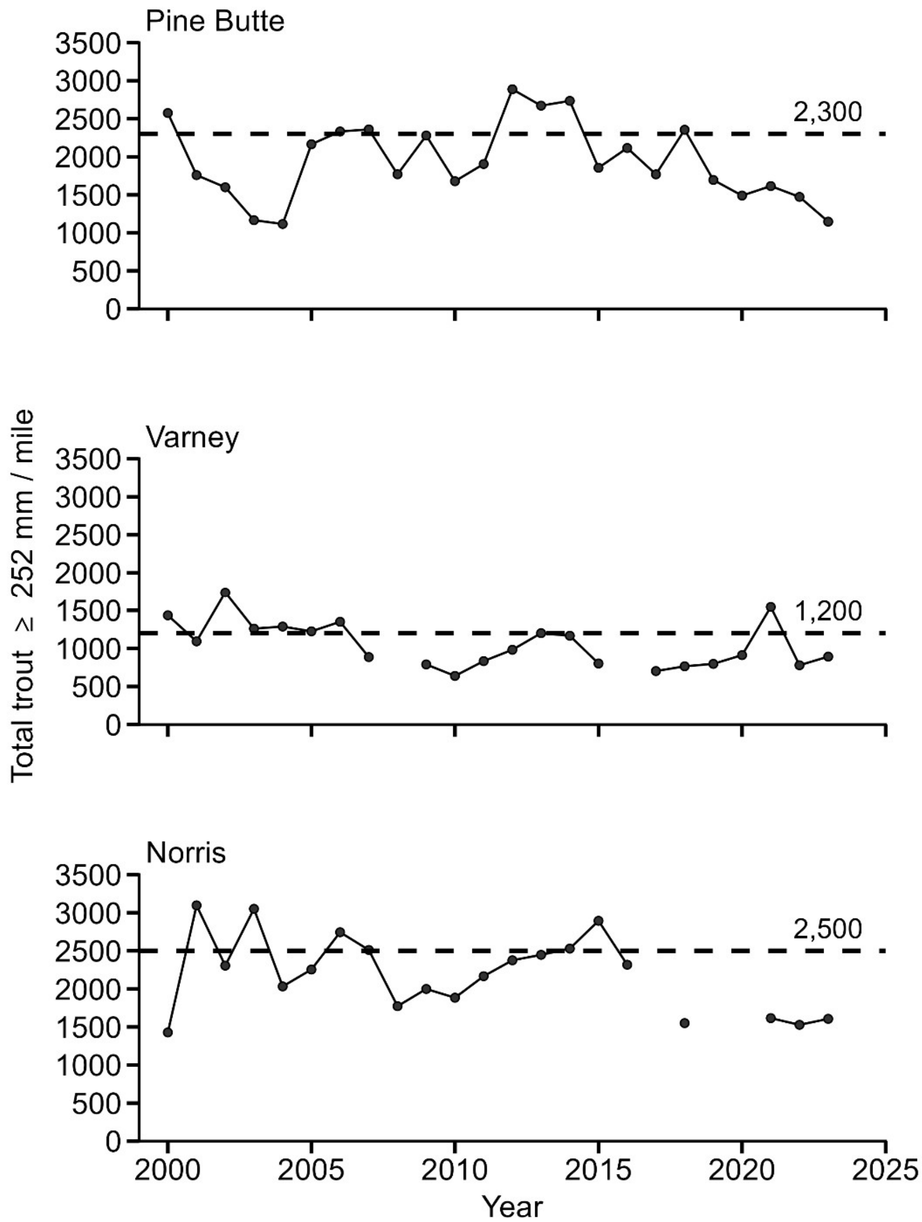

Figure 5. Estimated abundance of all trout ≥ 252 mm (≈10") in three long-term monitoring sections of the Madison River. Black dashed lines represent the management goals for trout abundance in each section.

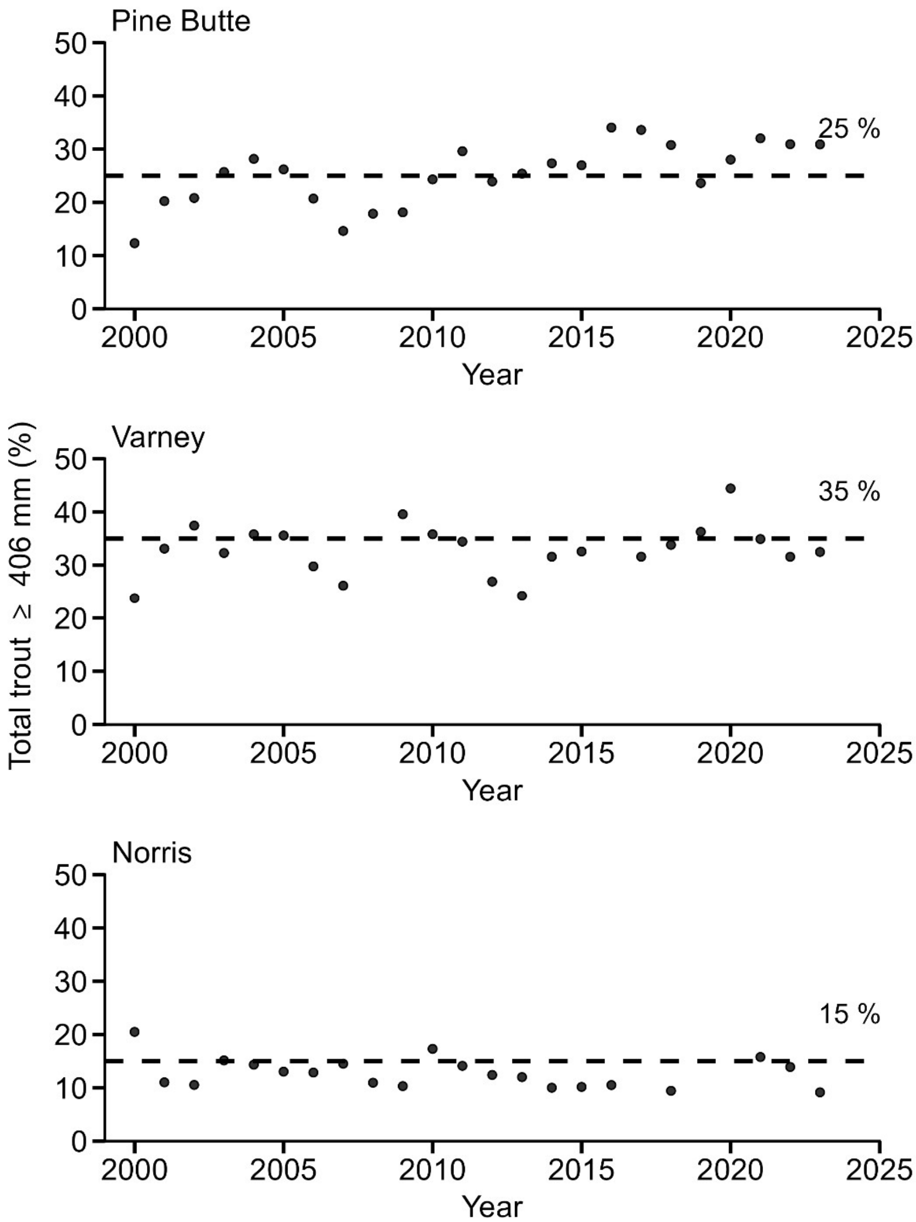

Figure 6. Percentage of ≥ 252 mm trout that are ≥ 406 mm (≈16") in three long-term monitoring sections of the Madison River. Black dashed lines represent the management goals for trout size structure in each section.

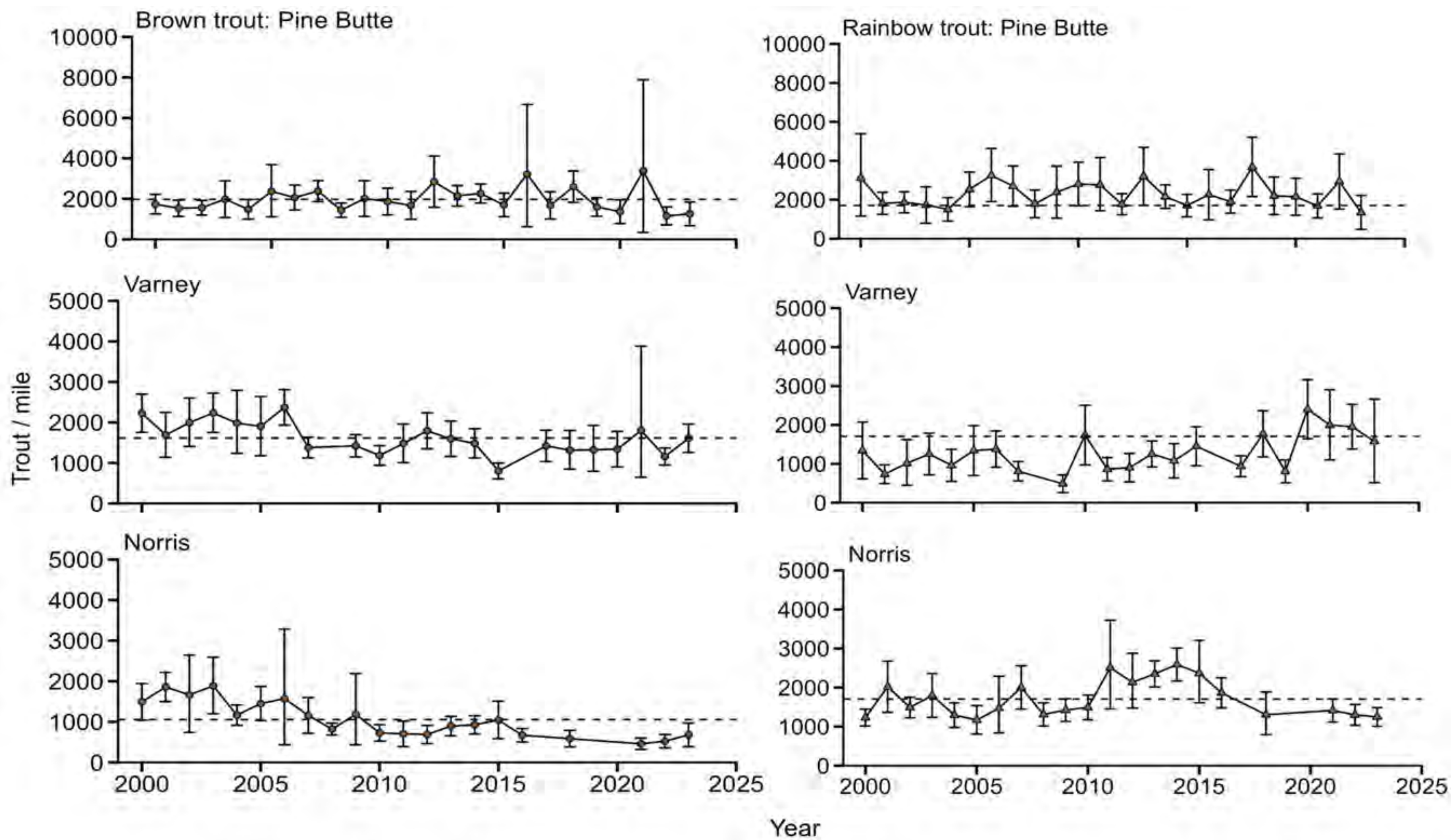

Figure 7. Estimated abundances of Brown (brown circles) and Rainbow Trout (green triangles) ≥ 152 mm (≈ 6") in the three long-term sampling sections of the Madison River. Dashed lines represent the long-term average trout abundance (2000 to 2023), and error bars represent 95% confidence intervals.

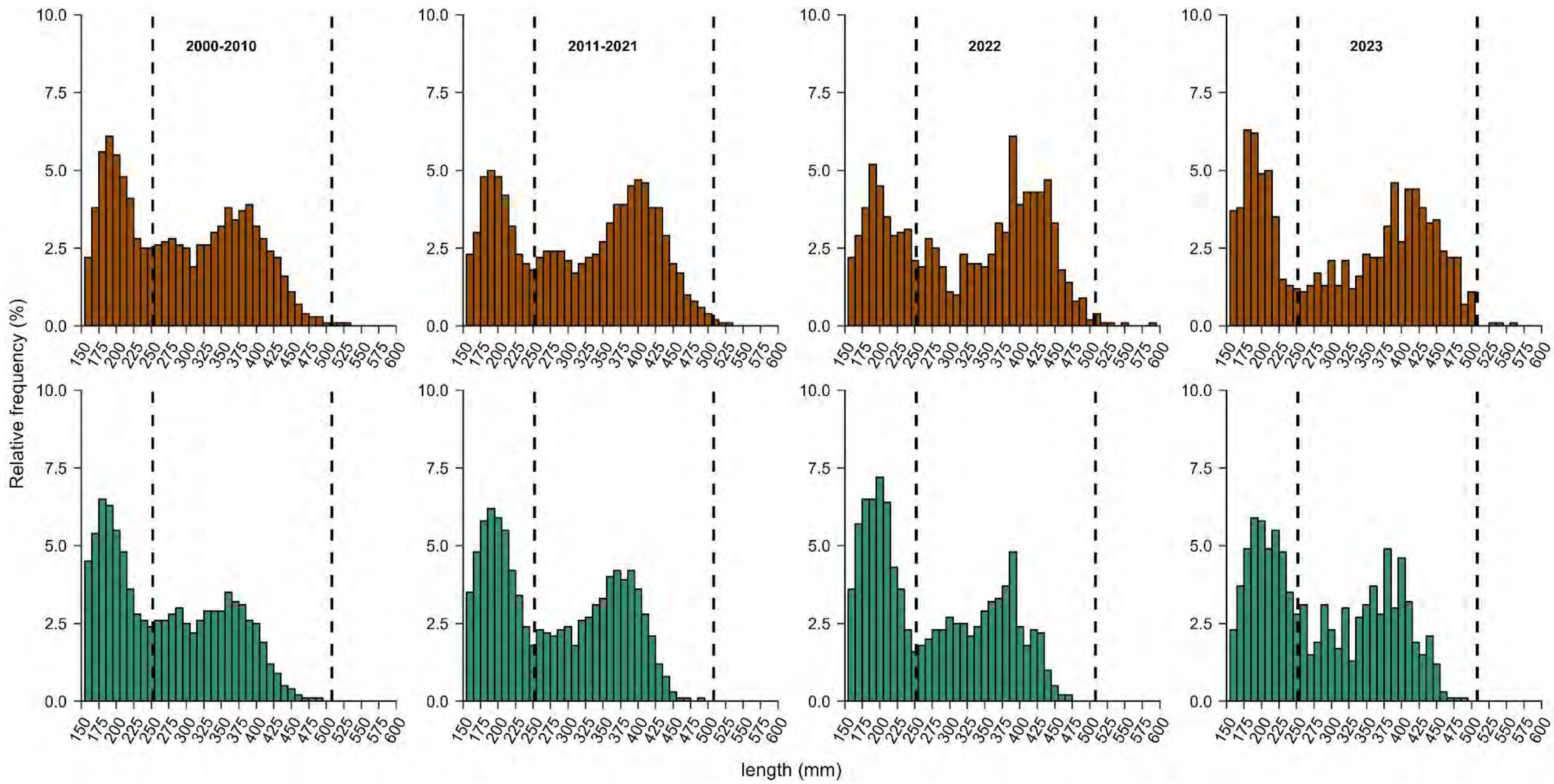

Figure 8. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6”) captured in the Pine Butte Section of the Madison River. Black dashed lines delineate 10 and 20 inches.

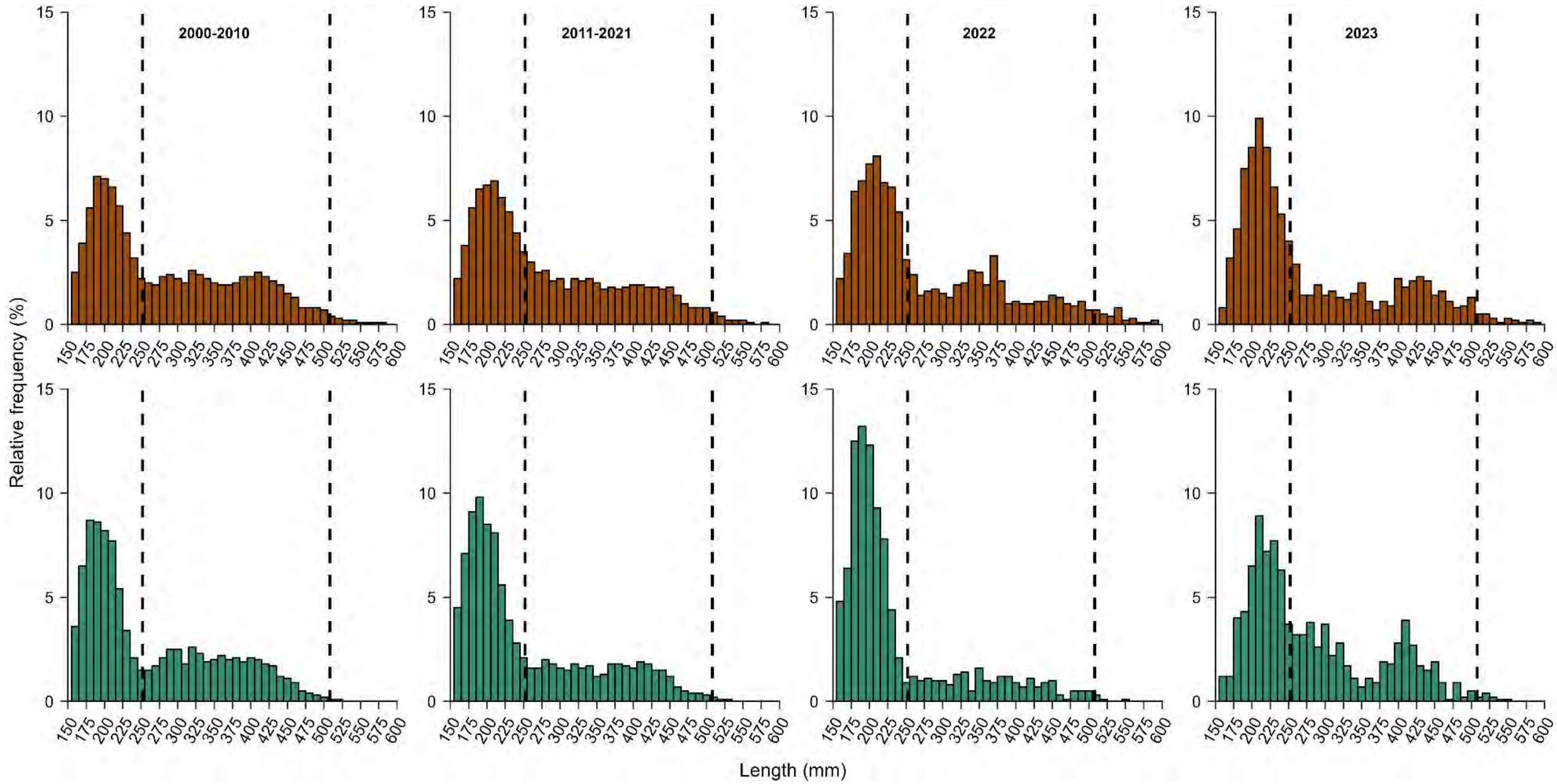

Figure 9. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6”) captured in the Varney Section of the Madison River. Black dashed lines delineate 10 and 20 inches.

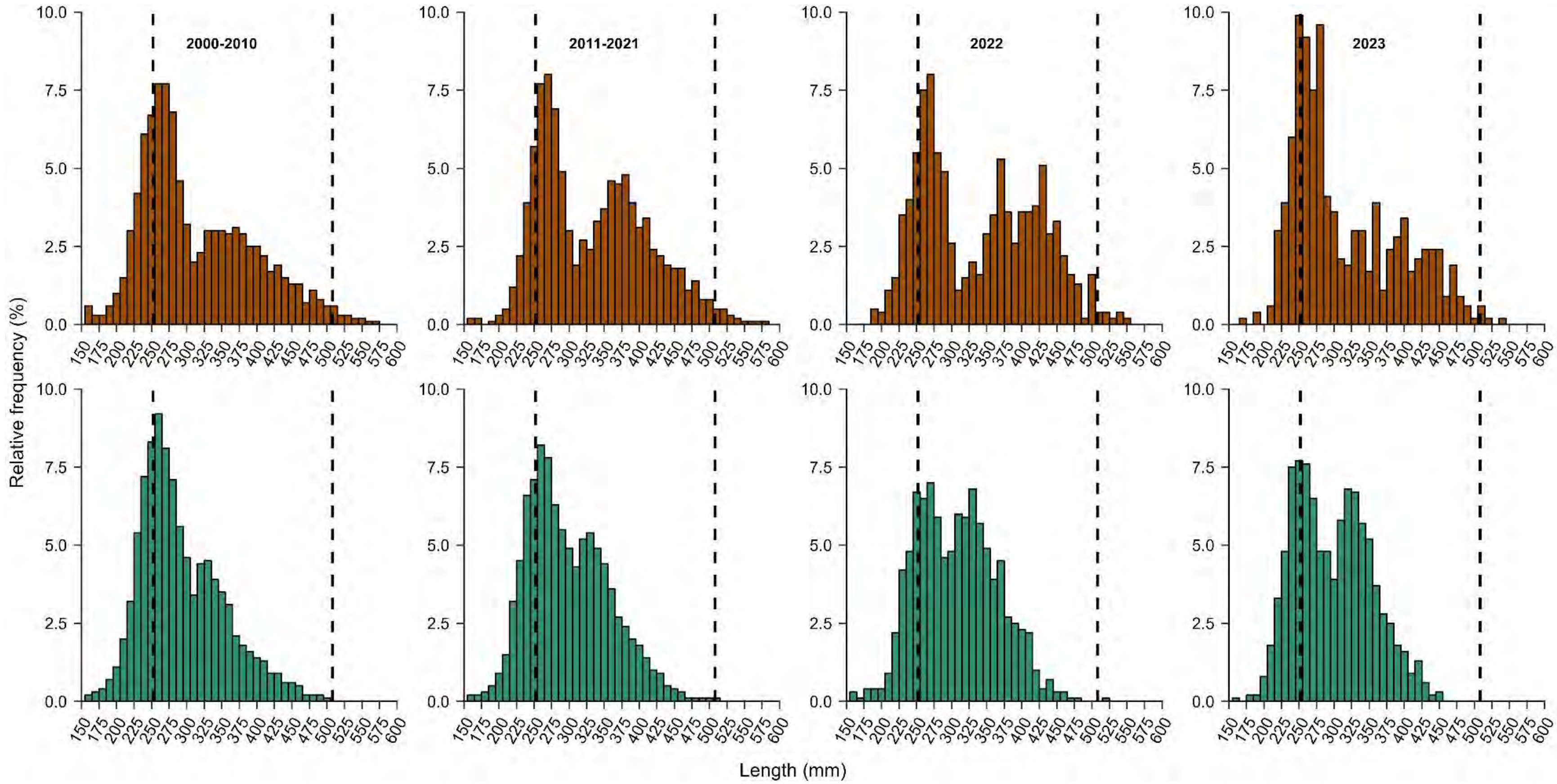

Figure 10. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6") captured in the Norris Section of the Madison River. Black dashed lines delineate 10 and 20 inches.

408-7) Monitor Species of Special Concern; Madison Arctic Grayling; Westslope Cutthroat Trout:

Opportunities to recover, conserve, and expand native fish distributions are regularly pursued by FWP and partner agencies. NWE is committed to implementing PM&E measures under Articles 408, 409, and 412 of the 2188 FERC License from Hebgen Reservoir to Three Forks, Montana to mitigate adverse effects to native fish species associated with Madison Project operations (FERC 2000).

Goals and objectives for the conservation and re-establishment of viable Arctic Grayling populations are defined in The Upper Missouri River (UMR) Arctic Grayling Conservation Strategy (MAGWG 2022). The strategy calls for the establishment of two viable grayling populations in Hebgen Reservoir and its tributaries. Previous efforts to re-establish populations in the Madison River below Hebgen Dam have been unsuccessful due to the high density of Brown Trout in mainstem and tributary waters. However, the removal of nonnative fish from Grayling Creek and the Gibbon River and low densities of resident Brown Trout in the upper South Fork Madison, all tributaries to Hebgen Reservoir, provide opportunities for the re-establishment of viable populations in the Madison River drainage. Reintroduction efforts will require using a minimum of 500,000 grayling eggs/year from fish of primarily Madison genetic ancestry for 3-5 consecutive years.

In 2023, FWP stocked 794,000 Arctic Grayling embryos in the upper South Fork Madison, 5,000-7,000 fry were stocked into Grebe Lake by Yellowstone National Park personnel, and Arctic Grayling introductions continued in the North Fork of Spanish Creek. Furthermore, FWP initiated an experiment to evaluate if Arctic Grayling embryo survival differed between stocking methods, remote site incubators (RSIs) (Figure 11), and simulated broadcast spawning. The complete study design and the 2023 results are in Appendix B.

Figure 11. Remote site incubators (RSIs) used to stock Arctic Grayling embryos in Black Sands Springs, a tributary to the South Fork Madison, in 2023.

FWP's Statewide Fisheries Management Plan calls for the protection and reintroduction of WCT conservation populations (i.e., populations with less than 5% hybridization by non-native fish) to 20% of historically occupied waters (Montana Statewide Fisheries Management Program and Guide 2018). To help facilitate and direct WCT conservation efforts, several state, federal, and nongovernment agency partners formalized the Westslope Cutthroat Trout Conservation Strategy for the Missouri Headwaters of Southwest Montana in 2022 (Jaeger et al. 2022). The strategy identifies the current status and conservation actions needed to protect and restore WCT to 20% of historically occupied tributaries in each of the nine subbasins that comprise the Missouri Headwaters: Ruby, Bighole, Beaverhead, Gallatin, Madison, Jefferson, Red Rock, Boulder, and Upper Missouri rivers.

Revised estimates of WCT conservation populations in the Madison River subbasin suggest that they currently inhabit 14.0% of historically occupied tributaries; and only 23% of the identified populations are considered secure (isolated from nonnative fishes, typically by a physical barrier, and have a population >2,500 fish >75mm and occupy enough habitat to ensure long-term persistence). The MadTAC granted funding to pursue WCT conservation efforts in the Madison subbasin. WCT PM&E activities in 2023 included the development and pursuit of a migration barrier plan and construction on the West Fork Madison, and population and genetic assessments of the West Fork Madison, Fox Creek, Horse Creek, Rose Creek, and Poison Creek.

FWP evaluated WCT population abundance and distribution in the West Fork, Fox Creek, Horse Creek, Rose Creek, and Poison Creek. Abundances were estimated by conducting 100-meter depletion estimates using a backpack electro-fisher at low, middle, and high sampling locations within the drainage. Successive electrofishing passes were conducted until the number of fish captured during a pass was 50% or less than the number collected during the previous pass. Fish collected during each pass were held in separate live cars below the sampling reach. Once sampling criteria were met, all fish were enumerated, measured (mm), and a fin clip was taken for genetic analysis. Estimates were produced by using an R-based proprietary FWP fisheries database and analysis tool.

West Fork Madison average fish abundance was 8 fish /100m (+/- 11; 95% CI) and Fox Creek average fish abundance was 6 fish/100m (+/- 5; 95% CI). Initial genetics results of these two creeks showed WCT populations were ≥95 % WCT, meeting FWP's conservation population standard and stakeholders elected to move forward with a fish barrier to protect and secure a genetically altered (95.0%-99.9% WCT) population. However, upon further analysis preliminary genetic results were inaccurate and both populations fell below the 95% threshold (WF Madison 92.8% WCT, Fox 91.9% WCT; Kovach et al. 2023). As a result of the new genetic information, FWP and partner agencies decided to not pursue the West Fork barrier project in 2023. Funding for the project was returned to the MadTAC .

Horse Creek average abundance was 26 fish/100m (+/- 21; 95% CI) with WCT ranging in size from 55 – 226 mm (Figure 12). Rose Creek single depletion estimated WCT abundance at 22 fish / 100m and size range of 63 – 169 mm (Figure 12). No further depletions were conducted in Rose Creek; therefore, average and 95% CI were not calculated. No fish were collected or observed in Hyde Creek due to poor habitat, stream degradation from livestock, and a likely waterfall fish barrier. Fin clips from Horse Creek and Rose Creek were submitted for genetic analysis in October of 2023 and results are pending.

Poison Creek and Ruby Creek abundance and demographics were both updated in 2022 and genetic results received in 2023. Average abundance of Poison Creek and Ruby Creek were 23 fish/100m (+/- 18; 95% CI) and 19 fish/100 m (+/- 11; 95% CI), respectively. Genetic analysis revealed a mixed 100% WCT population in Poison Creek and 100% WCT population in Ruby Creek (Kovach et al. 2023). FWP plans to translocate 100% WCT from Poison Creek to Ruby Creek in 2025. Poison Creek fish will be individually marked and genetically tested for purity in 2024 for translocation to Ruby Creek in 2025. Translocations from Last Chance and Wally McClure creeks to Ruby Creek have boosted genetic diversity significantly, and increased fitness, and abundance (Feuerstein 2021). No fish from donor streams were translocated to Ruby Creek in the summer of 2023.

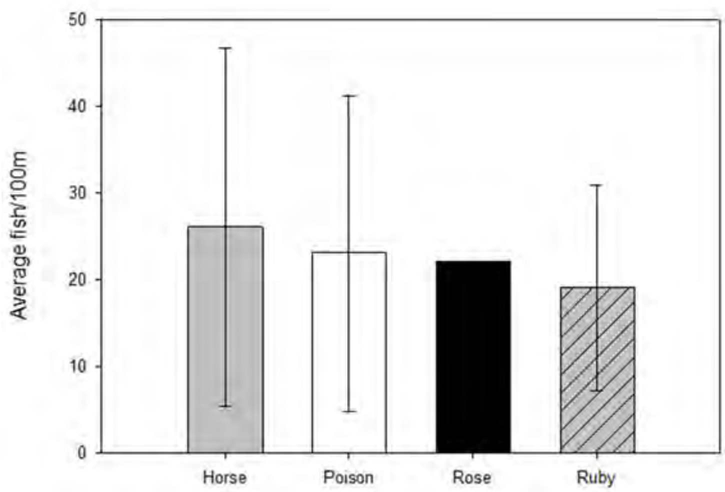

Figure 12. Westslope Cutthroat Trout estimates for Horse, Poison, *Rose (point estimate), and Ruby creeks measured in average fish / 100 m. Error bars indicate 95 % confidence intervals.

In 2016, NWE committed funding to aid in the North Fork of Spanish Creek native fish restoration project. Environmental DNA (eDNA) sampling throughout the North Fork of Spanish Creek drainage confirmed that the 2022 treatment had been successful in eradicating brook trout from the system and continued treatments were not warranted. On October 17, 2023, FWP, with the assistance of TEI personnel translocated 160 WCT from Green Horn Creek in the Ruby drainage to North Fork Spanish Creek (Figure 13).

Figure 13. WCT from Green Horn Creek transferred to North Fork Spanish Creek.

Article 409- 3) Fish habitat enhancement both in mainstem and tributary streams:

With the development of Hebgen Dam in 1917, gravel sources to replenish downstream spawning habitats were greatly diminished. The 1959 earthquake and subsequent landslide that impounded the Madison River provided a new source of gravel; however, the river has since incised through the material left by the slide leaving it largely inaccessible to flows under normal operations. The scarcity of gravel sources to replenish spawning habitats is further exacerbated by the loss of existing gravel to Ennis Lake due to the frequent capacity of the river to mobilize the D_{50} of the active streambed 59 to 364 days a year, a process that typically only occurs 7 to 14 days a year in unregulated systems (Pioneer Technical Services 2022). Currently, FWP and NWE are pursuing a side-channel reconnection project in the upper river near the Ruby fishing access site (FAS), and island construction in the lower river near Warm Springs FAS. It is anticipated that these projects will help mitigate the loss of spawning habitat and improve general habitat conditions for fish production and recruitment to the mainstem fishery.

Article 413-Pulsed Flows

Temperature affects all aquatic organisms and fish species have specific thermal ranges that are optimal for their persistence. Exposure to extreme temperatures for extended durations can be lethal to fish. In 1988, a fish kill occurred in the Lower Madison River when temperatures reached 82.5°F. FWP and NWE have since implemented monitoring programs to mitigate the effects of high-water temperatures on fish. FWP has monitored water and air temperatures throughout the Madison River basin from upstream of Hebgen Reservoir to the mouth of the Madison River at Headwaters State Park since 1993 (Figure 14). Temperature data has been used by FWP as criteria for implementing angling restrictions to reduce the mortality of adult trout during periods of thermally induced stress. Angling restrictions are implemented when the daily maximum water temperature is ≥ 73°F for three consecutive days. Additionally, to mitigate high water temperatures and reduce the risk of a thermally induced fish kill in the Lower Madison River, NWE implemented the Madison Decision Support System (DSS) program. The Madison DSS program is designed to predict a pulse volume of water that will limit thermal heating sufficiently to keep maximum daily water temperatures ≤ 80°F at Sloan and avoid the 82.5°F lethal thermal limit of resident fish in the Lower Madison River. The Madison DSS is comprised of two methods to determine a pulse volume to be delivered to the Lower Madison River: a thermo-dynamic physics model (physics model) and a manual protocol. Pulsed flows are triggered when the water temperature at the Madison (Ennis) Powerhouse is 68°F or higher and the predicted air temperature at the Sloan Station (River Mile 17) near Three Forks, MT for the following day is 80°F or higher. NWE enters the maximum water temperature recorded at the McAllister USGS gage and the next day's forecasted maximum air temperature at Three Forks to the manual protocol and the physics model to derive the volume of the pulse needed for the following day (Table 2). NWE determines the larger derived pulse of the two methods and directs operations to release that volume the following day from 6:00 am to noon. The timing of the release is designed to allow for the travel time of the water to arrive in the lower Madison River near Sloan Station during the late afternoon when daily solar radiation is greatest.

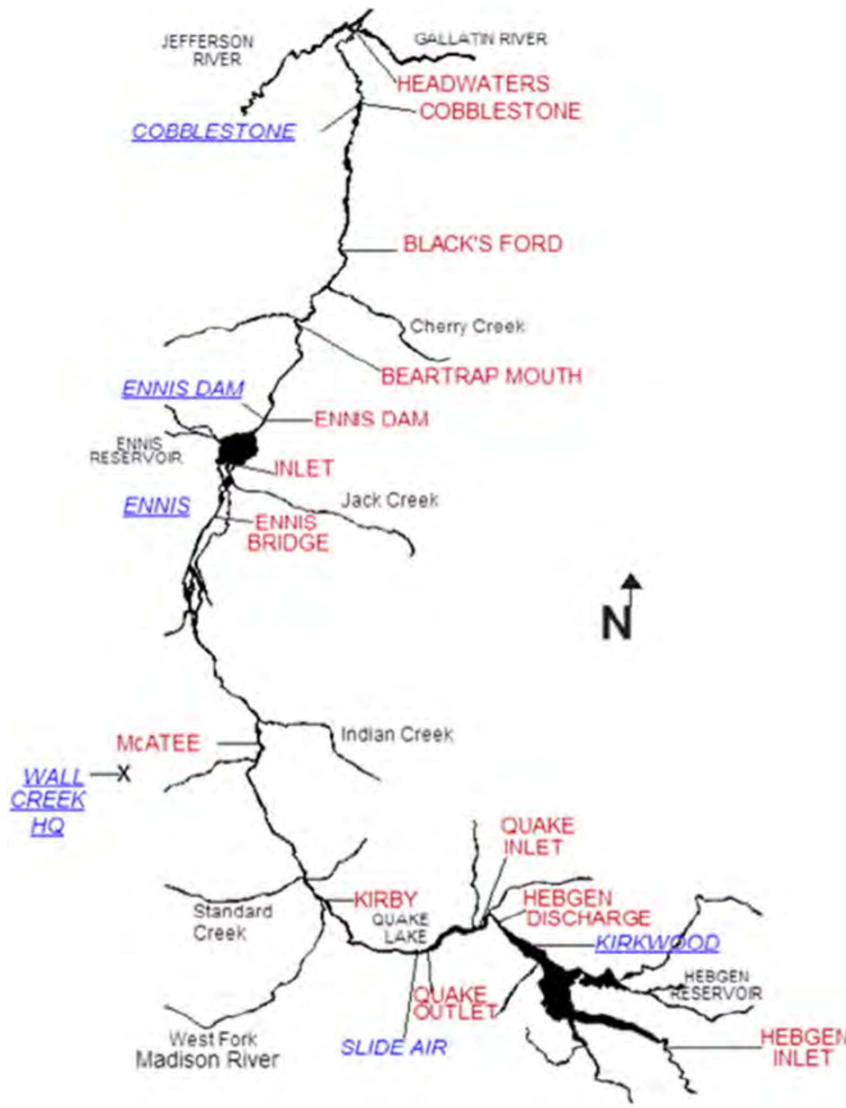

Figure 14. FWP temperature monitoring sites. Air temperature monitoring sites are blue and underlined; water temperature monitoring sites are red.

Table 2. Madison DSS Manual Protocol (Northwestern Energy 2020).

Maximum powerhouse release temperature (◦F) at the Madison DSS website or USGS McAllister gage on or after 8:30 p.m.	Predicted maximum air temperature (◦F) at Sloan Gage the following day and corresponding pulse flows (cfs).		
	75.0—84.9	85.0—94.9	≥ 95.0
68.0—68.9	1150	1150	1400
69.0—69.9	1150	1400	1600
70.0—70.9	1150	1600	2000
71.0—71.9	1400	1600	2100
72.0—72.9	1450	1800	2400
73.0—73.9	1600	2100	2800
74.0—74.9	1800	2600	3000
≥ 75.0	2600	3200	3200

Daily maximum temperatures were ≥ 73◦F at the lower river monitoring sites, Blacks Ford and Cobblestone for 47, and 53 days, respectively (Table 3). Since 2000, maximum daily water temperatures at the Blacks Ford monitoring site have been ≥ 73◦F an average of 46 times a year causing FWP to regularly implement restrictions that prohibited angling from 2 p.m. to 12 a.m. during summer months.

In 2023, there were 46 calls for a pulse flow, but only 28 of those resulted in operational changes to accommodate a pulse flow. Maximum daily water temperatures did not reach 80◦F at Sloan Station. Downstream of Sloan Station at the Cobble Stone FAS water temperatures reached or exceeded 80◦F on July 22. (Table 3; Figure 15). Pulse flows have been implemented an average of 19 days since 2009 and have been effective at moderating maximum daily water temperatures and preventing the occurrence of a thermally induced fish kill in the lower river (Figure 16).

Table 3. Maximum and minimum temperatures (˚F) recorded at monitoring sites in the Madison River Drainage, 2023. The mean temperature is the mean daily temperature ± 95% confidence intervals (CI). Days ≥ 73˚F are the number of days daily maximum temperatures were at or exceeded 73˚F, and days ≥ 80˚F are the number of days daily maximum temperatures were at or exceeded 80˚F. NA denotes that temperature data was unable to be recovered.

Site	Max ◦F	Min ◦F	Mean daily temperature ±95% CI	Days ≥ 73◦F	Days ≥ 80◦F
Hebgen inlet	76.0◦	48.9◦	62.1◦ ±0.2◦	20	0
Hebgen discharge	66.3◦	37.1◦	53.9◦ ±0.2◦	0	0
Quake Lake inlet	66.7◦	46.9◦	58.1◦ ±0.2◦	0	0
Quake Lake outlet	66.3◦	38.5◦	54.7◦ ±0.2◦	0	0
Kirby Bridge	69.3◦	37.2◦	54.6◦ ±0.2◦	0	0
McAttee Bridge	71.0◦	37.7◦	55.8◦ ±0.2◦	0	0
Ennis Bridge	72.7◦	41.8◦	58.0◦ ±0.2◦	0	0
Ennis Reservoir inlet	78.0◦	41.9◦	58.5◦ ±0.2◦	10	0
Madison Dam	74.2◦	50.9◦	63.5◦ ±0.2◦	3	0
Bear Trap Mouth	NA	NA	NA	NA	NA
Blacks Ford	78.8◦	46.9◦	62.5◦ ±0.2◦	47	0
Cobblestone	80.0◦	49.2◦	64.0◦ ±0.2◦	53	1
Headwaters S.P. (Madison mouth)	NA	NA	NA	NA	NA

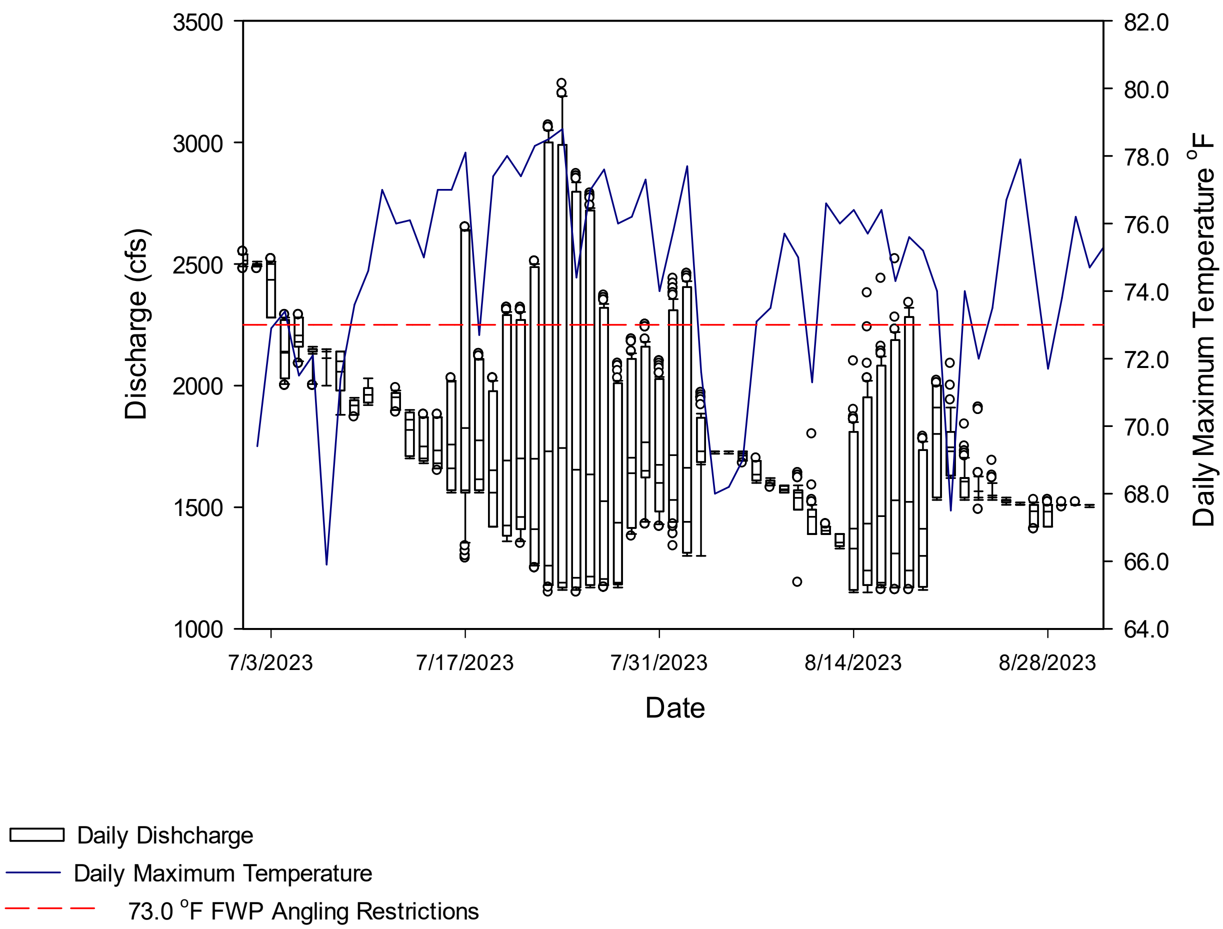

Figure 15. Daily distribution of discharges (left axis) collected every 15 minutes from July 1-Aug 31 2023 (pulse flow season) at USGS gage # 6-410 and daily maximum water temperature at Sloan (right axis). Boxes extend from the 25th to the 75th percentile and whiskers are the 5th and 95th percentile. Horizontal black lines are the median values of the groups' distribution and horizontal red lines are the mean values of the groups' distribution. o's are values outside the 5th and 95th percentiles. The red dashed line denotes the 73°F threshold used by FWP to implement angling closures.

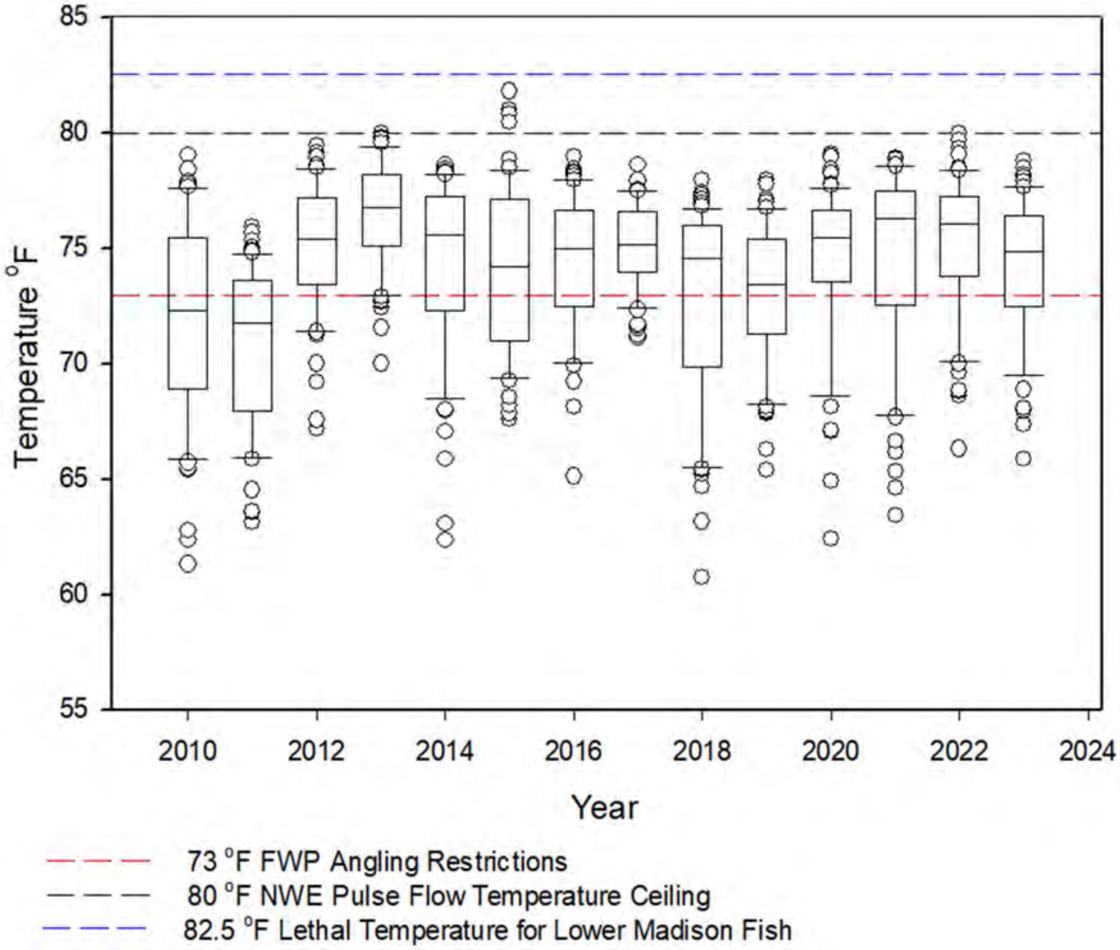

Figure 16. Distribution of daily maximum water temperatures at Sloan from July 1-August 31 from 2010-2023. Boxes extend from the 25th to the 75th (interquartile range) percentile, whiskers are the 5th and 95th percentile and circles are values beyond the 5th and 95th percentiles. The red dashed line denotes the 73°F threshold used by FWP to implement angling restrictions, the black line is the 80°F NWE pulse flow temperature ceiling goal for the lower river, and the blue dashed line denotes the lethal temperature for fish in the lower Madison River of 82.5°F.

FWP's implementation of angling restrictions and NWE's pulse flow program appear to be effective in limiting thermally induced fish mortality in the lower river. Pulse flows have kept summertime water temperatures in the lower river below lethal thermal limits for trout. However, a negative correlation between the abundances of age-1 and age-2 Rainbow Trout and the frequency of pulses has been observed (Lohrenz et al. 2022). This may be attributable to the lack of habitat complexity in the Norris reach that would provide velocity refugia (Lohrenz et al. 2022). FWP and NWE are currently reviewing designs to improve habitat complexity in the Norris reach. FWP recommends NWE continue the pulse flow program and implementation of projects that will increase habitat complexity and diversity in the Norris reach for all life stages of fish.

Article 419-Coordinate and Monitor Flushing Flows:

Article 419 of the 2188 FERC license requires NWE to develop and implement a plan to coordinate and monitor flushing flows in the Madison River downstream of Hebgen Dam. A flushing flow should be large enough to mobilize substrates and produce scour in some locations and deposition in other locations. This is a natural occurrence in unregulated streams and rivers that maintains and creates spawning, rearing, and foraging habitats for fish as well as providing fresh mineral and organic soil for terrestrial vegetation and other wildlife needs (Poff et.al 1997; Reiser, Ramey, and Wesche 1990). Impoundments such as dams interrupt the natural hydrograph of rivers and high flow events responsible for the replenishment and cleaning of spawning gravels are often reduced in magnitude and duration. These effects may be exacerbated by operational parameters the owner or operators of the dam prefer or must comply with. Streambed embeddedness and excessive amounts of fines (particles ≤ 0.84 mm) in spawning gravels can adversely affect the survival of embryos and the emergence of fry by inhibiting the delivery of oxygenated water and reducing the amount of interstitial space required for development (McNeil and Ahneil 1964; Kondolf 2000). Accordingly, a goal to maintain ≤ 10% fines in the upper Madison River and ≤ 15% in the lower Madison River was established with the understanding that releasing a flushing flow from Hebgen Dam has limited influence on sediment mobility in the lower Madison River. This goal was selected because these targets are known to provide suitable conditions for salmonid spawning.

Operational constraints for Hebgen Reservoir outflow and reservoir elevation limit implementation, magnitude, and duration of a flushing flow. These constraints 1) limit discharge at USGS gage no. 6-388 (Kirby gage) to no more than 3500 cubic feet per second (cfs) to limit erosion of the Quake Lake outlet, 2) limit changes in the outflow from Hebgen Dam to no more than 10% per day for the entire year, and 3) require that snowpack and runoff forecasts allow for the filling of Hebgen to a minimum elevation of 6532.26^{ft} msl by June 20. Snowpack conditions and forecasted runoff for the spring of 2023 allowed NWE to make operational changes at Hebgen Dam to accommodate a flushing flow from May 28 through May 31, 2023. The 2023 flushing flow was similar in magnitude and duration to the scheduled flushing flows of prior years (Table 4). Maximum river discharge was 5440 cfs at the McAllister gage (USGS no. 6-410) and 3520 cfs at the Kirby gage (USGS no. 6-388). Peak discharge recorded at the Varney gauge (USGS no. 6-400) was 4870 cfs on May 30, 1470 cfs less than that observed (6340 cfs) in 2022.

Table 4. Flushing flow peak discharges (cfs) at the Kirby (USGS no. 6-388), Varney (USGS no. 6-400), and McAllister (USGS no. 6-410) gages in years when a flushing flow was scheduled. * represent years when the Varney gage was not operational.

Year	Peak Flow at USGS no. 6-388	Peak Flow at USGS no. 6-400	Peak Flow at USGS no. 6-410	Duration
2006	3450	*	5390	May 23-26
2008	3368	*	5390	June 3-6
2011	4050	6510	7100	June 20-24
2018	3680	5850	6510	May 26-June 1
2020	3600	6060	6150	June 4-7
2023	3520	4870	5440	May 28-31

Flushing flow and spawning gravel recruitment:

Since 2002, evaluation of the efficacy of flushing flows to recruit spawning gravels and maintain fine sediment thresholds under current operational constraints has primarily been achieved through annual sediment core sampling at four established monitoring sites representative of stream conditions present in the upper (Kirby and Ennis) and lower (Norris and Greycliff) Madison River. Appropriate substrate for sampling was identified by conducting spring and fall redd surveys at each monitoring location. Areas where redds typically occurred contained gravels ranging in size from 10-60 mm with minimal amounts of organic debris and sediment. Core samples from these areas were collected in 2023 with a 12-inch McNeil core sampler that was manually drilled into the substrate to a depth of 8”. Substrate from within the 12” x 8” area was removed, dried, and sorted using a sieve method. The percentage composition of the sample was calculated according to particle size. The results from annual core sampling provide an index of relative spawning habitat suitability (Kleinshmidt 2022). There is no statistical difference in the % fines ≤ 0.84 mm between years when a flushing flow were and were not implemented (Lohrenz et al. 2021; Kleinshmidt 2022). This is consistent with the findings of a 2021 study that examined sediment transport, storage, and spawning gravel recruitment within the range of flows allowed under the current operational conditions (Pioneer Technical Services 2022). The results indicated normal, non-flushing flows have the capacity to mobilize particles of the active streambed layer that are ≤ D_{50} 59 to 364 days a year and that a flushing flow is not needed to transport spawning gravels (Pioneer Technical Services 2022). Core sample data and results from 2023 will be reported by NWE.

Flushing flow and riparian plant community maintenance and regeneration:

Riparian plant communities are largely influenced by fluvial processes. These processes are often disrupted on regulated streams through the timing and magnitude of high-water events. In unregulated river systems, high flows typically occur in early summer and coincide with the release of wind and water-dispersed seeds from riparian plant species. Seed germination and seedling establishment occur in areas of fresh alluvial deposition created during high flows, which are critical to the establishment of riparian species, such as cottonwood and willows. The timing of high flows is also critical to riparian plant recruitment. Cottonwoods, for example, disperse their seeds from roughly the end of May through the end of July. Natural or contrived high flows outside of this window would not likely support cottonwood recruitment. Due to its lack of hydrologic complexity as a predominately single-thread channel and operational constraints, processes that support riparian regeneration and expansion are limited throughout much of the Madison River. However, suitable conditions for riparian regeneration and expansion do occur in some reaches of the river, such as Varney and Greycliff (Figure 18), which are characterized by multi-thread, high-complexity channels that dissipate stream energy and create depositional areas during high flows.

Per recommendations made by FWP in 2022, Geum Environmental Consulting was hired to evaluate whether there was evidence flushing flows were adequate for cottonwood and willow establishment and maintenance along the Madison River under current operational constraints. On May 16, 2023, FWP, NWE, and Geum personnel floated the Varney reach (Figure 18) to assess whether riparian recruitment was occurring. Stops were made at depositional features such as point bars and islands where it appeared newly established cottonwood and willows were growing. Plants were identified and an approximation of their age was made by examining their base and growth rings in their stem. Additionally, FWP and NWE personnel collected drone imagery from reaches of the Madison River with established cottonwood and willow communities (Varney and Channels; Figures 17 and 18) on May 30th at the peak of the flushing flow (4870 cfs at USGS no. 6-400) to document the extent of floodplain inundation.

Young (1-6 years) cottonwood, willow, and alder were observed growing on depositional features throughout the Varney reach; however, analysis of drone footage and river stage showed little inundation of the flood plain during the 2023 flushing flow. This suggests that the river stage required for fluvial processes that support riparian recruitment is not always met during a flushing flow but can at times be achieved. FWP recommends pursuing a more comprehensive investigation into the frequency, timing, and magnitude of a flushing flow required to sustain and promote the regeneration of riparian plant communities along the Madison River. This information could be used in conjunction with recent sediment transport and habitat evaluations to help inform MadTac whether a flushing flow would be beneficial, given year-specific conditions and expected magnitude and duration.

Figure 17. Drone photo of the flushing flow in the Varney section on May 30, 2023.

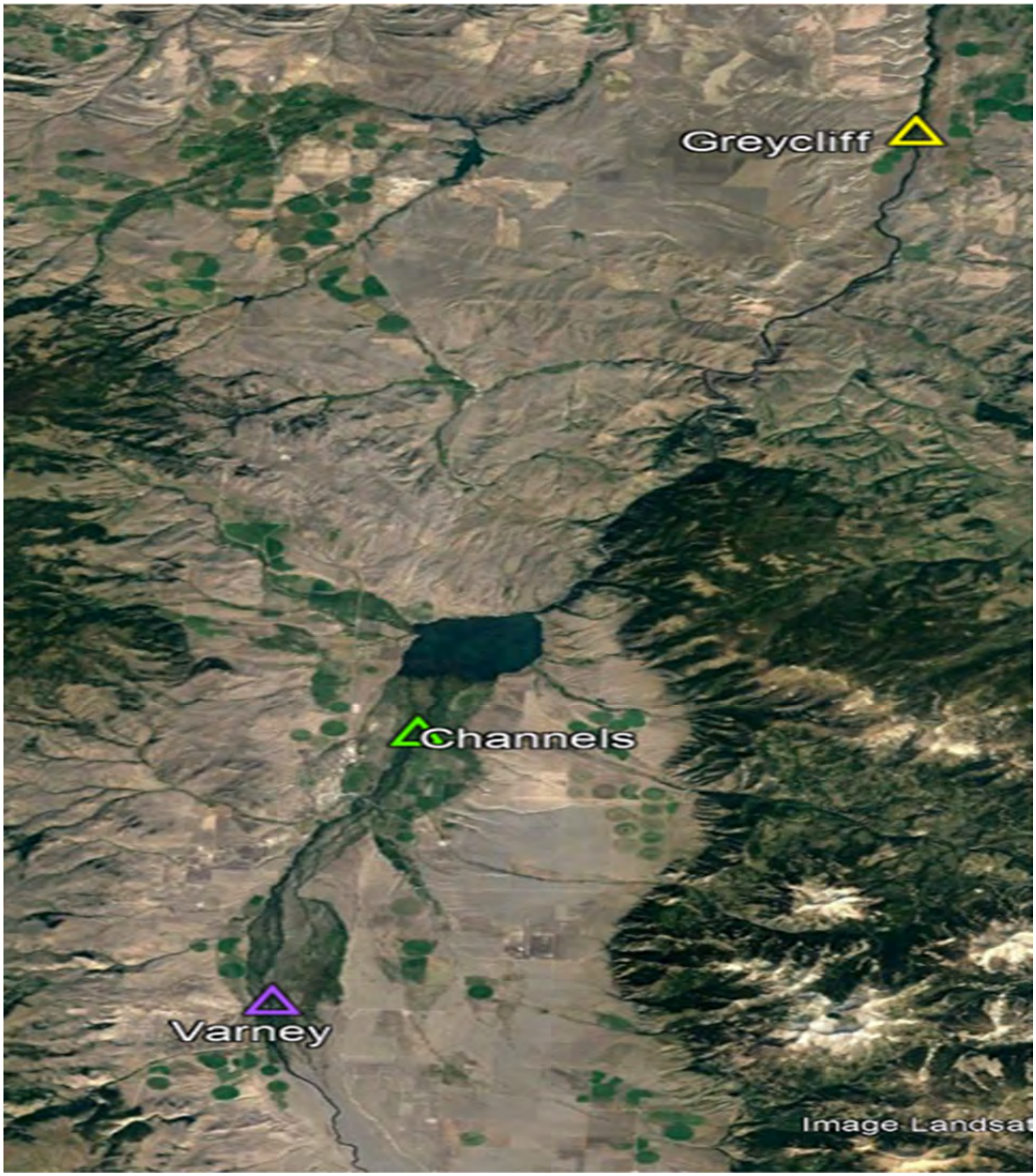

Figure 18. Reaches of the Madison River where riparian surveys and flushing and pulse flow side-channel habitat evaluations were conducted in 2023.

River flows and side-channel habitat

While the focus of the flushing flow program has largely been on the maintenance of spawning gravels and pulse flows for thermal mitigation in the lower river, in 2023 FWP initiated monitoring to discern how discharges associated with flushing flows and pulse flows affect habitats in complex reaches, such as side-channels. Side-channels can be important to the survival of salmonids, as they can contain spawning gravels close to habitats with reduced discharge such as pools, cobbles, and woody debris that are commonly used by young-of-the-year and age-1 trout for rearing.

The respective effects of flushing and pulsed flows on physical habitat were assessed by monitoring ten locations in the Varney reach, seven locations in the Channels reach, and three locations in the Greycliff reach (Figure 18). These reaches of the river were chosen for monitoring because they are geomorphically and hydrologically more complex than the Kirby or Norris reach, which are characterized as single-thread channels. Monitoring locations were selected using the following criteria: 1) channel bank full width was < 40ft and 2) there were identifiable pool-riffle complexes. Scour and deposition at each location was assessed by deploying scour chains, surveying streambed elevations and residual pool depths, and doing pebble counts before and after flushing and pulsed flows. A scour chain is 2.50 ft in length and constructed of heavy metal links. Prior to the flushing flow, scour chains were installed in the streambed at the crest of a riffle by driving it into the streambed with a post-pounder. The length of the chain that remained exposed above the streambed was recorded before and after the flushing flow and the pulsed flow season, respectively, and the amount of scour was determined by subtracting the chain length previously recorded. Elevation measurements were made with a stadia rod and laser level by comparing a benchmark above bankfull elevation on a streambank to the riffle crest where the scour chain was installed. Changes in streambed elevation were calculated by subtracting measurements from those previously recorded. Similarly, residual pool depth was measured from the streambed at the deepest part of the pool located immediately upstream from a riffle selected for monitoring relative to its benchmark with a stadia rod and laser level and changes calculated by subtracting previous measurements. Finally, FWP conducted 100 sample pebble counts at each monitoring location using the heel-toe method, which entails proceeding across the riffle in a zig-zag pattern by placing the heel of the lead foot against the toe of the trailing foot and reaching down without looking to retrieve, count, and categorize the first particle touched by passing through the smallest hole possible in a standard gravelometer. The percentages of particles ≤ 11mm were calculated and compared for each pebble count before and after flushing and pulsed flows. The 11 mm threshold was selected for analysis because Kondolf and Wolman 1993 identified 10mm as the smallest-sized gravel utilized by Rainbow Trout for spawning. Paired t-tests ($\alpha = 0.05$) were used to test whether mean differences between riffle crest and pool elevations and percentage of particles ≤ 11 mm in riffles were significantly different between flushing and pulse flows. Monitoring occurred pre-flushing flow on May 11, post-flushing and pre-pulse flow on July 7, and post-pulsed flow on August 25.

The duration of the 2023 flushing flow was three days (May 28-31) when flows at the Kirby gage (USGS no. 6-388) were at or near 3500 cfs. A Peak discharge of 5440 cfs was recorded at the McAllister gage (USGS no. 6-410) on May 28th. These flows are more than the flows needed to mobilize the active layer of substrate in the mainstem river as were the flows during the pulse flow season (July 7- August 25; Pioneer Technical 2022). Flows required to mobilize the active layer of the main channel, on average occur 357 days a year in the Varney reach, and 364 days a year in the Greycliff reach (Pioneer Technical, 2022). However, flows during the pulse flow season declined from 1730 cfs to 1270 cfs in the Varney and Channels reach during this time frame, with a change in mean daily discharge of 72.1 cfs ± 9.3; 95% CI (Figure 19). In the Greycliff reach, daily changes in discharge were more pronounced; the mean daily change in discharge was 535.9 cfs ±139.6; 95% CI (Figure 19).

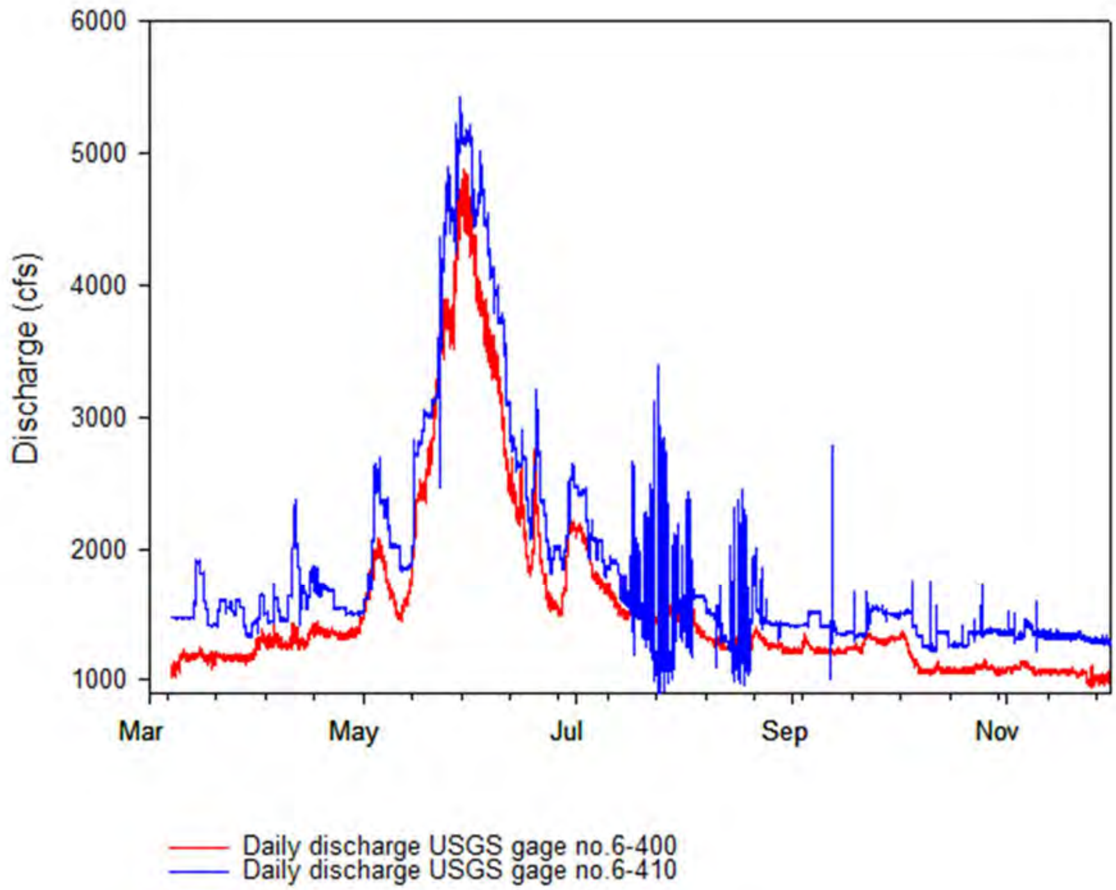

Figure 19. Daily distribution of discharges collected every 15 minutes from March 7-Dec 31, 2023 for Varney (USGS gage no. 6-400) and McAllister (USGS gage no 6-410).

The 2023 flushing flow induced scour in 45% of riffles and 50% of pools and deposition within 55% of riffles and 45% of pools. In total, scour (0.10-0.90 ft) occurred at nine riffles and deposition (0.02-1.27 ft) at 11 riffles among reaches (Tables 5, 6, 7). Residual pool depth increased (0.10-0.80 ft) at 10 locations and decreased (0.20-1.00 ft) at nine locations (Table 5, 6, 7). Because scour chains were interfered with by the public between flushing and pulsed flows they were not included in our analyses.

The 2023 pulse flows induced scour in 30% of riffles and 10% of pools and deposition within 60% of riffles and 90% of pools. In total, scour (0.01-0.20 ft) occurred at four riffles and deposition (0.05-0.50 ft) at 14 riffles among reaches (Table 5, 6, 7). Residual pool depth increased (0.01-0.30 ft) at two locations and decreased (0.06-0.40) at 18 locations (Table 5, 6, 7).

Significant differences in riffle scour (P = 0.03) and pool scour (P = 0.01) between flushing and pulse flows were observed in the Varney reach (Table 5). A marginally significant difference in riffle scour (P = 0.06) and a significant difference in pool scour (P = 0.05; Table 6) was detected between flushing and pulse flows in the Channels reach. No difference in riffle or pool scour was detected between the flushing and pulse flow in the Greycliff reach (Table 7). There was no significant difference in deposition at riffles or pools between flushing and pulse flows at any of the monitoring locations (Table 7).

Table 5. Bed scour and deposition after the 2023 flushing and pulse flow at side-channel riffles and pools in the Varney reach by monitoring location, riffle scour (ft), riffle deposition (ft), pool scour (ft), and pool deposition (ft). Mean scour and deposition at riffles and pools; P value from paired t-test at α=.05.

Location	Riffle scour (ft)		Riffle deposition (ft)		Pool scour (ft)		Pool deposition (ft)	
Varney	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow
V1	0.20	0.00	0.00	0.30	0.50	0.00	0.00	0.20
V2	0.80	0.00	0.00	0.20	0.00	0.00	0.00	0.30
V3	0.20	0.00	0.00	0.20	0.70	0.00	0.00	0.30
V4	0.10	0.00	0.00	0.30	0.20	0.00	0.00	0.20
V5	0.00	0.00	0.50	0.50	0.00	0.00	0.80	0.40
V6	0.40	0.00	0.00	0.50	0.40	0.00	0.00	0.30
V7	0.00	0.00	0.30	0.30	0.80	0.30	0.00	0.00
V8	0.00	0.00	0.30	0.00	0.00	0.00	0.60	0.30
V9	0.80	0.00	0.00	0.30	0.00	0.00	0.30	0.10
V10	0.00	0.20	0.40	0.00	0.20	0.00	0.00	0.30
Mean	0.25	0.02	0.15	0.26	0.28	0.03	0.17	0.24
P value	0.03		0.12		0.01		0.23	

Table 6. Bed scour and deposition after the 2023 flushing and pulse flow at side-channel riffles and pools in the Channels reach by monitoring location, riffle scour (ft), riffle deposition (ft), pool scour (ft), and pool deposition (ft). Mean scour and deposition at riffles and pools; *P* value from paired t-test at α=.05.

Location	Riffle scour (ft)		Riffle deposition (ft)		Pool scour (ft)		Pool deposition (ft)	
Channels	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow
C1	0.00	0.00	0.30	0.30	0.00	0.00	0.20	0.30
C2	0.00	0.00	0.02	0.20	0.00	0.00	0.50	0.30
C3	0.30	0.00	0.00	0.10	0.10	0.00	0.00	0.20
C4	0.50	0.60	0.00	0.00	0.30	0.00	0.00	0.20
C5	0.20	0.00	0.00	0.00	0.20	0.00	0.00	0.00
C6	0.00	0.00	1.30	0.10	0.00	0.00	1.80	0.10
C7	0.00	0.10	0.50	0.00	0.00	0.00	0.50	0.20
Mean	0.14	0.10	0.30	0.10	0.09	0.00	0.43	0.19
P value	0.06		0.14		0.05		0.30	

Table 7. Bed scour and deposition after the 2023 flushing and pulse flow at side-channel riffles and pools in the Greycliff reach by monitoring location, riffle scour (ft), riffle deposition (ft), pool scour (ft), and pool deposition (ft). Mean scour and deposition at riffles and pools; *P* value from paired t-test at α=.05.

Location	Riffle scour (ft)		Riffle deposition (ft)		Pool scour (ft)		Pool deposition (ft)	
Greycliff	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow	Flushing Flow	Pulse Flow
G1	0.00	0.00	0.50	0.30	0.00	0.00	1.00	0.30
G2	0.00	0.00	0.20	0.30	0.00	0.00	0.70	0.30
G3	0.00	0.04	0.00	0.00	0.10	0.00	0.00	0.30
Mean	0.00	0.01	0.23	0.20	0.03	0.00	0.57	0.30
P value	0.21		0.30		0.21		0.23	

Analysis of the percentage of fines ≤ 11mm in riffles between flushing and pulse flows was only significant in the Varney reach (*P* =0.02; Table 8). No significant difference in the percent fines ≤ 11mm in riffles was detected between the flushing and pulse flow in either the Channels or Greycliff reach (Table 9, 10).

Table 8. Percentage of fines ≤11 mm by location in the Varney reach post flushing and pulse flow. *P* value from paired t-test at α=.05.

Location	% Fines ≤ 11mm	
Varney	Flushing Flow	Pulse Flow
V1	15.00	2.00
V2	11.90	8.80
V3	10.00	5.00
V4	8.00	4.00
V5	13.00	10.70
V6	9.00	6.00
V7	24.50	21.00
V8	31.40	27.00
V9	14.70	10.10
V10	7.90	14.10
P value	0.02	

Table 9. Percentage of fines ≤11 mm by location in the Channels reach post flushing and pulse flow. *P* value from paired t-test at α=.05.

Location	% Fines ≤ 11mm	
Channels	Flushing Flow	Pulse Flow
C1	15.00	2.00
C2	11.90	8.80
C3	10.00	5.00
C4	8.00	4.00
C5	13.00	10.70
C6	9.00	6.00
C7	24.50	21.00
P value	0.16	

Table 10. Percentage of fines ≤11 mm by location in the Greycliff reach post flushing and pulse flow. *P* value from paired t-test at α=.05.

Location	% Fines ≤ 11mm	
Greycliff	Flushing Flow	Pulse Flow
G1	4.90	13.0
G2	18.00	7.00
G3	7.60	33.30
P value	0.27	

Flushing flows in regulated systems are often designed to provide sediment maintenance and not channel and habitat maintenance (e.g., side-channels, pools, undercut banks). In many instances, the normal flow regime is adequate to mobilize sand and gravel in the active streambed of the main river channel and a flushing flow is not warranted (Kondolf 1996; Pioneer Technical 2022). The flushing flow evaluation conducted by Pioneer Technical (2022), showed discharges of 600 cfs were adequate to mobilize the D_{50} of the active streambed in the Varney and Greycliff reaches 365 days a year, which suggests that even without the implementation of a flushing or pulse flow, base flows would be capable of mobilizing gravel of sufficient size for spawning and keep them relatively free from sediment. However, these calculations only applied to the main river channel and were specific to spawning habitat maintenance within the active layer.

Little is known about the minimum discharge required to maintain side-channel habitats; however, we suspect the increased discharge of the flushing flow was able to mobilize portions of the coarse streambed, creating and maintaining complex habitat features of the side-channels we monitored. Scour can loosen compacted streambed surfaces and reduce the amount of fine sediment present in spawning habitat and in the interstices between cobble that is often occupied by juvenile trout (Raleigh et al. 1984; Klemetsen et al. 2003). The loosening of the coarse stream bed associated with the scour we observed in side-channels may allow for smaller trout to excavate redds to a depth below which eggs could be lost during a high flow event if compacted conditions persisted (Montgomery et al. 1999). We observed significantly more scour of riffles and pools after the flushing flow than following the pulse flow season in the upper river reaches (Varney and Channels).

Scour observed at riffles was somewhat contrary to the hydraulic process typically observed during high flows. During high-flow events, scour characteristically occurs in pools and suspended material is deposited in riffles where their roughness and transition in elevation slows velocities. However, scour at riffles can occur on the descending limb of high-flow events as water surface elevation drops and velocity increases over the riffle because of the slope of the streambed. Additionally, the increased velocities resulting from the steeper streambed slope of a riffle are often sufficient to remove fine sediment and sands during low flows. In general, this appears to be consistent with our findings where the percent of particles ≤ 11mm declined significantly in the Varney reach (Table 8; Figure 20) and Channels reach following the pulse flow season (Table 9; Figure 21). It is reasonable to assume that the reduction of particles ≤ 11mm through the pulse flow season was beneficial for trout. Additionally, pool scour was significantly different between flushing and pulse flows in the Varney and Channels reaches (Table 5, 6), suggesting the flushing flow more effectively removed sediment from pools. Modifications to pool depth through scour can improve available cover, thermal refugia, and areas of reduced velocity for juvenile trout (Raleigh et al. 1984; Klemetsen et al. 2003).

Assessments of flushing and pulse flows suggest the flushing flow provides beneficial maintenance of side-channel habitats in the upper river, which would not likely occur during the pulse flow season when discharges are lower (Figure 19). Conversely, because of channel degradation and widening of the lower river, flows greater than current operational constraints are likely required to achieve appreciable change in habitat. A reduction in fine sediment present in core samples collected at lower river monitoring sites (Norris and Greycliff) occurred when discharge was greater than 7600 cfs (R2 Resources 2018). Pulse flows are an effective tool for thermal mitigation in the lower river, but they do not appear to be a viable tool for upper river side-channel habitat maintenance. FWP recommends further evaluation of changes in side-channel habitat in a year when a flushing flow is not implemented.

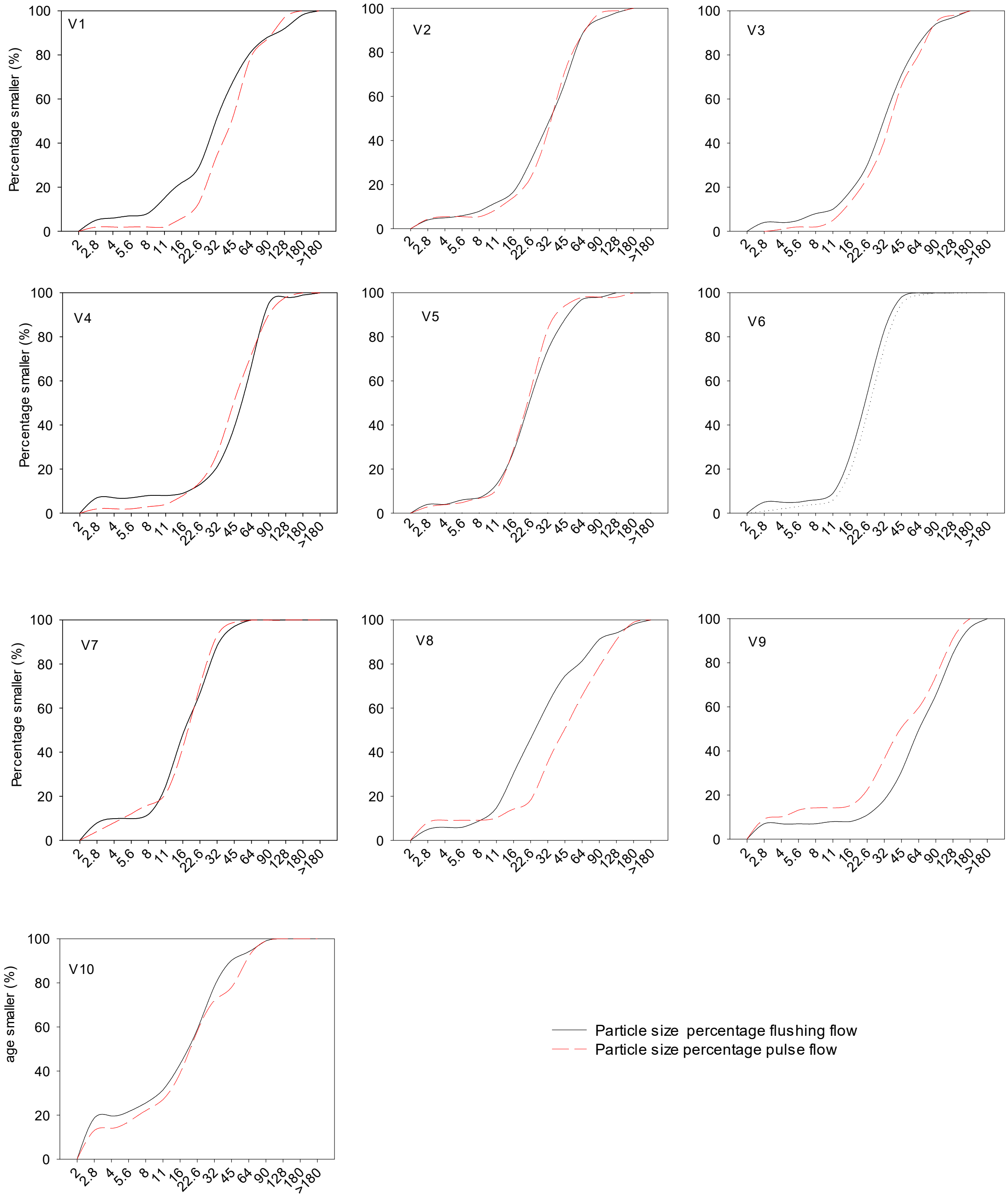

Figure 20. Percentage of Particles ≤ 11mm flushing and pulse flow events for monitoring locations within the Varney reach; y-axis is the percentage smaller (percent); x-axis is particle size.

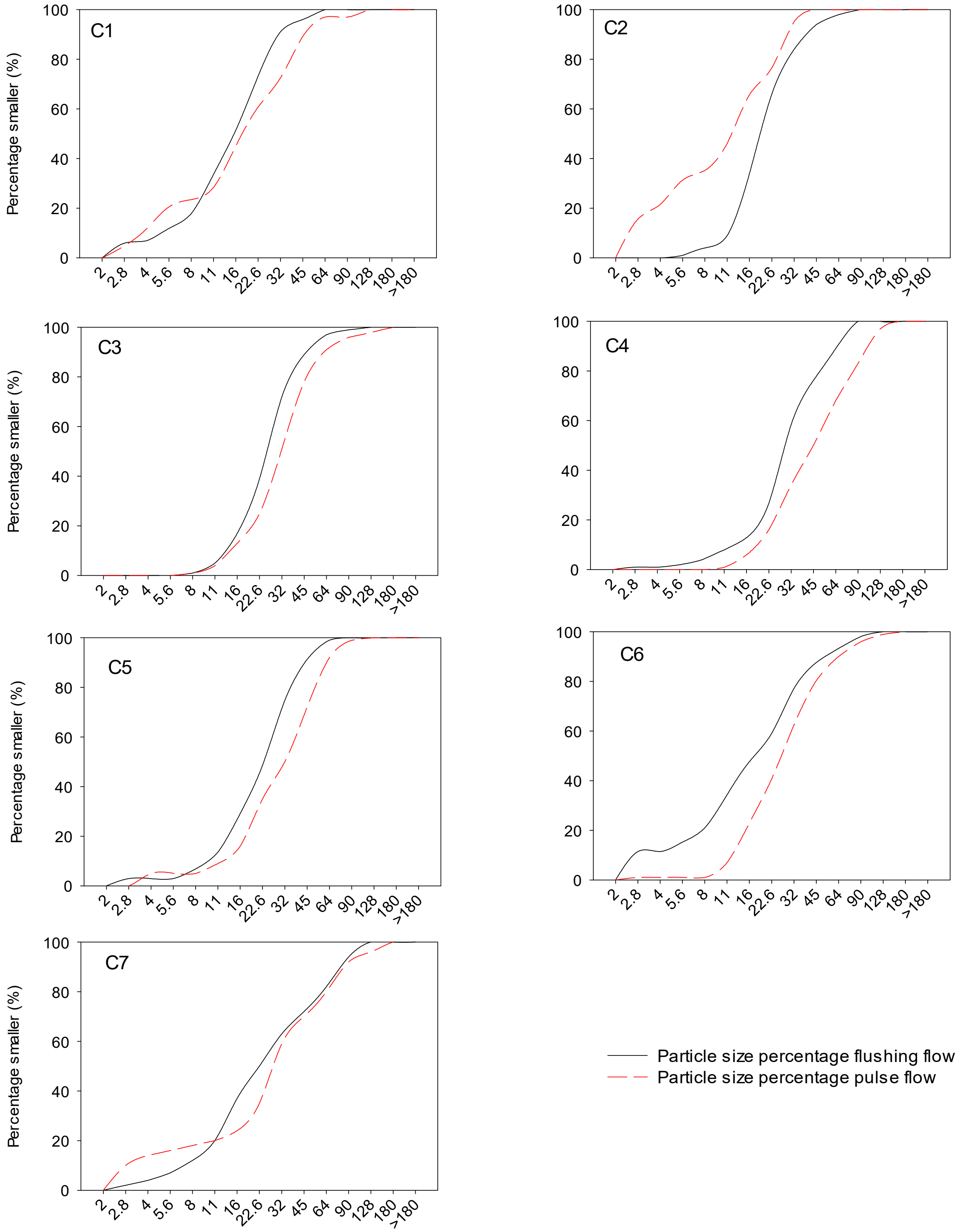

Figure 21. Percentage of Particles ≤ 11mm flushing and pulse flow events for monitoring locations within the Channels reach; y-axis is the percentage smaller (percent); x-axis is particle size.

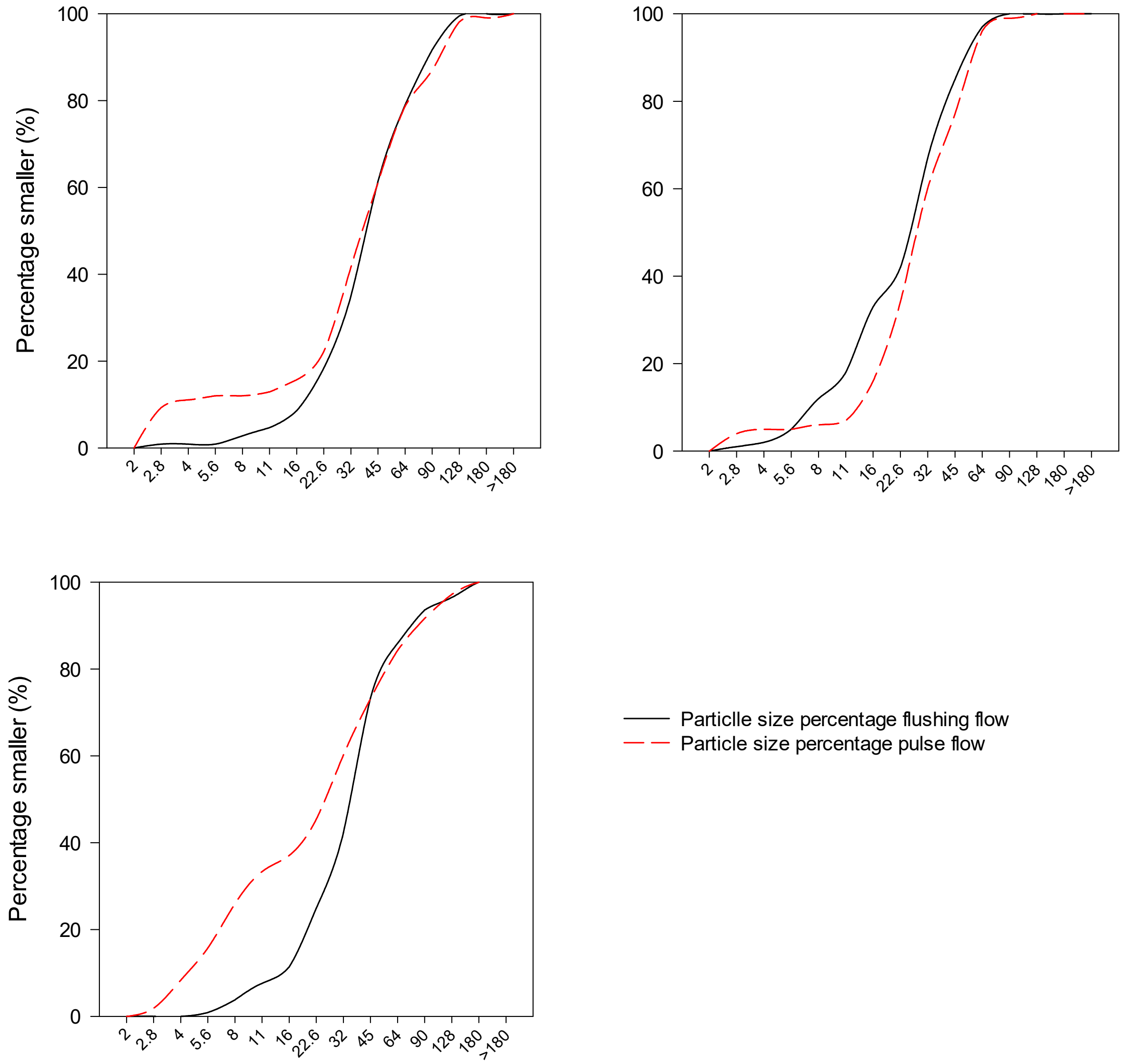

Figure 22. Percentage of Particles ≤ 11mm flushing and pulse flow events for monitoring locations within the Greycliff reach; y-axis is the percentage smaller (percent); x-axis is particle size.

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Appendix A

Madison River Fishery Monitoring related to the Hebgen Dam Gate Failure

Compliance Report 2023

Prepared by

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For

NorthWestern Energy

Introduction

On November 30, 2021, a mechanical failure of the Hebgen Dam gate resulted in an abrupt decrease in the stage of the Madison River. Madison River flows between Hebgen Dam and Quake Lake declined 370 cfs, from 648 cfs to 278 cfs, within 15 minutes (Figure 1). The decline was more protracted in the 13-mile reach downstream of Quake Lake to Lyons Bridge (Figure 1) with flows decreasing 381 cfs, from 780 cfs to 399 cfs, in roughly 48 hours. The rate and volume of water reduction resulted in deviations from NorthWestern Energy's (NWE) Project 2188 Article 403 requirements to: (1) maintain…, a continuous minimum flow of 600 cfs at USGS Gauge No. 6-388 near the Kirby Ranch and; (3) limit changes in the outflow from Hebgen Dam to no more than 10 percent per day for the entire year.

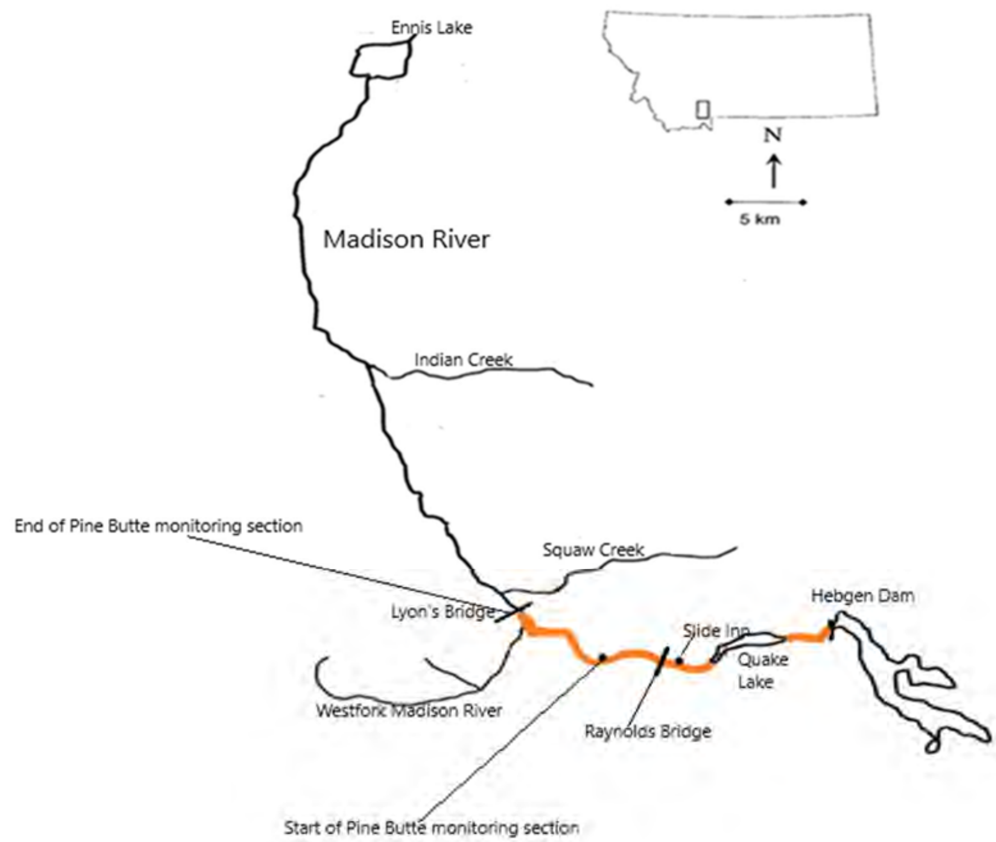

Figure 3. Map of the Madison River and the areas of the river affected by the Hebgen Dam gate failure on November 30, 2021. The area highlighted in orange indicates the areas of greatest concern and the focal area of 2022 monitoring.

Observed impacts to the fishery immediately following gate failure were greatest between Hebgen Dam and Quake Lake where numerous Brown Trout redds along channel margins and in side-channels were dewatered and adult and juvenile salmonids and sculpins became stranded in disconnected side-channels and pools (Figure 2). Below Quake Lake to Lyons Bridge, some Brown Trout redds in shallow side-channels were partially dewatered and juvenile salmonids and sculpin were stranded; however, no stranding of adult fish was observed in this reach. There was minimal change in the river stage downstream of Lyons Bridge to the town of Ennis and no dewatered Brown Trout redds or stranded fish were observed in this reach during initial surveys (Figure 1).

Figure 4. The left panel shows a Brown Trout redd that was dewatered, and the right panel shows stranded juvenile salmonids in the Madison River between Hebgen Dam and the Quake Lake inlet following the rapid reduction in flow and stage during the Hebgen gate failure.

Figure 5. A partially dewatered Brown Trout redd in a side-channel of the Madison River near Lyon's Bridge.

Plan to assess impacts:

To assess the long-term impacts of the Hebgen Dam gate failure to the Madison River fishery the Madison Technical Advisory Committee, comprised of NWE, Montana Fish, Wildlife & Parks (FWP), United States Forest Service, United States Fish and Wildlife Service, and the Bureau of Land Management suggested the following monitoring plan, which was approved by The Federal Energy Regulatory Commission (FERC) on August 18, 2022.

1. Continue developing population estimates in the Pine Butte section (a longstanding electrofishing survey area) on an annual basis to gain information on species ratios and to track cohorts;
2. Conduct backpack electrofishing surveys in the side-channels and margins of the mainstem Madison River (but possibly as far downstream as Kirby) to determine the presence or absence of young-of-the-year (YOY), 1-, and 2-year-old salmonids during the summer of 2022;
3. Conduct electrofishing surveys between Hebgen Dam and Quake Lake to determine catch-per-unit-effort (C/f) and population structure information (provided that electrofishing remains safe in swift currents) in 2022 and 2025; and,
4. Conduct fall redd counts in the Madison River between Hebgen Dam and Quake Lake to identify and document key areas of fish use from 2022 through 2025.

Additionally, a literature review to evaluate whether impacts from the low flow event could have resulted in a total loss of the population or an individual age class was prepared (Appendix A) and mitigation measures to benefit the Madison River fishery, with a focus on improving embryo or young-of-the-year survival, developing or enhancing spawning habitat, and/or protecting key habitats from Hebgen Dam to Lyons Bridge (e.g., tributary habitat improvement, an alternative analysis and preliminary engineering report to evaluate alternatives to improve spawning habitat, gravel recruitment, and embryo survival within the affected reach of the mainstem Madison River) will be developed.

To date, FWP has completed prescribed monitoring (tasks #1-4), and a literature review that evaluated whether impacts from the low flow event could have resulted in a total loss of the population or an individual age class (Appendix A). Additionally, a tributary habitat improvement project and an alternative analysis and preliminary engineering report to evaluate projects that improve spawning habitat, gravel recruitment, and embryo survival within the affected reach of the mainstem Madison River are being developed with completion anticipated in 2024.

This report summarizes the ongoing monitoring tasks completed in 2023 to evaluate the effects of the Hebgen Gate failure on Madison River fish populations.

1) Pine Butte Cohort Recruitment and Species Ratios

FWP estimated trout abundances using mark-recapture techniques in the Pine Butte monitoring section to evaluate the influence of modified project operations at Hebgen Dam and the gate failure (Figure 1). Trout were collected by electrofishing from a drift boat-mounted mobile anode system. Fish captured in the initial trip (marking run) were weighed in grams and their length measured to the nearest millimeter, marked with a fin clip, observed for hooking scars, and released to redistribute. After seven days, FWP conducted a second trip (recapture run) where fish were examined for marks, measured, and unmarked fish weighed. Species ratios and length-specific mark-recapture log-likelihood closed population abundance estimates by age group were generated and standardized to stream mile for Brown and Rainbow Trout using an R-based proprietary FWP fisheries database and analysis tool. Age classifications were adopted from scale data previously summarized for the Madison River fishery as follows: age 1 (152.0mm-276.9mm), age 2 (277.0mm-376.9mm), and age 3+ (>377mm) (Vincent 1973).

All cohorts of Rainbow and Brown trout were observed in 2022 and 2023; however, the proportional composition and abundance of juvenile Brown Trout were relatively low the past two years. The proportion of age 1 and 2 Brown Trout in 2022 were below the 25th percentile, with the cohort that were age 0 during the gate failure (age 1 in 2022 and age 2 in 2023) having the lowest proportional composition in the past 20 years. However, proportional representation of adult Brown Trout is similar to or better than previous years; proportion of age 3+ Brown Trout in 2022 was similar to the 25th percentile and was above the 75th percentile in 2023. Proportion of age 2 Rainbow Trout in 2023 was below the 25th percentile; however, this same cohort was proportionally above the 75th percentile in 2022, suggesting it was not adversely affected by the gate failure.

Table 1. Comparison of the percent composition of Brown Trout (LL) and Rainbow Trout (RB) for the 2022 and 2023 total combined trout estimate and the total combined trout estimated 20-

year median and 25th and 75th percentiles by age group in the Pine Butte section. Values with * are below the 25th or above the 75th percentile.

	Age 1		Age 2		Age 3+	
Species	2022	2023	2022	2023	2022	2023
Brown Trout	14%*	21%	5%*	4%*	9%*	25%*
Rainbow Trout	52%*	38%	9%	6%*	10%	7%
Brown Trout 20-year median	21% (19%, 27%)		8% (7%, 11%)		13% (10%, 17%)	
Rainbow Trout 20-year median	36% (31%, 40%)		10% (8%, 14%)		6% (5%, 10%)	

Overall abundances of age 1 and 2 Brown Trout were below the 20-year average each of the past two years; however, age 3+ Brown Trout abundances were above the 20-year average. (Figure 4). The high abundance of age 1 Brown Trout observed in 2021 did not translate into a strong age 2 cohort in 2022; however, the age 1 estimate obtained in 2021 should be interpreted cautiously because of sampling inefficiency and resultantly high confidences intervals associated with the abundance estimate that year. The age 1 abundance estimates in 2022 and 2023 are likely more representative of actual abundances. The low abundance of age 1 Brown Trout observed in 2022, which was the cohort anticipated to be most affected by the Hebgen gate failure (i.e., age 0 in 2021; Dukovcic et al. 2022), translated to similarly low abundances of age 2 Brown Trout in 2023. However, age 2 Brown Trout abundances have been below the twenty-year average since 2018, suggesting that other factors may also be influencing recruitment. All cohorts of Rainbow Trout were below average in 2023, including those (age 1 and 3+) that were likely minimally or entirely unaffected by the gate failure. The 2022 age 1 cohort, which would have likely been most affected by the gate failure as age 0 fish in 2021, has translated to a below-average number of Age 2 fish in 2023 but the apparent reduction in cohort size occurred well after the gate failure. Adult Rainbow Trout remain statistically similar to the 20-year average and the 2022 estimate (Figure 4). To determine the effects of the 2021 gate failure on the trout population, tracking of cohorts and species ratios in the Pine Butte monitoring reach will be continued for the next three years, and new length-at-age data from otoliths incorporated into the analysis to derive a more precise classification of age groups.

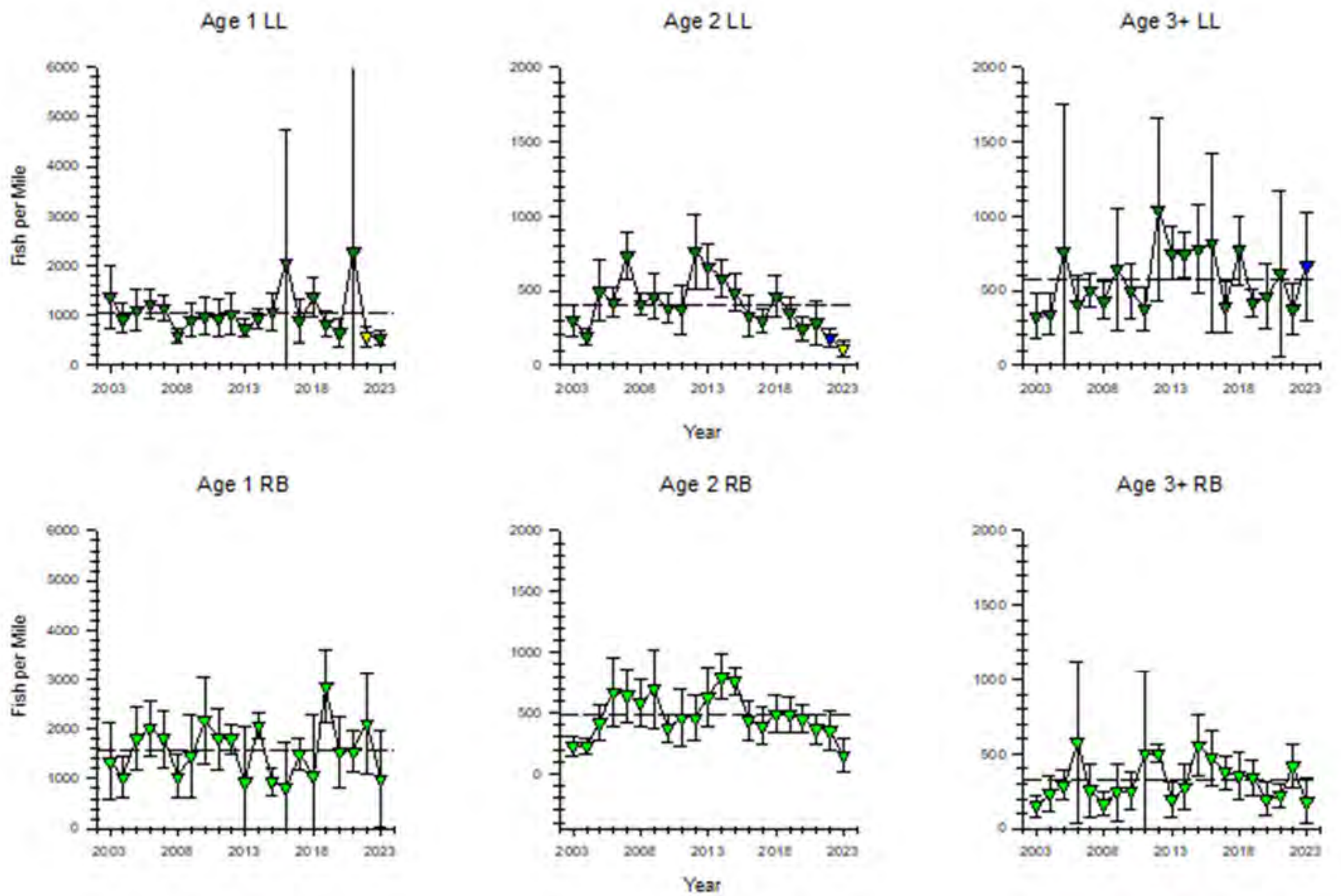

Figure 6. The estimated abundances of Brown and Rainbow Trout by age group in the Pine Butte monitoring section. The dashed lines are the 20-year averages (2003-2023), and the error bars are the 95% confidence intervals. Note that the y-axis is not on the same scale.

2) Juvenile Salmonid Presence Absence Survey

Presence/Absence surveys were completed in 2022 and confirmed that YOY and juvenile salmonids persisted in habitats throughout the reaches of the river most affected by the Hebgen Dam gate failure. Brown Trout YOY were present in 90% of the side-channels sampled in June and 95% in July, while YOY Rainbow Trout were present in 90% of the side-channels sampled in July. Rainbow Trout YOY absence from the June sample is attributable to emergence timings described by Downing (2001) and resulted in clear size differentiation between Brown and Rainbow Trout YOY; Brown Trout YOY were on average 20mm longer than Rainbow Trout YOY. Age 1 Brown (70% and 75%) and Rainbow Trout (80% and 40%) were present in the majority of side-channels during both sampling periods. Age 2 Brown (15% and 35%) and Rainbow trout were present in (10% and 35%) of the side-channels sampled. No Mountain Whitefish YOY were observed, age 1 Mountain Whitefish were present in 5% and 20% of side-channels, and age 2 Mountain Whitefish were present in 5% of side-channels in the respective sampling periods (Lohrenz et. al 2022).

3) Catch-per-unit effort survey of the Madison River between Hebgen Dam and the Quake Lake inlet

FWP performed a catch-per-unit (C/f) survey to collect population structure information for salmonid species in the Madison River between Hebgen Dam and the Quake Lake inlet on September 6, 2023. Fish were collected by electrofishing from a drift boat-mounted mobile anode system. Fish captured were weighed in grams and measured to the nearest millimeter. The section length was used as the measure of effort and age-specific C/*f* estimates of relative abundance were generated and standardized to stream mile for Brown and Rainbow Trout, and Mountain Whitefish using an R-based proprietary FWP fisheries database and analysis tool.

Catch-per-unit-effort sampling between Hebgen Dam and Quake Lake showed lower relative abundances for all fish species and age classes than anticipated, which may be a direct result of the swift and deep river conditions present throughout the section; sampling efficiencies were low and not directly estimated or corrected for. Rainbow Trout and Mountain Whitefish comprised the majority of the fish sampled in 2022 and 2023, and Brown Trout were at low relative abundances in both years (Table 2). The paucity of Brown Trout observed in the section may be attributable to the lack of habitat features such as undercut banks and large woody debris throughout the sampling reach. As reported previously, YOY, age 1, and age 2 Brown and Rainbow Trout were present in the side-channels between Hebgen Dam and Quake Lake; however, only mainstem habitats were sampled during the C/*f* survey (Lohrenz et.al. 2022).

Table 2. Catch per unit effort (C/*f*) per mile by age group in millimeters for Brown Trout (LL), Rainbow Trout (RB), and Mountain Whitefish (MWF) below Hebgen Dam to the Quake Lake inlet.

	Age 0		Age 1		Age 2		Age 3+	
Species	2022	2023	2022	2023	2022	2023	2022	2023
LL	1	0	1	0	0	0	5	4
RB	8	2	28	4	12	6	15	27
MWF	11	0	4	39	5	82	70	57

Data collected in 2023 suggested the age 0 and 1 MWF cohorts of 2022 recruited well to the age 1 and age 2 classes in 2023 (Table 2). The Rainbow Trout 2022 age 2 cohort translated into a slightly higher relative abundance of age 3+ fish in 2023, while the age 1 2022 Rainbow Trout cohort showed a marked decline as age 2 in 2023 (Table 2). Brown Trout numbers were similar between years (Table 2). C/f surveys will continue to be conducted through 2025 and compared to subsequent surveys to assess potential effects of the Hebgen gate failure. However, general, sampling conditions, normal fluctuations in abundances, and the lack of prior data in this section may make statistically linking future observations to the gate failure difficult. Electrofishing surveys in large rivers inherently produce abundance estimates with notable uncertainty (i.e., relatively large confidence intervals for abundance estimates), which inhibits our ability to statistically detect and attribute population changes to the dam failure. Estimated Brown and

Rainbow trout abundances of fish 152 mm (~6”) or greater in the Pine Butte Section fluctuated on average 28% and 31%, respectively, from year-to-year since 2000. If the trout population downstream of Hebgen Dam has similar variation as the population in the Pine Butte Section, the low and uncertain efficiency associated with C/f sampling may mask potential influence of the dam failure in this reach. However, observed trends in long-term sampling reaches elsewhere that are influenced by similar environmental conditions found downstream of Hebgen Dam may be used to help explain deviations in abundances in the new monitoring section from what might be expected based on conditions in future years (i.e., are the trout populations between the lakes exhibiting different trends than tailwaters elsewhere in SW Montana).

4) Fall Redd Counts

FWP conducted Brown Trout redd counts on November 6, 2023, in the Madison River between Hebgen Dam and Quake Lake to identify and document key areas utilized by Brown Trout for spawning. River discharge at the time redd counts were conducted was 834 cfs (measured at the USGS 06038500 Grayling gage below Hebgen Lake). Redd counts were done by walking in an upstream direction and visually identifying streambed disturbances consistent with redd morphology (Gallagher et al. 2007). A typical redd consists of a defined pit where gravel was excavated with a mound of gravel (tail spill) immediately downstream of the pit (Figure 5). GPS coordinates were recorded and redd locations were mapped using Google Earth (Figure 6).

Figure 5. Brown Trout redds in a side-channel of the Madison River between Hebgen Dam and the Quake Lake inlet, November 2022.

Figure 6. Locations of redds identified in the Madison River between Hebgen Dam and the Quake Lake inlet. The blue dots are redds observed in 2022 and the yellow dots are redds observed in 2023. The size of the dot is a general representation of redd density (i.e., the larger the dot the greater the number of redds at that location).

Similar to redd counts in 2022, side-channel habitats were used most by Brown Trout for spawning in the Madison River between Hebgen Dam and the Quake Lake inlet in 2023 (Figure 6; Table 3). Of the 161 redds identified, 136 were located in side-channels and 29 were located within the main river channel, which is an increase from 2022 (Table 6). The increase in the number of mainstem redds observed is likely due to greater discharge (834 cfs, November 9, 2023) than in 2022 (689 cfs, November 15) a difference of 145 cfs, which based upon the wetted perimeter and discharge relationship curve for the Madison River below Hebgen Dam is approximately 0.9 acres of nearshore habitat that would have been wetted in 2023 (FWP 1989). The high concentration of redds within side-channels may be a function of higher quality habitat and more suitable water velocities. Gravels selected for redd construction typically have a median diameter ≤ 10% of the female's body size and can be easily excavated (Chambers et. al 1955; Kondolf and Wolman 1993). While side-channel habitats had the potential to be dewatered and disconnected during the 2021 gate failure, egg mortality was likely low because flows were restored within 44 hours. Literature reviewed by Dukovcic et al. (2022) suggested trout eggs early in development can withstand 1-5 weeks of complete dewatering as long as the relative humidity in the gravel remains fairly high. This is consistent with the findings of the 2022 side-channel survey where numerous Brown Trout YOY were observed.

Table 3. The number of Brown Trout (LL) redds observed by year and habitat type. Discharge (Q) cfs at the time of counts.

Year	Q (cfs)	Main stem LL redds	Side-channel LL redds	Total LL redds
2022	689	14	151	165
2023	834	29	132	161

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Hebgen Dam Gate Failure Literature Review: Effects of Dewatering on Salmonid Species

Madison River, Montana

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Introduction

A well-known tailwater trout fishery, the Madison River runs for approximately 180 miles from its headwaters in Yellowstone National Park through Southwest Montana before joining with the Jefferson and Gallatin rivers to form the Missouri River. The Madison River is one of the most heavily used water bodies in the state, logging over 300,000 angler days in 2020 (FWP 2020). The high angler and commercial guide and outfitter use it receives combine to make it regionally economically important. The Upper Madison averages approximately 1,500 trout per mile near Pine Butte (Lohrenz et al. 2023). Brown Trout (*Salmo trutta*), Rainbow Trout (*Oncorhynchus mykiss*), and Mountain Whitefish (*Prosopium williamsoni*) are the most prevalent and commonly targeted fish species in the Upper Madison River from Hebgen Dam to Ennis Lake (Lohrenz et al. 2022a). Other fish species within the Upper Madison River include native Westslope Cutthroat (*Oncorhynchus clarkii lewisi*), Arctic Grayling (*Thymallus arcticus*), Rocky Mountain Sculpin (*Cottus bondi*), Mountain Sucker (*Catostomus platyrhynchus*), and Longnose Sucker (*Catostomus Catostomus*).

Flows on the Madison are regulated by two dams, Hebgen Dam and Madison Dam, owned and operated by NorthWestern Energy (NWE) under the 2188 license granted by the Federal Energy Regulatory Commission (FERC) for hydropower operations on the Madison and Missouri rivers. Minimum flows within the 2188 project license (Article 403) are set at no lower than 150 cfs at Hebgen outflow (USGS gage # 6-3850), 600 cfs at Kirby (gage # 6-388), and 1100 cfs at Madison Dam (gage # 6-410) with no more than a 10% change in daily outflows from Hebgen Dam. To minimize erosion of Quake Lake, maximum flow at Kirby is 3500 cfs. The average annual flow of the Upper Madison River from Hebgen to Ennis Dam is 1444 cfs (USGS gauge #6040000; 1951-2023).

On November 30, 2021, a gate failure at Hebgen Dam decreased the flow on the Madison River between Hebgen and Quake Lake from 648 cfs to 228 cfs in 45 minutes. The flow remained at 248 cfs for 40 hours with an estimated of 3.4 acres of near shore habitat and several side-channels dewatered (Lohrenz et al. 2022b). The rapid decrease in flow left numerous Brown Trout redds exposed to potentially lethal air temperatures and many juvenile and adult Brown Trout, Rainbow Trout, Mountain Whitefish, and Rocky Mountain Sculpin stranded and disconnected from flow. This event caused a 65% change of flow in 45 minutes and a deviation from the 10% per day change allowed at Hebgen Dam by Article 403 of the 2188 license. Flow also decreased below the Article 403 minimum of 600 cfs at the Kirby gage to 395 cfs for approximately 48 hours. Flows were restored to 648 cfs and all side-channels and near shore habitat was re-inundated on December 2, roughly 48 hours after initial loss of flow.

NWE submitted a proposal for protection, mitigation, and enhancement measures in response to the gate failure on March 23, 2022 that was confirmed by FERC on August 18, 2022 that included conducting a literature review to evaluate whether impacts from the low flow event could have resulted in a total loss of the population or an individual age class. Investigation of literature that describes the effects of hydropower-related flow fluctuations on fish life stage and assemblage provides insight into the potential effects the sudden flow reduction may have had on the Madison River fishery. To provide framework for evaluating the extent of impacts on the Madison River fishery, the goals of this literature review are to 1) describe life histories of affected fish species (Brown Trout, Rainbow Trout, Mountain Whitefish, and Rocky Mountain Sculpin), 2) synthesize effects of similar stranding and dewatering events on all fish life stages, and 3) identify knowledge gaps relevant to the gate failure and stranding and dewatering events for the Madison River.

Life History

Brown Trout, Rainbow Trout, and Mountain Whitefish

Brown Trout, Rainbow Trout, and Mountain Whitefish belong to the Salmonidae Family and have overlapping ranges (Moyle and Cech 2004b). Salmonids inhabit cold-water streams in North America and are highly regarded for their economic, social, and recreational value (Moyle and Cech 2004b). Brown Trout are native to Europe, North Africa, and Western Asia, but were first introduced to the United States in 1883 (Gilbert and Williams 2002; Klemetsen et al. 2003). Rainbow Trout native range includes much of Western North America in the Pacific Coast drainages from Mexico to Alaska (Raleigh et al. 1984). Similarly, Mountain Whitefish are indigenous to Western North American rivers (Brown 1972; Meyer et al. 2009). In Montana, both Brown Trout and Rainbow Trout were introduced to the headwaters of the Madison River in 1889 (Alvord 1991).

Although from the same family, Brown Trout, Rainbow Trout, and Mountain Whitefish exhibit different life history strategies (Table 1). Brown Trout and Mountain Whitefish spawn in the fall while Rainbow Trout spawn during spring months (Table 1; Brown 1972; Raleigh et al. 1984; Klemetsen et al. 2003). Female Brown Trout and Rainbow Trout construct and deposit eggs into a redd, a mound of gravel designed to increase the flow of water and dissolved oxygen to the egg pocket for proper development (Tonina and Buffington 2009). Mountain Whitefish are dispersal spawners and their eggs are released directly into the water column without construction of a nest and displace downstream into low velocities areas (Boyer 2016). Variation in duration and timing of incubation and emergence of salmonid fry is largely a function of water temperature, but emergence of fry typically occurs in early spring for Brown Trout and Mountain Whitefish with Rainbow Trout fry emerging later in the spring to early summer months (Table 1; Bjorn and Reiser 1991; Gilbert and Williams 2002; Klemetsen et al. 2003; Boyer 2016).

Differences in habitat selection occur between juvenile and adult salmonids, but habitat needs between species are relatively similar. Juvenile and young-of-year (YOY) trout prefer shallower habitat and lower velocity areas with stream cover such as log jams, woody debris, overhanging banks, inundated bank margins and interstices of cobbles (Lewis 1967; Raleigh et al. 1984; Klemetsen et al. 2003). Mountain Whitefish rearing areas include slow silty backwaters, eddies, and beaver ponds (Brown 1972; Boyer 2016). In addition, Mountain Whitefish are characterized as being benthically oriented and would typically inhabit lower parts of the water column than Brown Trout and Rainbow Trout (Brown 1972; DosSantos 1985). As body size increases, larger salmonids prefer deeper habitats with cover and can occupy higher velocity areas than juveniles (Raleigh et al. 1984; Bjornn and Resier 1991; Klemetsen et al. 2003). However, habitat use varies seasonally and salmonids tend to seek out areas with deep pools and low velocity to maximize energy savings and survival for overwintering (Lewis 1967; Brown 1972; Cunjak 1996; Klemetsen et al. 2003).

Diet and feeding behavior of salmonids are highly variable by season, time of day, age, and body size within and between populations (Bradford and Higgins 2001; Railsback et al. 2005). Brown Trout, Rainbow Trout, and Mountain Whitefish are visual hunters and feed mainly on drifting aquatic invertebrates or actively forage for insects (Brown 1972; Klemestsen et al. 2003; Syrjänen et al. 2011; Vinson and Budy 2011). Larger salmonids tend to have a wider range of prey items available and larger trout are known to switch to a more piscivorous diet (DosSantos 1985; Klemestsen et al. 2003; Syrjänen et al. 2011; Vinson and Budy 2011). Additionally, larger salmonids outcompete smaller individuals for better feeding positions and habitat (Raleigh et al. 1984; Klemetset et al. 2003). Increased foraging usually occurs during warmer spring and summer months and decreases during the winter (Cunjak 1996; Klemetsen et al. 2003).

Rocky Mountain Sculpin

Sculpin are characterized as a small-bodied, bottom dwelling fish, known for their lack of swim bladder, large pectoral fins, and propensity to feed on salmon and trout eggs (Moyle and Cech 2004a). The Rocky Mountain Sculpin, *Cottus bondii*, is one of six species of sculpin located within Montana. Their range extends from Western to Central Montana although they are also found in two river basins in Canada (Rudolfsen et al. 2018). A non-game species, sculpin have recently gained more attention as a bioindicator of stream health and ecology for fisheries management (Adams and Schmetterling 2007). While many aspects of sculpin ecology and life history remain unknown, fisheries managers and researchers are investigating interactions between salmonids and sculpin with more intensity because of similar diet, behavior, and habitat (Adams and Schmetterling 2007; Adams et al. 2015).

Freshwater sculpins occupy cold-water streams and prefer swift to moderate riffle-run habitats with cobbles and boulders (Moyle and Cech 2004a). Rocky Mountain Sculpin sexually mature at age 2 and spawn in the spring from April to June (Bailey 1951). Male adults construct nests on the undersides of rocks, submerged wood, and/or aquatic vegetation where females will deposit egg clusters (Bailey 1951). The male sculpin remain near the nests while eggs are incubating to guard and clean the eggs of slit and debris. Eggs incubate in roughly 20-30 days and hatchlings average 7.1 mm in length (Bailey 1951). Adult Rocky Mountain sculpin can range in length from 45-70 mm (Bailey 1951). Juvenile sculpin occupy near shore habitats within rocks and larger adults will occupy slightly deeper waters but remain relatively close to the shoreline (Bailey 1951). An analysis of stomach contents shows sculpin mostly feed on benthic macroinvertebrates with a smaller portion of their diet consisting of small trout and trout eggs (Bailey 1951).

Table 1. General life history summaries for Brown Trout (LL), Rainbow Trout (RB), Mountain Whitefish (MWF), and Rocky Mountain Sculpin (RMS). Spawning is the time period from beginning to end of

spawning, spawn method refers to embryo disposition (redd, dispersal, nest), incubation is the time in days for embryos to develop and hatch (FWP unpublished data 2023). Emergence period defines the window when young-of-year fish hatch, habitat describes preferences for juvenile (J) and adult (A) salmonids and sculpin, and food highlights fish diets.

Species	Spawning	Method	Incubation	Emergence	Habitat	Food
LL	Oct-Dec	redd	157-257	Mar-Jun	(J) Cobble interstices, woody debris, channel margins, (A) undercut banks, riffles, pools	Aquatic and terrestrial invertebrates, fish
RB	Mar-Jun	redd	78-136	Jun-Jul		
MWF	Oct-Nov	dispersal		Spring		
RMS	Apr-Jun	nest	20-30	Jun-Jul	(J)(A) Cobble interstices, channel margins	Aquatic invertebrates, fish eggs, juvenile fish

Fish Stranding and Dewatering Effects on Life Stage

The most obvious and direct impact observed by fisheries personnel and volunteers following the Hebgen Dam gate failure and from literature review of hydropower operations was fish stranding. Fish stranding occurs when fish become disconnected from suitable habitat without means of escaping. Stranding due to both natural and anthropogenic events has been documented worldwide (Nagrodski et al. 2012). The most frequent causes of fish stranding are on regulated river systems during dam operations such as hydropeaking and plant shutdowns (Nagrodski et al. 2012). Hydropeaking is a method of meeting high energy demands on regulated river systems by rapidly ramping up flow and down ramping when energy usage is lower. Several studies investigated the relationship between down ramping rate and fish stranding using rates of 6-60 cm/hr to simulate hydropeaking dewatering scenarios (Bradford et al. 1995; Saltveit et al. 2001; Halleraker et al. 2003; Irvine et al. 2009; Sauterleaute et al. 2016). Saltveit et al. (2001) found 60% of wild, young-of-year Atlantic Salmon stranded during a flow reduction from 110 m^3/s to 30 m^3/s in 42 minutes, a proportional change in flow of 73%. The magnitude of flow reductions were set at 12.5% or 20% to emulate fish stranding for a study on the Columbia River and ramping rates used ranged from 3.9 – 35.3 cm/hr (Irvine et al. 2009). The gate failure at Hebgen dam resulted in a proportional change in flow of approximately 65% and a change in stage of 22 cm in 45 minutes (29 cm/hr), which is within the range of down ramping rates that caused or was used to assess the effects of fish stranding in other studies. Effects of fish stranding on life stage is outlined below and summarized in Table 2.

Eggs, embryos, alevins: Salmonid eggs are more tolerant to periods of dewatering than later stages of development (Becker et al. 1982; Reiser and White 1983; Neitzel and Becker 1985; McMichael et al. 2005). High relative humidity within the gravel of the redd allows eggs to survive periods of dewatering because eggs can absorb oxygen through the air (Bjornn and Reiser 1991). Reiser and White (1983) found salmonid eggs could survive 1-5 weeks of complete dewatering with no negative effect on development or growth if eggs were close (10 cm below egg pocket) to groundwater. McMichael et al. (2005) concluded that many redds were not truly dewatered because Chinook Salmon egg pocket depths can range from 18 to 43 centimeters, therefore redds may have remained moist or near groundwater during stranding. Similar findings from Neizel and Becker (1985) showed no mortality of Chinook Salmon eggs that were dewatered for 24 hours in 100% humidity. Additionally, a lab experiment testing the tolerance of Robust Redhorse eggs to dewatering found eggs survived longer periods of dewatering than emerging larvae (Fisk II et al. 2013). Higher mortality rates seen at later developmental phases of fish eggs in dewatered redds is partly due to the lack of available dissolved oxygen to support gill respiration (Becker et al. 1982; McMichael et al. 2005, Fisk II et al. 2013).

Temperature also plays a key role in egg and embryo survival. Freezing and extreme heat conditions within the gravel can be lethal to eggs and later developmental stages (Neizel and Becker 1985; Bjornn and Reiser 1991). Redds that are dewatered lose thermal insulation which may subject them to greater fluctuations in intragravel temperatures from exposure to the ambient air (Becker et al. 1982; Bjornn and Reiser 1991). Eggs and embryos exposed to higher temperatures resulted in altered timing of hatch, development, and growth (Becker et al. 1982; Reiser and White 1983; Bjornn and Reiser 1991). Low air and water temperatures can increase the risk of egg and developing embryo mortality by freezing and slowing growth (Becker et al. 1982; Bjornn and Reiser 1991). Becker et al. (1982) observed lack of advancement in cell division phases in development of Chinook Salmon eggs and higher mortality when eggs had been dewatered for 16 hours, during which mean intragravel temperatures were higher than in shorter treatments. Resier and White (1983) found that dewatered Steelhead eggs hatched earlier than watered eggs due to exposure to higher temperatures within egg pocket which resulted in larger alevins from the earlier hatched group. Garrett et al. (1998) observed faster development and earlier hatching of Kokanee Salmon in a stream in Idaho that was influenced by groundwater; upwelling sites were 2°C warmer than redd areas without upwellings.

Juvenile Fish: Juvenile fish are more vulnerable to stranding and mortality because they tend to occupy high risk habitats and have a weaker swimming ability than adult fish (Hayes et al. 2019). However, juvenile fish respond differently to rapid flow decreases depending on season and time of day (Bradford et al. 1995; Saltveit et al. 2001; Halleraker et al. 2003; Nagrodski et al. 2012; Irvine et al. 2015). Higher stranding and mortalities in juvenile salmonids are associated with high ramp rates, low gradients, coarse substrate (i.e., more cover), and cold-water temperatures (Bradford et al. 1995; Halleraker et al. 2003; Sauterleute et al. 2016). Bradford et al. (1995) found juvenile Rainbow Trout stranding in the winter significantly decreased during experiments that simulated down ramping at night compared to day-time experiments in an artificial stream channel. In the winter during the day, juvenile salmonids typically seek shelter within the interstices of streambed cobbles and are less active than at night (Bradford et al. 1995; Irvine et al. 2015). Therefore, rapid changes in flow during the day in the winter put juvenile fish at greater risk to stranding because they are not active in the water column (Bradford et al. 1995). Stream areas with low cover (i.e., smaller substrate, no large wood debris) are expected to have lower stranding potential because juvenile fish do not occupy areas where stranding is likely (Halleraker et al. 2003). These studies support that the proportion of stranded juvenile salmonids decreased significantly when down ramping occurred at a slow rate at night due to diurnal and seasonal behavior changes (Bradford et al. 1995; Saltveit et al. 2001; Halleraker et al. 2003; Nagrodski et al. 2012; Irvine et al. 2015).

Rapid flow decreases can have negative effects on juvenile fish even when stranding and direct mortality do not occur. Sub-lethal effects on juvenile trout include increased stress levels, higher energy use, and reduced growth (Flodmark et al. 2002; Halleraker et al. 2003). A lab experiment on age 1 juvenile Brown Trout measured cortisol levels in a control (constant flow) and experimental group (rapid reduction in flow) and found stress levels to be significantly higher in the experimental group (61.3 ng/ml +/- 26.8 ng/ml) than the control group (4.9 +/- 3.7 ng/ml) after one day of the trial (Flodmark et al. 2002). However, after 4 days of treatment cortisol levels returned to “pre-stress” values in the experimental group. Flodmark et al. (2002) showed juvenile salmonids acclimated to their environment but that over time constant exposure to stressful stimuli may still be detrimental and have population level effects (i.e., decreased growth rate, poor recruitment).

Adult Fish: In general, adult fish are expected to be less vulnerable to mortality due to stranding because they are more adaptive to sudden changes in discharge on regulated river systems than juvenile fish. Pander et al. (2022) observed smaller, weaker swimming fish had higher rates of stranding than larger fish that preferred open water habitat. Using habitat preference curves, Jelovcia et al. (2022) showed adult Arctic Grayling had higher average suitability indices during 5 different hydropeaking scenarios than juvenile Brown Trout, suggesting that adult fish had a wider range of suitable habitats during different flows. Adult fish are more mobile, have better swimming ability, and occupy deeper habitats that have lower risk of dewatering compared to juvenile fish that occupy near shore habitats (Irvine et al. 2015; Vollset et al. 2016; Hayes et al. 2019; Jelovica et al. 2022).

Other factors affecting adult fish during rapid fluctuations in flow, are access to spawning areas, abandoning nest sites, altered migration, displacement of food, increased predation, and increased stress (Quinn et al. 2001; Grabowksi and Isley 2007; Young et al. 2011, Vollset at al. 2016). Grabowski and Isely (2007) suggest the possibility of increased mortality of Robust Redhorse due to redd superimposition because of decreased flows on the Savannah River that limit access to critical spawning habitat. Chaotic swimming behavior and frequent abandoning of nest sites was observed by Vollset et al. (2016) when Atlantic Salmon and Brown Trout were subject to rapid fluctuations in flow during spawning, indicating increased stress. Conversely, rapid increases in flow on two hydropeaking rivers in Finland triggered spawning migrations in Atlantic Salmon (Vehanen et al. 2020).

The effects of dewatering can vary among salmonid life stages from direct mortality to non-lethal effects such as altered emergence, development, and increased stress (Becker et al. 1982; Reiser and White 1983; Flodmark et al. 2002; Vollset et al. 2016). Impacts of dewatering can also depend on season, time of day, and river channel morphology (Bradford et al. 1995; Saltveit et al. 2001; Halleraker et al. 2003; Nagrodski et al. 2012; Irvine et al. 2015). Table 2 summarizes dewatering impacts.

Table 2. Summary of dewatering effects on fish life stage (eggs, juveniles, and adults). Level of impact ranges from low (L), medium (M), and high (H) based on findings in this literature review.

		Impact		
Life Stage	Range	L	M	H
Eggs	L-H	Diffuse 0_2 through air with high humidity, Groundwater buffer	Altered timing of development and emergence	Increased risk of lethal intragravel temperatures, Increased reliance on gill respiration as eggs develop
Juveniles	M-H		Increased stress, Lower growth rates, Diurnal and seasonal behavior changes	Occupy shallow near shore habitats, Weaker swimming ability
Adults	L-M	Occupy deeper habitats Better swimming ability	Increased stress, Limited access to spawning areas, Altered migration, Increased predation, Food displacement	

Population Level Effects and Vital Rates

Survival rates vary greatly depending on the timing of dewatering. If dewatering occurred during the early stages of egg incubation, survival rates of eggs could be higher than if the dewatering occurred just prior to hatching when alevins have formed. For example, researchers on the Columbia River compiled over 30 years of data to describe average survival rates of Chinook Salmon presmolts (age 1-2) in relation to new dam operations. This study observed high mortality and low survival rates during a dewatering event occurring in March and April just prior to hatching (0.15; Table 3; Harnish et al. 2014). A similar dewatering event occurred in mid-November and presmolt average survival was much higher, supporting higher tolerances to dewatering at early egg stages (0.54; Table 3; Harnish et al. 2014). These two dewatering examples highlight the importance of timing of dewatering and the range of effects on survival rates at differing life stages.

Managing flow during critical juvenile life stages may influence population dynamics to a greater extent than other age classes because of density dependence. Two studies using vital rates looked at fry (0+) and juvenile (1+) age classes to determine the effects of stranding on Atlantic Salmon and Coho Salmon populations due to hydropeaking (Sauterleaute et al. 2016; Gibeau and Palen 2021). Both models incorporated density dependence that illustrated how some mortalities due to flow fluctuations may be offset if there is high density dependent compensation. Gibeau and Palen (2021) found high density dependence was able to compensate for mortalities in low impact scenarios (1-5 dewatering events per year), but density dependence did little to offset mortalities when dewatering events were frequent (16-20 events per year) for Coho Salmon. In addition, Sauterleaute et al. (2016) suggested that stranding of older Atlantic Salmon juveniles plays a larger role in population dynamics because of reduced density compensation at later life stages. Whereas fry to smolt survival and ocean survival for Coho Salmon appeared to have the largest impact on population growth (Gibeau and Palen 2021), these studies point towards dam mitigation strategies that prioritize juvenile age classes when considering flow alterations for these systems.

Population dynamics and vital rates can vary widely between systems and species (Table 3). Brown Trout, Chinook Salmon, and Atlantic Salmon are fall spawners with similar life history characteristics; therefore, it may be appropriate to use vital rates for these species to understand potential effects of dewatering in the Madison River. For instance, average Brown Trout age 0+ survival, in a system that was not regulated (no dewatering), was 0.26 and maximum survival was 0.47 (Table 3; Dieterman and Hoxmeier 2011). Average Chinook Salmon age 0+ survival during dewatering was 0.29 with a maximum of 0.67 (Table 3; McMichael et al. 2005). In contrast, average age 0+ survival for Atlantic Salmon during a dewatering experiment was 0.89 with a maximum of 1.00 (Table 3; Casas-Mulet et al. 2014). While comparisons of survival rates among salmonids with and without dewatering are limited by few studies and parochial factors, it is important to note that 100% cohort mortality did not occur in any study.

Table 3. Summary of dewatering (D) average survival rates and no-dewatering (ND) average survival rates from published sources by age class (0, 1, 2+) for Brown Trout, Chinook Salmon, Atlantic Salmon, Bull Trout, Bonneville Cutthroat, and Mountain Whitefish. Survival rates in () are maximum survival rates observed.

	0+		1+		2+	
Species	D	ND	D	ND	D	ND
Brown Trout[a]		**0.26** (0.47); 9 months		**0.43** (0.50); 1 year		
Chinook Salmon[bc]	**0.29** (0.67); 5 months		**0.15** (0.54); 1 year			
Atlantic Salmon[d]	**0.89** (1.00); 4 months	**1.00** (1.00); 4 months				
Bull Trout[e]				**0.09** (0.60); 1 year		
Bonneville Cutthroat[f]				**0.41** (0.52); 1 year		**0.45** (0.55); 1 year
Mountain Whitefish[g]						**0.82** (0.91); 1 year

[a] Dieterman and Hoxmeier 2011; [b] McMichael et al.2005; [c] Harnish et al. 2014; [d] Casas-Mulet et al.2014; [e] Al-Chokhachy and Budy 2008; [f] Budy et al. 2007; [g] Meyer et al. 2009

Discussion

Several papers discuss water management approaches to reduce the stranding of fish due to rapid changes in flow on hydropeaking rivers. Duration, timing, and magnitude of flow fluctuations appear to have the largest influence on stranding rate. As discussed earlier, juvenile salmonids were found to strand less frequently if flow reductions occurred at night and were conducted more slowly during the winter (Salveit et al. 2001; Halleraker et al. 2003; Nagrodski et al. 2012; Irvine et al. 2015; Sauteleute et al. 2016). Conditioning flows have been used to train fish to avoid areas of stranding by rapidly reducing flow and increasing flow again before a significant reduction; however, this type of manipulation produced mixed results (Irvine et al. 2015). Avoiding large reductions in flow during spawning and intragravel development is considered critical to survival of several fish species on the Columbia and Kootenay Rivers (Irvine et al. 2015). Hayes et al. (2019) emphasizes the importance of establishing the “emergence window” on a river system for salmonid species and to stabilize flow during this time period. Overall, knowledge of specific habitat use of different life stages of fish species is crucial when considering flow fluctuations in a regulated river system.

Brown Trout and Mountain Whitefish egg mortality was likely low during the Hebgen gate failure that caused Brown Trout redds to be dewatered for approximately 48 hours. Salmonid eggs can tolerate several weeks of dewatering depending on temperature and humidity (Resier and White 1983). Neitzel and Becker (1985) observed 0% mortality of salmonid eggs that were dewatered for 24 hours in 100% humidity. Average air temperature near Hebgen Dam during the dewatering period was 36.5°F and the minimum temperature was 25°F (Montana SNOTEL Site West Yellowstone (924)). Although near lethal temperatures, this SNOTEL site is roughly 300 feet higher in elevation than where the dewatered redds were located; therefore, it is possible temperatures were not as low at the dewatered area or within the gravels. In addition, relative humidity within the dewatered redds may have been maintained at or near 100% because of trapped water and groundwater influence. Lastly, the gate failure on the Madison River occurred at the end of November, during the end of Brown Trout spawning. In this respect, the timing of the gate failure on the Madison that resulted in dewatering of redds, may not have had detrimental effects on Brown Trout eggs because eggs were early in development and can diffuse oxygen through the air rather than relying on gill respiration.

Juvenile Brown Trout, Rainbow Trout, Mountain Whitefish, and Rocky Mountain Sculpin likely experienced the highest mortalities from the gate failure because of swimming ability, habitat use, and behavior (Bradford et al. 1995; Halleraker et al. 2003; Pander et al. 2022). Juvenile fish typically occupy shallow near shore habitats with overhead cover or burrow in the interstices of cobble to hide from larger predators. An estimated 3.4 acres of juvenile habitat was dewatered between the lakes during the Hebgen gate failure (Lohrenz et al. 2022b). Although some juveniles escaped or were rescued, many mortalities were observed in these areas on the Madison River. However, it remains possible that demographic effects of the gate failure are negligible if compensatory density dependence occurs. Future monitoring will directly assess cohort-specific abundance of Brown and Rainbow Trout to determine whether high morality of juvenile fish occurred.

Adult Brown Trout, Rainbow Trout, and Mountain Whitefish were likely the least affected by dewatering below Hebgen Dam. Reviewed literature suggests that adult fish suffered fewer direct mortalities from dewatering because of their larger body size, greater mobility, and diverse habitat use (Irvine et al. 2015; Vollset et al. 2016; Jelovica et al. 2022). However, indirect effects such as increased stress, limited access to spawning areas, and disrupted spawning during the dewatering period, could have population level effects such as reduced growth rate and produce a weak cohort (Grabowski and Isely 2007; Vollset et al. 2016).

Given the variation in vital rates and the wide range of anthropogenic flow fluctuations among systems, it is somewhat difficult to make conclusive inferences about potential impacts to fish populations on the Madison River from other studies. Vital rates are a valuable tool for fisheries managers to assess management alternatives and, in the case of regulated systems, operational impacts, but developing precise estimates of these parameters is often costly and labor intensive. Few studies have quantified population level effects and survival rates of fish during a dewatering event or comparatively assessed differences between dewatering and non-dewatering demographic rates (Gibeau and Palen 2021). This summary of estimated survival rates based on published literature for salmonid species provides a coarse indication of potential population level effects and should be viewed conservatively.

Reviewed literature suggests the gate failure at Hebgen dam is unlikely to have caused catastrophic damage to the Madison River fishery or total loss of fish populations or individual age classes. Juvenile Brown Trout, Rainbow Trout, Mountain Whitefish, and Rocky Mountain Sculpin likely had the highest mortalities, followed by adults and salmonid eggs. In addition, it is possible that demographic effects could be reduced if density dependent compensation occurs. Gibeau and Palen (2021) showed greater negative impacts on fish populations when there are frequent hydropeaking events. The dewatering event on the

Madison River was not the result of a scheduled decrease in flow. Most reviewed studies described scheduled and repeating hydropeaking events. Furthermore, Hebgen Dam is not a power producing facility and therefore would not be subject to hydropeaking. The incident on the Madison River was a unique situation; however, research on rivers that experience regular rapid increases or decreases in flow and experiments highlighting the effects of dewatering on fish provide valuable insight about potential effects of the Hebgen gate failure.

Future research on the Madison should consider available habitat, depth and water stage for critical life stages of trout, especially juveniles, when evaluating changes in flow. Specifically, loss of shoreline and other complex habitats to dewatering at different discharges should be quantified. This information, in conjunction with ongoing monitoring, would provide a better understanding of how typical or unplanned hydropower operations may affect Madison River fish populations. If a higher resolution understanding of effects of hydropower operations in general or the Hebgen gate failure in particular is desired, then precise estimation of vital rates may be necessary. However, this is a costly and labor-intensive approach, and this resolution of data may not be necessary to inform management decisions or make inference about effects. Continuing to pursue novel information specific to the Madison River will aid in refinement of hydropower operations and prioritization of protection, mitigation, and enhancement measures.

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Appendix B

Arctic Grayling- Remote Site Incubator vs Simulated Broadcast Spawning Study

Introduction

Throughout the Mountain West, RSIs (Remote Site Incubators) have been used to introduce salmonid embryos into waters in remote locations. They provide developing embryos with shelter and increase survival rates (Shepard, et al 2021). However, RSI deployment is labor intensive and their success has varied widely among species (Haugen et al. 2000; Magee et al. 2006; Anderson 2016; Anderson 2019). Arctic Grayling embryos are placed in RSIs at a relatively high density but are highly susceptible to fungus, which can spread rapidly causing mortality. This can be mitigated by removing infected embryos, adjusting flow, and repositioning the egg basket but the labor requirements are extensive and additional handling embryos could be detrimental to their survival. Unlike other salmonids that dig a nest in the streambed for embryos to develop, Arctic Grayling are broadcast spawners and their embryos are dispersed in the water column where they eventually settle into the interstices of the stream bed. The dispersal of embryos likely reduces the probability of fungal infection compared to when they are concentrated in RSIs. Given the time constraints and varied success of stocking Arctic Grayling with RSIs, an alternative method may be appropriate. One method to reduce the labor required and increase survival rate for Arctic Grayling embryo introduction is to simulate embryo dispersal as it occurs during spawning.

Our study compared the survival rates of Arctic Grayling embryos stocked using RSIs and a simulated broadcast spawning method. Our goal was to determine if simulated broadcast spawning is a viable alternative to RSIs for stocking Arctic Grayling embryos.

Study Area

Black Sands Springs is located in Custer Gallatin National Forest at an elevation of roughly 9000 ft and flows through approximately 1 mile of lodgepole pine (*Pinus contorta*) forest and riparian plant assemblages before joining the South Fork Madison, which flows into Hebgen Reservoir near West Yellowstone (Figure 1). Black Sands Springs is a low-gradient stream with a year-round flow of 18.7 cfs (Montana Fish, Wildlife & Parks 1989) and was selected for grayling restoration because of the low densities of resident nonnative trout, and overall habitat characteristics that were identified as important to fluvial Arctic Grayling by Hubert et al. (1985) and Kaya (1992), such as constant water temperature, low-velocities, and the presence of gravel substrate for spawning.

Figure 1. Black Sands Springs (red dot) flows into the South Fork Madison River, a tributary to Hebgen Reservoir.

Methods

Arctic grayling propagation approaches were evaluated in Black Sands Springs by comparing embryo emergence rates between 5 RSIs and 5 simulated broadcast spawning net pens . RSIs were installed in the spring heads of Black Sands Springs to provide the elevation drop needed for adequate flow following Rupert et al. (2007) with fry trap boxes attached (Figure 2). The simulated broadcast spawning method used 4 ft x 2 ft x 3 ft rectangular 1/32" mesh net pens anchored to the stream bottom with T-posts with a fry trap attached to the downstream end (Figure 2). Site selection for the broadcast pens was based on Arctic grayling spawning suitability criteria described by Hubert et al. (1985); pens were placed in areas with spawning gravels ranging from 2-64 mm with < 25% fines (< 3 mm), velocities of 0.75-3 ft/s, depths of 0.5-3.0 ft, and water temperatures ranging from 40-55°F. Onset hobo temperature loggers were deployed in each RSI and net pen and recorded water temperatures every hour during embryo incubation from May 20 - June 8.

Arctic Grayling embryos of Madison River genetic origin were obtained from the Rogers Lake population located in Northwestern Montana. Embryos were held until eye-up (approximately 1 week from spawning) at FWP state hatcheries prior to being placed in the stream. About 6,000 Arctic Grayling embryos were enumerated by volume (750 eggs per fluid ounce; Piper et al. 1983) and placed in each RSI and net pen. Fry trap boxes were checked daily during the hatching period from (May 19 to June 8) and fry were enumerated and released. Emergence rates were calculated by dividing the total number of fry observed in each RSI and net pen by the initial number of embryos.

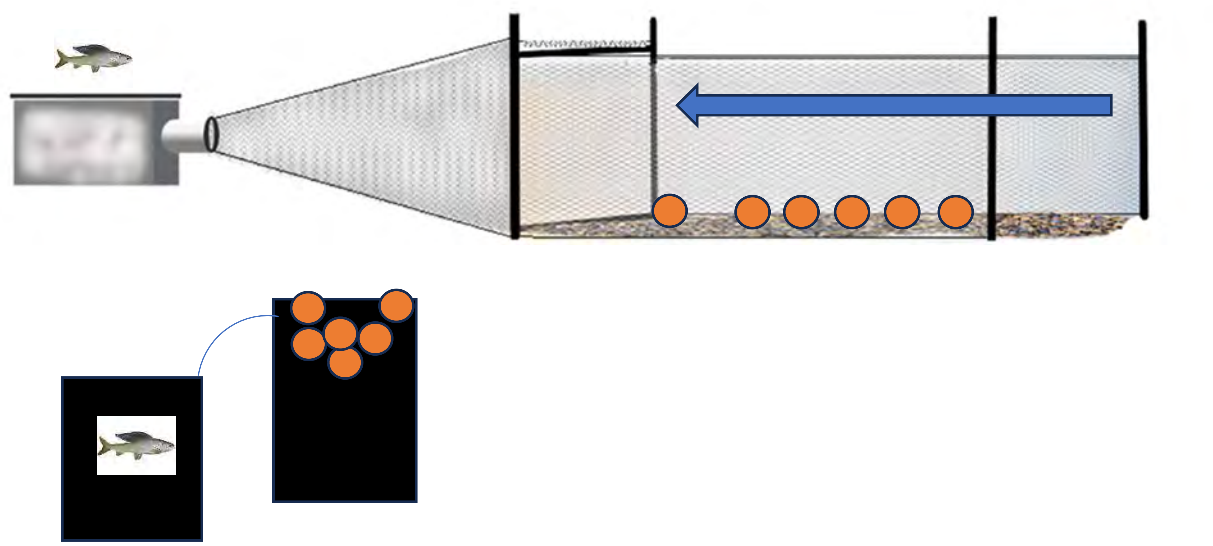

Figure 2. Diagram of experimental design. Top picture depicts broadcast pen set up. Bottom picture depicts remote site incubator (RSI). Orange circles show location of initial egg placement, blue arrow indicates direction of flow. Fry trap boxes are shown with fish picture.

Figure 3. Remote site incubators (RSI) with Arctic Grayling eggs at Black Sands Springs (trap buckets not featured).

Figure 4. Broadcast pen located in Black Sands Spring May 16, 2023.

Results

Embryo survival during the eye-up period at the hatcheries was estimated to be ≤ 40% and likely resulted from not implementing prophylactic measures to prevent fungal growth during the eye-up period (Montana FWP Hatchery personnel; Figure 7) and additional embryo mortality likely occurred during delivery from the hatchery. We were unable to separate viable and dead embryos before distribution, which likely increased the probability of embryo mortality due to fungal contamination.

We found no significant difference in survival between the RSI spawning method and the broadcast spawning method (Figure 5; Mann-Whitney Ranked Sum Test, P = 0.421). Embryo survival for both methods was extremely low; survival rate was less than 0.5% in RSIs and slightly above 1.0% in broadcast spawning net pens. There was a significant difference in the median values of mean daily water temperatures between RSIs (47.4 °F) and broadcast pens (49.6 °F) [Mann-Whitney ranked sum test; U=57, P= <0.001]. Both temperatures are within spawning temperatures for Arctic Grayling, but the slight increase in temperature observed in the broadcast spawning pen may have accelerated embryo development and emergence, which could have reduced the chance of fungal exposure and increased survival. Emergence seemingly occurred sooner in RSIs than in the broadcast pens; however, we speculate that newly emergent grayling within the pens were simply less visible because they were able to occupy interstitial spaces in the stream bed until their egg sacks were absorbed and swimming ability improved. FWP will reconduct the experiment in the spring of 2024 due to poor embryo quality in 2023.

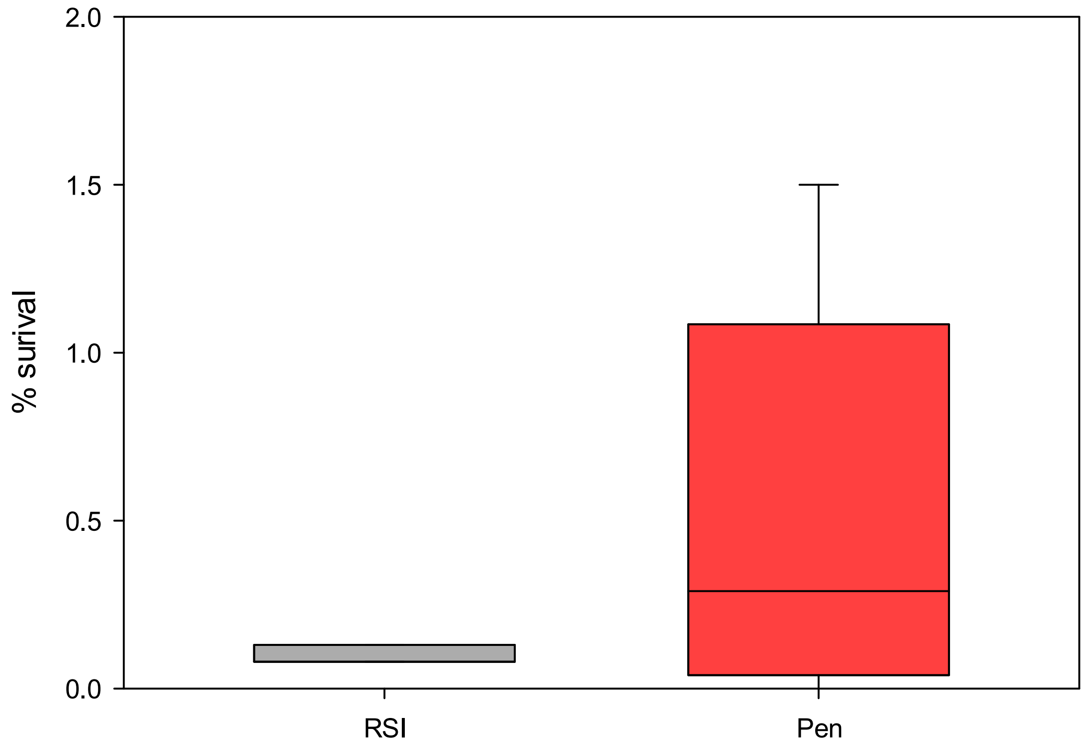

Figure 5. Percent survival of Arctic Grayling embryos in remote site incubators (RSI) and broadcast spawning pens (Pen). Solid lines represent median values, and box whiskers are 95% confidence intervals.

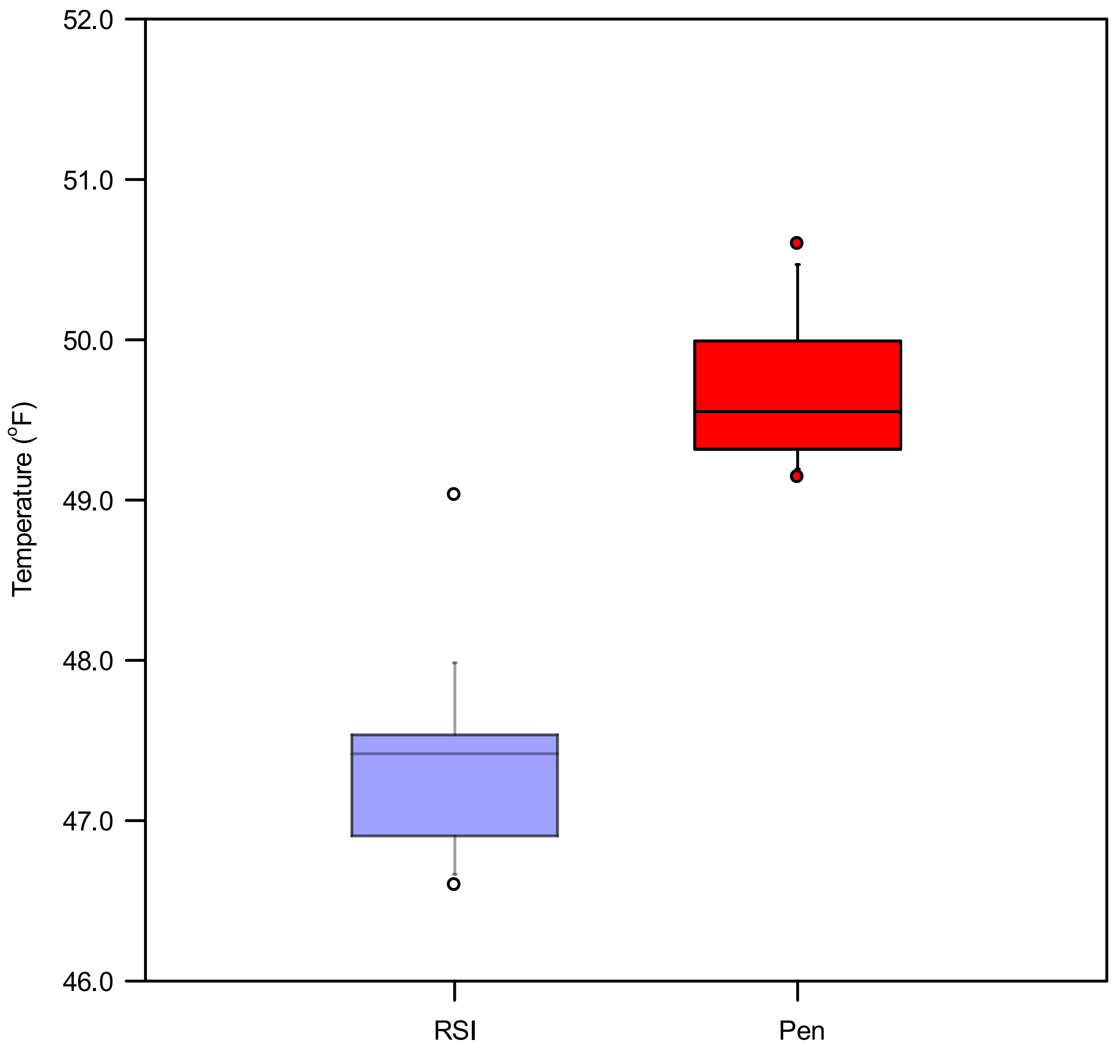

Figure 6. Mean daily temperatures of remote site incubators (blue) and net pens (red) from May 19th-June 8th, 2023. Box represents interquartile range (IQR), solid line indicates the median, whiskers are 5th and 95th percentiles, and dots are outliers.

Figure 7. Arctic grayling eggs with fungus in broadcast net pen.

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