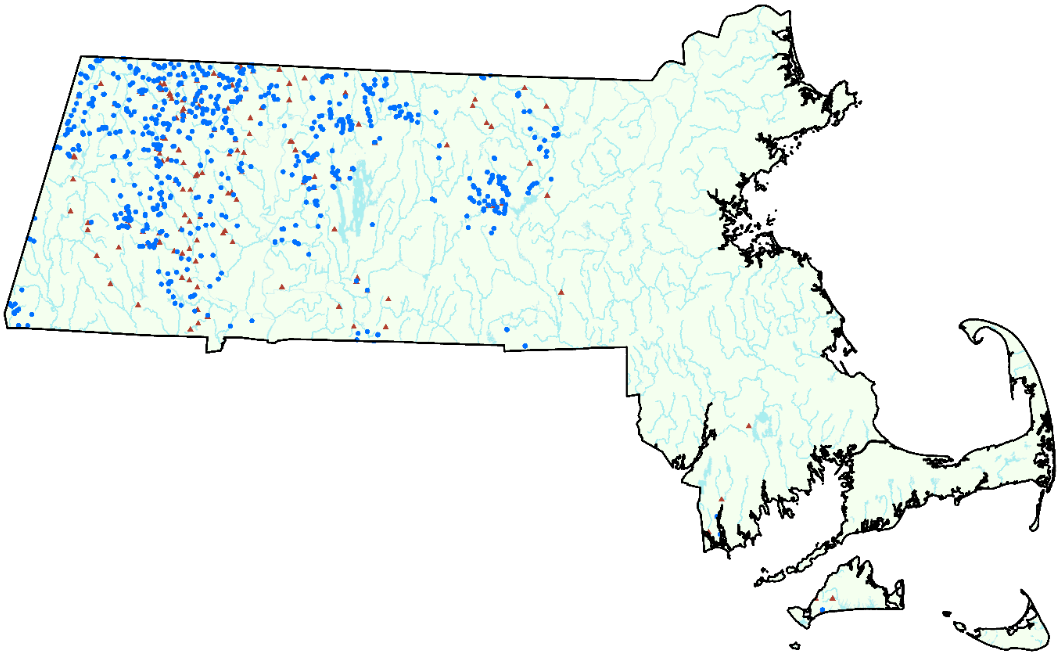
JL Ebersole *et al.* – Supporting Information

WebPanel 1. Modeling climate-change refugia in Massachusetts

Managers and researchers in Massachusetts have used modeling to identify cold-water climate-change refugia. Beyond locating potential refugia, this effort visualizes the probable future network of these areas, as well as a measure of the relative longevity of each. Preliminary results suggest that the number of sites across the state with >50% probability of brook trout (*Salvelinus fontinalis*) occurrence may decrease by 36% with a 2°C increase in average July temperatures. With a 4°C average increase, the number of sites may decrease by 54%, with additional losses largely concentrated in the southwestern part of the state and in the eastern Berkshire Mountains. A 6°C average increase may reduce the number of sites by as much as 75% in the eastern, central, and southwestern parts of the state, with the exception of sites in largely forested watersheds (Figure3. Cold-water climate-change refugia with the largest capacity to support cold-water species based on temperature are most likely to linger in the northwestern part of the state. Smaller, but perhaps equally important, cold-water refuges are likely to persist in other areas of the state.

Changes in precipitation associated with climate change are also expected to alter flow regimes, including the frequency and length of droughts. Massachusetts experienced its longest drought, lasting 48 weeks, from June 2016 to May 2017 (www.drought.gov), providing a rare opportunity to survey fishes during extremely low flows. In order to identify refugia that may also provide habitat under drought conditions, sites that harbored cold-water fishes in 2016 were layered over modeled results (WebFigure 1). Although fewer sites were sampled in 2016, results suggest that cold-water refugia in the central and western parts of the state may buffer cold-water fishes from multiple climate-change effects.



WebFigure 1. Map of Massachusetts showing areas likely to support brook trout (>50% probability of occurrence) with an increase of 6°C in average July air temperatures (blue circles) and areas where cold-water species were captured during the 2016 drought (red triangles). Areas that overlap show potential refuges that buffer cold-water species from both warming temperatures and drought conditions. Not all areas in blue were sampled in 2016.

WebPanel 2. Water is critical for sustaining cold-water climate-change refugia

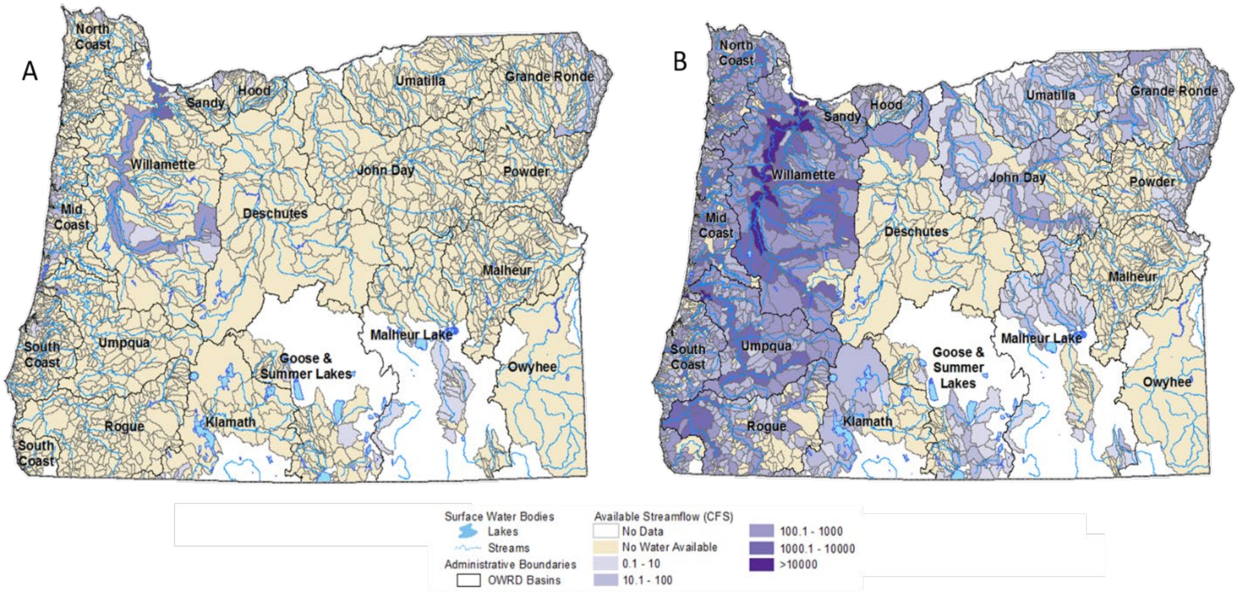
Providing in-river water will be the single greatest challenge to ensuring effective climate-change refugia in many Oregon rivers. This is because (1) during summer in many locations, human demand for water already exceeds supply; (2) under climate change, water supply is predicted to decrease during critical periods when fish will most need refugia, thereby widening the gap between supply and demand; and most critically (3) for extended parts of the year and across wide swaths of the state, available water has already been overallocated for out-of-river uses (WebFigure 2).

Expanding on this last point, water is regulated in Oregon under a prior appropriation system, where the right to withdraw water is associated with a "priority date" based on when the application was submitted. During times of shortage, water is allocated to users in order of their priority date such that users with more recent priority dates often receive little or none of their allocation. In all but one basin in Oregon, all of the water in summer was allocated by the 1920s, primarily for agricultural or municipal use, not for instream uses that include habitat for fish. Only recently has the state begun to apply for instream water rights in an effort to ensure some portion of the stream/river remains wet. Because these instream rights typically have a junior priority date, in many cases they only ensure that some water remains instream during periods of average to high flow. The lack of water allocated to instream uses increases exposure of fish to low flows and correspondingly higher temperatures, as well as fragmenting the riverscape so that fish cannot access refugia or migrate to more favorable areas.

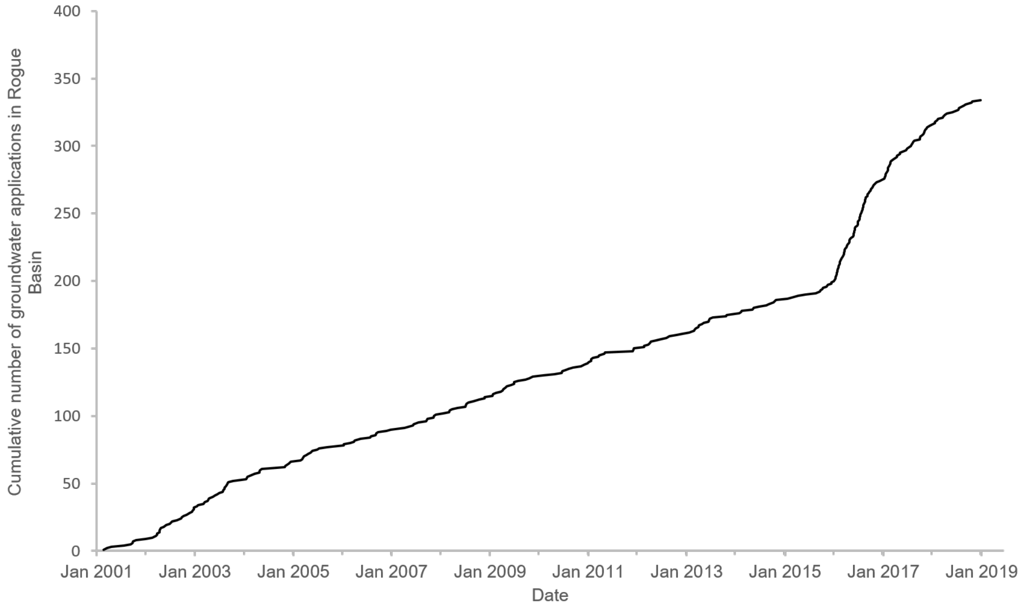
Because summer water is already overallocated in most locations in Oregon there has been a recent and rapid shift to appropriate water in winter, often for the purposes of storing it for use in summer. At the current rate of permit applications, it is expected that all winter water in Oregon will be allocated within 20 years. The impact of withdrawing water out of streams in winter for use in summer is unclear, but there will likely be detrimental impacts to fish as a result of altered stream flows. This is an example where there is a clear and urgent need for a better understanding of the cumulative impacts of this type of development, and for the development of best management practices to balance all needs. In some cases, supplementing the storage of winter water and its release during summer low-flow periods specifically for the benefit of fish will be critical for their survival through summer.

Not all water is equal

In addition to a shift toward allocating winter water, groundwater is also increasingly being targeted for extraction in Oregon because of a lack of surface water availability in some locations and concerns about increasing drought frequency. For example, the Rogue basin in southwestern Oregon has seen an exponential increase in applications for groundwater since 2015, coinciding with a severe region-wide drought (WebFigure 3). This is problematic with respect to establishing and managing refugia for cold-water fishes because groundwater is typically much cooler than surface water. Therefore, a reduction in groundwater input to streams has more impact on the frequency of both stream warming and drying than does a similar loss of surface water. Often, however, the groundwater resource is poorly defined and the link to surface water is not well understood. In the absence of this information, there is major risk of overextraction of the resource.



WebFigure 2. Estimate of available streamflow (ie water that is not currently allocated to instream or out-of-stream use) in (a) August and (b) January. Available streamflow is calculated at the 80% and 50% exceedance level for August and January, respectively. Source: Oregon Water Resources Department.



WebFigure 3. Cumulative number of applications for groundwater extraction in the Rogue River basin of southwestern Oregon between 2001 and 2019.

WebPanel 3. Incorporating needs of salmon into flow management of regulated rivers: Oregon's Rogue River spring Chinook salmon

During the late 1800s and up to the mid-1900s, hundreds of dams were built in the watersheds along the West Coast of the US, primarily for purposes of flood control, power generation, and irrigation. In most instances, however, little consideration was given to how dam construction and operation would impact fish populations, with two notable exceptions in Oregon: Round Butte Dam on the Deschutes River and Lost Creek Dam on the Rogue River. Planning for the Rogue River basin project was initiated in the 1950s as a result of severe flooding and economic losses over the previous century. The planning phase included 22 public meetings at which public testimony emphasized the water resource needs of the basin. Notably, many parties strongly emphasized that "the flood control plan for the basin must be compatible with Rogue River basin fishery resources" (Department of the Army 1962). On the basis of public input during planning, the US Congress authorized construction of two dams for the primary purposes of flood control, fish and wildlife enhancement, irrigation, and water supply, with the secondary purposes consisting of power generation, recreation, and water-quality enhancement.

The authorizing document specified that the state be allocated a large portion of the water that is released for fishery enhancement. In addition, the authorization noted that the project operations should be sufficiently flexible to permit desirable modifications to flow releases for fishery enhancement. Currently, the state is allocated 222 million m^3 of water for fishery enhancement purposes. The increased flow of lower temperature water is currently used to reduce exposure to low flows and higher temperatures that result in pre-spawn mortality of spring and fall Chinook salmon (*Oncorhynchus tshawytscha*), minimize dewatering of spring Chinook redds (nests in streambed gravel) by reducing exposure to flow fluctuations, and maintain the adaptive capacity of spring Chinook by minimizing hybridization with fall Chinook salmon.

WebReferences

Department of the Army. 1962. Rogue River basin, Oregon and California. Letter from the Secretary of the Army. US Government Printing Office, Washington DC.

WebPanel 4. Is win–win possible? Using ecosystem models to quantify co-benefits and trade-offs of forest management strategies

There is growing interest in an innovative governance model that places the management of forests back in the hands of local communities and enables forests to be managed for both conservation and economic development values. In the timber-producing communities of the US Pacific Northwest, this interest is rooted in the concern that local communities may receive little of the profits from timber harvest but are left bearing the environmental impacts associated with the current intensive industrial harvest regime that favors a short (~40 year) harvest cycle. The shift to such rapid turnover in forests began in the 1940s and has had a major impact on stream flow. Empirical studies in western Oregon have established that young, rapidly growing forests transpire over three times as much water as do mature forests (Moore *et al*. 2004). This causes a 40–60% decrease in summer flow during the period 20–45 years post-harvest relative to old growth forest (Perry and Jones 2017). Process-based modeling that accounts for this effect highlights the substantial impact that forest practices can have on stream flows (Abdelnour *et al*. 2011). To balance the economic and environmental objectives of the different stakeholders, some managers and communities are turning to ecosystem models like Visualizing Ecosystem Land Management Assessments (VELMA, www.epa.gov/water-research/visualizing-ecosystem-land-management-assessments-velma-model-20) to inform forest management strategies. An example of this can be found in the Mashel watershed of southwestern Washington State. Landowners in the Mashel watershed include private timber companies, the Washington State Department of Natural Resources, the Nisqually Land Trust and Community Forest, and the Town of Eatonville. These owners each have distinct goals that are often conflicting. To determine if there were forest management strategies that could balance the trade-offs between these diverse objectives, the stakeholders asked Environmental Protection Agency (EPA) researchers to simulate alternative management strategies. Using VELMA, EPA researchers are simulating different scenarios of forest management to examine trade-offs among volume of forest products, the local income from forest products, salmon habitat quality, and ecosystem carbon stocks. Model outputs are being used by stakeholders to envision future options for managing shared resources.

WebReferences

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Moore GW, Bond BJ, Jones JA, *et al.* 2004. Structural and compositional controls on transpiration in 40- and 450-year-old riparian forests in western Oregon, USA. *Tree Physiol* **24**: 481–91.

Perry TD and Jones JA. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. *Ecohydrology* **10**: e1790.