Integrating regional and local monitoring data and assessment tools to evaluate habitat conditions and inform river restoration

Francine H. Mejia\textsuperscript{a,}*, Jason M. Connor\textsuperscript{b}, Philip R. Kaufmann\textsuperscript{c,d}, Christian E. Torgersen\textsuperscript{a}, Eric K. Berntsen\textsuperscript{b}, Todd K. Andersen\textsuperscript{b}

\textsuperscript{a}U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Cascadia Field Station, Seattle, WA 98195, USA

\textsuperscript{b}Kalispel Tribe Natural Resources Department, Usk, WA 99180, USA

\textsuperscript{c}U.S. Environmental Protection Agency, Center for Public Health and Environmental Assessment, Pacific Ecological Systems Division, Corvallis, OR 97333, USA

\textsuperscript{d}Department of Fisheries & Wildlife, Oregon State University, Corvallis, OR 97333, USA

Abstract

Restoring degraded rivers requires initial assessment of the fluvial landscape to identify stressors and riverine features that can be enhanced. We associated local-scale river habitat data collected using standardized national monitoring tools with modeled regional water temperature and flow data on mid-sized northwest U.S. rivers (30–60 m wide). We grouped these rivers according to quartiles of their modeled mean August water temperature and examined their physical habitat structure and flow. We then used principal components analysis to summarize the variation in several dimensions of physical habitat. We also compared local conditions in the Priest River, a river targeted for restoration of native salmonid habitat in northern Idaho, with those in other rivers of the region to infer potential drivers controlling water temperature. The warmest rivers had physical structure and fluvial characteristics typical of thermally degraded rivers, whereas the coldest rivers had higher mean summer flows and greater channel planform complexity. The Priest River sites had approximately twice as many deep residual pools (>50, >75, and >100 cm) and incision that averaged approximately twice that in the coldest rivers. Percentage fines and natural cover in the Priest were also more typical of the higher-temperature river groups. We found generally low instream cover and low levels of large wood both across the region and within the...
Priest River. Our approach enabled us to consider the local habitat conditions of a river in the context of other similarly sized rivers in the surrounding region. Understanding this context is important for identifying potential influences on river water temperature within the focal basin and for defining attainable goals for management and restoration of thermal and habitat conditions.

Keywords
Environmental Monitoring and Assessment; Program; National Rivers and Streams Assessment; Water temperature; Priest River; Salmonids; Incision; Instream habitat

1. Introduction

Aquatic ecosystems are under threat globally (Geist and Hawkins, 2016, Gangloff et al., 2016). Freshwater ecosystems, rivers, and streams in particular face enormous demands to support a growing population and a changing climate (Dudgeon et al., 2006, Geist, 2011, Reid et al., 2019). Declines in populations of freshwater fishes in many parts of the world (Mueller et al., 2018, Nicola et al., 2018, Jones et al., 2020, Leidy and Moyle, 2021) and reorganization of fish communities (Comte et al., 2021) highlight the need to develop systematic and integrative approaches that incorporate scale-dependent analyses of monitoring data to identify mechanisms driving these changes (Geist, 2015, Bierschenk et al., 2019, Mueller et al., 2020, Comte et al., 2021, Feio et al., 2021). Restoring degraded rivers and streams requires an evaluation of the fluvial landscape to identify environmental stressors and determine whether landscape features are altered and can be enhanced or restored. However, finding the appropriate scale to assess ecosystems degradation and recovery is difficult because different levels of biological organization recover at different rates (Pander and Geist, 2013).

Much of the research and application of habitat quality monitoring are done at local scales, with some assessments conducted at the regional, national, and continental level (Kamp et al., 2007, Hill and Blair, 2005, Szoszkiewicz et al., 2006, Fernández et al., 2011, Bierschenk et al., 2019, Mueller et al., 2020). In Europe, the Habitats and Water Framework directives require the consideration of modifications to flow regime, sediment transport, river morphology, and lateral channel mobility. As a result, several geomorphological assessment tools have been developed to be integrated with biological monitoring and to evaluate overall ecological conditions (Rinaldi et al., 2017; Belletti et al., 2018; 2017). In the United States, The U.S. Environmental Protection Agency’s (USEPA) Environmental Monitoring and Assessment Program (EMAP) developed a framework in the early 1990s for regional and national scale assessment of aquatic resources to quantify associations between anthropogenic disturbance and the quality of water and habitat (Hill and Blair, 2005).

Field measurements collected using standardized protocols employed by regional and national monitoring programs enable comparisons to be made among rivers that provide a better understanding of their ecological condition. The EMAP and the National Rivers and Streams Assessment (NRSA) field sampling protocols quantify numerous physical habitat attributes organized in several categories: stream size and gradient, substrate size and stability, habitat complexity and cover, riparian vegetation cover and structure,
anthropogenic disturbances, and channel-riparian interaction (Kaufmann et al., 1999, U.S. Environmental Protection Agency, 2013). These habitat characterizations were designed to be used as a complement to biological data and other ecological data such as water temperature and land use.

Concerns about declines of cold-water fishes have resulted in extensive water temperature monitoring and restoration expenditures globally (Daigle et al., 2016, Jackson et al., 2016, Isaak et al., 2017). Across the western United States, hundreds of millions of dollars have been spent (Barnas et al., 2015). Combining this water temperature data with regional hydrologic modeling and field assessments of habitat condition can help infer potential processes at play to inform strategies to restore, augment, and conserve salmonid habitat. In the western United States, recent declines in Bull Trout (Salvelinus confluentus) and Westslope Cutthroat Trout (Oncorhynchus clarkii lewisi) populations have been associated with changes in habitat connectivity, water temperature, channel morphology, and introduction of invasive fish species (Shepard et al., 2005, Al-Chokhachy et al., 2010, Kovach et al., 2017, Howell, 2018), but these studies are mostly in small streams and rivers (<30 m wide). Many studies investigating the effects of instream and riparian characteristics on water temperature have also focused on small streams and rivers (Ebersole et al., 2003, Johnson and Wilby, 2015, Ouellet et al., 2017, White et al., 2017, Klaar et al., 2020, but see Jackson et al., 2021, Kalny et al., 2017, Kuhn et al., 2021). Smaller rivers are more vulnerable to heating and cooling than medium- and large-sized rivers due to their lower buffering capacity (Caisse, 2006). Thus, inferences from studies of small streams and rivers may not always apply to medium- and large-sized rivers.

Our objectives were to (1) examine how instream and riparian characteristics relate to thermal conditions in medium-sized rivers (30–60 m wide) across a region, and (2) evaluate how local habitat characteristics measured with standardized survey protocols within a single watershed (Priest River in northern Idaho) can be compared to existing monitoring data from rivers throughout the region. The rivers were grouped based on their mean August water temperature to compare associations with habitat attributes. We hypothesized that the coldest rivers had (1) smaller cross-sectional areas and were steeper because water in these rivers is less exposed to solar radiation and has shorter retention times, (2) higher mean summer flows that increase buffering thermal capacity, and (3) greater channel planform complexity that increases lateral and vertical connectivity and enhances surface water and groundwater exchange. Lastly, by placing our site-specific findings in this regional context, we aim to inform local habitat restoration and management efforts for native salmonids and other coldwater organisms in rivers.

2. Methods and materials

2.1. Study area

We examined rivers located in the mountains of Idaho, Montana, Washington, and Oregon (USA) that ranged in wetted width from 30 to 60 m, with slopes <1% and mean summer flows scaled to drainage area not exceeding 0.06 m$^3$s$^{-1}$ km$^{-2}$ (Fig. 1a). These rivers are all within the Marine Coast Forests and Northwestern Forested Mountains Level I ecoregions (McMahon et al., 2001). We refer to this group of rivers collectively as medium-sized
rivers. Sites were located along a range of latitudes from 44 to 49° north latitude in Idaho, Montana, Washington, and Oregon. Inland sites were mostly in the Rocky Mountains, whereas the coastal sites were in the Cascade and Pacific Coast ranges. Elevations of sites ranged from close to sea level in the Elochoman River in Washington to over 2,000 m in the Madison River in Montana. Elevation and proximity to the Pacific Ocean drive precipitation in the form of snow or rain that occurs mostly from October to April. We targeted the lower 73 km of the Priest River in northern Idaho for extensive monitoring in 2011 (Fig. 1b) and used NRSA data (2008–2014) for comparison (Fig. 1a).

The lower Priest River is located within the USEPA Northwestern Forested Mountains Level I ecoregion. It originates from the outlet dam at Priest Lake and flows south 73 km to the confluence with Pend Oreille River (Fig. 1b). It has a drainage area of 2,545 km² and elevations ranging from 2,045 m in the Selkirk Mountains to 632 m near the confluence with the Pend Oreille River. Elevations at the sites sampled ranged from 635 m near the confluence to 714 m near the outlet dam. The Priest has a snowmelt-driven flow regime with high flows in late spring (May to June) and early summer and low flows in late summer and winter (August to January). Mean annual flow from 1952 to 2019 at the U.S. Geological Survey (USGS) Gage 12395000 (Priest River near Priest River, Idaho) was approximately 48 m³s⁻¹ (0.02 m³s⁻¹ km⁻²). The outlet dam at Priest Lake was first constructed in 1951, but the existing outlet dam was constructed in 1978 (upstream of all our Priest River study sites) to control flows in the summer depending on snowpack and to maintain water levels sufficient for recreational activities and dock access on Priest Lake. The lake is drawn down 1 m in October and flows are unimpeded through the following June.

The geology underlying the mainstem Priest is primarily erodible sedimentary rocks, glacial outwash and till, alluvial deposits, and lacustrian deposits. The surrounding highlands geology consists of an igneous granitic batholith. Accelerated erosion from roads and streambed and bank erosion has led the Idaho Department of Environmental Quality to list the lower 55 km of the Priest from the Upper West Branch Priest River confluence to the Pend Oreille River as impaired for temperature and sediment on the most current (2020) Clean Water Act Section 303 d list, §303(d). The entire mainstem is also impaired for water temperature.

The lower Priest Lake dam is low head and allows upstream passage of salmonids when in spill position. However, native salmonid populations in the lake are depressed due to competition and predation by non-native Lake Trout, *Salvelinus namaycush* (Venard and Scarneechia, 2005). In the lower Priest River, densities of native salmonids are also low relative to those in nearby rivers (Fredericks et al., 2013). The non-native Smallmouth Bass, *Micropterus dolomieu*, population has been increasing steadily in the mainstem, as are non-native Brook Trout, *Salvelinus fontinalis*, in the tributaries (T. Andersen, unpublished data). Portions of the lower Priest River are used as a seasonal migratory corridor for native adfluvial Bull Trout (DuPont et al., 2007) and Westslope Cutthroat Trout (Andersen, 2016) that migrate from Lake Pend Oreille into the lower Priest River tributaries to spawn.
2.2. Sampling protocol and data sources

We paired modeled regional water temperature and flow datasets with field-collected habitat data to assess how the thermal and geomorphic landscape of the mainstem Priest River compares to other similar-sized rivers in the Pacific Northwest and Northern Rockies regions. The EMAP habitat data were collected using a two-stage sampling process for picking a spatially balanced, randomized set of stream monitoring sites (Herlihy et al., 2000). Data were collected at the scale of habitat units at multiple transects and summarized at the reach scale (20 times the channel width upstream and downstream for a total length of 40 times the channel width ranging from 1.2 km to 1.8 km). The reach length was similar to the 1-km resolution of the modeled temperature data. The geographic location of the reach was the midpoint (±50 m to account GPS accuracy). The sampling unit scales for regional and watershed analyses matched the scales of instream and channel processes (Beechie et al., 2010).

Field surveys in the Priest were conducted on August 4–18, 2011 (Fig. 1b) using the EMAP- NRSA protocol for non-wadeable streams (U. S. Environmental Protection Agency, 2013). The sample reach was divided into ten sub-reaches (11 transects per reach) and had a systematic design to locate habitat observations on these stream reaches. The EMAP protocol defines the length of each sampling reach proportionally based on wetted stream width at the time of sampling, with evenly spaced measurements to represent the entire reach. Field crews measured upstream and downstream distances of 20 times the wetted channel width from the predetermined midpoints to center each 40 channel-width field sampling reach.

Survey data were summarized as stream reach-scale attributes describing multiple aspects of riverine physical habitat. These attributes were organized into seven habitat categories: stream size, channel gradient, channel substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, anthropogenic alterations, and channel-riparian interactions (Kaufmann, 1993, Kaufmann et al., 1999). Attributes related to stream size and channel morphology represented riverine habitat quantity (e.g., thalweg depth, depth cross-sections, and wetted and bankfull widths), whereas other attributes provided inferences on the quality of the habitat and potential anthropogenic disturbances. Habitat attributes used in this study are provided in Table 1. Definitions and calculations are described in detail by Kaufmann et al. (1999; 2008) and Faustini and Kaufmann (2007).

We complemented the Priest survey data with data collected in the summer from 2008 to 2014 by the National Rivers and Streams Assessment (NRSA) program to compare the Priest River to similar medium-sized rivers from the USEPA Level I ecoregions (Marine Coast Forests and Northwestern Forested Mountains) (n = 75; Fig. 1a). The NRSA is a collaborative program between the USEPA, states, and tribes designed to assess the quality of rivers and streams in USA using a statistical survey approach and consistent field sampling protocols. NRSA data (https://www.epa.gov/national-aquatic-resource-surveys/data-national-aquatic-resource-surveys) includes various measures of human disturbance associated with each site and its watershed (contributing drainage area).
Because of the lack of paired water temperature data for all our sites, we obtained modeled August mean stream temperature data for the 1993 to 2011 period from the NorWeST Interagency Stream Temperature Database and Model, https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html (Isaak et al., 2017). The database consists of regional temperature data (>220,000,000 temperature recordings at > 22,700 stream and river sites), coupled with spatial statistical network models to develop historical and future climate scenarios at the 1-km resolution (Isaak et al., 2017). Covariates derived from remote sensing, flow gages, and expert consultation were included in the predictive models: elevation, reach slope, percentage of the upstream watershed area composed of lakes, percentage of the upstream watershed area composed of glaciers, annual precipitation, northing coordinate, base-flow index, cumulative drainage area, and percentage riparian canopy coverage, air temperature, discharge and tailwater. Predictive performance of the SSN models is discussed in detail by Isaak et al. (2017).

We also used modeled mean summer flow for the 1915 to 2006 period from the most current Western U.S. Stream Flow Metric Dataset, https://www.sciencebase.gov/catalog/item/508eccefe4b0b59cf7f5a7f8 (Wenger et al., 2010). This dataset contains historical and projected future stream flows for the western USA derived from daily runoff and baseflow predictions from the Variable Infiltration Capacity (VIC) macroscale hydrologic model (Wenger et al., 2010). The VIC model has been employed at regional scales to describe and forecast hydrologic changes. This model has been calibrated and applied mainly to large rivers and has a spatial resolution of 1/8° (latitude–longitude), which is roughly equivalent to a grid of 12 km by 10 km, varying in size depending on latitude (Hamlet et al., 2005). We considered using modeled mean August flow to be consistent with the mean August temperature from the NorWeST Interagency Stream Temperature Database and Model. However, we chose to use modeled mean summer flow instead, because the estimated mean August flow metric predictions are known to be less accurate for sites with strong groundwater influence (Wenger et al., 2010).

2.3. Statistical analyses

To calculate physical habitat attributes and condition used in the NRSA program from field surveys in the Priest River, we used the aquamet package for R, version 2.5.1 (Seeliger and Blocksom, 2018). This package estimates over 380 habitat attributes, most of which are subcomponents that contribute to more inclusive summary variables (e.g., numerous wood size class tallies contributing to total wood volume). We used only the summary variables to characterize habitat condition in the Priest River and similarly sized rivers in the region, grouping habitat attributes into four categories: (1) channel size and morphology, (2) substrate size and bed stability, (3) instream and riparian cover, and (4) habitat complexity and riparian human disturbance (Table 1).

To evaluate differences in habitat characteristics along the thermal ranges observed across the region, we calculated the quartiles for the modeled mean August water temperature, including all 85 sites. We grouped the rivers by quartiles but made an additional group for the Priest River sites (Priest). The coldest rivers belonged to the first quartile group (Q1), whereas the warmest rivers belonged to the fourth quartile (Q4) group.
had two sites in the third quartile (Q3) and 8 sites in the fourth quartile (Q4). We refer to these temperature groups as Q1, Q2, Q3, Q4, and Priest. We then performed a rank-based Kruskal–Wallis test. If the Kruskal–Wallis test was significant ($p < 0.05$), we also performed the post-hoc Dunn test to determine which groups differed from each other.

We used four principal component analyses (PCA) to summarize the reach-scale variation among rivers for each of the habitat condition categories selected. We computed ordinations using centered and unit variance-scaled data for each habitat condition category. We report the variance explained by each principal component (i.e., axis), the loadings for each variable included in the first two axes, and their Pearson correlations. We also created a Pearson correlation coefficient matrix with the resulting eigenvalues of each habitat condition category to describe their relationships. We defined strong correlations as those >0.70.

3. Results
3.1. Characterization of habitat attributes

3.1.1. Channel morphology and stream size—The coldest rivers had smaller cross-sectional areas ($x_{wxd}$) and were steeper (slope) than the warmest rivers (Fig. 2d and Fig. 2i). Mean residual depth ($rp_{100}$), a flow-independent metric, was not significantly different between warmest and coldest rivers. Although the Priest River had mean residual depth similar to rivers in the Q2 and Q3 temperature groups, it had more deep residual pools than the other groups, with almost twice as many in the >50, >75, and >100 cm residual depth classes (Table 2).

Mean bankfull width and mean bankfull depth in the Priest River were 62 m and 1.2 m, respectively. The Priest River was approximately 20% wider and almost twice as deep as the coldest rivers (49 m and 0.67 m, respectively). Median incision height was greatest for the Priest River (3.2 m; $p < 0.02$; Fig. 2j) and least for the coldest rivers (1.3 m).

3.1.2. Stream stability and substrate size—Overall, temperature quartile groups had relatively stable streambeds, but stream bed stability ($lrbs_{g08}$) and critical substrate diameter ($ldcbf_{g08}$) varied greatly among rivers within their groups (Fig. 3). Substrates were progressively finer from the coldest to the warmest river temperature quartile groups, with substrate in the warmest rivers significantly finer than in the coldest rivers (Fig. 3e). The geometric mean bed surface particle diameter in the thalweg for the coldest group (Q1) and Priest sites was cobble (117 and 72 mm, respectively) whereas the mean substrate size for Q2 and Q3 sites was coarse gravel (37 and 46 mm, respectively). The warmest rivers (Q4) had the smallest mean substrate diameter (10 mm). Mean percentage of sands and fines in the channel thalweg ranged from near 0% in the coldest rivers to 3% in the Priest sites. Sand or finer substrate percentages in the shallower river margins (“littoral” zone) were progressively greater as water temperature increased, except in the Priest River where the average was 9% (median was also 9%).

3.1.3. Instream and riparian cover—Attributes related to instream cover were highly variable within the groups. Thus, there were no significant differences between river
temperature quartile groups for most attributes except for areal proportions of the sum of all-natural instream cover (Fig. 4d). The mean areal cover proportions for the sum of all-natural instream cover features were <0.30 for all groups (Fig. 4d). One site in the Priest River had a proportion >1, skewing its mean considerably. Maximum proportions for the other groups did not exceed 0.63 (Q2 group). The mean proportion of the sum of all sizes of areal instream cover ranged from 0.25 to 0.41 (Fig. 4f), but three sites—one in the Priest River and two in the Sprague River (Sprague River belongs to the Q4 group)—had proportions >1 influencing the mean values. Mean counts of all size wood were generally low, ranging from 1.4 pieces per 100 m in the warmest rivers to 5 pieces per 100 m in the Priest. Mean volume of large woody debris (LWD) also was lowest in the warmest rivers, approximately one third of the next group, Q3 (2.45 vs. 7.42 m$^3$ 100 m$^{-1}$). The mean areal riparian cover proportion from trees of all sizes was low for all groups and ranged from 0.12 in the warmest rivers to 0.31 in the cooler rivers and Priest. The mean riparian woody areal cover proportion (trees, shrubs, and ground) within the groups ranged from 0.53 in the warmest rivers (Q4) to 0.76 in the coldest rivers (Q1).

3.1.4. Habitat complexity and riparian human disturbance—Channel planform complexity, calculated as the percentage of side channels, was lowest in the Priest River (2%, SD ± 3.3), approximately 10% of that in the coldest rivers, which had the highest mean (22%, SD ± 22.4 Fig. 5a). The proximity-weighted indices of total riparian human disturbances were driven by non-agricultural disturbances. The agricultural disturbance index score was about 4% of the total disturbance in the coldest rivers, and 40% in the warmest rivers (Fig. 5b to Fig. 5d). Differences in total riparian disturbances between the warmest and the coldest rivers were significant ($p = 0.02$; Fig. 5d). The warmest rivers had the highest index of disturbance (index of 1.5), whereas the coldest rivers had the lowest (index of 0.67). The mean index of total riparian disturbances in the Priest River was almost 20% more than that of the mean of the coldest rivers (index of 0.82).

3.2. Modeled water temperature and areal mean flows

The Middle Fork of the Flathead River in Montana was the coldest site (8.4 °C), whereas the John Day River in Oregon was the warmest site (23 °C; Fig. 6). The water temperature in the coldest group, Q1, ranged from 8.4 °C to 14.8 °C. In contrast, water temperature in the warmest group, Q4, ranged from 18.8 °C to 23.0 °C. The Priest River water temperatures ranged from 18.6 °C to 19.8 °C.

Areal mean flows (Fig. 7) were generally lowest in the warmest group (0.005 m$^3$s$^{-1}$ km$^{-2}$), whereas flows were over 4 times higher (0.022 m$^3$s$^{-1}$ km$^{-2}$) in the coldest group ($p < 0.0001$). The Sauk River, in the Western Cascades, and the Quinault River, on the Olympic Peninsula in Washington, both of which were included in the first quartile group, had the highest summer flows per drainage area (0.056 and 0.048 m$^3$s$^{-1}$ km$^{-2}$, respectively). However, the two rivers with the lowest flows per drainage area (0.001 m$^3$s$^{-1}$ km$^{-2}$) were the Madison River in Montana (in the coldest group) and the Sprague River in Oregon (in the warmest group).
3.3. Variability of habitat conditions

To summarize variation in physical habitat among rivers, we computed an ordination of variables in each habitat category (Fig. 8). The first and second axes of the channel morphology and stream size PCA (Morph), explained, respectively, 33% and 17% of the variance, with 50% cumulative variance explained. Three out of the 10 habitat attributes, cross-sectional area (xwxd), mean depth (xdepth), and depth variability (sddepth), had strong correlations $\geq |0.70|$ with $p < 0.0001$ (Table 3), whereas only two habitat attributes, mean width (xwidth) and mean bankfull width (xbkf_w), had strong ($\geq |0.70|$) correlations with the second axis. Comparison of the first axis of the Morph ordination revealed that the coldest group was significantly different from the other groups ($p < 0.0001$) except for the next warmer group (Q2) and that these differences were mostly driven by slope.

The first two axes of the relative bed stability and substrate size PCA (Bed) explained a cumulative variance of 72%, with most of the variability explained by the first axis (54%). For the first axis, five out of the eight habitat attributes had correlations $\geq |0.70|$, with $p < 0.0001$; Table 3): substrate size (lsub_dmm), percentage sands and fines in the thalweg (pct_safn), percentage of shallow river margins or littoral zone with sands and fines as dominant substrate (LitSB1_SF), erodible substrate diameter at bankfull or the shear stress of the stream at bankfull flood stage (ldcbf_g08), and bankfull hydraulic resistance from bed particles (cp3_mill). For the second axis, only bankfull total hydraulic resistance (ct_rpwd), had strong correlations. Comparison of the first Bed axis revealed that the cooler groups, Q1 and Q2, were significantly different from the warmest group, Q4 ($p = 0.004$, and $p = 0.03$ respectively). These differences were mostly driven by substrate size.

The first two axes of the instream and riparian cover PCA (Cover) together explained 61% of the variance. Two-thirds of this variability was explained by the first axis (41%) and only three out of the 10 habitat attributes had significant strong correlations ($r \geq 0.70$): sum of all natural areal cover (xfc_nat), sum of all large areal cover (xfc_big), and sum of LWD areal cover (xfc_lwd).

The first two axes of the habitat complexity and riparian human disturbance ordination (Comp-Dist) explained a cumulative variance of 81%, the most variability of all four ordinations (Fig. 8). The first axis of the Comp-Dist ordination explained 57% of the variance, and the second axis explained 24%. For this ordination, riparian human disturbance index for all types (w1_hall) and riparian human disturbance from other sources than agriculture (w1_hnoag) had strong correlations. Percentage side channels (pct_side) was negatively correlated ($r = -0.41$) with the major axis of human activities, suggesting loss of habitat complexity in response to human activities. Comparison of the first Comp-Dist axis revealed that the coldest group, Q1, was significantly different from the warmest group, Q4 ($p = 0.003$). These differences were mostly driven by percentage side channels and riparian human disturbances from agriculture.

We also evaluated the correlation between axes of habitat condition categories. Most of these correlations were not significant (Figure S1). The few significant correlations were weak to moderate and ranged from −0.24 to 0.46.
4. Discussion

The results of this study indicate that stream morphology, channel planform complexity and mean summer flows are associated with water temperature in medium-sized rivers through various mechanisms. Steeper rivers with smaller cross-sectional areas are less exposed to solar radiation and have less area for convective heat exchange (Poole and Berman, 2001), whereas rivers with higher mean summer flows and complex channel planforms have greater buffering capacity from thermal inertia and surface water-groundwater exchange (Poole and Berman, 2001, Arrigoni et al., 2008). These results also demonstrate how regional monitoring protocols can be leveraged to evaluate physical habitat and thermal and fluvial conditions at the watershed scale, and then to place these smaller, more detailed basin studies in the context of the surrounding region. We found that the warmest rivers had physical structure (e.g., excess fine sediments, and higher levels of anthropogenic disturbances) and fluvial characteristics typical of thermally altered rivers, whereas the coldest rivers had higher mean summer flows and greater channel planform complexity. The Priest River sites were within the two higher temperature quartiles but shared contrasting habitat characteristics of rivers in both the coldest and warmest temperature groupings. For instance, the Priest River sites had approximately twice as many deep residual pools (>50, >75, and >100 cm) and as much LWD as the coldest sites. In contrast, incision in the Priest River sites averaged approximately twice that in the coldest rivers. Percentage fines, natural cover, and percent of side channels in the Priest River were also more typical of the higher-temperature groups of rivers. We found generally low instream cover and low levels of LWD both across the region and within the Priest River. We compared the Priest River physical habitat with that in other medium-sized rivers subject to a range of thermal conditions within the same ecoregion to understand which processes may be responsible for creating favorable thermal conditions for native salmonids (e.g., lateral, longitudinal, and vertical connectivity). This approach can be used by managers to set baselines, inform decisions and expectations for recovery of salmonids (e.g., determining the extent of restoration or mitigation efforts), and infer potential processes driving water temperature within a basin and region.

The four physical habitat attribute categories described in our study comprise important elements of fish habitat and serve as the template on which aquatic habitat is created (Reid et al., 2020). The quality of this physical habitat, within and above the active channel, and associated processes can be further evaluated to understand how they can limit the distribution of biota, e.g., native salmonids (Geist, 2011). Systematic removal of LWD and boulders, splash damming, and log drives were common across the United States, Canada, and northern European countries like Sweden and Finland (Sedell and Luchessa, 1982, Steel et al., 2017, Tornlund and Ostlund, 2002, Wohl, 2014, White et al., 2017). Scour from these activities and other legacy land uses widened rivers (White et al., 2017) and decreased the frequency of large, deep pools (McIntosh et al., 2000) in the Columbia River basin. In the lower 73 km of the Priest River, log drives occurred from the 1890s to the 1950s and extended almost the entire length of the lower 73 km (Sims, 1998; 2002). Splash dams were not built in the mainstem of the Priest River, and there are records of splash dams in only two tributaries: Big Creek and the lower West Branch Priest River (Sims, 1998). Extensive logging likely increased sediment supply that aggraded channel beds (White et al., 2017)
and accelerated deposition on river floodplains (Knighton, 1998). However, excess sediment in the main channel was scoured out as the result of log drives. These two sequential processes, aggradation and incision, led to a greater elevation difference between the floodplain and the channel thalweg. Specifically, the sediment deposited in the floodplain created a greater elevation difference between the floodplain and the scoured channel thalweg, amplifying the degree of floodplain detachment (Wohl, 2004). Our findings on the Priest River are consistent with rivers that have undergone excessive anthropogenic channel scouring. The resultant habitat characteristics include greater mean bankfull depth, greater mean incision height, and low instream areal cover, compared with the least-disturbed streams and historical information (Surian and Rinaldi, 2003, Wohl, 2014). The legacy of log drives, as well as the low head dam that restricts flow from the lake during the summer and releases warm lake surface water, may have led to increased downstream temperatures, simplified geomorphology, sparse instream cover, and decreased amounts of LWD. This corroborates the findings of other studies examining landscape changes affecting biota and channel morphology of rivers and streams (Bierschenk et al., 2019, Poepppl et al., 2015, Wohl, 2015, 2020).

In general, residual pool attributes provide a flow-independent measure of habitat volume and complexity (Kaufmann and Faustini, 2011). Residual pools provide deep water habitat for salmonids during the summer when water temperatures are higher than their optimum temperatures, thereby affecting the carrying capacity of the river (Lisle, 1987). Bull Trout in small streams (<10 m wide) are generally absent from reaches where residual pool depths are <30 cm (Al-Chokhachy et al., 2010). In our study, the Priest River had two to three times as many deep residual pools (>50 cm, >75 cm, and >100 cm) as the other river groups (Table 2). Some of these pools may stratify thermally, providing refuge to native salmonids thermoregulating in the summer during low flows and when water temperatures are above the optimum for these fish (Mejia et al., 2020). However, the thermal advantage of these large pools to salmonids are severely restricted if these pools are occupied by competing non-native fishes such as Smallmouth Bass and Brook Trout.

Bankfull width and bankfull depth are associated with high flows. Flows that exceed bankfull conditions can access adjacent floodplain habitats important to salmonids because they provide additional rearing capacity during wet months by supporting a more heterogenous landscape with abundant prey, diverse temperatures, low velocities, and refuge from predators (Muhlfeld et al., 2003, Armstrong and Schindler, 2013, Hall et al., 2018). However, extreme bankfull depth may be the result of streambed degradation (incision) and floodplain disconnection where incision prevents high flows from diffusing over the floodplain and causes channel deepening due to very high shear stresses at the bottom of the channel (Schumm et al., 1984, Cluer and Thorne, 2014). The correlations of between axis scores from the ordinations suggest that these mechanisms maybe occurring in the region (i.e., moderate associations between the first axes of Comp-Dist, Morph and Bed ordinations and the second axis of Cover). Our results for the Priest sites also suggest that floodplain disconnection may have a warming effect because compared to the coldest rivers in the region, the Priest sites have (1) 100% deeper mean bankfull depth, (2) 2.3 times higher mean incision height, and (3) only 10% of the side channels observed in other rivers.

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The narrow range of substrate sizes in the Priest River may be related to the small amount of large-scale channel roughness that potentially provides varied hydraulic conditions to sort cobble, gravel, and fines. Large instream structures (natural or man-made) add hydraulic roughness that also facilitates sediment fining and deposition (Buffington and Montgomery, 1999). Overall, the means for the area of natural cover of fish concealment features were low in all temperature groupings (<0.30) but were about a 30 to 40% higher in the coldest rivers (0.28 vs. 0.17). Additionally, mean counts of LWD (1.4–5.0 pieces of all sizes 100 m\(^{-1}\)) and volume (2.5–11 m\(^3\) 100 m\(^{-1}\)) in rivers throughout the region were low or near the minimum targets set by the U.S. National Marine Fisheries Service (>5 pieces 100 m\(^{-1}\) with diameter ≥1.5 cm and length ≥15.2 m. The Oregon Watershed Enhancement Board recommends >20 pieces 100 m\(^{-1}\) (Fox and Bolton, 2007). Fox and Bolton (2007) found in Washington’s unmanaged forested watersheds that the number and volume of LWD in streams increased with bankfull width, but that these values varied widely from one area to another depending on climatic variations that affected the species composition and size of the riparian trees. They reported the largest counts and volumes in western Washington rivers with bankfull width >30 m, where the median counts and volume were 106 pieces 100 m\(^{-1}\) and 93 m\(^3\) 100 m\(^{-1}\), respectively. Kaufmann et al. (2008) reported an overall median of 28 pieces 100 m\(^{-1}\) (range of 6 to 97) with a median of 7.7 m\(^3\) 100 m\(^{-1}\) (0.99–105) in streams <5 m wide in the central Oregon Coast Range. The highest counts in our study (21 pieces 100 m\(^{-1}\)) were in the Quinault, a Q1 site, but these values were still only 20% of those reported by Fox and Bolton (2007). In contrast, eastern Washington medians were 17 pieces 100 m\(^{-1}\) and 7 m\(^3\) 100 m\(^{-1}\) for streams narrower than 30 m (bankfull width) (Fox and Bolton, 2007). Riparian vegetation in the Priest River is more like the forest types found in eastern Washington. However, we found that counts of LWD pieces were about 30% of those reported by Fox and Bolton (2007). The low LWD numbers and volumes in the Priest River are consistent with our understanding of the impacts of scour from log drives.

The mean woody riparian cover from ground layer, mid-layer, and upper layer vegetation ranged from 0.53 (warmest rivers) to 0.77 (coldest rivers), with 25 to 50% coming from large riparian trees >5 m tall. This contribution generally decreased as water temperature increased except in the Priest River where the largest contribution was observed (50%). Abundant riparian vegetation supports numerous ecological functions (National Research Council, 2002). For example, the low cover and complexity of riparian vegetation on the Priest River may limit in-channel and floodplain hydraulic resistance, stability of stream banks, interception, evaporation of the incoming precipitation, and buffering of stream temperature. Riparian cover can be described as the relative amount of sky obscured by riparian vegetation at a given point. Shade is influenced by cover but changes throughout each day, as the position of the sun varies spatially and temporally with respect to the canopy cover (Kelley and Krueger, 2005). During the summer, when flows are low and water temperature is high, shade from riparian cover may help to maintain cool downstream temperatures, provided that riparian vegetation is tall enough and the stream is sufficiently narrow (DeWalle, 2008, Jackson et al., 2021).

Given the opportunistic nature of our study (i.e., most data were collected for other monitoring purposes), we were limited with respect to study design. Nonetheless, we were able to make inferences about the region and the Priest River. Most datasets used
in this study had been used in previous studies, but they had not been used specifically to analyze medium-sized rivers. Thus, we gained new insights into the relevance of mean summer flows, the small amounts of instream cover, and generally low levels of LWD in medium-sized rivers throughout the region. Additional investigation into the influences of legacy land use and hydrological modifications by dams is needed because it would further inform how past disturbances and current dam-altered flows can affect the magnitude, frequency, duration, timing, and variability of thermal regimes of rivers (Olden and Naiman, 2010). However, this level of analysis was beyond the scope of our study. Understanding past land use in the region may help explain some of the variability observed among groups, considering that current land use may not reflect past land uses (Depauw et al., 2019, Steel et al., 2017). Across the region, further examination of the interaction between epilimnetic releases of warm water from low head dams, reach-scale groundwater-surface water exchange, contributions from cold tributaries, and the effects of water withdrawals is needed to understand how these factors may influence summer thermal conditions. For instance, there were two exceptions in the coldest group where summer flows were low: the Madison River in Montana, and the Wallowa River in Oregon. Both rivers are influenced by groundwater but are affected by irrigation withdrawals that may reduce their summer flows (Clifton et al., 2018, Dwire et al., 2018, Vanderhoof et al., 2019).

5. Management implications

The environmental impacts of anthropogenic activities and climate change influence the distribution of native fishes (Bierschenk et al., 2019, Isaak et al., 2015, Mueller et al., 2018, Woodward et al., 2010). Out of the 85 sites included in this study, 62 (73%) have been listed as impaired for water temperature, 22 (26%) for both temperature and sediment, and no sites are listed as impaired for sediment only. Furthermore, most sites in the Q3 and Q4 temperature groups were listed for temperature except for four sites in Idaho: the Payette River (n = 2) and the North Fork of the Clearwater River (n = 2). The Priest River is listed as impaired for temperature and sediment on the most current (2020) §303(d) list under the Clean Water Act due primarily to temperatures above Bull Trout thresholds and accelerated erosion from unpaved roads and stream bank erosion (https://www.deq.idaho.gov/water-quality/surface-water/total-maximum-daily-loads/priest-river-subbasin/; accessed on April 14, 2021). Excessive sedimentation was not apparent in our results, except in one reach in the shallow river margins or littoral zone (30% of littoral area dominated by <2 mm diameter substrates). In the thalweg, percentage sands and fines never exceeded 19% (median of 3%). The median areal percentage of littoral area dominated by sand and silt was 9%. Bryce et al. (2010) estimated that optimum sediment tolerance values (areal percentage of sand and fines) were about 11% and 19% for Bull Trout and Westslope Cutthroat Trout, respectively. In the state of Washington, the percentage of sand and fines is on average 5.5% greater in the river littoral zone or shallow river margins than in the thalweg (Glenn Merritt, Washington State Department of Ecology, unpublished data). Although the data collection approach that we used does not allow a direct comparison, we observed greater areal cover of sand and fines in the shallow river margins, where 9% of the area had >50% sand and fines, compared with the thalweg, which had 3% areal cover of sand and fines. These results suggest potential bank erosion and localized deposition due to lower energy in the channel.
margins and scouring of fines from the thalweg. Consequently, sediment delivered to the channel from bank erosion is evident in the near-bank sediments but is quickly transported downstream and does not remain in the thalweg. However, in one reach where the areal percentage of sand and fines was 18% in the thalweg and 18% of the littoral area, sand and fines were the dominant substrates. In this reach, fine sediment loading was apparently large enough to remain in the thalweg.

In this study, we have elucidated potential processes driving water temperature in the Priest River that are applicable to other medium-sized rivers in temperate regions of the world experiencing similar legacy stressors (Gardeström et al., 2013, Mueller et al., 2018, White et al., 2017). The ecological consequences of channel incision are complex because lowered streambed elevation and disconnection from the floodplain can have multiple effects on lotic and riparian structure and function due to lowered groundwater table, loss of wetlands, lower summer base flows, warmer water temperatures, and loss of riparian plant biomass (Steiger et al., 2005, Cluer and Thorne, 2014, Pollock et al., 2014, Schindler and Smits, 2016). Specifically, incised rivers have greater rates of bank erosion, less sediment deposited onto the floodplains, and lower groundwater and nutrient exchange that collectively may decrease instream and terrestrial floodplain productivity and habitat diversity and affect riparian forest community composition (Pander et al., 2018, Pollock et al., 2014, Schindler and Smits, 2016). These changes to riparian communities also influence stream temperature patterns (National Research Council, 2002).

Although our study did not explicitly determine causal mechanisms, the analyses provide context for process-based restoration in the Priest River and other medium-sized rivers with similar habitat characteristics. Because landscape restoration actions are better than reach-scale actions at improving the health of streams and rivers, integrating these two perspectives better inform the probability of success of local restoration efforts (Palmer et al., 2010). Additionally, at the regional level, the insights we gained on (1) the potential influence of summer flows on mean August temperature, and (2) the small amounts of instream cover and LWD constitute important areas for future research and management.

6. Conclusions

In this study, we showed how regional and local habitat monitoring protocols and data combined with streamflow and broad-scale modeled water temperature data can be integrated to determine baseline conditions that inform and guide riverine restoration and management efforts across a large region. We compared habitat conditions from the Priest River to other rivers throughout the Pacific Northwest region of the USA and, specifically, to rivers representing a range of thermal conditions. These findings underscore the need to investigate how historical land use may have contributed to the thermal degradation of rivers. For example, the small amounts of instream cover and LWD in rivers across the region suggest that riparian vegetation may have decreased due to land-use changes. Further investigation of these patterns with historical aerial photography and data on past forestry practices is needed to better understand the temporal context of habitat change in rivers throughout the region.
Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Arrigoni AS, Poole GC, Mertes LAK, O’Daniel SJ, Woessner WW, Thomas SA, 2008. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels. Water Resour. Res 44, W09418.

Al-Chokhachy R, Roper BB, Bowerman T, Budy P, 2010. A review of Bull Trout habitat associations and exploratory analyses of patterns across the interior Columbia River basin. North Am. J. Fish. Manag 30 (2), 464–480.

Andersen T, 2016. Kalispel Joint Stock Assessment Annual Project Report Project Number 1997–004–00 Report to Bonneville Power Administration BPA Document ID #P151121 Cusick, WA.

Armstrong JB, Schindler DE, 2013. Going with the flow: spatial distributions of juvenile coho salmon track an annually shifting mosaic of water temperature. Ecosystems 16 (8), 1429–1441.

Barnes KA, Katz SL, Hamm DE, Diaz MC, Jordan CE, 2015. Is habitat restoration targeting relevant ecological needs for endangered species? Using Pacific Salmon as a case study. Ecosphere 6 (7), art110.

Beechie TJ, Sear DA, Olden JD, Pess GR, Buffington JM, Moir H, Roni P, and Pollock MM. 2010. Process-based principles for restoring river ecosystems. Bioscience 60:209–222.

Belletti B, Nardi L, Rinaldi M, Poppe M, Brabec K, Bussettini M, Comiti F, Gielczewski M, Golferi B, Hellsten S, Kail J, Marchese E, Marcinkowski P, Okruszko T, Paillex A, Schirmer M, Stelmaszczuk M, Surian N, 2018. Assessing restoration effects on river hydromorphology using the process-based morphological quality index in eight European river reaches. Environ. Manage 61 (1), 69–84. [PubMed: 29150720]

Belletti B, Rinaldi M, Bussetti M, Comiti F, Gurnell AM, Mao L, Nardi L, Vezza P, 2017. Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. Geomorphology 283, 143–157.

Bierschenk AM, Mueller M, Pander J, Geist J, 2019. Impact of catchment land use on fish community composition in the headwater areas of Elbe, Danube and Main. Sci. Total Environ 652, 66–74. [PubMed: 30359803]

Buffington JM, Montgomery DR, 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resour. Res 35 (11), 3507–3521.

Bryce SA, Lomnicky GA, Kaufmann PR, 2010. Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria. J. North Am. Benthol. Soc 29 (2), 657–672.

CAISSIE D, 2006. The thermal regime of rivers: a review. Freshw. Biol 51 (8), 1389–1406.
Clifton CF, Day KT, Luce CH, Grant GE, Safeeq M, Halofsky JE, Staab BP, 2018. Effects of climate change on hydrology and water resources in the Blue Mountains, Oregon, USA. Clim. Serv 10, 9–19.

Cluer B, Thorne C, 2014. A Stream evolution model integrating habitat and ecosystem benefits. River Res. Appl 30 (2), 135–154.

Comte L, Olden JD, Tedesco PA, Ruhi A, Giam X 2021. Climate and land-use changes interact to drive long-term reorganization of riverine fish communities globally. Proc. Natl. Acad. Sci. USA 118: e2011639118. [PubMed: 34155095]

Daigle A, Caudron A, Vigier L, Pella H, 2016. Optimization methodology for a river temperature monitoring network for the characterization of fish thermal habitat. Hydrol. Sci. J 62, 483–497.

DeWalle DR, 2008. Guidelines for riparian vegetative shade restoration based upon a theoretical shaded-stream model. JAWRA J. Am. Water Resour. Assoc 44, 1373–1387.

Depauw L, Landuyt D, Perrin MP, Blondeel H, Maes SL, Kopecký M, Máliš F, Vanhellemont M, Verheyen K, 2019. A general framework for quantifying the effects of land-use history on ecosystem dynamics. Ecol. Ind 107, 105395.

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA, 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. Camb. Philos. Soc 81 (02), 163. [PubMed: 16336747]

DuPont JM, Brown RS, Geist DR, 2007. Unique alacustrine migration patterns of a Bull Trout population in the Pend Oreille River drainage, Idaho. North Am. J. Fish. Manag 27 (4), 1268–1275.

Dwire KA, Mellmann-Brown S, Gurrieri JT, 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. Clim. Serv 10, 44–52.

Ebersole JL, Liss WJ, Frissell CA, 2003. Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. Can. J. Fish. Aquat. Sci 60 (10), 1266–1280.

Faustini JM, Kaufmann PR, 2007. Adequacy of visually classified particle count statistics from regional stream habitat surveys. J. Am. Water Resour. Assoc 43 (5), 1293–1315.

Feio MJ, Hughes RM, Callisto M, Nichols SJ, Odume ON, Quintella BR, Kuemmerlen M, Aguilar FC, Almeida SFP, Alonso-Eguíalís P, Arimoro FO, Dyer FJ, Harding JS, Jang S, Kaufmann PR, Lee S, Li J, Macedo DR, Mendes A, Mercado-Silva N, Monk W, Nakamura K, Ndiritu GG, Ogden R, Peat M, Reynoldson TB, Rios-Touma B, Segurado P, Yates AG, 2021. The biological assessment and rehabilitation of the world’s rivers: An Overview. Water (Basel) 13 (3), 371. [PubMed: 33868721]

Fernandez F, Barquín J, Raven PJ, 2011. A review of river habitat characterisation methods: indices vs. characterisation protocols. Limnnetica 30, 217–234.

Fox M, Bolton S, 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington state. North Am. J. Fish. Manag 27 (1), 342–359.

Fredericks J, Maiolie M, Hardy R, Ryan R, Litér M 2013. Idaho Department of Fish and Game Fishery Management Annual Report Panhandle Region IDFQ Report #12–110

Gangloff MM, Edgar GJ, Wilson B, 2016. Imperilled species in aquatic ecosystems: emerging threats, management and future prognosis. Aquat. Conserv. Mar. Freshwater Ecosyst 26 (5), 858–871.

Gardeström J, Holmqvist D, Polvi LE, Nilsson C, 2013. Demonstration restoration measures in tributaries of the Vindel River catchment. Ecol. Soc 18, 8.

Geist J, 2011. Integrative freshwater ecology and biodiversity conservation. Ecol. Ind 11 (6), 1507–1516.

Geist J, 2015. Seven steps towards improving freshwater conservation. Aquat. Conserv. Mar. Freshwater Ecosyst 25 (4), 447–453.

Geist J, Hawkins SJ, 2016. Habitat recovery and restoration in aquatic ecosystems: current progress and future challenges. Aquat. Conserv. Mar. Freshwater Ecosyst 26 (5), 942–962.
Hall JE, Greene CM, Stefankiv O, Anderson JH, Timpane-Padgham B, Beechie TJ, Pess GR, Fujiwara M, 2018. Large river habitat complexity and productivity of Puget Sound Chinook salmon. PLoS One 13 (11), e0205127. [PubMed: 30383778]

Hamlet AF, Mote PW, Clark MP, Lettenmaier DP, 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. J. Clim 18, 4545–4561.

Herlihy AT, Larsen DP, Paulsen SG, Urqhart NS, Rosenbaum BJ, 2000. Designing a spatially balanced, randomized site selection process for regional stream surveys: The EMAP Mid-Atlantic pilot study. Environ. Monit. Assess 63, 95–113.

Hill BH, Blair R, 2005. Monitoring the condition of our nation’s streams and rivers: from the mountains to the coasts. Environ. Monit. Assess 103, 1–4.

Howell PJ, 2018. Changes in native bull trout and non-native brook trout distributions in the upper Powder River basin after 20 years, relationships to water temperature and implications of climate change. Ecol. Freshw. Fish 27 (3), 710–719.

Isaak DJ, Young MK, Nagel DE, Horan DL, Groce MC, 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Glob. Change Biol 21 (7), 2540–2553.

Isaak DJ, Wenger SJ, Peterson EE, Ver Hoef JM, Nagel DE, Luce CH, Hostetler SW, Dunham JB, Roper BB, Wollrab SP, Chandler GL, Horan DL, Parkes-Payne S, 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resour. Res 53, 9181–9205.

Jackson FL, Malcolm IA, Hannah DM 2016. A novel approach for designing large-scale river temperature monitoring networks. Hydrol. Res 47:569–590.

Jackson FL, Hannah DM, Ouellet V, Malcolm IA, 2021. A deterministic river temperature model to prioritize management of riparian woodlands to reduce summer maximum river temperatures. Hydrol. Process 35 (8)

Jones LA, Schoen ER, Shafilet R, Cunningham CJ, Mauger S, Rinella DJ, St. Saviour A, 2020. Watershed-scale climate influences productivity of Chinook salmon populations across southcentral Alaska. Glob. Change Biol 26 (9), 4919–4936.

Johnson MF, Wilby RL, 2015. Seeing the landscape for the trees: Metrics to guide riparian shade management in river catchments. Water Resour. Res 51 (5), 3754–3769.

Kalny G, Laaha G, Melcher A, Trimmel H, Weihs P, Rauch HP, 2017. The influence of riparian vegetation shading on water temperature during low flow conditions in a medium sized river. Knowl. Manage. Aquat. Ecosyst (418), 5.

Kamp U, Binder W, Hölz K, 2007. River habitat monitoring and assessment in Germany. Environ. Monit. Assess 127 (1–3), 209–226. [PubMed: 17058007]

Kaufmann PR 1993. Physical Habitat Pages 59–69 in Stream Indicator and Design Workshop. EPA/600/R-93/138 U.S. Environmental Protection Agency, Corvallis, OR.

Kaufmann PR, Faustini JM, 2011. Simple measures of channel habitat complexity predict transient hydraulic storage in streams. Hydrobiologia 685 (1), 69–95.

Kaufmann PR, Faustini JM, Larsen DP, Shirazi MA, 2008. A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99 (1–4), 150–170.

Kaufmann PR, Levine P, Seeliger C, Robison EG, Peck DV 1999. Quantifying Physical Habitat in Wadable Streams. EPA/620/R-99/003 U.S. Environmental Protection Agency, Washington, D.C.

Kelley CE, Krueger WC, 2005. Canopy cover and shade determinations in riparian zones. J. Am. Water Resour. Assoc 41 (1), 37–046.

Klaar MJ, Shelley FS, Hannah DM, Krause S, 2020. Instream wood increases riverbed temperature variability in a lowland sandy stream. River Res. Appl 36 (8), 1529–1542.

Knighton D, 1998. Fluvial Forms and Processes: A New Perspective Oxford University Press Inc, New York, NY, USA.

Kovach RP, Al-Chokhachy R, Whited DC, Schmetterling DA, Dux AM, Muhlfeld CC, Strecker A, 2017. Climate, invasive species and land use drive population dynamics of a cold-water specialist. J. Appl. Ecol 54 (2), 638–647.

Ecol Indic. Author manuscript; available in PMC 2022 November 01.
Kuhn J, Casas-Mulet R, Pander J, Geist J, 2021. Assessing stream thermal heterogeneity and cold-water patches from UAV-based imagery: a matter of classification methods and metrics. Remote Sensing 13 (7), 1379.

Leidy RA, Moyle PB, 2021. Keeping up with the status of freshwater fishes: A California (USA) perspective. Conserv. Sci. Pract 3, e474.

Lisle TE 1987. Using residual depths to monitor pool depths independently of discharge. Res. Note PSW-394 Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, CA.

McIntosh BA, Sedell JR, Thurow RF, Clarke SE, Chandler GL, 2000. Historical changes in pool habitats in the Columbia River Basin. Ecol. Appl 10 (5), 1478–1496.

McMahon G, Gregonis SM, Waltman SW, Omernik JM, Thorson TD, Freeouf JA, Rorick AH, Keys JE, 2001. Developing a spatial framework of common ecological regions for the conterminous United States. Environ. Manage 28 (3), 293–316. [PubMed: 11531234]

Mejia FH, Torgersen CE, Berntsen EK, Johnsen A, Andersen T 2020. Water temperature data from the Priest River, Idaho, 2018–2019: U.S. Geological Survey data release

Mueller M, Pander J, Geist J, 2018. Comprehensive analysis of >30 years of data on stream fish population trends and conservation status in Bavaria, Germany. Biol. Conserv 226, 311–320.

Mueller M, Bierschenk AM, Bierschenk BM, Pander J, Geist J, 2020. Effects of multiple stressors on the distribution of fish communities in 203 headwater streams of Rhine, Elbe and Danube. Sci. Total Environ 703, 134523. [PubMed: 31734505]

Muhlfeld CC, Glutting S, Hunt R, Daniels D, Marotz B, 2003. Winter diel habitat use and movement by subadult bull trout in the upper Flathead River, Montana. North Am. J. Fish. Manag 23 (1), 163–171.

National Research Council, 2002. Riparian Areas: Functions and Strategies for Management The National Academies Press, Washington, DC.

Nicola GG, Elvira B, Jonsson B, Ayllón D, Almodóvar A, 2018. Local and global climatic drivers of Atlantic salmon decline in southern Europe. Fish. Res 198, 78–85.

Olden JD, Naiman RJ 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshw. Biol 55:86–107.

Ouellet V, Gibson EE, Daniels MD, Watson NA, 2017. Riparian and geomorphic controls on thermal habitat dynamics of pools in a temperate headwater stream. Ecoscience 10 (8).

Palmer MA, Menninger HL, Bernhardt E, 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshw. Biol 55, 205–222.

Pander J, Geist J, 2013. Ecological indicators for stream restoration success. Ecol. Ind 30, 106–118.

Pander J, Mueller M, Geist J, 2018. Habitat diversity and connectivity govern the conservation value of restored aquatic floodplain habitats. Biol. Conserv 217, 1–10.

Poepl RE, Keesstra SD, Hein T, 2015. The geomorphic legacy of small dams—An Austrian study. Anthropocene 10, 43–55.

Pollock MM, Beechle TJ, Wheaton JM, Jordan CE, Bouwes N, Weber N, Volk C. 2014. Using beaver dams to restore incised stream ecosystems. Bioscience 64, 279–290.

Poole GC, Berman CH, 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manage 27 (6), 787–802. [PubMed: 11393314]

Reid DA, Hassan MA, Bird S, Pike R, Tschaplinski P. 2020. Does variable channel morphology lead to dynamic salmon habitat? Earth Surf. Proc. Land 45 (2), 295–311.

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ, 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. Camb. Philos. Soc 94 (3), 849–873. [PubMed: 30467930]

Rinaldi M, Belletti B, Bussetti M, Comiti F, Golfieri B, Lastoria B, Marchese E, Nardi L, Surian N, 2017. New tools for the hydromorphological assessment and monitoring of European streams. J. Environ. Manage 202, 363–378. [PubMed: 27889363]

Ecol Indic. Author manuscript; available in PMC 2022 November 01.
Schindler DE, Smits AP, 2016. Subsidies of aquatic resources in terrestrial ecosystems. Ecosystems 20 (1), 78–93.

Schumm S, Harvey MD, Watson CC, 1984. Incised Channels: Morphology, Dynamics, and Control of Water Resources. Publications, Littleton CO.

Sedell JR, Luchessa KJ 1982. Using the historical record as an aid to salmonid habitat enhancement. Pages 210–223 in American Fisheries Society, Western Division. American Fisheries Society, Portland, OR.

Seeliger C, Blocksom K 2018. aquamet: Calculate NRSA and NLA metrics. R package version 2.5.1

Shepard BB, May BE, Urie W, 2005. Status and conservation of Westslope Cutthroat Trout within the western United States. North Am. J. Fish. Manag 25 (4), 1426–1440.

Sims C, 1998. The Flumes and Fluming in Northern Idaho Forest Service. Coeur D’Alene, ID, U.S.

Sims C 2002. The Dalkena logging railroad, Bonner County, Idaho. Page 35. U.S. Forest Service, Coeur D’Alene, ID.

Steel EA, Muldoon A, Flitcroft RL, Firman JC, Anlauf-Dunn KJ, Burnett KM, Danehy RJ, 2017. Current landscapes and legacies of land-use past: understanding the distribution of juvenile coho salmon (Oncorhynchus kisutch) and their habitats along the Oregon Coast, USA. Can. J. Fish. Aquat. Sci 74 (4), 546–561.

Steiger J, Tabacchi E, Dufour S, Corenblit D, Peiry J-L, 2005. Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: a review for the temperate zone. River Res. Appl 21 (7), 719–737.

Surian N, Rinaldi M, 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50 (4), 307–326.

Szoszkiewicz K, Buffagni A, Davy-Bowker J, Lesny J, Chojnicki BH, Zbierska J, Staniszewski R, Zgola T, 2006. Occurrence and variability of River Habitat Survey features across Europe and the consequences for data collection and evaluation. Hydrobiologia 566 (1), 267–280.

Tornlund E, Oslund L, 2002. Floating timber in Northern Sweden: The construction of floatways and transformation of rivers. Environ. History 8 (1), 85–106.

U.S. Environmental Protection Agency. 2013. National Rivers and Streams Assessment 2013–2014: Field Operations Manual – Non-Wadeable. EPA-841-B-12–009a U.S. Environmental Protection Agency, Office of Water Washington, DC U.S. Environmental Protection Agency, Office of Water Washington, DC.

Vanderhoof MK, Christensen JR, Alexander LC, 2019. Influence of multi-decadal land use, irrigation practices and climate on riparian corridors across the Upper Missouri River headwaters basin, Montana. Hydrol. Earth Syst. Sci 23 (10), 4269–4292. [PubMed: 33354099]

Venard JA, Scarnecchia DL, 2005. Seasonally dependent movement of Lake trout between two northern Idaho lakes. North Am. J. Fish. Manag 25 (2), 635–639.

Wenger SJ, Luce CH, Hamlet AF, Isaak DJ, Neville HM, 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resour. Res 46, W09513.

White SM, Justice C, Kelsey DA, McCullough DA, Smith T 2017. Legacies of stream channel modification revealed using General Land Office surveys, with implications for water temperature and aquatic life. Elementa Sci. Anthropocene 5:1–18.

Wohl E 2004. Conquering a New World. Pages 40–93 Disconnected rivers: Linking rivers to landscapes. Yale University Press.

Wohl Ellen, 2014. A legacy of absence: Wood removal in US rivers. Prog. Phys. Geogr. Earth Environ 38 (5), 637–663.

Wohl Ellen, 2015. Legacy effects on sediments in river corridors. Earth Sci. Rev 147, 30–53.

Wohl E 2020. Rivers in the anthropocene: The U.S. perspective. Geomorphology 366: 106600.

Woodward G, Perkins DM, Brown LE, 2010. Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos. Trans. Royal Soc. Biol. Sci 365 (1549), 2093–2106.

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Fig. 1.
(a) Medium-sized rivers (30–60 m wide) with slopes <1% included in the study for comparison with the Priest River sites in northern Idaho, USA (b). All sites were sampled using the U.S. Environmental Protection Agency’s Environmental Monitoring and Assessment Program (EMAP) protocol for non-wadeable streams. Circles represent all sites of medium-sized rivers (a) and transect locations for Priest River (b).
Fig. 2.
Comparison of channel morphology and stream size attributes (a-j) for mean August temperature groups and the Priest River (Priest) in USEPA Level-I ecoregions (Marine Coast Forests, and Northwestern Forested Mountains). Temperature groups are defined by quartiles (Q1, Q2, Q3, and Q4). Violin plots show the probability density smoothed by a kernel density estimator of each metric by group of the data and include the median (white circle) and the interquartile range (cyan box). Means with different letters indicate a significant difference (Kruskal Wallis test, $p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 3.
Comparison of stream stability and substrate size attributes (a-e) for mean August temperature groups and the Priest River (Priest) in USEPA Level-I ecoregions (Marine Coast Forests, and Northwestern Forested Mountains). Temperature groups are defined by quartiles (Q1, Q2, Q3, and Q4). Violin plots show the probability density smoothed by a kernel density estimator of each metric by group of the data and include the median (white circle) and the interquartile range (cyan box). Means with different letters indicate a significant difference (Kruskal Wallis test, p < 0.05). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Fig. 4.
Comparison of instream and riparian cover attributes (a-j) for mean August temperature groups and the Priest River (Priest) in USEPA Level-I ecoregions (Marine Coast Forests, and Northwestern Forested Mountains). Temperature groups are defined by quartiles (Q1, Q2, Q3, and Q4). Violin plots show the probability density smoothed by a kernel density estimator of each metric by group of the data and include the median (white circle) and the interquartile range (cyan box). Means with different letters indicate a significant difference (Kruskal Wallis test, p < 0.05). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 5.
Comparison of indices of percentage of side channels (a), and riparian human disturbance (b - d) attributes for mean August temperature groups and the Priest River (Priest) in USEPA Level-I ecoregions (Marine Coast Forests, and Northwestern Forested Mountains). Temperature groups are defined by quartiles (Q1, Q2, Q3, and Q4). Violin plots show the probability density smoothed by a kernel density estimator of each metric by group of the data and include the median (white circle) and the interquartile range (cyan box). Means with different letters indicate a significant difference (Kruskal Wallis test, $p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 6.
Mean August water temperature for medium-sized rivers in the USEPA Marine Coast Forests and Northwestern Forested Mountains Level I ecoregions. Violin plots show the probability density of each metric by group and include the median (white circle) and the interquartile range (black box).
Fig. 7.
Mean summer flow for medium-sized rivers in the USEPA ecoregions Level I Marine Coast Forests and Northwestern Forested Mountains. Violin plots show the probability density of each metric by group and include the median (white circle) and the interquartile range (black box). Means with different letters indicate a significant difference (Kruskal Wallis test, \( p < 0.05 \)).
Fig. 8.
Principal component analysis (PCA) biplots of habitat attributes for (a) channel morphology and stream size (Morph), (b) stream stability and substrate size (Bed), (c) instream and riparian cover (Cover), (d) habitat complexity and riparian human disturbance (Comp-Dist) from the NRSA and EMAP surveys conducted from 2008 to 2014 mean August temperature groups and the Priest River (Priest) in USEPA Level-I ecoregions (Marine Coast Forests, and Northwestern Forested Mountains). Temperature groups are defined by quartiles (Q1, Q2, Q3, and Q4). Ellipses represent the 95% confidence intervals on the group means. The biplots explain 50, 72, 61, and 81% of the variance across all sites ($n = 85$) for each of the habitat categories, respectively. Correlations and loadings are reported in Table 3.
Table 1

Distributions of selected reach-scale habitat attributes to describe multiple aspects of riverine physical habitat in the Priest River (Idaho, USA). Sites were sampled on August 4–18, 2011. These attributes were organized into categories: hydrologic variables, channel morphology and size, stream stability and substrate size, instream and riparian cover and large woody debris (LWD), and index of riparian human disturbance. The same habitat attributes were measured or estimated at 75 sites based on the NorWeST mean August water temperature quartiles (Q1, Q2, Q3, and Q4). Citations: (1) Isaak et al., 2017; (2) Wenger et al., 2010; (3) Kaufmann et al., 1999; (4) Kaufmann et al., 2008; (5) U.S. Environmental Protection Agency, 2013.

| Habitat metric | Definition                                                                 | Citation | Units          | Median | Median SD | Min | Max |
|----------------|---------------------------------------------------------------------------|----------|----------------|--------|-----------|-----|-----|
| **Hydrologic variables** |                                                                                        |          |                |        |           |     |     |
| S1_93_11       | Mean August water temperature (NorWeST 1993–2011)                          | 1        | °C             | 19.4   | 19.2      | 0.47| 18.6| 19.9|
| MS_FcmsDA      | Mean summer flow (VIC output 1915 to 2006) scaled to drainage area        | 2        | m³ s⁻¹ km⁻²    | 0.014  | 0.014     | 0.001| 0.012| 0.015|
| **Channel morphology and size** |                                                                                     |          |                |        |           |     |     |
| xdepth         | Mean thalweg depth                                                         | 3        | cm             | 120    | 120       | 13  | 100 | 140 |
| sdepth         | Standard deviation of thalweg depth                                         | 3        | m              | 0.67   | 0.96      | 0.60| 0.34| 1.92|
| xwidth         | Mean wetted width                                                          | 3        | m              | 48.1   | 47.8      | 5.0 | 36.8| 54.2|
| xwxd           | Mean wetted width × depth                                                  | 3        | m²             | 56.4   | 55.6      | 12.5| 40.0| 80.9|
| rpl100         | Mean residual depth                                                        | 3        | [cm; equivalent to residual pool vertical profile area (m² 100 m⁻¹ of reach)] | 44.4  | 44.0      | 23.7| 0.0 | 79.2|
| xbf_w          | Mean bankfull width                                                        | 3        | m              | 62.4   | 62.0      | 3.8 | 55.9| 68.5|
| xbf_dc         | Mean bankfull depth                                                        | 3        | m              | 1.2    | 1.2       | 0.2 | 0.8 | 1.6 |
| xbfwd_ratc     | Bankfull width to depth ratio                                              | 3        | m m⁻¹          | 50.5   | 53.8      | 13.8| 37.1| 84.8|
| xslope         | Water surface gradient for the reach                                       | 3        | %              | 0.13   | 0.16      | 0.12| 0.03| 0.35|
| xinc_h         | Mean incision height                                                       | 3        | m              | 3.2    | 3.2       | 0.4 | 2.6 | 4.1 |
| **Streambed particle size and stability** |                                                                                     |          |                |        |           |     |     |
| cp3_mill       | Bankfull hydraulic resistance from bed particles                           | 4        | dimensionless  | 0.01   | 0.006     | 0.005| 0.0 | 0.01|
| ce_trpwd       | Bankfull total hydraulic resistance including that from large-scale features (wood, pools, etc) | 4        | dimensionless  | 0.02   | 0.02      | 0.02| 0.0 | 0.06|
| cp3_trpwd      | Ratio of cp3_mill and ce_trpwd                                             | 4        | dimensionless  | 0.28   | 0.33      | 0.25| 0.0 | 0.74|
| ldcbf_g08      | Log10(Erodible (Critical) substrate diameter at thalweg during flow bankfull) | 4        | mm             | 1.43   | 1.23      | 0.53| 0.0 | 1.72|
| lrbs_g08       | Log10(Relative bed stability) at thalweg                                   | 4        | dimensionless ratio: Log (Dgm Dcbf⁻¹) | 0.41   | 0.41      | 0.45| −0.35| 1.27|
| LittSB1_SF     | Percentage of littoral (shallow river margins) observations sites that have sand or fines as the dominant substrate. | 5        | %              | 9.1    | 9.4       | 9.2 | 0.0 | 30  |
| pct_safn       | Thalweg substrate percentage sand + fines (<2 mm)                          | 3        | %              | 2.9    | 4.8       | 5.5 | 0.9 | 18.3|
| Habitat metric | Definition                                                                 | Citation | Units        | Median | Median | SD  | Min | Max |
|----------------|----------------------------------------------------------------------------|----------|--------------|--------|--------|-----|-----|-----|
| l\textsubscript{dmm} | Log_{10}[estimated geometric mean thalweg substrate diameter] | 3        | mm           | 1.99   | 1.86   | 0.32| 1.37| 2.19|
| Cover (instream, LWD and riparian) | | | | | | | | |
| xfc\_rck | Boulder and rock ledge areal cover | 3 | Areal cover proportion | 0.00 | 0.04 | 0.08 | 0.00 | 0.26 |
| xfc\_brs | Brush and small woody debris areal cover | 3 | Areal cover proportion | 0.03 | 0.05 | 0.07 | 0.00 | 0.18 |
| xfc\_hwd | Large woody debris areal cover | 3 | Areal cover proportion | 0.01 | 0.05 | 0.11 | 0.00 | 0.37 |
| xfc\_nat | Sum of cover from large wood, brush, overhanging vegetation, boulders and undercut banks | 3 | Areal cover proportion | 0.07 | 0.21 | 0.39 | 0.00 | 1.28 |
| xfc\_big | Sum of cover from large wood, boulders, over-hanging banks and humanstructures | 3 | Areal cover proportion | 0.03 | 0.11 | 0.19 | 0.00 | 0.63 |
| xfc\_all | Sum of areal cover from all fish concealment types except algae and aquatic macrophytes | 3 | Areal cover proportion | 0.13 | 0.25 | 0.38 | 0.00 | 1.28 |
| xc | Riparian canopy cover | 3 | Areal cover proportion | 0.29 | 0.31 | 0.18 | 0.11 | 0.73 |
| xcmgw | Riparian woody cover, sum of 3 layers | 3 | Areal cover proportion | 0.43 | 0.62 | 0.49 | 0.24 | 1.78 |
| c1tm100 | Large woody debris in and above active channel | 3 | Pieces 100\textsuperscript{-1} m | 4.77 | 5.05 | 3.01 | 1.82 | 10.00 |
| v1tm100 | Large wood debris volume in and above active channel | 3 | m\textsuperscript{3} 100\textsuperscript{-1} m | 10.87 | 10.25 | 6.35 | 1.90 | 21.35 |
| Habitat complexity and riparian human disturbance | | | | | | | | |
| w1\_hag | Riparian human disturbance index - Agricultural types | 3 | Proximity-weighted sum | 0.00 | 0.15 | 0.27 | 0.00 | 0.86 |
| w1\_hnoag | Riparian human disturbance index - Non-agricultural types | 3 | Proximity-weighted sum | 0.41 | 0.67 | 0.57 | 0.12 | 1.58 |
| w1\_hall | Riparian human disturbance index - All types | 3 | Proximity-weighted sum | 0.41 | 0.82 | 0.78 | 0.12 | 1.98 |
| pct\_side | Percentage side channel | 5 | Channel length (%) | 0.42 | 2.25 | 3.27 | 0.00 | 7.50 |
Table 2
Number of residual pools of various depths per reach for sites across the study area (mean and range). Columns represent groups based on the NorWeST (Isaak et al., 2017) modeled mean August water temperature quartiles (Q1, Q2, Q3, and Q4) and Priest (Priest River).

| Number of residual pools per reach | Q1     | Q2     | Q3     | Q4     | Priest |
|-----------------------------------|--------|--------|--------|--------|--------|
| Residual depth > 50 cm            | 5 (0–8) | 4 (0–8) | 5 (0–8) | 3 (0–6) | 9 (0–12) |
| Residual depth > 75 cm            | 3 (0–6) | 3 (0–7) | 3 (0–7) | 2 (0–5) | 6 (0–9)  |
| Residual depth > 100 cm           | 2 (0–6) | 2 (0–6) | 3 (0–7) | 2 (0–5) | 4 (0–9)  |
Table 3

Principal component analysis (PCA) correlations and loadings for all rivers and all habitat attributes with variables arranged in order of strength of association (Pearson correlation and loading) with axis 1 and variance (%) and cumulative variance (%) for axis 1 and axis 2. Four different ordinations are listed with their associated variables and loadings: *Morph, Bed, Cover,* and *Comp-Dist.* Pearson correlation coefficients in bold are >0.70 and are considered strong correlations.

| Variable                  | PCA-Morph: Channel morphology & size | PCA-Bed: Stream stability & substrate size | PCA-Cover: Instream & riparian cover | PCA-Cover: Instream & riparian cover |
|---------------------------|--------------------------------------|-------------------------------------------|--------------------------------------|--------------------------------------|
|                           | Axis 1 | Axis 2 |                           | Axis 1 | Axis 2 |                           | Axis 1 | Axis 2 |                           | Axis 1 | Axis 2 |                           | Axis 1 | Axis 2 |                           |
|                           | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) | \(r\) | \(\text{loading}\) |
| xdepth                    | 0.87   | 0.76   | 0.34   | 0.11   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| sddepth                   | -0.75  | 0.56   | 0.12   | 0.01   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xwidth                    | -0.46  | 0.21   | -0.67  | 0.45   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xwd                       | -0.93  | 0.87   | 0.08   | 0.01   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| rp100                     | -0.65  | 0.42   | 0.36   | 0.13   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xbfk_w                    | -0.33  | 0.11   | -0.82  | 0.67   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xbfk_dc                   | -0.25  | 0.06   | -0.52  | 0.27   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xbfwd_ratc                | 0.03   | 0.00   | 0.01   | 0.00   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xslope                    | 0.52   | 0.27   | -0.03  | 0.00   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| xinc_h                    | 0.05   | 0.00   | -0.09  | 0.01   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| Variance explained (%)    | 33     | 17     |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| Cumulative variance explained (%) | 33     | 50     |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| lsub_dmm                  | -0.95  | -0.46  | 0.18   | 0.15   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| pct_safn                  | 0.87   | 0.42   | -0.20  | -0.17  |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| LitSB1_SF                 | 0.80   | 0.39   | -0.23  | -0.19  |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| lcbf_g08                  | -0.79  | -0.38  | -0.21  | -0.18  |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| cp3_mill                  | -0.78  | -0.37  | -0.10  | -0.09  |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| cp3trpwd                  | -0.62  | -0.30  | -0.58  | -0.49  |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| lrbs_g08                  | -0.58  | -0.28  | 0.52   | 0.44   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| ct_rpwd                   | 0.28   | 0.14   | 0.80   | 0.67   |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| Variance explained (%)    | 54     | 18     |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |
| Cumulative variance explained (%) | 54     | 72     |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |                          |

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| Variable       | Axis 1 |                  | Axis 2 |                  |
|---------------|--------|------------------|--------|------------------|
|               |        |                  |        |                  |
| v1tm100       | 0.42   | 0.21             | −0.59  | −0.41            |
| Variance explained (%) | 41      |                  | 20     |                  |
| Cumulative variance explained (%) | 41      |                  | 61     |                  |
| PCA-Comp-Dist: Habitat complexity and riparian human disturbance |        |                  |        |                  |
| w1_hall       | **0.98** | 0.65             | 0.11   | 0.12             |
| w1_hnoag      | **0.88** | 0.58             | −0.15  | −0.15            |
| w1_hag        | 0.60   | 0.40             | 0.57   | 0.59             |
| pct_side      | −0.42  | −0.28            | **0.77** | 0.78            |
| Variance explained (%) | 57      |                  | 24     |                  |
| Cumulative variance explained (%) | 57      |                  | **81** |                  |