DECEMBER 2021

A DEEP DIVE INTO SHALLOW WATERS

Understanding and Responding to Climate-Induced Impacts on Stream Permanence in the Northwestern U.S.

NORTHWEST
Climate Adaptation
Science Center

CLIMATE IMPACTS GROUP

2021 Deep Dive Summary Report

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1 | EXECUTIVE SUMMARY

Northwest streams represent important cultural values for communities and provide critical habitat for our region's fish, wildlife, insects, avian species, and ecosystems. Most streams in the region currently run dry at some point in the year, and many more are likely to dry as the climate changes. Understanding which Northwest streams will be resilient to drier conditions, which will dry up and when -- in other words, understanding more about streamflow permanence -- can help communities make climate-smart decisions to protect streams and the fish, wildlife and people that depend on them, along with the cultural values they support.

This report summarizes the process and outcomes of the Northwest Climate Adaptation Science Center's (CASC) Deep Dive on climate change and stream permanence in the Northwest. We convened natural resource managers and scientists from Northwest Tribes, universities, non-profit and private sectors, and federal, state and local governments to collaboratively review what is currently known about stream permanence and how it affects people and places in the region. We also identified research and capacity needs for understanding and responding to changes in stream permanence. As in previous years, the Deep Dive served as an opportunity for participants to share knowledge, network, and collaborate on an issue of shared interest and importance.

The Deep Dive was designed to facilitate coproduction of all aspects of the process, from problem identification to the specifics of the action agenda. As in 2020, the entire process was conducted virtually in accordance with public health guidelines regarding the novel coronavirus.

Key findings from the research synthesis:

- People value intermittent streams differently, and those values shape policy and management actions. Equitable and efficient management decisions are challenged by inequitable power dynamics, a scale mismatch between river systems and societal expectations, and the constraints of western water law.
- Changes in stream permanence are being observed across the Northwest and are projected to continue under a changing climate. Yet little is known about the implications of changing stream permanence for specific communities across the Northwest.
- Streams culturally, physically, and biologically connect landscapes. As stream drying increases, these connections will become more seasonal, change, or stop altogether.
- Declining snowpack is expected to be a primary driver of climate-driven changes in stream permanence. Other potential factors include higher water demand by forests/crops, declines in summer precipitation, and changes in the amount and timing of groundwater recharge.

- Changes in stream permanence threaten stream-dependent species and can influence ecosystem processes, with potential downstream and cascading effects. Ecological diversity can buffer stream-dependent plant and animal communities against negative effects of stream drying.
- Though various land and water stewardship actions could potentially mitigate climate-induced changes in stream permanence, little is known about which actions are most effective or how their effectiveness will vary across different landscapes.
- Incorporating different forms of knowledge, especially Traditional Knowledge, into science, education, training and management decisions can facilitate equitable, innovative outcomes related to decisions that affect stream permanence.

In addition to synthesizing the research, our report proposes both research and capacity needs that, if pursued, could improve our understanding of changing stream permanence and our capacity to manage these changes. As part of the workshop, participants voted on the needs. Below is a summary of the top-scoring needs:

Research Needs:

- Hydrologic and climate studies to better quantify climate impacts on stream permanence. Including surface water – groundwater connections.
- Studies linking land and water use activities (e.g., logging, irrigation), and disturbance (e.g., wildfire, bark beetles), with changing stream permanence.
- Evaluate the adaptive capacity of flora and fauna to intermittency of varying durations (weeks, months, years), and resilience of ecological functions.
- Evaluate effectiveness and potential scope of mitigation actions, including: land and riparian cover, water conservation, groundwater recharge.
- More and better baseline data to support improved predictions of stream permanence.

Capacity Needs:

- Facilitate data collection through standardized practices and by expanding low-cost, robust, and automated monitoring systems for non-perennial streams.
- Facilitate knowledge sharing across the region (e.g., best practices, research).
- Improved collaboration between Tribes and non-Tribal entities; better incorporation of Traditional Ecological Knowledge, more widespread training on ethical collaboration and knowledge-sharing.
- Tools and strategies to support adaptation to changing stream permanence, tailored to address the needs of different contexts (e.g., regulatory vs voluntary mitigation, high desert vs montane ecosystems).

From this list, participants identified four key needs to discuss in further detail; breakout sessions for each of these needs were used to brainstorm specific actions that could address each need (Appendix D).

We also identified eight pilot project ideas (Appendix E). Ranging from mapping tools to training resources to fact sheets, these are low-effort / low-cost actions that could be taken in the near term to advance our understanding and capacity to address changing stream permanence.

2 | INTRODUCTION

Northwest1[1] streams represent important cultural values for communities and provide critical habitat for our region's fish, wildlife, insects, avian species, and ecosystems. A majority of streams in the region currently run dry at some point in the year, and many more are at risk of drying as the climate changes. Understanding which Northwest streams will be resilient to drought conditions and continue to flow year-round, which will dry up, and how early in the season -- in other words, knowing more about **streamflow permanence** -- can help communities make climate-smart decisions to protect streams and the fish, wildlife and people that depend on them, along with the cultural values they support.

Where and when different streams and rivers go dry has a profound influence on aquatic and riparian ecosystems and can have important policy and management implications. In recent years, scientific, practitioner and Indigenous communities have:

1. Developed ways to understand and unify classifications of stream permanence that allow meaningful comparisons and shared learning across watersheds and ecosystems,
2. Improved knowledge of the physical and ecological conditions that affect stream permanence (ranging from riparian vegetation to regional rainfall patterns), and
3. Increased measurements of the connections between stream permanence and the ecological communities within a watershed.

This has resulted in increased understanding of the climate-linked factors affecting stream permanence, which include late summer precipitation, evaporative water demand, amount of winter snow accumulation, as well as geographic features related to topography and land cover.

Despite these recent advances, there remain significant uncertainties related to how climate change will affect stream permanence in a variety of Northwest systems, the degree to which models and data are capable of predicting shifts in stream permanence, the impacts on humans and ecosystems, and what Northwest communities can do to respond and adapt to future changes in stream permanence. The issue of stream permanence is of particular urgency given the pace of climate change and the significant complexities tied to social and ecological processes related to water availability.

In the following sections, we summarize the Deep Dive process and outcomes, key findings from our knowledge synthesis on understanding and responding to climate-induced changes in Northwest stream permanence, and propose both research and capacity needs that, if pursued, could improve our understanding and capacity to manage these changes.

[1] The Northwest CASC defines the "Northwest" to include all of Idaho, Oregon, and Washington, and the major watersheds that extend beyond the borders of these three states. This includes the Nchiwana or Columbia River Basin.

2.1 | Understanding Streamflow Permanence

Streamflow permanence refers to the spatial distribution and temporal frequency with which streams and rivers go dry. Changes in streamflow permanence can be understood in the context of different types of streams and flow conditions. ***Perennial streams*** refer to those which always flow. ***Non-perennial*** streams, which comprise the majority of all streams globally (51-60% of river miles, Messager et al. 2021), go dry for some period of the time, and include both intermittent and ephemeral streams. ***Intermittent streams*** are those which generally have a seasonal no-flow period. ***Ephemeral streams*** refer to those which only flow in response to precipitation events. Non-perennial streams are found across a wide range of geographies from alpine regions to valley floors, and arid plains. Non-perennial streams often dry out when stream outputs (e.g., evapotranspiration, groundwater losses) exceed inputs (e.g., rain and snowmelt). **Changes in streamflow permanence include any changes to flow-timing and frequency related to stream drying.** This could take place if perennial streams shift from having year-round flows to having periods of dry conditions. It could also include shifts in timing or frequency of flows in non-perennial streams.

While climate is a significant driver of water flow in non-perennial streams, climate change impacts on stream permanence must also be understood within the broader context in which societies shape and are shaped by landscapes. Societal relationships with land and water vary spatially and temporally and are intertwined with systems of power (e.g. Indigenous land stewardship, settler colonialism, capitalism, and Euro-centric resource management). These relationships relate to different land and water management priorities and practices which subsequently shape changes to, and impacts from, streamflow permanence. For example, industrialisation and Euro-centric resource management centered around maximizing efficiencies have created systems that drain and divert rivers for shipping, energy and agricultural uses. These actions have tradeoffs and impacts on streams and stream permanence, causing some streams to shift from perennial to non-perennial or shifts in timing and frequency of flow in non-perennial streams, etc. Decisions about how to manage climate impacts on stream permanence are also shaped by different knowledge and contexts around what we know about streams and what can be done (e.g. current land use and disturbance, varied knowledge and resources about streams, community-relevant land and water management practices, prioritizing actions within institutional and legal frameworks).

3 | DEEP DIVE PROCESS

3.1 | Process

We convened natural resource managers and scientists from Northwest Tribes, universities, non-profit and private sectors and federal, state and local governments to collaboratively review what is currently known about stream permanence and how it affects people and places. We also identified research and capacity needs for understanding and responding to changes in stream permanence. As in previous years, the Deep Dive also served as an opportunity for participants to share knowledge, network, and collaborate on an issue of shared interest and importance.

The Deep Dive was designed to facilitate coproduction of all aspects of the process, from problem identification to the specifics of the action agenda. As in 2020, the entire process was conducted virtually in accordance with public health guidelines regarding the novel coronavirus. The process was organized as follows:

- ***Research Fellows:*** Four Deep Dive Fellows (listed in cover materials) led the science synthesis, with backgrounds in forest ecology, hydrology, soil science and landscape ecology. Fellows did the bulk of the research for the Deep Dive, compiling the research and capacity needs and facilitating feedback discussions with the Planning Committee, Advisory Group, and workshop participants.

- ***Planning Committee:*** We convened a Planning Committee (listed in cover materials) to advise on our approach and collaborate on all aspects of the process. Planning committee members were selected to include at least one Tribal representative and federal agency staff.

- ***Advisory Group:*** We convened a larger Advisory Group (Appendix A) to provide input on our process and findings. Advisory Group members participated in three 2-hour meetings over the course of the summer, advising on the following topics:

    1. June meeting: Key questions to guide the synthesis
    2. July meeting: Preliminary findings from the synthesis
    3. August meeting: Research and capacity needs and workshop invitation list

- ***Workshop:*** The workshop, which occurred over three two-hour sessions, provided participants with an opportunity to share their stories regarding stream permanence, weigh in on the synthesis and needs, and develop ideas for future work. The workshop agenda is provided in Appendix B. Workshop participants included scientists, managers and community members from organizations across the Northwest, including universities, Tribal, federal, state and other entities (Appendix A).

- A storytelling panel on the first day featured the perspectives of three Tribal members:

  Wilbur Slockish Jr, Hereditary Chief of the Klickitat Tribe

  Mike Durglo, Tribal Preservation Department Head and Climate Change Advisory Committee Chairman, Confederated Salish and Kootenai Tribes http://csktclimate.org/

  Gabe Sheoships, Executive Director of Friends of Tryon Creek, and member of the Cayuse and Walla Walla Nations, from the Confederated Tribes of the Umatilla Reservation

  After discussing the synthesis and needs on Day 2, workshop participants identified four key needs to discuss in further detail in breakout sessions on Day 3. A graphic recorder provided artistic representations of key parts of the workshop discussions (thumbnail images in Figure 1 below; full-page images are in Appendix B). Additional details on the workshop outcomes are provided in Section 5 of this report.

We provided honoraria to support Tribal members' participation in the Planning Committee and Advisory Groups, as well as to the three Tribal members who participated in the storytelling panel during the workshop. Follow-up surveys after each advisory group meeting and the workshop allowed participants to share impressions and additional feedback on the process. This information will provide a basis for evaluating the Deep Dive process and inform the design of future Deep Dives.

Figure 1. *Graphic recordings of the storytelling panel (top left), State of Knowledge Synthesis (top right), participants' reflections (bottom left), and the final panel discussion of the workshop (bottom right).* ***Image credit:*** *Maisie Richards. Full-page images are included in Appendix B.*

4 | STATE OF KNOWLEDGE SYNTHESIS

This section synthesizes what is known and what knowledge and capacities are needed that can help address climate change impacts on stream permanence in the Northwest. Our synthesis combines information from peer reviewed publications, reports, and feedback from workshop participants to reflect scientific, management and cultural perspectives on this emerging climate risk.

We developed a framework to organize this synthesis in a way that reflects the interdependencies of hydrological, ecological, cultural and decision contexts in shaping climate change impacts on stream permanence (Figure 1). This framework was used to organize the findings into two major components: (1) the state of our understanding of how climate change is impacting stream permanence in the Northwest and the subsequent effects (or potential effects) on Northwest communities and ecosystems, and (2) the current and potential response of communities to current and projected changes in stream permanence.

The synthesis is organized around a series of guiding questions, developed in collaboration with the Advisory Group:

1. Are Northwest communities experiencing changes in stream permanence and how are they impacted by those changes?
2. How is climate change impacting stream permanence in the Northwest?
3. How are ecosystems impacted by changes in stream permanence?
4. What land and water stewardship approaches and tools can help address changes in stream permanence?
5. How are communities connecting multiple forms of knowledge (e.g. Traditional Knowledge, local knowledge and western science) to address drivers and impacts of stream permanence?

Each of the subsections that follows deals with one of these guiding questions.

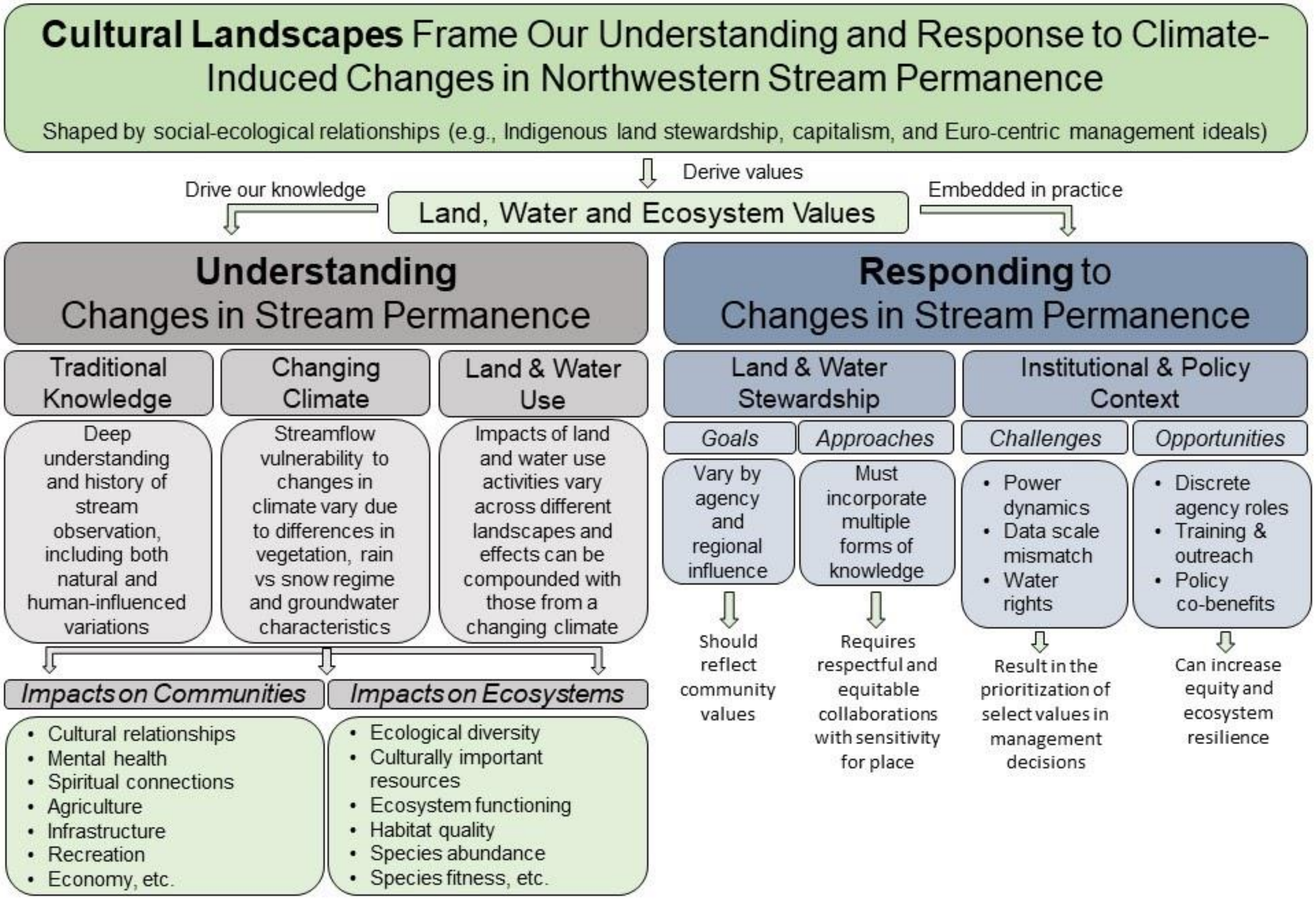

Figure 2: *Knowledge synthesis framework begins with an understanding that our values are derived from past and present cultural landscapes. Light green boxes and arrows provide examples of how these values drive our understanding of, are embedded in our responses to, and are impacted by changes in stream permanence. Gray and blue boxes represent key findings.*

4.1 | Are Northwest communities experiencing changes in stream permanence and how are they impacted by those changes?

People and communities across the Northwest are affected by changes in stream permanence via its connection to a variety of economic, cultural and societal values. These connections differ across the region, as do the social and knowledge contexts in which communities shape their responses. With some exceptions, past research and management have not adequately represented Traditional or Local knowledge.

Communities are experiencing changes in stream permanence and are concerned about its impacts. Reports on drought indicate that Northwest communities are significantly impacted by changes to aquatic flows. For example, the 2020 Pacific Northwest Water Year Impacts Assessment reported a significant loss of cultural resources due to drought impacts on streamflow, across drinking water supply, agriculture, forestry, fisheries, hydropower, recreation and stormwater sectors.

Many Deep Dive Advisory Group members discussed observations and experiences of changes in water supply -- in both the timing and amount of water. Deep Dive workshop participants also reported anecdotal observations of changes in stream permanence in their communities (94%, n = 50). Observations spanned ecoregions, from snow-dominated alpine environments, to the high-desert plateau, to coastal watersheds. Increasingly frequent and earlier stream drying was widely observed in headwater locations during the late season. These changes were often observed during drought years, when winter precipitation failed to replenish aquifers, leading to both insufficient in-stream flow and high water temperatures. Such climate change impacts on stream permanence were also reported to be of concern to participants' affiliated organizations, including research, management, and Tribal institutions. Several identified that the harmful impacts of stream drying on culturally and economically significant native salmon populations (along with other aquatic species such as freshwater mussels, Pacific lamprey and Steelhead) were of particular concern. Other points of concern relating to increasing frequency and extent of stream drying included: reduced water availability, agricultural loss, increased fire danger, diminished recreational opportunities, and loss of biodiversity (which is closely tied to the loss of cultural connections). Given the widespread concern for stream drying in the Northwest and the potential and existing impacts on important environmental services and ecosystem wellbeing, stream permanence is considered a priority among research, management and cultural institutions.

People value intermittent streams differently, and those values shape policy and management actions. The degree to which people value intermittent streams in comparison to perennial streams can be influenced by where the person grew up and their educational background (Rodríguez-Lozano et al. 2020). In general, people value perennial streams and rivers over intermittent streams. This cultural under-recognition of intermittent streams has shaped policy.

In 2020, ephemeral streams temporarily lost protections under the U.S. Clean Water Act (CWA), in part because the spatial extent and distribution was not readily understood by the regulatory agencies. The CWA defines streams as perennial or intermittent based on the Waters of the United States (WOTUS) "Navigable Waters Protection Rule." This rule hinges on whether a stream contributes to navigable waters based on 30-year rolling average flows, which are often poorly quantified by existing stream monitoring systems (Jaeger et al., 2021; Shanafield et al., 2021). As a result, loss of stream permanence can lead to deregulation, in which a stream and its upstream connections no longer qualify under the "Navigable Waters Protection Rule" of the CWA. Due to the interactions between intermittent streams and human systems (policy, water use, etc.), research is needed to understand how policy and management actions reflect implicit judgements about the value of non-permanent streams, and how this could affect our ability to respond to changes in stream permanence (Fovet et al. 2021)

Little is known about the implications of changing stream permanence for specific communities across the Northwest. This is particularly true for historically marginalized or environmentally vulnerable communities (e.g. Indigenous communities, urban communities of color, agricultural workers). While Advisory Group Members discussed the importance of changes in streamflow permanence and the impacts on communities from those changes, they also shared that these changes and impacts are place and context dependent. Advisory Group members also noted that most of the impacts are framed in terms of production value (e.g. agriculture, water utility), whereas other social impacts (e.g. mental health and stress of drought), cultural values, and adaptive capacities, are under researched. A more holistic understanding of impacts -- for example, via a collection of place-based narratives about the importance of water and streamflow permanence -- would allow for a more complete assessment of the risks posed by climate change.

Perceptions of risk shape opinions about the importance of taking action. While there is limited information on changes in stream permanence more specifically, we can look at impacts on water shortages to identify how such changes in the timing and flow of water might be perceived by surrounding communities. In a recent study of water-related risks across Oregon, Hubbard (2020) found that survey respondents perceived agriculture and forestry as most at risk of water shortages due to drought induced by climate change, and that private wells were the lowest risk. A 2018 study showed that only a small percentage of interior Northwest farmers intend to take preventative measures in anticipation of climate change impacts, including water related impacts (Roesch-McNally, 2018). Evans et al. (2015) demonstrated that increased exposure to drought in the southern U.S. increased perceived risks about drought, suggesting that personal experience changes public opinion. In the western U.S., where drought is increasingly frequent, a 2021 study investigating water policy perspectives shows that a large percentage of the population is supportive of a restructuring of water policy to address climate-induced water shortages in order to meet the basic needs of society (Wolters and Steel, 2021).

Management and stewardship of non-permanent streams lacks diversity. In our Fall 2021 Deep Dive workshop, participants identified two principal ways to increase diversity: (1) sharing/returning more regulatory authority with Tribes or local governments, and (2) increasing BIPOC educational efforts and pathways into the natural sciences. Specifically regarding partnerships between Tribal and non-Tribal entities, these collaborations could further emphasize honorable engagement and respect for Tribal sovereignty. When Tribal land is concerned, priorities and actions should be driven by the needs and objectives identified by Tribal partners rather than externally

Integrating multiple knowledges into research and management is another strategy to increase understanding and potentially increase applicability of management decisions with multiple benefits. Doing so can result in research and conservation efforts that are more effective and responsive to community needs. This topic is further discussed in section 4.5 below.

Table 1. *Research and capacity needs related to human dimensions.*

<table>
<tr><td colspan="2">Guiding Question: Are Northwest communities experiencing changes in stream permanence and how are they impacted by those changes?</td></tr>
<tr><td>Research Needs</td><td>Capacity Needs</td></tr>
<tr><td>Cultural values associated with different types of non-perennial streams
Impacts of stream drying on communities
Localized, community assessments and case studies of the drivers and impacts of changes in stream permanence:
Include perceptions, knowledge, attitudes and behaviors
Expand beyond production activities (e.g. agriculture) and consider other social impacts (e.g. mental health and stress of drought), cultural values, and adaptive capacities
Identify policies or programs that affect stream permanence
Apply a justice and equity lens</td><td>Resources (funding, guidance, case studies) to support incorporation of cultural values and community input in land and water management policies and practices.
Support for increased diversity by facilitating pathways into natural science careers.</td></tr>
</table>

4.2 | How is climate change impacting stream permanence in the Northwest?

Annual precipitation and air temperature are the strongest predictive variables for stream drying in the Northwest and both are changing in ways that induce more frequent or earlier stream drying. When precipitation is less than average or air temperature is greater than average, stream drying tends to happen earlier and more often (Jaeger et al., 2019; Hammond et al. 2021; Zipper et al., 2021). Climate modeling suggests temperatures will increase significantly (~2.7 - 4.4 °C) through the next century, barring large reductions in greenhouse gas emissions or advancements in greenhouse gas sequestration (IPCC, 2021). This level of projected warming will induce significant decreases in winter snow accumulation and may also lead to increases in evapotranspiration (ET) and reductions in aquifer recharge across the Northwest.

Decreasing winter snow accumulation, due to warming, is leading to lower spring and summer streamflows and more frequent/earlier stream drying. In alpine regions of the Northwest, winter precipitation that falls as snow is stored in place until temperatures warm above the freezing point. When snow melts, soils are wetted (recharging aquifers) and streams and rivers receive water from melting snow. Both the amount of snow and the timing of snowmelt is important for streamflow permanence in alpine systems (Sando and Blasch, 2015). As the climate warms and snowpacks shrink, summer streamflows that have historically been supported by snowmelt are declining (Stewart et al., 2005; Hamlet and Lettenmaier, 2007), leading to earlier and more frequent stream drying (Raymondi et al., 2013). Mixed rain-snow and snow-dominated watersheds whose winter temperatures have consistently been at or below freezing (e.g., Yakima [WA], Spokane River [WA and ID], Big Wood River [ID], Flathead [MT], McKenzie River [OR]) are experiencing the greatest degree of change in streamflow timing as a result of climate-induced decreases in winter snow accumulation (Mote et al., 2005; Ikeda et al., 2021). Because of the importance of snowpack to stream permanence in many alpine basins, decreases in the amount of precipitation falling as snow will substantially affect the hydrologic characteristics of these basins, leading to increases in winter and early spring streamflow and declines in summer streamflow (or earlier drying). These shifts in streamflow timing and magnitude will have diverse implications for river channels and floodplains in the Northwest, including producing greater seasonality in sediment transport and flooding (East and Sankey, 2020).

Warming temperatures and shrinking snowpacks are lengthening the growing season. A longer growing season could result in increased evapotranspiration (ET) by plants, leaving less water available for streams. Snow-covered landscapes are less ecologically active during winter months when the potential for photosynthesis is limited. As snowpacks shrink and temperatures warm, the growing season for historically snow-covered and dormant portions of landscape will begin earlier and last longer. Similarly, temperature affects the germination, growth, and flowering phases of plants, with the amount of growth strongly linked to the length and warmth of the growing season (Hatfield and Prueger, 2015). Trees and plants require water to grow, some of which is lost via transpiration -- a byproduct of the process that plants use to absorb carbon dioxide for photosynthesis.

As a result, longer growing seasons may translate to greater annual ET and drier soils. This in turn leaves less water for streams and groundwater (Jung et al., 2019; Montibeller et al., 2021).

There are other reasons that ET could be affected by climate change:

- Some research indicates that climate change will increase the drying potential of the atmosphere, thereby driving an increase in ET. This theory is based on the observation that vapor pressure deficit -- the difference between saturated and actual vapor pressure, which directly affects water loss by foliage -- increases with warming even if humidity stays the same (Baldocchi and Ma, 2013).

- Global climate models generally project that summer precipitation in the Northwest will decline in the future (Easterling et al. 2017). This would lead to decreased water availability for streams, making the effects of summer ET more dire for streams and groundwater. However, there is a considerable range among model projections, including some that project both more intense precipitation events and/or increases in total summer precipitation.

- Higher atmospheric carbon dioxide concentrations will allow some plants to reduce the amount of water they lose to evaporation via their stomata (Kirschbaum and McMillan, 2018). Overall this effect is expected to be small relative to other impacts on ET.

Each of these fields of research may help us evaluate ET-related stream drying in the future.

Earlier and more frequent stream drying is reducing the capacity of non-perennial streams to provide water to adjacent soils and aquifers. Non-perennial streams are often losing streams, meaning they provide water to underlying aquifers and adjacent soils (Shanafield et al., 2020). The process of water infiltrating into and moving through soils or bedrock is limited by the physical properties (e.g., porosity, grain size, physical structure, etc.) of the soil/bedrock being infiltrated. When non-perennial streams stop flowing, they stop providing water to adjacent soils and aquifers. Conversely, when streamflows are high but streams remain within their channels (i.e., floodplains remain disconnected), their recharge capacity remains limited by underlying soil/bedrock infiltration rates (i.e., increases in winter flows will not necessarily produce greater aquifer recharge despite their higher flows). Continued decreases in dry-season streamflow, whether due to climate change or other factors, will reduce the capacity of streams to wet soils and recharge groundwater (Barnett et al., 2005; Wu et al., 2020). The increased prevalence of wildfires in a changing climate will likely compound this effect as wildfires can reduce a soil's ability to hold and transport water, resulting in water moving through watersheds faster (Wieting et al., 2017).

There is some evidence that losses in snowpack and glacier cover may expose new recharge pathways in montane zones via “mountain front” or “mountain block” recharge mechanisms (Hayashi, 2019; Meixner et al., 2016). In theory, these montane recharge mechanisms could serve similar watershed functions as non-perennial headwater streams by delivering water from alpine regions to higher order tributaries and aquifers via highly permeable subsurface features (e.g., bedrock joints, talus fields, etc.). However, these mechanisms are often not well understood at local scales and their ability to mitigate the effects of regional climate-induced stream drying remains unknown (Cochand et al., 2019; Markovich et al., 2019). Regardless of the net effect on water availability, these potential new recharge zones could present an issue for existing infrastructure, such as municipal drinking water systems, by altering the balance of flows among groundwater and surface water as well as the proportion of flow among individual tributaries (Siirila-Woodburn et al., 2021).

Stream connectivity is crucial for many ecological and hydrological processes. As stream drying increases, these connections will become more seasonal, change, or stop altogether. The downstream effects of stream drying include decreased habitat connectivity, declines in sediment and nutrient transport, and declines in water availability (Liebowitz et al., 2018; Beechie et al., 2013). These climate-induced effects can compound with existing impacts related to human changes to land cover (e.g., logging, road and city building, grazing), stream channel modification (e.g., channel straightening, levy building/flood control, riparian vegetation removal), and water use (reservoirs, water extraction; Poff et al., 2010). Additional research is needed to understand how changes in stream permanence can affect ecosystems and hydrology downstream of affected reaches. Management practices, such as increasing floodplain and stream connectivity or reducing impermeable land cover, can mitigate some of these changes; this is discussed in section 4.4.

The impacts of climate change on stream permanence, and the associated consequences for watersheds, will vary across the Northwest. Regional tools that relate stream drying vulnerability to climatic, land cover, geologic, and other characteristics can help watershed managers as they plan for climate-change induced changes in stream permanence. Two such tools are presented in Figure 2. The U.S. Geological Survey developed the PRObability of Streamflow PERmanence (PROSPER) model to provide estimates of unregulated stream channels having year-round flow (Figure 2A; Jaeger et al., 2019). The model incorporates physical characteristics (e.g., topography, land cover, soil types, estimated ET, etc.) along with climatic observations (e.g., temperature, precipitation, snow water equivalent) to predict the likelihood of stream channel drying at the grid scale. Another tool, produced by scientists at the Environmental Protection Agency, used physical and climatic conditions to define a typology of hydrologic landscapes across the Northwest (Figure 2B; Leibowitz et al., 2016).

These tools provide context for evaluating the present state of non-perennial streams in the Northwest. The geographic diversity of the Northwest presents a challenge for watershed managers and scientists trying to understand and manage stream permanence. Regional tools like these can help build working relationships across municipal and physical boundaries to mitigate climate change impacts to stream permanence. Additional research, guided by input from regional managers and stewards of the land is needed to build on existing tools in a way that supports climate-resilient planning (Table 2). Specifically, current tools lack the ability to project future changes in stream permanence at the regional and reach scale, whether due to climate change or other factors. They are also unable to provide information on the potential effectiveness of mitigation actions (see section 4.4 for a more detailed review). Physically based hydrologic models such as the variable infiltration capacity model (VIC, Liang et al., 1994) can incorporate projected climate scenarios and alternative land use scenarios; however, their complexity and a lack of viable observational data on stream drying and low flows limits their usability.

Table 2. Research and capacity needs related to hydrology

***Guiding Question:* How is climate change impacting stream permanence in the Northwest?**	
Research Needs	Capacity Needs
• Applied hydrologic research that is guided by watershed managers and water users • Improved hydrological and meteorological models to resolve how changes in climate will impact evaporation and transpiration rates across ecosystems • Improve geologic, land cover, and topographic datasets at decision-relevant scales • Integrate existing research across spatial scales, tying local process-based research to regional patterns, landscapes, and models • Identify if/when stream drying is detrimental to local water balances and habitats • Studies linking changes in flow regime/stream drying to downstream physical and ecological outcomes • Improved understanding of stream and aquifer connectivity across different spatial and temporal scales • Methodological improvements for hydrologic model calibration • Tools for identifying climate projections that are best suited to specific management questions • Additional research focused on mountain front and mountain block aquifer recharge mechanisms • Refine remote sensing techniques to monitor stream drying and landscape precursors (e.g., vegetation stress, land cover change, ET rates, etc.)	• Develop/expand low-cost, robust, and automated monitoring systems focused on non-perennial streams (e.g., Arduino monitoring networks) • Continue to standardize language and data collection for non-perennial streams • Cultivate cross-sector relationships with watershed stakeholders, hydrologists, ecologists and climate scientists to facilitate community-driven science evaluating the risk of future stream drying and potential mitigation strategies

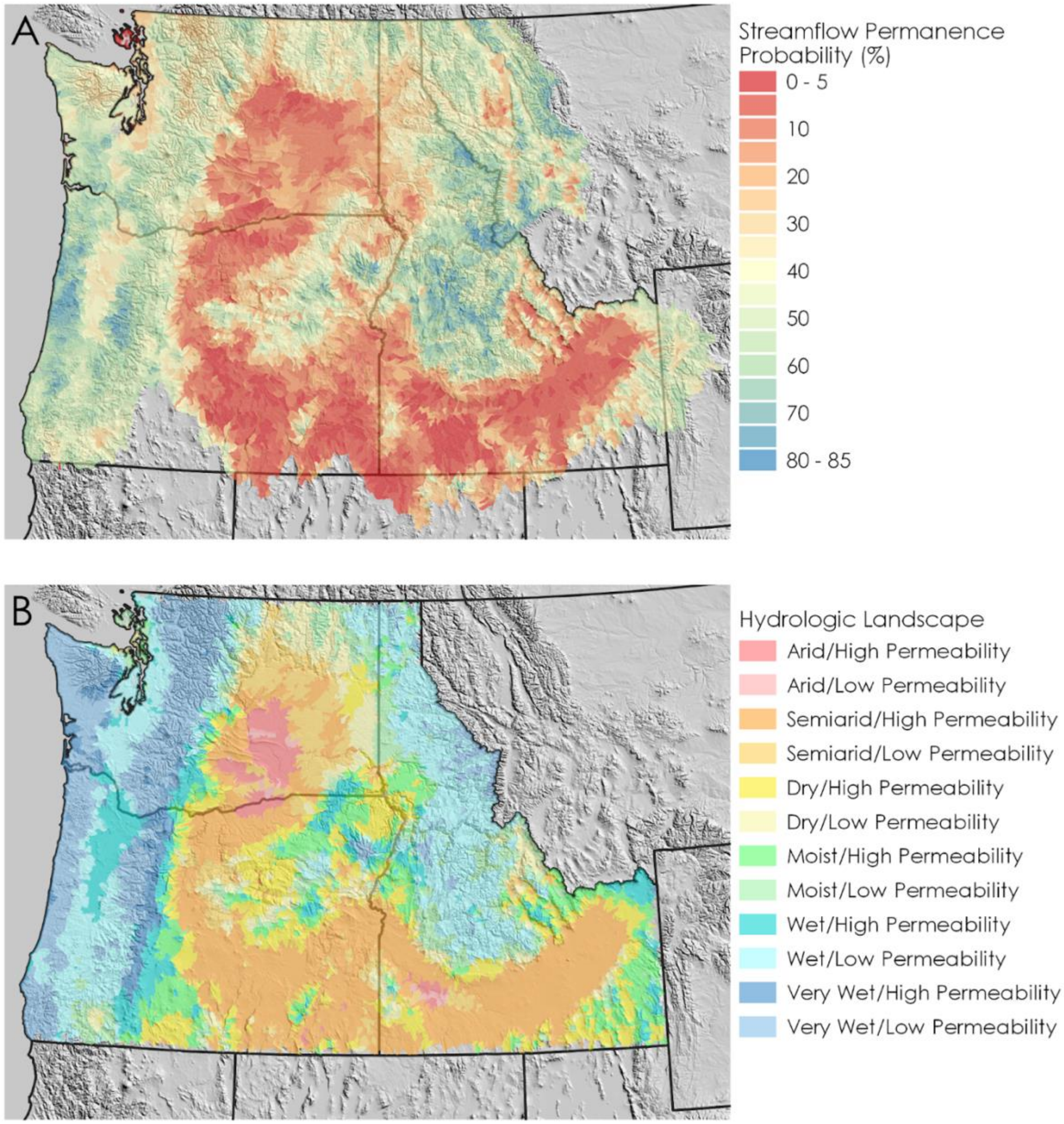

Figure 3: *Maps of (A) Stream Permanence Probability and (B) Hydrologic Landscapes across the Northwest. In (A), the likelihood of year-round stream permanence was calculated using the U.S. Geological Survey's PRObability of Streamflow PERmanence (PROSPER) model (Jaeger, et al., 2019). In (B), different Hydrologic Landscapes are shown based on wetness and aquifer permeability class (Leibowitz et al., 2016). These maps show the wide range of climatic and physical conditions that exist across the Northwest. These varied conditions create complex place-based stream permanence patterns. Maps like these can help scientists and managers identify similar hydrologic settings to build cross-municipal/regional research and working groups to address climate impacts to stream drying. Developed by James Robinson.*

4.3 | How are ecosystems impacted by changes in stream permanence?

Climate change-driven changes in stream permanence impact individual species, including fish, amphibians, macroinvertebrates, riparian plants, and animals that depend on riparian habitat, as well as ecosystems as a whole. Of particular concern are the culturally important species (e.g., Pacific lamprey, salmon populations, the freshwater mussel) that threaten the livelihood, spiritual relationships and cultural connections of Tribal communities. These cultural connections are strongly tied to the health and biodiversity of aquatic ecosystems.

Changing stream permanence can alter ecosystem functions including water quality, nutrient cycling, and ecosystem response to disturbances. The ecological implications of changing stream permanence are context-dependent and vary across ecological and climatological gradients in the region. The relative importance of snow vs rain and geologic features governing connections to groundwater both affect the vulnerability of stream permanence to changes in climate as well as the ecosystems, species, and land/water use activities that can occur in a given place. While changes in stream permanence have been observed across these gradients, most research on ecological impacts comes from relatively dry areas, where baseflow is low and changes to the precipitation regime are already occurring (i.e., transition from snow- to rain-dominated or decreased precipitation/increased drought and evapotranspiration). With continued climate warming, impacts are likely to occur more frequently in wetter areas where less research has been conducted, while impacts in dry areas may change as warming intensifies. Similarly, the downstream and cumulative watershed effects of stream drying are likely significant and have only recently been the subject of one collaborative research effort (AIMS, or Aquatic Intermittency effects on Microbiomes in Streams; https://osf.io/ga8uk/).

Many stream-dependent species are threatened by changes in stream permanence, but identifying thresholds of vulnerability to drying remains challenging for many taxa. Reduced water availability threatens native fish populations through habitat fragmentation, increased predation and loss of pools for refuge during extreme and anomalous droughts (Poff and Zimmerman 2010, Perkin et al. 2019, Parker et al. 2021). Many species that depend on non-perennial streams are adapted to hydrologic variability, suggesting some level of tolerance to changes in stream permanence (Zimmer et al. 2020). Fish species that rely on intermittent streams for habitat, especially in arid or semi-arid systems, often have opportunistic life history strategies including short life spans and early reproductive maturity that allow individuals to capitalize on favorable conditions (Perkin et al. 2019). Similarly, salmon populations of a given species often respond differently through adaptation to their local habitat to the same set of environmental conditions (Moore et al. 2010). For example, variability in growth rates and migration timing result in populations with variable life histories (Achord et al. 2011). This allows persistence of the species through variable hydrologic conditions, even if individual populations collapse (Ward et al. 2015).

In spite of adaptations like these, projected changes in stream permanence, especially those associated with changes in the amount and timing of snowpack, are likely to exceed the range of conditions to which species are adapted (Leigh et al. 2016).

Most of the evidence of negative effects from changes in stream permanence on fish comes from arid and semiarid ecosystems (Ruhí et al. 2015, 2016, Perkin et al. 2019, Parker et al. 2021). Nonetheless, observations do show impacts (e.g., altered fish behavior) that are the result of low flow events across the Northwest region. Examples include increased reliance on cover from boulders and large wood for refuge from predators, and changes in the placement of redds within the channel for Pacific salmon and trout (Ward et al. 2015, Penaluna et al. 2021). Groundwater inputs may become increasingly important for maintaining local refugia for fish (and other aquatic species) as drying continues (McLaughlin et al. 2017; Larsen and Woelfle-Erskine 2018). Further, small fish species that can persist in localized habitat may be less vulnerable to stream drying than large fish species that require large areas of perennial habitat with high connectivity (Allen et al. 2019).

Within the stream channel, aquatic invertebrates (e.g., insects, microcrustaceans, gastropods) have similar adaptations as many fish species to flow intermittency, and often seek refuge in residual pools or migrate to the hyporheic zone during dry periods (Zimmer et al. 2020). However, as stream drying continues, aquatic invertebrate species present within a stream are likely to shift toward species adapted to flow regimes with longer dry periods (England et al. 2019). Given their adaptation to specific flow regimes, aquatic invertebrate composition can serve as biological indicators of flow regime change (Chadd et al. 2017, England et al. 2019). Shifts in the aquatic invertebrate composition may also have cascading effects on the food web, although studies are lacking. Amphibians represent a taxonomic group for which physiological thresholds to stream drying are relatively well-understood, given their high sensitivity to dehydration (Lertzman-Lepofsky et al. 2020). Although some amphibian species may be able to adapt their behavior to survive individual dry years (e.g., northern leopard frog observed laying eggs in deeper part of the stream channel in a dry year, Dennis Longknife personal observation). Amphibians that are dependent on headwater streams or montane wetlands to complete their life cycles are particularly at risk due to projected losses of both habitat types, possible loss of connectivity or already low connectivity (Ryan et al. 2014, Lee et al. 2015, Olson and Burton 2019).

Changes in stream permanence are likely to affect many species beyond those that occupy the stream channel. Birds, small mammals, and ungulates are dependent on riparian areas for water sources, forage, and habitat, while carnivores rely on prey from these areas, and many deciduous tree species dominate only within riparian areas (Gomez and Anthony 1998, Jenkins et al. 2013, Averett et al. 2017, Levi et al. 2020). Changes in stream permanence may decrease habitat and/or food sources for many species that depend on riparian areas. However, little is known about how these species will respond to increased stream drying and what the implications may be for their populations.

Ecological diversity can buffer stream-dependent plant and animal communities against negative effects of stream drying. In addition to individual species effects, changing stream permanence is likely to have effects on plant and animal communities as a whole. For example, riparian vegetation communities are vulnerable to increased mortality, non-native invasion, and desertification where flows are decreased (Poff and Zimmerman 2010). This vulnerability varies with community composition. Where there is high plant diversity in riparian areas along non-perennial streams, a variety of plant traits and functions can buffer plant communities against variable conditions (Shanafield et al. 2021, Scott and Merritt 2020). Similarly, macroinvertebrate communities often retain functional composition (i.e., species with similar traits) over time and hydrological fluctuations, despite fluctuations in which species are present over time (Leigh et al. 2016).

Low ecological diversity can also leave habitats more vulnerable to invasion by non-native species tolerant of dry or variable stream conditions, both in the riparian zone and within the stream channel (Poff and Zimmerman 2010). Invasion by non-native fish may compound the effects of stream drying on native fish species through multiple mechanisms. Non-native species often have greater survival rates during drought conditions and can outcompete native species for resources (Ruhí et al. 2015, Parker et al. 2021). Predation of native fish by non-native fish can also be exacerbated when available habitat is decreased (and prey density increases) under low flow conditions (Propst et al. 2008). Non-native fish have further negative impacts on native fish through crowding and increased disease transmission (Gozlan et al. 2010). Non-native predatory fish introductions have also resulted in disruptions to food webs in montane lakes, pushing native frogs, salamanders, and invertebrates to ephemeral ponds that are most susceptible to climate change (Ryan et al. 2014). Understanding how changes in stream permanence interact with species invasions is important for predicting ecological changes in plant and animal communities. Insights regarding ecological diversity may be particularly important to incorporate when considering stream restoration activities, post-disturbance management, and planning in urban and residential areas.

Changes in stream permanence can influence ecosystem processes with potential downstream and cascading effects. Nutrient cycling within non-perennial streams is subject to high magnitude change throughout the wet-dry period (Zimmer et al. 2020). Stream chemistry shifts over the season as drying occurs (MacNeille et al. 2020), and hypoxic events (characterized by low dissolved oxygen) are triggered when flow returns and dissolved organic carbon is mobilized (Leigh et al. 2016). Low levels of dissolved oxygen can lead to low survival of fish and aquatic invertebrates, especially where there is little exchange with shallow groundwater (Woelfle-Erskine et al. 2017, Zimmer et al. 2020). Excess nutrients, pesticides and heavy metals from agricultural and industrial practices can also concentrate within sediment of dry reaches and mobilize at high levels following the return of streamflow, degrading water quality (Ademollo et al. 2011).

Stream biofilms (bacteria, fungi, and algae), which play an important role in biogeochemical cycling in non-perennial streams, change rapidly with respect to composition and function across the dry-wet cycle (Timoner et al. 2012, Colls et al. 2021). Litter decomposition, nutrient release rates, and soil carbon storage are considerably lower in drier flow regimes, suggesting that these changes can be expected as streams go dry (Lohse et al. 2020). Further, streams can act as sources of carbon dioxide to the atmosphere (Raymond et al. 2013), though the effect of how drying on atmospheric gas exchange is poorly understood.

Changes in stream permanence can alter ecosystem functions including sediment deposition and habitat connectivity. Altered sediment dynamics can in turn influence streamflow and infiltration, thereby potentially further altering stream permanence, but understanding of this relationship is limited (Shanafield et al. 2021). Changes in stream permanence are also connected to drying in lakes and wetlands, which can lead to disconnected habitats and isolated populations of wetland- and lake-dependent species, as well as disruptions to food webs and nutrient exchange between habitats (Lee et al. 2015; Streib et al. 2021). Stream drying can have ecological implications that accumulate downstream (e.g. decreased habitat connectivity from tributaries to mainstem, concentration of pollutants or nutrients), yet few studies have quantified cumulative impacts on downstream conditions or the environmental response time of such impacts. However, this is an active area of research, with collaborative groups such as Aquatic Intermittency effects on Microbiomes in Streams (AIMS, https://osf.io/ga8uk/) working to understand downstream effects of changing stream permanence.

Land and water use activities, and increased disturbance activity may interact to exacerbate effects of stream drying on ecosystems, but activities and effects are place-dependent. Many land and water use activities have a strong influence on stream permanence. Logging is common across much of the region where precipitation is sufficient to support forest cover. Although summer streamflow increases for the first decade following clearcut harvest (Costigan et al., 2016), by the second decade post-harvest, evapotranspiration rates are high in young regrowth resulting in decreased summer streamflow compared with an old growth forest (Jones and Post 2004). Further decreases in summer streamflow are typical until at least 50 years post-harvest (Perry and Jones 2017, Gronsdahl et al. 2019, Segura et al. 2020, Crampe et al. 2021). However, in systems with a seasonal snowpack, harvest can lead to increased streamflow during the snowmelt period for several decades (Jones and Post 2004). Although riparian buffers can help maintain cooler stream temperatures following logging (Janisch et al. 2012), effects on low flow stream conditions vary (Coble et al. 2020). Compared with mature forest, riparian buffers composed of young conifer trees can lead to decreased stream permanence through increased evapotranspiration (Segura et al. 2020). Effects of promoting early successional (i.e., non-tree dominated) conditions following harvest are poorly understood, as most research is focused on effects following replanting.

Fire suppression, a central focus of land management for most of the past century, represents both a water use activity and has led to substantial land cover change in forested regions. For example, conifer encroachment has led to a decline in wetland meadows due to the interception of precipitation and increased evapotranspiration from trees, both of which lead to a reduction in available surface water (Lubetkin et al. 2017). Grazing is common, especially in arid and semi-arid areas within the region, and can alter floodplains and degrade stream and riparian habitat through vegetation removal, soil compaction, and increased erosion (Goss and Roper 2018, Kovach et al. 2019). Direct effects of both fire suppression and grazing on stream permanence are poorly understood, and additional research is needed to connect observed effects on wetland meadows and floodplains to changes in streamflow, timing, and connectivity.

There is evidence that alternate management strategies could avoid many of these impacts. For logging, decreasing compacted area (e.g., roads, skid trails, landings) can increase infiltration and groundwater recharge, while reducing clearcut harvest unit size and promoting a diversity of species in post-harvest stands can decrease the duration and magnitude of high evapotranspiration rates from young regrowth forests (Coble et al. 2020). Thinning may improve stream permanence compared with clearcut harvests, but this effect often declines over time (Coble et al. 2020). Similarly, adjustments to grazing intensity and duration and fencing to keep livestock away from riparian areas can both substantially decrease habitat degradation associated with grazing (Swanson et al. 2015, Fesenmyer et al. 2018). For example, implementation of alternative grazing practices can increase beaver activity by creating more favorable riparian habitat, with one study showing that these effects combined can lead to an increase in >250 mm in water year precipitation (Fesenmyer et al. 2018).

Human-caused alterations to streamflow (i.e., through water use) can disrupt riparian vegetation through several mechanisms. Groundwater pumping can lead to stream drying, and can result in the depletion of fish habitat (Falke et al. 2011; Perkin et al. 2017) and rapid decline and mortality of riparian vegetation, especially when the water table changes too rapidly for plants to respond by reducing leaf area (Scott et al. 1999). Surface-water withdrawals leave less water in the streams and can result in abrupt changes to discharge when water demands are further stressed by heat events (e.g. late in the irrigation season; Deitch et al. 2009, Benejam et al. 2010). Drainage from agricultural fields (e.g., tile drainage), in contrast, can increase stream permanence by supplying additional surface water to streams (Schilling and Helmers 2008; Klaus et al., 2013). Although recycled water inputs (e.g. drainage from agricultural fields or treated wastewater in urban areas) can contribute to a positive feedback between riparian canopy cover and streamflow permanence, such water subsidies can also disrupt successional processes and undermine native plant adaptations to natural hydrologic variation, leaving them less resilient to future drying (Rohde et al. 2021).

Land use changes such as urbanization or afforestation/reforestation efforts can also promote intermittent flows by altering the flashiness of a basin (Rolls et al., 2012; Walsh et al., 2005) and increasing evapotranspiration, respectively (Azarnivard et al., 2020; Costigan et al., 2016). Although many land and water use activities affect stream drying, little is known about their combined effects or how they will vary across ecosystems.

Drought, heatwaves, and fire activity are expected to increase in frequency and severity across much of the region with climate change. Increasing occurrence of droughts and heatwaves is expected to lead to increased transition of perennial streams to non-perennial, and this effect is likely to be compounded by effects of land and water use activities (Larsen and Woelfle-Erskine 2018). Fire has direct impacts on streams through increases in stream temperature, run-off, erosion, and streamflow immediately following fire (MacNeille et al. 2020), and can lead to indirect impacts through changes in evapotranspiration over time as the riparian and upland environment recovers (Niemeyer et al., 2020). As disturbance activity increases, drought and fire are likely to overlap in time and space more frequently, with the potential for compound effects that degrade fish habitat (Schultz et al. 2017) and lead to post-fire vegetation transformation (Krosby et al. 2020). Little is known about the specific consequences of increased disturbance for stream permanence, nor how different ecosystems may respond to these changes over time. Further, post-fire management responses, such as salvage logging and active reforestation, have unknown impacts on stream permanence.

Table 3. *Research and capacity needs related to ecosystems*

Guiding Question: **How are ecosystems impacted by changes in stream permanence?**	
Research Needs	Capacity Needs
• Identify thresholds of change in stream permanence that lead to species loss and ecosystem transitions • Quantify effects of changing stream permanence on land-atmosphere and groundwater-surface water feedbacks • Study effect of increased temporal and spatial hydrologic variability on ecosystems • Evaluate effect of land-water use activities on stream permanence,	• Improve collaboration between Tribes and non-Tribal agencies to promote more Tribal involvement and use of Traditional Knowledge on non-Tribal lands • Foster collaboration between hydrologists and ecologists to integrate ecological data collection with stream observation networks • Engage interdisciplinary collaborative teams to develop integrated maps of ecosystem vulnerability and capacity to adapt to changes in stream permanence that can assist in policy/management

and how they vary across the urban-wilderness gradient • Study effects of increasing disturbance activity on stream permanence and combined effects on ecosystems • Develop of trait-based models for understanding potential effects on species where observational data are lacking • Develop models of adaptive capacity that link ecosystem-scale function with change in community composition and individual species over time • Study species-specific responses to low flows and drying using standardized methods that take into account multi-scale impacts and adaptive capacity • Use regional landscape models to quantify vulnerability of ecosystem values (e.g., species, processes, ability to conduct land/water use activities). Models should integrate hydrology, land/water use activities, land cover, and ecosystem processes. • Obtain data to support the development of regional landscape models. • Integrate place-based local knowledge with biophysical observations (e.g., stream gauging). • Evaluate connectivity between non-perennial streams and watersheds, in particular to quantify the effects of changing stream permanence on downstream ecosystems	decision-making and can identify locations for “living laboratories” to study ecosystem resiliency • Training and educational outreach on the use of culturally-relevant science for species and ecosystem management • Facilitate knowledge exchange across the region through a platform for sharing local observations and place-based narratives of ecological impacts related to changing stream permanence

4.4 | What land and water stewardship approaches and tools can help address changes in stream permanence?

There are many approaches and tools that can directly or indirectly help water stewards address changes in stream permanence. Information on these strategies can be drawn from case studies directly related to changing stream permanence, the environmental flow literature, and restoration work. Though there are a variety of options available to land and water stewards, the collective understanding of the effectiveness of specific approaches to mitigate changes in stream permanence is quite limited. Deep Dive participants emphasized the need for localized studies, as well as studies across scales, to better understand the effectiveness of various land and water stewardship approaches.

Many resource stewardship actions can have impacts on stream permanence. In the cross-jurisdictional Northwestern landscape, various land and water stewardship actions offer opportunities to achieve a diversity of goals related to stream permanence. In some cases, stream permanence is a co-benefit of approaches that may address other conservation- or restoration-focused goals (for example, forest thinning for wildfire risk reduction). Other actions directly target changes in stream permanence. For example: updating presumptive standards (Gleeson and Richter 2017) for groundwater withdrawals, providing water transfer incentives, and promoting aquifer recharge. Table 4 provides a non-exhaustive list of both direct and indirect actions identified in the literature (primarily in the low-flow rather than stream permanence literature), or by Deep Dive participants, that could potentially address changing stream permanence in the Northwest. Some of these actions have already been included in climate change mitigation plans or have been implemented by land and water stewards, particularly by Tribal governments (source: Deep Dive survey responses). Additional resources are listed in Table 5.

Table 4. *Example land and water approaches for mitigating changes in stream permanence.*

Land Stewardship Approaches	Water Stewardship Approaches
Agriculture & Rangeland • Tile drainage (Klaus et al., 2013 ; Schilling and Helmers 2008) • Water storage to offset withdrawals for agriculture during extreme temperatures • Transition to crops with lower water use • Reduce near-stream grazing • Other strategies and educational programs for sustainable farming and ranching can be found here: (Holistic	**Groundwater & Springs** • Groundwater withdrawal presumptive standards (Gleeson and Richter 2017) • Well permits (e.g., drill below aquitard or in aquifers that are separated from tributaries) • Increase aquifer recharge (e.g., detention ponds, increased permeability in urbanized areas) • Preserve natural conditions around spring sources

Management Institute; Petersen et al., 2019) **Forestry** • Forest management (e.g., gap creation) to increase snow retention (Jones and Post 2004) • Thinning of overstocked forests to reduce ET (Roche et al., 2018) • Reduced clearcutting (Coble et al. 2020) • Staggered replanting after clear cutting or wildfire to reduce ET demand of young trees **Floodplain & Riparian Zone** • Designate riparian management zones (RMZ) for ephemeral streams and non-perennial headwaters streams (Kampf et al., 2021) • Update outdated state RMZs • Riparian buffer restoration • Replanting with species that consume less water • Floodplain restoration & connectivity to increase groundwater exchange **Urban Ecosystems** • Building designs founded in climate and environmental science (e.g., Net-zero passive houses by ValiHomes) • Bigger bridges that don't disrupt riparian and floodplain functioning	• Maintain environmental flows using metrics that account for the timing of ecosystem impacts by groundwater pumping (e.g., environmental response time; Gleeson and Richter 2017) • Engineered or natural catchments (e.g. wetlands) to promote groundwater recharge **Surface Water** • Stream and estuary habitat restoration • Restore beaver populations (https://nr.tulalipTribes.com/Programs/Wildlife/Beaver) • Minimum streamflow regulations • Channel restoration to increase shallow groundwater storage • Increase channel complexity • Remove diversions from non-perennial streams • Instream leasing of water rights **Combined Water Sources** • Promotion, education, and implementation of water conservation practices (timing and quantity restrictions, incentives, or volunteer options) • Repair or update irrigation infrastructure • Water reallocation, under drought conditions, that prioritizes community values • Increase flexibility and use of water transactions (volunteer programs; incentives) • Legislative actions (e.g., water right protest applications) to prevent new water withdrawal permits

	Urban Water Management • Expand recycled water infrastructure, usage and education • Incentives/regulations for low-flow water appliances

Existing studies document a clear impact of land and water stewardship actions on stream permanence. Nevertheless, isolating the impact of a particular stewardship approach from other changes is extremely challenging. When documented, effectiveness studies typically focus on impacts on environmental low flows, with results that are scale and system specific (Rolls et al., 2012). As one Deep Dive Advisory Group member puts it, *"There are many factors involved in these systems, so it is difficult to accurately predict outcomes of a particular action"*. Further, the complex, often cross-jurisdictional connectivity of these Northwestern stream systems and the factors that impact them can decrease the transferability of such studies from one location to another. Nonetheless, there are a few case studies that directly mention stream permanence.

One particularly useful resource for case studies is the collaborative (written, funded, and implemented) 30-year Yakima Basin Integrated Plan, which documents a number of projects aimed at community-driven sustainable water management and ecosystem restoration in the Yakima River Basin of Washington State. A notable project, with the goal of increasing fish passage, involved the removal of a diversion from Manastash Creek. Since the removal, summer flow has been restored in the lower Manastash Creek, which prior to restoration had gone dry by mid-July. In addition, steelhead have returned to parts of the creek that had been unpassable for over a century (Office of Columbia River 2018). Other Yakima Basin projects currently being implemented include crack sealing of an old irrigation channel which is expected to conserve nearly 700 ac-ft of water annually in the Roza Irrigation District, and an expansion of the current Yakima River Basin water market programs to an estimated 30,000 to 60,000 ac-ft of water available for market-driven reallocation (Office of Columbia River 2019). This market-driven water reallocation provides financial incentives for water conservation and facilitates the transfer of low-value water uses to high-value water uses during periods of low water availability.

At the federal level, riparian management zone (RMZ) designations limit or recommend limitations on certain land use activities around both perennial and non-perennial streams in an effort to maintain stream habitat and ecosystem functions. US Forest Service monitoring of these RMZs indicate a general effectiveness in protecting water quality of perennial streams from forest management activities such as logging (Cristan et al., 2016). However, evaluations of RMZ effectiveness rarely mention non-perennial streams and most states do not even designate RMZs for ephemeral streams (Kamp et al., 2021).

Further, many states have not updated their guidelines (both permitted activities and intermittent designations) for perennial and intermittent stream RMZs to account for changing climate conditions in the past 10-20 years (Kamp et al., 2021).

Additional studies are needed that specifically address management effects on stream permanence. Specifically, case studies at federal, state, regional, and local scales that evaluate the effectiveness of stewardship actions that specifically target climate-induced changes in stream permanence. Until there are more accessible, transferable evaluation studies, alternative approaches can assist decision-making by land and water stewards to meet the goals of preserving in-stream flows. For instance, conservation or restoration-focused actions "*that will likely yield co-benefits (improved habitat, or other ecosystem services) can increase the likelihood of desirable outcomes [for stream permanence],*" as suggested by one member of the Deep Dive Advisory Group. An example case study is the Tulalip Tribe Beaver Project (https://nr.tulalipTribes.com/Programs/Wildlife/Beaver) which aims to relocate nuisance suburban beavers to tributaries in the upper Snohomish Watershed. Increasing beaver populations in hydrologically impaired streams can improve cold water rearing habitat for salmon, and increase summer month water availability by 20% (Dittbrenner 2019), though not all beavers build dams and the hydrologic impacts of relocation studies vary (Nash et al. 2021).

Table 5. *Additional resources for land and water stewards interested in mitigating changes in stream permanence. Though some of these options originate in the Northwestern US, others are drawn from the international literature which focuses predominantly on low-flow conditions or on adjacent stewardship topics (Table below).*

Holistic Planning Strategies	• Landscape science focused planning
	  ○ Applies principles of landscape ecology and cross-jurisdictional interactions to support decision-making (Carter et al., 2020)
	• Place-based water planning
	  ○ Incorporates community values
	  ○ e.g., Harney Basin Community-Based Water Planning Collaborative (https://harneyswaterfuture.com/)

Stewardship Decision Frameworks	• Resist, Adapt, Direct framework
	  ○ Assists decisions on whether to resist change, adapt to change, or direct change
	  ○ e.g., Lynch et al., 2021
	• Holistic flow frameworks
	  ○ Incorporates input from diverse stakeholders
	  ○ Can be used to evaluate the social and cultural implications of water stewardship actions

	○ e.g., Arthington et al., 2018; King et al., 2003; Opperman et al., 2018; Jackson et al., 2015; Lokgariwar et al., 2014; Conallin et al., 2017; Capon et al., 2018
Stream Permanence Knowledge Sharing Resources and Networks	• USDA Northwest Climate Hub ○ Highlights adaptation case studies, provides climate adaptive management recommendations, provides educational resources, vulnerability assessments, and climate adaptation toolkits (https://www.climatehubs.usda.gov/hubs/northwest) • Instream Flow Council ○ Training and informational opportunities ○ List of state specific regulations, recommendations, and decision support tools (https://www.instreamflowcouncil.org/) • Climate Adaptation Knowledge Exchange (CAKE) ○ Provides climate-adaptation case studies, virtual resources, tools database, and networking opportunities • (https://toolkit.climate.gov/tool/climate-adaptation-knowledge-exchange-cake)
Tools to Advise Stewardship Decisions	• Flow models ○ Forecast changes in flow conditions ○ PROSPER ○ Watershed Flow Evaluation Tool (Sanderson et al., 2011) • Restoration tools ○ Riverscape Consortium Tools https://riverscapes.xyz/Tools/ ○ Low Tech Process Based Restoration of Riverscapes (Wheaton et al., 2019) • More comprehensive models and tools list available here (link to tools database) • Environmental response time metrics ○ Quantification of the timescales for groundwater pumping to impact environmental flows (Gleeson and Richter 2017) • Community sourced field data collection ○ Low cost data collection procedures (e.g., Njue et al., 2019) ○ StreamTracker Project https://www.streamtracker.org/

__Table 6.__ Research and capacity needs related to practice

Guiding Question: **What land and water stewardship and management approaches and tools can help address changes in stream permanence?**	
Research Needs	Capacity Needs
• Applied hydrologic research that is guided by watershed managers and water users • Place-based narratives for case studies and evaluations of stewardship actions to directly address changes in stream permanence • Evaluation of decision tradeoffs, particularly the Resist, Adapt, Direct (RAD) options related to stream permanence • Evaluation of various timber and agricultural "best management practices" on stream permanence • Identification of multi-benefit stewardship approaches that can be applied in the short-term and adaptively adjusted according to monitoring and evaluation efforts	• Identification of opportunities and options for diverse management and stewardship pathways • Application of decision frameworks to manage stream permanence for community priorities and goals • Synthesis of utility and limitations of existing hydrologic models for predicting stream permanence • Case studies database or other centralized data hub for stewardship approaches and data/terminology standardization • Expansion of RAD decision framework for post-fire vegetation transitions to include changing ET impacts on stream permanence (Krosby et al., 2020; Williams 2021 for more information on RAD framework) • Education and implementation of adaptive management strategies • Funding structures that allow for time consuming feedback loops (e.g., implementation of mitigation actions, environmental response, monitoring, and changing climate conditions) • Decision-support tools that reflect the state of the science

4.5 | How are communities connecting multiple forms of knowledge (e.g. Traditional Knowledge, local knowledge and western science) to address drivers and impacts of stream permanence?

Linking different forms of knowledge with science and decision-making about climate change impacts on stream permanence has the potential to open-up new ideas, increase collaboration and knowledge sharing and advance communication through developing shared understanding of the challenges and possible solutions.

Incorporating different forms of knowledge, especially Traditional Knowledge, into science and management decisions can facilitate equitable, innovative outcomes related to decisions that affect stream permanence. Some communities are responding to changes in stream permanence by implementing place-based collaborative governance. Collaborative governance is a process of consensus-oriented decision making and management driven by discussions between local stakeholders and public agencies (Ansell and Gash, 2008). For example, the Yakima Basin Integrated Plan for sustainable water management in Washington State's Yakima Basin brings together state, Tribal, private, and federal partners to plan, fund, and implement a three-phased program to mitigate basin-wide water supply issues and wildlife loss (Washington State Department of Ecology, 2013).

Collaborative approaches to managing water present both opportunities for innovative and equitable outcomes, as well as challenges. Opportunities include greater coordination and cooperation among community members and stakeholders, more flexibility for implementing socially equitable practices, locally-relevant management decisions based on multiple forms of knowledge, including western science, community knowledge, and traditional ecological knowledge (Flitcroft et al. 2016; Oliver and Flitcroft, 2011). For example, Sheoships (2014) used both Traditional Ecological Knowledge (TEK) and western science to evaluate Pacific lamprey populations in the Willamette River Basin to investigate possible reasons for population decline. This approach captured Indigenous knowledge and cultural values relating to Pacific lamprey, as well as longitudinal information on species-habitat relationships, and potential ways climate change influences the futures of the culturally and ecologically important species. There are also challenges to implementing approaches like these. Challenges may include lack of resources and social fabric to implement long-term coordination efforts and excluded voices (Woelfle-Erskine 2017).

Recent community governance efforts in the PNW have explicitly recognized the need for sensitivity, equity, and respect for place. For example, the Confederated Tribes of the Umatilla Reservation used the creation concept of reciprocity and first foods to frame and guide local water protection and conservation work (Quaempts et al., 2018). Other communities have used transgressive knowledge collaborative frameworks, which explicitly attempt to decolonize science by recognizing all forms of knowledge equally (Woelfle-Erskine, 2017).

This approach is unique in that it decenters western science, facilitates the sharing and exchange of community knowledge through working groups, and is specifically intended to be useful beyond academic settings. The approach was implemented in the Salmon Creek watershed, California, through annual workshops that brought willing community members together to share data, citizen science, and knowledge, which contributed to the way that water shortages were locally addressed.

Advisory Group members emphasized the valuable knowledge held by members of the agricultural community, given their experience innovating and testing new practices that address flow conditions. These include water trading, increasing irrigation efficiencies, plant selection, harvest timing, and others. While farmers often have ideas on how to manage water to support streamflow, they are often siloed from conversations where they could share their knowledge, and from funding sources and associated research communities to test those strategies. Intentional engagement with agricultural communities early on in the problem identification and decision-making process could facilitate generation of new ideas that have co-benefits.

Several projects have used community science approaches to gather local knowledge about wet and dry reaches of intermittent rivers. These include recent studies investigating spatial and temporal patterns of drying in the southwestern US (Allen et al. 2019), Colorado (https://www.streamtracker.org/), and the northwest with FlowPer (Jaeger et al. 2020). While the value of community science is well-accepted, the subsequent impacts on community knowledge and perceptions are understudied.

Table 7. *Additional research and capacity needs related to Human Dimensions.*

Theme: Human dimensions	
Guiding Question: **How are communities connecting multiple forms of knowledge (e.g. Traditional Knowledge, local knowledge and western science) to address drivers and impacts of stream permanence?**	
Research Needs	Capacity Needs
• Co-develop tools, protocols and research with Tribal communities that integrate Traditional Knowledge with western science to better understand climate change impacts on stream permanence, and options for responding to these changes. • Identify and evaluate the potential of existing collaborative efforts to understand and address climate	• Elevate experience and expertise of Tribal Nations: Support opportunities (e.g., workshops, field trips and case studies) for sharing relevant knowledge and practices used by Tribal Nations with other Tribes, local and federal governments, and the public. • Application of collaboration frameworks that are culturally sensitive, respectful, and equitable (e.g., ethical space and

impacts on stream permanence using case studies and other assessments (e.g. collaborative efforts with Tribal and Indigenous entities, farmers, community science)	two-eyed seeing frameworks Bartlett et al., 2012; Ermine 2007) • Support Tribal communities leading efforts while addressing the needs of Indigenous communities and supporting Tribal sovereignty and self-determination. • Expand collaborative monitoring networks that promote diversity, equity, and inclusion

4.6 | What are the challenges and opportunities surrounding stewardship/management decisions related to stream permanence?

Responding to changes in stream permanence is challenging: priorities vary from one community to another, the scales of biophysical importance do not correspond with social and jurisdictional boundaries, and western water law severely limits both the incentives and the flexibility to make changes. Yet, these challenges also point to opportunities to change the way we manage these systems. In this section we highlight the importance of collaborating across interests, planning at the watershed scale, and devising better ways to allocate water.

The scale of river systems are mismatched with those of social systems and associated expectations. Watersheds rarely align with the cultural, jurisdictional, economic, or other domains over which humans engage with the landscape. As a result it is typical to find a variety of overlapping authorities and institutions, and a divergent range of expectations and interests regarding how to engage with and steward the landscape. This is a challenge for coordination and is the primary motivation behind watershed coordinating bodies such as the Watershed Councils in Oregon and the Water Resource Inventory Areas (WRIAs) in Washington.

The mismatch in scale between river systems and social systems make it difficult to pursue the kind of watershed-scale strategies that are likely to be both cost effective and provide the greatest benefits to people and ecosystems. State and federal land management agencies typically manage most of the upper elevations of many watersheds, whereas the lower elevations are typically either municipal or unincorporated agricultural lands. Many Tribes, in contrast, historically occupied land extending well beyond the limits of a single watershed. Each has a different set of needs and priorities, and rarely do all parties collaborate on identifying shared solutions.

Similarly, data collection is rarely coordinated across jurisdictions, leading to a patchwork of observations across the landscape. Even when these do cross jurisdictional boundaries, observational networks are typically designed to serve a particular interest (Smith et al., 2021). For example, EPA requires reach-level observations and modeling to classify streams given the implications for regulation under the Clean Water Act and the high potential for litigation. This level of detail does not lend itself to generalization across larger landscapes, as is done with the USGS PROSPER model, though the PROSPER data could be quite useful in other contexts for setting large-scale land management priorities.

Priorities for resource stewardship differ according to community, jurisdiction, and role. Nearly all responses from Tribal participants, representing over ten Tribes, mention fish population or habitat as their major concern for changing stream permanence. Many respondents specifically name impacts related to salmonid populations, including rearing habitat, access to cold water passages, treaty rights, and food security. As one participant noted:

"Anadromous fishes are critical to economic stability and food security in our communities. These species are extremely vulnerable to progressive, climate related changes in regional marine ecosystems and local freshwater habitats".

These priorities reflect the cultural and spiritual connection to stream corridors and the wildlife habitat they support on Tribal lands. Similarly, the priorities of non-Tribal local or regional government organizations reflect the interests and values of communities they serve. For instance, in regions where agriculture is the principal water demand, irrigation supply and water conservation strategies are major priorities for county or state water resource agencies:

"Many landowners rely on water from nearby creeks and rivers for their crops and livestock and it is often a concern in my work to take measures to reduce water waste, evapotranspiration, and evaporation".

When planning future water usage and regulation, state agencies must balance competing water priorities such as protecting and restoring Endangered Species Act listed species, ensuring adequate water supply to support community growth, improving water quality, and reducing flood risk. These competing priorities were noted, and attributed to a frustrating lack of mitigation action, in many stories and reflections shared by Deep Dive participants. At the federal level, priorities for the resource management agencies include management uses and actions that promote biodiversity, protect headwater streams, preserve stream ecological functioning, and recognize an ever-growing societal water demand. A number of federal funding programs are available to support water conservation investments, educational programs, restoration projects, and data collection initiatives, though these programs are not accessed to their fullest extent by many state and Tribal governments (Kim et al., 2021).

Northwest water law limits water redistribution in many regions where water resources are fully allocated. Western water law is generallerally built on the prior appropriations doctrine, which establishes water rights for "beneficial use" (e.g., irrigation, agriculture, drinking, recreation) by water user seniority -- "first in time, first in right". While this has largely been a useful mechanism to regulate water as a limited resource, the associated legal mechanisms make the system relatively inflexible. For example, voluntary water rights transfers are often considered a good mechanism for a senior water rights holder with excess water in a given year to supplement in-stream flow or divert flow to another, more junior water user in need. Similarly, water banking, or alternative water markets have been posed as viable adaptive management mechanisms to allow an irrigator to temporarily sell their water rights to another user. While practical in theory, the process for instituting these water transfer mechanisms poses significant bureaucratic and legal barriers (Flaccus and Peterson, 2021). Furthermore, poor outcomes from mismanaged water transfer programs limit their adoption elsewhere (Clarren, 2005). The highly bureaucratic nature of water rights management is further complicated by legal variations between states and the inherent challenges of institutional and policy change.

While there are other conservation policy mechanisms that may also have positive impacts on stream permanence, there has been limited research on the co-benefits of these policies (e.g., soil health, reduced erosion, reduced nutrients to the stream), particularly with regards to intermittent streams (Stahl et al., 2021). As with the management of any social-ecological system, the mismatch between jurisdictional areas, funding sources, and uniqueness of a given location and community priorities makes identifying policies that would be beneficial for the region as a whole near- impossible.

Table 8. *Additional research and capacity needs related to Practice.*

<table>
<tr><th colspan="2">Guiding Question: What are the institutional and policy contexts surrounding stewardship and management decisions related to stream permanence?</th></tr>
<tr><td>Research Needs</td><td>Capacity Needs</td></tr>
<tr><td>Feasibility studies for water redistribution or conservation strategies
Analysis of potential co-benefits of conservation targeted policies related to stream permanence
Identify and prioritize fine-resolution data needs where litigation may be required for water reallocation
Track water usage alongside stream permanence vulnerability to identify sources in need of conservation mitigation
Identify policy processes and opportunities to enable alternative water policy</td><td>Identify specific data needs required to meet the objectives and goals of local stewardship jurisdictions
Widespread adoption of place-based, water planning collaboratives across jurisdictions
Cross-jurisdictional knowledge sharing about effective water redistribution strategies
Regular training and education for environmental stewards and resource managers to share knowledge and to update best practices and methods related to changing stream permanence</td></tr>
</table>

5| DEEP DIVE OUTCOMES

Workshop participants provided comments and feedback on the State of Knowledge Synthesis and preliminary research and capacity needs (Section 4 of this report). Developed with input from the Planning Committee and Advisory Group, workshop attendees refined the existing needs and suggested new ones, then voted on the needs that would be the focus of the third and final day of the workshop. Based on the voting, participants identified four key needs to discuss in further detail (Table D1):

1. Better Models and Data on Stream Permanence
2. Adaptive Capacity of Species and Ecosystems
3. Ethical and Constructive Collaborations
4. Impacts of Land Use and Disturbance on Stream Permanence

Breakout sessions for each of these needs were used to brainstorm specific actions that could address each need (Appendix D). These breakout sessions served the dual purpose of both identifying more specific next steps and also highlighting potential peer groups who may wish to collaborate on advancing these efforts.

Both the Knowledge Synthesis and the "Action Brainstorms" highlighted key resources that could be useful in assessing and adapting to changes in stream permanence. An initial compendium of resources are included in a companion spreadsheet, ranging from climate science to management, with descriptions and links to each.

In addition, the Deep Dive process also highlighted small pilot projects that could support efforts to better understand and prepare for changes in stream permanence. These are projects that were beyond the scope of the Deep Dive but are nonetheless quite small in scope -- generally ranging from one week to a few months of effort. An initial list of potential projects is included in Appendix E.

All of the results and products from the 2021 Deep Dive are intended to inform actionable science investments by the NW CASC in order to advance climate-resilient management and stewardship of non-permanent streams in the Northwest. Our efforts to co-produce the Deep Dive are intended to provide a starting point for a community of practice around this emerging climate risk, bringing together scientists, managers, and community representatives in a context that fosters shared learning and collaboration.

APPENDIX A| DEEP DIVE ADVISORY GROUP

The Deep Dive Advisory Group provided input on our process and findings. Advisory Group members participated in three 2-hour meetings over the course of the summer, advising on the following topics:

- June meeting: Key questions to guide the synthesis
- July meeting: Preliminary findings from the synthesis
- August meeting: Research and capacity needs and workshop invitation list

Participants are listed in the table below.

Table A1. Advisory Group Members. *Participants are grouped by the type of organization they represent, then listed in alphabetical order by last name. NGO stands for "Non-Governmental Organization".*

Name	Organization	Type
Mike Brown	BLM (Bureau of Land Management)	Federal Agency
Janine Castro	US FWS (Fish and Wildlife Service)	
Shannon Claeson	US Forest Service, PNW Research Station	
John Colby	BLM (Bureau of Land Management)	
Jason Dunham	USGS (US Geologic Survey)	
Kris Jaeger	USGS (US Geologic Survey)	
Mary Lindenberg	US FWS (Fish and Wildlife Service)	
Charlie Luce	US Forest Service, Rocky Mountain Research Station	
Tom Miewald	USDA NRCS (Department of Agriculture: Natural Resource Conservation Service)	
Tracie Nadeau	EPA (Environmental Protection Agency)	
Brian Staabe	US Forest Service, Pacific Northwest Region	

Travis Warziniack	US Forest Service, Rocky Mountain Research Station	
Joel Freudenthal	Yakima County	Local
Meghan Halabisky	Conservation Science Partners	NGO
Alex Leone	Clark Fork Coalition	
Ryan Niemeyer	Upper Columbia Salmon Recovery Board	
Jordan Beamer	OWRD (Oregon Water Resources Department)	State Agency
Shaun Clements	ODFW (Oregon Department of Fish and Wildlife)	
Kiza Gates	WA DFW (Department of Fish and Wildlife)	
Rachel Lovellford	OWRD (Oregon Water Resources Department)	
Jeff Marti	WA DOE (Department of Ecology)	
Joel Rocchio	WA DNR (Department of Natural Resources)	
Spencer Sawaske	ODFW (Oregon Department of Fish and Wildlife)	
Jim Shedd	WA DOE (Department of Ecology)	
David Graves	CRITFC (Columbia River InterTribal Fisheries Commission)	Tribal
Chantel Greene	Nez Perce Tribe	
Scott Hauser	Upper Snake River Tribes Foundation	
Stefanie Krantz	Nez Perce Tribe	

Dennis Longknife	Fort Belknap Indian Community	
Phil North	Tulalip Tribe	
Scott O'Daniel	CTUIR (Confederated Tribes of the Umatilla Indian Reservation)	
Gene Shippentower	CTUIR (Confederated Tribes of the Umatilla Indian Reservation)	
Jonalee Squeochs	Yakama Tribe	
Greg Stewart	NWIFC (Northwest Indian Fisheries Commission)	
Jarod Swan	Yakama Tribe	
Caroline Walls	Quieleute Nation	
Jenny Adam	WSU (Washington State university)	University
Alex Fremier	WSU (Washington State university)	
Rebecca Hale	ISU (Idaho State University)	
Jamie McEvoy	UMT (University of Montana)	
Amanda Stahl	WSU (Washington State university)	
Cleo Woelfe-Erskine	UW (University of Washington)	

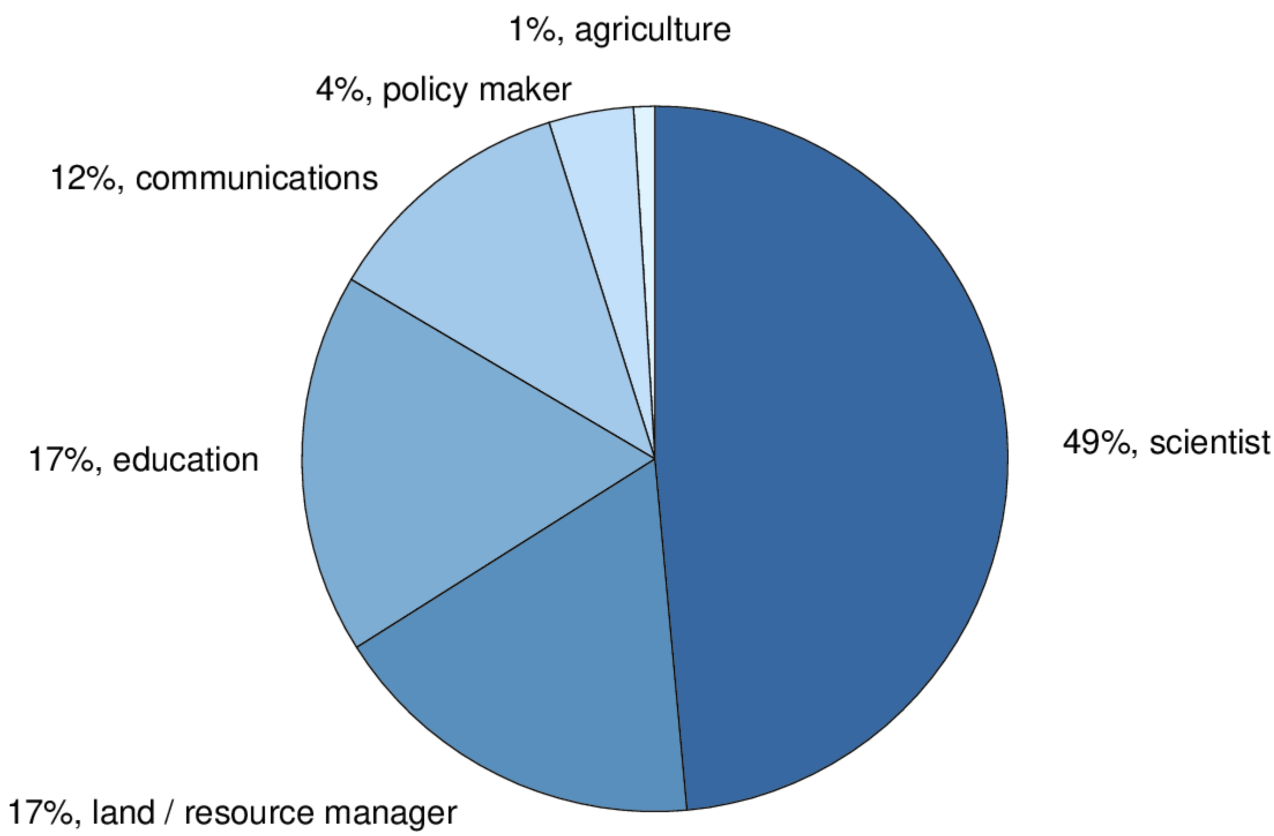

Figure A1. *Workshop participants' professional roles. Deep Dive participants represented a wide range of professional roles relevant to stream permanence, though the majority were scientists or managers.*

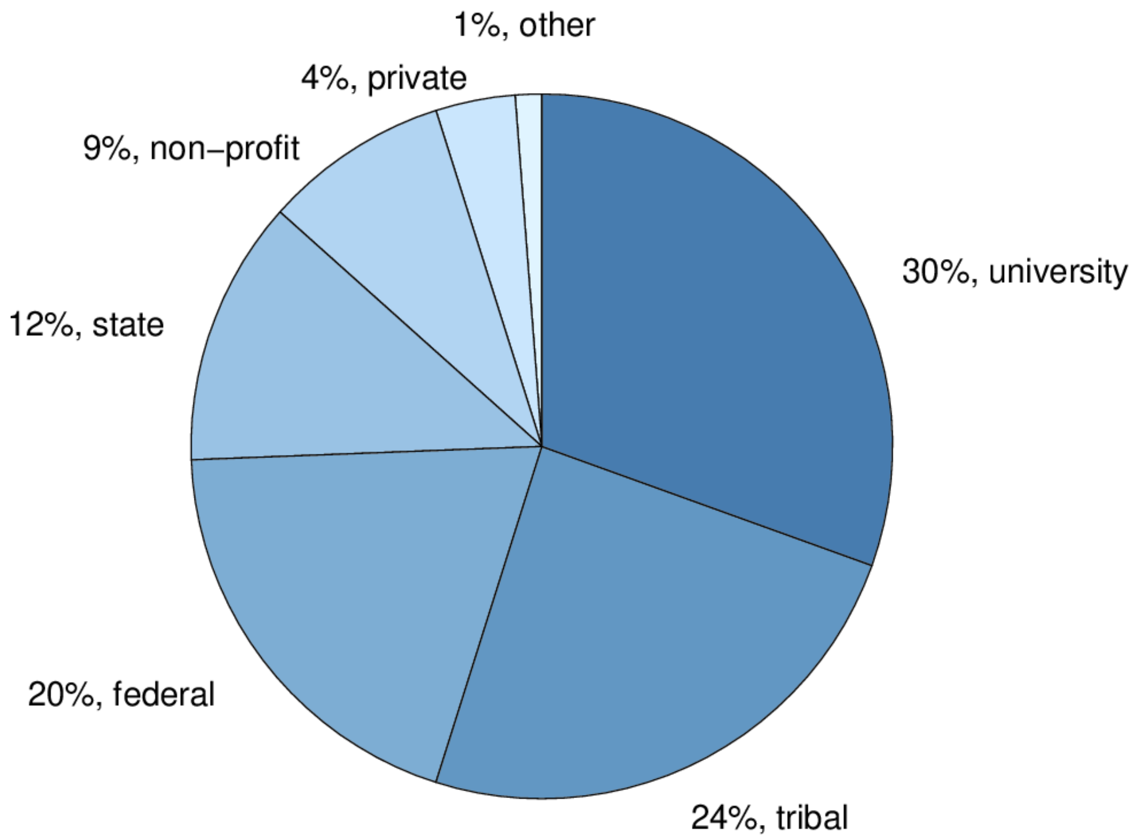

Figure A2. *Workshop participants' professional roles. Deep Dive participants represented a wide range of professional roles relevant to stream permanence, though the majority were scientists or managers.*

APPENDIX B| WORKSHOP AGENDA

A Deep Dive Into Shallow Waters:
Managing Climate Change Effects on Stream Drying in the Northwest
October 5, 6, and 7, 2021
1 to 3 pm Pacific Time/2 to 4 pm Mountain Time

2021 Deep Dive Objectives:

1. Share and understand the state of knowledge on climate change effects on stream permanence, and the state of practice, policy and human dimensions in preparing for, and responding to, stream drying.

2. Foster integration of diverse perspectives and ways of sharing knowledge on climate impacts on stream permanence into Deep Dive products.

3. Develop an actionable science agenda that identifies research and coordination needs for managing climate change impacts on stream permanence and achieving management goals.

4. Enable communities of practice by fostering peer-to-peer learning, networking and cross-disciplinary exchange of knowledge and ideas around management of changes in stream drying.

AGENDA

Preparation for Day 1:

- Read State of Knowledge Synthesis Summary (sent out ahead of time)
- Come prepared to tell a story about your experience with stream drying (instructions sent out ahead of time)

Desired outcome for Day 1: Participants listen, learn and understand the breadth of personal perspectives and knowledge around managing climate change effects on stream permanence, and make personal connections with other participants and their stories.

DAY 1 - OCTOBER 5	
Time	**Topic**
1:00 - 1:10	**Welcome, Opening Remarks**
1:10 - 1:35	**Introduction to the 2021 Deep Dive**

	Nicole DeCrappeo, Director, North Central and Northwest Climate Adaptation Science Centers, U.S. Geological Survey *Amy Snover, Director, Climate Impacts Group - Univ. Washington, and University Director, Northwest Climate Adaptation Science Center* *Kendra Kaiser, Assistant Research Faculty, Department of Geosciences, Boise State University*
1:35 - 2:20	**Storytelling Panel - Perspectives on Climate Change and Stream Permanence** *Wilbur Slockish Jr - Hereditary Chief of the Klickitat Tribe* *Mike Durglo, Tribal Preservation Department Head and Climate Change Advisory Committee Chairman, Confederated Salish and Kootenai Tribes* http://csktclimate.org/ *Gabe Sheoships - Executive Director of Friends of Tryon Creek, and member of the Cayuse and Walla Walla Nations, from the Confederated Tribes of the Umatilla Reservation*
2:20 - 2:55	**Storytelling Activity - Perspectives on Climate Change and Stream Permanence** *Breakout Groups* *Instructions to prepare for this activity*
2:55 -3:00	**Day 1 Wrap up and Preparation for Day 2**

Preparation for Day 2:

- Reflect on stories you listened to and how they can complement or add new dimensions to your way of thinking and your work.
- Add one or more comments to the Reflections Mural by 11 am PT/noon MT.
- Come prepared to share your reflection on Day 2.

Desired outcomes for Day 2: Participants deepen their understanding of the state of knowledge on managing climate change impacts on stream permanence and identify and refine research and capacity-building gaps in this understanding that need to be filled to manage these impacts effectively.

DAY 2 - OCTOBER 6

Time	Topic
1:00 - 1:05	**Welcome, Day 1 recap and Day 2 agenda overview** *Sonia Hall, Principal at SAH Ecologia LLC*
1:05 - 1:25	**Participants' Reflections on Day 1** *Breakout Groups*
1:25 - 1:55	**Deep Dive State of Knowledge Synthesis** *Guillaume Mauger, Research Scientist, Climate Impacts Group - Univ. Washington* *Mary Ann Rozance, Postdoctoral Fellow, Climate Impacts Group - Univ. Washington*
1:55 - 2:40	**Research and Capacity Building Needs** *Breakout Groups* *Guiding questions:* • *What research and capacity building needs do you agree are important?* • *Are there any that are missing?* • *Are there any that you would define differently?* • *Are there any that are unclear?*
2:40 - 2:55	**Actionable Science Agenda Topics** *Voting activity*
2:55 -3:00	**Day 2 Wrap up and Preparation for Day 3**

Preparation for Day 3:

- Reflect on the discussions of Day 2. What did you find really important, whether it pertains to the actionable science agenda or informs other work?
- Add one or more comments to the Reflections Mural by 11 am PT/noon MT.
- Add your topic preferences to the Day 3 Groups Google Sheet before 9 am PT/10 am MT, to help assign you to a breakout group

Desired outcomes for Day 3: Participants connect with others interested in specific research and capacity building needs, and brainstorm possible ways to fill those needs. Each group's products will be their own, to continue working on after this Deep Dive as they see fit.

DAY 3 - OCTOBER 7	
Time	**Topic**
1:00 - 1:05	**Welcome, Day 2 recap and Day 3 agenda overview** *Sonia Hall, Principal at SAH Ecologia LLC*
1:05 - 1:25	**Participants' Reflections on Day 2** *Breakout Groups*
1:25 - 2:30	**Novel Ideas for Informing Management of Climate Change Impacts on Stream Drying** *Breakout Groups* *Brainstorming Activity* *Report out*
2:30 - 2:50	**Moving Forward on Managing Climate Change Impacts on Stream Drying - Reflections Panel** *Betsy Glenn, Partnerships Ecologist, Northwest Climate Adaptation Science Center* *Rosemary Pazdral, Executive Director, Siuslaw Watershed Council* *Lejo Flores, Associate Professor of the Department of Geosciences, and Director of the Lab for Ecohydrological Applications and Forecasting at Boise State University* *Pah-tu Pitt, Native Kut, and member of the Confederated Tribes of Warm Springs*

2:50 - 3:00	**Thank You and Next Steps** *Guillaume Mauger, Research Scientist, Climate Impacts Group - Univ. Washington*

APPENDIX C| GRAPHIC RECORDINGS

Maisie Richards, a graphic recorder, provided artistic representations of key parts of the workshop discussions. The resulting pieces are included below.

__Figure C1.__ Graphic recording of the storytelling panel. Image credit: Maisie Richards.

Figure C2. *Graphic recording of the synthesis and needs discussion. Image credit: Maisie Richards.*

Figure C3. *Graphic recording of the actions discussion. Image credit: Maisie Richards.*

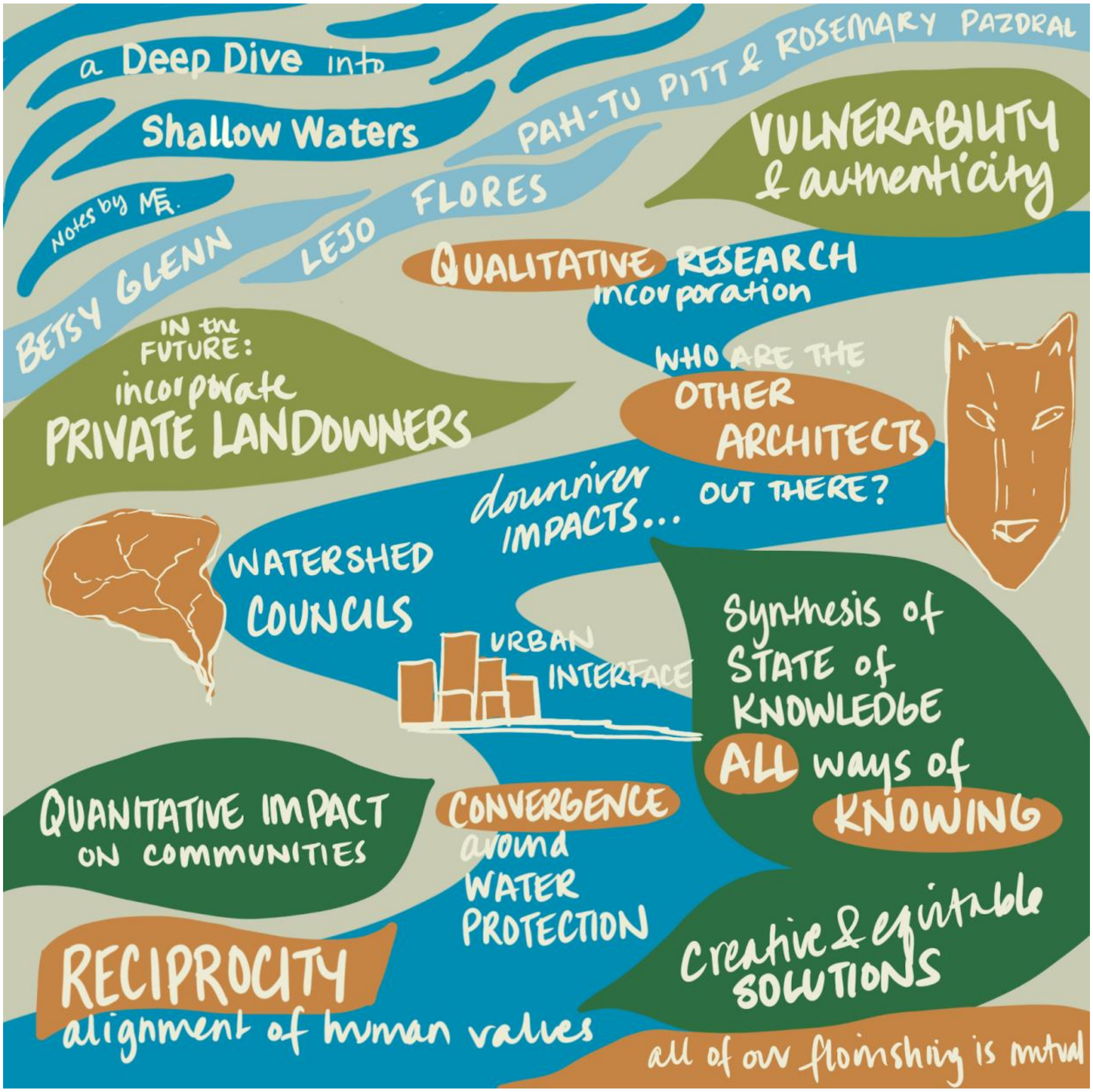

Figure C4. Graphic recording of the final reflections panel. Image credit: Maisie Richards.

APPENDIX D| VOTING AND ACTIONS BRAINSTORMS

Workshop participants voted on the key needs outlined in the synthesis (Table C1). Among the top-scoring needs, participants then selected which topics they would like to discuss in breakout sessions. The purpose of these discussions was to get into the specifics of how to address each need and foster collaboration among participants with shared interests.

Table D1. *Voting results from the workshop. Participants voted on the needs that they saw as most important to support climate-resilient planning for stream permanence. Shaded rows are the ones that were selected for further discussion.*

Topic	Need	Votes
Research	Hydrologic and climate studies to better quantify climate impacts on stream permanence. Including surface water – groundwater connections. 19	19
	Studies linking land and water use activities (e.g., logging, irrigation), and disturbance (e.g., wildfire, bark beetles), with changing stream permanence.	15
	Identify adaptive capacity of flora and fauna to intermittency of varying durations (1 yr, 5 yr. 10 yr); and identify resilience of ecological functions as related to adaptive capacity	11
	Evaluate effectiveness and potential scope of mitigation actions, including: land and riparian cover, water conservation, recharge.	10
	More + better Baseline data (to support better predictions of stream permanence)	8
	Regional landscape models that map species/ecosystem vulnerability to changing hydrology, land/water use activities, land cover.	7
	Need for hyper local studies (e.g., case studies) and connect hyper local resource decision makers with scientists/cohesive monitoring networks	7
	Evaluate decision tradeoffs. Identify “no regrets” stewardship strategies. [Clarification on: No regrets or multi-benefit actions are important as I see them working with natural watershed processes and potentially bridging interests that may not always agree.]	5

	Identify the cultural values associated with different types of non-perennial streams across the region, and the impacts of stream drying on communities.	5
	economic cost-benefit analysis of taking certain water conservation or regulatory actions and how that impacts cultural values or lifestyles	5
	Localized, community assessments and case studies of the knowledge, values, and behaviors associated with non-permanent streams.	4
	Feasibility studies for water redistribution or conservation strategies	3
	Research into creative partnerships and adaptation strategies to conserve water both on public and private land	3
	Identify data needs where litigation may be required for water reallocation.	2
	Analyze potential co-benefits of conservation targeted policies	1
Capacity	Expand low-cost, robust, and automated monitoring systems for non-perennial streams (e.g., Arduino monitoring networks). Standardized data collection.	12
	Facilitate knowledge sharing across the region (e.g. best practices, research).	10
	Teaching how to do collaboration with Tribes that isn't extractive -- should be truly co-developed with the ethics of what the Tribe or community needs, center ethical knowledge sharing	10
	Different contexts require different strategies: Clarify which ones apply where/when (for example, mitigation for regulatory purposes is very different than voluntary mitigation. Similarly, strategies to address stream permanence in the high desert may not be the same as those in mountain ecosystems)	10
	Improved collaboration between Tribes and non-Tribal entities; better incorporation of Traditional Ecological Knowledge.	8

	Standardize stream drying data collection methods and terminology.	6
	Case studies or other centralized data hub for stewardship approaches	6
	Link stewardship with community priorities and goals (e.g. via water planning collaboratives).	5
	Training on use of modeling for species and ecosystem management	4
	Identify opportunities to diversify management and stewardship	3
	Build relationships between managers with different areas of expertise and viewpoints to plan landscape management strategies - forest managers, water managers, fisheries managers	3
	how to design and fund work that mitigates the divide between place based research and synthesis	2
	Resources (funding, guidance, case studies) to support incorporation of cultural values and community input in land and water management planning	1

D.1 | Better Models and Data on Stream Permanence

Needs addressed by this brainstorm:

- Hydrologic and climate studies to better quantify climate impacts on stream permanence. Including surface water – groundwater connections.
- More and better Baseline data to support better predictions of stream permanence.

Group Members:

- James Robinson (facilitator)
- Elizabeth Crowther
- Sarah Godsey
- Konrad Hafen
- Kristin Jaeger
- Sanjeev Joshi
- Charlie Luce
- Guillaume Mauger

Novel Ideas for new Research Directions and/or Capacity Building:

Highlights:

- We need more and better data to improve the parameterization and predictive skill of stream dying models. Some potential "dream" datasets would include: standardized stream drying observations (e.g., where/when/in what physical environment), higher resolution geological and soil data (e.g., permeability, porosity, transmissivity, field capacity, etc.), continuous stream gaging in headwater streams, and spatially distributed evapotranspiration estimates.
- We need to build additional connections between reach scale observation-based stream drying research and regional empirically-based models

Additional Notes:

- Can we find interactions of GCMs and RCMs with streams as well? What role do the models play in projecting stream permanence?
- Developing methods to blend scales of existing research -> methods for tying reach scale modeling efforts to larger, regional scale empirical models
- Advance remote sensing methods for groundwater detection to inform stream drying observational datasets
- Tie spatial structure of drying streams to stream drying drivers
- Collect higher resolution geological data to inform hydrological models (e.g., higher resolution soil data, data on springs (locality and temporality). (Notes that spatial autocorrelation for saturated soil conductivity (i.e., permeability) is much shorter than for stream permanence)
- Collecting stories (qualitative hypotheses) of how streams go dry. Lots of different mechanisms for streams to go dry -- circumstances/conditions. (e.g.: one set is the vertical distribution of water -- from headwater tributaries to the mouths of large rivers mapping losing/gaining reaches, etc.)
- Studies at multiple scales - local process vs synoptic patterns
- Build new and add to existing data sets:
    - flow records -- more discharge measurements:
        - Focus more typically dry streams
        - Distributed discharge -- more than presence/absence -- would be helpful for understanding subsurface processes
        - [Kris]: would this be helpful? Identifying resistant and resilient locations within the landscape in terms of identifying areas with stable baseflow or unstable baseflows for targeted field studies for streamflow intermittency.
    - Higher resolution geologic records (i.e., depth of Quaternary Alluvium (Qa) seds for quantifying subsurface storage/flux, so also conductivity/transmissivity),
    - spatially continuous time series for headwater stream networks;

    - spatially distributed evapotranspiration records
    - Synoptic records of streamflows in headwater streams over multiple years
    - Spring locations and inventory
- Stream drying isn't all bad -- these areas are also key recharge areas. They're important for supplying cool water to downstream areas. Need some way of evaluating the detrimental effects of stream drying on a reach by reach basis.
- What areas are more/less sensitive to drying? Can be backed out of PROSPER and other empirical models but that wasn't the intent and not sure it's reliable.

Suggested categorization from Sarah:

Spatiotemporal Metrics

	Moment	*Season*
Point	Presence/absence of flow [flow/no flow]	Seasonal flow permanence [% of season with flow at a given location]
Network	Instantaneous flowing network extent [% of sensors flowing *or* % of mapped stream flowing at a given moment]	Seasonal flowing network extent [% of sensors flowing integrated across season]

D.2 | Adaptive Capacity of Species and Ecosystems

Need addressed by this brainstorm:

- Identify adaptive capacity of flora and fauna to intermittency of varying durations (weeks, months, years); and identify resilience of ecological functions as related to adaptive capacity.

Group Members:

- Betsy Glenn (facilitator)
- Nicole DeCrappeo
- Lindsey Thurman
- Lejo Flores
- Rebecca Hale
- Dennis Longknife
- Stefanie Krantz
- Leona Svancara

Novel Ideas for new Research Directions and/or Capacity Building:

Evaluating AC:

- Scaling up the adaptive capacity (AC) of species to habitats (i.e., community- or habitat-level AC; ecosystem-level AC)
    - Example metrics of community-level AC related to ecosystem function:
        - Biodiversity/spp richness
        - Cultural survival and species that occur in intermittent systems is an area of particular concern for Tribes
        - Degree of habitat fragmentation (or, conversely, degree of connectivity)
        - Socio-political constraints such as level of conservation protection (extent of protected areas vs private lands), multi-jurisdictional boundaries, etc.
    - Linking ecosystem-scale function (e.g, production) with changes in community *composition*, individual species, how these all shift through time with drying/rewetting
        - Differences in community composition/ecosystem function dynamics in systems that are newly drying vs historically intermittent streams
- How to reconcile different scales (temporal, spatial)?
    - How does the scale of drying affect the ability of species/communities to adapt? Role of metapopulations?
- Reciprocal AC: Linking AC of flora across terrestrial-aquatic transition zones. How does the AC of terrestrial communities influence the corresponding AC of aquatic flora and fauna? How do changes in stream permanence influence the AC of terrestrial vegetation communities?
- Determining range of variability in AC across a species range (e.g., is AC greater/less at range edges? Or in Idaho vs WA, etc).
- Understanding AC through the lens of means, extremes, vs. variable or stochastic trends in climate change. How does this change our predictions or prediction accuracy?

Managing to support AC:

- Evaluating the efficacy of “adaptation experiments” for facilitating species AC
    - Can we develop the institutional capacity to leverage short-term disturbances or climate change analogs to assess AC? For example, leverage drought conditions to rapidly design and carry out short-term field investigations to evaluate AC.

- How frequently should we be evaluating the success or failure of these adaptation actions?
    - For example, are management actions that extend water on the landscape for say 2 weeks 'successful', or successful enough? Such as extending wet conditions long enough to allow spotted frog tadpoles to metamorphose (and thus increase survival in drought conditions).
    - What are the metrics of success? Dependent on values, management priorities, etc.
  - What are the risks of doing nothing vs acting? Depends on the action (some are more "transformative" or risky than others).
    - Further, what are the risks to other species in the community? Considering ecosystem-level implications of actions taken.
    - Could assess these risks using the RAD Framework
- What are key physical determinants of AC for specific species and at what scale do they influence AC?

D.3 | Ethical and Constructive Collaborations

Need addressed by this brainstorm:

- Teaching how to do collaboration with Tribes that isn't extractive -- should be truly co-developed with the ethics of what the Tribe or community needs, center ethical knowledge sharing.
- Improved collaboration between Tribes and non-Tribal entities; better incorporation of Traditional Ecological Knowledge.

Group Members:

- Mary Ann Rozance (facilitator)
- Emma Kuster
- Guillaume Mauger
- Karen Mitchell
- Rosemary Pazdral
- Pah-Tu Pitt
- Masie Richards
- Jennifer Riedmayer
- Katie Swensen
- Caroline Walls
- Tristan Weiss

Novel Ideas for new Research Directions and/or Capacity Building:

Highlights:

- Capacity building needs:
    - Training for respectful Tribal engagement must include:
        - Building relationships first, identifying Tribal needs, mutual goal development, data sovereignty, share-back to the community, ethical standards, recognition of the lens of scientists / privilege, shared authorship, an understanding of cultural and terminology differences across Tribes
    - How to incorporate deeper engagement beyond an individual project
        - Consider our own connections to nature, uplift all kinds of education, engage the intergenerational community, and change the face of "the scientist"

Notes:

- "Who" are we teaching?
    - Different approaches for scientists, rural communities, resource managers, federal agencies
    - Particular need to educate on-the-ground federal agency employees that work on co-management with Tribes
    - Though agencies may hold knowledge and establish co-management protocols, not all employees that work with Tribes understand Tribal rights
    - Reverence for working with Tribes; federal partners need honorable engagement practices
    - **Near-term action: compile resources for collaborations between federal managers, scientists, etc. with Tribes**
- Need collaborations to go beyond workshops/webinars/training; ensure equity in goal development; building relationships to work towards shared goals; need to move away from "what is in it for me" mindset
- **Relationships first**, not a one size fits all approach to working with Tribes (particularly important that federal agencies know how to work with different Tribes)
- Need to create a space to have conversations about various terminology within institutions (e.g., there may be agency "rules of engagement" but may be friction as it moves down the chain to those that are actually interacting with Tribal communities) to make sure that TEK is not appropriated
- **Inaccessibility of science**; who is the scientist? (not very diverse); outdoor school can be helpful for increasing JEDI to connect science, communities, management/regulatory
- Need more Indigenous and BIPOC led organizations; need to make sure engagement/collaboration with Tribal communities is not tokenism

- Elevating Tribal voices and engagement in scientific programs - **change who gets trained in science, transform who becomes a scientists**
- “Indigenous Science” instead of TEK→there is so much more to science than lab coats; there are multiple ways of engaging with the world
- Changing our lens to be as part of nature; need to bring in both youth and elders; need DEI to include intergenerational engagement (K-12!)
- To be truly inclusive, need to have grassroots efforts to really engage with the community; having someone from the community helps engage younger generation
- “Between Two Worlds” program; Tribal members are the faces of the program and engage with the youth
- Teaching others how to work with Tribes→Tribal introductions or **more Tribal scientists in the federal government**
- Uplift all kinds of education; not only degrees
- Importance of respectful interactions regardless of background
- Decolonization of Western science→ensure that Tribal voices are included in the conversations of how to incorporate TEK (e.g., **co-created programs**)
- **What is the share-back to the community?** Need some kind of compensation, can the community get a copy of the work for their library?
- What privilege do these outside faces/voices have to come into a Tribal community? Need to address the ethical lens of the scientist (Tribal authors)
- When approaching a Tribe, “what do you need” - simple and effective for relationship building (shared benefits)
- Data sovereignty
- **IRB/Human subjects doesn’t capture full ethical needs**

D.4 | Impacts of Land Use and Disturbance on Stream Permanence

Need addressed by this brainstorm:

- Studies linking land and water use activities (e.g., logging, irrigation), and disturbance (e.g., wildfire, bark beetles), with changing stream permanence.

Group Members:

- Michelle Agne (facilitator)
- Mike Brown
- Elise Elliott-Smith
- Derek Godwin
- Kendra Kaiser
- Jeff Marti
- Jarod Swan
- Constanza von der Pahlen

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Novel Ideas for new Research Directions and/or Capacity Building:

Highlights:

- Increase open access publications and synthesis reports
- Continued baseline data collection, especially repeated/long term data
- Development and training on models that managers can "turn the dials" on
- Implementation of innovative management ideas, use seed projects as research opportunities
- Improved collaboration between scientists and practitioners
- Education on water management in areas where water is currently less limiting
- Increased two way engagement between Tribal partners and western scientists could increase both data collection and sharing of TEK
- Improved understanding of synergistic effects of climate change, land use activities, and disturbance impacts on stream permanence

Notes:

- Making research open access will be key
- Inventory - knowing where impermanence is occurring is valuable. An interactive map that can be overlayed with other layers (e.g. land use) would be valuable, particularly viewing change over time at USGS gagesLocal scale is particularly relevant for action
- Knowledge from Dept. Fish and Wildlife and other resource managers(e.g. where streams go dry due to diversions), data is not always written down, need an effort to do so (how can we get FlowPer everywhere?)
    - Opportunistic observations doesn't work as well - need to invest in crews to do it specifically, or added into a given contract
    - How accurate do your predictive models need to be?
- Policy requirements are based on the flow permanence status -- so we need to be able to inform management around a given policy
- Both monitoring and modeling (Bob McCain, Velma model - deploying in coastal OR to be able to "turn the dials" on covariates, particularly when you incorporate changing climate futures - baseline data can be problematic)
    - Perhaps need more baseline data for parameterizing models?
- Adaptation perspective- how can we think creatively to not only track effects, but to work with folks to try new methods to increase flow
    - Try management before it's too late -- use those trials as monitoring/research opportunities
    - Capacity need -- partnerships between scientists and practitioners to make these projects happen
    - If we know a management practice will have a negative impact do we need to know how negative?
    - Creative ideas that are outside the box - e.g. solar panels in ag fields resulting in higher soil moisture

    - "Slow water infrastructure" - Peru -- tap into the knowledge of our native communities and their knowledge of the system
- PNNL came in and were doing some work in the tributaries that flow into the Yakima, to understand GW, nutrient cycling and impacts on fisheries; reciprocity e.g. they helped bring new data to the Tribe, while the Tribe contributed knowledge of the systems,
    - Need to understand the structure of processes within the Tribe and agreements on how to share/not share data
- Carlos Ochoa OSU - desert arid/semi arid climates -- when vegetation changes how does the stream respond (10+ year projects); how can we find more funding for projects like these established locations, the depth of understanding that can result is really important
- Irrigation and water management -- if they are'nt on the cutting edge of irrigation (e.g. west side), what can they be doing in their management to make water available at the end of the summer? Irrigation education on how to modernize, they understand the subsurface components inherently because of tiling and drainage work. How can they capture precipitation in the winter to have more water available in the summer? Reservoirs to capture winter flow will help with water supply for irrigation and other ecosystem services (i.e., stream and wetland permanence).
- Will improving efficiency actually help??
- Water quality side -- stream temperature, nutrients, bacteria
- What is the state of knowledge of land use impacts on stream permanence (again open access for non academics is key)
- better understanding synergistic effects on species (land uses that may impact water quality as well as stream permanence).
- better understanding how wildfire impacts stream permanence (and water quality) in the short and long term and in different habitats.... and the multiplicative climate change impacts and threats such as wildfire and invasive species.

APPENDIX E| PILOT PROJECT IDEAS

Throughout the Deep Dive process, participants identified relatively low-effort projects that would advance the science and practice of climate-adapted planning for stream permanence, but were nonetheless beyond the scope of the Deep Dive. These are projects that are small enough that they would take anywhere from a few days to 1-2 months of effort, total -- most would require less than a month of effort. They include fact sheets, trainings, literature reviews, mapping, and workshops.

Title	Description (1-2 sentences)
Stream Permanence Fact Sheets	These could be on a variety of topics that were covered in the Deep Dive, ranging from the science synthesis to policy and management solutions.
Communications training for Deep Dive collaborators	The purpose of this training would be to identify key audiences with whom the group wants to elevate the importance of stream permanence and potential climate change impacts, develop talking points, and a strategy for disseminating the messages.
Mapped case studies that evaluate mitigation approaches	Develop an interactive map or database of studies that evaluate the effectiveness of particular mitigation approaches (e.g., https://storymaps.arcgis.com/stories/d78e5021c3554fb8a1af1c5020b8d741; https://drewlyons.shinyapps.io/fire_map/)
Summary of ecological studies on changing stream permanence	Table and/or map of studies of species and ecosystem impacts from changes in stream permanence with info on location, ecosystem/study species, precipitation regime, effects observed
Mapping Existing Stream Permanence Studies	Develop an interactive GIS-based map where users can discover basic project findings tied to existing stream drying research in the Northwest.
Maps Comparing National Hydrology Dataset to Existing Stream-Drying Related Models	Create a map with National Hydrology Dataset (NHD) stream permanence classifications superimposed over geospatial data from the Probability of Stream Permanence (PROSPER; Jaeger et al., 2019) or the EPA Hydrologic Landscapes framework (Leibowitz et al., 2016). Calculate basic statistics between datasets (e.g., % of dry steam pixels correlating with non-

	perennial stream vectors; % of low permeability shallow soils correlating with non-perennial stream vectors)
Resources for ethical collaborations with Tribes	Compile resources for ethical engagement with Tribes (possibly a factsheet) for scientists, rural community leaders, federal and state resource managers, etc. (note that IRB/Human subjects doesn’t capture full ethical needs of working with Tribes)
Climate attribution workshop	Workshop to plan research studies that could differentiate between climate change and land/water use impacts on stream permanence.

REFERENCES

Achord, S., B.P. Sandford, E.E. Hockersmith, M.G. Nesbit, N.D. Dumdei, J.J. Lamb, K.W. McIntyre, N.N. Paasch, S.G. Smith, and R.W. Zabel. Monitoring the migrations of wild Snake River spring/summer chinook salmon juveniles, 2009-2010. 2011. Technical Report for U.S. Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife.

Ademollo, N., S. Capri, L. Patrolecco, A. Puddu, S. Polesello, M. Rusconi, S. Valsecchi, and J. Froebrich. 2011. Fate and monitoring of hazardous substances in temporary rivers. TrAC Trends in Analytical Chemistry 30:1222–1232.

AIMS, https://osf.io/ga8uk/

Allen, D. C., D. A. Kopp, K. H. Costigan, T. Datry, B. Hugueny, D. S. Turner, G. S. Bodner, and T. J. Flood. 2019. Citizen scientists document long-term streamflow declines in intermittent rivers of the desert southwest, USA. Freshwater Science 38:244–256.

Arthington, A. H., J. G. Kennen, E. D. Stein, and J. A. Webb. 2018. Recent advances in environmental flows science and water management—Innovation in the Anthropocene. Freshwater Biology 63:1022–1034.

Averett, J. P., B. A. Endress, M. M. Rowland, B. J. Naylor, and M. J. Wisdom. 2017. Wild ungulate herbivory suppresses deciduous woody plant establishment following salmonid stream restoration. Forest Ecology and Management 391:135–144.

Azarnivand, A., M. Camporese, S. Alaghmand, and E. Daly. 2020. Modeling hydrological impacts of afforestation on intermittent streams. Science of The Total Environment 728:138748.

Baldocchi, D., and S. Ma. 2013. How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA. Tellus B: Chemical and Physical Meteorology 65:19994.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309.

Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua. 2013. Restoring salmon habitat for a changing climate: restoring salmon habitat for a changing climate. River Research and Applications 29:939–960.

Benejam, L., P. L. Angermeier, A. Munné, and E. García-Berthou. 2010. Assessing effects of water abstraction on fish assemblages in Mediterranean streams. Freshwater Biology 55:628–642.

Capon, S. J., C. Leigh, W. L. Hadwen, A. George, J. M. McMahon, S. Linke, V. Reis, L. Gould, and A. H. Arthington. 2018. Transforming environmental water management to adapt to a changing climate. Frontiers in Environmental Science 6:80.

Carter, S. K., D. S. Pilliod, T. Haby, K. L. Prentice, C. L. Aldridge, P. J. Anderson, Z. H. Bowen, J. B. Bradford, S. A. Cushman, J. C. DeVivo, M. C. Duniway, R. S. Hathaway, L. Nelson, C. A. Schultz, R. M. Schuster, E. J. Trammell, and J. F. Weltzin. 2020. Bridging the research-management gap: landscape science in practice on public lands in the western United States. Landscape Ecology 35:545–560.

Chadd, R. P., J. A. England, D. Constable, M. J. Dunbar, C. A. Extence, D. J. Leeming, J. A. Murray-Bligh, and P. J. Wood. 2017. An index to track the ecological effects of drought development and recovery on riverine invertebrate communities. Ecological Indicators 82:344–356.

Coble, A. A., H. Barnard, E. Du, S. Johnson, J. Jones, E. Keppeler, H. Kwon, T. E. Link, B. E. Penaluna, M. Reiter, M. River, K. Puettmann, and J. Wagenbrenner. 2020. Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. Science of The Total Environment 730:138926.

Cochand, M., P. Christe, P. Ornstein, and D. Hunkeler. 2019. Groundwater storage in high alpine catchments and its contribution to streamflow. Water Resources Research 55:2613–2630.

Colls, M., X. Timoner, C. Font, V. Acuña, and S. Sabater. 2021. Biofilm pigments in temporary streams indicate duration and severity of drying. Limnology and Oceanography 66:3313–3326.

Conallin, J., E. Wilson, and J. Campbell. 2018. Implementation of environmental flows for intermittent river systems: adaptive management and stakeholder participation facilitate implementation. Environmental Management 61:497–505.

Costigan, K. H., K. L. Jaeger, C. W. Goss, K. M. Fritz, and P. C. Goebel. 2016. Understanding controls on flow permanence in intermittent rivers to aid ecological research: integrating meteorology, geology and land cover. Ecohydrology 9:1141–1153.

Crampe, E. A., C. Segura, and J. A. Jones. 2021. Fifty years of runoff response to conversion of old-growth forest to planted forest in the H. J. Andrews Forest, Oregon, USA. Hydrological Processes 35.

Cristan, R., W. M. Aust, M. C. Bolding, S. M. Barrett, J. F. Munsell, and E. Schilling. 2016. Effectiveness of forestry best management practices in the United States: literature review. Forest Ecology and Management 360:133–151.

Deitch, M. J., G. M. Kondolf, and A. M. Merenlender. 2009. Hydrologic impacts of small-scale instream diversions for frost and heat protection in the California wine country. River Research and Applications 25:118–134.

Dittbrenner, B. J. 2019. Restoration potential of beaver for hydrological resilience in a changing climate. Thesis.

East, A. E., and J. B. Sankey. 2020. Geomorphic and sedimentary effects of modern climate change: current and anticipated future conditions in the Western United States. Reviews of Geophysics 58:e2019RG000692.

Easterling, D. R., J. R. Arnold, T. Knutson, K. E. Kunkel, A. N. LeGrande, L. R. Leung, R. S. Vose, D. E. Waliser, and M. F. Wehner. 2017. Ch. 7: Precipitation change in the United States. Climate Science Special Report: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program.

England, J., R. Chadd, M. J. Dunbar, R. Sarremejane, R. Stubbington, C. G. Westwood, and D. Leeming. 2019. An invertebrate-based index to characterize ecological responses to flow intermittence in rivers. Fundamental and Applied Limnology 193:93–117.

Evans, J. M., J. Calabria, T. Borisova, D. E. Boellstorf, N. Sochacka, M. D. Smolen, R. L. Mahler, and L. M. Risse. 2015. Effects of local drought condition on public opinions about water supply and future climate change. Climatic Change 132:193–207.

Falke, J. A., K. D. Fausch, R. Magelky, A. Aldred, D. S. Durnford, L. K. Riley, and R. Oad. 2011. The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. Ecohydrology 4:682–697.

Fesenmyer, K. A., D. C. Dauwalter, C. Evans, and T. Allai. 2018. Livestock management, beaver, and climate influences on riparian vegetation in a semi-arid landscape. PLOS ONE 13:e0208928.

Fovet, O., A. Belemtougri, L. Boithias, I. Braud, J.-B. Charlier, M. Cottet, K. Daudin, G. Dramais, A. Ducharne, N. Folton, M. Grippa, B. Hector, S. Kuppel, J. L. Coz, L. Legal, P. Martin, F. Moatar, J. Molénat, A. Probst, J. Riotte, J.-P. Vidal, F. Vinatier, and T. Datry. 2021. Intermittent rivers and ephemeral streams: Perspectives for critical zone science and research on socio-ecosystems. WIREs Water 8:e1523.

Gleeson, T., and B. Richter. 2018. How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers. River Research and Applications 34:83–92.

Gomez, D. M., and R. G. Anthony. 1998. Small mammal abundance in riparian and upland areas of five seral stages in western Oregon. Northwest Science 72:293–302.

Goss, L., and B. Roper. 2018. The relationship between measures of annual livestock disturbance in western riparian areas and stream conditions important to trout, salmon, and char. Western North American Naturalist 78.

Gozlan, R. E., J. R. Britton, I. Cowx, and G. H. Copp. 2010. Current knowledge on non-native freshwater fish introductions. Journal of Fish Biology 76:751–786.

Gronsdahl, S., R. D. Moore, J. Rosenfeld, R. McCleary, and R. Winkler. 2019. Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. Hydrological Processes 33:3152–3168.

Hamlet, A. F., and D. P. Lettenmaier. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. Water Resources Research 43.

Hammond, J. C., M. Zimmer, M. Shanafield, K. Kaiser, S. E. Godsey, M. C. Mims, S. C. Zipper, R. M. Burrows, S. K. Kampf, W. Dodds, C. N. Jones, C. A. Krabbenhoft, K. S. Boersma, T. Datry, J. D. Olden, G. H. Allen, A. N. Price, K. Costigan, R. Hale, A. S. Ward, and D. C. Allen. 2021. Spatial patterns and drivers of nonperennial flow regimes in the contiguous United States. Geophysical Research Letters 48.

Hatfield, J. L., and J. H. Prueger. 2015. Temperature extremes: Effect on plant growth and development. Weather and Climate Extremes 10:4–10.

Hayashi, M. 2019. Alpine hydrogeology: The critical role of groundwater in sourcing the headwaters of the world. Groundwater:gwat.12965.

Hubbard, M. L. 2020. The risky business of water resources management: assessment of the public's risk perception of Oregon's water resources. Human and Ecological Risk Assessment: An International Journal 26:1970–1987.

Ikeda, K., R. Rasmussen, C. Liu, A. Newman, F. Chen, M. Barlage, E. Gutmann, J. Dudhia, A. Dai, C. Luce, and K. Musselman. 2021. Snowfall and snowpack in the Western U.S. as captured by convection permitting climate simulations: current climate and pseudo global warming future climate. Climate Dynamics.

IPCC_AR6_WGI_SPM.pdf. (n.d.). . https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf.

Jackson, S., C. Pollino, K. Maclean, R. Bark, and B. Moggridge. 2015. Meeting Indigenous peoples' objectives in environmental flow assessments: Case studies from an Australian multi-jurisdictional water sharing initiative. Journal of Hydrology 522:141–151.

Jaeger, K. L., K. C. Hafen, J. B. Dunham, K. M. Fritz, S. K. Kampf, T. B. Barnhart, K. E. Kaiser, R. Sando, S. L. Johnson, R. R. McShane, and S. B. Dunn. 2021. Beyond streamflow: Call for a national data repository of streamflow presence for streams and rivers in the United States. Water 13:1627.

Jaeger, K. L., R. Sando, R. R. McShane, J. B. Dunham, D. P. Hockman-Wert, K. E. Kaiser, K. Hafen, J. C. Risley, and K. W. Blasch. 2019. Probability of Streamflow Permanence Model (PROSPER): A spatially continuous model of annual streamflow permanence throughout the Pacific Northwest. Journal of Hydrology X 2:100005.

Janisch, J. E., S. M. Wondzell, and W. J. Ehinger. 2012. Headwater stream temperature: Interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270:302–313.

Jenkins, S. R., M. G. Betts, M. M. Huso, and J. C. Hagar. 2013. Habitat selection by juvenile Swainson's thrushes (Catharus ustulatus) in headwater riparian areas, Northwestern Oregon, USA. Forest Ecology and Management 305:88–95.

Jones, J. A., and D. A. Post. 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. Water Resources Research 40.

Jung, C., J. Lee, Y. Lee, and S. Kim. 2019. Quantification of stream drying phenomena using grid-based hydrological modeling via long-term data mining throughout South Korea including ungauged areas. Water 11:477.

Kampf, S. K., K. A. Dwire, M. P. Fairchild, J. Dunham, C. D. Snyder, K. L. Jaeger, C. H. Luce, J. C. Hammond, C. Wilson, M. A. Zimmer, and M. Sidell. 2021. Managing nonperennial headwater streams in temperate forests of the United States. Forest Ecology and Management 497:119523.

King, J., C. Brown, and H. Sabet. 2003. A Scenario-based holistic approach to environmental flow assessments for rivers. River Research and Applications 19:619–639.

Kirschbaum, M. U. F., and A. M. S. McMillan. 2018. Warming and elevated CO2 have opposing influences on transpiration. which is more important? Current Forestry Reports 4:51–71.

Klaus, J., E. Zehe, M. Elsner, C. Kuuls, and J. J. McDonnell. 2013. Macropore flow of old water revisited: experimental insights from a tile-drained hillslope. HESS 17:103–118.

Kovach, R. P., J. B. Dunham, R. Al-Chokhachy, C. D. Snyder, B. H. Letcher, J. A. Young, E. A. Beever, G. T. Pederson, A. J. Lynch, N. P. Hitt, C. P. Konrad, K. L. Jaeger, A. H. Rea, A. J. Sepulveda, P. M. Lambert, J. Stoker, J. J. Giersch, and C. C. Muhlfeld. 2019. An integrated framework for ecological drought across riverscapes of North America. BioScience 69:418–431.

Krosby, M., K. Davis, M. A. Rozance, A. Bagley, C. Dohrn, D. Lyons, K. Swensen, M. McClure, and C. Walls. 2020. Managing post-fire, climate-induced vegetation transitions in the Northwest: A synthesis of existing knowledge and research needs. Northwest Climate Adaptation Science Center, University of Washington, Seattle, WA.

Larsen, L. G., and C. Woelfle-Erskine. 2018. Groundwater is key to salmonid persistence and recruitment in intermittent Mediterranean-climate streams. Water Resources Research 54:8909–8930.

Lee, S.-Y., M. E. Ryan, A. F. Hamlet, W. J. Palen, J. J. Lawler, and M. Halabisky. 2015. Projecting the hydrologic impacts of climate change on montane wetlands. PLOS ONE 10:e0136385.

Leibowitz, S. G., P. J. Wigington Jr., K. A. Schofield, L. C. Alexander, M. K. Vanderhoof, and H. E. Golden. 2018. Connectivity of streams and wetlands to downstream waters: An integrated systems framework. JAWRA Journal of the American Water Resources Association 54:298–322.

Leibowitz, S. G., R. L. Comeleo, P. J. Wigington Jr., M. H. Weber, E. A. Sproles, and K. A. Sawicz. 2016. Hydrologic landscape characterization for the Pacific Northwest, USA. JAWRA Journal of the American Water Resources Association 52:473–493.

Leigh, C., A. J. Boulton, J. L. Courtwright, K. Fritz, C. L. May, R. H. Walker, and T. Datry. 2016. Ecological research and management of intermittent rivers: an historical review and future directions. Freshwater Biology 61:1181–1199.

Lertzman-Lepofsky, G. F., A. M. Kissel, B. Sinervo, and W. J. Palen. 2020. Water loss and temperature interact to compound amphibian vulnerability to climate change. Global Change Biology 26:4868–4879.

Levi, T., G. V. Hilderbrand, M. D. Hocking, T. P. Quinn, K. S. White, M. S. Adams, J. B. Armstrong, A. P. Crupi, C. T. Darimont, W. Deacy, S. L. Gilbert, W. J. Ripple, Y. N. Shakeri, R. E. Wheat, and C. C. Wilmers. 2020. community ecology and conservation of bear-salmon ecosystems. Frontiers in Ecology and Evolution 8:433.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research: Atmospheres 99:14415–14428.

Lohse, K. A., E. L. Gallo, and T. Meixner. 2020. Influence of climate and duration of stream water presence on rates of litter decomposition and nutrient dynamics in temporary streams and surrounding environments of Southwestern USA. Frontiers in Water 0.

Lokgariwar, C., R. Chopra, V. Smakhtin, L. Bharati, and J. O'Keeffe. 2014. Including cultural water requirements in environmental flow assessment: an example from the upper Ganga River, India. Water International 39:81–96.

Lubetkin, K. C., A. L. Westerling, and L. M. Kueppers. 2017. Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. Ecological Applications 27:1876–1887.

Lynch, A. J., L.M. Thompson, E.A. Beever, D.N. Cole, A.C. Engman, C. Hawkins Hoffman, S.T. Jackson, T.J. Krabbenhoft, D.J. Lawrence, D. Limpinsel, R.T. Magill, T.A. Melvin. J.M Morton, R.A. Newman, J.O.Peterson, M.T. Porath, F.J. Rahel, G.W. Schuurman, S.A. Sethi, and J.L. Wilkening. 2021. Managing for RADical ecosystem change: applying the Resist-Accept-Direct (RAD) framework. Frontiers in Ecology and the Environment 19:461-469.

MacNeille, R. B., K. A. Lohse, S. E. Godsey, J. N. Perdrial, and C. V. Baxter. 2020. Influence of drying and wildfire on longitudinal chemistry patterns and processes of intermittent streams. Frontiers in Water 2:563841.

Markovich, K. H., A. H. Manning, L. E. Condon, and J. C. McIntosh. 2019. Mountain-block recharge: A review of current understanding. Water Resources Research 55:8278–8304.

McLaughlin, B. C., D. D. Ackerly, P. Z. Klos, J. Natali, T. E. Dawson, and S. E. Thompson. 2017. Hydrologic refugia, plants, and climate change. Global Change Biology 23:2941–2961.

Meixner, T., A. H. Manning, D. A. Stonestrom, D. M. Allen, H. Ajami, K. W. Blasch, A. E. Brookfield, C. L. Castro, J. F. Clark, D. J. Gochis, A. L. Flint, K. L. Neff, R. Niraula, M. Rodell, B. R. Scanlon, K. Singha, and M. A. Walvoord. 2016. Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology 534:124–138.

Messager, M. L., B. Lehner, C. Cockburn, N. Lamouroux, H. Pella, T. Snelder, K. Tockner, T. Trautmann, C. Watt, and T. Datry. 2021. Global prevalence of non-perennial rivers and streams. Nature 594:391–397.

Montibeller, B., J. Jaagus, Ü. Mander, and E. Uuemaa. 2021. Evapotranspiration intensification over unchanged temperate vegetation in the Baltic countries is being driven by climate shifts. Frontiers in Forests and Global Change 4:663327.

Moore, J. W., M. McClure, L. A. Rogers, and D. E. Schindler. 2010. Synchronization and portfolio performance of threatened salmon. Conservation Letters 3:340–348.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society 86:39–50.

Nash, C. S., G. E. Grant, S. Charnley, jason B. Dunham, H. Gosnell, M. B. Hausner, D. S. Pilliod, and J. D. Taylor. 2021. Great expectations: deconstructing the process pathways underlying beaver-related restoration. BioScience 71:249–267.

Niemeyer, R. J., K. D. Bladon, and R. D. Woodsmith. 2020. Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest. Hydrological Processes 34:1182–1197.

Njue, N., J. Stenfert Kroese, J. Gräf, S. R. Jacobs, B. Weeser, L. Breuer, and M. C. Rufino. 2019. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. Science of The Total Environment 693:133531.

Office of Columbia River. 2018. Yakima River Basin integrated water resource management plan implementation status report 2017. Pages 0–41. Department of Ecology, Washington State.

Olson, D. H., and J. I. Burton. 2019. Climate associations with headwater streamflow in managed forests over 16 years and projections of future dry headwater stream channels. Forests 10:968.

Parker, S. D., J. S. Perkin, M. G. Bean, D. Lutz-Carrillo, and M. R. Acre. 2021. Temporal distribution modelling reveals upstream habitat drying and downstream non-native introgression are squeezing out an imperiled headwater fish. Diversity and Distributions 27:533–551.

Penaluna, B. E., J. B. Dunham, and H. V. Andersen. 2021. Nowhere to hide: The importance of instream cover for stream-living Coastal Cutthroat Trout during seasonal low flow. Ecology of Freshwater Fish 30:256–269.

Perkin, J. S., K. B. Gido, J. A. Falke, K. D. Fausch, H. Crockett, E. R. Johnson, and J. Sanderson. 2017. Groundwater declines are linked to changes in Great Plains stream fish assemblages. Proceedings of the National Academy of Sciences 114:7373–7378.

Perkin, J. S., T. A. Starks, C. A. Pennock, K. B. Gido, G. W. Hopper, and S. C. Hedden. 2019. Extreme drought causes fish recruitment failure in a fragmented Great Plains riverscape. Ecohydrology 12:e2120.

Perry, T. D., and J. A. Jones. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. Ecohydrology 10:e1790.

Poff, N. L., and J. K. H. Zimmerman. 2010. Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. Freshwater Biology 55:194–205.

Propst, D. L., K. B. Gido, and J. A. Stefferud. 2008. Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. Ecological Applications 18:1236–1252.

Raymond, P. A., J. Hartmann, R. Lauerwald, S. Sobek, C. McDonald, M. Hoover, D. Butman, R. Striegl, E. Mayorga, C. Humborg, P. Kortelainen, H. Dürr, M. Meybeck, P. Ciais, and P. Guth. 2013. Global carbon dioxide emissions from inland waters. Nature 503:355–359.

Raymondi, R. R., J. E. Cuhaciyan, P. Glick, S. M. Capalbo, L. L. Houston, S. L. Shafer, and O. Grah. 2013. Chapter 3, Water resources: Implications of changes in temperature at precipitation. Pages 41–66 Climate Change in the Northwest: Implications for our Landscapes, Waters and Communities. Island Press.

Rodríguez-Lozano, P., C. Woelfle-Erskine, M. T. Bogan, and S. M. Carlson. 2020. Are non-perennial rivers considered as valuable and worthy of conservation as perennial rivers? Sustainability 12:5782.

Roesch-McNally, G. E. 2018. U.S. Inland Pacific Northwest wheat farmers' perceived risks: Motivating intentions to adapt to climate change? Environments 5:49.

Rohde, M. M., J. C. Stella, D. A. Roberts, and M. B. Singer. 2021. Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow. Proceedings of the National Academy of Sciences 118.

Rolls, R. J., C. Leigh, and F. Sheldon. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. Freshwater Science 31:1163–1186.

Ruhí, A., E. E. Holmes, J. N. Rinne, and J. L. Sabo. 2015. Anomalous droughts, not invasion, decrease persistence of native fishes in a desert river. Global Change Biology 21:1482–1496.

Ruhí, A., J. D. Olden, and J. L. Sabo. 2016. Declining streamflow induces collapse and replacement of native fish in the American Southwest. Frontiers in Ecology and the Environment 14:465–472.

Ryan, M. E., W. J. Palen, M. J. Adams, and R. M. Rochefort. 2014. Amphibians in the climate vise: loss and restoration of resilience of montane wetland ecosystems in the western US. Frontiers in Ecology and the Environment 12:232–240.

Sando, R., and K. W. Blasch. 2015. Predicting alpine headwater stream intermittency: a case study in the northern Rocky Mountains. Ecohydrology & Hydrobiology 15:68–80.

Schilling, K. E., and M. Helmers. 2008. Effects of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: Exploratory hydrograph analysis. Hydrological Processes 22:4497–4506.

Schultz, L. D., M. P. Heck, D. Hockman-Wert, T. Allai, S. Wenger, N. A. Cook, and J. B. Dunham. 2017. Spatial and temporal variability in the effects of wildfire and drought on thermal habitat for a desert trout. Journal of Arid Environments 145:60–68.

Scott, J. A., and D. M. Merritt. 2020. Riparian response guilds shift in response to flow alteration in montane streams of the southern Rocky Mountains. Ecosphere 11:e03253.

Scott, M. L., P. B. Shafroth, and G. T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23:347–358.

Segura, C., K. D. Bladon, J. A. Hatten, J. A. Jones, V. C. Hale, and G. G. Ice. 2020. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. Journal of Hydrology 585:124749.

Shanafield, M., K. Gutiérrrez-Jurado, N. White, M. Hatch, and R. Keane. 2020. Catchment-scale characterization of intermittent stream infiltration; a geophysics approach. Journal of Geophysical Research: Earth Surface 125.

Shanafield, M., S. A. Bourke, M. A. Zimmer, and K. H. Costigan. 2021. An overview of the hydrology of non-perennial rivers and streams. WIREs Water 8:e1504.

Siirila-Woodburn, E. R., A. M. Rhoades, B. J. Hatchett, L. S. Huning, J. Szinai, C. Tague, P. S. Nico, D. R. Feldman, A. D. Jones, W. D. Collins, and L. Kaatz. 2021. A low-to-no snow future and its impacts on water resources in the western United States. Nature Reviews Earth & Environment 2:800–819.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18:1136–1155.

Streib, L. C., J. R. Stone, E. C. Lyon, H. H. Quang, K. M. Yeager, S. R. H. Zimmerman, and M. M. McGlue. 2021. Anthropogenic climate change has altered lake state in the Sierra Nevada (California, USA). Global Change Biology n/a.

Swanson, S. R., S. Wyman, and C. Evans. 2015. Practical grazing management to meet riparian objectives. Journal of Rangeland Applications 2:1–28.

Timoner, X., V. Acuña, D. Von Schiller, and S. Sabater. 2012. Functional responses of stream biofilms to flow cessation, desiccation and rewetting. Freshwater Biology 57:1565–1578.

Walsh, C. J., A. Roy, J. Feminella, P. Cottingham, P. Groffman, and R. Morgan II. 2005. The urban stream syndrome: Current Knowledge and the Search For A Cure. Am. Benthol. Soc 24:706–723.

Ward, E. J., J. H. Anderson, T. J. Beechie, G. R. Pess, and M. J. Ford. 2015. Increasing hydrologic variability threatens depleted anadromous fish populations. Global Change Biology 21:2500–2509.

Wieting, C., B. A. Ebel, and K. Singha. 2017. Quantifying the effects of wildfire on changes in soil properties by surface burning of soils from the Boulder Creek Critical Zone Observatory. Journal of Hydrology: Regional Studies 13:43–57.

Woelfle-Erskine, C., L. G. Larsen, and S. M. Carlson. 2017. Abiotic habitat thresholds for salmonid over-summer survival in intermittent streams. Ecosphere 8:e01645.

Wolters, E. A., and B. S. Steel. 2021. Environmental efficacy, climate change beliefs, ideology, and public water policy preferences. International Journal of Environmental Research and Public Health 18:7000.

Wu, W.-Y., M.-H. Lo, Y. Wada, J. S. Famiglietti, J. T. Reager, P. J.-F. Yeh, A. Ducharne, and Z.-L. Yang. 2020. Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. Nature Communications 11:3710.

Zimmer, M. A., K. E. Kaiser, J. R. Blaszczak, S. C. Zipper, J. C. Hammond, K. M. Fritz, K. H. Costigan, J. Hosen, S. E. Godsey, G. H. Allen, S. Kampf, R. M. Burrows, C. A. Krabbenhoft, W. Dodds, R. Hale, J. D. Olden, M. Shanafield, A. G. DelVecchia, A. S. Ward, M. C. Mims, T. Datry, M. T. Bogan, K. S. Boersma, M. H. Busch, C. N. Jones, A. J. Burgin, and D. C. Allen. 2020. Zero or not? Causes and consequences of zero-flow stream gage readings. WIREs Water 7:e1436.

Zipper, S. C., J. C. Hammond, M. Shanafield, M. Zimmer, T. Datry, C. N. Jones, K. E. Kaiser, S. E. Godsey, R. M. Burrows, J. R. Blaszczak, M. H. Busch, A. N. Price, K. S. Boersma, A. S. Ward, K. Costigan, G. H. Allen, C. A. Krabbenhoft, W. K. Dodds, M. C. Mims, J. D. Olden, S. K. Kampf, A. J. Burgin, and D. C. Allen. 2021. Pervasive changes in stream intermittency across the United States. Environmental Research Letters 16:084033.