Finding water scarcity amid abundance using human–natural system models

William K. Jaeger[a,1], Adell Amos[b], Daniel P. Bigelow[c], Heejun Chang[d], David R. Conklin[e], Roy Haggerty[f], Christian Langpap[a], Kathleen Moore[a], Philip W. Mote[g], Anne W. Nolin[h], Andrew J. Plantinga[i], Cynthia L. Schwartz[j], Desiree Tullos[j], and David P. Turner[k]

[a]Department of Applied Economics, Oregon State University, Corvallis, OR 97331; [b]School of Law, University of Oregon, Eugene, OR 97403; [c]Economic Research Service, US Department of Agriculture, Washington, DC 20024; [d]Department of Geography, Portland State University, Portland, OR 97201; [e]Oregon Freshwater Simulations, Portland, OR 97213; [f]College of Science, Oregon State University, Corvallis, OR 97331; [g]Oregon Climate Change Research Institute, Oregon State University, Corvallis, OR 97331; [h]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331; [i]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106; [j]Biological and Ecological Engineering Department, Oregon State University, Corvallis, OR 97331; and [k]Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331

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Water scarcity afflicts societies worldwide. Anticipating water shortages is vital because of water's indispensable role in social-ecological systems. But the challenge is daunting due to heterogeneity, feedbacks, and water's spatial-temporal sequencing throughout such systems. Regional system models with sufficient detail can help address this challenge. In our study, a detailed coupled human–natural system model of one such region identifies how climate change and socioeconomic growth will alter the availability and use of water in coming decades. Results demonstrate how water scarcity varies greatly across small distances and brief time periods, even in basins where water may be relatively abundant overall. Some of these results were unexpected and may appear counterintuitive to some observers. Key determinants of water scarcity are found to be the cost of transporting and storing water, society's institutions that circumscribe human choices, and the opportunity cost of water when alternative uses compete.

water scarcity | climate change | coupled human–natural system | hydro-economic model | conveyance cost

Declining access to water is a significant problem for up to 2 billion people, impairing food production, human health, economic development, and ecosystem services (1). Water scarcity can result in crop failures, wildfire, fish die-offs, urban water shutoffs, and groundwater depletion leading to irreversible land subsidence (2). Contributing factors include growing populations, incomes, and a changing climate. Recent droughts in the western United States have resulted in substantial losses to agriculture and other sectors, and damages to forests, fish, and wildlife (3, 4).

Water is an integral part of social-ecological systems. Predicting water scarcity and designing mitigation and adaption policies can be extremely challenging because these systems are complex and are characterized by nonlinear feedbacks, strategic interactions, and social, spatial, and temporal heterogeneity (5).

Previous studies have investigated water scarcity at regional or national scales using aggregate measures of water abundance relative to overall demand (6, 7). Supply has typically been measured as annual basin discharge, and demand projections have reflected average per capita water use (7, 8). Given the complex role water plays in human–natural systems, such aggregate approaches may not be able to anticipate when and where water scarcity may emerge, making it difficult for policymakers to address rising water scarcity.

This study examines how climate change, population growth, and economic growth will alter the availability and use of water in coming decades, using the example of the Willamette River Basin (WRB), Oregon. The model developed for this purpose has high spatial and temporal resolution, and detailed representations of economic and biophysical subsystems (see *SI Appendix* for details). Models of coupled human–natural systems take many forms (5, 9). Where markets and incentives partly drive allocation and use of land, water and other resources have been integrated in human process and biophysical models in a simulation or optimization framework (e.g., refs. 10 and 11) including climate-economy models (12). The main components and linkages of this model are characterized in Fig. 1, indicating how human uses of land and water interact with flows of surface and groundwater, mediated by water rights, markets, and regulations. The goals of the study are twofold: first, to understand where and when water scarcity may arise and to recognize the factors contributing to, and potentially mitigating, future water scarcity; and second, to assess the importance of a high level of system detail to gain insights into emerging water scarcity.

The results are illuminating in two main ways. First, the model reveals unexpected changes in water availability and use arising from interactions between human and natural subsystems. In some cases, feedbacks or indirect effects in one component of the model offset expected direct scarcity impacts. Second, the model demonstrates that water scarcity, defined as the marginal value of a unit of water (13), varies significantly across small distances (meters) and brief time periods (days), even in our study basin, where water is relatively abundant overall. There are three key contributors to water scarcity: (*i*) the costs of transporting water across locations, storing water over time, and transforming the quality

Significance

Climate change will heighten the need to anticipate water shortages worldwide. The task is daunting due to water's variability, spatial-temporal movement, feedbacks, and other system complexities. A high-resolution coupled human–natural system model identifies how both climate change and socioeconomic drivers will alter water scarcity in future decades. The results illuminate how water scarcity varies greatly across small distances and brief time periods, even in basins where water may be relatively abundant overall. These findings, and other unexpected results that may seem counterintuitive, underscore the potential value of such models for policy.

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[1]To whom correspondence should be addressed. Email: wjaeger@oregonstate.edu.

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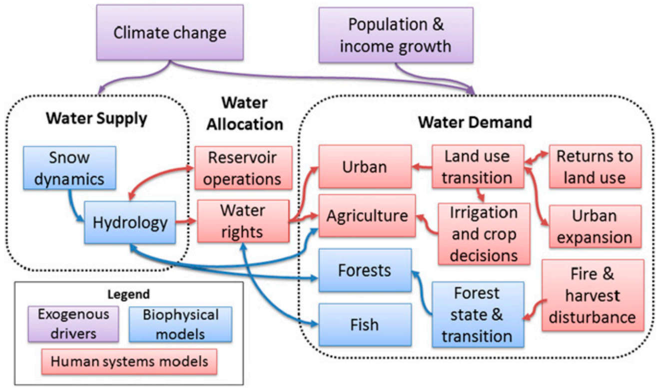

Fig. 1. Diagram of WRB model components and linkages.

of water (e.g., temperature, salinity); (*ii*) the effectiveness of institutions in allocating water, including property rights, regulations, and other governance mechanisms that impact water use (14); and (*iii*) the opportunity cost of water, when one use for water competes with other, possibly more valuable, uses. These economic and institutional factors are key to explaining how scarcity can coexist with overall abundance.

Modeling the WRB, Oregon

The WRB faces water scarcity due to declining snowpack, population growth, rising demands from agriculture, and the effects of warmer air temperatures on forest health, wildfires, river temperatures, and endangered fish. The WRB covers 29,728 km^2, ~12% of Oregon's land area. The Willamette River—a major tributary of the Columbia River—is the 19th largest river in the United States. Its mainstem is 301 km long, flowing north between the Oregon Coast and Cascade Ranges. The WRB is home to over 70% of the state's population of nearly 4 million. Two-thirds of the basin's population is concentrated in the Portland Metro area (Fig. 2*A*).

The basin's hydrology is notable for the mismatch between winter inflows and summer demand. The valley is prone to flooding from November to March due to precipitation on saturated soils, atmospheric rivers, and snowmelt (15), whereas streamflows are lowest during the dry summer farming season.

The Willamette Valley is one of the most fertile agricultural regions in North America, with about 1.5 million acres of farmland, 30% of which has irrigation water rights. Human uses of water are governed under western US water law by a seniority system, environmental regulations, and public infrastructure, including 13 federal dams constructed for flood mitigation but also providing hydropower, storage, and recreation. In addition, large instream flows are protected for navigation, pollution abatement, recreation, and aquatic habitat.

The Model. We developed a hydroeconomic process model of the basin's major human and natural systems with high spatial resolution (160,000 polygons averaging 18.6 ha in size) and daily to annual timescales from 2010 to 2100 (Fig. 1). Exogenous elements include daily meteorology (temperature, precipitation, humidity, wind, radiation) for three representative climate change scenarios derived from regional climate data downscaled to 4-km resolution (16–18), and annual population and income projections.

Annually modeled processes include spatially explicit forest growth, harvest and wildfires (19), endogenous land values and land-use changes (predicted using empirically based functions adapted from refs. 20 and 21, respectively), endogenous regulatory adjustments to urban growth boundaries (similar to ref. 20), water rights, crop choices, and irrigation decisions (22). Daily modeled processes include spatially referenced routing of surface hydrology based on algorithms developed by Bergström and others (23, 24). Snow accumulation and ablation uses a modified version of the Hydrologiska Byråns Vattenbalansavdelning (HBV) degree-day model of Seibert (25). Evapotranspiration of forests (described in

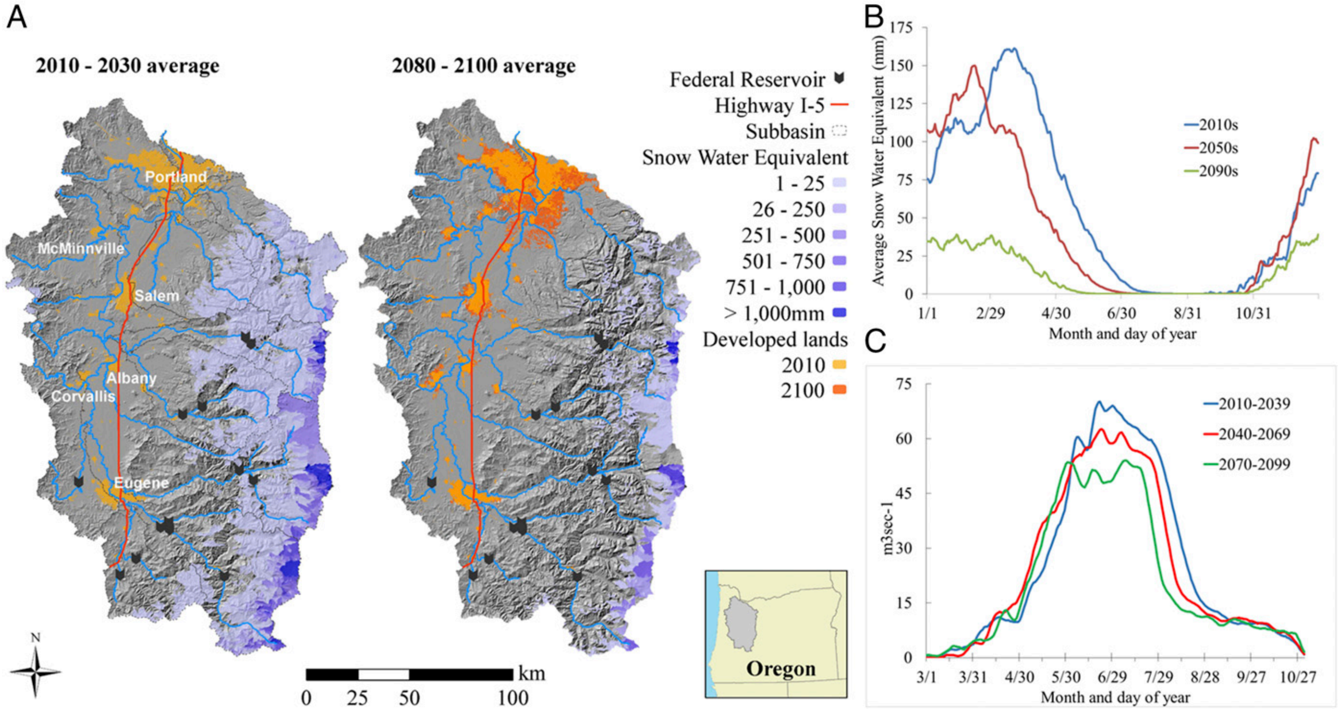

Fig. 2. Projected changes in the WRB 2010–2100: developed land use and April 1 average snowpack (snow–water equivalent, SWE) (*A*); projected seasonal average snow accumulation and melt in future decades (*B*); and projected changes in levels and timing of irrigation diversions (*C*).

ref. 26) adapted the Penman–Monteith approach. Spatially explicit irrigation and municipal water rights were fully represented. Crop planting, growth, and daily evapotranspiration were modeled following FAO-56 (27, 28) and similar to Seibert (29). Additionally, soil moisture, groundwater flows, economic models of farm irrigation decisions and urban water use, as well as the releases from 13 federal dams, were developed for this study. See *SI Appendix* for detailed descriptions.

These submodels are linked using *Willamette Envision*, an integrated modeling framework that simulates spatially and temporally explicit human and natural system processes, as described in *SI Appendix*. The reference case and alternative scenarios were developed working closely with a broad stakeholder community.

Reference Case Scenario. The central simulation is a "reference case" scenario that reflects midrange projections for climate change and population and income growth, as well as status quo assumptions for most institutions (water rights, land use regulations, reservoir and forest management), for technology, and for most prices. Over 20 alternative scenarios were simulated for sensitivity analysis (e.g., high climate change, high population growth), counterfactual comparisons to isolate specific changes (no population growth, stable climate), to evaluate policies to mitigate future water scarcity (irrigation expansion, high water prices), or as combinations. See *SI Appendix* for details.

The reference case scenario finds that annual outflow from the Willamette River averages 29.6×10^9 m^3 [24×10^6 acre-feet (af)], whereas human withdrawals plus instream regulatory flows average 5.5×10^9 m^3 (4.5×10^6 af). This apparent surplus would appear to preclude water scarcity. Nevertheless, notable scarcity emerges when we examine finer spatial and temporal scales.

Based on over 40 climate scenarios, the downscaled general circulation model (GCM)-derived outputs indicate that by the year 2100, the WRB will be between 1.1 °C (2 °F) and 7 °C (12.6 °F) warmer than today (19, 20). Winter temperatures are projected to rise between 0.5 °C (33 °F) and 5.5 °C (42 °F). The months of July to September are projected to warm about 2 °C (3.6 °F) more than in winter. Climate models differ about whether the WRB will be drier or wetter, but the majority of climate model runs examined show slightly wetter winters and drier summers.

Population is projected to increase from 2.6 million to 5.4 million over the period (*SI Appendix*, Table S1), expanding developed land area by 53% (716 km^2) and displacing 469 km^2 previously in agriculture and 235 km^2 previously in forest use (Fig. 2*A*). Urban water use is projected to rise by 110%, due mainly to population growth. Real household income is expected to increase by 175% by 2100.

Snowpack, in the midrange climate scenarios, declines between 87% and 94% by 2100 (Fig. 2 *A* and *B*), hastening runoff and reducing spring and summer flows. In subbasins without reservoirs or with low groundwater contributions, these changes reduce the water available at lower elevations. In particular, the federal reservoirs fill to lower levels during the summer when reservoir recreation competes with "minimum conservation flows" established under the US Endangered Species Act (ESA) (30) and other obligations, including irrigation water rights tied to stored water.

Variations Across Subbasins. Snow provides winter storage and spring-summer flows for higher elevation eastern subbasins, but very little for lower elevation western subbasins (Fig. 2*A*). Even among eastern subbasins, the impact of snow on streamflow varies substantially due to differences in elevation and geologic mediation of low flows by groundwater contributions (15, 31). These differences are reflected in Table 1 (columns A and B), where the April–September flux varies by a factor of eight. The adequacy of existing flows to meet regulatory minimums also varies by subbasin (Table 1, columns C and D). Moreover, April–August flows in some subbasins decline relative to instream requirements (column E).

Some of the differences affecting water scarcity across subbasins are due to changes in urban and agriculture land uses (columns F–H), differences in forest growth due to harvest and wildfires, and differences in how land cover changes affect snow and runoff due to evapotranspiration and snow sublimation. For example, forest harvest and wildfires can cause large changes in forest water use (discussed below).

Finding Scarcity Amid Abundance

The Role of Costs. If it were costless to store and transport water, or to improve its quality, water scarcity could in principle be eliminated given the overall abundance of water in the WRB (barring institutional impediments). Our analysis, however, indicates that water scarcity in the WRB varies seasonally and across locations and uses. Relatively fine-scale processes such as market adjustments, barriers due to costs and profitability, or government regulations can have large consequences for scarcity.

Water storage and transportation costs are not uniform across the WRB. In some cases, these costs are very low, as with gravity-based conveyance in summer along watercourses below federal reservoirs. Although built primarily for flood regulation, in summer the reservoirs normally store 2×10^9 m^3 (1.6×10^6 af) of water, much of which could be released to flow downstream at

Table 1. Differences in hydrology and economics across subbasins

River Basin	Avg. flow April-Sept, m^3/s (A)	Flow April-Sept, mm/d (B)	Regulatory min. April-Sept, m^3/s (C)	Avg. flow/reg. min., July-Aug. (D)	Change in April-Aug. flow 2010–20s to 2080–90s, % (E)	Farmland , % of area (F)	Surface irrigation, % of basin (G)	Developed land, % of land area (H)
Clackamas	64	2.3	14.7	2.8	−4.1	7.9	0.5	1.7
Long Tom*	8	0.7	0.8	2.1	8.0	29.9	4.3	6.5
Marys*	9	1.0	1.8	1.5	13.5	22.9	2.7	2.9
McKenzie	107	2.7	29.0	2.4	−7.3	2.0	0.4	0.5
Molalla	42	1.6	9.2	2.7	−0.5	39.0	4.8	3.2
North Santiam	128	5.6	36.8	2.3	−3.9	9.9	1.6	0.5
South Santiam	66	2.1	30.2	1.3	−1.4	14.8	2.5	0.6
Tualatin River*	21	1.0	4.4	1.6	17.0	28.4	6.3	18.2
Yamhill River*	18	1.2	0.9	1.7	11.3	54.6	12.1	3.8
Willamette, Coast & Middle Forks	88	1.5	61.4	0.7	−3.4	3.4	0.4	0.5
Average	55	2	19	1.9	2.9	23.3	3.9	4.2

*Indicates subbasins on the western side of the WRB (Fig. 3).

negligible cost. Most farmland, however, is not adjacent to watercourses downstream of federal dams. Farmers invest in new irrigation if it is profitable—if the additional cost of transporting reservoir-released surface flows to currently unirrigated farmland is less than the added revenue from irrigating. For each of the 405,000 ha (1×10^6 ac) currently without irrigation water rights, both the added conveyance costs and increased revenue were estimated (*SI Appendix*, section 5.4.5). When farmers were allowed to adopt new irrigation from stored water in an alternative scenario, it was found to be profitable on only about 3,240 ha (8,000 ac) due to the high water conveyance costs. Even when the costs are assumed to be optimistically low, less than 11,130 ha (28,000 ac) adopt irrigation.

One example of rising water scarcity in the WRB pertains to forests, where climate change is increasing moisture stress and threatening forest health (32). As the climate warms, rising air temperatures increase atmospheric evaporative demand and forest evapotranspiration (ET). In mid- to late summer, however, soil water limits ET so that warmer temperatures, when combined with less snow, lead to a longer summer dry period. Given the prohibitive cost of transporting water from reservoirs to forests, the anticipated result is increased water scarcity resulting in a 200–900% increase in forest wildfires across the three climate scenarios (26). The likely outcome will be increased costs for fire suppression, the transition to new forest types, and reduced availability of forestland for timber harvest (26) (*SI Appendix*, section 4.2).

The Role of Water Rights and Other Institutions. Water rights and other federal, state, and local regulations play a critical role in determining where, when, and for what uses water may be scarce (14). Surface water "live flow" rights were fully appropriated in the WRB by the 1990s, meaning that farms without these rights have no access to surface water for irrigation. Under western US water law, the amounts, timing, and uses of water rights are limited, and yearly fluctuations in supply lead to allocations based on a seniority system that can "shutoff" deliveries for relatively junior water rights (33). Indeed, the scarcity created by irrigation water rights is one key factor that produces a 10-fold variation in agricultural land values in the basin (Fig. 3 and *SI Appendix*, Fig. S3).

Instream flows, however, represent by far the largest societal allocation of water in the WRB. State and federal laws protect instream flows for navigation, pollution abatement, recreation, and aquatic habitat. Perennial minimum streamflows were established in the 1960s, although a fraction of these have yet to be implemented as instream water rights (33). Indeed, when the remaining ("unconverted") perennial minimum streamflows are implemented, they will add 1.35×10^9 m^3 to minimum outflows from the 11 major tributaries that join the mainstem Willamette River (based on model results).

Federal laws also have a substantial influence on water allocation in the WRB. Minimum flows are mandated under the ESA, in turn prompting targeted releases from federal reservoirs. These federal laws interact in complex ways with state law (33). Indeed, current ESA-related requirements for April–October minimum flows have led regulators to cap stored water irrigation contracts at 6% of the total stored volume (30) (a nonbinding limit in our model).

Differentiation Across Space, Time, and Use. Analyses at the basin or national scale, such as global assessments of the impacts of climate change and population growth on future water shortages (8, 34–37), will be unable to detect these kinds of causal relationships that produce localized scarcity. For example, the 2×10^9 m^3 of water stored each summer would appear to be an ample source for the 405,000 ha of currently nonirrigable farmland (indeed this water is currently "reserved" for agriculture under federal law), but the cost of conveyance makes this economically prohibitive. Within the basin, the scarcity contrasts are stark. In some areas, farmers have abandoned water rights or use them intermittently, suggesting low marginal value of water. In the Pudding River basin, by contrast, conflict has emerged over a proposed $60 million reservoir that would permanently flood some farmland to ensure irrigation water for other farmers. The conflict is emblematic of the complex ways that economics and institutions interact: Increased instream flows for three endangered fish, combined with declining groundwater, have led one group of irrigators on high-value land with low-priority irrigation water rights to enlist an extraordinary legal tool (eminent domain) to gain approval for a storage reservoir that will inundate other, relatively low-value farmland (38).

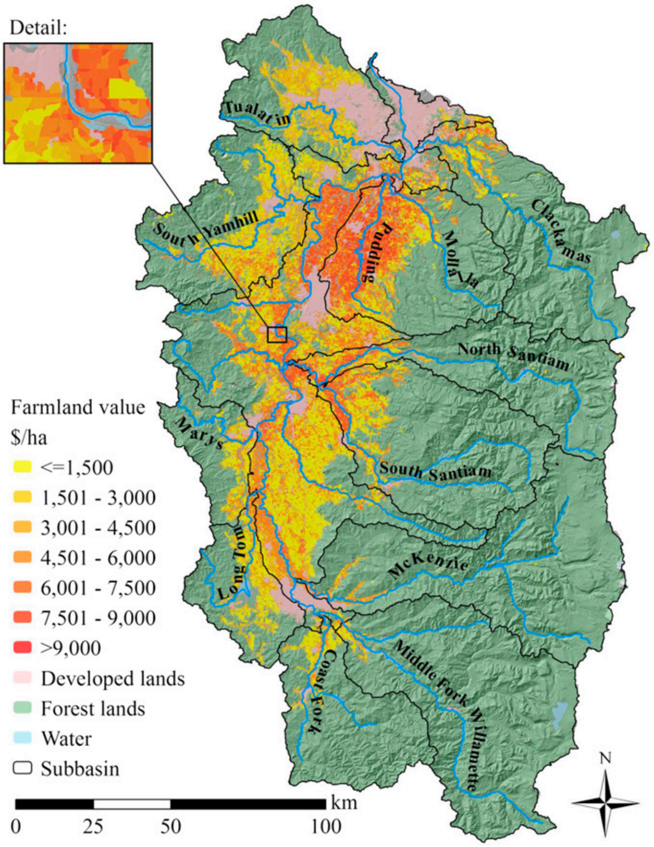

Fig. 3. Variation in agricultural land values; subbasin locations.

That scarcity can exist amid aggregate abundance is not unique to water. Indeed, in the case of food, for example, Sen (39) showed that major famines were not generally the result of an aggregate shortage of food. Sen found large differences among households in their ability to acquire food, due to differences in economic and institutional factors including costs, market conditions, rights of ownership, and exchange. These factors are analogous to the cost, profitability, water rights, and other institutions identified here in the case of water in the WRB.

The Challenge of Predicting Future Water Scarcity

The dynamics of water demand and supply in regional systems have the potential to generate unexpected outcomes, often arising from the linkages and feedbacks between system components. In the WRB, expanded urban development will displace agriculture and forests, but also increase the magnitude of potential flood damages, which could alter the optimal timing of reservoir refill (40). A warmer climate melts snowpack earlier, increases wildfires, affects vegetation and ET; encourages earlier planting and irrigation; and possibly changes crop choice. Additionally, instream minimum flow requirements aimed at protecting ecosystem services will increase competition with out-of-stream demands (33).

System linkages and feedbacks can be highly idiosyncratic across subbasins and vary at fine spatial and temporal scales. Without a model, it would have been extremely difficult to identify and predict these relationships for the WRB. Three examples illustrate the challenges that such dynamics represent for predicting water scarcity and designing policy responses.

Offsetting Seasonal Shifts in Supply and Demand. In the first example, climate warming generates two responses, one in water supply and one in demand. The first response to warmer temperatures is a reduction in snow accumulation and melt, along with a shift in melt timing to earlier in spring. This response reduces summer surface flows. The second response is a human response. Because of warmer spring temperatures, farmers are able to plant earlier, which shifts both the start and the completion of irrigation (Fig. 2*C*). Thus, a larger proportion of irrigation occurs earlier in the year, when snowmelt runoff and precipitation are higher. This decreases the projected number of irrigation shutoffs due to water scarcity by 10–30% in both the reference case and high climate change scenarios. This is because, although in future decades surface water supplies become relatively scarce in late July and August, irrigators have increasingly completed irrigating by that time, resulting in fewer regulatory shutoffs.

The shift to earlier planting dates has an additional positive effect on water scarcity: Although warmer midsummer temperatures would generally raise crop ET and increase irrigation requirements, the earlier planting has an offsetting effect. More of the plant's growth takes place when temperatures are lower and precipitation is higher, resulting in no rise in average crop ET during the 90-y simulation.

Urban Demand Growth and Reduced Irrigation. The second example involves the potential mitigating effect of urban growth on water scarcity. Projected growth in urban water demand is the single largest change in direct human water use through 2100. Many city governments in the basin face uncertainty about how best to secure adequate future water supplies. Surface flows are already fully appropriated, and rights to federally stored water are reserved for agriculture. Moreover, instream flow requirements account for a majority of summer water allocations. However, a city's growing demand for water will coincide with urban land expansion, and the likely patterns of this expansion overlap with some of the spatially referenced irrigation water rights in our model. For the six main metropolitan areas, the model predicts urban consumptive use of water (from outdoor use only since indoor water use is returned to streams with minor losses) to increase 45×10^6 m^3 (Table 2). However, due to the land use changes accompanying this growth, the displacement of surface irrigation offsets one-third of the increase. These effects vary significantly across cities depending on the extent and direction of urban expansion and on the proximity to surface irrigated farmlands. When groundwater irrigation is included, more than 80% of the urban water use increases are offset by reduced irrigation in our model (Table 2).

Forest Water Use and Wildfire. The third example involves climate change and forest water use. With warmer temperatures, water requirements for a given stand of forest will increase, but drier forests are also more prone to wildfires. Increases in wildfire frequency will result in a more open and patchy landscape with fewer mature trees and, thus, a lower average foliage density (leaf area) (19). Because forest water use (ET and canopy snow sublimation) varies positively with leaf area, more wildfires mean a reduction in water use. This, in turn, allows more precipitation falling in forest zones to be routed downstream. This means that climate change could actually lead to increases in the runoff ratio despite increasing evaporative demand (26). In our reference case scenario, there is a projected decrease in forest water use of 315 million m^3 for April–July between the 2010s and 2090s due mainly to the effects of projected wildfires (*SI Appendix*, section 4.2). Efforts to suppress wildfires can be expected to increase forest water use. Indeed, a counterfactual scenario that represents the high climate scenario but with no wildfires finds increased forest water use by 1.4 billion $m^3 \cdot y^{-1}$. While subbasin-specific impacts from wildfire are impossible to predict since the location of future wildfires is unknown, this example illustrates the possibility of unexpected results that may appear counterintuitive.

Fine Scale and Large Magnitudes. In addition to these examples of how feedbacks and linkages can produce unexpected results, we find a strikingly high variability in water scarcity at fine spatial and temporal scales. For example, upland forested areas will exhibit high water stress and increased wildfire risk (*SI Appendix*, section 4.2), despite in some cases being close to large federal reservoirs. Similarly, distances as small as 100 m separate irrigators whose legal right to water exceeds what can be put to beneficial use from farmers who have no economically feasible options to acquire irrigation water rights, due to protected instream flows or high conveyance costs that make more distant options uneconomical.

Another powerful way in which this type of model is valuable is that it compels us to recognize what is large versus what is small. Many components related to water supply or demand turn out to be much larger (or smaller) than initially believed. For example, initially Willamette Water 2100 researchers and stakeholders focused on future urban industrial water and did not pay attention to forest water use, but the former has turned out to be nearly negligible relative to the latter. Similarly, the anticipated expansion in crop irrigation in the basin has been a central rationale for reserving the water stored in federal reservoirs for agriculture. However, we find that only 1–3% of unirrigated land would be able to bring stored surface water into use profitably, due to the high transport costs.

Using Regional System Models for Water Policy

Water shortages frequently come with high social costs. The annual costs of California's recent experience have been estimated

Table 2. Urban water demand growth net of displaced irrigation, 2010–2100 (1,000 m^3)

		Net of displaced irrigation:	
Urban area	Change in urban water use	Surface only	Surface and groundwater
Portland	30,872	21,626	7,195
McMinnville	1,457	−819	−1,528
Salem	7,391	4,616	989
Albany	1,510	1,208	393
Corvallis	1,004	486	−155
Eugene	3,158	2,513	618
Total	45,392	29,629	7,512

at $2–3 billion (41). Whether shortages are the result of short-term drought conditions, the cumulative impacts of decades of misguided water policies, or long-term shifts in water supply and demand, the costs are high, and hence so too are the potential benefits from intervening to mitigate future water crises. A system model can be a critical tool for designing effective policy interventions. The value of a given model will depend on whether it sheds new light on critical factors or key processes, and whether this new information is heeded by policymakers. In the case of the WRB, the model has allayed some fears (urban water shortages), while shifting focus toward other, less easily remedied sources of scarcity (forest health, instream flows, and stream temperatures).

Many of the insights from this model have clear relevance, applicability, and implications for other basins. For example, elsewhere in the western United States, emerging water scarcity can also be expected to exhibit high spatial and temporal specificity, even while the particular causes and potential solutions may differ. In California, for example, rather than wildfires reducing water use by forests, climate change may cause changes in vegetation that increase forest consumptive use (42). Models of this kind may be particularly valuable in basins such as the Indus or Nile, where climate change, population growth, poverty and institutional failures place large vulnerable populations at high risk.

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