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Madison River Drainage 2188 Project Monitoring Report 2022

To:
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Contents

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 for the operation of 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 2022 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.

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).

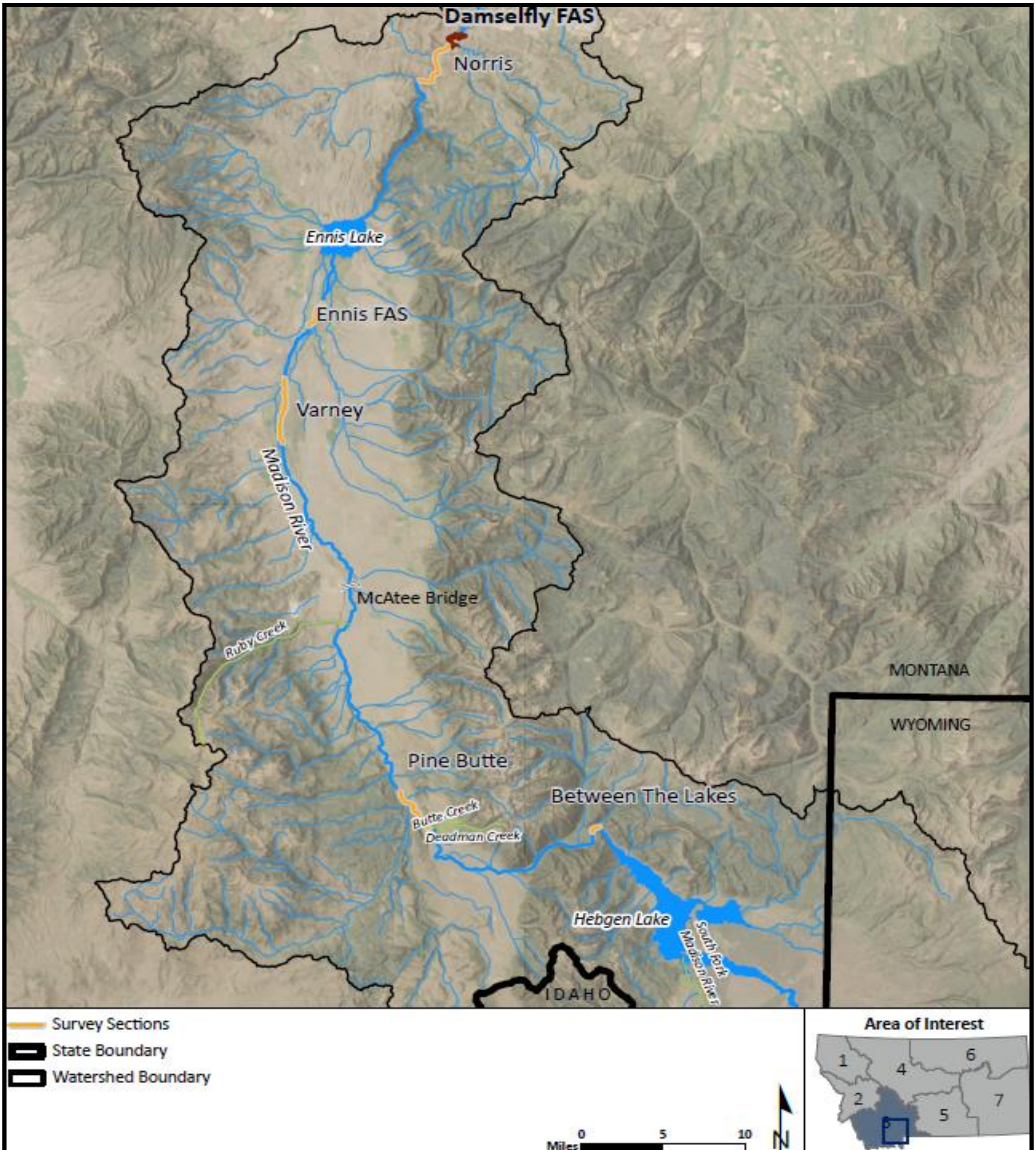

Figure 1. Locations of NWE dams on the Madison River (FERC Project 2188), FWP annual abundance estimate sections, Ennis and Hebgen Lakes, and project areas discussed in this report.

Monitoring and Projects

Article 403-River Discharge:

Article 403 of the Project 2188 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 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 gauge 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 were the result of 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 2022 is summarized in Appendix A and FWP's review of literature relevant to the gate failure is described in Appendix B of this report.

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 was about 20 trout/net in 2022, which was slightly above the long-term average (Figure 2). The CPUE of Brown Trout decreased by about 21% to 14.8 trout/net while Rainbow Trout decreased by 12% to 5.2 trout/net, which are below the management goals for each species (Brown Trout management goal = 15.5 fish/net; Rainbow Trout = 7.5 fish/net). However, the mean lengths of Brown and Rainbow Trout increased to 459 mm (≈ 18") and 433 mm (≈ 17"), respectively, which were above the long-term averages. Eighty-five percent of the Brown Trout captured in gill nets were ≥ 406 mm [≈ 16"], which exceeded the management goal of 75%. Sixty-six percent of the Rainbow Trout captured were ≥ 406 mm, which met the management goal.

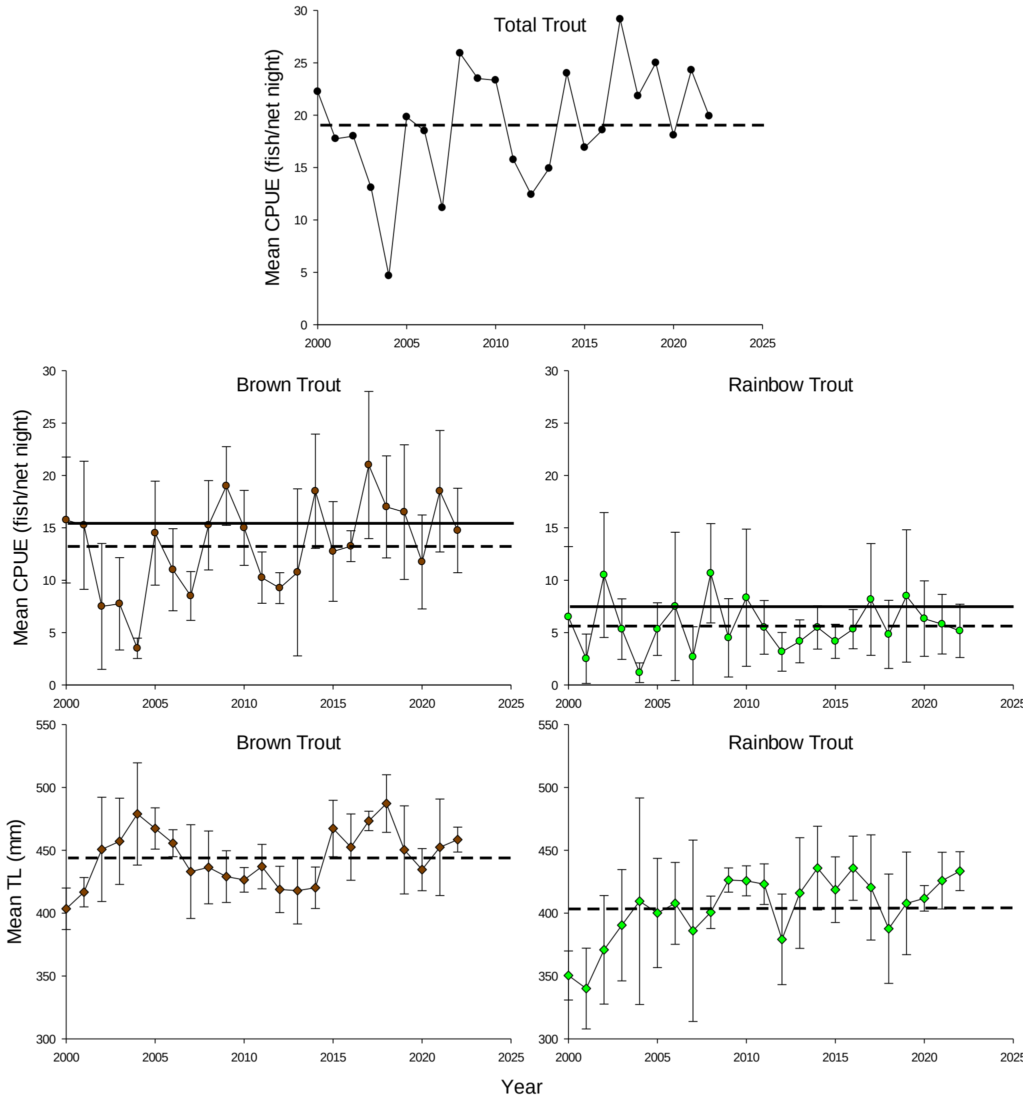

Figure 2. Mean catch-per-unit-effort (CPUE) of total, Brown, and Rainbow Trout captured in Hebgen Reservoir from 2000 to 2022. Total trout abundances represent all trout captured in four sinking and six floating gill nets. Brown and Rainbow Trout CPUE were limited to either sinking or floating gill nets, respectively. Mean total lengths were calculated using all Brown and Rainbow Trout captured each year. Dashed lines are the long-term averages (2000-2022), solid lines are management goals, and error bars are the 95% confidence intervals.

FWP completed a creel survey on Hebgen Reservoir in 2020-2021 (hereafter referred to as the "2020 survey) to characterize angler success and satisfaction following the transition to a wild Rainbow Trout fishery in the reservoir. Creel clerks used similar methodology to a creel survey completed in 2000-2001 (hereafter referred to as the "2000 survey"; Byorth 2004) to assess changes in angler use. However, travel restrictions following the onset of COVID-19 influenced angler use in the recent creel survey, which likely decreased nonresident angler-days and influenced other metrics used to characterize anglers and their use of the fishery as well.

Montana residents composed 56% of the anglers interviewed during the 2020 survey compared to only 39% in 2000. The 2020 creel survey represents nonresident anglers from 38 states and the District of Columbia with nonresidents from Idaho (13%), California (6%), and Utah (6%) composing about 25% of the total anglers interviewed. Anglers were generally pleased with their overall experience with 85% being satisfied or very satisfied (1 being “very unsatisfied” to 5 being “very satisfied; mean = 4.5; Figure 3). Catch rates of Rainbow and Brown Trout nearly doubled between the 2000 and 2020 surveys while harvest rates of Rainbow and Brown Trout were similar between the creel surveys (Figure 4). The mean lengths of Rainbow and Brown Trout harvested by interviewed anglers increased 24 mm and 27 mm (≈ 1”), respectively (Figure 4). Anglers indicated they were slightly more satisfied with the size of fish caught (mean = 3.6) than the number of fish caught (3.2; Figure 3). A thorough analysis and summary of the 2020 creel survey will be provided in a separate report in 2023.

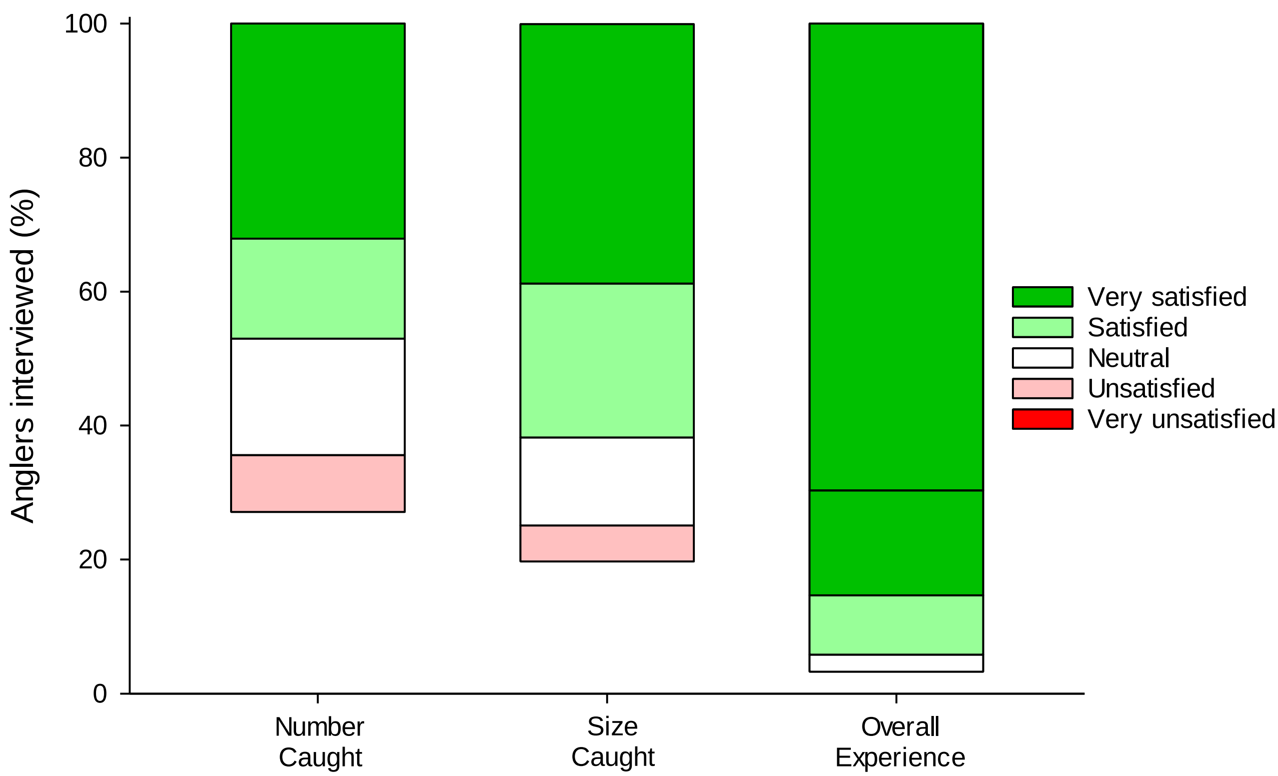

FIGURE 3. Angler satisfaction about the number and size of fish caught as well as the overall experience during the 2020 Hebgen Reservoir creel survey (*N* = 1287).

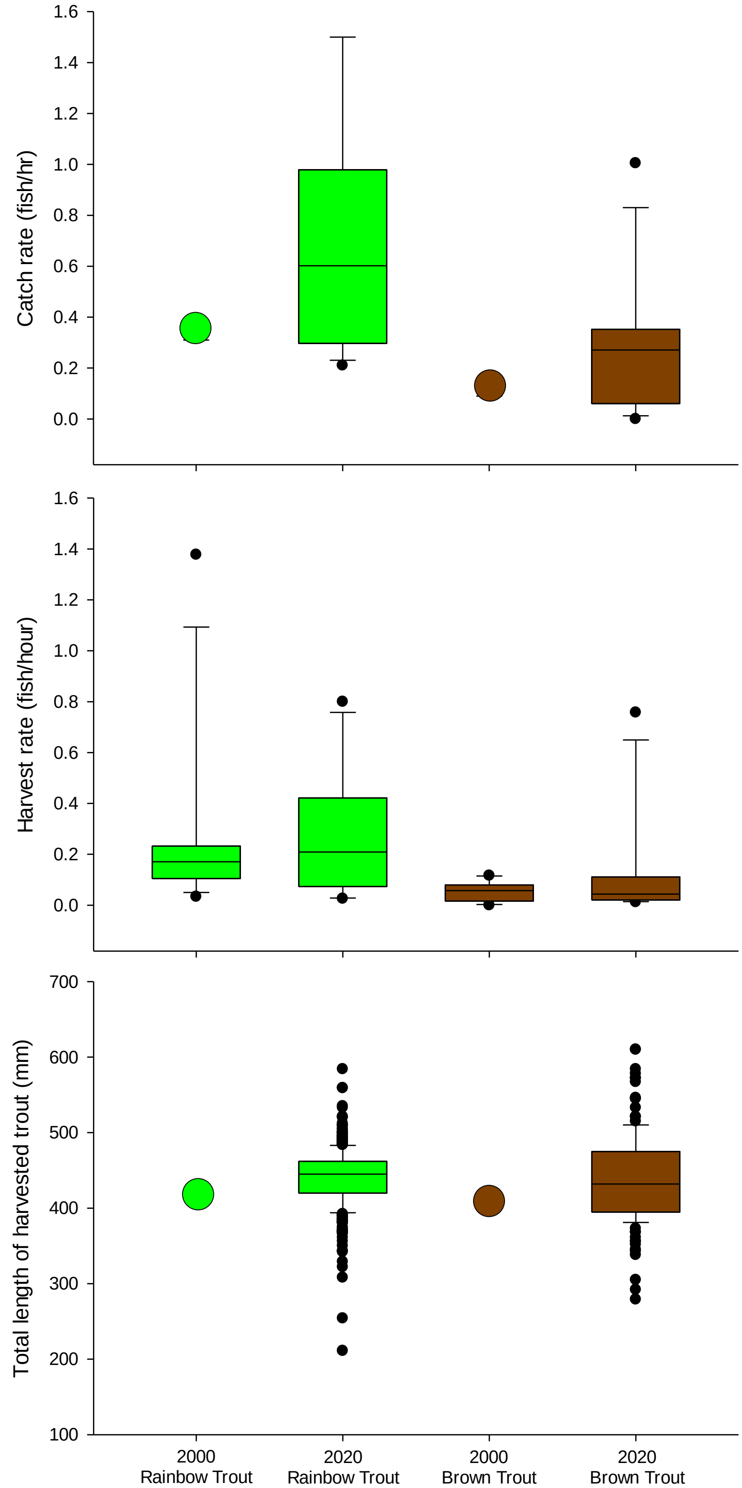

FIGURE 4. Catch rates, harvest rates, and total lengths of Rainbow (green) and Brown Trout (brown) from 2000 and 2020 Hebgen Reservoir creel surveys. Green and brown circles are means from 2000 creel report (Byorth 2004). Within each boxplot, horizontal black lines are medians; boxes extend from the 25th to 75th percentiles, vertical lines denote the 5th and 95th percentiles, and black circles are observations beyond those percentiles.

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. Sampling will occur annually for at least three consecutive years to provide data that can be used to establish management goals for the Rainbow and Brown 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. Taking that into consideration, the mean catch-per-unit-effort (CPUE) of total trout, Brown Trout, and Rainbow Trout were near the long-term averages as were the mean lengths of Brown Trout (402 mm [≈ 16”]) and Rainbow Trout (356 mm [≈ 14.0”]; Figure 5).

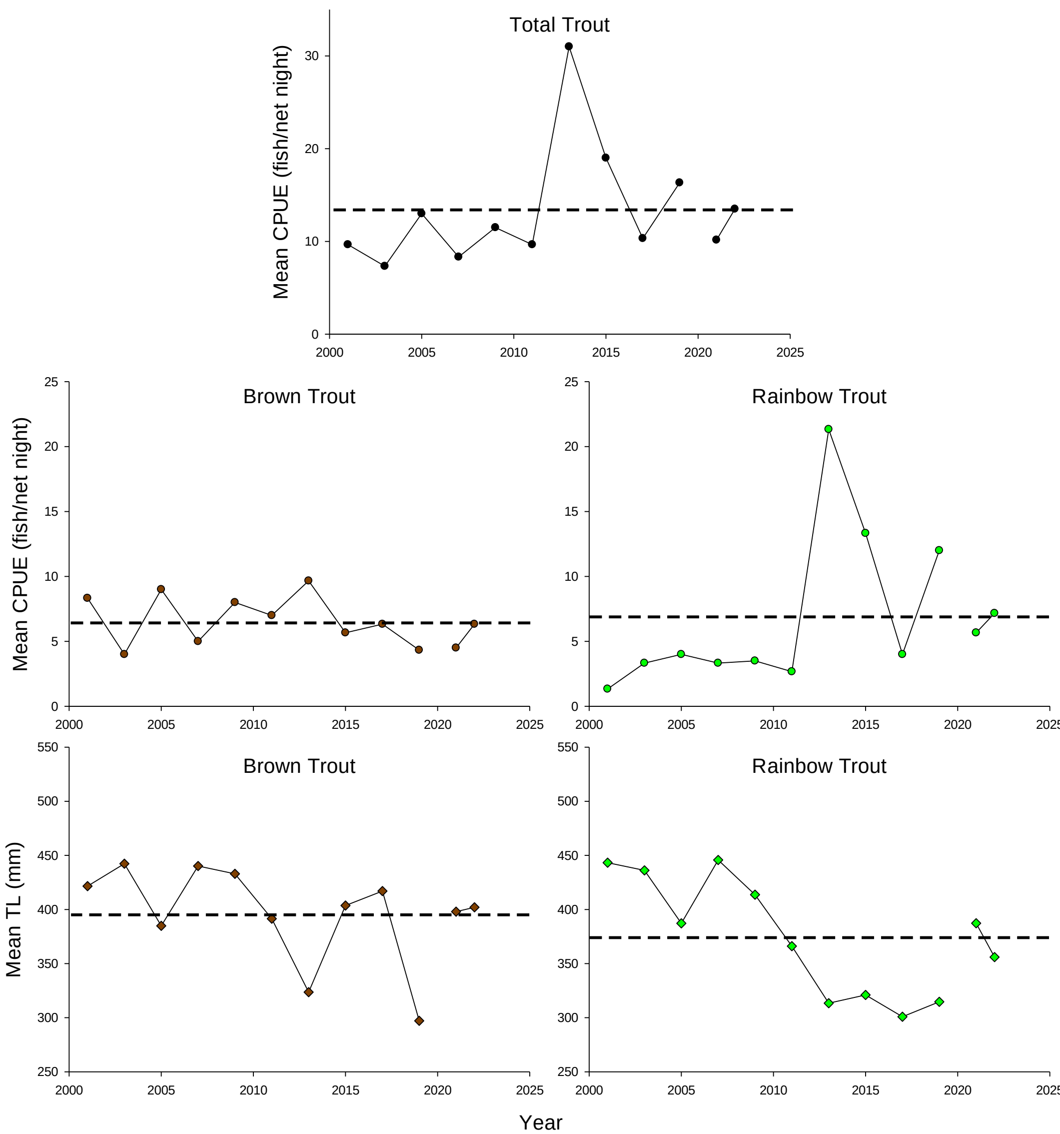

Figure 5. Mean catch-per-unit-effort (CPUE) of total, Brown and Rainbow Trout captured in gill nets set in Ennis Reservoir from 2001 to 2021. Brown and Rainbow mean CPUE and were calculated using all nets set

each year. Mean total lengths were calculated using all Brown and Rainbow Trout captured each year. Dashed lines are long-term averages (2001-2022) and error bars are 95% confidence intervals for mean lengths.

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 conducted limnological sampling at nine established sites on Hebgen reservoir in 2022. Sampling consisted of measuring light penetration into the water column with a Secchi disk and vertical zooplankton tows to evaluate zooplankton community densities. Secchi depths were recorded as the distance (in meters) between the water surface and point in the water column where the disk becomes indiscernible. Zooplankton samples were collected by towing a 153-micron mesh (1 micron = 1/1,000th millimeter) plankton net vertically through the entire water column at a rate of one meter/second. Samples were rinsed and preserved in a 95% ethyl alcohol solution for enumeration and identification. Zooplankton were identified to groups (cladocera or copepoda) and the densities of each sample was calculated.

There was no statistical difference in zooplankton densities between the months of June and July or between July and August (ANOVA, $p>0.05$). However, there was a difference in densities between June and August (Figure 6; ANOVA, $p=0.037$). Copepoda comprised 76% of the sample in June, 70% in July, and 79% in August. Cladocera comprised 24%, 30%, and 21% of the samples respectively. No relationships between trophic status, zooplankton abundance, or trout and zooplankton abundances have been identified under the current reservoir operation criteria; however, zooplankton abundances were different among years in June, July, and August (Figure 7; ANOVA, $p < 0.05$). Therefore, FWP recommends continuing limnological sampling occur every other year and in years when departures from normal operations occur.

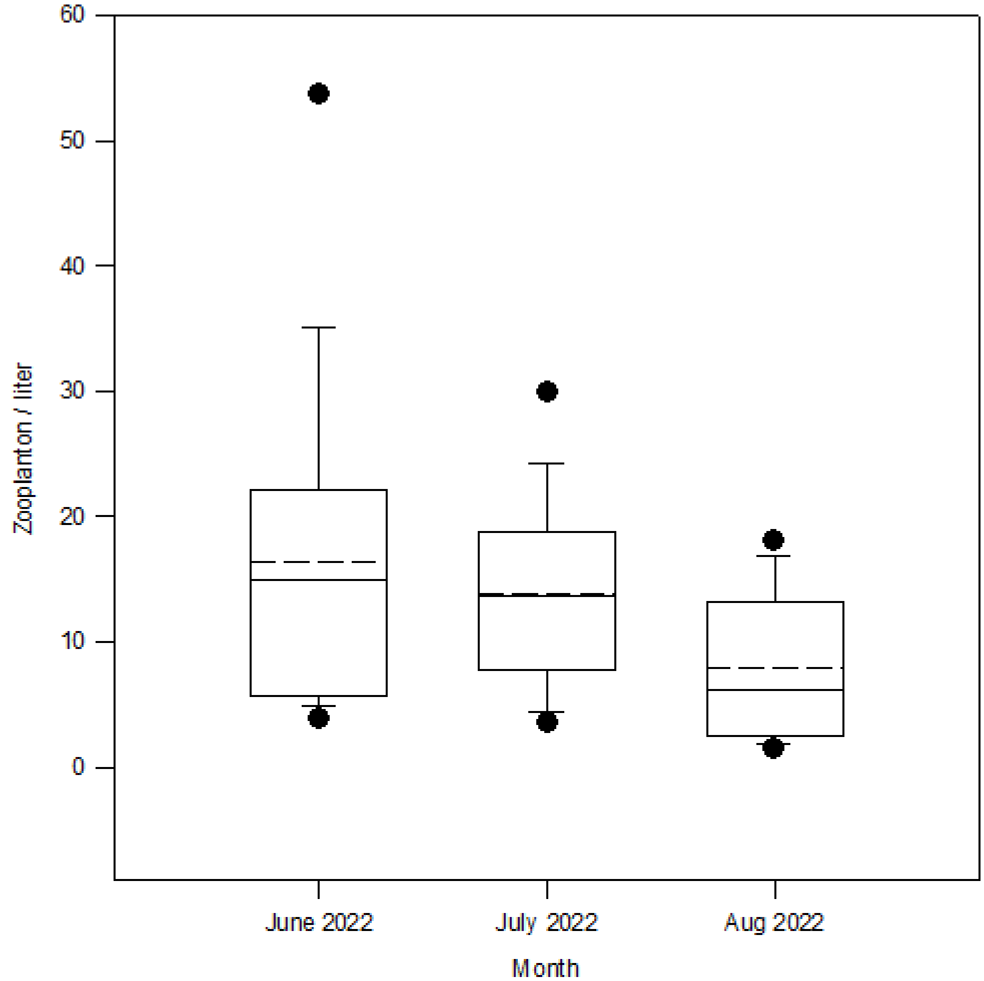

Figure 6. Total zooplankton abundance in June, July, and August 2022. Within each box, horizontal black lines denote median values and dashed lines represent mean values; boxes extend from the 25th to the 75th percentile of each group's distribution of values, vertical lines denote the 5th and 95th percentile of each group's distribution of values, black dots are observations beyond those percentiles.

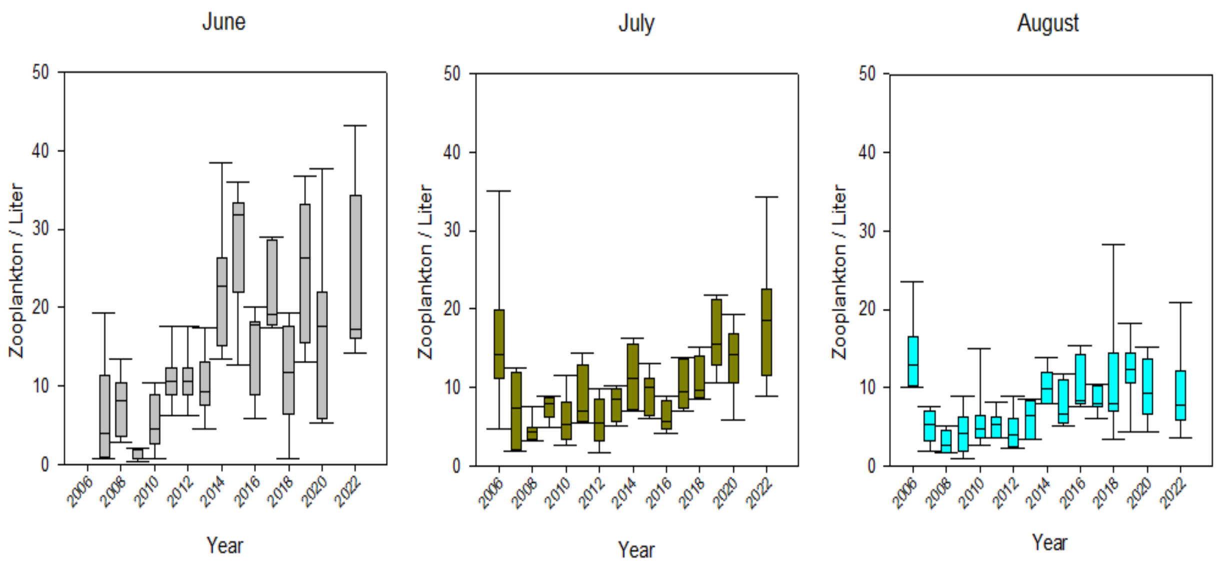

Figure 7. Total zooplankton abundance among months June, July, and August 2006-2022. Within each box, horizontal black lines denote median values; boxes extend from the 25th to the 75th percentile of each group's distribution of values, and vertical lines denote the 5th and 95th percentile of each group's distribution of values.

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

FWP estimated Rainbow and Brown Trout abundances using mark-recapture surveys in three long-term monitoring sections for the Madison River (Pine Butte, Varney, and Norris) to evaluate the influence of modified project operations at Hebgen and Madison dams on the trout fisheries. Although this report is limited to a discussion of potential influences of project operations, other potential population drivers (e.g., angling pressure, disease) are hypothesized to be influential and evaluated elsewhere. Trout were collected by electrofishing from a drift boat mounted mobile anode system. Fish captured in the initial trip (marking run) were weighed (g) and measured (mm), marked with a fin clip, and released. FWP conducted a second trip (recapture run) about a week later to examine trout for fin clips administered during the marking run, record lengths of marked fish, and record lengths and weights of unmarked fish. Length-specific mark-recapture 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 total 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 (Figures 8 and 9). The abundance goals for the Pine Butte, Varney, and Norris sections are 2,200, 1,100, and 2,500 trout/mile, respectively. The proportional size structure goals for each section are Pine Butte – 25%, Varney – 35%, and Norris – 15% (Figures 8 and 9). 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.

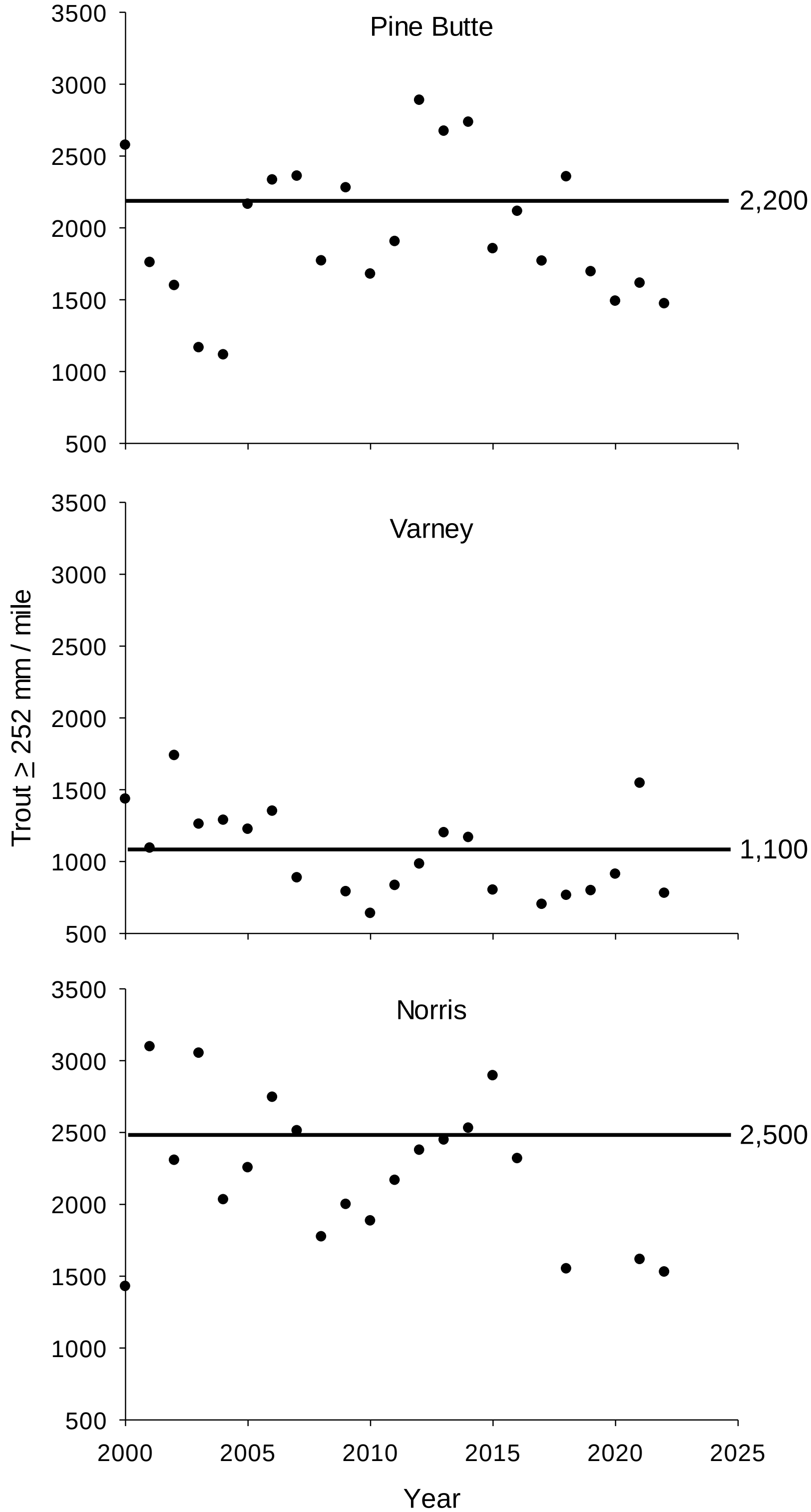

Figure 8. Estimated abundances of trout ≥ 252 mm (≈ 10”) in the Madison River. Black lines are the management goals for each section.

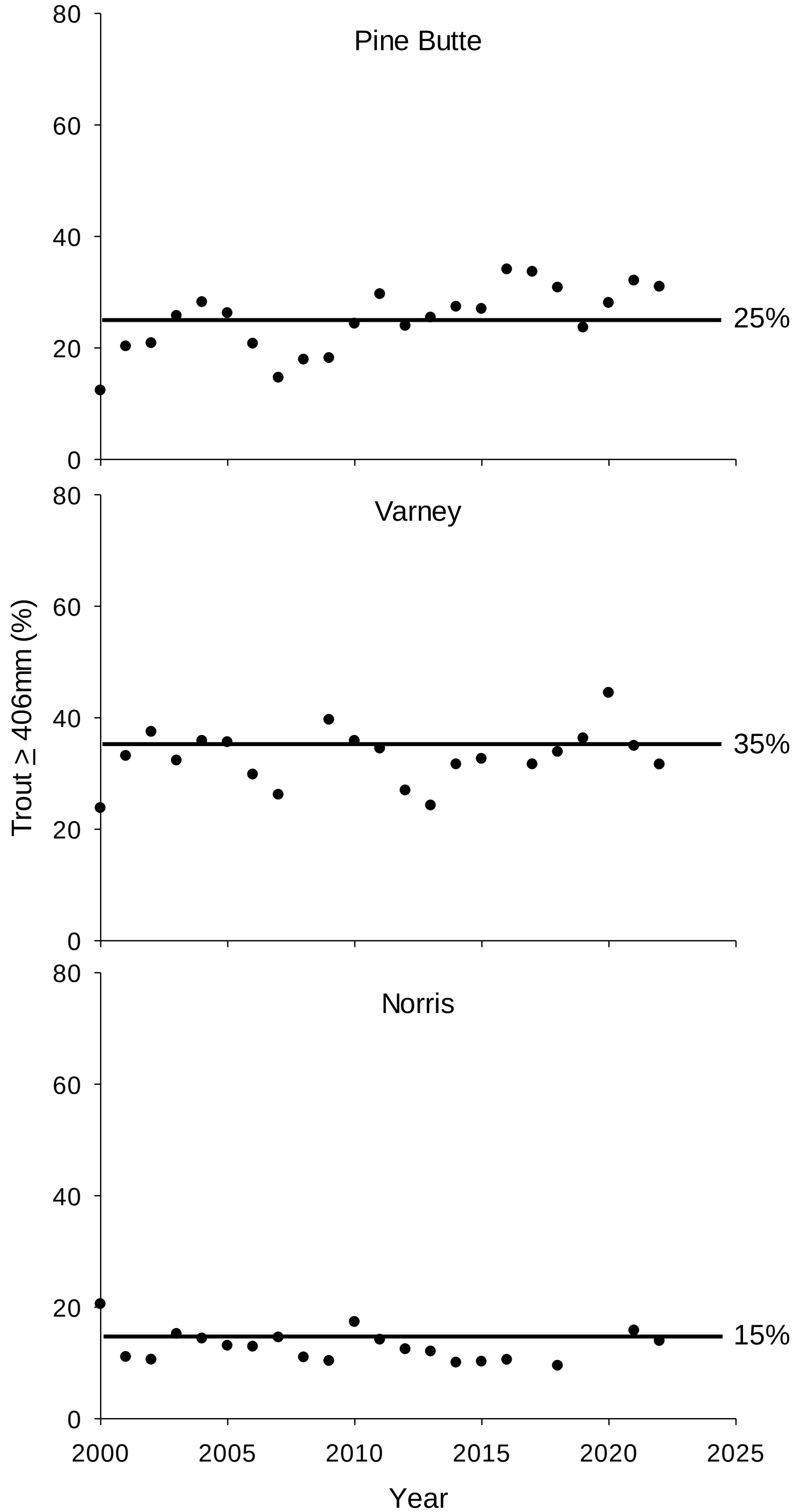

Figure 9. Percentages of ≥ 252 mm (≈ 10”) trout captured in the Madison River that were ≥ 406 mm (≈ 16”). Black lines are management goals for each section.

In 2022, each sampling section failed to achieve abundance management goals and Pine Butte was the only section where the size structure goal was achieved (Figures 8 and 9). The estimated abundance of Rainbow Trout ≥ 152 mm (≈ 6") nearly doubled in the Pine Butte Section to 2,937 trout/mile in 2022 (Figure 10), which was primarily a result of the high abundance of fish < 252 mm (≈ 10"; Figure 11). Brown Trout in Pine Butte continued to decline to a 20-year low in 2022. It should be noted that water was released from the surface of Hebgen for a portion of the year as repairs to the failed gate component were being made. While no difference in trout abundance has been attributed to this kind of operational change, an increase in the proportion of fish ≥406mm in the Pine Butte section has been attributed to surface release (Lohrenz et al. 2020).

Abundances of trout ≥ 254 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 well above the long-term average at 1,946 trout/mile in the Varney Section (Figure 10) primarily because of a high abundance of relatively small Rainbow Trout < 252 mm (Figure 12), which will hopefully contribute to relatively high abundances of large Rainbow Trout in the upper Madison River and potentially Ennis Reservoir in the coming years.

Abundances of trout ≥ 252 mm remain at historical lows in Norris with that section of the river also failing to meet the size structure goal since 2015 (Figure 8). The estimated abundances of trout ≥ 152 mm remained below the long-term averages in the Norris Section with 1,301 Rainbow Trout/mile in 2022 and Brown Trout at a near historical low of 523 trout/mile (Figure 10). The truncated length-frequency histograms of both populations in recent years (Figure 13) indicate the survival of juvenile and adult Rainbow and Brown Trout have decreased in the lower Madison River relative to the populations observed in the 2000s and 2010s. The estimated abundance of Westslope Cutthroat Trout was 82 trout/mile, which is similar to 2021.

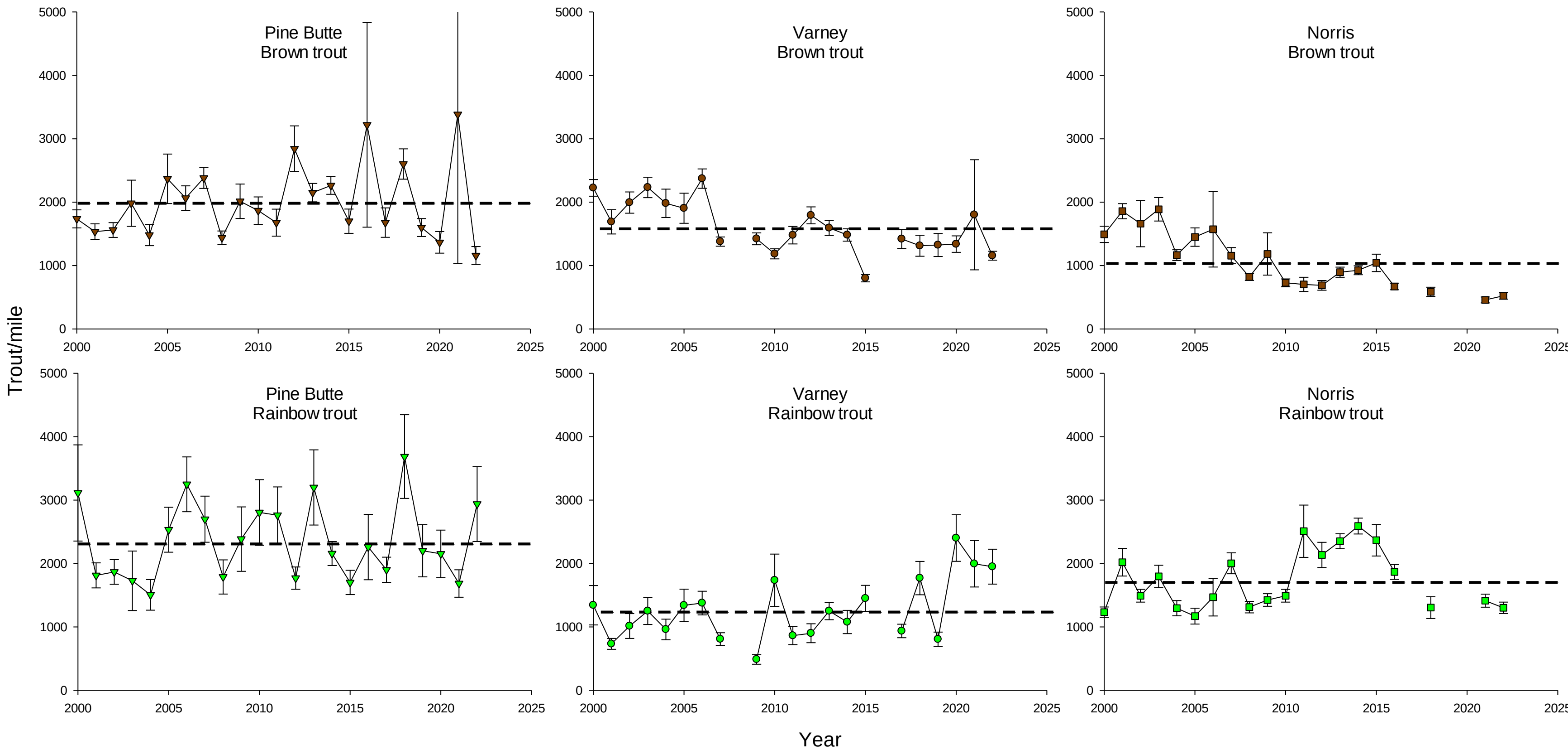

Figure 10. Estimated abundances of Brown and Rainbow Trout ≥ 152 mm (≈ 6”) captured in the three long-term sampling sections of the Madison River. Dashed lines are the long-term averages (2000-2022) and error bars are the 95% confidence intervals.

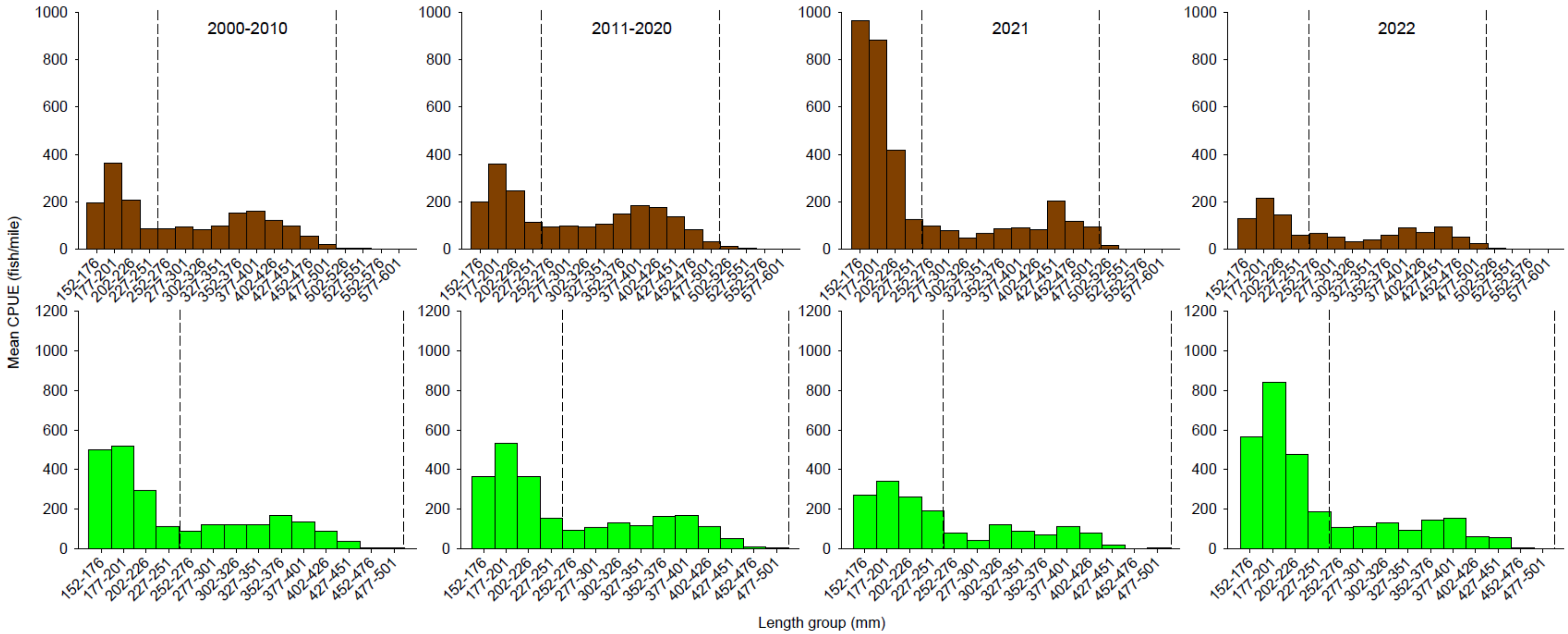

Figure 11. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6”) captured in the Pine Butte Section of the Madison River. Dashed lines delineate 10” and 20.”

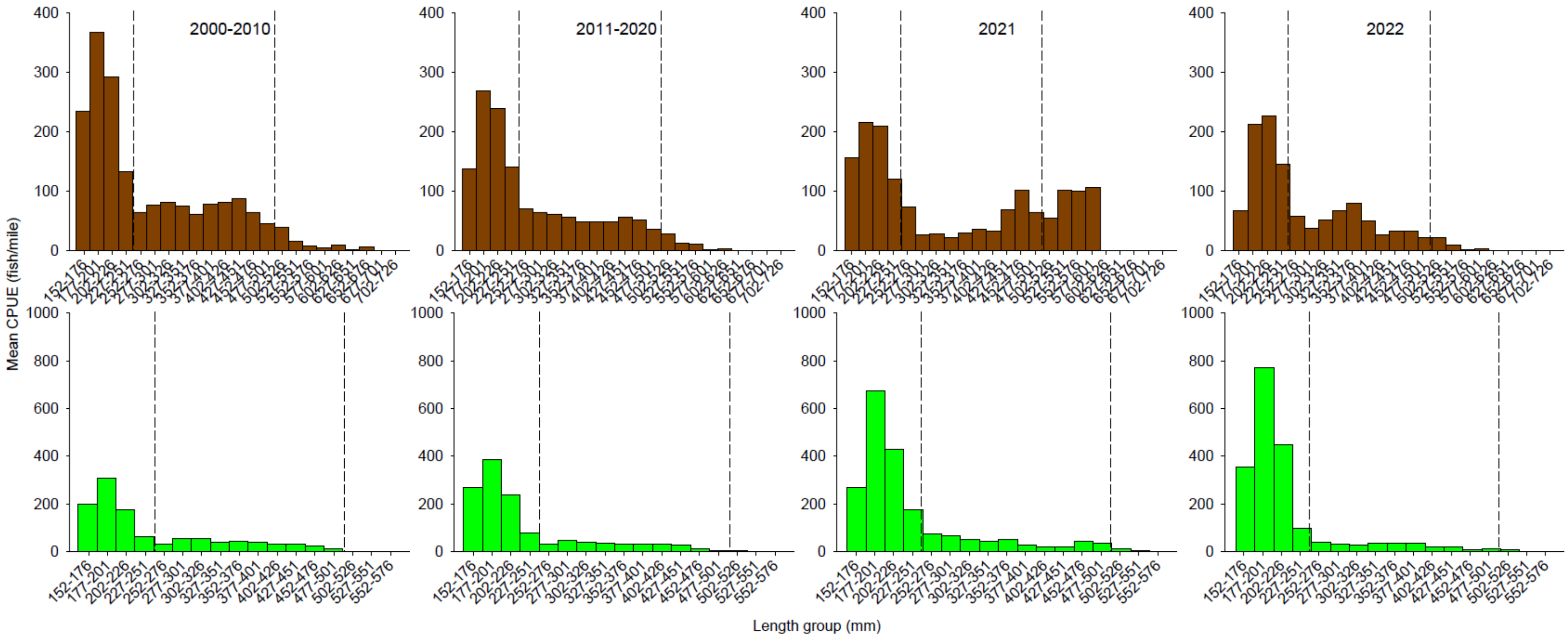

Figure 12. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6”) captured in the Varney Section of the Madison River. Dashed lines delineate 10” and 20.”

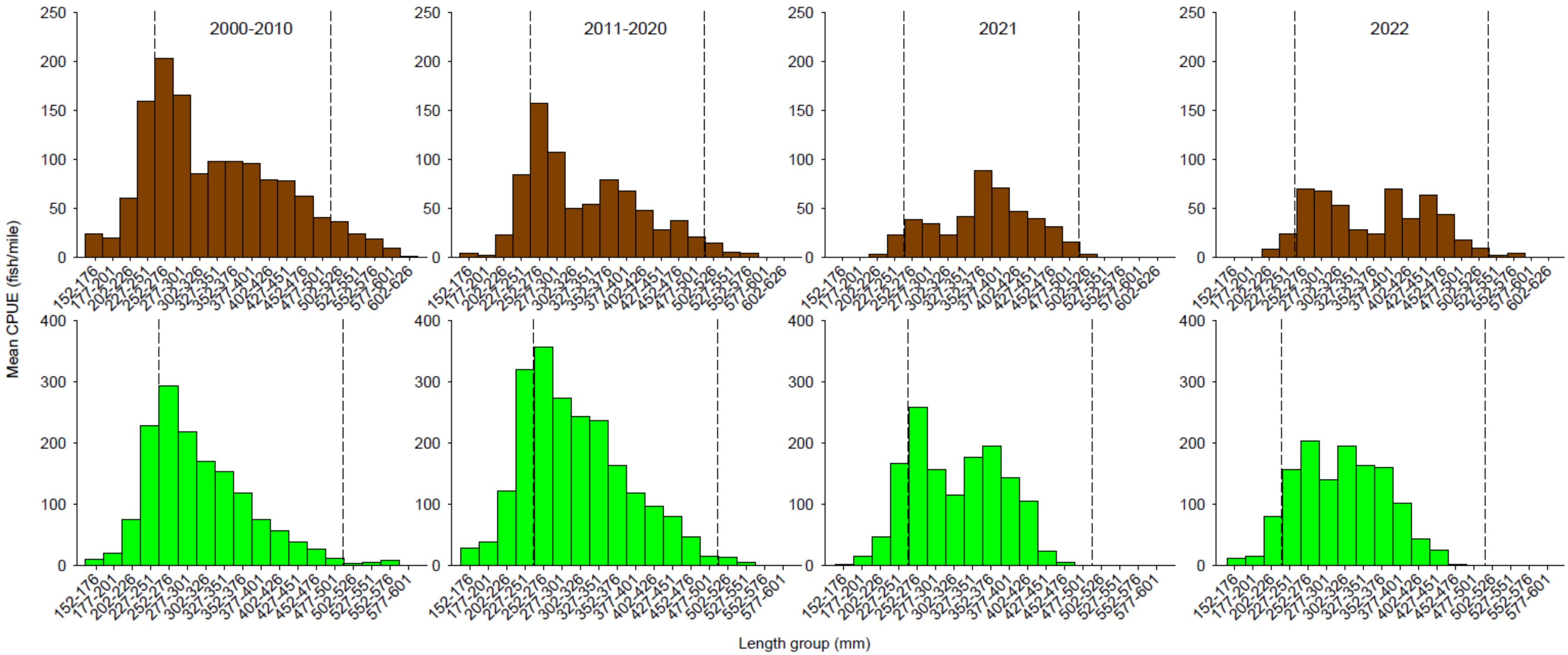

Figure 13. Length frequency histograms of Brown (brown bars) and Rainbow Trout (green bars) ≥ 152 mm (≈ 6”) captured in the Norris Section of the Madison River. Dashed lines delineate 10” and 20”.

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 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 the use of a minimum of 500,000 grayling eggs/year from fish of primarily Madison genetic ancestry for 3-5 consecutive years.

In 2022, FWP stocked 500,000 Arctic Grayling embryos in the South Fork Madison and 78,570 fry into the southwest arm of Hebgen Reservoir (Figure 1). Embryos were placed in remote site incubators (RSI; Figure 14) and entered the stream as fry (Figure 15). Additionally, fry reared at FWP hatcheries were introduced in the fall of 2022. To date, FWP has introduced 650,000 embryos and 94,709 fry into the Hebgen Basin.

Introductions of Arctic Grayling into the North Fork of Spanish Creek continued in 2022. Although the North Fork of Spanish Creek is outside of the Madison drainage, NWE committed funds in 2016 to native fish recovery there due to limited opportunities in the Madison drainage at that time. About 12,000 Arctic Grayling fry (6,000 per year) were introduced into Chiquita Lake in 2021 and 2022 and observed migrating into the North Fork of Spanish Creek. Arctic Grayling introductions will continue in 2023 and will be expanded in the drainage to include Willow Swamp Creek.

Figure 14. Remote site incubators used to hatch Arctic Grayling eggs in Black Sands Springs, a tributary to the South Fork Madison, in 2022.

Figure 15. Arctic Grayling Fry in the South Fork Madison hatched from RSI's.

FWP's Statewide Fisheries Management Plan calls for the protection and reintroduction of WCT conservation populations (i.e., populations with less than 10% 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, Big Hole, Beaverhead, Gallatin, Madison, Jefferson, Red Rock, Boulder, and Upper Missouri rivers.

WCT conservation populations in the Madison River subbasin inhabit 15.9% of historically occupied tributaries; however, only 30% 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 2022 included completion of the Pine Butte and Deadman creeks fish migration barriers, wild fish transfers of WCT from Last Chance and McClure creeks into Ruby Creek, genetic and population assessments of Ruby Creek and other Madison River tributaries.

The re-establishment of an unaltered WCT population in Ruby Creek has been ongoing since 2015, with translocations of genetically unaltered, aboriginal Madison WCT from McClure and Last Chance creeks. In the summer of 2022, FWP translocated 10 WCT from McClure and 13 from Last Chance creeks, respectively. Fish from McClure and Last Chance Creek were collected with a backpack electro-fisher, measured (mm), and had a fin clip taken for genetic analysis. Fish were transported to Ruby Creek in an aerated cooler. Before being released, fish were placed in a net and allowed to acclimate to the temperature of Ruby Creek for approximately 10 minutes. Since 2015, 130 individuals from McClure (81) and Last Chance Creek (49) have been translocated to Ruby Creek. Although fewer Last Chance Creek fish have been introduced, their genetic contribution to the Ruby Creek population has been greater than expected (Feuerstein 2021). FWP anticipates the 2022 introduction of McClure and Last Chance trout will continue to improve genetic diversity and increase the fitness of the population. FWP does not intend to translocate fish from either donor stream in 2023.

In addition to the translocations, FWP evaluated WCT population abundance and distribution throughout the Ruby Creek drainage. 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.

The average WCT abundance in Ruby Creek was 19 fish/100 m (± 11.0; 95% *CI*) or roughly 306 fish/mile (± 176; 95% *CI*). WCT abundances increased from 8 fish/100 m at the lowest site to 29 fish/100 m at the top of the drainage (Figure 16). The average length was 222 mm (± 10.0mm) and ranged from 353 mm to 104 mm. Given the current abundance of the Ruby Creek WCT population, roughly 2295 over 7.5 miles, FWP may consider using Ruby Creek as a donor source to re-establish WCT populations in streams targeted for reintroduction in the Madison or nearby drainages.

FWP updated the abundance, demographic, and genetic status of populations identified in the Missouri Headwaters WCT conservation strategy.

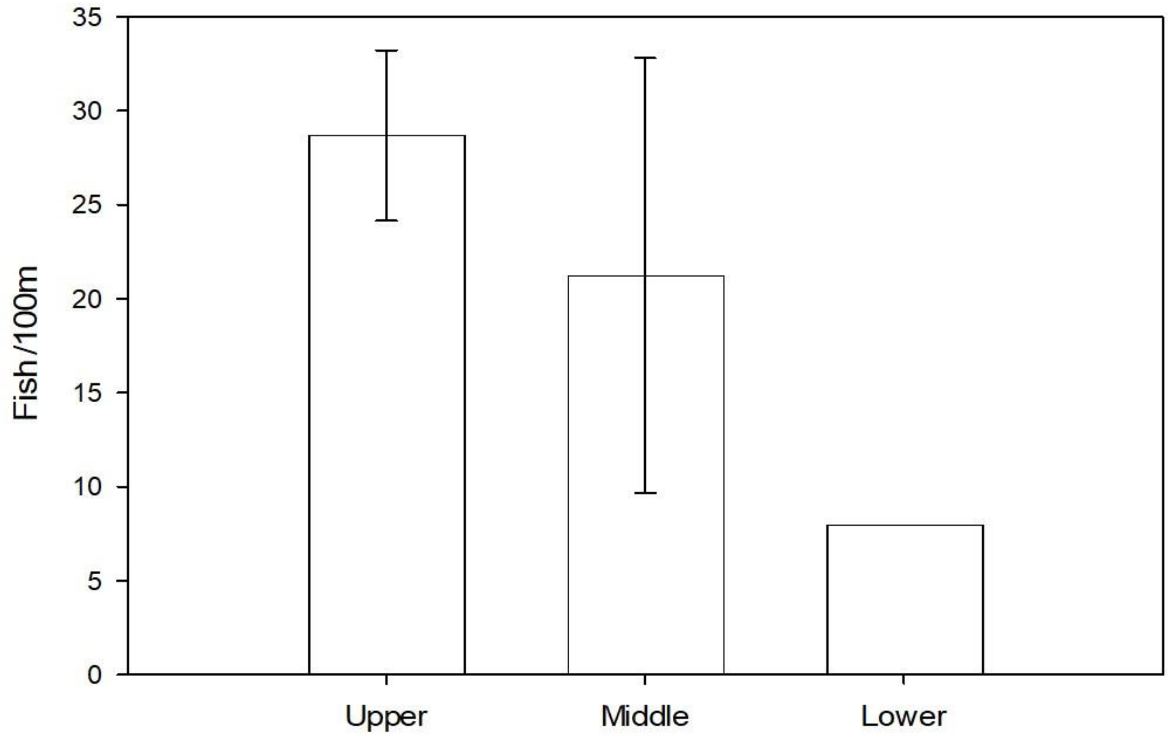

Figure 16. WCT abundances per 100 meters in Ruby Creek by sampling reach. Error Bars are 95% confidence intervals.

Fish barriers were constructed with MadTAC funding on Pine Butte and Deadman creeks in 2022 as prescribed by the Missouri Headwaters WCT conservation strategy (Figure 16). The installation of these barriers protects roughly 7 miles of stream occupied by WCT conservation populations (98.4% and 97.8% WCT, respectively) from further hybridization with or displacement by nonnative fish species.

Figure 17. Wooden migration barriers installed on Pine Butte (top photo) and Deadman (bottom photo) creeks in 2022.

In 2016 NWE committed funding to aid in the North Fork of Spanish Creek native fish restoration project, which is nearing completion. FWP continued their participation in the project in 2022. Results from environmental DNA testing (eDNA) showed Brook Trout had not been eradicated from the system during prior removal efforts. Consequently, another removal with piscicide was initiated in August 2022. Two of the three Brook Trout identified by eDNA were accounted for during the removal effort and it is expected this removal effort was successful in eliminating Brook Trout from the project area. eDNA will be conducted in the early summer of 2023 to confirm the success of the 2022 removal effort.

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). Consequently, in 2022 FWP and NWE initiated efforts to develop projects to mitigate the loss of spawning habitat and improve general habitat conditions for fish production and recruitment to the mainstem fishery. Projects that restore spawning habitat in side channels, tributaries, and associated with constructed islands are under consideration.

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 18). 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 1). 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.

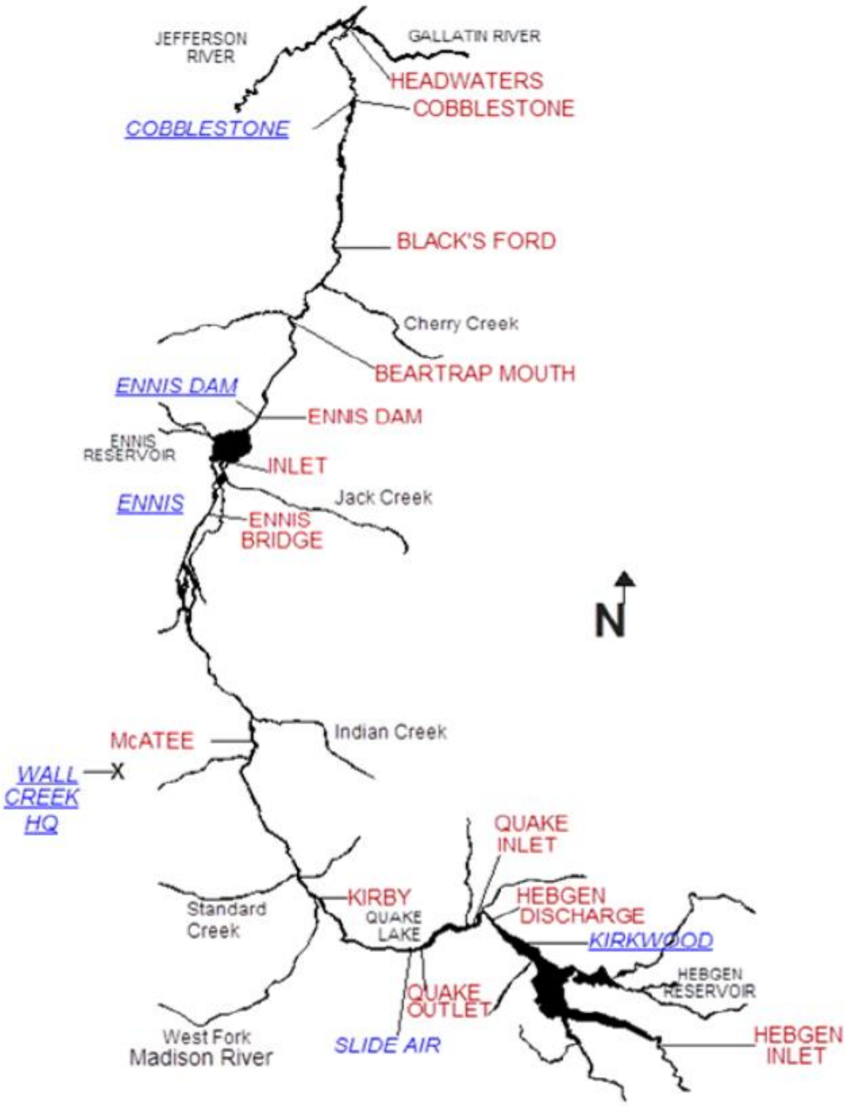

Figure 18. FWP temperature monitoring sites. Air temperature monitoring sites are blue and underlined; water temperature monitoring sites are red.

Table 1. 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, Bear Trap Mouth and Black's Ford and Cobblestone for 46, 55, and 59 days, respectively (Table 2). Since 2000, maximum daily water temperatures at the Black's 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 2022, there were 64 calls for a pulse flow, but only 45 of those resulted in operational changes to accommodate a pulse flow. Maximum daily water temperatures reached 80° F at Sloan Station for a total of 15 minutes on August 12. Downstream of Sloan Station at the Cobble Stone FAS water temperatures reached or exceeded 80°F on August 11 and 12. (Table 2; Figure 19). 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 20).

Table 2. Maximum and minimum temperatures (˚F) recorded at monitoring sites in the Madison River Drainage, 2022. 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	NA	NA	NA	NA	NA
Hebgen discharge	69.7°	49.2°	58.0.° ± 0.8°	0	0
Quake Lake inlet	70.2°	43.0°	58.5° ± 1.0°	0	0
Quake Lake outlet	66.6°	40.8°	58.1° ± 1.0°	0	0
Kirby Bridge	68.7	36.4°	58.6° ±0.9°	0	0
McAtee Bridge	72.9°	40.8°	58.5° ± 0.9°	0	0
Ennis Bridge	74.9°	41.7°	59.5° ± 1.2°	5	0
Ennis Reservoir Inlet	77.5°	48.4°	60.8° ± 1.0°	19	0
Madison Dam	75.1°	50.0°	65.1° ± 1.1°	11	0
Bear Trap Mouth	78.1°	50.4°	65.1° ± 1.0°	46	0
Blacks Ford	79.7°	49.3°	63.9° ± 1.2°	55	0
Cobblestone	80.4°	51.1°	65.5° ±1.0°	59	2
Headwaters S.P. (Madison mouth)	NA	NA	NA	NA	NA

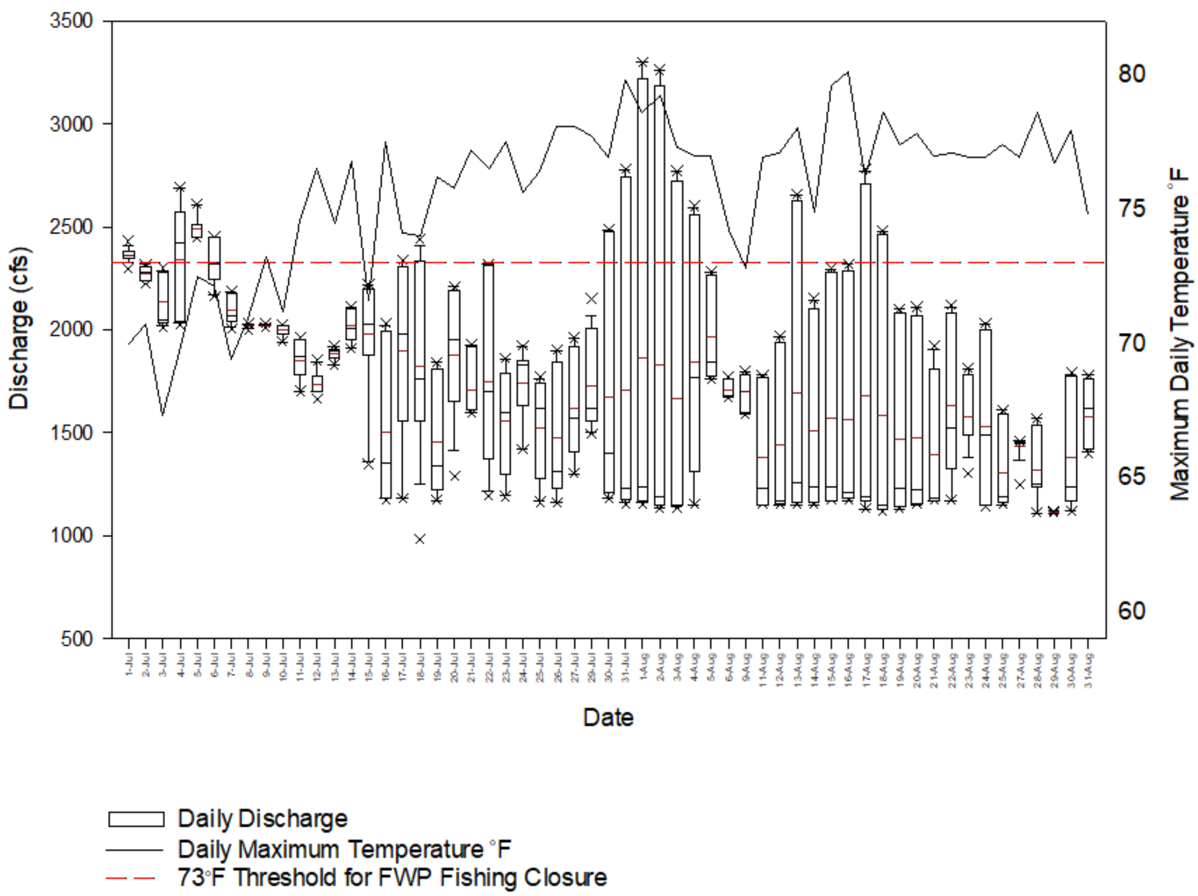

Figure 19. Daily distribution of discharges (left axis) collected every 15 minutes from July 1-Aug 31 2022 (pulse flow season) at USGS gage # 6041000 and daily maximum water temperature at Sloan (right axis). Boxes extend from the 25th to the 75th percentile and whiskers are the 5th and 95th percentile. Horizontal black lines are the median values of the groups' distribution and horizontal red lines are the mean values of the groups' distribution. X'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.

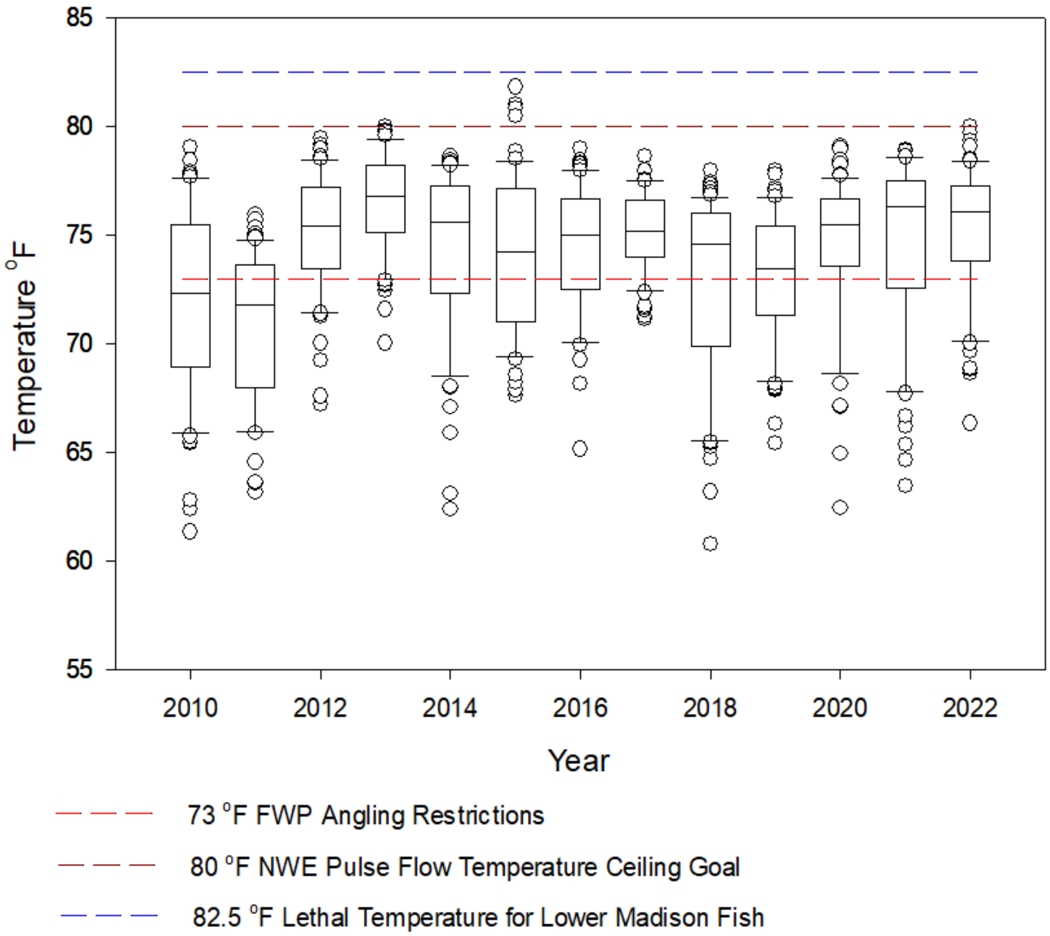

Figure 20. Distribution of daily maximum water temperatures at Sloan from July 1-August 31 from 2010-2022. Boxes extend from the 25th to the 75th (interquartile range) percentile, whiskers are the 5th and 95th percentile and circles are values beyond the 5th and 25th percentiles. The red dashed line denotes the 73°F threshold used by FWP to implement angling restrictions, the green 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.

General linear models (linear regression) were used to determine whether negative correlations existed between abundances of age-3+ Rainbow and Brown Trout and the number of days water temperatures were ≥ 73°F, age-1, age-2, and age 3+ Rainbow and Brown Trout and average pulse change, and between age-1, age-2 Rainbow and Brown Trout and the number of days a pulse flow occurred in the Norris section. Age-specific abundances were generated using length-age relationships described by Vincent (1978; Table 3). Because the Norris section is sampled in the spring prior to the pulsed flow season within year comparisons (i.e., at time t) were not relevant. Therefore, we assessed whether covariates at time t_{-1}, t_{-2}, predicted abundances of age-1, age-2, or age-3+ Rainbow or Brown Trout at time t. For example, an age-1 trout in 2022 would have been affected as an age-0 fish by conditions during the pulsed flow season in 2021 (t_{-1}) and the quality of the spawning habitat that produced it would have potentially been affected by the pulsed flow season in 2020 (t_{-2}).

Table 3. Madison River length at age for Rainbow and Brown Trout in the Norris Section (Vincent 1978).

	Rainbow trout			Brown trout		
Location	**Age 1**	**Age 2**	**Age 3+**	**Age 1**	**Age 2**	**Age 3+**
Norris	0-226mm	227-305mm	≥305mm	0-226mm	226-328mm	≥328mm

There was no correlation between the abundances of age-1 or age-2 Rainbow or Brown Trout at t_{-1} or t_{-2}, or age-3+ Rainbow or Brown Trout at t_{-2} and average pulse flow change. Additionally, no correlation was found between the number of days water temperatures were ≥ 73°F and the abundance of age-3+ Rainbow or Brown Trout at t_{-1}. The abundances of age-1 or age-2 Brown Trout and the number of days a pulse flow occurred at t_{-1}, t_{-2} were not correlated (Table 4); however, there were significant negative correlations between age-1 Rainbow Trout and the number of pulse flows at a t_{-1} ($R^2 = 0.22$; P = 0.04) and age 2 Rainbow Trout at t_{-2} ($R^2 = 0.54$; P = 0.05) (Table 4).

Table 4. Summary of hypothesis tested for negative correlations.

Hypothesis	*P*	R^2
Age 3+ RB negatively correlated with # days >73°F max temp (t-1)	>0.05	na
Age 3+ LL negatively correlated with # days >73°F max temp (t-1)	>0.05	na
Age 1 RB negatively correlated with # pulses (t-1)	0.04	21.9%
Age 2 RB negatively correlated with # pulses (t-2)	0.05	21.3%
Age 1 LL negatively correlated with # pulses (t-1)	>0.05	na
Age 2 LL negatively correlated with # pulses (t-2)	>0.05	na
Age 1 RB negatively correlated with average pulse flow change (t-1)	>0.05	na
Age 2 RB negatively correlated with average pulse flow change (t-2)	>0.05	na
Age 1 LL negatively correlated with average pulse flow change (t-1)	>0.05	na
Age 2 LL negatively correlated with average pulse flow change (t-2)	>0.05	na

Statistical results suggest that FWP's implementation of angling restrictions and the pulse flow program are effective in limiting thermally induced mortality in the lower river. No correlation between the average pulse flow change and Rainbow and Brown Trout age-1, age-2, and age-3+ abundances were found and is likely because pulse flow changes are proportionally small. However, negative correlations between age-1 and age-2 Rainbow Trout and the number of pulses might suggest that YOY Rainbow Trout displacement is a cumulative effect. For example, if one pulse flow equates to 100 YOY Rainbow Trout being displaced then 5 pulse flows would equate to 500 YOY Rainbow Trout being displaced. The Norris section has very little habitat complexity in the form of features such as side channels and islands that may provide velocity refugia. Limited complexity could prohibit juvenile fish from finding areas of reduced velocity during pulse events. An examination of the relationships between habitat features and total trout abundance showed a suggestive positive relationship between island and side channel density and large fish ≥ 16" (Lohrenz et al. 2021). While the effect of these features was not evaluated on young-of-the-year and age-1 fish, the relative abundances of young-of-the-year fish are commonly linked to complex habitats like side channels and high island density (Lohrenz et al. 2021). Pioneer Technical (2022) suggested that island construction could improve hydraulic diversity and habitat conditions for trout in the river. Pulse flows have been very effective at keeping water temperatures in the lower river below lethal thermal limits for trout and FWP recommends NWE continue the pulse flow program. FWP also recommends pursuing mainstem projects in this reach to improve habitat complexity and diversity to improve conditions 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 et al. 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 ≤ 0.8 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; Kondolof 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 the release of 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.

While 2022 was not considered a flushing flow year operationally by NWE, the rain-on-snow event in the Spring of 2022 resulted in river discharges that were greater in magnitude and longer in duration than with scheduled flushing flows. River discharges were at or exceeded 3500 cfs at the Kirby gage for five days and resulted in a peak discharge of 6340 cfs at Varney. 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 # 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 6,532.26^{ft} msl by June 20. 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 2022 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 percent composition of the sample was calculated according to particle size. The results from annual core sampling are reported elsewhere and provide an index of relative spawning habitat suitability (Kleinshmidt 2022). There is no statistical difference in the % fines ≤ 0.8 between years when a flushing flow was implemented or years when a flushing flow was 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).

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 and are critical to the establishment of riparian species, such as cottonwood and willows. Due to its lack of hydrologic complexity as a predominately single-thread channel and operational constraints that limit flows, the formation of depositional features, such as point bars and islands, which provide moist barren surfaces for cottonwood and willow regeneration and expansion is largely 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, that are characterized by multi-thread channels of high complexity that dissipate stream energy and create zones of deposition during high flows.

FWP conducted a cursory evaluation of riparian vegetation recruitment at three islands in the Varney reach following the high flow event. Sites selected for evaluation were in close proximity to an island where new growth cottonwood and or willow was observable. At each site, the high-water mark was delineated by identifying a depositional band of debris on the river banks created as high water began to recede. Elevation measurements from the top of the bank, the high-water mark, the water's surface, and the top of the adjacent island were made using a stadia rod and laser level. Elevation measurements were used to calculate the level to which islands were inundated during high flows and the difference in elevation between the observed high-water mark and bank full elevation. Additionally, photos of areas with new vegetation growth were taken to document the environmental conditions in which new growth occurred. New cottonwood growth was observed on perched banks as well as on island surfaces and bank margins. Cottonwood growth observed on the perched banks were likely suckers from mature trees, that developed as a result of the banks becoming saturated during high flows (Payne and Parker pers. com. 2022). New cottonwood and willow growth observed on the islands was likely from seeds dispersed through the air and water that were deposited as water levels receded (Figure 21). Achieving bank full discharges under normal operations is uncommon; however, the river stage achieved during the implementation of a flushing flow is likely sufficient to create conditions conducive to promoting cottonwood and willow regeneration on depositional features, such as islands and point bars. Established stands of cottonwood and willows stabilize and increase the capacity of islands and point bars to store gravels that can slowly be recruited back into the system to replenish spawning gravels, which could become important as upstream sources of gravel are depleted. FWP recommends pursuing more in-depth evaluations of the relationship between flushing flows and the establishment and maintenance of cottonwood and willow communities along the Madison River.

Figure 21. Depositional features in the Varney reach where new riparian vegetation (cottonwoods) were observed growing after high water in 2022.

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Appendix A

Madison River Fishery Monitoring related to the Hebgen Dam Gate Failure

Compliance Report 2022

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. Within 15 minutes of the failure, Madison River flows between Hebgen Dam and Quake Lake declined 370 cfs, from 648 cfs to 278 cfs (Figure 1). From Quake Lake to Lyons Bridge (a 13-mile reach; Figure 1), the decline was more protracted with flows decreasing 381 cfs, from 780 cfs to 399 cfs in roughly a 48-hour period. The rate and volume of water reduction resulted in deviations from NorthWestern Energy's (NWE) Project 2188 Article 403 requirements: (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 1. Areas of the Madison River affected by the Hebgen Dam gate failure on November 30, 2021. Orange segments indicate the areas of greatest concern and the focal area of 2022 monitoring.

Impacts to the fishery immediately following gate failure were greatest between Hebgen Dam and Quake Lake where Brown Trout redds were dewatered along channel margins and within side channels. Adult and juvenile salmonids and sculpins were stranded in disconnected side channels and pools (Figure 2). From 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 Lyon’s Bridge and no dewatered Brown Trout redds or stranded fish were observed in this reach during initial surveys (Figure 1).

Figure 2. 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 3. A partially dewatered Brown Trout redd in a side channel of the Madison River near Lyon's Bridge.

Assessment of impacts:
To assess the potential 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 flows could have resulted in a total loss of the population or an individual age class will be prepared 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, alternative analysis to evaluate improvements to spawning habitat, gravel recruitment, and embryo survival), will be developed.

This report summarizes the monitoring completed in 2022 related to the Hebgen Gate failure.

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 during the marking run were weighed (g) and measured (mm), marked with a fin clip, observed for hooking scars, and released. 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).

The ratio of Brown to Rainbow Trout was lower than average and age-1 Rainbow Trout comprised the largest proportion of the total combined trout population in 2022. Brown and Rainbow Trout are typically found in similar abundances in the Pine Butte Section; however, 73% of the trout captured in 2022 were Rainbow Trout (Table 1). Age-1 Rainbow Trout made up 53% of the total trout captured, age-2 9%, and age-3+ 10%. Age-1 Brown Trout comprised 14%, age-2 5%, and age-3+ 9% (Table 1). The proportion of Age-1 Rainbow was 18% higher and the proportion of age-1 Brown Trout 10% lower than the 20-year average. Similarly, the proportion of age-2 Brown and Rainbow Trout and age-3+ Brown Trout were 1%, 5%, and 4% lower than the 20-year average, respectively, while age-3+ Rainbow Trout was 3% higher than the 20-year average (Table 1).

Future monitoring will improve inference about potential effects of the Hebgen gate failure on the trout population. Brown Trout abundances were below the 20-year averages for all ages (Figure 4). The high abundance of age-1 Brown Trout in 2021 did not translate into a strong age-2 cohort in 2022; however, difficult sampling conditions (high water temperatures and crew inexperience) in the fall of 2021 led to unreliable abundance estimates and inferences should be cautious. It is presently unclear whether the apparent decrease in abundance of that cohort is attributable to the 2021 Hebgen gate failure, given the uncertainty in the 2021 estimate and the observed relative decline in age 2 Brown Trout in previous years. Age 2 Brown Trout have been below the 20-year average since 2018, indicating other factors may also affect brown trout abundance in the upper Madison River. Continued monitoring in 2023 will provide more insight into the effects of the gate failure on YOY Brown Trout as fish from the 2022 cohort that were eggs in the gravels of spawning redds during the dam failure will have recruited to electrofishing surveys. The estimated above average abundance of age 1 Rainbow Trout suggests the gate failure did not have a major negative effect on that cohort (Figure 4). The 2020 cohort declined on a relative basis from average abundances of 2021 age-1 fish to below average abundances of 2022 age-2 fish. However, the previous cohort of rainbow trout followed a similar pattern without being subjected to gate failure (Figure 4). To ascertain the effects of the 2021 gate failure on the trout population, tracking of cohorts and species ratios in the Pine Butte reach will be continued for the next four years and new length-at-age data from otoliths will improve aging precision.

Table 1. Percent composition of Brown Trout (LL) and Rainbow Trout (RB) for the 2022 total combined trout estimate and the total combined trout estimated 20-year average by age group in the Pine Butte section.

	Age Group			
Species	1	2	3+	Total
LL 2022	14%	5%	9%	28%
RB 2022	53%	9%	10%	72%
LL 20-year average	24%	10%	13%	47%
RB 20-year average	35%	11%	7%	53%

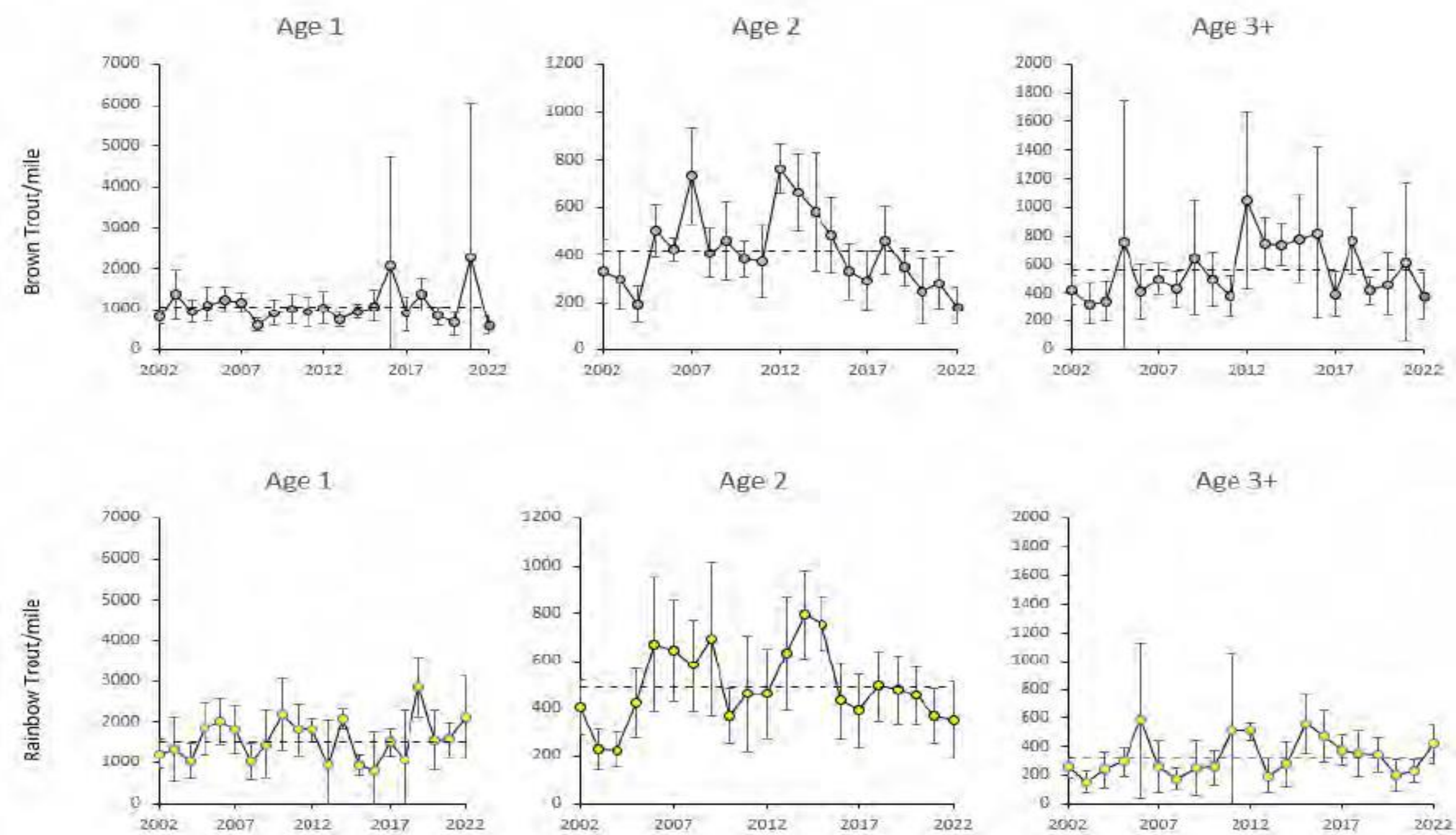

Figure 4. Estimated abundances of Brown and Rainbow Trout by age group in the Pine Butte monitoring section. Dashed lines are the 20-year averages (2002-2022), and error bars are the 95% confidence intervals. Note that the y-axis is not on the same scale.

2) Juvenile Salmonid Presence-Absence Survey

FWP conducted backpack electrofishing surveys in the side channels and margins of the mainstem Madison River between Hebgen Dam and Lyons Bridge to determine the presence or absence of YOY, age-1, and age-2 salmonids during the summer of 2022 (Figure 5). Four monitoring reaches were selected using satellite imagery: Between the Lakes (BTL)was from Hebgen Dam to the Quake Lake inlet (Figure 6), Upper (U) was from the Slide Inn to below Raynolds Bridge (Figure 7), Middle (M) was from below Raynolds Bridge to the Pine Butte primitive boat launch (Figure 8), Lower (L) was from the Pine Butte primitive boat launch to Lyons Bridge (Figure 9). Side channels that had a minimum of 300 feet of island shoreline and did not have a wetted width greater than one-third of the total wetted width of the mainstem river were identified within each reach. Those criteria were based on previous observations of spawning gravel recruitment and juvenile salmonid habitat use. Twenty-five side channels were identified among the four sampling reaches (9 BTL, 8 U, 9 M, and 8 L; Table 2). Four side channels were randomly selected from each reach with the exception of BTL. All but one of the side channels in BTL were sampled (side channel 5 was dry) because the effects of the gate failure were likely greatest in this reach due to the rapid decline in discharge. Sampling occurred on June 7-8 and July 25-26 following emergence of YOY Brown and Rainbow Trout, respectively (Downing 2001). Side channels were sampled in an upstream direction with a backpack electrofisher focusing on shorelines and habitat features used by juvenile salmonids such as woody debris, pools, and backwaters. The ages of captured fish were assigned in the field based on length; YOY (< 152mm), age-1 (152.0mm-276.9mm), and age-2 salmonids (277.0mm-376.9mm; Vincent 1973). Sampling continued until one of each species and age class was observed or the entire side channel was sampled. Additionally, about 100 YOY salmonids were collected from each side channel, preserved in ethanol, and identified in the laboratory (Weisel 1966; Figure 10).

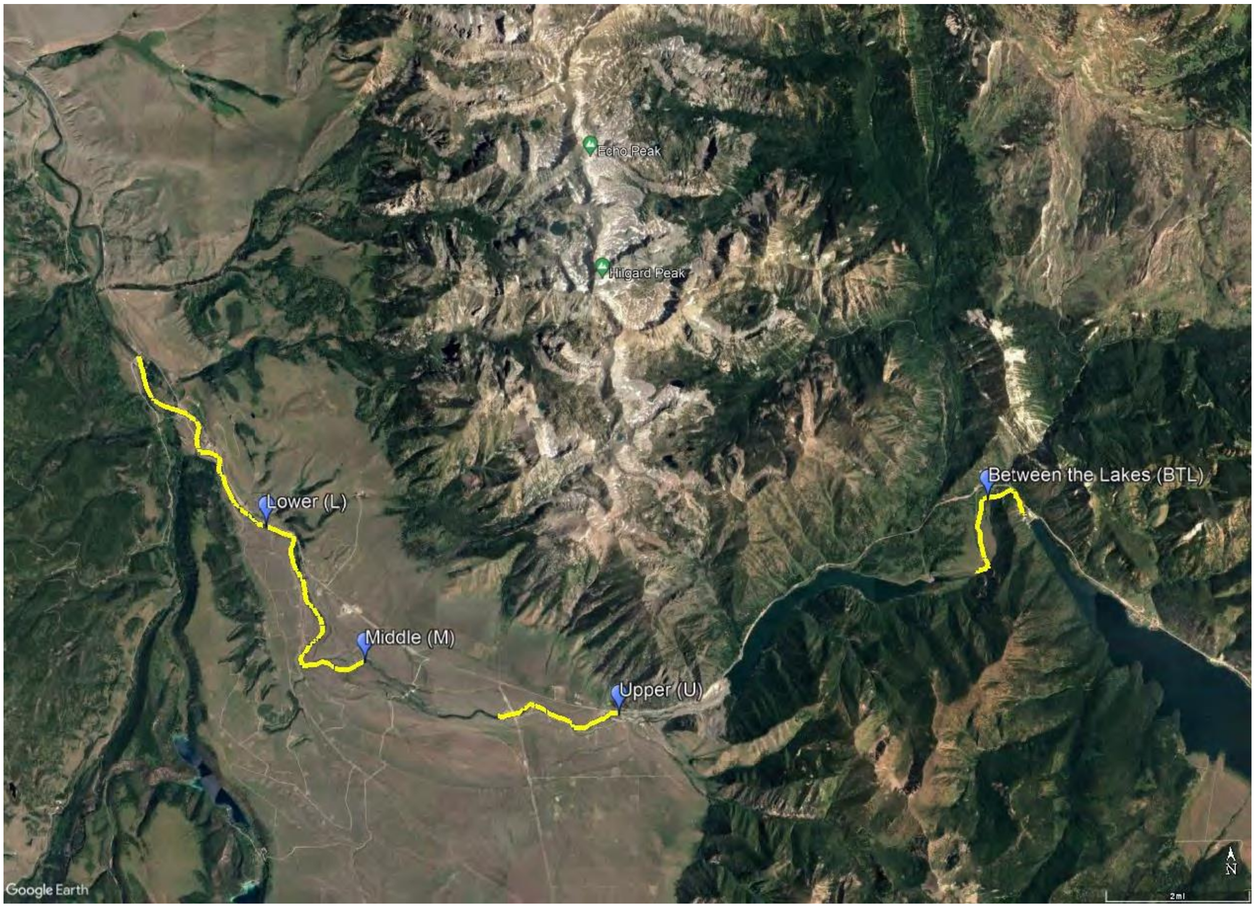

Figure 5. Madison River sections selected for juvenile presence/absence surveys.

Figure 6. Selected side channels for juvenile salmonid sampling in the Between The Lakes (BTL) reach. All side channels were sampled except side channel 5.

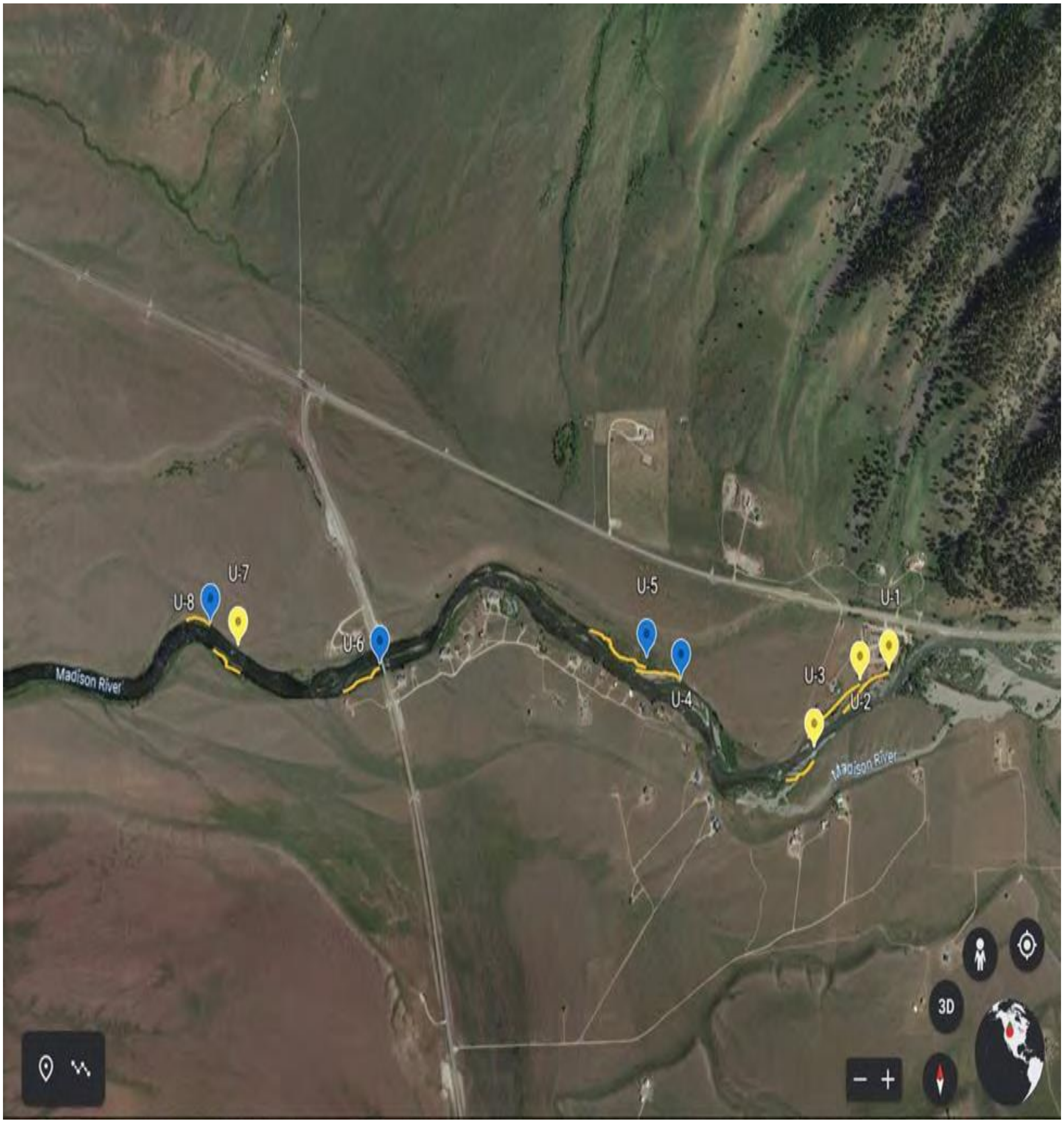

Figure 7. Side channels in the Upper reach (U). Blue markers represent side channels not sampled and yellow markers represent side channels that were randomly selected for sampling.

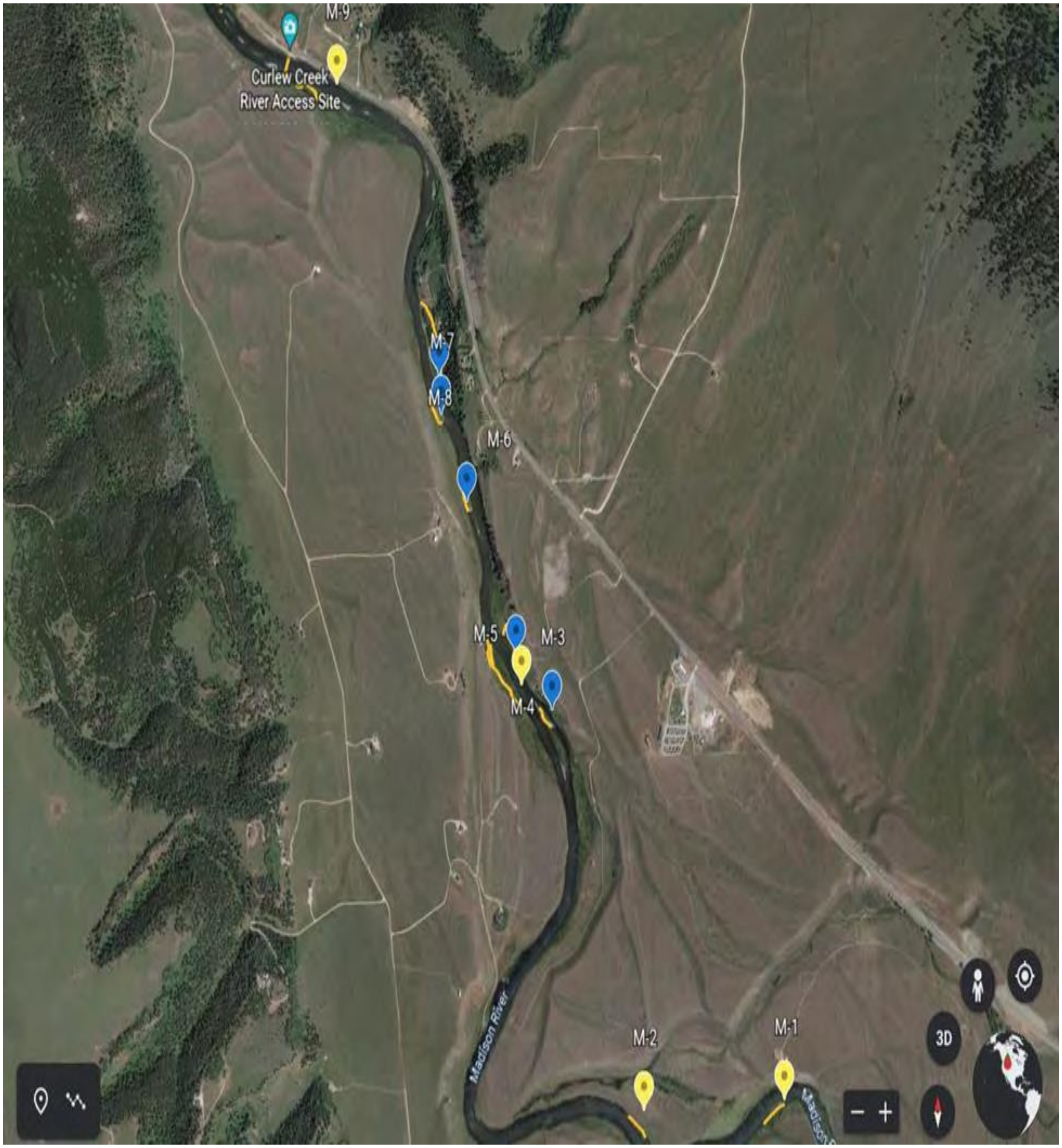

Figure 8. Side channels in the middle reach (M). Blue markers represent side channels not sampled and yellow markers represent side channels that were randomly selected for sampling.

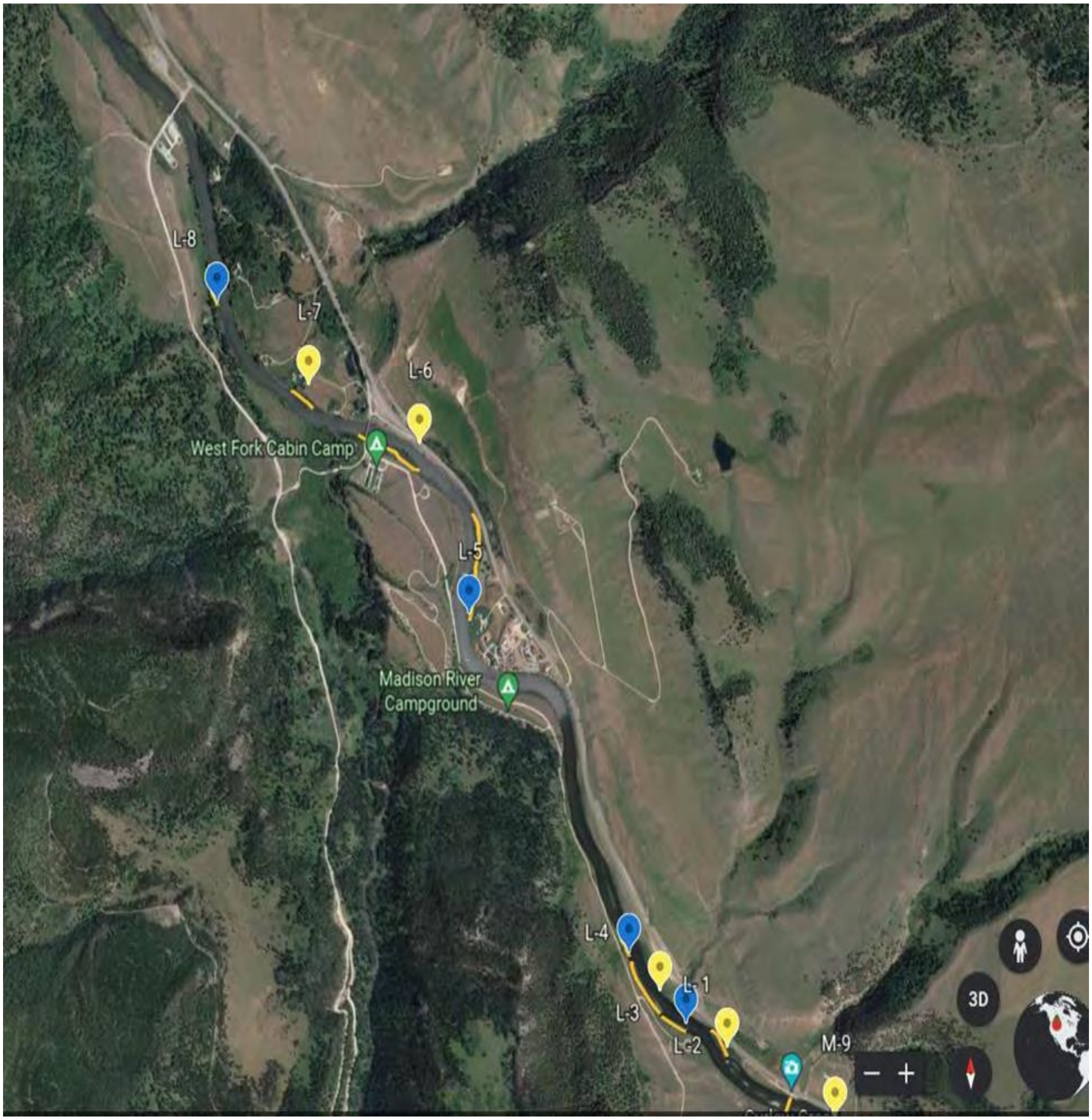

Figure 9. Side channels in the Lower reach (L). Blue markers represent side channels not sampled and yellow markers represent side channels that were randomly selected for sampling.

Table 2. Side channels selected for sampling by reach Between the Lakes (BTL), Upper (U), Middle (M),and Lower (L).

Reach	Side Channel Number	Latitude	Longitude
BTL	1	44.869701	-111.342301
BTL	2	44.869113	-111.348333
BTL	3	44.868643	-111.348551
BTL	4	44.865800	-111.348256
BTL	5	44.863263	-111.349883
BTL	6	44.863063	-111.350606
BTL	7	44.861304	-111.349335
BTL	8	44.858382	-111.348953
BTL	9	44.855846	-111.347920
U	1	44.825465	-111.459008
U	2	44.824053	-111.462250
U	3	44.825060	-111.467977
U	8	44.827633	-111.493859
M	1	44.838111	-111.529385
M	2	44.837105	-111.535760
M	6	44.853858	-111.544382
M	7	44.856010	-111.545619
L	1	44.867208	-111.558981
L	3	44.868999	-111.563532
L	6	44.888190	-111.579357
L	7	44.889932	-111.584686

Figure 10. Young-of-year salmonids collected for identification.

Presence-absence surveys confirmed that YOY and juvenile salmonids occupied 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. Young-of-year Rainbow Trout were present in 90% of the side channels sampled in July (Table 3). Rainbow Trout YOY absence from the June sample is attributable to relatively late emergence compared to brown trout (Downing 2001), which resulted in clear size differences between YOY Brown and Rainbow Trout; Brown Trout YOY were on average 20mm longer than Rainbow Trout YOY during July sampling. Age-1 Brown (70% and 75%) and Rainbow Trout (80% and 40%) were present in most side channels during both sampling periods (Table 3). Age-2 Brown (15% and 35%) and Rainbow trout (10% and 35%) were present in some 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 (Table 3). Larval drift of Mountain Whitefish may have distributed juveniles to areas of slower velocities than sampled for this report (Boyer 2016). However, YOY Mountain Whitefish are common throughout the mainstem Madison River and are frequently observed by FWP personnel during annual electrofishing surveys.

Table 3. June and July 2022 presence-absence survey of Madison River side channels Between the Lakes (BTL), Upper (U), Middle (M), and Lower (L) for young-of-the-year (YOY), age-1, and age-2, Brown Trout (LL), Rainbow Trout (RB), and Mountain Whitefish (MWF), X denotes presence. X? was a suspect Rainbow Trout later identified as a Cutthroat Trout.

Side Channel	YOY LL		Age-1 LL		Age-2 LL		YOY RB		Age-1 RB		Age-2 RB		YOY MWF		Age-1 MWF		Age-2 MWF	
	June	July	June	July	June	July	June	July	June	July	June	July	June	July	June	July	June	July
BTL1	x	x		x				x										
BTL2	x	x				x		x	x			x			x			
BTL3	x	x	x					x	x									
BTL4	x	x		x				x	x		x?	x						
BTL6	x		x	x				x	x									
BTL7	x			x				x								x		
BTL8	x	x		x				x		x						x		
BTL9	x	x	x	x				x	x							x		
U1	x	x	x	x	x	x		x	x	x	x	x						
U2		x	x			x		x	x		x	x						
U3		x	x	x					x									
U8	x	x	x	x				x	x	x								
M1	x	x	x		x	x		x	x									
M2	x	x		x		x		x		x		x					x	x
M6	x	x	x	x				x	x							x		
M7	x	x	x	x	x	x		x	x	x		x						
L1	x	x	x	x				x	x	x								
L3	x	x	x	x				x	x	x								
L6	x	x	x	x				x	x	x								
L7	x	x	x	x		x		x	x	x		x						

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

FWP performed a catch-per-unit effort (C/*f*) survey to assess population structure and relative abundances of salmonids in the Madison River between Hebgen Dam and the Quake Lake inlet on September 6, 2022. Fish were collected by electrofishing from a drift boat-mounted mobile anode system, weighed (g) and measured (mm). Age-specific C/*f* estimates 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.
Sampling between Hebgen Dam and Quake Lake showed lower C/*f* for all fish species and age classes than anticipated, which may be a result of the swift and deep river conditions throughout the section. Rainbow Trout and Mountain Whitefish comprised the majority of the fish sampled, and Brown Trout were at relatively low abundances (Table 5). The paucity of Brown Trout observed in the section may be attributable to the lack of habitat complexity (e.g.,undercut banks, large woody debris) throughout the sampling reach. As discussed 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.

Table 4. 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.

	0	1	2	3+
Species	< 152	152-276	277-376	> 377
LL	1.0	1.0	0	4.7
RB	8.2	28.2	11.8	15.3
MWF	10.7	3.6	5.0	67.9

Data collected in 2022 will be compared to subsequent surveys to assess the potential effects of the Hebgen gate failure. In general, sampling conditions, normal fluctuations in abundances, and the lack of baseline data could confound our ability to attribute future changes in the trout populations to the gate 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. Assuming the trout populations immediately downstream of Hebgen Dam possess comparable vital rates to those in the Pine Butte Section, similar fluctuations, including declines, in electrofishing C/*f* could be expected in the monitoring section between Hebgen Dam and Quake Lake regardless of potential effects caused by the dam failure. Moreover, electrofishing efforts in large rivers inherently produce abundance estimates with notable uncertainty (i.e., relatively large confidence intervals for abundance estimates), which further inhibits our ability to statistically detect and attribute population changes to the dam failure. 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 the Madison River between Hebgen Dam and Quake Lake on November 15, 2022 to identify and document key spawning areas used by Brown Trout. Discharge at the time redd counts was 689 cfs (measured at the USGS 06038500 Grayling gage below Hebgen Lake). Redd counts were completed by walking upstream and identifying streambed disturbances consistent with redd morphology (Gallagher et al. 2007). A typical redd consists of a defined pit where gravels were excavated with a mound of gravels (tail spill) immediately downstream of the pit (Figure 11). GPS coordinates were recorded and redd locations were mapped using Google Earth (Table 6; Figure 12).

Figure 11. Brown Trout redds in a side channel of the Madison River between Hebgen Dam and the Quake Lake inlet, November 2022.

Table 5. Redd locations and the number of redds observed during surveys conducted November 15, 2022, in the Madison River between Hebgen Dam and Quake Lake.

Latitude	Longitude	Redds observed
44.85481	-111.34861	1
44.85497	-111.34633	7
44.85498	-111.34822	11
44.85529	-111.34819	19
44.85530	-111.34820	5
44.85564	-111.34840	17
44.85576	-111.34819	2
44.85575	-111.34833	2
44.85576	-111.34830	3
44.85564	-111.34840	17
44.85590	-111.34849	2
44.85616	-111.34870	1
44.85758	-111.34891	5
44.85626	-111.34940	4
44.86198	-111.35023	4
44.86239	-111.35029	6
44.86276	-111.35040	6
44.86266	-111.35058	2
44.86314	-111.35061	6
44.86953	-111.34012	5
44.86942	-111.34005	1
44.86949	-111.33990	1
44.86958	-111.33988	1
44.86957	-111.34014	1
44.86973	-111.34006	1
44.86959	-111.34045	1
44.86970	-111.34046	1
44.86979	-111.34027	1
44.86993	-111.34041	1
44.86997	-111.34054	1
44.87000	-111.34060	1
44.87002	-111.34055	1
44.87026	-111.34104	1
44.87029	-111.34102	1
44.87029	-111.34101	1
44.87035	-111.34096	1
44.87037	-111.34095	1
44.87038	-111.34104	1
44.87038	-111.34103	1
44.87043	-111.34113	1
44.87039	-111.34118	1
44.87033	-111.34119	1
44.87033	-111.34120	1
44.87042	-111.34133	1
44.87043	-111.34135	1
44.87044	-111.34142	1
44.87031	-111.34158	1
44.87039	-111.34171	1
44.87037	-111.34171	1
44.87033	-111.34171	1
44.86658	-111.35117	1
44.86577	-111.35114	1

Most Brown Trout redds between Hebgen Dam and Quake Lake occurred in side channels, which were the habitat most impacted by gate failure. Of the 165 redds identified, 151 were located in side channels and 14 were located within the main river channel (Figure 12). 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). Based upon the wetted perimeter and discharge relationship curve for the Madison River below Hebgen Dam, the reduction in discharge during the gate failure dewatered an estimated 3.4 acres of nearshore mainstem habitat (FWP 1989; Figure 13). Although the graph represents a single thread channel, it demonstrates the potential effect of reduced river stage on redds in shallow or nearshore habitats and the potential for side channels within the reach to become disconnected. Future investigations into the relationship between stage and discharge in this section of the river would provide insight into the flows required to maintain adequate spawning conditions.

Figure 12. Locations of redds identified in the Madison River between Hebgen Dam and the Quake Lake inlet. The size of the diamond is a general representation of redd density (i.e., the larger the diamond the greater the number of redds at that location).

Feet=204+.0329(cfs)

648 cfs=225.31ft

216 cfs=211.10ft

Difference=14.22ft

Acres=(10560ft*14.22ft)/43560ft^2

3.44 acres of exposed near shore habitat

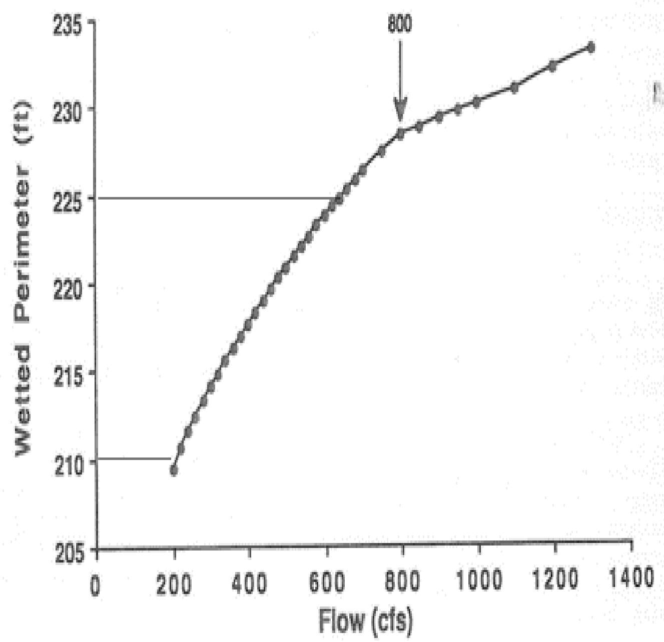

Figure 13. The wetted perimeter of the Madison River between Hebgen Dam and the Quake Lake inlet (FWP, 1989). The area of exposed nearshore habitat is estimated from the following equation: Feet=204+0.0329(cfs).

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Appendix B

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 4. 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 RB MWF	Oct-Dec Mar-Jun Oct-Nov	redd redd dispersal	157-257 78-136	Mar-Jun Jun-Jul Spring	(J) Cobble interstices, woody debris, channel margins, (A) undercut banks, riffles, pools	Aquatic and terrestrial invertebrates, fish
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 5. 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 6. 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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