Investigating patterns in stream temperature and restorable alluvial water storage for climate resilience of freshwater habitat for salmon and trout

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Abstract

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As climate change shifts the availability of habitat for aquatic species, watershed management must focus on the conservation and restoration of cold-water habitats for species such as salmon and trout that require cold water. Management actions that focus on restoring hydrologic processes can be used to adapt to climate impacts by re-establishing groundwater exchange and cold-water habitats. The formation of cold-water habitat can be promoted by reconnecting rivers to their adjacent floodplains and restoring alluvial water storage. In this study, I applied a systematic method for identifying spatial patterns in stream temperature and prioritizing restoration locations for climate adaptation. I made use of available data derived from airborne thermal infrared imagery to identify spatial patterns of stream temperature in the Teanaway River watershed in Washington, USA and compared these patterns to modeled predictions of restorable alluvial water storage. By investigating patterns in continuous stream temperature at a 1-

km scale in the watershed, I provide information that can be used to locate where restoration may address both water storage and water temperature and improve climate resilience of freshwater habitat for cold water-dependent species, such as salmon and trout. This work contributes to scientific understanding of how spatial analyses can be used to evaluate climate resilience of freshwater habitat and prioritize locations for ecosystem restoration.

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Introduction

The Intergovernmental Panel on Climate Change (IPCC) has stated that climate change will significantly impact conservation efforts, identifying climate adaptation as a priority for natural resource management agencies (Calvin et al., 2023). Climate adaptation, or the capacity of management agencies to buffer the impacts of climate change, first requires an understanding of the vulnerabilities produced by climate impacts, as well how management actions are likely to improve ecosystem and species resilience to climate impacts (Weiskopf et al., 2020). Globally, climate impacts are a major driver in the availability of suitable habitats, forcing shifts in species distribution and persistence (Parmesan & Yohe, 2003), as well as increased risk of extinction as warming temperatures drive loss of suitable habitat (Yang et al., 2023). For example, climate change is predicted to significantly reduce the availability of suitable habitat for Asiatic toads in China, leading to shifts in their distribution and possibly population declines (Yang et al., 2023). In contrast, some populations of species will expand their range and abundance, such as white tail deer in the midwestern region of North America (Weiskopf et al., 2019). However, in many geographies, climate change is predicted to negatively impact populations as availability of food sources and suitable habitat decline (Handler et al., 2014). For example, the by the end of this century habitat loss due to climate impacts could lead to a 22% reduction in available suitable habitat for salmon in Washington state (USGCRP, 2018).

Across the Pacific Northwest (USA), climate change is driving an increase in stream temperatures, impacting temperature-sensitive aquatic species like anadromous salmonids *(Oncorhynchus spp., Salvelinus spp.)* (Isaak et al., 2018). The increase of average summer stream temperatures in western North America is attributed to climate derived shifts in the timing and magnitude of streamflow, in conjunction with rising summer air temperatures (Abatzoglou & Redom, 2007; Cassie, 2006). The mountainous watersheds in the North American west are currently seeing (Isaak et al., 2010) a shift towards a greater proportion of winter precipitation falling as rain rather than as snow(Abatzoglou & Redmond, 2007). The cumulative effects of reduced winter snowpack and warming air temperatures results in earlier timing of snow melt and peak flows, and increasing peak summer stream temperatures (Barnett et al., 2005; Raymond et al., 2014). These climate impacts on stream temperatures are further exacerbated by other anthropogenic disturbances to stream flows such as changes in land cover, lack of riparian shade, disconnection from floodplains and hyporheic flow, streambed simplification and the removal of surface and groundwater for agriculture (Andrews et al., 2022; Caissie, 2006; Gibeau & Palen, 2020; Isaak et al., 2010).

In mountainous watersheds, water temperatures are typically coldest at the high elevation headwaters, and increase as water flows downstream from higher to lower elevations, or along the longitudinal profile (Gresswell et al., 1989; Poole et al., 2022; Vatland et al., 2015). Various topographic, atmospheric, hydrologic and geomorphic factors (e.g., air temperature, hyporheic exchange, flow heat exchange with the streambed; (Caissie, 2006) drive variability in patterns in change in temperature as water flows downstream (Dugdale et al., 2017). These various drivers cause naturally occurring spatial heterogeneity of stream temperature along the longitudinal profile (Fullerton et al., 2015), and create cold-water refuges, discrete patches of cold water adjacent to warmer temperatures (Torgersen et al., 2012). Cold-water refuges can occur where the channel is shaded by vegetation, where tributaries enter the river mainstem, and where the upwelling of cooler subsurface water enters the channel through groundwater or hyporheic exchange

(Dugdale et al., 2015; Fullerton et al., 2015; Torgersen et al., 2012). Hyporheic exchange occurs where subsurface water and surface river water mix along the channel bed and underlying sediments, called the hyporheic zone (Dugdale et al., 2017). Hyporheic exchange is one process by which patches of cold water can occur, where this cooled water re-emerges and mixes with the surface water (Ebersole et al., 2015; Poole et al., 2022). Water stored in the alluvial aquifer, or alluvial water storage, can contribute cooler water to streams, when it mixes with the river channel (Arrigoni et al., 2008). Alterations to channel complexity and sinuosity can disconnect the river channel from its adjacent alluvial water storage, thereby reducing the capacity for exchange between ground and surface water (Poole et al., 2022). In this way physical changes to river morphology can result in shifts in the size and persistence of cold-water habitat in mountainous systems (Shrestha & Pesklevits, 2023; Torgersen et al., 2012). Because stream temperatures are sensitive to shifts in groundwater exchange, information about a systems capacity for alluvial water storage and groundwater exchange may help to predict patterns of the persistence of cold-water refuges in the face of climate change (Wondzell et al., 2019).

Cold-water refuges improve the likelihood of survival of fish survival during peak summer stream temperatures by reducing thermal stress or the physiological impacts of warm temperatures over time (Greer et al., 2019). Salmonid species are particularly vulnerable to elevated stream temperatures during their freshwater residence (Montgomery et al., 1996) because they are physiologically unable to tolerate high temperatures for extended periods of time (Ebersole et al., 2001). Stream temperatures exceeding 20°C can diminish growth rates in juveniles salmonids (Sullivan et al., 2000), temperatures exceeding 25°C can be lethal for adult salmon(Dugdale et al., 2017) and temperatures exceeding 29.6°C can be lethal for steelhead trout (Greer et al., 2019). During peak summer water temperatures, salmonids rely on cold-water refuges to provide both spawning and holding habitat (FitzGerald & Martin, 2022; Isaak et al., 2010, 2015). For example juvenile steelhead trout in the California Central valley tend to select habitat where water temperatures were between 17°C and 20°C (Myrick & Cech, 2001). Ebersole et al., (2015) observed that once stream temperatures exceed 18°C in eastern Oregon trout and salmon exhibited increased use of thermal refuges. Shifts in thermal landscapes will reduce the success of salmonids at various life stages during the freshwater portion of their lifecycle (Steel et al., 2019), consequently, thermal refuges are likely to be increasingly important to salmon survival as stream temperatures rise over the next century (Kurylyk et al., 2015). However, the availability of such refuges is expected to decrease (Jones et al., 2014). Thus, preservation and restoration of cold water habitat such as thermal refuges is important to enhance the resilience of salmonids to climate change (Mejia et al., 2020).

Process-based river restoration encompasses strategies to improve the resilience of watersheds and salmonid populations to climate change by re-establishing cold water habitat forming watershed processes (Flitcroft et al., 2022). Addressing the root causes of habitat degradation is one approach to preservation and restoration of cold-water habitat (Beechie & Bolton, 1999). Natural resource managers are exploring restoration actions which re-establish important cold water habitat forming processes, such as hyporheic and groundwater exchange to improve the resilience of both watersheds and salmon to climate change (Beechie et al., 2013; Perry et al., 2015). Such restoration tactics which may promote hyporheic and groundwater exchange include: large woody debris placement, beaver dam-analog construction and restoration to stage zero condition, a process-based approach aimed at re-establishing floodplain connectivity and restoring alluvial water storage functions (Flitcroft et al., 2022; Wohl et al., 2017).

The impact of restoration actions on flow and stream temperature varies widely based on the local conditions of the system being restored. By infilling sediments to channels that have eroded down to the bedrock, restoration actions can increase alluvial water storage and the capacity for groundwater exchange (Boulton, 2007; Loheide et al., 2009). The amount of groundwater and hyporheic exchange that occurs throughout mountain river systems depends on channel morphology (Wondzell et al., 2019). A study of post treatment sites in eastern Washington found that where restoration actions had reconnected the river channel to the greater floodplain, and to the alluvial aquifer hyporheic flow improved (Singh et al., 2018). Improved hyporheic exchange reduces stream temperatures at specific locations where this process occurs (Fernald et al., 2006). In northwestern Oregon, anomalous patches of cold water frequently occur at specific geomorphic features, for example locations where the river channel was connected to the adjacent alluvial aquifer, or alluvial water storage (Burkholder et al., 2008). Furthermore, studies in the Puget Sound region indicate that reconnecting river channels to their floodplains can reestablish historical hydrological processes, positively impacting water quality and the quantity of flows, and chinook salmon productivity (Flitcroft et al., 2022).

Hydrologic models use high resolution digital elevation models (DEMs) derived from light detection and ranging (LIDAR) imagery to estimate values for slope, valley width and stream incision (Hopkins et al., 2023). Dickerson-Lange and Abbe 2019, applied similar methods to model values for the potential alluvial water storage that could be restored within the alluvial aquifer under certain restoration actions (Dickerson-Lange & Abbe, 2019; Hopkins et al., 2023). Alluvial aquifers form where slower velocity flows allow for sediments to deposit and aggrade the channel bottom along a river system's longitudinal profile(Abbe & Montgomery, 2003). Alluvial aquifers, referred to in this paper as alluvial water storage, can temporarily store water within this deposited alluvium, which is a mix of clay, sand, gravel and cobbles (Baxter & Hauer, 2000; Venarsky et al., 2018; Wohl & Scott, 2017). Subsurface flow paths, known as hyporheic flow pathways, form throughout the alluvial substrate (Boulton, 2007). In these regions, water that enters the alluvial water storage is temporarily stored as shallow groundwater and reemerges into the main river channel at some distance downstream (Baxter & Hauer, 2000). Surface waters are more readily stored and recharged in alluvial water storage, compared to bedrock aquifers, due to their comparatively shallow depth surface (Robson, 1989). The degree to which hyporheic and groundwater exchange occurs is influenced by variation in the geomorphology of the location, such as: depth of the alluvial water storage, and the connectivity between the alluvial water storage and the river channel (Ebersole et al., 2015). In mountainous streams, the scale of the alluvial water storage can range in size from tenths of a meter deep and several meters wide in smaller headwater streams, to a meter deep and thousands of meters wide lower in the valley, leading to spatial heterogeneity in the volume of alluvial water storage available throughout the longitudinal profile of a river (Poole et al., 2022). Stream degradation such as vertical erosion, and stream incision reduces alluvial storage capacity by severing the connection between the river channel and the alluvial soils adjacent storage (Kondolf et al., 2006).

While previous studies have evaluated the extent to which restoration of incised channels may improve alluvial water storage capacity (Greer et al., 2019), few have compared the capacity to restore watershed functions to stream temperature at the resolution useful for planning the implementation of restoration actions (Laurel & Wohl, 2017; Vatland et al., 2015). For managers working with limited restoration resources, it is critical to know where to focus their efforts to implement climate adaptive projects. To prioritize restoration action along the length of a river, it is key to analyze data at the scale and resolution of the restoration action (Dugdale et al., 2017; Lawrence et al., 2014). The use of spatially continuous data can improve understanding of the patterns in stream temperature throughout the longitudinal profile (Dugdale et al., 2015; Fullerton et al., 2015). Identification of these patterns can then help managers to prioritize restoration actions that may buffer for potential climate impacts (Dugdale et al., 2015; Fullerton et al., 2015).

My objective is to advance the understanding of how information on stream temperature and alluvial water storage can be used to inform the siting of process-based restoration actions for promoting climate resilience. Here, I illustrate a systematic approach for prioritizing locations of climate adaptive restoration for salmonids, using the Teanaway River watershed in Washington, USA, as a case study. A critical first step to protecting and restoring cold water habitat is identifying the location and extent of cooling and warming spatial patterns (Torgersen et al., 2012). Thus, in this paper I investigate the following questions:(1) Are spatial patterns in stream temperature associated with spatial patterns in alluvial water storage? (2) Can this information be used to help prioritize restoration of alluvial water storage? I explore the relationship between stream temperatures and restorable alluvial water storage. Using these data, I identify areas where restoration actions may improve alluvial water storage and address stream warming. In this way, I aim to help managers maximize the efficiency of selecting sites for process-based restoration and inform conservation decision-making.

Study Area

The study area encompasses the Teanaway River Basin (Figure 1), a headwater to the Yakima watershed in the Central Cascades of Washington State, USA. The Teanaway gets between 980 mm and 1230 mm of precipitation per year, falling primarily as snow in the winter (Schanz et al., 2019). The Teanaway River has main three tributaries, the West, Middle and North forks, that flow into the mainstem approximately 16 km upstream of the confluence of the Teanaway and the Yakima River (Figure 1). Previous periods of glaciation have eroded the underlying geologic formations producing the steep valley walls and plateaus seen in lower elevations of the subbasins (Schanz et al., 2019). Lower elevations of the watershed are more susceptible to erosion due to the higher prevalence of sand and gravel alluvium overlying more erodible bedrock formations Swauk, Roslyn and Teanaway formations (Schanz et al., 2019; Schanz & Colee, 2022; Washington Department of Fish and Wildlife, 2015).

The vegetation of the Teanaway basin is dominated by Ponderosa Pine (*Pinus ponderosa)* forest type(Schanz et al., 2019). The Teanaway basin has been impacted by post-colonial human activities over the last 150 years. The region was heavily logged between the 1890s and 1940s (Schanz & Colee, 2022). Additionally, between 1892 and 1916 the Teanaway River was splash-dammed--a logging practice that straightens and clears channels of woody debris to allow for transport of timber (Schanz & Colee, 2022). These logging practices, in addition to other anthropogenic disturbances, such as clearing for agriculture have led to a reduction of wood in the system (Washington Department of Fish and Wildlife, 2015).

Over the years of decreased wood load to the river, channels have been simplified, degraded, and disconnected from floodplains (Abbe, 2019; Dickerson-Lange & Abbe, 2019). As a consequence of these relatively recent human impacts, the Teanaway River basin exhibits vertical erosion, and incision. In many parts of the watershed, the stream bed is not only eroded down to bedrock, but in some cases has eroded several meters into bedrock (Schanz et al., 2019). Stream incision has separated the Teanaway river from its floodplain, and alluvial water storage, and increased the effect of solar radiation on summer water temperature as water travels over exposed bedrock (Washington Department of Fish and Wildlife, 2015). Rising stream temperatures, driven by climate change (Isaak et al., 2015, 2018) are exacerbated by the combination of widened stream channels, decreased riparian shading, exposed stream bedrock, and disconnection from water storage (Washington Department of Fish and Wildlife, 2015).

Methods

The goal of this thesis is to illustrate a systematic approach to evaluating where to target management actions for climate adaptation, using the Teanaway watershed as a case study. I reasoned that by comparing spatially continuous data sets for stream temperature and modeled values for restorable alluvial water storage potential, I could assess how the relationship between patterns in stream temperatures and alluvial water storage. By comparing these spatial patterns, I could provide a means to prioritize process-based-management activities that improve flow and decrease temperature. My general approach was to generate longitudinal profiles of each dataset and compare patterns in values to locate where managers may wish to prioritize climate-adaptive restoration. Below, I provide details of the data and analyses I conducted to implement this approach.

To characterize the patterns in stream temperature, I obtained the most recently collected spatially continuous stream temperature data in the watershed (Watershed Sciences, 2002). Values for the median stream temperatures of surface water in the North, Middle and West forks and Mainstem Teanaway were calculated, at approximately 100- to 200-m intervals, using thermal image data processing techniques (Watershed Sciences, 2002). Thermal imagery was collected via an airborne thermal infrared (TIR) flight in September of 2001. Stream temperatures of tributaries and side channel inflows were calculated based on what was detectable in the thermal imagery. In all three forks of the Teanaway, temperature estimated using thermal imagery was within 0.6^{o}C of stream temperature measured using instream data loggers at the time of the flight (Watershed Sciences, 2002). Further details regarding the methods of data collection and processing are provided by Watershed Sciences.

Although stream temperature data were collected in 2001 and LIDAR data were collected during flights in 2015 and 2018, I reasoned that relative patterns in stream temperature would be similar to those captured in the TIR flight in 2001. The location of the stream channel location did not shift dramatically between 2001, and 2015 and 2018 when the LIDAR data were collected. Data were collected flying upstream from the mouth to approximately the headwaters of each fork.

Using linear referencing in ArcPro 3.1.1(ESRI Inc., 2023), I generated longitudinal profiles for water temperatures for three sections of the Teanaway watershed (Welty et al., 2015). I delineated the Mainstem and the North Fork section of the Teanaway River starting from the mouth of the Teanaway to the headwaters of the North Fork (Figure 1). I then delineated the Middle Fork and Mainstem section of the Teanaway starting from the reference point at the confluence of Mainstem Teanaway and the North Fork Teanaway, moving in the upstream direction to the headwaters for the Middle Fork (Figure 1). I delineated the West Fork Teanaway section starting from the reference point at the confluence of West Fork and the Mainstem Teanaway in the upstream direction to the headwaters of the West Fork Teanaway (Figure 1).

I created longitudinal profiles for water temperature versus distance for each section of the river (Fullerton et al., 2015). To explore spatial patterns of stream temperature in each section on the Teanaway, I plotted the longitudinal profiles of water temperature at each river kilometer where values were recorded as well as temperature at the locations of inflow and tributaries to identify areas where they may be influencing temperatures in the thermal profile. I expected that stream temperatures would rise from headwaters to river mouths, and that sections of river will have anomalously low or high temperatures compared to the general trend in temperature values over distance. Areas with anomalously cooler temperatures may indicate thermal refuges, and conversely when temperatures are near biological thresholds with relatively higher temperatures may indicate thermal stress points. Understanding locations of relatively lower temperatures may indicate where to focus conservation, and areas with relatively high temperatures may reveal locations that may benefit from restoration activities to buffer against climate impacts.

I summarized values for the mean stream temperature per river kilometer to assess patterns in change in stream temperature using the R package linbin (R Core Team., 2023; Welty et al., 2015). I chose to analyze the stream temperature values at a 1 km resolution to match the smallest stream segment in modeled values of restorable alluvial water storage(Dickerson-Lange & Abbe, 2019). I calculated the change in mean stream temperature as the difference between the upstream and downstream values for mean stream temperature per river kilometer. I expected to find an overall positive change in mean stream temperatures in the downstream direction. Stream segments with negative values for change in stream temperature could indicate locations where processes, such as groundwater exchange, are contributing cooler water to the system, and potentially generating thermal refuges. Conversely areas which have anonymously high positive values for change in stream temperature may indicate stream segments that are prone to warming and, therefore, could be more vulnerable to climate impacts. Areas with high values for change in stream temperature may benefit from restoration activities which could improve hydrologic processes that provide cool water in the system.

To assess patterns in alluvial water storage, I generated longitudinal profiles for alluvial water storage versus distance upstream for each section of the river. I then aggregated the volume of alluvial water storage per river kilometer with the R package linbin (Welty et al., 2015). Estimates of the volume of potential restorable alluvial water storage were generated by Dickerson and Abbe (2019) throughout the entire Teanaway River basin. Dickerson and Abbe (2019) used LIDAR imagery collected in 2015 and 2018 to generate three variables relevant to stream morphology: slope, valley width and channel depth. These LIDAR derived measurements were then used to predict the volume of alluvial water storage that could be restored to the alluvial aquifer assuming the streambed of the channel were raised 0.9 m via restoration activities, thereby reversing channel incision, reconnecting the streambed to the alluvial floodplain aquifer, and raising water levels. Dickerson and Abbe (2019) chose 0.9 m based on the assumption that the restoration of incised channels would decrease the channel depth (and thus raise water elevation) by 0.9 m vertically, and a constant specific yield of 0.15, porosity of 0.3 and saturated hydraulic conductivity of 0.0001 m/sec (Dickerson-Lange & Abbe, 2019). Based on the lack of major landform shifts in the basin since 2018, I reasoned that predictions for restorable groundwater volume would be representative of current conditions. This model predicted continuous values for the potential to restore alluvial water storage at variable channel unit lengths. Due to discrepancies between the Geographic Names Information Systems (GNIS) (*U.S. Geological Survey, GNIS*, 2023) names in the modeled predictions and the National Hydrography Dataset (*U.S. Geological Survey, GNIS*, 2023), I corrected for inaccuracies in the location of values for the predicted volumes associated with mainstems that were incorrectly named as smaller order tributary streams by performing cross comparison of GNIS stream names with satellite imagery.

To assess the relationship between potential alluvial water storage and temperature change, I plotted the change in mean stream temperature overlaid with the summed values for volume of alluvial water storage at each river kilometer. I then performed a Spearman's rank order test to determine if there was a correlation between high ranked values of alluvial water storage and positive temperature change, using the R package Ggpubr (Kassambara, 2023).

Lastly, I mapped the overlay of ranked values for alluvial water storage and temperature change. I used bivariate color symbology to visualize locations at which the following overlaps occurred, throughout the three sections of the river: (1) where both variables had high ranked values, (2) where there were low values for both variables, (3) where temperature change was negative but alluvial water storage was high and (4) where temperature change was positive but alluvial water storage was low. This map allowed for visualization of where there was a high potential to restore alluvial water storage in the same location where temperature change was anomalously high.

Results

Mainstem and Middle Fork Section

The stream temperature in the Mainstem and North Fork section increased linearly from river km 45 to approximately river km 25, after which it was highly variable. Notable temperature decreases in a downstream direction occurred at river km 25 to 20 and 6 to 0 (Figure 2a). Tributary inputs did not appear to be different from mainstem temperatures (n=4), whereas tributary inputs with temperatures that were lower than the mainstem appeared to occur more commonly in the downstream section, downstream of river km 10 (n=2). (Figure 2a).

The change in temperature between adjacent 1-km stream segments increased at about 0.5°C/km, from river km 45 to approximately river km 24, except for a slight decrease in change in temperature at the location of a cooler tributary inflow at river km 37. Downstream of river km 24 temperature change exhibited higher variability between stream segments in the downstream direction. Between river km 24 and river km 0, temperature change reached a maximum of 1°C/km, and as low as decreasing more than a 1 °C/km (Figure 2b).

Alluvial water storage in the Mainstem and North Fork section increased in the downstream direction with notable peaks at 1-2, 4-5, 6-7, and 17-18 km (Figure 2b). Two of the highest peaks in alluvial water storage occurred at the same stream segment location as relative peaks in stream temperature (Figure 2).

Mainstem and Middle Fork Section

Water temperatures in the Mainstem and Middle Fork section increased linearly from the headwaters at river km 21 to river km 12 (Figure 3a). Water temperatures decreased substantially from river km 12 to river km 9 downstream of the inflow of a cooler tributary and then continued to increase in the downstream direction between river km 9 and river km 2 (Figure 3a) with relative peaks in temperature approximately at river km 12 and river km 2. Stream temperatures continued to fluctuate between river km 2 to 0. Water temperatures of tributaries (Figure 3a) were generally lower than the stream temperatures of the mainstem (n=3), with one exception where the North Fork flows into the mainstem at river km 0.3 of the Mainstem and Middle Fork section.

The change in temperature between adjacent 1-km sections in the Mainstem and Middle Fork increased at around 0.5°C/km between river km 21 and river 12 km. A notable negative change in stream temperature occurred at river km 12 where water temperatures changed nearly 2°C/km. Another substantial negative change occurred at river km 4 (Figure 3b). Stream temperatures also decreased between river km 2 and river km 1.

Alluvial water storage in the Mainstem and Middle Fork section generally increased in the downstream direction with a substantial increase in values beginning at river km 11 and continuing in the downstream direction (Figure 3b). The most notable peak in alluvial water storage occurred at river km 11 just downstream of the greatest negative change in stream temperature (Figure 3b).

West Fork Section

Water temperatures in the West Fork section increased linearly in the downstream direction between river km 17 to approximately river km 7 with considerable fluctuation in stream temperatures between river km 7 and 0 (Figure 4a). Relative peaks in stream temperature occurred at river kilometers 10, 8, 7 and 2. No significant contributions of surface water entering the mainstem were recorded in the TIR flight.

The average temperature change per kilometer in the West Fork section generally increased in the downstream direction (Figure 4b). Slightly negative changes in stream temperatures occurred between river kilometers 16-15, 10-9, and 4-3. A notable negative change in stream temperature occurred at river km 1 to 0 where the West Fork section flows into the Middle Fork Teanaway.

Values for potential restorable alluvial storage in the West Fork section were the lowest in all three sections by several orders of magnitude (Figure 4b). Values for alluvial water storage increased from river km 12 to river km 0.

Correlation between temperature and alluvial water storage

There was a weak negative correlation between restorable alluvial water storage and change in stream temperature (ΔT/km) $\rho = -0.22$, $p = 0.05$ (Figure 5). My results suggest that areas with high potential for restoring alluvial water storage are not associated with positive changes in stream temperature. Conversely, there is a significant, albeit weak, pattern of decreasing stream temperatures with increasing restorable alluvial water storage potential.

Segments from all the three sections analyzed (the Mainstem and North Fork, Mainstem and Middle Fork and West Fork sections of the Teanaway River) demonstrated variability in restorable alluvial water storage and temperature change. Generally, higher ranked values for both variables were found at lower elevations; however, there were also moderate values for potential for restoration and temperature change in the upper elevations of the Mainstem and North Fork (Figure 6). Most stream segments with moderately ranked values for both temperature change and restorable alluvial water storage were found in the Mainstem and North Fork section, with a few segments in the Mainstem and Middle Fork section. No stream segments with both moderately ranked values for restoration potential and moderate rate of change of stream temperature were found in the West Fork section. Stream segments with high values for temperature change and high values for restoration potential were highlighted in red at river kilometers 17-18 in the Mainstem and North Fork section (Figure 6). Stream segments with moderate values for temperature change and moderate values for restoration potential were found at river kilometers 3-4, 7-8, 10-11, 12-13, 15-16, 19-20, 26-27, 28-29 on the Mainstem and North Fork section, and from river km, 2-3 and 5-7 in the Mainstem and Middle Fork section (Figure 6, Table S1).

Discussion

Global climate change is expected to change the availability of thermally suitable habitat, thus driving shifts in distribution and abundance of species which require specific thermal ranges to survive (Handler et al., 2014; Parmesan & Yohe, 2003; Rieman et al., 2003; Yang et al., 2023). Aquatic species that require cold water may be especially sensitive to climate impacts (Isaak et al., 2018). Global population declines in salmonids which are driven by many factors such as: fishing practices, habitat degradation and loss of habitat connectivity, are further impacted by climate impacts on thermally suitable habitat for salmonids (Mills et al., 2013). Shifts in stream temperatures are predicted to be one of the most important climate threats to persistence of aquatic species (Isaak et al., 2010). In the Pacific Northwest (USA), rising stream temperatures are predicted to be a key driver in reduced salmon survival in freshwater environments (Steel et al., 2019). For example, endangered spring chinook salmon populations in the Snohomish watershed in western Washington, are projected to decline by 20% by 2050 as rising stream temperatures decrease the availability of thermally suitable habitat (Battin et al., 2007). There is an increased need to anticipate how climate impacts will shift availability of thermally suitable habitat as managers consider how to prioritize watershed restoration to improve salmonid climate resilience (Mejia et al., 2020; Roni et al., 2002) Evaluating patterns in stream temperatures is a necessary first step in this process (Torgersen et al., 2012). By locating where existing habitat degradation may result in heightened vulnerability to climate impacts, managers can consider how future hydrological conditions may impact the availability of habitat for threatened and endangered salmon populations (Seavy et al., 2009).

This case study introduces an approach for (1) identifying locations within a watershed that are prone to reaching thermal thresholds versus those that may potentially provide cold water refuges, and (2) assessing where restoration of watershed processes may be the most effective climate adaptation to improve the climate resilience of freshwater ecosystems. I found that overlaying areas with the highest positive change in stream temperature onto areas with high restorable alluvial water storage potential may be an effective way to identify and prioritize areas for future conservation actions. Generally, I found that the stream segments which exhibited peaks in stream temperature and high values for change in temperature per kilometer existed at lower elevations in the watershed. Temperatures in all three sections of the Teanaway showed a general increase in temperature from their headwaters to intermediate reaches, where relative change in stream temperature became considerably more variable. My method of evaluating spatial patterns in restorable alluvial water storage is spatially coarse, in that it does not account for the spatial heterogeneity in alluvial water storage at a spatial resolution less than 1 km. It is possible that hyporheic flow paths are still intact in stream segments that are less than 1 km in length, but where wider stream channels have stratified alluvial deposits, driving upwelling of cooler water where the channel widths narrow downstream (Poole et al., 2022).

Generally, water temperature increases as water flows downstream, and heterogeneity in stream temperatures is often observed downstream of inflows of cooler tributaries, or near geomorphic futures where groundwater or hyporheic exchange are likely to occur (Burkholder et al., 2008). This study does not address the impacts of riparian shading on stream temperatures, which are theorized to impact streams at intermediate reaches (Vannote et al., 1980).

My findings suggest that areas with high alluvial water storage may occur at the same locations as anomalous peaks in stream temperature within a given stream segment.

Additionally, my data suggests a lagged decrease in stream temperature values downstream of some stream segments where Dickerson- Lange et al. 2019, identified high potential for restoration of alluvial water storage. This suggests that in some instances, stream segments with high alluvial water storage potential may still facilitate sufficient hyporheic or groundwater exchange, despite being areas where loss of alluvial water storage has been identified.

There was a week negative association between alluvial water storage restoration potential and change in stream temperatures. While one might expect a positive relationship between alluvial water storage potential and downstream change in stream temperatures, the literature indicates that temperature response to restoration treatment may be highly variable (Flitcroft et al., 2022). This in turn indicates that stream temperature is dictated by a complex set of interactions. However, the inability to detect a positive correlation between change in stream temperature and modeled alluvial water storage can also be explained in part by the methods used to calculate change in stream temperature. By calculating the difference between average temperatures per river kilometer, I was unable to capture the relative change in average temperature over space. This may have been more evident if temperature change had been calculated using a moving average. Additionally, I calculated the sum of restorable alluvial water storage potential per river kilometer, which, like temperature, increases in the wide, lower reaches of river valleys. A proportional restorable alluvial water storage metric that quantifies the amount of water storage that could be recovered compared to the total amount of alluvial water storage possible per section of river, could provide a more appropriate metric for identifying anomalously degraded areas along the length of the river. It is possible that areas with the highest potential to restore alluvial water storage may occur at the same locations where peaks in change in stream temperature occur, indicating that restoration action may result in a response of decreased stream temperature. In a previous study, Tague et al (2008) found that restoration of alluvial water storage caused an increased inflow from groundwater inputs after spring melt off (Tague et al., 2008).

Although TIR data provide spatially continuous temperature data, they are temporally limited in that they only show a single snapshot in time and cannot represent diel fluctuation in water temperature (Cristea & Burges, 2010). It should also be noted that stream water temperature varies annually based on seasonal fluctuations in flow and ambient temperature conditions. For the purposes of this analysis, I assumed that inter- and intra-annual spatial patterns in stream temperature would be like those observed in 2001. Anomalous patterns in temperature may be the result of cooler groundwater stored in alluvial storage entering the system, riparian shading, topographic shading, air temperature, solar radiation, and flow (Arrigoni et al., 2008; Caissie, 2006; Vannote et al., 1980). Further investigation is needed to evaluate the variables that are principally responsible for shifts in temperature. Such information is needed to more accurately predict the relative impact that restoration of alluvial water storage may have on buffering stream temperatures from climate change impacts.

Previous work in climate adaptive management has demonstrated that assessment of climate change impacts alone provides incomplete information for site prioritization (Ettinger et al., 2021). My project demonstrates that comparing spatial patterns in the capacity to restore ecosystem processes to patterns in vulnerability to climate impacts has the potential to improve climate adaptive decision making. Specifically, in freshwater ecosystems, understanding existing spatial patterns in stream temperature may help to (1) highlight areas that may be more susceptible to climate impacts and (2) anticipate areas where thermally suitable habitat may be lost. By comparing these spatial patterns to patterns in the capacity to restore processes which may contribute cooler water to the system, managers may be able to improve site prioritization for restoring resilience to climate change and better inform decision making and conservation (Fontaine et al., 2009).

This approach for selecting sites for climate adaptive restoration by overlaying areas that may be more vulnerable to climate impacts with areas with the highest potential to improve ecosystem function could be applied in other climate adaptation restoration contexts (Harris et al., 2006). Previous studies have shown that process based restoration can improve habitat conditions (Kondolf et al., 2006). Many models applied to site selection in restoration focus on predicting locations with the highest potential for habitat restoration (Burnett et al., 2007). For example, a beaver intrinsic potential (BIP) model was developed to locate stream segments with the highest likelihood for successful beaver relocation (Dittbrenner et al., 2018). My study builds on these other approaches by illustrating how decision making in climate adaptation can be improved by comparing patterns in both modeled predictions and empirical data on climate risk (i.e., heterogeneity in stream temperature). Globally, climate impacts are projected to reduce critical habitat and impact species persistence. In a changing climate, conservation management of freshwater ecosystems and aquatic species must consider climate change impacts to improve the resilience of ecosystems and capacity of species to adapt to climate change impacts.

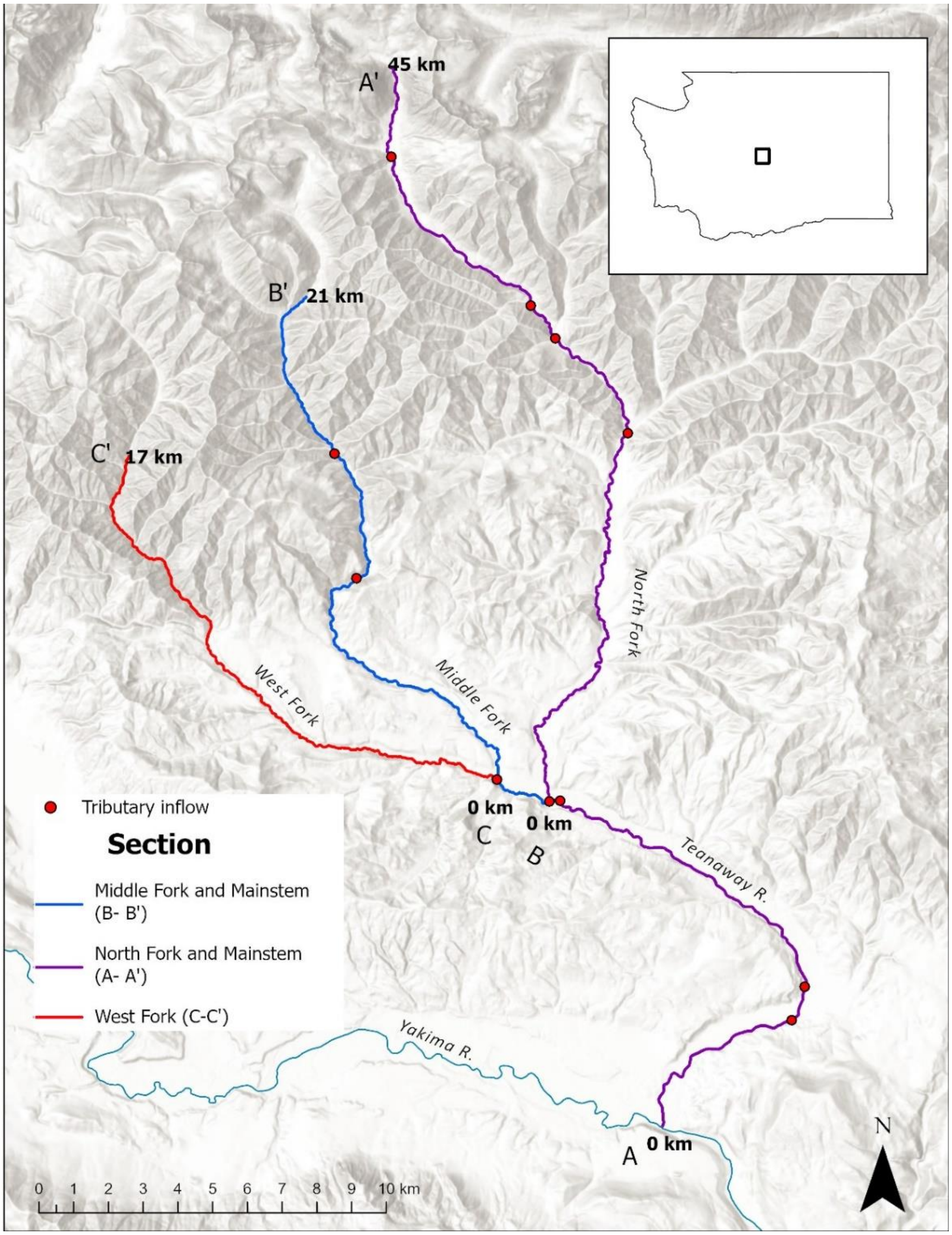

Figure 1: Map of study area encompassing the (A-A') Mainstem and North Fork section", (B-B') Mainstem and Middle Fork section, and C) West Fork section of the Teanaway River Basin. Distance upstream in kilometers are labeled for the Mainstem and North Fork section starting at the confluence of Mainstem Teanaway and the Yakima River (A, 0 km) in the upstream direction to the headwaters at 45 river km (A'); for the Middle Fork starting at the confluence of the Mainstem Teanaway and the North Fork (B) in the upstream direction to the headwaters at 21 km (B'); and for the West Fork starting at the confluence of the West and Middle Forks in the upstream direction to the headwaters of the West Fork at 17 km (C').

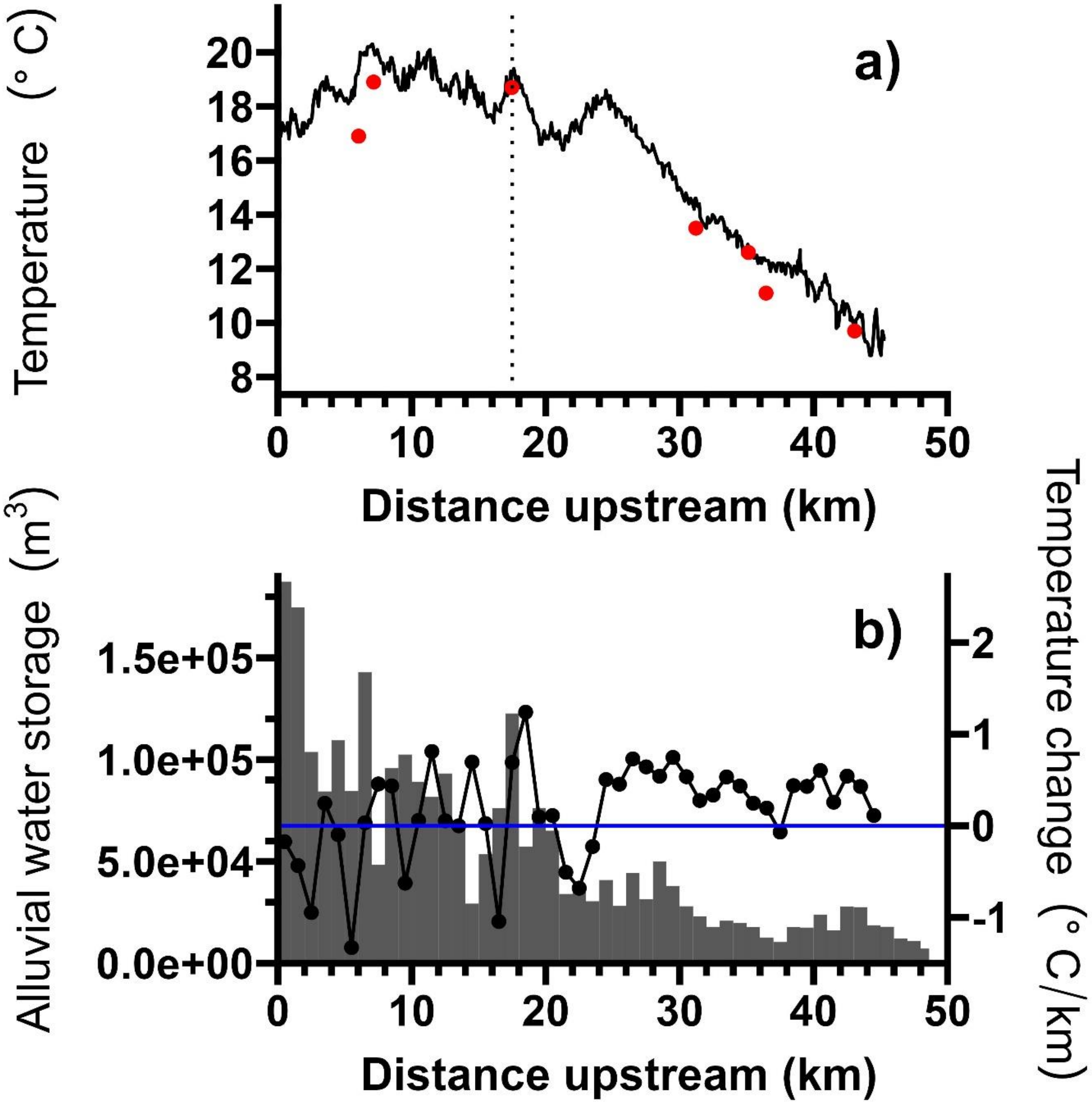

Figure 2. (a) Surface water temperatures at each river kilometer along the Mainstem and North Fork section the Teanaway. Red points are the locations of surface water inputs along the longitudinal profile. A vertical dashed line indicates where the North Fork flows into the Mainstem Teanaway. (b) Alluvial water storage (bars) with change in mean temperature is also shown at each river kilometer (black line). Blue line indicates where there is no change mean temperature.

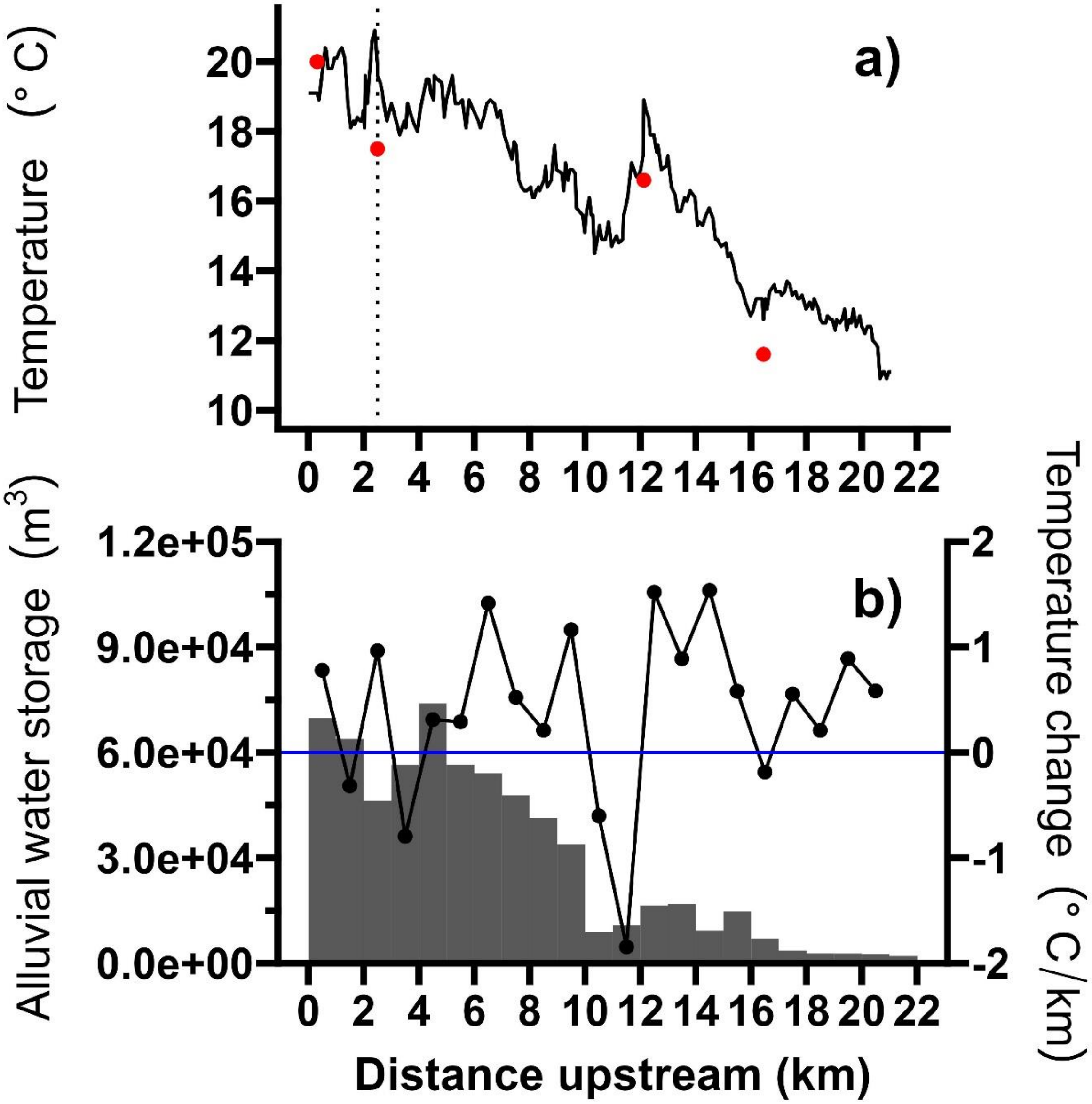

Figure 3. (a) Surface water temperatures at each river kilometer along the Mainstem and Middle Fork Teanaway. Red points are the locations of surface water inputs along the longitudinal profile. A vertical dashed line indicates where the Middle Fork flows into the Mainstem Teanaway. (b) Alluvial water storage (bars) with change in mean temperature is also shown at each river kilometer (black line). Blue line indicates where there is no change mean temperature.

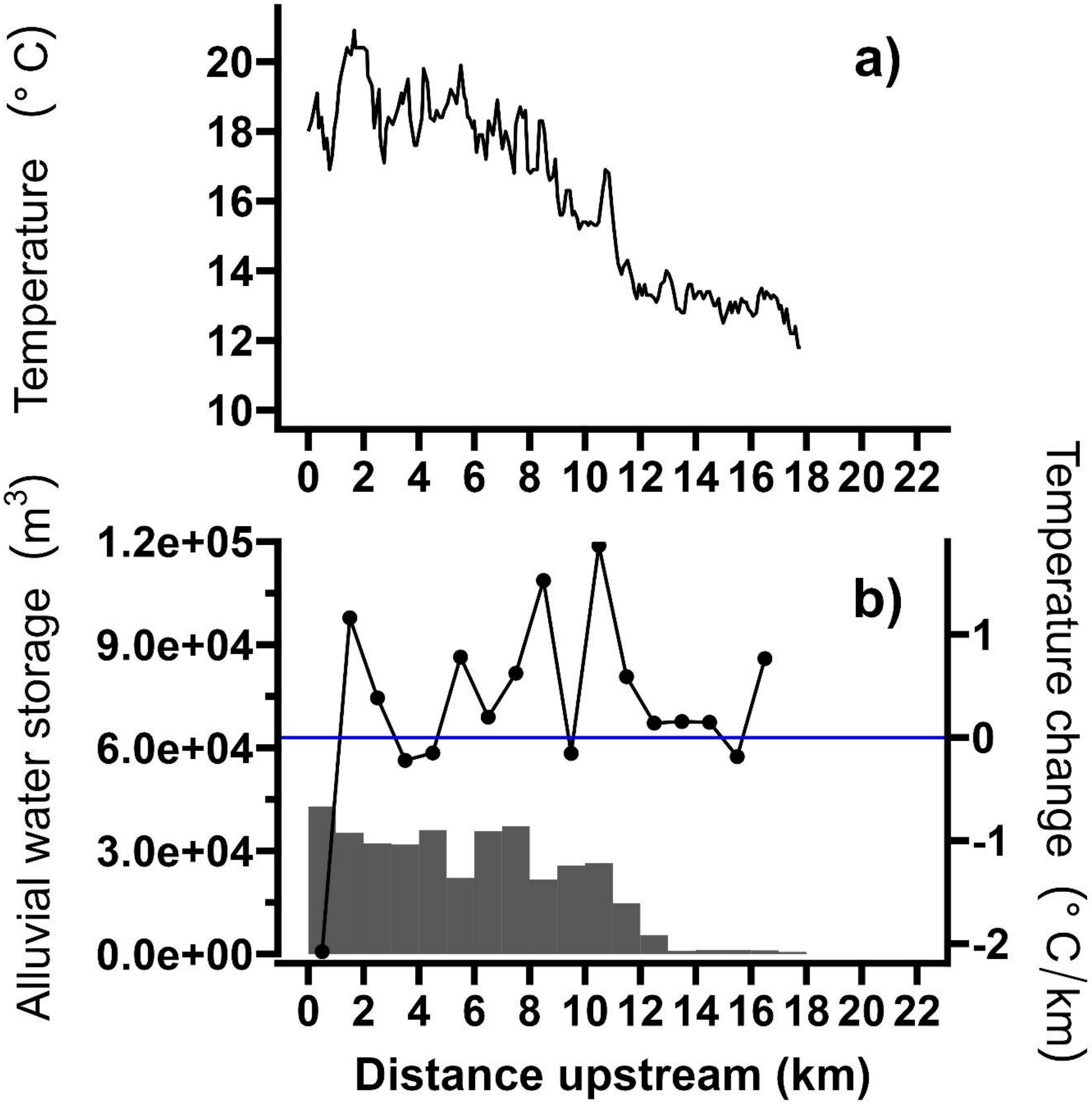

Figure 4. (a) Surface water temperatures at each river kilometer along the West Fork section. (b) Alluvial water storage (bars) with change in mean temperature is also shown at each river kilometer (black line). Blue line indicates where there is no change mean temperature.

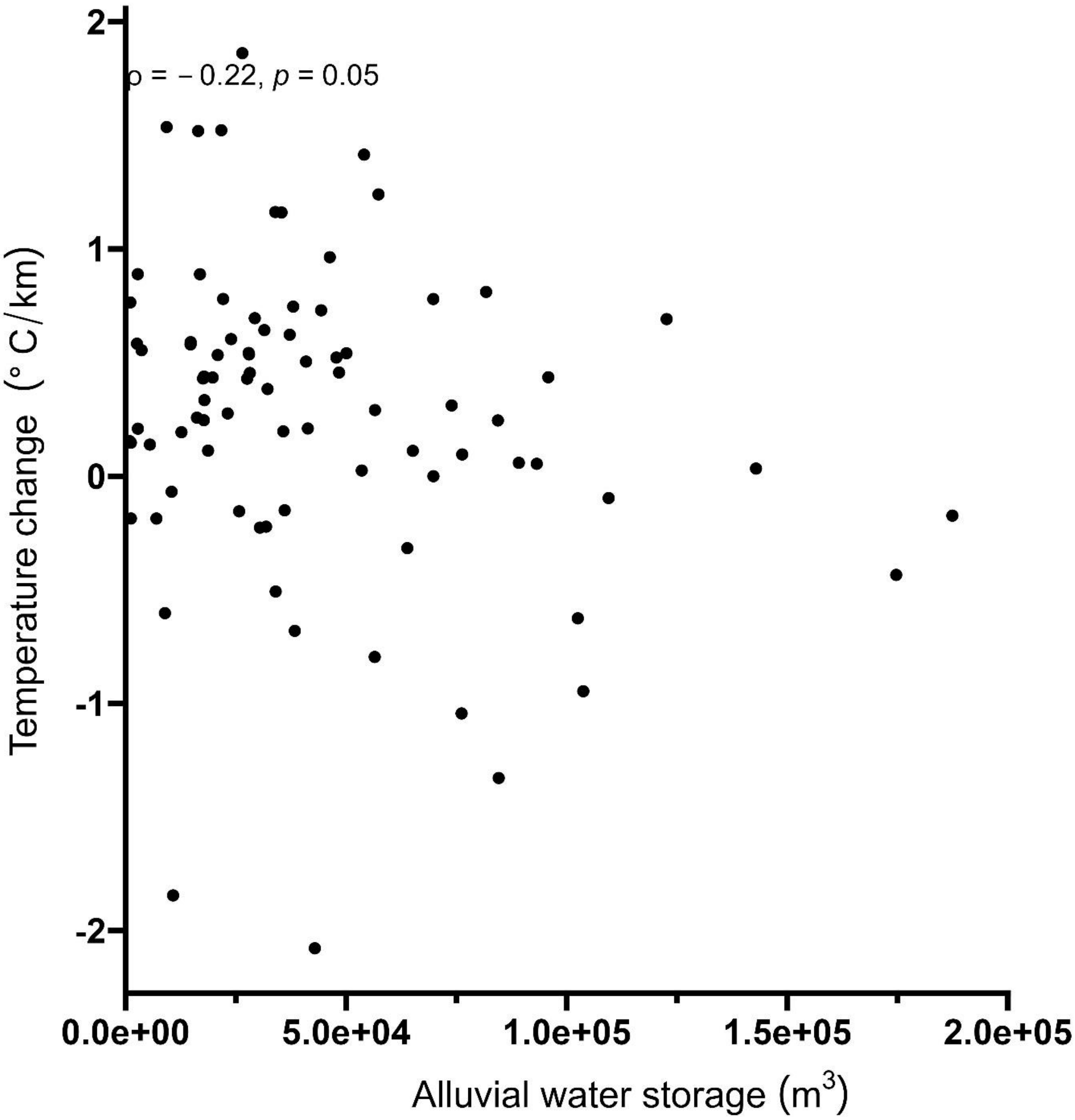

Figure 5. Change in mean stream temperature from upstream to downstream river kilometer segments in and values of alluvial water storage, for all sections of the Teanaway. Rank order correlation coefficient (ρ) the p-value of this correlation coefficient are given.

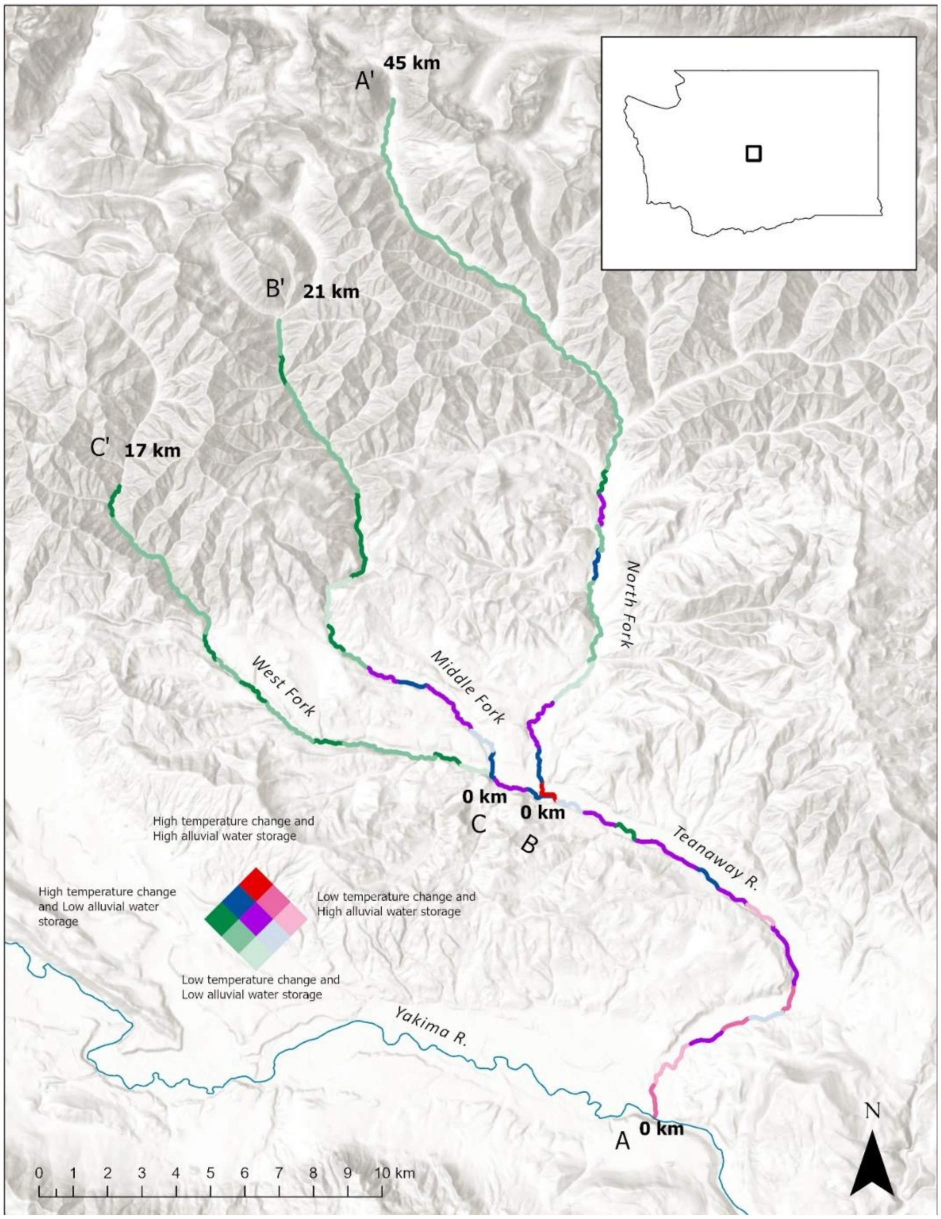

Figure 6. Map displays bivariate color values for alluvial water storage and temperature change in each section of the Teanaway watershed. Values for alluvial water storage were calculated by the sum of volume per river kilometer. Values for temperature change were calculated as the difference in mean temperature from the adjacent upstream river kilometer to downstream river kilometer channel segment. Segments with moderate values for temperature change and moderate values for volume of alluvial water storage are depicted in purple. Segments with high values for temperature change and high values for volume of alluvial water storage are depicted in red. Segments with high values for temperature change and low values for volume of alluvial water storage are depicted in dark green, with low values for temperature change and high values for alluvial water storge are depicted in light pink, low values for temperature change and low values for alluvial water storage are depicted in light green.

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Supporting information

Table S1: Alluvial water storage and temperature change for all sections.

Section	Downstream river (km)	Upstream river (km)	Temperature change (ΔT/km) (°C)	Alluvial water storge (m³)
Mainstem and Middle Fork	22	21	NA	2030
Mainstem and Middle Fork	21	20	0.58	2570
Mainstem and Middle Fork	20	19	0.89	2752
Mainstem and Middle Fork	19	18	0.21	2779
Mainstem and Middle Fork	18	17	0.55	3608
Mainstem and Middle Fork	17	16	-0.19	6980
Mainstem and Middle Fork	16	15	0.58	14714
Mainstem and Middle Fork	15	14	1.54	9291
Mainstem and Middle Fork	14	13	0.89	16853
Mainstem and Middle Fork	13	12	1.52	16441

Mainstem and Middle Fork	12	11	-1.84	10761
Mainstem and Middle Fork	11	10	-0.60	8904
Mainstem and Middle Fork	10	9	1.16	33925
Mainstem and Middle Fork	9	8	0.21	41302
Mainstem and Middle Fork	8	7	0.52	47765
Mainstem and Middle Fork	7	6	1.42	54051
Mainstem and Middle Fork	6	5	0.29	56519
Mainstem and Middle Fork	5	4	0.31	73909
Mainstem and Middle Fork	4	3	-0.80	56460
Mainstem and Middle Fork	3	2	0.94	46285
Mainstem and Middle Fork	2	1	-0.29	63850
Mainstem and Middle Fork	1	0	0.78	69740

Mainstem and North Fork section	46	45	NA	17895
Mainstem and North Fork section	45	44	0.11	18689
Mainstem and North Fork section	44	43	0.43	27539
Mainstem and North Fork section	43	42	0.54	27892
Mainstem and North Fork section	42	41	0.26	16163
Mainstem and North Fork section	41	40	0.60	23902
Mainstem and North Fork section	40	39	0.43	17538
Mainstem and North Fork section	39	38	0.44	17768
Mainstem and North Fork section	38	37	-0.07	10424

Mainstem and North Fork section	37	36	0.19	12657
Mainstem and North Fork section	36	35	0.25	17723
Mainstem and North Fork section	35	34	0.43	19730
Mainstem and North Fork section	34	33	0.53	20874
Mainstem and North Fork section	33	32	0.33	17851
Mainstem and North Fork section	32	31	0.28	23125
Mainstem and North Fork section	31	30	0.54	27976
Mainstem and North Fork section	30	29	0.75	37985
Mainstem and North Fork section	29	28	0.54	50054

Mainstem and North Fork section	28	27	0.64	31448
Mainstem and North Fork section	27	26	0.73	44322
Mainstem and North Fork section	26	25	0.45	28158
Mainstem and North Fork section	25	24	0.50	40894
Mainstem and North Fork section	24	23	-0.23	30446
Mainstem and North Fork section	23	22	-0.68	38346
Mainstem and North Fork section	22	21	-0.51	34014
Mainstem and North Fork section	21	20	0.11	65101
Mainstem and North Fork section	20	19	0.10	76292

Mainstem and North Fork section	19	18	1.24	57313
Mainstem and North Fork section	18	17	0.69	122630
Mainstem and North Fork section	17	16	-1.04	76153
Mainstem and North Fork section	16	15	0.03	53523
Mainstem and North Fork section	15	14	0.70	29273
Mainstem and North Fork section	14	13	0.00	69769
Mainstem and North Fork section	13	12	0.05	93190
Mainstem and North Fork section	12	11	0.81	81709
Mainstem and North Fork section	11	10	0.06	89131

Mainstem and North Fork section	10	9	-0.63	102500
Mainstem and North Fork section	9	8	0.44	95810
Mainstem and North Fork section	8	7	0.46	48387
Mainstem and North Fork section	7	6	0.03	142896
Mainstem and North Fork section	6	5	-1.33	84571
Mainstem and North Fork section	5	4	-0.10	109489
Mainstem and North Fork section	4	3	0.25	84390
Mainstem and North Fork section	3	2	-0.95	103740
Mainstem and North Fork section	2	1	-0.43	174677

Mainstem and North Fork section	1	0	-0.17	187409
West Fork	18	17	NA	573
West Fork	17	16	0.77	1055
West Fork	16	15	-0.19	1198
West Fork	15	14	0.15	1190
West Fork	14	13	0.15	868
West Fork	13	12	0.14	5498
West Fork	12	11	0.59	14733
West Fork	11	10	1.86	26454
West Fork	10	9	-0.15	25730
West Fork	9	8	1.52	21687
West Fork	8	7	0.62	37190
West Fork	7	6	0.20	35737
West Fork	6	5	0.78	22098
West Fork	5	4	-0.15	36049
West Fork	4	3	-0.22	31834
West Fork	3	2	0.38	32173

West Fork	2	1	1.16	35335
West Fork	1	0	-2.08	42886