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# Legacies of Stream Channel Modification Revealed using General Land Office Surveys, with Implications for Water Temperature and Aquatic Life

Seth M. White
*Columbia River Inter-Tribal Fish Commission*

Casey Justice
*Columbia River Inter-Tribal Fish Commission*

Denise A. Kelsey
*Columbia River Inter-Tribal Fish Commission*

Dale A. McCullough
*Columbia River Inter-Tribal Fish Commission*

Tyanna Smith
*Portland State University*



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RESEARCH ARTICLE

# Legacies of stream channel modification revealed using General Land Office surveys, with implications for water temperature and aquatic life

Seth M. White*, Casey Justice*, Denise A. Kelsey*, Dale A. McCullough* and Tyanna Smith†

Land use legacies can have a discernible influence in present-day watersheds and should be accounted for when designing conservation strategies for riverine aquatic life. We describe the environmental history of three watersheds within the Grande Ronde subbasin of the Columbia River using General Land Office survey field notes from the 19th century. In the two watersheds severely impacted by Euro-American land use, stream channel widths—a metric representing habitat simplification—increased from an average historical width of 16.8 m to an average present width of 20.8 m in large streams; 4.3 m to 5.5 m in small, confined or partly confined streams; and 3.5 m to 6.5 m in small, laterally unconfined steams. Conversely, we did not detect significant change in stream widths in an adjacent, wilderness stream with minimal human impact. Using a mechanistic water temperature model and restoration scenarios based on the historical condition, we predicted that stream restoration in the impacted watersheds could notably decrease average water temperatures—especially when channel narrowing is coupled with riparian restoration—up to a 6.6°C reduction in the upper Grande Ronde River and 3.0°C in Catherine Creek. These reductions in water temperature translated to substantial changes in the percentage of stream network habitable to salmon and steelhead migration (from 29% in the present condition to 79% in the fully restored scenario) and to core juvenile rearing (from 13% in the present condition to 36% in the fully restored scenario). We conclude that land use legacies leave an important footprint on the present landscape and are critical for understanding historic habitat-forming processes as a necessary first step towards restoration.

**Keywords:** historical ecology; land use legacies; fluvial geomorphology

## Introduction

A major challenge of the Anthropocene—the period in which human activity is the dominant influence on climate and the environment—is to solve the interrelated problems leading to irreversible damage to planetary life support systems. These intertwined problems include human population growth, overconsumption, land use, climate change, and subsequent extinctions to biodiversity and elimination of ecosystem services (Foley et al., 2005; Barnosky et al., 2016). A common approach to forecasting the effects of human activity on the environment is through modeling scenarios of land use change and climate conditions, revealing various possible futures that can be embraced, avoided, or mitigated (Moss et al., 2010; Jantz et al., 2015; Isaak et al., 2016). In order to accomplish this, a comprehensive understanding of past human activities is needed, especially when past actions propagate a legacy extending to the present (Foster et al., 2003). The integrity of rivers and streams is especially vulnerable to human activities because hydrology and water temperature are strongly influenced by climatic effects (Dittmer, 2013) and the landscapes over which they flow (Hynes, 1975; Fausch et al., 2002; Allan, 2004). Streams and rivers provide important ecosystem services including clean and abundant water supply that are difficult to valuate but nonetheless essential (Arthington et al., 2010). Degradation of riverine ecosystems represents an important loss in terms of aquatic biodiversity (Dudgeon et al., 2006) and to people that depend upon rivers for food and other cultural values (Close et al., 2002).

Modifications to river ecosystems in Europe, U.S., and other locations across the globe have been well documented. The European subcontinent has experienced land use change—specifically urbanization—since 700 B.C. (Antrop, 2004); these patterns have been manifested in several ways, but primarily as landscape fragmentation (Jaeger et al., 2011) and river channelization (Jurajda, 1995)

* Department of Fishery Science, Columbia River Inter-Tribal Fish Commission, Portland, Oregon, US

† School of the Environment, Portland State University, Portland, Oregon, US

Corresponding author: Seth M. White (whis@critfc.org)

with negative consequences to aquatic life (Muxika et al., 2007; Haidvogl et al., 2015). Tropical and subtropical rivers have experienced intense localized impacts from human settlement over several decades (Webb, 1992), with more ominous threats looming from increased interest in building large dams (Bergkamp et al., 2000; White et al., 2012). Perhaps because of a longer period of human settlement as compared to the U.S. West coupled with extensive historical documentation, land use legacies in the U.S. have been broadly implicated in degradation of streams and rivers east of the Continental Divide (Harding et al., 1998; Scott, 2006; Wenger et al., 2008; Gardiner et al., 2009; Walter and Merritss, 2008; Maloney and Weller, 2011; Einheuser et al., 2013). Land use impacts in watersheds of the U.S. West are also pervasive (McIntosh et al., 1994; Robbins and Wolf, 1994; Wallin et al., 1994), yet legacies have been described for streams and rivers in the region less frequently (see however Sedell and Froggatt, 1984; McIntosh et al., 2000; White and Rahel, 2008).

Land use has been implicated as a leading cause of river channel simplification with subsequent consequences to aquatic life. Channel widening is one common form of simplification (**Figure 1**) and occurs through various human-related causes including increased flooding after removal of native hillslope vegetation, riparian vegetation, and large woody debris (Knox, 1977; Faustini and Jones, 2003); eroding banks and sediment deposition in the stream channel (Beschta, 1983; Simon and Rinaldi, 2006; Allan, 2004); and is linked to various upstream land use such as timber harvest, road networks, and livestock grazing (Dose and Roper, 1994; Ralph et al., 1994; Knapp et al., 1998; Kondolf et al., 2002). The capacity for river width adjustment is also strongly reliant on geomorphic setting of the river channel. Broader alluvial channels with less confinement by hillslopes are more sensitive to changes in channel morphology (Montgomery and Buffington, 1997; Thorne, 1998; Faustini et al., 2009). In addition to decreasing habitat complexity important for rearing salmonids and other aquatic biota, channel widening increases surface water area and the capacity for solar radiation to reach the stream, thereby increasing water temperature (Poole and Berman, 2001) which can have negative physiological and behavioral impacts on organisms adapted to cold temperatures (Margesin and Schinner, 1999; Dell et al., 2014).

In this study, we describe the implications of watershed history to changes in average stream conditions from the 19th century to present. To accomplish this, we made use of General Land Office (GLO) surveys within three watersheds of the Columbia River basin, each encompassing distinct spring Chinook Salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss* populations (NMFS, 2016). The GLO surveys are a unique resource of historical information prior to major Euro-American impacts, and have been used by historical ecologists to describe past conditions and set restoration targets (Egan, 2005). The GLO surveys were intended to provide information on the quality of conditions for rangeland, agriculture, and forestry for


**Figure 1: Illustration of channel complexity in a wilderness versus modified stream.** Stream channel complexity contrasted in two watersheds including the Minam River—a designated wilderness area representing historical conditions—as seen from **(A)** aerial photography and **(B)** ground photography in 2013, and a simplified and unnaturally widened stream channel in the heavily impacted upper Grande Ronde River as seen from **(C)** aerial photography and **(D)** ground photography in 2015. Aerial images courtesy of Google Earth; ground images courtesy of the Columbia Habitat Monitoring Program. DOI: https://doi.org/10.1525/elementa.192.f1

prospective land claims. However several studies have used GLO information for other purposes, primarily for describing historical riparian vegetation communities (Johnson, 1994; Galat et al., 1998; Hulse et al., 2000; McAllister, 2008; Dilts et al., 2012). Less frequently, GLO surveys have been employed to represent in-channel characteristics of streams and rivers, such as wood recruitment (Sedell and Froggatt, 1984; Collins et al., 2002) or river channel morphology (McDowell, 2000; Collins et al., 2003; Hereford and Betancourt, 2009).

To define a historical baseline for fish habitat, we described changes to stream channel widths since the late 1800s, with expectations that the magnitude of change would be greater in areas with more intense ranching, logging, agriculture, and other forms of land use. Therefore, the specific objectives of this study were to: (1) evaluate overall patterns of stream channel widening since the 19th century, with reference to the geomorphic context where modification has been most severe and where restoration efforts may have the greatest physical capacity for improvement; and (2) simulate the effects of stream channel widening and riparian vegetation on water temperature using a mechanistic stream temperature model, with implications for aquatic life.

## Methods

### *Study area*

This study was conducted in tributaries of the Grande Ronde River originating in the Blue Mountains and Wallowa Mountains of Northeast Oregon, United States, and flowing 334 km to its confluence with the Snake River and eventually the Columbia River. Focal watersheds include two tributaries heavily impacted by anthropogenic land use—the upper Grande Ronde River above the town of La Grande (draining 1,896 $km^2$) and Catherine Creek (1,051 $km^2$)—and one least-impacted watershed in the Eagle Cap Wilderness—the Minam River (618 $km^2$) (**Figure 2A**). Topography is characterized by rugged mountains in the headwaters (2,269 m) and a broad, low gradient valley at the confluence of the upper Grande Ronde River and Catherine Creek (820 m). The climate is characterized by cold, moist winters and warm, dry summers with average temperatures near La Grande averaging –0.42°C in January and 21°C in July. Average annual precipitation ranges from 36 cm in the valleys to 152 cm in the mountains, with most of the precipitation in the mountains falling as winter snow. Due to the lower elevation of the Blue Mountains relative to the Wallowas, snowmelt generally occurs earlier in its tributaries, often resulting in very low stream flows during summer (Kelly and White, 2016).

Watershed conditions in the upper Grande Ronde River and Catherine Creek, like many watersheds in the U.S. West, have experienced degraded ecological health caused by cumulative influence of past human activity since the 19th century (McIntosh et al., 1994; Wissmar et al., 1994). In the upper Grande Ronde River and Catherine Creek, intensive land use impacts occurred beginning in 1812 (**Table 1**) with beaver (*Castor canadensis*) trapping and proceeded through the late 1980s with activities as diverse as draining marshland and diking river sections for agriculture in the Grande Ronde Valley; logging hillslopes and riparian areas with associated splash damming and, later, road building; cattle and sheep grazing on public and private land; dredge mining; and damming (Gildemeister, 1998). These land use practices have been implicated in decades-long trends in simplification of stream habitat through loss of deep pools across the Columbia River basin, whereas streams in wilderness or roadless areas retained their more complex nature relative to streams in managed watersheds (McIntosh et al., 2000).

We selected the Minam River as a reference watershed based on its less intensive land use history and its near proximity to the other focal watersheds. The Minam River flows through the Wallowa-Whitman National Forest and Eagle Cap Wilderness Area at an average elevation of 1251 m in our study extent. The Eagle Cap was established as a primitive area in 1930, designated as wilderness in 1940, and registered in the National Wilderness Preservation System in 1964. In 1988, the Minam River was registered as a Wild and Scenic River from its headwaters at Minam Lake, 62.8 river km downstream to Cougar Creek. The protected status of the Minam River provides a stark contrast to the intense present and historical agricultural, grazing, and logging use in the upper Grande Ronde and Catherine Creek basins, making the Minam River a good candidate stream to represent reference conditions.

However, intrinsic physical conditions unrelated to land use are somewhat different among the basins. While most of the Grande Ronde River and lower sections of Catherine Creek flow out of Miocene and younger volcanic and sedimentary rocks (with some higher elevations in the Grande Ronde River flowing from older, pre-Cenozoic sedimentary and volcanic rock), the Minam River and upper sections of Catherine Creek flow out of Oligocene and lower Miocene volcanic and sedimentary rock (Walker, 1990). Both the Minam River and upper sections of Catherine Creek have notable, U-shaped valleys carved by glaciers, and wet climate due to the orographic effect. The geomorphology of reaches in the Minam River is most similar to that of Catherine Creek, but with a smaller proportion of tributaries with low gradient and with a larger proportion of valleys constrained by hillslope walls. The upper Grande Ronde River is unique compared to the other two watersheds having a higher proportion of tributaries with low gradient and unconstrained valleys. Study sites in the Minam River were selected within a range of intrinsic watershed characteristics (elevation, upstream watershed area, cumulative precipitation, valley width index, etc.) that most corresponded with the impacted watersheds.

Spring Chinook Salmon populations in the upper Grande Ronde River and Catherine Creek were listed as threatened under the Endangered Species Act in 1992. Population declines over the past century were due in part to severely degraded habitat conditions resulting from the aforementioned anthropogenic disturbances. Specifically, stream temperature, streamflow, fine sediment, habitat diversity, and quantity of key habitats such as large pools in these basins have been identified as key limiting factors for recovery of fish populations (Nowak and Kuchenbecker, 2004).

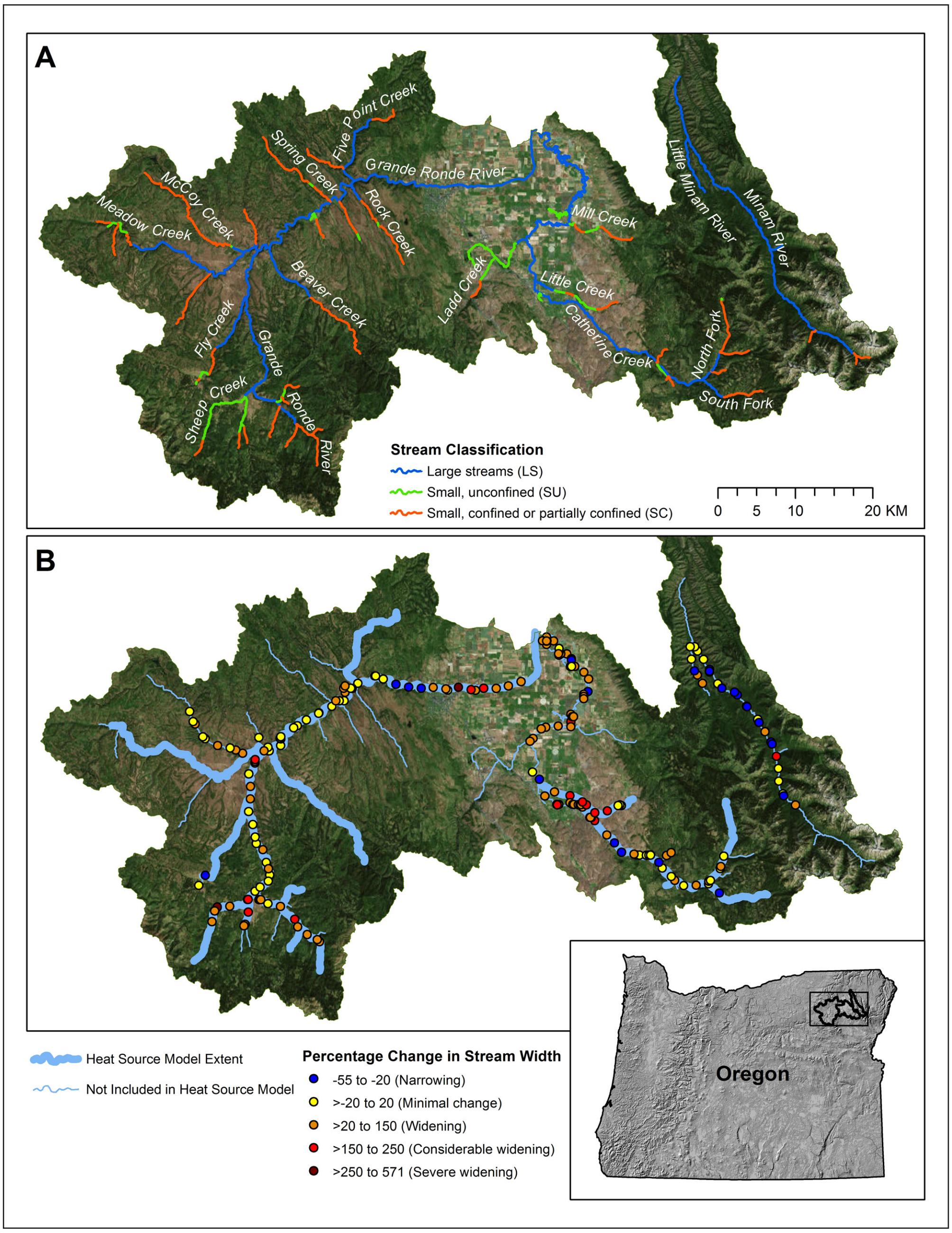


**Figure 2: Study area, stream classification, and historical changes to channel widths in three focal watersheds.** Location of study watershed in northeast Oregon including **(A)** major salmon-bearing tributaries and the stream classification described in the methods and **(B)** values of channel change estimates where historical General Land Office surveys intersected with contemporary Aquatic Inventory Program surveys. Focal watersheds include the upper Grande Ronde River, Catherine Creek, and Minam River. The upper Grande Ronde River and Catherine Creek have significantly modified stream conditions from over a century of intensive land use. The Minam River is in the Eagle Cap Wilderness area and most approximates historical reference conditions. DOI: https://doi.org/10.1525/elementa.192.f2

***Assessing historical stream conditions***

Historical estimates of channel width were based on GLO surveys conducted in the mid- to late-1800s within the area of study in the Grande Ronde subbasin. The GLO established the Public Land Survey System of townships and ranges in 1812 (White, 1983), with subsequent modifications to methods in Oregon that were applied in other U.S. States (Principle Clerk of Surveys, 1855). Public lands were apportioned into townships 9.7 km (6 mi) on a side, and townships were further divided into 36 sections, each 1.6 km (1 mi) on a side. The survey involved GLO surveyors walking the section lines for each section in a township. In addition to recording the general character of vegetation, soil, and rangeland conditions, surveyors recorded the location and bank-to-bank channel width (active channel width) of any streams or rivers crossed. We accessed GLO field notes on the U.S. Bureau of Land Management's Official Land

**Table 1:** Land use history of the upper Grande Ronde River and Catherine Creek from 1812 to 1989[a]. DOI: https://doi.org/10.1525/elementa.192.t1

| Year | Event |
|---|---|
| 1812 | Fur trader Robert Stuart observes beaver as common; War of 1812 intensifies beaver trapping |
| 1850 | Donation Land Claim Law enacted, encouraging settlement by emigrants |
| 1855 | Treaty between U.S. and upper Columbia River Indian Tribes exchanging ceded lands for reservations and reserving rights to traditional hunting, fishing, and gathering |
| 1861–1862 | First land claim in Grande Ronde Valley; first sawmill and salmon-blocking dam built on Grande Ronde River |
| 1865–1869 | Water-powered flourmill established on Catherine Creek; railroad route laid out across Grande Ronde Valley |
| 1870 | Construction begins on State Ditch and Catherine Creek ditch draining lakes and swamplands in the Grande Ronde Valley |
| 1890 | Grande Ronde Lumber Company acquires timberland and begins constructing splash dams on Grande Ronde River and tributaries |
| 1890s–1900 | Development of railroad network in Grande Ronde tributaries; estimated 50 sawmills in watershed, annual timber export estimated at 32.5 million board feet |
| 1934 | Taylor Grazing Act leads to decline of livestock grazing on public lands |
| 1939 | Mine dredging begins in Grande Ronde River |
| 1946 | Establishment of Union Co. Soil and Water Conservation District leads to substantial land leveling, ditching, and stream channeling projects |
| 1984–1985 | Log jams blasted on Catherine Creek to alleviate flooding; Army Corps of Engineers clears willow and cottonwood from riparian zones |
| 1989 | Recognition that peak flows shifting as much as 30 days earlier based on 1904–1989 record, partly attributed to land use in watershed |

[a]Abbreviated from Gildemeister, 1998.

Records Site (BLM, 2016) and translated the handwritten notes into spatial data in a geographic information system (GIS) (ESRI, 2011). Estimates of channel width were converted from chains and links (1 chain = 100 links) to meters (1 link = 0.20 m).

### *Assessing contemporary stream conditions*

Contemporary estimates of channel width were based on Oregon Department of Fish and Wildlife's Aquatic Inventories Project (AIP) (Moore et al., 2008). The AIP survey is a rapid assessment of common fish habitat characteristics collected in a spatially continuous fashion across the stream network. Two AIP surveyors walked smaller streams or canoed unwadeable sections and recorded the characteristics and location of channel units (i.e., pools, riffles, and glides) with a hand-held global positioning system (GPS) with accuracy 5–7 m. Data from the 1990s were used as the baseline for present conditions, except where surveys were conducted outside the low flow period (ordinal date 200–300; Kelly and White, 2016). When surveys did not match those criteria we used surveys from years 2000 or 2010 that fell within the low flow period. In our study, channel width was used as a proxy of width:depth ratio—a metric strongly tied to integrity of stream channels (e.g., Beschta and Platts 1986; Myers and Swanson 1996) and commonly used in fish-habitat models (Fausch et al., 1988)—because historical estimates of water depths were not available. Constraining the use of all survey data to only the low flow period presumably provided consistency in discharge over the years that would allow change in width to be a valid surrogate for change in width:depth ratio.

Whereas AIP surveyors recorded wetted width at every channel unit, active channel width was recorded only at every 10th channel unit and at tributary junctions. We therefore developed a linear relationship between co-occurrences of measured wetted and active channel width using data from the Columbia Habitat Monitoring Program (CHaMP, 2016) collected during low-flow periods in 2011–2015 within the study basins. CHaMP is an intensive stream habitat survey focusing on detailed, reach-scale stream channel geomorphology; a much larger sample size was available from this program ($n$ = 131) than from AIP ($n$ = 23) and encompassed a broader range of stream sizes. This provided confidence in extrapolating spatially extensive channel widths comparable to active width as recorded in historical GLO surveys:

$$W_P = 2.12 + 1.22 \times W_W,$$

where $W_P$ is the predicted present active channel width and $W_W$ is the present wetted width (m) measured by AIP crews ($n = 131$, $R^2 = 0.89$, $p < 0.001$) (**Figure 3**). In estimating channel change over time (described below), locations where the historical active channel width was equal to or smaller than the model intercept (i.e., ≤ 2.12 m) were removed from the analysis to avoid potential upward bias in estimated stream widths for small channels in the present time period.

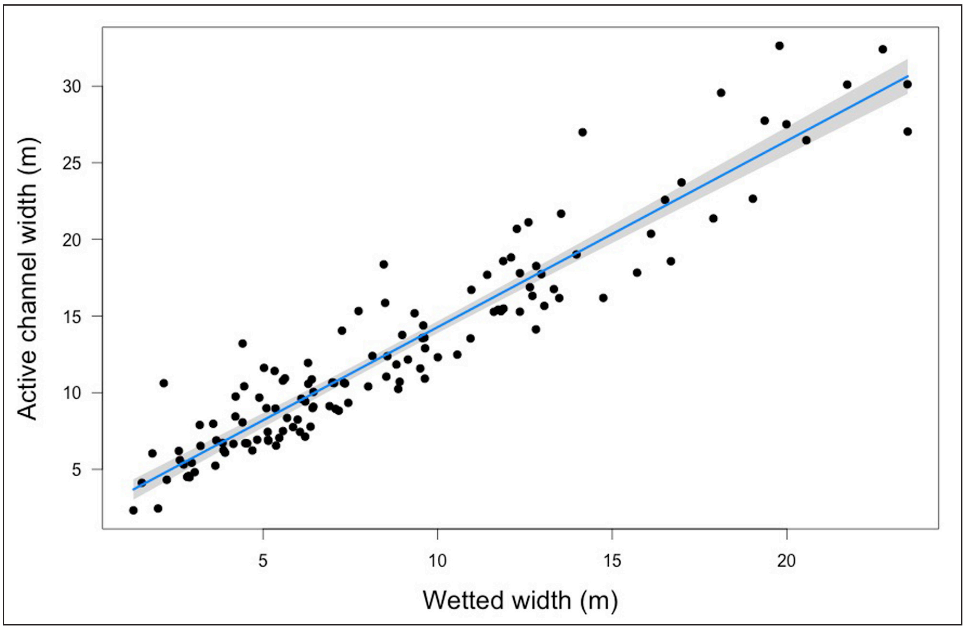


**Figure 3: Relationship between active versus wetted stream width.** Linear relationship between active ($W_P$) versus wetted ($W_W$) stream channel widths from contemporary Aquatic Inventory Program stream surveys ($W_A = 2.12 + 1.22 \times W_W$, $n = 131$, $R^2 = 0.89$, $p < 0.001$). Shaded area represents 95% confidence band. DOI: https://doi.org/10.1525/elementa.192.f3

***Estimating historical changes to stream channel width***

We calculated the percentage change in channel width from the historical to present periods based on GLO and AIP estimates of active channel width:

$$\Delta W = \frac{W_P - W_H}{W_H} \times 100,$$

where $\Delta W$ is percentage change in channel width, $W_P$ is present channel width, and $W_H$ is historical channel width (m). We then evaluated the magnitude of change since the historical period according to watershed identity and a geomorphic valley setting classification. Watershed identity was defined by the extent of the following spring Chinook Salmon populations: Catherine Creek Chinook (CCC), upper Grande Ronde Chinook (UGC), and Minam River Chinook (MRC). The classification system consisted of dividing the stream network into small and large streams using an 8-m bankfull width criterion based on the work of Beechie and Imaki (2014). Next, the stream network was further divided into three different valley types based on valley confinement (laterally unconfined, partly confined, and confined) following the methodology described in the River Styles Framework (Brierley and Fryirs, 2005). Based on exploratory analysis of fish habitat conditions among stream types, we simplified the classification into three classes for our study: large streams (LS), small/partly confined and confined streams (SC), and small/laterally unconfined streams (SU) (**Figure 2A**). The effect of watershed identity on magnitude of channel change was tested using one-way analysis of variance (ANOVA). One-way ANOVA was also used to test the effect of valley setting on magnitude of channel change, but only for sites in the impacted watersheds (CCC and UGC) because all locations in the Minam River where estimates of channel change existed were in large stream types. Model assumptions were confirmed as valid by visually evaluating residuals versus fits, normal Q-Q plots, scale-location plots, residuals versus leverage, and histograms of residuals. Tukey's HSD test was used for post-hoc evaluations of individual group differences.

***Water temperature modeling and assessing importance to aquatic life***

To evaluate the contribution towards cooling stream temperatures from restoring channel widths to their historical state in combination with revegetation of riparian zones, we employed a mechanistic water temperature model called Heat Source (Boyd and Kasper, 2003). The model integrates stream channel geometry, hydrology, climatic conditions, and riparian vegetation cover and height to simulate stream temperature and effective shade at 100-m intervals throughout the stream network. The model was calibrated for a 10-week period between 10 July and 20 September 2010. This period was chosen to best represent present conditions for summer base-flow conditions when water temperatures are typically highest and salmonids are consequently at risk.

Model parameters from present conditions were used as a baseline for evaluating restoration scenarios including (1) restoring stream channels to their historical widths, (2) restoring riparian vegetation to its potential natural state, and (3) a combination of channel width and riparian restoration. Channel width scenarios were developed by assigning the average value of channel width change by geomorphic stream classification across the modeled extent. Potential natural vegetation scenarios were developed by estimating the potential height and canopy cover of trees and shrubs in the riparian zone under natural historical conditions using a detailed map of present vegetation and potential natural vegetation (PNV) along the entire extent of the Chinook-bearing portion of the upper Grande Ronde River and Catherine Creek watersheds (Wells et al., 2015). Additional details of water temperature model development, riparian scenario development, and application of additional restoration and climate change scenarios are discussed in McCullough et al. (2016) and Justice et al. (2017).

We summarized the water temperature predictions for each model scenario by calculating the maximum 7-day running average of the daily maximum temperature (*MWMT*) in degrees Celsius. This metric has been demonstrated as an important metric for various salmon life stages in Pacific Northwest streams (EPA, 2003). The median *MWMT* was compared for both upper Grande Ronde River and Catherine Creek (including major tributaries) for present conditions and all restoration scenarios. To visualize spatial patterns in how restoration scenarios affected water temperature, we mapped *MWMT* across the upper Grande Ronde River and Catherine Creek for present conditions and under the channel width restoration scenario. Lastly, we reported the percentage of stream length in the river networks having water temperatures below critical Pacific salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) water temperature thresholds for both watersheds combined for present conditions and restoration scenarios Thresholds corresponded to 16°C for adult holding and core juvenile rearing and 20°C for fish migration (EPA, 2003).

## Results

### *Changes to channel widths since historical period*

A total of 193 intersections between GLO and AIP surveys throughout the three watersheds allowed for the estimation of historical and present stream widths (**Figure 2B**). There was a significant effect of watershed identity on the percentage change in channel width as determined by one-way ANOVA ($F[2, 190] = 10.71$, $p < 0.001$) (**Figure 4A**). Post-hoc Tukey comparisons revealed that percentage change in channel width in Catherine Creek (CCC) was greater than in the Minam River (MRC) by 63.8 (*p-adj* < 0.001, 95% CI = 30.5–97.1). Percentage change in

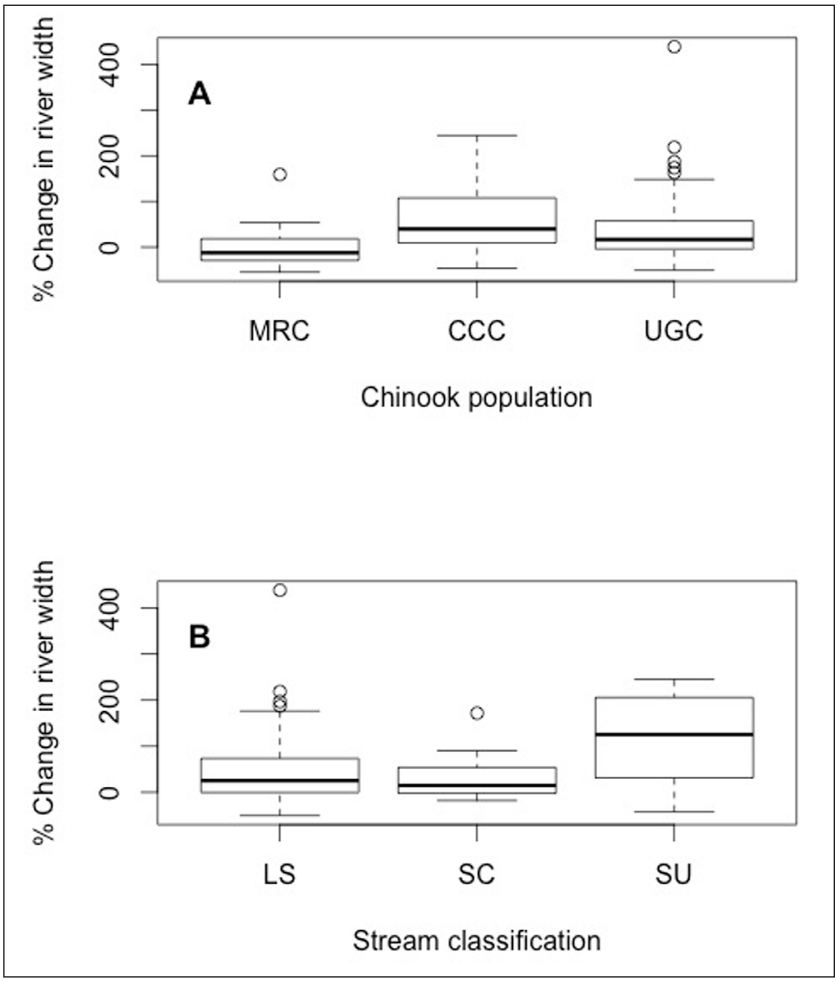


**Figure 4: Percentage change from historical stream widths by watershed and stream type.** Boxplots of percentage change in channel widths from historical (1880s) to present (1990s and later) by **(A)** Chinook population (all locations combined, $n = 193$) and **(B)** Stream type (impacted watersheds only, $n = 174$). Channel width change in Catherine Creek (CCC) and upper Grande Ronde River (UGC) was significantly different than in the Minam River (MRC), but not from each other. All stream classification groups—large streams (LS); small, partly confined or confined streams (SC); and small, laterally unconfined streams (SU)—were significantly different from one another. DOI: https://doi.org/10.1525/elementa.192.f4

channel width in the upper Grande Ronde River (UGC) was greater than in the Minam River by 37.9 (*p-adj* = 0.02, 95% CI = 4.4–71.4). Percentage change in channel width in the upper Grande Ronde River was less than Catherine Creek by 25.9 (*p-adj* = 0.03, 95% CI = –50.1–1.7). Because the Minam River was more homogenous regarding stream classification type (i.e., having a majority of reaches in the large stream category, some reaches in the small/partly confined and confined category, and no reaches in the small/laterally unconfined category), we additionally tested for the effect of watershed identity on percentage change in channel width using only sites in the large stream category to ensure that the differences were not a function of disparity in stream classification types. Again, we noted a significant effect of watershed identity on the percentage change in channel width as determined by one-way ANOVA ($F[2, 167] = 8.2$, $p < 0.001$). A similar pattern of differences in percentage change in channel widths among impacted versus wilderness watersheds was confirmed using post-hoc Tukey comparisons (*p-adj*[CCC-MRC] > 0.001, *p-adj*[UGC-MRC] = 0.01), whereas channel change between the two impacted streams did not significantly differ (*p-adj*[UGC-CCC] = 0.30). These results provided justification for evaluating percentage change in channel width as a function of stream classification for upper Grande Ronde and Catherine Creek watersheds combined, and separately from the Minam River.

A total of 164 intersections between GLO and AIP surveys throughout Catherine Creek and the upper Grande Ronde River allowed for the estimation of historical and present stream widths in these two watersheds where intensive land use had occurred (**Table 2**). A majority of the locations available for comparison were in large streams (LS) ($n$ = 141) with fewer in the small, partly confined and confined streams (SC) ($n$ = 15) and small, laterally unconfined streams (SU) ($n$ = 8). However this roughly matched the proportion of stream types by river kilometer within the Heat Source model extent: LS (66.7%), SC (20.7%), and SU (12.6%). Stream channel widths increased from an average historical width of 16.8 m to an average present width of 20.8 m in large streams; 4.3 m to 5.5 m in small, confined or partly confined streams; and 3.5 m to 6.5 m in small, laterally unconfined steams. There was a significant effect of stream classification type on the percentage change in channel width as determined by one-way ANOVA ($F[2, 161] = 4.5$, $p$ = 0.01) (**Figure 4B**; **Table 2**). Post-hoc Tukey comparisons revealed that percentage change in channel width in small/laterally unconfined sites (SU) was significantly greater than in large stream sites by 69.8 (*p-adj* = 0.02, 95% CI = 11.2–128.5). Percentage change in channel width in small/laterally unconfined sites was significantly greater than in small/partly confined and confined sites by 84.5 (*p-adj* = 0.01, 95% CI = 13.9–155.2). Percentage change in channel width in small/partly confined and confined sites (SC) was not significantly different than in large stream sites (LS) (*p-adj* = 0.71).

### *Water temperature simulations and implications for aquatic life*

Mean percentage change in channel width by stream classification (**Table 2**) was applied to channel widths in the Heat Source water temperature model to yield estimates for water temperature under the restoration scenarios (**Table 3**). Water temperatures under present conditions were substantially higher in the upper Grande Ronde River (median *MWMT* = 24.4°C) compared with Catherine Creek (median *MWMT* = 18.3°C). The predicted change in median *MWMT* relative to the present condition for the restored channel width scenario was –2.2°C in the upper Grande Ronde River, compared with –0.6°C for Catherine Creek. The predicted change in median *MWMT* relative to the present condition for the restored potential natural vegetation (PNV) was –5.5°C in the upper Grande Ronde River, compared with –2.4°C for Catherine Creek. The combined PNV and channel width restoration was estimated to change median water temperatures by –6.6°C in the upper Grande Ronde River compared with –3.0°C in Catherine Creek.

The longitudinal profile of present (i.e., 2010) *MWMT* in the mainstem upper Grande Ronde River (**Figure 5A**) showed rapidly increasing water temperatures from about 12°C near its headwaters to approximately 25°C just downstream of the Sheep Creek confluence. At that point, the river enters a canyon with considerable topographic shade and higher tree cover, and consequently, river temperatures declined moderately to approximately 22°C near the mouth of Fly Creek. From that point downstream to its confluence with Catherine Creek, the river temperature increased gradually with some relatively minor cooling effects at tributary junctions to a maximum of approximately 29°C. In Catherine Creek, water temperature starts out at approximately 16°C at the confluence of North and South Fork Catherine Creek (with upstream

**Table 2:** Mean stream channel widths, increases from historical dimensions, and percentage change from historical condition in impacted watersheds. DOI: https://doi.org/10.1525/elementa.192.t2

| Stream type | Sample size ($n$) | Mean historical channel width (m) ±SE | Mean present channel width (m) ±SE | Mean increase (m) ±SE | Mean change (%) ±SE |
|---|---|---|---|---|---|
| Large streams (LS) | 141 | 16.8 ± 0.8 | 20.8 ± 0.8 | 4.0 ± 0.6 | 45.9 ± 5.7 |
| Small/partly confined & confined (SC) | 15 | 4.3 ± 0.2 | 5.5 ± 0.4 | 1.2 ± 0.5 | 31.2 ± 13.0 |
| Small/laterally unconfined (SU) | 8 | 3.5 ± 0.5 | 6.5 ± 0.7 | 3.0 ± 1.1 | 115.8 ± 37.6 |

**Table 3:** Simulated water temperature under current conditions and restoration scenarios. DOI: https://doi.org/10.1525/elementa.192.t3

| Mainstem | Median *MWMT*[a] (°C) | | | |
|---|---|---|---|---|
| | Current | Width[b] | PNV[c] | PNV_Width[d] |
| Upper Grande Ronde River (UGC) | 24.4 | 22.2 | 18.9 | 17.8 |
| Catherine Creek (CCC) | 18.3 | 17.7 | 15.9 | 15.3 |

[a]Maximum weekly maximum water temperature.
[b]Restored potential channel width scenario.
[c]Restored potential natural vegetation scenario.
[d]Combination of vegetation and channel width restoration scenarios.

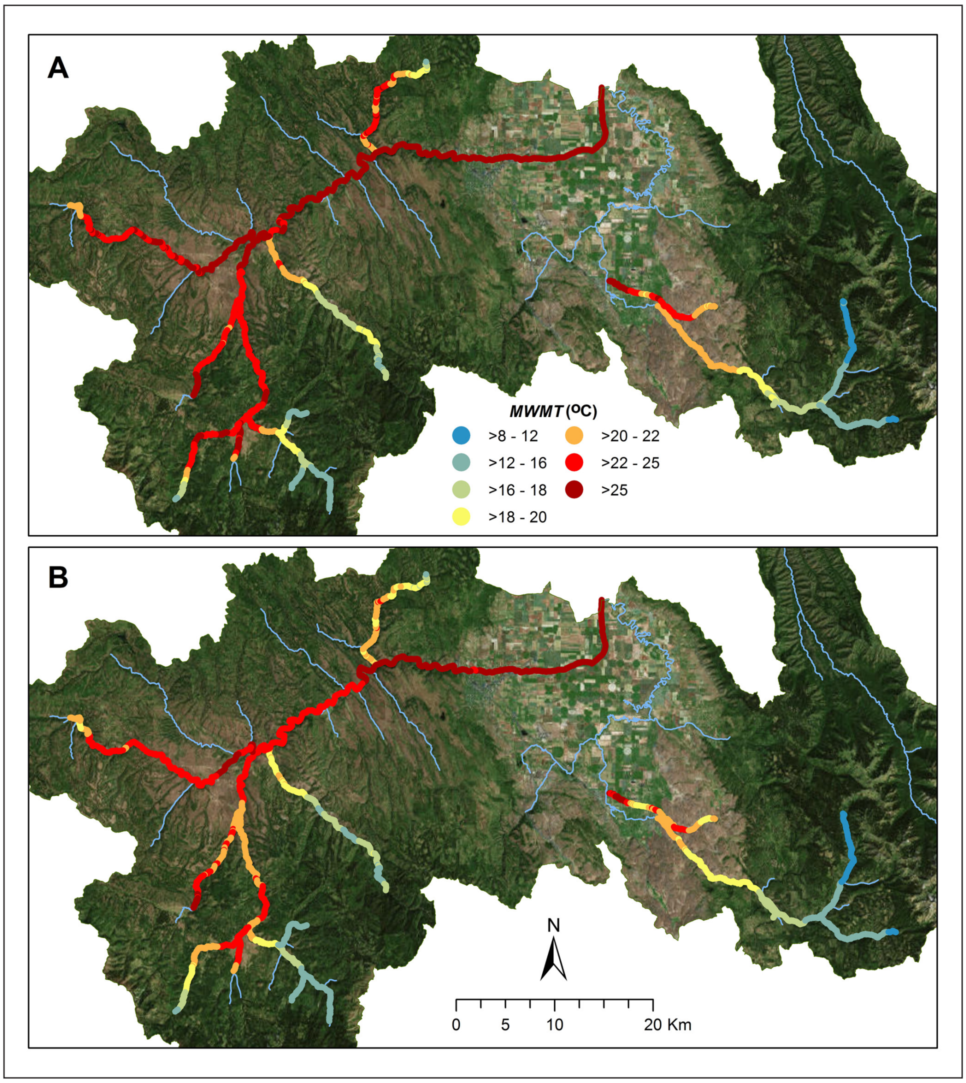


**Figure 5: Simulated water temperature for present conditions and restoration scenarios.** Map of simulated maximum weekly maximum water temperatures (*MWMT*) in the upper Grande Ronde River and Catherine Creek under **(A)** present conditions (Current) and **(B)** the restored channel width scenario (Width). See Figure 2 for stream names. DOI: https://doi.org/10.1525/elementa.192.f5

*MWMT* < 12°C), with gradual warming to approximately 22°C in the Grande Ronde Valley.

In the channel width restoration scenario, we noted patterns of decreasing *MWMT* throughout the two impacted watersheds after mapping model results (**Figure 5B**). For example, in the upper Grande Ronde River, narrowing channel widths in headwater tributaries (upper mainstem Grande Ronde and Sheep Creek) cooled water with beneficial effects extending downstream to the mouth of Fly Creek. From that point downstream, *MWMT* increased gradually to temperatures matching those of the present condition. In Catherine Creek, restored channel widths led to cooler water temperatures extending from the confluence of North and South Fork Catherine Creek downstream, through the river's canyon and alluvial reaches, and into the Grande Ronde Valley. However *MWMT* values at the model's downstream extent in the valley were similar between present condition and the restored channel width scenario.

For both upper Grande Ronde River and Catherine Creek watersheds combined, the percentage stream length with *MWMT* below critical salmon and steelhead thresholds increased with restoration scenarios as compared to present conditions (**Figure 6**). Percentage stream length having *MWMT* below migration and holding/rearing thresholds was approximately 29% and 13% for present conditions (respectively), 39% and 17% for restoration of channel widths, 67% and 32% for restoration of potential natural vegetation, and 79% and 36% for the combination of channel width and vegetation restoration.

## Discussion

### *Stream channel widening since the 19th century*

Using estimates of channel width from 1880s General Land Office surveys as compared to present day estimates, we noted significant widening of stream channels in the watersheds impacted by anthropogenic land use (upper Grande Ronde River and Catherine Creek) as opposed to a wilderness stream with less human disturbance (Minam River), where channel widening was absent or minimal. Channel widening has been described as one response of unstable, alluvial stream channels to watershed land use via eroding stream banks and channel incision (Thorne, 1998; Simon and Rinaldi, 2006). The upper Grande Ronde River and Catherine Creek—alongside other watersheds in the American West—have been subjected to intensive land use activities including removal of beaver, logging and associated road building, railroad and road encroachments, diking, ditching, dredging, sheep ranching, and cattle grazing (Robbins and Wolf, 1994; Gildemeister, 1998; McIntosh et al., 2000). This cocktail of land use has likely contributed to stream channel simplification in numerous ways, including channel widening as noted in our study, but also loss of large pools (McIntosh et al., 2000) that are important refugia for spawning and rearing fish (Torgersen et al., 2006). Channel widening in the wilderness stream (Minam River) was absent or minimal, lending evidence to the premise that multiple forms of land use are linked to stream channel simplification.

In the upper Grande Ronde River and Catherine Creek, an important driver of stream channel widening is likely increased flooding after widespread modifications to riparian and hillslope vegetation. Historical accounts of settlers and newspaper articles describe drastic increases of the magnitude and timing of flooding corresponding to increasing land use, especially forest harvest and

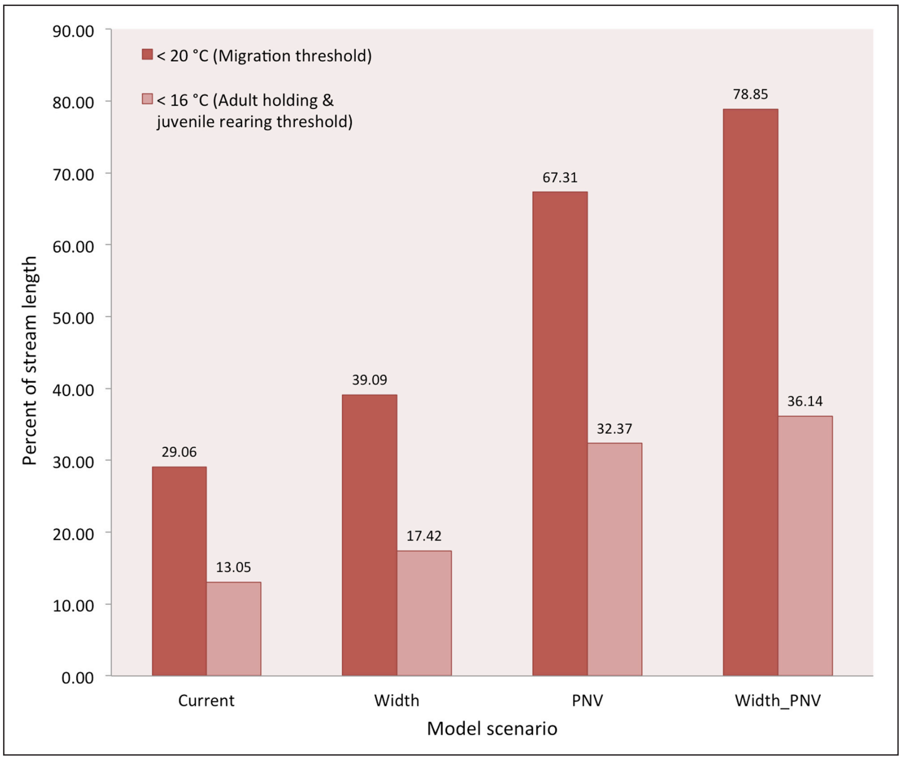


**Figure 6: Percentage stream length below biological water temperature thresholds for model scenarios.** Estimated percentage of stream length below critical salmon and steelhead thresholds for maximum weekly maximum water temperatures (*MWMT*) (EPA, 2003) in the upper Grande Ronde River and Catherine Creek watersheds combined. Model scenarios represent current conditions (Current), restored channel width (Width), restored potential natural vegetation (PNV), and the combination of vegetation and channel width restoration (Width_PNV). DOI: https://doi.org/10.1525/elementa.192.f6

associated activities (Gildemeister, 1998) (**Table 1**). In New England watersheds, changes to channel morphology from increased flooding were attributed to a large-scale natural disturbance (hurricane) combined with reduced interception of precipitation by vegetation, evaporation from leaf surfaces, and transpiration of moisture from the forest canopy (Foster et al., 2004). Subsequent increases in flood magnitude can lead to channel widening by scouring the stream channel with sediment, bedload material, and coarse woody debris (Ralph et al., 1994). Splash damming—the practice of staging logs in a dammed pond with a sudden release for transporting logs to downstream mill sites—also occurred historically in the upper Grande Ronde River (Gildemeister, 1998) and has been implicated in simplifying stream channels elsewhere in the Pacific Northwest (Miller, 2010). Stream channels in the upper Grande Ronde River may have also been intentionally widened to promote better drainage and decrease the impacts of localized flooding (Gildemeister, 1998).

Cattle grazing is widespread in the upper Grande Ronde River and Catherine Creek watersheds, an activity implicated in increasing channel widths through bank erosion and deposition of fine sediments over the stream channel in other watersheds (Dose and Roper, 1994; Ralph et al., 1994; Knapp et al., 1998; Kondolf et al., 2002). Unnaturally high populations of native ungulates, specifically elk (*Cervus canadensis*), may also have similar effects due to lack of native predators (i.e., wolves, *Canis lupus*) that would otherwise reduce ungulate populations (Beschta and Ripple, 2006) or cause behavioral shifts in foraging, reducing grazing impacts to streams (Ripple and Beschta, 2004).

Understanding the geomorphic context of channel widening may help inform the kinds of restoration activities that will halt or reverse these trends. For example, researchers in the nearby Middle Fork John Day River concluded that the potential for adjusting the channel planform to desired conditions was limited by natural planform, but that adding large woody debris may overcome this impediment (McDowell, 2000). In our study, channel widening as a proportion of the original width was more predominant in smaller channels that were laterally unconfined by hillslopes. This was not surprising, given that laterally unconfined stream channels are zones of deposition and net sediment accumulation (Brierley and Fryirs, 2005); any anthropomorphic changes in the upstream watershed would register downstream in these unconfined reaches (Allan, 2004). However, small channels that were either partly confined or confined by hillslopes exhibited less overall proportional change in channel widths, indicating that width adjustments were indeed more prevalent in laterally unconfined channels. Streams in alluvial valleys—corresponding to the laterally unconfined stream classification in our study—have a higher potential for channel geometry responses to changes in sediment supply and discharge (Montgomery and Buffington, 1997) and are known to respond to increases in discharge and sediment by becoming wider and shallower (Ralph et al., 1994). Channel widening in alluvial streams occurs through various pathways including bank erosion without incision; retreat of outer banks when toe scouring exceeds the rate of advance of the opposite bank; or in braided channels, by erosion from flows deflected around advancing bars (Thorne, 1998).

A significant body of literature indicates that channel widening via various pathways can be arrested or reversed through restoration activities. Restoration or protection of riparian vegetation enhances root strength, contributing to increased stability of streambanks (Simon and Collison, 2002), especially in loosely-packed alluvial deposits that are characteristic of unconfined channels (Montgomery and Buffington, 1997). Rooting of riparian vegetation on bars and streambanks can help channels narrow by trapping sediment and removing soils that would otherwise remain suspended in the water column (Boon and Raven, 2012). Riparian vegetation and large woody debris additionally provide sources of roughness that can reduce erosion during high streamflows (Gregory et al., 1991; Ralph et al., 1994). Reduction in the intensity of land use that reduces hillslope or riparian vegetation (e.g., forest harvest and cattle grazing) decreases erosion and sedimentation (Allan, 2004) and increases water storage capacity of soils, thereby reducing the potential for unnaturally high peak flows (Poff et al., 1997). Fortunately, these and other restoration activities meant to address channel simplification are already being initiated in the upper Grande Ronde River and Catherine Creek basins (Booth et al., 2016). However, it remains to be seen whether the extent and intensity of stream channel restoration, along with changes to upstream land use, are sufficient to meet biological objectives for the ESA-listed fish populations (Simon, 2016).

#### *Implications to water temperature and aquatic life*

Restoration scenarios yielded positive results in terms of reducing water temperature. Riparian vegetation restoration yielded the greatest benefit alone of any one single approach, but the combination of riparian and channel width restoration yielded the greatest benefit overall. If intensive and widespread restoration actions were successfully implemented in the upper Grande Ronde River, temperatures could be reduced below the present temperature by as much as 6.6°C in the upper Grande Ronde River and 3.0°C in Catherine Creek. The pattern of increasing water temperature with increasing channel width has been documented in other modeling analyses investigating land use impacts (LeBlanc et al., 1997; ODEQ, 2009; Butcher et al., 2010). Simulations of channel narrowing yielded a small cooling benefit as compared to restored vegetation in another study in the upper Grande Ronde River (ODEQ, 2000); however, justification for baseline channel widths in that study was unstated. In the nearby John Day River, a modeling analysis demonstrated that a 30% reduction in channel width yielded an approximately equivalent reduction in water temperature compared with vegetation restoration in the upper 100 km of the river, and a substantially greater reduction compared with vegetation restoration in the lower 325 km (Butcher et al., 2010); justification for baseline channel widths for that study came from unreferenced "basin literature" indicating historical channel widths were 5–50% narrower. Restoration scenarios in our study did not account for climate change and hyporheic exchange, factors that are also important determinants of stream temperature (Poole and Berman, 2001) but were beyond the scope of our analysis. A fruitful restoration program with the goal of reducing water temperature would address riparian shade, channel morphology (width, average depth, sinuosity, bed roughness, etc.), groundwater-hyporheic-surface water connectivity, and upstream sources of sedimentation. The potential benefits of these actions should additionally be evaluated in the context of climate change (Wu et al., 2012).

In our study, all permutations of riparian and channel width restoration scenarios increased the amount of stream length below critical biological thresholds (EPA, 2003). The greatest single benefit was from riparian vegetation; however restoring channel width alone provided an increase from 29% to 39% of stream length with water temperatures less than the 20°C migration threshold and from 13% to 17% of stream length less than the 16°C adult holding and juvenile rearing thresholds for salmon and steelhead. Not surprisingly, the greatest benefit was from the combined riparian and channel width scenarios: the percentage of usable habitat increased to 79% and 36% of stream length for migration and holding/rearing, respectively. This finding underlines the importance of applying a combination of restoration efforts in a comprehensive program accounting for short-term and long-term benefits from habitat actions (Roni et al., 2002, 2008), especially considering that riparian restoration can take decades to yield improvements (Hasselquist et al., 2015).

We used a simplified approach to assessing the biological importance of water temperature by merely tallying the stream kilometers that could be utilized by fish according to published thresholds (EPA, 2003). Determining the true benefit to fish from reduction in water temperature would include accounting for other local factors linked to riparian restoration that also improve fish habitat, such as large wood delivery or pool development (Fausch et al., 1988), food availability and growth (Weber et al., 2014), fish carrying capacity (Lobón-Cerviá, 2008), fish behavioral responses (White et al., 2014), physiological responses of fish (Feldhaus et al., 2010), and other spatial factors such as the juxtaposition of habitats meeting requirements for multiple life stages (Jackson et al., 2001; White and Rahel, 2008). Fish response to temperature regimes may also be highly dependent on spatially discontinuous coldwater refuges (Ebersole et al., 2003) that are not captured in coarse-grained stream temperature models. These factors would ideally be used in a life cycle modeling framework accounting for survival bottlenecks in multiple life history stages (e.g., Scheuerell et al., 2006). However, a broad assessment of water temperature across the stream network was helpful for documenting the existing and potential template over which more nuanced factors affecting fish distribution can play out. The concept of thresholds implies that above certain thermal limits, physiological performance is severely limited enough to preempt colonization or success in warm-water sections of the stream network (EPA, 2003; McCullough, 2010). Therefore, the simulated increases in available stream length from restoration (**Figure 6**) should be considered the potential gain in available habitat; whether or not fish occupy or thrive there will depend on additional factors.

#### *Using General Land Office surveys for constructing watershed histories*

In combination with other historical data sources, General Land Office surveys can provide valuable information on watershed conditions prior to major Euro-American settlement and land use impacts (McAllister, 2008). These pre-impact descriptions can provide insights into how watershed conditions have changed over time, what are the major drivers, and how fish and other aquatic life may still be responding to land use legacies (Harding et al., 1998). Whereas numerous studies have employed GLO surveys to provide information on historical vegetation, to our knowledge, fewer studies have used GLO surveys to describe historical modifications to stream channel morphology across an entire stream network. Fitzpatrick and Knox (2000) used GLO surveys to describe historical versus present-day channel widths and sediment conditions in an assessment of flooding effects on channel geomorphology in North Fish Creek, Wisconsin. Beckham (1995) documented historical stream channel widths along the mainstem upper Grande Ronde River, Oregon, using GLO surveys, but the data were used for descriptive purposes and were not compared to contemporary estimates. Graf (1981) used a time series of GLO plat maps (along with other data sources) to assess potential zones of hazardous channel migration in the Gila River, Arizona. McDowell (2000) used GLO records from 1881 to describe original channel location (along with riparian vegetation) in an assessment of anthropogenic versus natural drivers for channel change in the Middle Fork John Day River, Oregon. Collins et al. (2003) used GLO surveys and other sources of information to reconstruct the historical riverine landscapes—including previous channel locations and riparian vegetation—of Puget lowlands, Washington. Each of these studies provided invaluable insights on reconstructing river channel and floodplain characteristics to help inform historical patterns of riverine habitat development, a necessary first step towards restoration (Ebersole and Liss, 1997).

### Conclusions

Historical ecology involves using multiple information sources as lines of evidence, often in a manner inconsistent with the original purpose of the data collection; however, if caution is taken we can begin to discern helpful insights regarding the character of the changing landscape (Fuller et al., 2004). Setting target conditions for restoration typically involves inferring conditions from nearby, undisturbed reference areas and using statistical models to extrapolate the expected, unimpacted conditions from within the existing range of anthropogenic disturbance in a watershed (Pollock et al., 2012). However, when historical information is available, it can provide a more realistic estimate of baseline conditions and range of natural variability (Motzkin and Foster, 2004). Reconstructing historical conditions does not necessarily imply a target for restoration. However, understanding the manner in which watersheds have been altered can improve our understanding of *how* and *why* conditions have changed (Pedroli et al., 2002). Furthermore, an understanding of the past may help us to avoid future mistakes. Using GLO surveys in comparison to contemporary stream surveys, we found that watersheds impacted by human land use had widened stream channels, especially in smaller streams in less-confined valleys. Restoration activities meant to return channels to their historical dimensions may have a greater physical impact in small, unconfined channels because those channels were most impaired by land use and have a greater capacity for geomorphic change. However, we emphasize that ability to affect change in a geomorphic context is only one of several criteria for prioritizing restoration actions; other important factors for planning restoration include biological benefits associated with actions and the social, economic, and overall land use objectives that set the context for restoration (Beechie et al., 2008). Restoration scenarios that included both restoration of riparian vegetation and stream channel narrowing projected reduced water temperature and increased length of the stream network habitable by salmonids. GLO surveys as a source of historical information can be valuable in describing broadscale watershed histories. Perhaps the most important benefit of reconstructing watershed histories in the present study—and in general—is the ability to use historical baselines to shed light on the legacy of processes constraining the abundance, productivity, and spatial distribution of aquatic life.

## Data accessibility statement

The following publicly available datasets were used for analyses:

- General Land Office (GLO) surveys: http://www.glorecords.blm.gov/default.aspx.
- Aquatic Inventories Project (AIP) fish habitat assessments: http://odfw.forestry.oregonstate.edu/freshwater/inventory/basinwid.html.
- Columbia Habitat Monitoring Program (CHaMP) fish habitat assessments: https://www.champmonitoring.org/.
- StreamNet map of spring Chinook salmon distribution: http://www.streamnet.org/gisdata/map_data_biological/FishDist_MSHv3_January2012/FishD_ChinookSpring_January2012.xml.

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## Competing Interests

The authors have no competing interests to declare.

## Author Contributions

- Contributed to conception and design: SMW, CJ, DAK, DAM
- Contributed to acquisition of data: SMW, CJ, DAM, DAK, TS
- Contributed to analysis and interpretation of data: SMW, CJ, DAK
- Drafted and/or revised the article: SMW, CJ, DAK, DAM
- Approved the submitted version for publication: SMW, CJ, DAK, DAM, TS

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