In-stream Flows

Under Oregon state law, all water rights must serve a beneficial use. In Oregon and some other western states, beneficial use includes in-stream flows to protect habitat for salmon, steelhead, and other native fish species, as well as for ecosystem services and other purposes.

In the WRB, in-stream water rights were established on various stream segments in the 1960s in order to provide minimum recommended perennial streamflows to protect fish habitat. Some of these water rights have been implemented or "converted" to certified water rights, i.e., put into place and enforced. Our reference scenario includes 93 certified in-stream water rights.

Many of these water rights, however, have not yet been converted to certified water rights. The OWRD has initiated a process for converting the remaining water rights. These additional regulatory allocations of water for in-stream flows represent a significant "new" use of water for many of the Basin's main tributaries. In some cases, conversion involves an increase in the minimum flows associated with existing in-stream water rights.

An alternative scenario ("new in-stream") assumes the conversion of in-stream water rights and gives them priority dates corresponding to their creation, typically in the 1960s. The implementation of these unconverted in-stream water rights is consistent with the Instream Water Rights Act (https://www.oregonlaws.org/ors/537.346) (see also Amos, 2013). Full implementation represents an additional commitment of surface water from April through August of 1.1 million acre-feet. This total is derived by summing the flow requirements at the outlet of each main tributary, some of which would increase.

Some of these streamflows, however, are already protected by existing in-stream water rights under state law. In other cases, the minimum flows coincide with the operations of federal dams, where flow targets are already mandated under Endangered Species Act (ESA) Biological Opinions (BiOps). (See Amos, 2013, for details about relevant state and federal laws.)

The 2008 final BiOps for ESA-listed salmon and steelhead in the Willamette Basin establish minimum in-stream flows below federal reservoirs in the WRB from April through October (NMFS, 2008). Required flows are highest from April through June. These flows have built-in flexibility, whereby required flows are reduced in years considered to be "deficit" or "insufficient" water years. This determination is based on reservoir fill levels.

The BiOp flow requirements are tied to downstream control points (see Appendix). Existing required BiOp flows are higher than those that would be required under state law by conversion of all remaining in-stream water rights. Although the addition of new in-stream water rights and continued BiOp flow requirements represent challenges for federal and state water managers, our model results suggest that these flow requirements can be met, based on average 10-year flows. Exceptions may occur in severe drought years.

Reservoirs

The system of 13 reservoirs that comprise the United States Army Corp of Engineers (USACE) Willamette Project is one of the primary mechanisms used to mitigate water scarcity in large parts of the WRB. Although the Willamette Project reservoirs were built primarily for flood control, they fortuitously have a large capacity (1.6 million acre-feet in total) to store water from abundant winter and spring streamflows. This stored water is available for use during the summer, when natural flows are low.

Flood damage reduction remains the priority authorized use of these reservoirs. Nonetheless, stored water uses have become increasingly important. These uses include reservoir recreation and the augmentation of downstream flows for endangered species and irrigated agriculture. By increasing mainstem flows, these releases also indirectly contribute to urban water supplies.

When water is released to maintain reservoir capacity to buffer storm events, that water is not available for later use. Thus, flood mitigation and water storage become competing objectives as reservoirs fill during the transition from the wet to the dry season.

The balance between these objectives is expressed in the operations rule curve for each reservoir, which specifies the target level to which the reservoir is filled throughout the year (Figure 44, p. 51). During the winter flood season from December to February, the volume of water stored in the reservoirs is kept at a minimum. Starting February 1, the USACE begins adding water to storage, with the goal of filling reservoirs by May 20, ahead of the Memorial Day weekend. The reservoirs are kept as full as possible during the summer (June–August) for recreation. However, releases during the spring and summer to maintain minimum flows, as required by the BiOps, can prevent reservoirs from achieving or maintaining full pool storage through the summer. To the extent possible, releases are managed to maintain higher water levels at reservoirs with high recreational use. After Labor Day, the reservoirs are gradually drawn down to minimum levels in preparation for the next winter flood season.

Our model projects increasing shortfalls in summer reservoir fill over the course of this century, particularly under the warmer climate scenario (Figure 45, p. 51). Lower summer water levels can impact recreational use in various ways, including loss of boat ramp access, increased mud flats, and compromised aesthetics such as "bathtub rings." Associated economic losses are based on empirical evidence that fewer people visit the reservoirs when water levels are reduced (Moore, 2015).

Lost recreational benefits across the Willamette Project reservoirs are estimated to remain relatively stable until late in the 21st century. By the 2080s and 2090s, these foregone benefits are projected to increase, to more than $12 million per year in the reference scenario. Under the high climate change scenario, they exceed $13 million per year (Figure 46, p. 52). These losses represent a 5 or 6 percent decline in total recreation visits, respectively.

Given the tradeoff involved in managing reservoirs for both flood reduction and stored water uses, these lost recreational benefits should be considered in light of the estimated value of flood damage reduction. The USACE estimates that, as of June 2015, the Willamette Project reservoirs have prevented more than $23 billion in flood damages since their completion in 1969 (USACE, 2015). Based on analyses undertaken to complement the WW2100 effort, the current annual value of reservoir buffering capacity is estimated at more than $1 billion (Moore, 2015). This estimate is based on avoided flood damages to downstream developed land, buildings, and their contents (Figure 47, p. 52). It reflects population and economic growth, but does not account for changes in flood risk due to climate change.

With the levels of economic growth and urban expansion projected under the reference scenario, this benefit is expected to triple by 2100. Under the high population scenario (Figure 47), it increases more than fivefold.

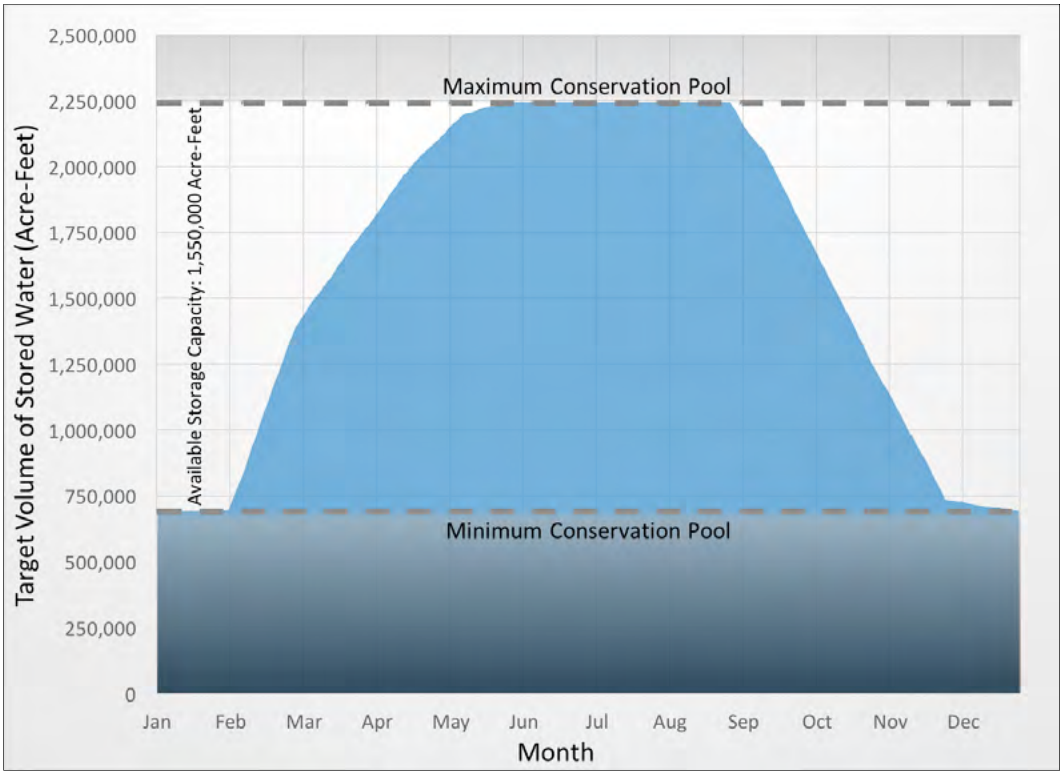

Figure 44. Total Willamette Project reservoir storage capacity and management rule curve.

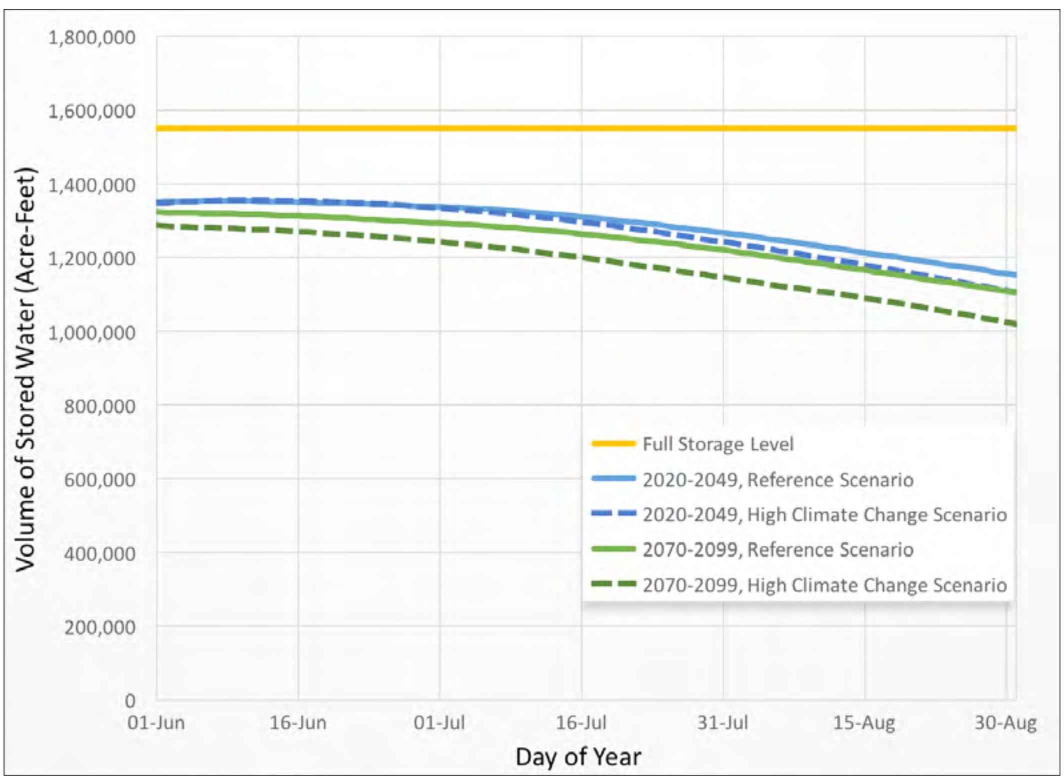

Figure 45. Reservoir summer fill levels.

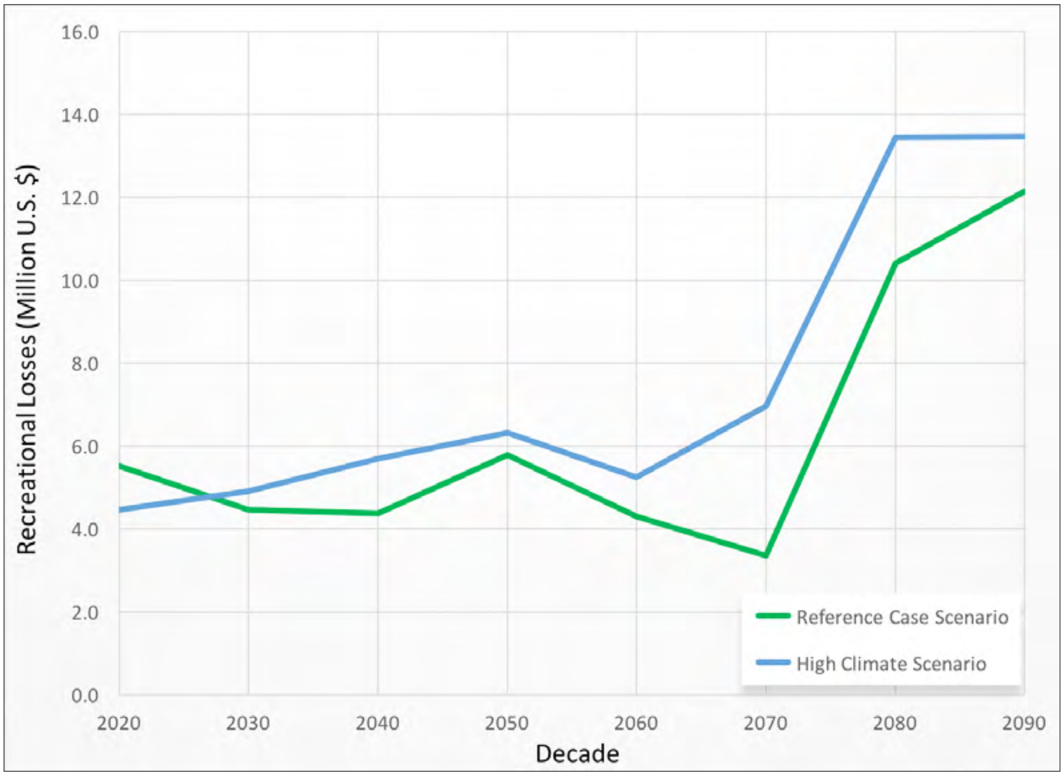

Figure 46. Reduced recreational benefits due to summer reservoir draw-down.

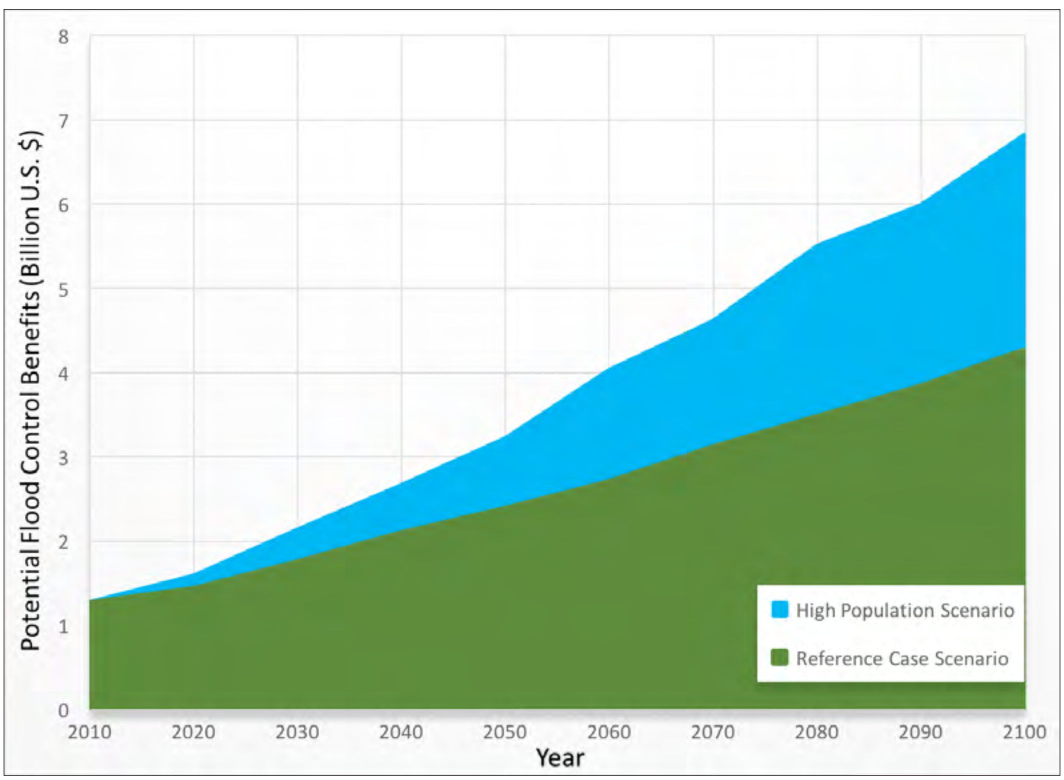

Figure 47. Annual economic benefits of flood risk reductions from Willamette Project reservoirs (January–May).

Subbasin Differences

The 11 WRB subbasins differ in size, acreage of farmland, developed land area (Table 2), precipitation patterns, changes in forest water use due to harvest and wildfire, and other ways. Thus, patterns of water supply and use vary considerably and will continue to do so in the future. This section examines the differences across subbasins, how those differences are likely to change in future decades, and what implications they may have for water scarcity at the subbasin scale. For this discussion, we are omitting the Willamette mainstem as a subbasin.

It is important to keep in mind that the hydrology of subbasins in the eastern half of the WRB differs significantly from that in western subbasins. In the eastern half of the WRB, snowmelt, reservoir storage, and summer in-stream flows are greater than in the western subbasins. As indicated in Table 2, several of the eastern tributaries have minimum summer flow requirements of 520 to 2,100 cfs, while several western tributaries require flows of only 30 to 150 cfs.

The scale of agricultural land and water use differs considerably among the 11 subbasins. The largest agricultural acreage, as a percentage of total land area, is in the Yamhill and Molalla subbasins, followed by the Tualatin and Long Tom subbasins. By contrast, very little agriculture is found in the McKenzie, Middle Fork Willamette, or Coast Fork Willamette subbasins (Table 2).

We are especially interested in identifying which subbasins have the most irrigation and in particular those with large-scale surface irrigation, since surface-water irrigation represents the largest out-of-stream human consumptive use of water during the summer when water may be scarce. Table 2 reveals

Table 2. Differences across subbasins in hydrology and land use.

Subbasin	Apr–Sep average flow rate (cfs)	Apr–Sep daily per-acre flow (inch/day)	Apr–Sep regulatory minimum flow (cfs)	Ratio of average flow to regulatory flow (Jul–Aug)	Projected change in Apr–Aug flow, 2010s–20s to 2080s–90s (%)	Farmland (% of land area)	Surface-irrigated farmland (% of land area)	Developed land (% of land area)
Clackamas River	2,259	271	520	2.8	-4.1	7.9	0.5	1.7
Coast Fork Willamette River[1]	735	127	—	—	—	7.9	1.0	1.1
Long Tom River	284	79	30	2.1	8.0	29.9	4.3	6.5
Marys River	317	119	65	1.5	13.5	22.9	2.7	2.9
McKenzie River	3,789	321	1,025	2.4	-7.3	2.0	0.4	0.5
Middle Fork Willamette River[1]	2,382	200	—	—	—	1.2	0.2	0.2
Molalla (Pudding) River	1,484	191	325	2.7	-0.5	39.0	4.8	3.2
North Santiam River	4,509	667	1,300	2.3	-3.9	9.9	1.6	0.5
South Santiam River	2,320	252	1,067	1.3	-1.4	14.8	2.5	0.6
Tualatin River	733	117	154	1.6	17.0	28.4	6.3	18.2
Yamhill River	637	139	32	1.7	11.3	54.6	12.1	3.8
Willamette River, Coast and Middle Forks[1]	3,117	176	2,167	0.7	-3.4	3.4	0.4	0.5
Average	1,768	226	502	—	2.9	19.8	3.3	3.6

[1] Flows for the two main Willamette tributaries are shown separately and combined, where the combined values are compared to in-stream water rights just below their confluence.

that the Yamhill subbasin has the most surface irrigation, followed by the Tualatin, Molalla, and Long Tom subbasins.

Developed urban land is greatest in the Tualatin subbasin, followed by the Molalla and Long Tom subbasins. A large fraction of developed land is not represented in subbasin data, however, because developed lands are concentrated along the mainstem (for example, portions of the Portland Metro area and Salem). The area designated as the Willamette mainstem subbasin also includes substantial areas of farmland and irrigation.

The period when water may become scarce is in spring (when dams are being filled and in-stream BiOp flow requirements are highest) and summer (when flows are lowest and out-of-stream use by agriculture and urban populations is highest). Ideally we would like to compare spring and summer flows in each subbasin to current and future demand for water. However, estimating urban water use by subbasin is difficult, as some major urban areas straddle multiple subbasins. In some cases, cities draw water from only one of these subbasins or from outside the WRB (for example, the City of Portland and some cities on the west side of the Portland Metro area). Moreover, because much of the water used in urban areas is returned to its original surface-water system, quantifying the net consumptive use from a given subbasin's water sources is not straightforward.

In the case of irrigation, the number of acres irrigated provides a rough idea of the demands placed on subbasin water sources. Each acre of irrigated land diverts 1.5 to 2 acre-feet of water during a season, typically between April and August.

In the reference scenario, subbasins vary greatly in projected changes in April–August streamflows. For some subbasins, April–August flows are projected to decline by as much as 7.3 percent; for others, the model results indicate increased flows of up to 17 percent (Table 2). In the case of the Tualatin, discharge from urban water systems that draw on out-of-basin reserves (Barney and Scoggins Reservoirs) is expected to increase. It is noteworthy that all of the subbasins showing decreased flows have their headwaters in the Cascades, whereas nearly all of those with increased flows are on the west side of the Basin.

Another way to look at changing subbasin water supplies is in terms of the changes in stream flow during spring (April–June), shown in Figure 48 (p. 55); and in summer (July–August), shown in Figure 49 (p. 56). We see small decreases in spring flows in several subbasins, although the pattern varies greatly.

The largest commitment of surface water in most subbasins is the allocation of water for in-stream water rights under state law (separate from the similarly large quantities of water allocated under federal BiOp flows). In-stream water rights are largest at the confluence of the Middle and Coast Forks of the Willamette River, both for the April–September irrigation season and for the July–August low-flow period. The McKenzie has the second highest total in-stream water rights. Based on unconverted in-stream water rights, the North and South Santiam rivers follow.

One of the largest factors affecting future water scarcity in some subbasins will be the conversion of perennial minimum streamflows into binding in-stream water rights. The largest increases are for the confluence of the Coast and Middle Forks of the Willamette and the McKenzie, each with increases of more than 600,000 acre-feet from April through August. An important factor for those tributaries with federal dams is the ability to control flows by modifying management rules for dam releases.

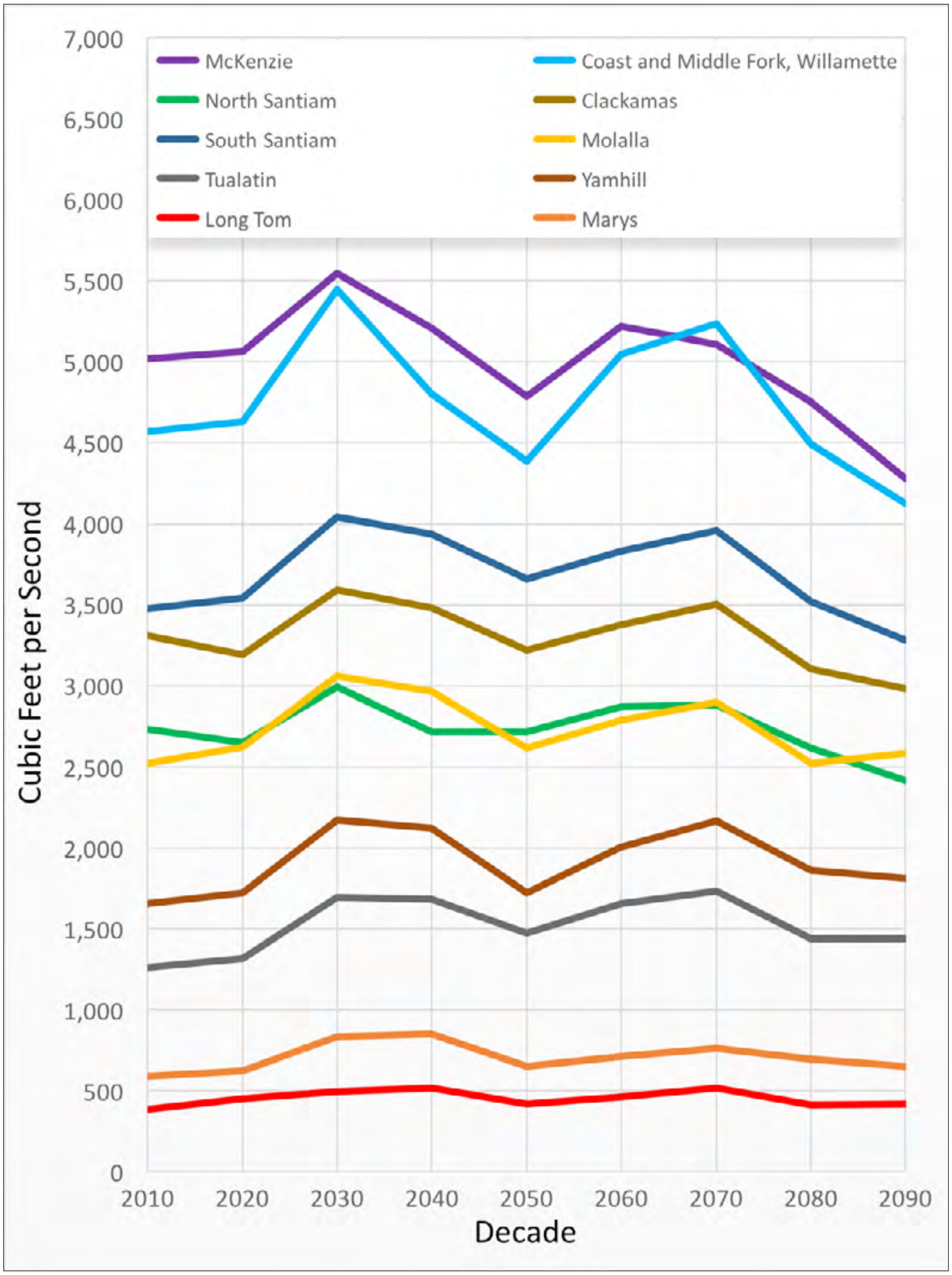

Figure 48. Subbasin outflows, April–June, reference scenario (decade average).

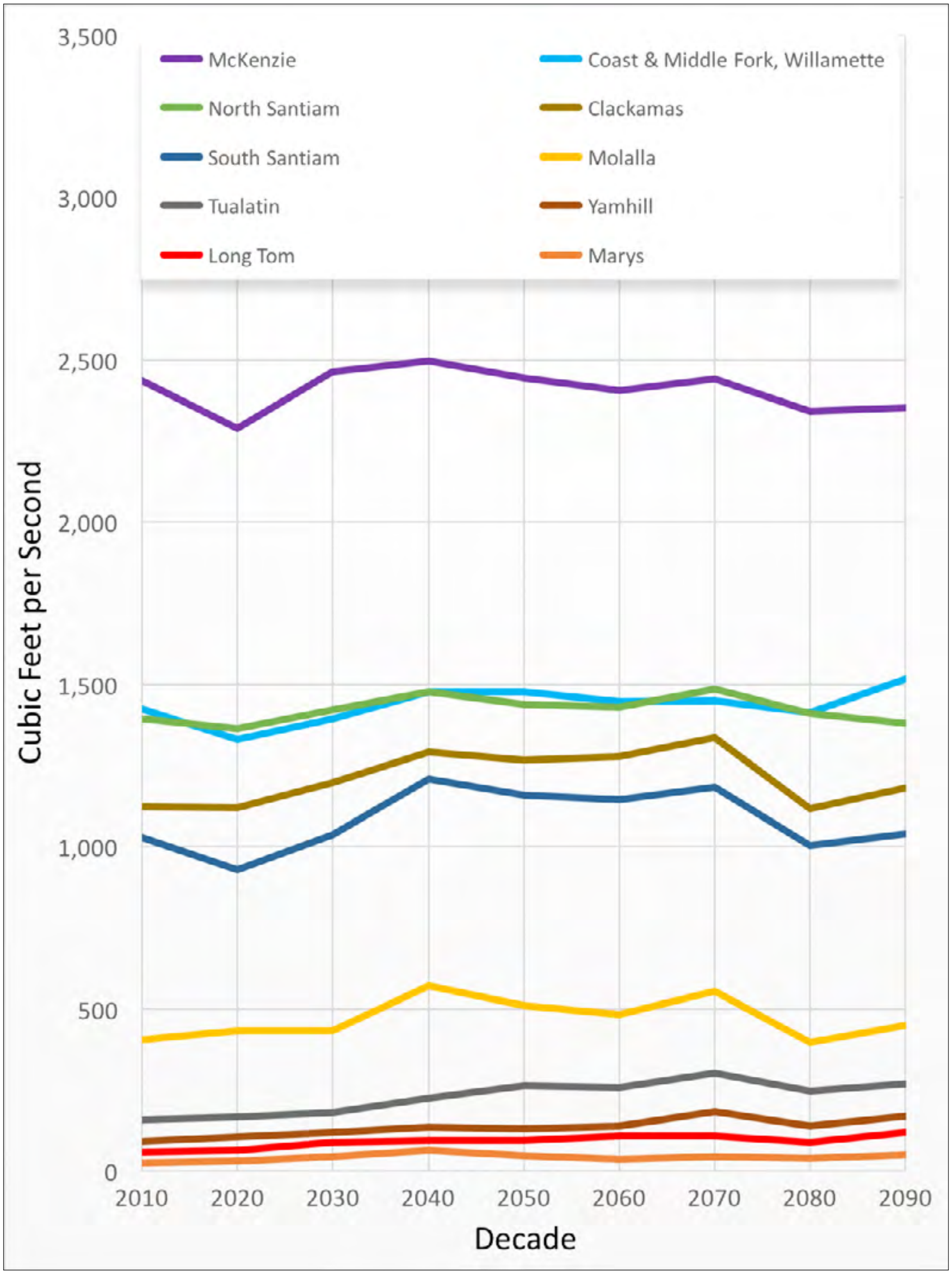

Figure 49. Subbasin outflows, July-August, reference scenario (decade average).

Conclusions

Our understanding of water supply relies heavily on hydrology and related natural sciences, whereas our understanding of the demand for, and allocation of, water comes from economics, law, engineering, and related social sciences. A hydro-economic model like the one presented here makes it possible to represent the important processes of both the natural and human systems.[17] The WW2100 model sheds light on how these components interact and helps us understand where, when, and why we may see more water scarcity in the future.

Changing supply

On the supply side, the severe decline in snowpack in the next 80 years will reduce the amount of snowmelt runoff from April to June. The projected reduction in average available snowmelt (as of April 1 each year) represents a decline of about 600,000 acre-feet of stored water. However, precipitation plays a far greater role than snowmelt in determining spring streamflows in the WRB. Indeed, the projected decline in snowmelt is only one-tenth of average April–July precipitation (nearly 7 million acre-feet).

As a result, unlike arid basins in eastern Oregon or neighboring western states, the loss of snowmelt will have a relatively small impact on water availability in the lower elevations of the WRB in spring and summer. Nevertheless, reduced snowpack, when combined with higher summer temperatures, is projected to increase stress on upland forests and, as a result, increase the risk of wildfire.

To the extent that drier forests result in more frequent wildfires, the consequent changes in forest cover will reduce forest water use (ET) and allow more surface water to flow into the Willamette Valley. Depending on the extent of wildfires and on fire suppression policies, these changes in forest cover may have a greater influence on water supply to the lower Basin than the projected reduction in snowmelt.

Changing demand

The economic forces related to where and when water is used or not used may at times be overlooked, in part because they are not visible or immediately recognizable. The locations of various types of economic activity are influenced by land markets, and these individual and societal choices in turn influence the demand for water at each location. Our model projections find that from 2010 to 2100 developed land as a percentage of total land area in the WRB will rise from 4.7 percent to about 7.2 percent, a 54 percent increase. Agricultural land is projected to decline from almost 22 percent to 20.2 percent, and forest land from 70.6 percent to 69.7 percent. The decline in agricultural lands is about 7.5 percent for farmland overall and about 5 percent for irrigated lands.

At each location, given a particular land use, water use is influenced by both the demand (willingness to pay) for water and the cost of transporting, storing, or transforming water to make it available for a given use. The importance of cost considerations is illustrated by the case of water conveyance costs. Demand for transported water depends on the value of water for a specific purpose relative to conveyance costs. For example, water is transported up to 25 miles from outside the WRB (often aided by gravity) to serve urban users. In contrast, we

[17] The projections in this report for both urban water use and agricultural water use are based on the set of behavioral economic models described here and elsewhere. These models reflect and are derived from economic theory. They are spatially and temporally explicit and take account of many factors, including the following: water price, household income, population, population density, water delivery costs, land values and farm profits, land-use change, crop choice, planting date, water availability across space and time, shifts in seasonality of crop growth due to climate change, daily determination of crop ET, and utilization rates for irrigation water rights. The 2015 Statewide Long-Term Water Demand Forecast Report, prepared by the consulting firm MWH for Oregon's Water Resources Department, also estimates future water demand in Oregon. Their model takes account of a far more limited set of factors than the WW2100 model: (1) In the case of agriculture, the MWH report draws on USGS estimates (which in turn are based on USDA Census of Agriculture data) for irrigated acres by county and by crop. Irrigation water demand is estimated based on average net irrigation water requirements, which are then adjusted to reflect the effects of climate change. (2) In the case of urban water demand, MWH relies on existing Water Management and Conservation Plans (WMCP), developed by various city governments. These plans were then adjusted in proportion to estimated population growth only. Changes in per-capita demand were estimated from 50 of the most recent WMCPs from communities across Oregon.

estimate that a quarter mile of horizontal or uphill conveyance can be costly enough to make delivery of water for irrigation uneconomic on most agricultural lands in the Basin. Indeed, economic considerations explain why one-third of irrigable farmland (parcels with irrigation water rights) goes unirrigated each year. Irrigation involves costs and benefits, and, in some years, and on some lands, the costs outweigh the benefits.

Urban demand

Urban water use is projected to rise significantly by 2100, due primarily to population growth, but also to rising income. The growth in demand will be tempered to some degree by recent and near-term price increases related to cost recovery for infrastructure investments.

However, most urban water is used indoors and is nonconsumptive, i.e., it is returned to the surface-water source from which it originated. Consumptive use (outdoor use that is not returned to streams via wastewater infrastructure) is projected to increase by only about 37,000 acre-feet per year by 2100. (Our model suggests that climate change will not lead to a significant direct increase in consumptive use.) The displacement of surface-irrigated farmland near expanding cities may offset as much as one-third of the increase in urban consumptive water use.

Moreover, a large fraction of urban water supplies in the WRB come from sources outside the Basin (primarily the Bull Run watershed on the slopes of Mt. Hood, but also reservoirs on the west side of the Coast Range). Thus, consumptive use from in-basin surface-water sources is projected to increase from 18,000 to 34,000 acre-feet per year, representing only about 7 percent of total urban water deliveries.

It is important to note that, compared to other uses, urban consumptive use of water from in-basin sources is small. Agricultural use (475,000 acre-feet) is 25 times greater, and regulatory minimum flows in the Willamette River (3.5 to 4 million acre-feet at Salem) are 200 times greater.

Irrigation

Water use for irrigated agriculture fluctuates from year to year, but has exhibited no significant upward trend in recent decades. The per-acre amount of water required for irrigation is expected to remain relatively stable. However, seasonal patterns of irrigation are likely to shift about 2 weeks earlier in response to earlier planting dates resulting from climate change.

The potential use of stored water to expand irrigation to farmlands that currently do not have irrigation water rights is limited by economic realities: conveyance costs are high relative to the economic gain from irrigating.

In-stream flows

The largest allocation of water in the Basin under human influence or control is the protection of in-stream flows. These flows serve multiple purposes, but are determined largely by habitat requirements of native fish. These minimum streamflows result from both federal BiOp requirements, which are tied to the Endangered Species Act, and state-mandated perennial minimum flows protected by in-stream water rights. Indeed, when completed, the implementation of currently unconverted in-stream water rights represents a significant increase in water allocation in the near term.

Reservoirs

The 13 federal storage reservoirs in the Basin produce enormous social value by reducing the risk of flood events. This benefit has been estimated at more than $1 billion per year. As urban areas expand, the value of potential damages during a flood will rise. Thus, the economic benefits of flood damage reduction will increase. To the extent that climate change leads to increases in high flow events, these benefits will become even more valuable.

Economics frames choices involving tradeoffs such as that between (a) the value of keeping reservoirs empty (for flood risk reduction) and (b) the value of filling reservoirs (for multiple summer uses). Since reservoirs cannot simultaneously be kept empty and full, the timing of refill during the spring is a critical economic decision. To maximize social benefits, the choice of reservoir fill level on any given date should balance the expected benefits of the competing uses (flood risk reduction versus storing water for summer uses).

Potential water scarcity

Based on results from the WW2100 model, the potential for increased water scarcity is likely to be location- and time-specific.

- Currently utilized municipal water rights may reach capacity in the Metro area (in 30 years) and in Salem (in 60 years). However, when the model accounts for currently underutilized water rights and those under development, urban water rights appear to be capable of meeting the overall growth in urban water demand.
- Our model shows a decrease in irrigation shut-offs of 10 to 30 percent under the reference scenario and the high climate change scenario. This result is due to earlier planting, which in turn leads to an earlier start, and completion, of irrigation. In the future, more farmers will have finished irrigating by the time the threat of a shutoff arises.
- The model results indicate increasing but modest shortfalls in reservoir fill levels during summer, resulting in some loss of recreational benefits, on the order of 5 percent.
- Implementation of all of the "unconverted" in-stream water rights intended to protect perennial flows would represent a significant increase in the amount of water allocated to environmental values. The effect, based on our model results, would be a small increase (5 percent) in the number of irrigation shutoffs. Overall, however, our results suggest that flow requirements to protect salmon and steelhead can be met, based on 10-year average flows. Exceptions are likely to occur in drought years.
- The effects of changes in forest wildfires and fire suppression policies could have a larger effect on water supply in the Valley than all of the changes in human water use combined. If forest cover is dramatically reduced, the resulting decrease in forest ET will increase streamflows and make more water available for human use, reducing the likelihood of scarcity.

The high spatial resolution of the WW2100 model makes it possible to identify specific land-use changes, such as those that displace irrigated agriculture, and to estimate the distances over which water conveyance is likely to be profitable for farmers. Models of this kind have important strengths but, like any model, also have limitations. Model projections should not be interpreted as precise quantitative predictions, but rather as indicators of the kinds of change that can be anticipated, based on what is known about the system being described.

References

Amos, A. 2013. Developing the law of the river: The integration of law and policy into hydrologic and socio-economic modeling efforts in the Willamette River Basin. *University of Kansas Law Review* 62:1091.

Bigelow, D. 2015. How Do Population Growth, Land-use Regulations, and Precipitation Patterns Affect Water Use? A Fine-scale Empirical Analysis of Landscape Change. Doctoral dissertation, Oregon State University.

Chang, H., S. Praskievicz, and H. Parandvash. 2014. Sensitivity of urban water consumption to weather and climate variability at multiple temporal scales: The case of Portland, Oregon. *International Journal of Geospatial and Environmental Research* 1(1).

Fisher, D. 1972. An Economic Analysis of Farms Producing Grass Seed in the Willamette Valley, with Special Attention to the Cultural Practice of Field Burning. Doctoral dissertation, Oregon State University.

Herrera, N., E. Burns, and T. Conlon. 2014. Simulation of Groundwater Flow and the Interaction of Groundwater and Surface Water in the Willamette Basin and Central Willamette Subbasin, Oregon. *U.S. Geological Survey Scientific Investigations Report* No. 2014-5136.

Jaeger, W., A. Plantinga, H. Chang, K. Dello, G. Grant, D. Hulse, et al. 2013. Toward a formal definition of water scarcity in natural–human systems. *Water Resources Research* 4506–4517.

Kalinin, A. 2013. Right as Rain? The Value of Water in Willamette Valley Agriculture. Master's thesis, Oregon State University.

Lewis, E. and G. Peri. 2015. Immigration and the economy of cities and regions. In *Handbook of Regional and Urban Economics,* volume 5. G. Duranton, V. Henderson, and W. Strange (eds.). North-Holland, Amsterdam.

Moore, K. 2015. Optimizing Reservoir Operations to Adapt to 21st Century Expectations of Climate and Social Change in the Willamette River Basin, Oregon. Doctoral dissertation, Oregon State University. http://hdl.handle.net/1957/56208 (accessed November 7, 2016).

National Marine Fisheries Service (NMFS). 2008. NMFS Willamette Project Biological Opinion. http://www.nwp.usace.army.mil/Portals/24/docs/environment/biop/USFWS_WillametteBO-Final_071108.pdf (accessed November 29, 2016).

Turner, D., D. Conklin, and J. Bolte. 2015. Projected climate change impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA. *Climatic Change* 133:335–348.

U.S. Army Corps of Engineers (USACE). 2007. HEC-ResSim Reservoir System Simulation User's Manual, version 3.0. USACE, Davis, CA. http://www.hec.usace.army.mil/publications/ComputerProgramDocumentation/HEC-ResSim_UsersManual_(CPD-82).pdf (accessed November 7, 2016).

U.S. Army Corps of Engineers (USACE). 2011. Willamette Valley: Operating the Reservoirs: Introducing the Rule Curve. USACE, Portland District.

U.S. Army Corps of Engineers (USACE). 2012. Willamette Basin Guide Standard Operating Procedures (SOP).

U.S. Army Corps of Engineers (USACE). 2015. A Primer on Flood Risk Management. http://usaceportland.armylive.dodlive.mil/index.php/2015/11/3274/ (accessed August 5, 2016).

U.S. Army Corps of Engineers (USACE) and Oregon Water Resources Department (OWRD). 2011. Small-scale Water Supply Allocation Process: Willamette River Basin. USACE, Portland District.

U.S. Environmental Protection Agency (USEPA). 2009. 2006 Community Water System Survey. https://www.epa.gov/dwstandardsregulations/community-water-system-survey (accessed November 29, 2016).

U.S. Environmental Protection Agency (USEPA). 2013. Drinking Water Infrastructure Needs Survey and Assessment: Fifth Report to Congress.

U.S. Fish and Wildlife Service (USFWS). 2008. Final Biological Opinion on the Willamette River Basin Flood Control Project.