

Case Study

Leveraging historical datasets to quantify the recovery of an impaired stream entering Yellowstone National Park

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Abstract

Environmental impacts from surface mining can extend beyond the lifetime of mining operations, persist for decades prior to formal clean-up, and span multiple jurisdictional boundaries. Using a case study from Soda Butte Creek which enters Yellowstone National Park, we demonstrate how existing datasets and longitudinal studies can be integrated to document early stages of recovery following reclamation. Nearly three decades of previous studies provided a baseline for biological and water quality impairments from a former mill and tailings site. Direct comparisons of water quality data, macroinvertebrate community summaries, and fish abundance data from reference reaches and common locations pre- and post-reclamation were used to quantify whether desired ecological benchmarks were met and characterize rates of recovery. Our results indicated that response times of water quality, macroinvertebrates, and fish to reclamation were relatively rapid and measured in years rather than decades. Specifically, concentrations of total metals below the former mill and tailings site were lower than pre-reclamation levels. Five years post reclamation (2015 to 2019), median total iron concentrations were just 3% of levels measured the decade (2000 to 2010) before reclamation began. Macroinvertebrate metrics (richness and abundance of sensitive groups) below the former mill and tailing sites were formerly a fraction of reference conditions. Post-reclamation, total taxa richness and stonefly abundance estimates at the formerly impaired site were equal to the mean multi-reach proportional estimates for other mainstem reference sites. Lessons learned from Soda Butte Creek could be used to inform and support other data-driven assessment work.

Keywords Stream impairments · Historical datasets · Ecological recovery · Acid mine reclamation · Collaborative conservation

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1 Introduction

Ecological recovery of degraded ecosystems is an often-stated goal of reclamation actions and is featured prominently in environmental policy [1]. In most general terms, recovery involves returning an impaired ecosystem to one that contains the full complement of species and services present in unimpaired, reference ecosystems [2, 3]. Recovering an impaired ecosystem first requires removing disturbances or contamination that has been central to the loss of ecosystem services [4]. Following that action, ecological recovery, like any ecological process, may take weeks to decades to unfold [5]. In some instances, recovery may be incomplete—not fully returning to an unimpaired or reference state [1, 6]. In these cases, documenting improvements relative to an impaired baseline can also provide useful information related to the trajectory of recovery [3].

Environmental and ecological reference points [7] or ‘ecosystems of reference’, an accumulation of information compiled from multiple reference sources (*sensu* Aronson [8]), can serve as benchmarks for evaluating the ultimate success of reclamation actions and for measuring the trajectory of recovery for attributes with longer response times [9]. Ecosystems are not unidimensional and therefore, once initiated, reclamation actions also set in motion the simultaneous return of multiple ecosystem attributes [10, 11]. Following an ecosystem’s initial restoration phase, recovery of some ecosystem components may be immediate (surface water quality) while others are expected to have lag times ranging from years (macroinvertebrates) to decades (riparian vegetation) [12]. For example, in acid mine drainage, the recovery of instream biological communities may be slow relative to water quality improvements [3, 11, 13], because acid mine drainage involves physical degradation of the benthic habitat and because recolonization rates of fish and insects are a function of distance and health of proximal source populations [3, 14–16]. Because of these anticipated differences in recovery rates, reference information for each ecosystem attribute or river health indicator [17] is critical to the formal evaluation of reclamation success [18, 19].

Historical datasets associated with ecosystems undergoing restoration or reclamation actions (e.g., Total Maximum Daily Loads, Superfund clean-ups, and Abandoned Mine Reclamations) provide important reference points from which to assess present-day or future ecosystem change [15, 20–22]. Total Maximum Daily Load (TMDL) rules, mandated by the U.S. Environmental Protection Agency (EPA), require individual U.S. states to develop and oversee implementation of restoration and/or reclamation plans that are designed to reduce pollutant discharges to waters protected by the Clean Water Act. The U.S. EPA also implements the U.S. Comprehensive Environmental Response, Compensation, and Liability Act of 1980, also known as ‘Superfund’—a program designed to support the remediation of hazardous waste sites in the U.S. [23]. Guidelines and policies associated with TMDLs, Superfunds, and other remediation, reclamation, rehabilitation, or restoration to an impaired or impacted site following closure often lack clarity on desired reference conditions of key ecosystem attributes—details that may exist and be accessed through historical studies and datasets [21]. While historical datasets offer unique insight on ecosystem attributes and, importantly, some of this information can be site specific, they cannot be strictly translated into contemporary restoration goals or endpoints [20]. Despite their value in project planning, not all reclamation actions benefit from the existence of previous studies or pre-reclamation datasets [13]. Further, most previous studies were not carried out with future resurveys in mind. Still, previous studies often contain landmarks or geo-referenced information from sampling locations that can be located and resurveyed [refer to Marcus et al. [24] as an example]. In such cases, these historical studies can be meaningfully leveraged to quantitatively evaluate and contextualize the success of reclamation actions.

Here we highlight examples of how historical datasets were used as the basis for an integrated evaluation of the McLaren Mill and Tailings reclamation and stream restoration project completed outside Yellowstone National Park, USA [25]. We offer our approach as a case study of how historical data on a suite of attributes or river health indicators [17] can be useful for comprehensively evaluating stream ecosystem recovery and acknowledge that this type of work remains uncommon in the restoration and reclamation literature (although refer to Clements et al. [13], Mebane et al. [3], Strobl et al. [10], Kotalik et al. [11]). The McLaren Mill and Tailings reclamation and stream restoration project was initiated with a goal of reversing decades of contaminant leaching to Soda Butte Creek. Soda Butte Creek is a tributary to the Lamar River, a designated Outstanding Natural Resource Water, in Yellowstone National Park [25]. Mining in this metal-rich region has largely been abandoned, however, mining’s legacy left reaches of this stream highly degraded (Figs. 1, 2) and largely absent of macroinvertebrates and fish [24, 26, 27]. Between 2010 and 2014, the McLaren Mill and Tailings site (hereafter the McLaren site) underwent extensive rehabilitation work. At that time, tailings were removed and the Soda Butte Creek stream channel was reconstructed [25].

Fig. 1 McLaren Gold Mine Mill near Cooke City, Montana, in 1946. The tailings impoundment extends outward from the mill and is likely encroaching on Soda Butte Creek. Photo courtesy of Cooke City Montana Museum

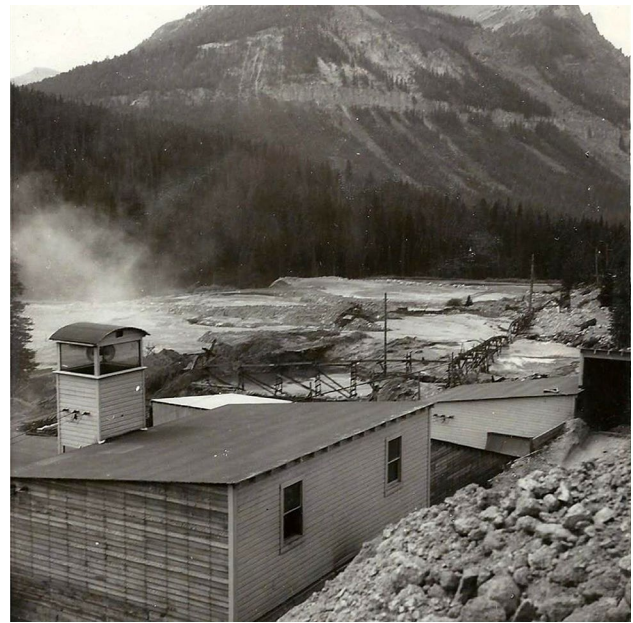
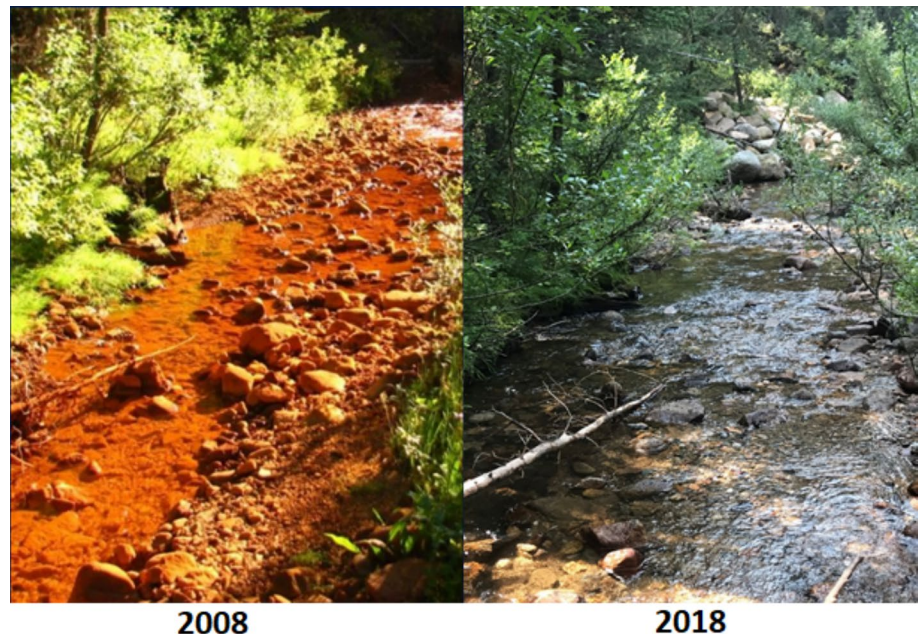


Fig. 2 Soda Butte Creek downstream of the McLaren site in 2008 prior to onset of extensive reclamation activity shows contamination by pyrite. Following weathering, pyrite yields sulfuric acid and dissolved iron. Some of that iron precipitates producing orange-colored, iron covered sediments (left) that are not evident in 2018 (right) following cleanup. Mountain Department of Environmental Quality (left) and National Park Service (right) photos



Beginning in 2015, studies were initiated with an overarching objective to characterize the early stages of ecosystem recovery for a suite of river health indicators. Specifically, environmental (e.g., water chemistry) and ecological (e.g., macroinvertebrate and fish) data were collected and evaluated along Soda Butte Creek using five distinct datasets (refer to methods and Table 1). We compared these contemporary datasets with similar data from previous studies on impaired and relatively unimpaired mainstem and tributary reaches in the watershed (refer too Table 2). We intentionally designed our contemporary work around water chemistry and ecological surveys that would be directly comparable to previous datasets and support secondary goal of understanding whether recovery of water chemistry and biological communities would occur in synchrony or whether biological responses would lag (*sensu* Clements et al. [13], Mebane et al. [3]). Comparability among current and historical datasets was therefore critical to informing which datasets could be rigorously and directly compared and analyzed together (e.g., water chemistry datasets) and which support informal analyses of biodiversity (e.g., macroinvertebrate summaries) and abundance patterns (e.g., fish summaries). To address our goal, of evaluating recovery we focused on five datasets; 1. A longitudinal water quality study of the mainstem of

Table 1 Summary of previous and current environmental and ecological datasets used to characterize the recovery of Soda Butte Creek following reclamation work completed at the McLaren site between 2010 and 2014

Study Category	Study Description	Previous studies	Sampling and surveys from this investigation
Environmental	Longitudinal water quality study	1999 [28] characterization of mainstem (n = 47) and all tributary (n = 17) water quality along focal segment: Yellowstone National Park boundary (downstream) to headwaters of Soda Butte Creek	2018 characterization of mainstem (n = 33) and major tributary (n = 8) water quality along focal segment: Yellowstone National Park boundary (downstream) to headwaters of Soda Butte Creek
	Targeted Monitoring pre- and post-reclamation from two mainstem locations	2000 to 2010 (USDA Forest Service annual web reports variously dated) sampling from 2 locations: immediately downstream of the McLaren site and at Yellowstone National Park boundary (pre-reclamation)	2015 to 2019 sampling from 2 mainstem locations: immediately downstream of the McLaren site and at Yellowstone National Park boundary (post-reclamation)
	Targeted Monitoring: mainstem and tributaries post-reclamation		2015 to 2020 sampling of mainstem Soda Butte Creek locations (n = 5) and select tributaries (n = 5)
Ecological	Macroinvertebrate surveys from multiple mainstem Soda Butte Creek locations	Multiple benthic macroinvertebrate surveys from mainstem locations; previous work completed in 1972 [26], 1975 [29], and 1986 [30]	2018 sampling of mainstem Soda Butte Creek locations
	Fish surveys from multiple mainstem Soda Butte Creek locations	1993 to 2013 multi-agency fish surveys of mainstem locations (Yellowstone National Park annual fisheries reports)	2014 and 2020 multi-agency fish-surveys of mainstem locations

Data sources from previous studies are listed with the corresponding reference. Data from water quality sampling or ecological surveys summarized as part of the current investigation are available in the figshare repository under: *Leveraging historical datasets to quantify the recovery of an impaired stream entering Yellowstone National Park* (<https://doi.org/10.6084/m9.figshare.28104665>)

Table 2 Summary of reference and impaired samples sites within the upper Soda Butte Creek drainage

Study Reach	Description	Status	Rationale
SBC-1	Mainstem Soda Butte Creek (SBC) upstream of the former McLaren site	Reference	Upstream, 1st order mainstem reference site
Miller Creek	Tributary entering SBC from the north and within the former McLaren site	Unknown/Potentially Impaired	Potentially copper impaired 1st order tributary entering SBC at the McLaren site [25]
SBC-2	Mainstem SBC immediately downstream of the former McLaren site	Impaired	Impaired 2nd order site (pre-reclamation)
Woody Creek	Tributary to Republic Creek. Republic Creek enters SBC from the south and downstream of the former McLaren site	Reference	Unimpaired 2nd order tributary reference site
Republic Creek	Tributary to SBC. Republic Creek meets with Woody Creek and mixed waters enter SBC from the south and downstream of the former McLaren site	Reference	Unimpaired 3rd order tributary reference site
SBC-SHP	Mainstem SBC below the confluence of Sheep Creek and SBC	Reference	Downstream, 3rd order unimpaired mainstem reference site
SBC-WY	Mainstem SBC below the confluence of Wyoming Creek and SBC	Reference	Downstream, 3rd order unimpaired mainstem reference site
Unnamed Tributary	Tributary entering SBC from the south and upstream of the Yellowstone National Park boundary	Unknown/Potentially Impaired	Potentially, iron impaired 2nd order tributary entering SBC near the Yellowstone National Park boundary [25]
Silver Creek	Tributary entering SBC from the north and upstream of the Yellowstone National Park boundary	Reference	Unimpaired 1st order tributary reference site
SBC-4	Mainstem Soda Butte Creek at the Yellowstone National Park boundary	Unknown/Reference	Downstream, 3rd order mainstem reference site with unknown impairment status

Site names are presented on map in Fig. 3 and water chemistry is summarized in Fig. 5, 6, and 7. Stream order information is from the U.S. Geological Survey's National Hydrography Data-set [43]

Soda Butte Creek [28], 2. Discrete, targeted water quality monitoring from (a) intensive repeat surveys at two locations and (b) extensive watershed surveys covering many sites [25], 3. Macroinvertebrate community studies [26, 29, 30], 4. Fish surveys used to assess fish abundance and distribution (multi-agency effort beginning in 1993) [31]. Collectively, these datasets serve as data-informed benchmarks of historical and recent ecological conditions [20, 32, 33] and offer unique insights for comparing more recent studies on Soda Butte Creek.

2 Materials and methods

2.1 Study area

Soda Butte Creek is a dynamic, unregulated, snowmelt-fed stream situated in the Beartooth Mountains and Absaroka Range; the upper reaches of the stream cross between the states of Montana and Wyoming, USA east of Yellowstone National Park (Fig. 3). The headwaters of this third order stream system (Hydrologic Unit Code 100700010602; watershed area 152 km²) originate east of Cooke City, Montana, USA at an elevation of approximately 2358 m. Soda Butte Creek enters Yellowstone National Park and flows west to meet the Lamar River at an elevation of approximately 2000 m (Fig. 3). The upper reaches of Soda Butte Creek are surrounded by mature Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) forests. In lower reaches, the riparia is dominated by willows (*Salix* spp.) and grass and sedge-dominated meadows predominate in areas prone to scouring by overbank flows [34].

In the mid-1800's, mineral deposits including gold, copper, and silver were unearthed in the headwaters of Soda Butte Creek and later mines and smelters were established [35]. Large-scale mining operations in this region resulted in degradation of certain stream reaches and some stream reaches remained degraded after mining operations ceased. As a result, a segment of Soda Butte Creek was included on the State of Montana's impaired waters or 303(d)-list. The 7.8 km segment of Soda Butte Creek extending from Cooke City (upstream extent of listing) to the Montana-Wyoming state border near the boundary of Yellowstone National Park (downstream extent of listing; refer to Fig. 3) was characterized as not supporting aquatic life and cold-water fisheries. The causes of impairment for Soda Butte Creek were listed as elevated concentrations of copper, iron, lead, and manganese [36]. Concentrations for these metals were consistently documented at levels exceeding State of Montana water quality standards and elevated metal levels were attributed to Soda Butte Creek's connection with mine tailings from the McLaren site (Fig. 1) [26, 28, 29, 37, 38]. Elevated metals, notably iron from weathered pyrite, also contributed to Soda Butte Creek's orange-stained appearance (Fig. 2).

Soda Butte Creek was recognized for its recreational fishery and described in the 1800's as having 'fast-fishing and large trout'; however, the stream fishery was later characterized as 'fair to poor' following surveys in 1931 [39]. Fish surveys of the mining-impaired reaches in the early 1970s were unable to detect salmonids below discharges from the McLaren site's mine tailings [26, 37]. An instream bioassay characterized fingerling salmonid mortality levels of 80% following a 48 h exposure to Soda Butte Creek water below its contact with tailings waters [26]. Based on this and other studies [24, 27], there was strong evidence indicating that reclamation activities were warranted. The U.S. Forest Service (USFS) began reclamation activities at isolated locations in the upper watershed between 2000 and 2008. Forest Service-led reclamation activities included removal of wastes and isolated reclamation actions to portions of the McLaren site. Between 2010 and 2014, extensive reclamation activities at the McLaren site were carried out. In brief, tailings at the McLaren site were dewatered and relocated, pumped waters were treated, and the Soda Butte Creek stream channel was reconstructed and returned to its historical location within the floodplain [25].

In addition to the mine-impaired waters of upper Soda Butte Creek, native Yellowstone Cutthroat Trout (*Oncorhynchus virginalis bouvieri*) were limited by presence of non-native fish in the drainage. Nonnative Brook Trout (*Salvelinus fontinalis*) were discovered in the headwater reaches of Soda Butte Creek in the late 1980's. Following USFS reclamation activities at the McLaren site in the early 2000's [25], Brook Trout began to spread downstream through the McLaren site into other waters of Yellowstone National Park. Yellowstone Cutthroat Trout are believed to have evolved in species-poor fish assemblages and as a result do not compete well when additional species are introduced [40]. Data also suggests that Yellowstone Cutthroat Trout are less likely to coexist with Brook Trout when compared with other salmonid species [41]. For almost two decades, fisheries crews from Montana Fish, Wildlife and Parks, USFS, the National Park Service (NPS), and Wyoming Game and Fish Department collaborated to remove the nonnative Brook Trout through mechanical means. Hundreds of hours were invested annually with field crews removing Brook Trout. While Brook Trout numbers were maintained, observations indicated their persistence and continual spread downstream. When the major reclamation action beginning in 2010 was approved for the McLaren

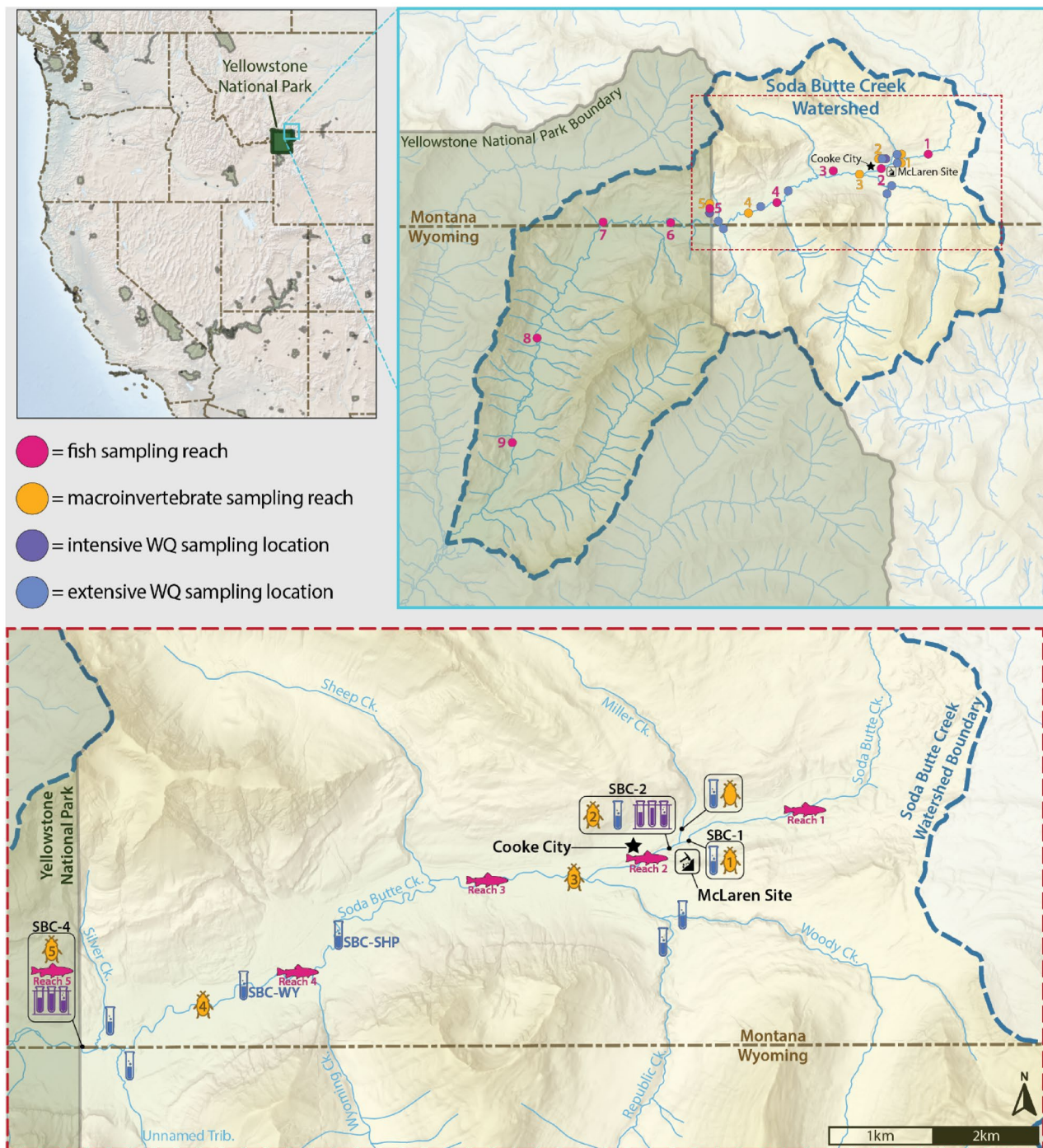


Fig. 3 Study map showing the location of the study area relative to Yellowstone National Park in the western United States (upper left). The studies that are summarized here spanned the Yellowstone National Park boundary (upper right) and occur within the upper Soda Butte Creek watershed (HUC 12 100,700,010,602 watershed area 152 km²; dashed blue line), but most of the work was completed upstream of Yellowstone National Park in the headwaters of the Soda Butte Creek watershed (bottom). Recovery of Soda Butte Creek was evaluated using multiple datasets: intensive water quality data spanning 20 years at two discrete locations (purple symbols), extensive water quality data collected in the mainstem and tributaries since 2015 (blue symbols), and variously dated macroinvertebrates (orange symbols) and fish (pink symbols) surveys. Mainstem Soda Butte Creek water quality sampling location names (e.g., SBC-4; refer to Table 2) are included as are sampling reach numbers for macroinvertebrates and fish

site, fisheries biologists from multiple state and federal land management agencies moved to completely eradicate Brook Trout in Soda Butte Creek through chemical means. Following reclamation of the McLaren site in 2014, Soda Butte Creek was treated with the piscicide rotenone in 2015 and 2016 to remove all nonnative fish. Before initiating rotenone treatments in 2015 and 2016, cutthroat trout were collected upstream of Ice Box Falls, a natural fish barrier on Soda Butte Creek, and held in waters to avoid chemical exposure during treatments of Soda Butte Creek and its tributaries. Approximately, 450 Brook Trout were removed during the treatment in 2015—this represented more than three times the number of Brook Trout captured during annual, week-long electrofishing removal efforts. In 2016 a second rotenone treatment was initiated to ensure all Brook Trout from Soda Butte Creek had been removed. Only two Brook Trout were captured in that effort [42].

2.2 Longitudinal characterization of water quality

Although numerous investigations had evaluated metal concentrations from discrete locations within the impaired segment of Soda Butte Creek [24, 26, 27], Boughton [28] completed a synoptic characterization of metal concentrations within the mainstem and tributaries of Soda Butte Creek from its headwaters to the Yellowstone National Park boundary (refer to Fig. 3; Table 1). In brief, the Boughton [28] study carried out on 20 August 1999 included 47 mainstem locations along the 8.5 km length from just above the former mill site to the Yellowstone National Park boundary. Discharge, documented by the U.S. Geological Survey streamgage 06187915 at the Yellowstone National Park boundary on that date was 0.99 m³/s.

A repeat of the Boughton [28] metal concentrations synoptic study was completed post-reclamation on 26 August 2018, using 33 of the original mainstem locations and 8 major tributaries, 7 of which matched Boughton's tributary sampling locations. The tributary network to the upper segment of Soda Butte Creek contains a mix of mining impaired (e.g., Miller Creek) and reference tributary streams (e.g., Woody Creek) outside the project area and from which recovery can be further contextualized. Within the McLaren site, tailings were removed as part of reclamation activities leaving none of the original seeps, originating from the tailings that were present in 1999, in existence during the 2018 sampling. Discharge documented at USGS streamgage 06187915 at the Yellowstone National Park boundary on 26 August 2018 was 0.62 m³/s. On both sampling occasions, water samples were collected using equal-width increment sampling methods using a DH-81 handheld depth-integrating sampler. This approach is used in wadeable streams [44, 45] and the method collects a water sample across the range of water velocities in a depth profile by collecting sample water from the water surface to the stream bottom (depth-integration) and at multiple, equally spaced locations across the sampled cross-section (width integration). Collected samples were composited in 2-L plastic jugs (Boughton [28]) or an 8-L churn splitter (current study) and dispensed into laboratory provided bottles for analysis.

2.2.1 Targeted monitoring: pre- and post-reclamation below the McLaren site

Monitoring location SBC-2 is on the mainstem of Soda Butte Creek immediately downstream of the McLaren site (Fig. 3). A branch of Miller Creek discharges to Soda Butte Creek upstream of this monitoring location. Monitoring location SBC-4 is located on the mainstem at the Yellowstone National Park boundary (Fig. 3). The USFS contracted with Tetra Tech (formerly Maxim Technologies) to monitor surface water quality during ice-free periods. On average, water samples were collected from each location three times annually from 2000 to 2010. Water quality samples from both locations were collected using grab techniques from the thalweg in accordance with the project water monitoring plan [46]. Sample bottles provided by the analytical laboratory were triple rinsed with native water prior to sample collection, preserved as necessary, and placed into coolers with ice.

Beginning in 2015 and post-reclamation, water samples were collected during snow-free periods and spanning the months of May through November from these same two locations (SBC-2 and SBC-4) using equal-width increment sampling methods and a DH-81 handheld depth-integrating sampler. Our goal was to achieve a balance of roughly 1/3 of samples occurring during high flow conditions (typically May and June). Flows during the month of July were considered high to intermediate depending on year. The remainder of samples collected during the months of August, September, October, and November represented low-flow conditions [47]. The samples were composited in an 8-L churn splitter and dispensed into laboratory bottles for analysis. Samples were kept on ice until analyses were completed at EPA-certified laboratories (ENERGY Laboratories in Billings, Montana and Helena, Montana, USA).

2.2.2 Targeted monitoring: mainstem and tributaries post-reclamation

Following the completion of the reclamation, an extensive sampling plan [47] was developed for mainstem reaches of Soda Butte Creek and its major tributaries (Table 2). This work was initiated in 2015 and designed to provide adequate data for the Montana Department of Environmental Quality (MT DEQ) to assess the water quality-impaired segment of Soda Butte Creek included on Montana's Clean Water Act Sect. 303(d) list and for which TMDLs were established in 2002 [48]. The impaired segment extended from the McLaren site to the Montana border and included water quality impairments from anthropogenic sources (i.e., historical mining) for four mining related metals: copper, iron, lead, and manganese. Copper has been documented at elevated concentrations [24, 25, 28] and is toxic to aquatic organisms at environmentally relevant concentrations [49], thus we formally evaluated the spatial patterns of copper in the upper Soda Butte Creek watershed.

We used depth- and width-integrated sample collection techniques to gather representative water samples from 10 locations throughout the upper Soda Butte Creek watershed. All locations selected for the characterization of mainstem and tributary water quality were accessible, representative of the targeted reach and met data objectives. Along with taking standard precautions (e.g., rigorously rinsing sampling equipment between sites, wearing clean sampling gloves at each location, and using laboratory-provided and sterilized sample containers) to prevent sample contamination, it was visually confirmed that all selected locations were well mixed without discernable flow aberrations (e.g., obvious side channels, tributaries, or other water inputs/outputs that could erroneously affect sample results) [45]. As noted above, water was collected using a DH-81 sampler and composited and homogenized in an 8L churn sample splitter. All sample collection and splitting equipment was triple rinsed with native water prior to sample collection. Water was dispensed from the churn into laboratory-provided bottles that were also triple-rinsed with native water. Water samples were preserved in the field using concentrated nitric acid (HNO_3). Sample containers were shipped to an EPA-certified analytical laboratories for analysis.

2.3 Macroinvertebrate response to reclamation

Chadwick [26] used in-situ Hester-Dendy artificial substrate samplers to sample and characterize the benthic macroinvertebrate community. Three samplers were placed near the benthic substrates within each of the five focal reaches. Benthic macroinvertebrate samples were collected from substrates at monthly time steps from July 1972 to November 1972. Macroinvertebrate samples were preserved in 10% formalin in the field and preserved specimens were identified to the lowest taxon level in the laboratory at Montana State University, Bozeman, Montana, USA. Spatially comparable surveys of benthic macroinvertebrates were carried out in 1975 [29] and 1986 [30] at multiple mainstem locations of Soda Butte Creek using a Surber Sampler. In the 2018 study, benthic macroinvertebrates were collected using composites of kick-net samples collected with a 500- μm D-frame kick net and from 11 transects in a target reach [50, 51]. Within each reach, samples were collected moving from downstream to upstream transects. The 11 samples were composited to obtain a sample that is representative of the entire reach. Samples were identified to lowest taxonomic level at Rhithron Associates, Missoula, Montana, USA.

Interpreting the macroinvertebrate community patterns across the datasets that were collected over 50 years apart and that used markedly different sampling methods and differing taxonomic resolution was a challenge. For example, each macroinvertebrate dataset included a site in the forested section of Soda Butte Creek upstream of the McLaren site, and several sites with progressing distance downstream (Fig. 3). The upstream location has been free from profound anthropogenic disturbances and conceptually, macroinvertebrate communities sampled at similar times of the year should be similar, other than for natural variation (e.g., Mebane et al. [3]). However, the 1972 sampling yielded an average of 12 distinct taxa at this location, the 1986 survey yielded 8 distinct taxa, and our 2018 sampling yielded 48 distinct taxa at this site. It is implausible that the taxa richness at the upstream, minimally disturbed site truly increased fourfold from the 1970s to 2018. To reduce the influence of sampling and processing differences described, we selected summary statistics for each survey and expressed them as a proportion of the reference condition occurring within each survey period (1972, 1975, 1986, 2018).

Further, we recognize that no single reference reach represents a perfect analog (i.e., reference) to a focal stream reach [20, 52] and within the context of the river-continuum [53]. For that reason, we employed an approach where we built an ecosystem of reference [8] using minimally impaired upstream and downstream mainstem reaches that varied in stream order [54] between 1st (upstream) and 3rd order (downstream). This approach acknowledges upstream differences in forest cover and stream gradient and downstream differences in discharge, gradient, channel width, and solar radiation

that can affect macroinvertebrate species richness [55] and incorporates these differences into an ecosystem of reference for the upper 7.8 km segment of Soda Butte Creek that served as the focus of our work. Using our ecosystem of reference approach, we assumed that within each published survey (1972, 1975, 1986) and this study, the highest metric value represented the highest attainable reference condition which we set to 1.0. This approach has the further advantage of comparing the conditions downstream of the McLaren site in the context of an attainable reference condition, reflected by both upstream and far field downstream sites, which is less at risk of artifactual differences that could result from using a single upstream reference site.

Because of differences in sampling and taxonomic resolution across the datasets, we selected simple metrics that previous research has found to be responsive to metals contamination or substrate alteration and could be reliably calculated with the available data. Overall, taxa richness and mayfly (Ephemeroptera) abundance declines in the presence of dissolved metals in streams [3, 12]. Stoneflies (Plecoptera), in contrast, are commonly tolerant to dissolved metals toxicity, but intolerant to substrate alterations associated with mining such as iron hydroxide or calcite accretion [56, 57].

2.4 Fish response to reclamation

Prior to reclamation, Soda Butte Creek's fish communities were surveyed annually since 1993 in conjunction with nonnative fish inventory and control efforts [31]. To simplify monitoring, Soda Butte Creek was divided into 9 sampling reaches starting at Highway 212 outside of Cooke City, Montana (Fig. 3) and continuing downstream in Yellowstone National Park. Each year, field crews from multiple agencies made one or more electrofishing passes through these sections to estimate the abundance and distribution of native and nonnative fish. Not all sections were sampled in all years. Following reclamation of the McLaren site in 2014 and subsequent (2015 and 2016) piscicide treatments to remove nonnative Brook Trout [42], long-term monitoring reaches (200-m reference reaches) were established in two of the nine historical 200-m reaches (Fish Reaches 3 and 7; Fig. 3) including the addition of a reach that included the newly created channel through the McLaren site.

Annual fish surveys consisted of using electrofishing techniques and single or multiple passes through each reach with a backpack (upper reaches) or boat-mounted (lower reaches) electrofishing unit. The methods used to estimate fish abundance within a reach was consistent across annual surveys within that reach. That means upper reaches were exclusively surveyed using backpack electrofishing gear and lower reaches near the confluence with the Lamar River were surveyed using boat-mounted equipment. For that reason, temporal trends summarized for individual reaches compare annual estimates using a single method for that reach. For consistency, we report only the results from the first electrofishing pass. Each stream reach was surveyed by systematically moving the anode continuously and across available stream and backwater habitat in a zig-zag manner. Care was taken to include areas with extensive structure (e.g., wood, undercut banks) and in shallow waters where most juvenile fish predominate. In pool habitat too deep for wading, the electrode could be thrown up to 15 m and retrieved, drawing fish with it.

2.5 Data analysis

2.5.1 Longitudinal data

Longitudinal datasets of copper, iron, manganese, and lead concentration from synoptic sampling events on 20 August 1999 [28] and 26 August 2018 (this study) were statistically evaluated for changes pre- and post-reclamation. Each of these datasets, except the 2018 iron dataset, included samples that were measured below the instrument detection limit, referred to hereafter as "censored data". The 1999 datasets were comprised of 5.0% and 70% censored data for iron and manganese, respectively. The 2018 datasets were 0.0% and 4.9% censored data for iron and manganese, respectively. All longitudinal data analysis was done using the R programming language [58]. Each longitudinal dataset and sub-dataset (e.g., mainstem or tributary) was evaluated for normality with the Shapiro–Wilk test via the R package *stats* [59]. All iron datasets were normally distributed and only some manganese datasets were normally distributed, requiring use of statistical tests compatible with non-normality for manganese datasets. Summary statistics for normally distributed datasets were calculated using Regression by Maximum Likelihood Estimation for Left-censored Data via the R package *NADA* [60]. Non-normally distributed dataset summary statistics were calculated using the Kaplan–Meier estimator of the empirical cumulative distribution function via the R package *EnvStats* [61, 62]. The 33 mainstem site data pairs and seven tributary site data pairs were evaluated for whether the median of the difference between the 1999 and 2018

result was equal to zero with either the Wilcoxon Signed-Rank test for censored, non-normally distributed data [63, 64], or the parametric paired t-test for censored normally distributed data [60].

Comparisons of total iron concentrations from two targeted mainstem locations, Soda Butte Creek below the McLaren site (SBC-2) and at the Yellowstone Stone National Park boundary (SBC-4) were sampled pre-reclamation (2000 to 2010) and again post-reclamation (2015 to 2019). Concentrations for this analyte were largely above the method reporting limits (174 out of 176 samples were reported) and we therefore used a one-tailed t-test to determine if mean concentration of iron was higher in the mainstem of Soda Butte Creek prior to reclamation (2000 to 2010) and at each location, respectively.

We summarized total copper concentrations from 2015 to 2020 across mainstem Soda Butte Creek locations and mainstem tributaries within the upper Soda Butte Creek watershed (refer to Fig. 3 and Table 2 for sampling locations) using box and whisker plots. Although we were interested in characterizing copper conditions for the upper watershed, we were particularly interested in evaluating post-reclamation copper concentrations from formerly impaired (e.g., SBC-2 and MC-1) and reference locations (e.g., SBC-1, SBC-SHP, SBC-WY, as well as, Republic Creek, Woody Creek; Fig. 3). We tested for pair-wise differences in median concentrations of total copper among all mainstem and tributary sites shown in Fig. 3. Differences were documented using a Kruskal–Wallis test with pairwise comparisons made using Wilcoxon rank sum test with continuity correction. The nonparametric Kruskal–Wallis test is well suited for comparing groups of right-skewed, asymmetric data based on their rank order [65].

Relative differences in the macroinvertebrate community structure were evaluated using a network of reference (Macroinvertebrate Reaches 1, 3, 4, and 5; refer to Fig. 3) and impaired (Macroinvertebrate Reach 2; refer to Fig. 3) reaches using three macroinvertebrate metrics (Total richness, Mayfly [Order Ephemeroptera] abundance, and Stonefly [Order Plecoptera] abundance) and the proportional reach estimates (relative to the maximum value documented in this segment and for each sampling year) relative to a reference value within this stream reach during a given year. Reference values are defined here as the highest abundances (or other metric) measured in the stream reach from upstream of the McLaren site (Macroinvertebrate Reach 1 or SBC-1) to the Yellowstone National Park boundary (Macroinvertebrate Reach 5) for each metric and at each site and during a given year [24, 26, 29, 30]. Because differences in sampling methodologies were used across years, we assumed that within each survey year (1972, 1975, 1986, 2018), the highest metric value represented the highest attainable reference condition which we set to 1.0. Macroinvertebrate surveys carried out in years 1972, 1975, and 1986 occurred before reclamation activities at the McLaren site. Macroinvertebrate summaries from 2018 occurred after reclamation activities at the McLaren site were completed.

Fish abundance estimates were available from multi-pass surveys carried out intermittently beginning in 1993 and across multiple mainstem reaches. Survey reaches located upstream (Fish Reach 1; see Fig. 3) from or more distant downstream (Fish Reaches 4, 5, 6, and 7; see Fig. 3) from the McLaren site served as references for within year comparison. Fish survey Reach 2 (see Fig. 3) located immediately downstream of the former mill and tailings site was considered the site most impacted by mining-related contamination. Survey years before 2010 represent conditions prior to reclamation activities and years after 2014 represent conditions following the reclamation. For consistency, we report only the results from the first electrofishing pass of our multi-pass surveys.

3 Results

3.1 Longitudinal characterization of water quality response to reclamation

Comparison of pre-reclamation longitudinal water quality data from the mainstem (Supplementary material: Appendix A: Table 1) and tributaries (Supplementary material: Appendix A: Table 2) of Soda Butte Creek collected in 1999 and a 2018 post-reclamation repeat of this work revealed decreases in iron concentration (mg/L) at nearly all sampling locations (37 of 40 paired locations; Fig. 4). Average iron concentration from mainstem and tributary sampling locations decreased from 0.42 ± 0.43 mg/L to 0.15 ± 0.15 mg/L between 1999 and 2018 (paired t-test, $p < 0.001$, $t = 8.6$). When we restricted the comparison to mainstem reaches only, there was a statistically significant decrease in average mainstem iron concentration between 1999 (0.44 ± 0.32 mg/L) and 2018 (0.11 ± 0.08 mg/L) (paired t-test, $p < 0.001$, $t = 9.3$). Tributary iron concentrations also decreased from 0.37 ± 0.61 mg/L in 1999 to 0.28 ± 0.26 mg/L in 2018 (paired t-test, $p < 0.01$, $t = 2.8$).

Copper concentrations from the 1999 study were all below the laboratory detection limit of 0.012 mg/L, except for concentrations in tailings features that no longer existed after reclamation. In 2018, all copper concentrations were below the laboratory detection limit of 0.002 mg/L, except for sites T-569 and T-825 which are branches of Miller Creek. These sites were still below the 1999 detection limit of 0.012 mg/L; in 2018 both sites contained concentrations of copper at

Soda Butte Creek Iron Concentration, 1999 and 2018

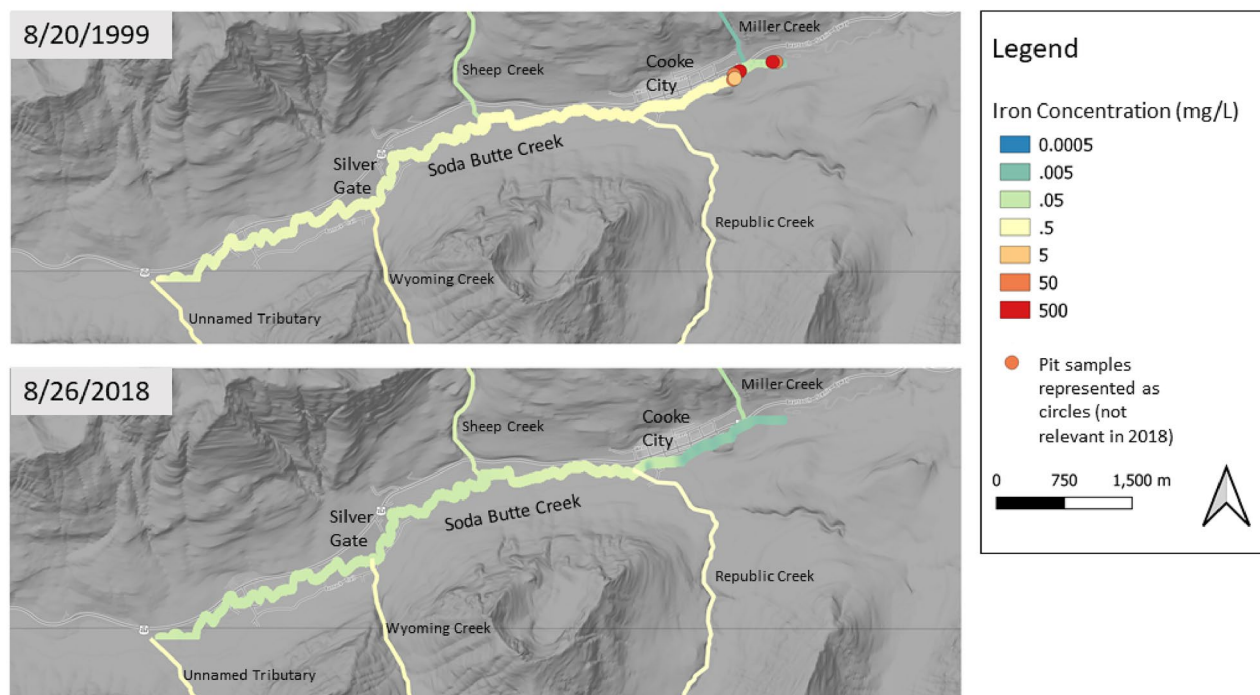


Fig. 4 Total iron concentration (mg/L) in Soda Butte Creek, its major tributaries, and from tailing seeps present at the McLaren site pre-reclamation. Results are shown as interpolation between 40 water quality sampling sites. Circles represent tailing seeps that contributed disproportionately to mainstem water quality pre-reclamation. Upper panel shows pre-reclamation values from Boughton[28], lower panel shows post-reclamation values collected in 2018 by the authors

0.003 mg/L. Lead concentrations from the 1999 study were all below the detection limit of 0.130 mg/L except for one tailing feature sample at T-569 that was 0.603 mg/L. This feature did not exist after reclamation. In 2018, lead concentrations were below the detection limit of 0.0003 mg/L at all sampling locations. Average mainstem and tributary manganese concentrations were lower after reclamation, but differences were not statistically significant between sampling periods (paired t-test, $p=0.41$, $t=-0.81$). Most (~80%) sample measurements for manganese were below the detection limit in 1999 and two were below the detection limit in 2018. The average mainstem and tributary manganese concentration was 0.010 ± 0.016 mg/L in 1999 and 0.003 ± 0.001 mg/L in 2018. Mainstem manganese concentrations were also lower but did not differ significantly (paired t-test, $p=0.67$, $t=-0.42$), averaging 0.013 ± 0.018 mg/L in 1999 and 0.003 ± 0.001 mg/L in 2018. Finally, tributary manganese did not differ (paired t-test, $p=0.34$, $t=-0.95$), averaging 0.004 ± 0.002 mg/L in 1999 and 0.004 ± 0.002 mg/L in 2018.

During the 1999 pre-reclamation sampling by Boughton [28], nine sites comprised of inflows to Soda Butte Creek from tailings and seeps from tailings were sampled in addition to in-stream water quality sampling. Iron concentrations at these sites were higher than concentrations in the channels (Fig. 4), ranging from 2.6 to 418.0 mg/L, with a mean concentration of 79.7 mg/L, and a median concentration of 45.4 mg/L. Copper concentrations at these sites ranged from below the detection level of 0.012 mg/L to 6.1 mg/L. Lead concentrations at these sites were all below the detection limit of 0.13 mg/L except for the site 569 m downstream, which was 0.60 mg/L. Manganese concentrations ranged from 0.13 mg/L to 7.7 mg/L. These data are available in Supplementary material: Appendix A (Table 3). This sampling was not repeated in 2018 because the tailing features including associated seeps were removed as a part of reclamation.

3.2 Targeted monitoring

3.2.1 Pre- and post-reclamation intensive sampling below the McLaren site and at Yellowstone National Park boundary

Pre-reclamation water quality was characterized using the USFS and NPS water quality datasets compiled from April 2000 through April 2010. At SBC-2, immediately downstream of the former mill and tailings site, iron concentrations

Fig. 5 Pre- and post-reclamation iron concentrations from samples collected between 2000 and 2010; (pre-reclamation) and 2015 and 2019 (post-reclamation) water samples collected from Soda Butte Creek below McLaren site (**a** SBC-2; $n = 32$ pre-reclamation and $n = 26$ post-reclamation) and the at the Yellowstone National Park boundary (**b** SBC-4; $n = 92$ pre-reclamation and $n = 26$ post-reclamation)

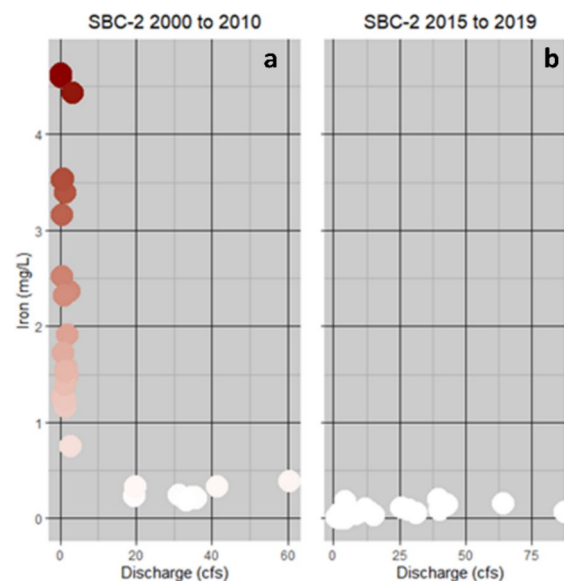
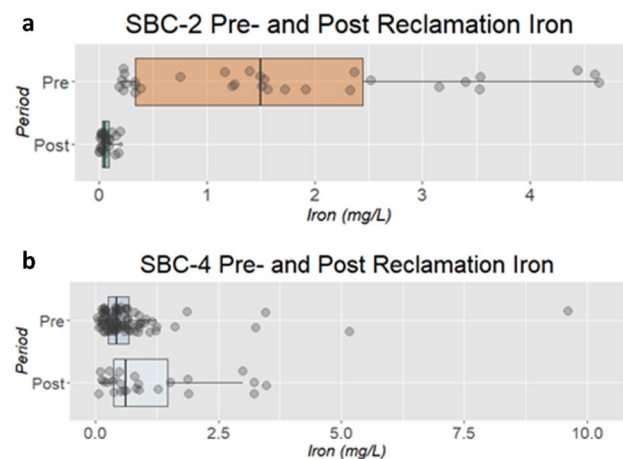


Fig. 6 Pre- and post-reclamation iron concentrations from samples collected between 2000 and 2010 (**a** pre-reclamation) and 2015 and 2019 (**b** post-reclamation) water samples collected from Soda Butte Creek below McLaren site (SBC-2). Water samples meeting the State of Montana iron standard are shown in white and those exceeding the standard are shown in red. Excluded from this figure (for presentation reasons) was a low flow water sample collected pre-reclamation on 9 April 2009 that had an iron concentration of 27.4 mg/L (result that was 5 times higher than the next highest pre-reclamation sample). Discharge at SBC-2 was estimated using an empirical relationship between discharge measured at SBC-2 and discharge measured at the USGS Soda Butte Creek streamgage (USGS 06187915) located at the Yellowstone National Park boundary (SBC-4). Color for individual points is shown in white for the lowest values. Point color increases in darkness (where darkest reds are shown for concentrations above 4 mg/L) as values increase and deviate from 0 mg/L

were variable pre-reclamation (2000 to 2010), ranging from 0.19 to 27.4 mg/L, and, at times, exceeded the Montana standard of 1 mg/L. The median concentration for iron was 1.50 mg/L during the pre-reclamation period (Fig. 5a). During this period, iron concentrations were strongly dependent on flows with the highest concentrations occurring during low or baseflow (Fig. 6a). Post-reclamation (2015 to 2019) and irrespective of discharge, iron concentrations were significantly lower than pre-reclamation ($p = 0.006$, one-tailed $t = 2.62$) and consistently met State of Montana water quality standards (Figs. 5a, 6b). Median iron concentration was 0.05 mg/L during the post-reclamation period.

In contrast to SBC-2, concentrations downstream at the Yellowstone National Park boundary (sampling location SBC-4) had similar median concentrations of iron pre- and post-reclamation and concentrations from these two periods did not differ significantly ($p = 0.084$). Pre-reclamation, concentrations ranged from 0.05 to 9.61 mg/L. Post-reclamation monitoring documented a range of 0.07 to 3.48 mg/L (Fig. 5b).

3.2.2 Post-reclamation extensive sampling

Between June 2015 and July 2020, we completed multiple (average of 14 visits for each site) water quality sampling visits to mainstem and tributary locations in the upper Soda Butte Creek watershed (refer to Fig. 3 for sampling locations). Most of the sampling was completed in 2015 and 2016 as part of a formal assessment of the water quality-impaired segments of Soda Butte Creek (refer to Ray et al. [47], Henderson et al. [25]). Over the 5 year period, samples were collected during snow-free conditions (typically May through November). Copper is a priority metal of concern in Soda Butte Creek [25, 28] and is toxic to aquatic organisms [49]; therefore, we tested for pair-wise difference in median concentrations of total copper among mainstem and tributary sites and focused our attention on comparisons between reference and impaired sites (Table 2). Median copper concentrations ranged from 0.001 to 0.003 mg/L for all tributary and mainstem locations except Miller Creek. In Miller Creek, the median copper concentration was 0.008 mg/L (range 0.003 to 0.018 mg/L total copper) and significantly higher than all other sites (chi-squared = 40.158, $p < 0.001$). The average copper concentrations in the mainstem of Soda Butte Creek directly below Miller Creek and the former McLaren site (SBC-2) was 0.003 mg/L (range 0.001 to 0.010 mg/L total copper) and SBC-2 had significantly higher copper concentrations than other mainstem Soda Butte Creek reference locations (SBC-1, SBC-SHP, and SBC-WY) and two tributary reference locations (Republic Creek ($p = 0.013$) and Silver Creek ($p = 0.004$)).

3.3 Macroinvertebrate response to reclamation

In 1972, the benthic invertebrate community was decimated in Soda Butte Creek downstream of the McLaren site (Macroinvertebrate Reach 2; Fig. 8). Although benthic invertebrates have a wide range of tolerance to the elevated metals and substrate alterations commonly occurring in mining-damaged streams [3, 56, 66], conditions in Soda Butte Creek were so extreme that nearly all the benthos were eliminated. Chadwick [26] conducted five seasonal surveys of Soda Butte Creek in 1972 and found that the total abundances of invertebrates downstream of the former McLaren site averaged only 2% (range 0 to 11%) of reference reaches (Macroinvertebrate Reaches 1, 3, and 5) values (refer to 2.4 Macroinvertebrate Response to Reclamation in the Materials and Methods for more details). Proportional abundances (and other metrics) largely recovered by Reach 3 (Fig. 8), which is downstream of a major diluting tributary (Republic Creek) with comparatively low copper levels (Fig. 7). The diversity of invertebrates (taxa richness, counts of distinct taxa identified) at the impaired reach (Reach 2) below the McLaren site averaged only 10% of reference reaches (Reaches 1, 3, and 5) in 1972. In contrast, during our 2018 survey, taxa richness at the corresponding location (Reach 2) downstream of the former mill and tailings site was 85% of reference Macroinvertebrate reference Reach 1 (Fig. 8). Using an ecosystem of reference approach and combining across multiple reference reaches (Macroinvertebrate Reaches 1, 3, and 5), taxa richness in 2018 was equivalent between formerly impaired Reach 2 (85% of maximum) and average of Reaches 1, 3, and 5 (multi-reach mean proportional estimate of 85%).

Mayflies (order Ephemeroptera) as a group are generally sensitive to elevated metals; some taxa such as Ephemerella, Cinygmula, and Rhithrogena tend to be particularly vulnerable in field settings [3, 56, 66]. All mayflies were eliminated from Soda Butte Creek downstream of the mill and tailings site (Reach 2) in 1972, whereas in 2018, mayflies were similarly abundant downstream of the former McLaren site as reference Reaches 1 and 5, but below levels documented at Reach 3. Notably, Ephemerella, Cinygmula, and Rhithrogena were common downstream of the former McLaren site in 2018.

Fig. 7 Box and whisker plots show total copper concentrations (in mg/L) from water samples collected from ten sampling locations in the upper Soda Butte Creek watershed (refer to Table 2 information on each location) from 2015 through 2020. Median copper concentrations were highest in Miller Creek a tributary to Soda Butte Creek that enters near the former McLaren site

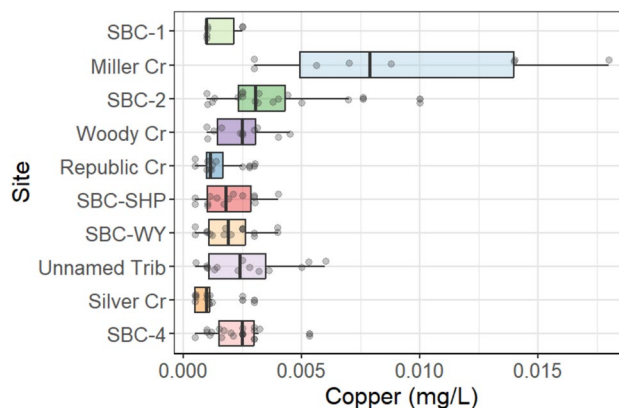
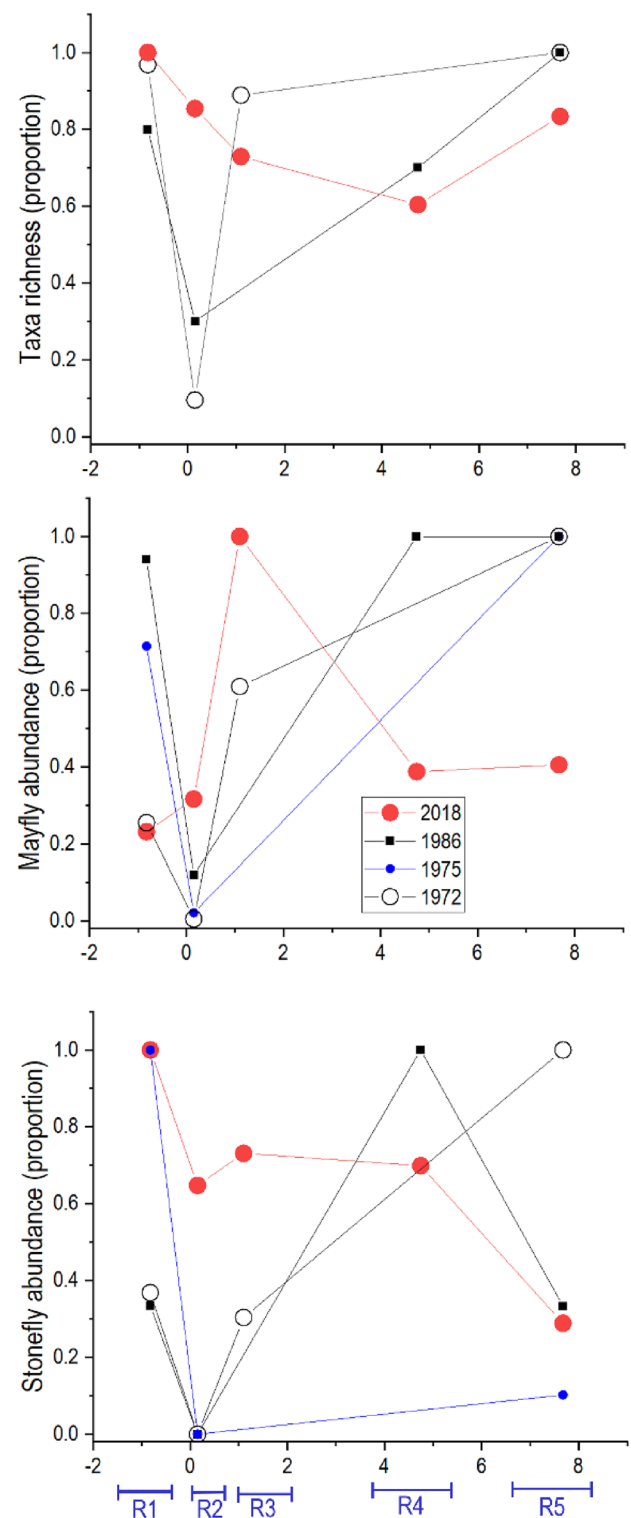


Fig. 8 Macroinvertebrate taxonomic richness, mayfly abundance, and stonefly abundance along a segment of Soda Butte Creek extending from upstream of the McLaren site (Reach 1; Fig. 3) to the Yellowstone National Park boundary (Reach 5; Fig. 3) during pre-reclamation (1972, 1975, 1986) and post-reclamation (2018) surveys. Macroinvertebrate metrics are normalized (from 0 to 1) relative to the maximum values documented in this segment and for each sampling period. Reference values are defined here as the highest abundances (or other metric) measured in the stream reach. Reach 2 was immediately downstream of the McLaren site. Reaches 3 and 4 were on the mainstem below Republic and Wyoming creeks, respectively. Data sources: 1972 [26]; 1975 [29]; 1986 [30]; 2018 present study



Location (in km) on Soda Butte Creek relative to the mill site (km 0) and reach (R) designations

Stoneflies (order Plecoptera) also tend to decline downstream of mining-damaged streams. However, at least some stoneflies are highly tolerant to metals [3, 67], and one reason for their decline in mining-affected streams may be intolerance to the iron hydroxide flocs that may coat substrates and eliminate refugia for stoneflies [16, 68]. In 1972, stoneflies were not detected in Soda Butte Creek downstream of the McLaren site (Reach 2), whereas in 2018, stoneflies were similar in abundance in Soda Butte Creek downstream of the former mill and tailings site (Reach 2 stonefly abundance with 65% of the maximum) and at other reference reaches in the study area (Reaches 1, 3, and 5 mean proportional reach estimate of 67%; Fig. 8).

3.4 Fisheries response to reclamation

In the years leading up to reclamation work, Yellowstone Cutthroat Trout densities remained low or nonexistent through the McLaren site (Fish Reach 2; Fig. 9). In 1993, just 0.5 fish/100 m were detected through the former mill and tailings site. Fish densities remained low (range 0–2.7 per 100 m) over the next two decades (Fig. 9). Four years post-reclamation and 3 years post-piscicide treatment, approximately 20 fish/100 m were sampled throughout the newly established Soda Butte Creek channel through the former mill and tailings site (Fish Reach 2). Similar results were noted in the reference site immediately downstream of Cooke City, Montana (Fish Reach 3). In the 2 years leading up to completion of reclamation and fish restoration, 7.8 and 2.8 Yellowstone Cutthroat Trout/100 m were detected in 2013 and 2014 surveys of this same downstream reach. A 2020 survey of Reach 3 following reclamation produced 12.1 Yellowstone Cutthroat Trout/100 m (data not shown). In contrast to the upstream reaches most heavily impacted by mining activities, further downstream at reference Fish Reach 7 (Fig. 9) Yellowstone Cutthroat Trout densities have remained relatively consistent through time (Fig. 9). In this downstream reference reach, a decline in abundance was observed through the early 2010's, but this decline is most likely attributable to the increase in nonnative Brook Trout found through this reach during this period (Ertel et al.[42]).

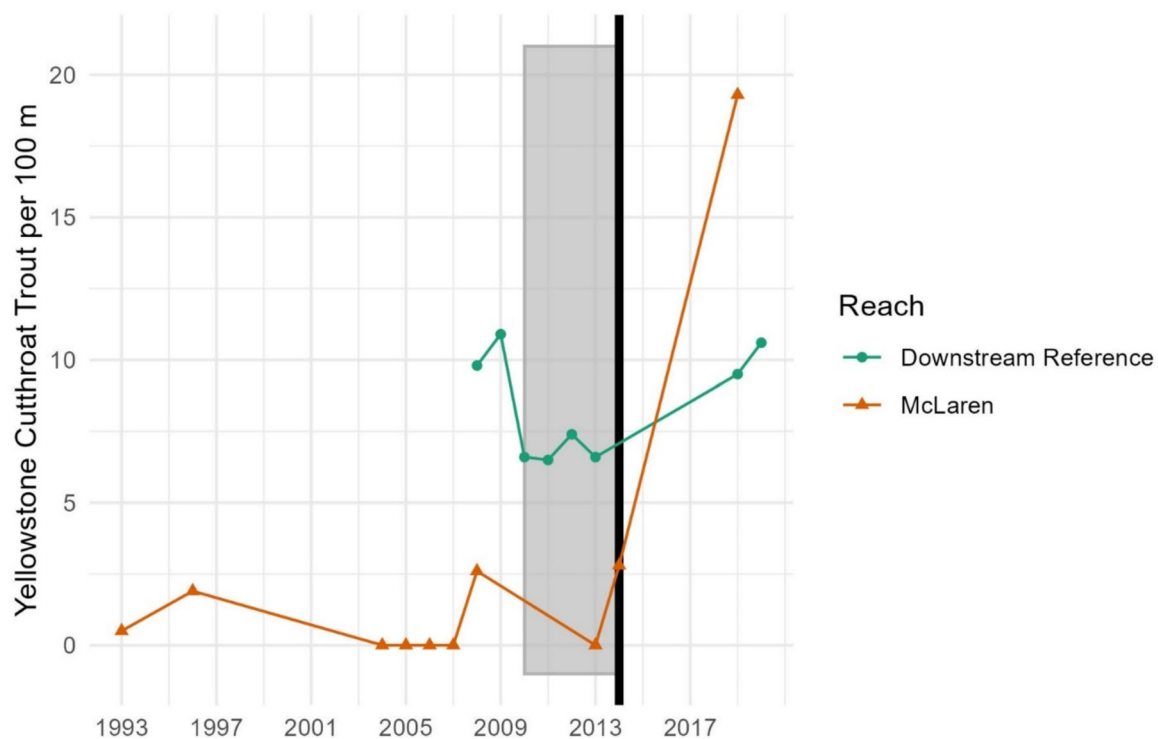


Fig. 9 Density of Yellowstone Cutthroat Trout per 100 m of stream reach. The blue line shows the downstream reference reach (Reach 7; Fig. 3) that was not affected by mining and reclamation, the brown line shows the McLaren site reach (Reach 2; Fig. 3) which was affected by mining and reclamation. The gray bar shows the period of the reclamation project, 2010–2014. The dark gray vertical line shows the commencement of reclamation activities in 2010 and the thick black line shows 2014, the year when reclamation was completed

4 Discussion

Through this case study on Yellowstone's Soda Butte Creek and consistent with other restoration actions to reverse mining induced metal impairments [3, 11, 13, 69], water quality conditions immediately downstream of the reclamation action showed marked improvements over pre-reclamation conditions. For decades, concentrations of metals in upper reaches of Soda Butte Creek during baseflow conditions were most affected by the seepage of metal-rich waters from the former mill and tailings site [28]. Baseflow concentrations of metals are now indistinguishable from conditions of metals across the hydrograph. In contrast to water quality summaries from below the former mill and tailings site, the discrete sampling results from the Yellowstone National Park boundary combined with the longitudinal water quality summaries show that the metal-rich watershed has historically contributed and continues to contribute disproportionately to concentrations of metals present and documented at the national park boundary. Results from our post-reclamation upper watershed sampling of the Soda Butte Creek mainstem and tributaries showed that current copper concentrations are now largely driven by copper concentrations in Miller Creek and iron concentrations were generally highest in an unnamed tributary just upstream of the Yellowstone National Park boundary. While we did not attempt to elucidate whether sources of iron in the unnamed tributary entering Soda Butte Creek near the Yellowstone National Park boundary or copper in Miller Creek were anthropogenic or from natural erosion in this ore-bearing region [70, 71], this type of multi-parameter assessment can provide insight into the sources and locations of different contaminants in a watershed [25].

It is also worth stating that while differences were detected in the concentrations of metal across the two synoptic studies (Boughton [28] and current study), these results do not directly account for modest differences in streamflow on the days of sample collection. Previous work from this region (including from tributaries to Soda Butte Creek), indicates that total iron concentrations in unimpaired waters increase with increasing streamflow. In Soda Butte Creek pre-reclamation, there was an inverse relationship between streamflow and iron concentration in locations immediately below the former mill and tailings site (Fig. 6). While this trend has not been observed during post-reclamation conditions, we want to emphasize that concentrations of total iron and other metals can strongly depend on streamflow [69]. During pre-reclamation water sampling in 1999, average daily streamflow was 0.99 m³/s and during post-reclamation sampling in 2018, average daily streamflow was 0.62 m³/s. This may not have a practical effect on the comparison of the two datasets but is important to note as context for these results.

In the Arkansas River in Colorado, USA, improvements in water quality were noted following reclamation actions (water treatment, tailings removal, and revegetation work); however, biological responses lagged and varied by sampling location potentially because of residue contamination of stream sediments [13]. In tributaries of Panther Creek Idaho, USA, reclamation actions associated with copper and cobalt mines supported the long-term recovery of water quality, fish, and macroinvertebrates. Although water quality was the first indicator of recovery, reductions in metal concentrations were idiosyncratic with some species (e.g., copper) persisting in waters nearly a decade after reclamation. Increases in macroinvertebrate richness generally trailed improvements in water quality but substantial increases in the most sensitive taxa (e.g., mayfly and stonefly groups [macroinvertebrates]) occurred within 10 years post-reclamation [3].

Past studies of macroinvertebrates in Soda Butte Creek [24, 26, 29, 30] indicate that the macroinvertebrate community immediately downstream of mill and tailings site was impacted for at least four decades prior to reclamation. Results from our 2018 sampling indicate substantial improvements relative to a persistently degraded historical state for each of the macroinvertebrate community metrics. In 2018, taxonomic richness and stonefly abundance measured at the reach downstream of the former mill and tailings were 85% and 65% of levels documented across mainstem reference reaches. Mayfly taxa *Ephemerella*, *Cinygmula*, and *Rhithrogena* were common downstream of the former McLaren site during our 2018 sampling. In the North Fork Clear Creek, a third order stream in Colorado, USA recovery of metal-sensitive mayflies trailed improvements in overall macroinvertebrate abundance and taxa richness two years after decreases in metal concentrations were measured following waste rock removal and initiation of waste treatment [11]. Based on our 2018 sampling, recovery of the macroinvertebrate community in upper reaches of Soda Butte Creek appears to be well underway and has occurred within four years after this persistent stressor was removed. The time to recovery in the present study was consistent with time to recoveries in previous studies of macroinvertebrate communities following release from persistent stress. Mebane [5] evaluated 50 studies of macroinvertebrate recovery following removal of persistent stressors and concluded that by 5 years, recovery had been achieved in 80% of the cases. Recoveries after relief from press (persistent) stressors such as mine reclamation were generally slower than from pulse disturbances such as

accidental spills or deliberate pesticide treatments. The median recovery time for aquatic communities following press disturbances was 5 years, with 50 percent of the cases showing recovery between 2 and 10 years [5].

Fish typically take one to multiple generations to recover following habitat reclamation and removal of previously constraining stressors [3, 5]. In the Panther Creek drainage in Idaho, Mebane et al. [3] showed that Rainbow Trout (*Oncorhynchus mykiss*) readily used habitats post-reclamation and within 4 years post-reclamation trout densities were similar to reference densities in Big Deer Creek. In Soda Butte Creek, the numbers of Yellowstone Cutthroat Trout detected in the former mill and tailings site and reaches immediately downstream were higher than expected considering that little additional stocking has taken place in Soda Butte Creek, and no stocking has occurred in or upstream from these sampling sections. Fish quickly recolonizing the McLaren site, when surrounded by other available habitat is a testament to the quality of this newly restored area. Eradication of nonnative Brook Trout may have aided in the recovery of Yellowstone Cutthroat Trout, but partitioning effects from eradication and reclamation actions is challenging. Further, our monitoring was not conducted in a way that allowed us to carefully document exact rates or the transitional steps of recovery, however our monitoring confirmed fish presence inside the reclamation area, and water chemistry data indicate that physical and chemical barriers do not impede fish passage.

4.1 Lessons learned

There are several key lessons learned from this case study. Principal among these, and possibly the most difficult to quantify, was the value of collaboration and a shared commitment to more fully evaluating Soda Butte Creek recovery through a suite of river health indicators. Committed partners in multi-jurisdictional projects like the efforts to recover Soda Butte Creek recognize that no agency or landowner has full authority, nor the capacity, to fully evaluate boundary-spanning responses using multiple lines of evidence [72]. Instead, these efforts require a diverse team with complementary skills working towards a shared goal of recovering degraded ecosystems.

Legacy effects of surface mining operations often extend well beyond the lifetime of the mining operations and present complex clean-up and monitoring challenges requiring stakeholder participation, resources to support all aspects of the work, and knowledge gained through careful review of past and similar work [73]. Understanding the history of past work on or near reclamation and restoration sites can provide multiple benefits. First, the integration of previous studies supports monitoring and assessment designs that plan for data comparability [74] and support direct comparisons [75]. In the case of Soda Butte Creek, we examined several previous studies [24, 26, 27, 29, 30, 46] from multiple investigators, and where possible, used common locations, consistent analytes, taxonomic groups, and publicly available data archived in agency reports and scholarly publications. By revisiting previous locations and repeating previous work we were able to quantify recovery in clear, common terms by comparing data collected on different sampling dates. This approach helped to summarize recovery and supported formal regulatory assessment needs associated with Clean Water Act impaired waters/303(d)-listings [25]. A long-term perspective will be essential to quantifying full recovery of all environmental and ecological indicators through future work [3, 12].

The work presented here built upon summaries of previous work and, specifically, the availability of raw datasets. However, we were unable to locate some historical records even when those datasets had been published in agency reports and cited in other scholarly publications focused on this issue (refer to Marcus et al. [24] as an example). The inability to recover some of these historical datasets demonstrates of the importance of publishing datasets, archiving historical reports, and safeguarding availability of information for future users. Today, publication of geo-referenced datasets is becoming commonplace through public (e.g., Data.gov) or private (e.g., The Dataverse Project or figshare) repositories. While there is growing interest and increased policy around the topic of data publication, public sector scientists have options available for managing and sharing monitoring and research data through the publication of datasets [76]. Despite this trend, publication of data is not a consistent requirement in scientific studies despite the growing appreciation for the enduring value of past observations [77].

Finally, this case study highlights the importance of establishing an ecosystem of reference [8] and using multiple lines of evidence [3, 11, 13, 78] in the assessment of river health [17] and documenting ecosystem recovery [12]. Multiple lines of evidence include a diversity of ecological indicators, reliance on discrete, synoptic, or continuous data sets, or more recently, through the characterization of multiple ecosystem processes. The Soda Butte Creek case study serves as a relatively data-rich example of how the integration of multiple-lines of historical and contemporary evidence were

used to more fully capture the recovery of an impaired stream ecosystem. Historical data on degraded conditions and a contemporary understanding of reference conditions compiled from sampling a collection of minimally impaired main-stem and tributary locations in the watershed [12] provided reference information from which to assess the recovery status of Soda Butte Creek.

4.2 Conclusion/Insights

Through this case study, we offer practical guidance for evaluations of riverine ecosystem responses to mine reclamation. More tractable examples of how the reclamation work and follow-up assessments have contributed to recent conservation planning was the inclusion of Soda Butte Creek in the multiagency Soda Butte Creek Yellowstone Cutthroat Trout Conservation Project initiated in 2015 to protect and secure habitat for Yellowstone Cutthroat Trout in the greater Lamar River watershed[79]. The collaboration between partners was also critical to the planning and post-reclamation inventory of water quality in the upper Soda Butte Creek drainage. Those data led to a determination that metal concentrations in Soda Butte Creek now support all designated beneficial uses. As a result, Soda Butte Creek was removed from the Montana DEQ's 2018 Integrated Report on water quality. These represent some of the realized benefits of the reclamation and recent and ongoing monitoring efforts. Given our reliance on historical data in the current study, the future benefits from this current work are difficult to fully assess today. However, this collection of work will serve as an enduring resource and foundation for future questions managers to Yellowstone National Park may have surrounding Soda Butte Creek.

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Data availability The datasets used to produce this manuscript are available in the figshare data repository <https://doi.org/10.6084/m9.figshare.28104665>. Ray, A. M., Mebane, C. A., Yoder, A. M., & Ertel, B. D. (2025). Leveraging historical datasets to quantify the recovery of an impaired stream entering Yellowstone National Park [digital dataset]. <https://doi.org/10.6084/m9.figshare.28104665>

Code availability No custom code was used to generate or process the data described in this manuscript.

Declarations

Competing interests The authors declare no competing interests.

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