Supplementary Information

Table SI-1. Contribution of study crops to irrigation and water consumption. *The model used to estimate crop water consumption is specified as the simple crop model (SCM) or AquaCrop-OS. The last two columns show each crop's percentage of the total national irrigated area and water consumption. National totals for irrigated area and crop water consumption come from USDA*[1] *and Marston et al.,, respectively.*

<table>
<tr><th>Crop</th><th>Model used</th><th>% of irrigated area[1]</th><th>% of water consumption[2]</th></tr>
<tr><td>Alfalfa</td><td>SCM</td><td rowspan="2">18.833</td><td rowspan="2">30.172</td></tr>
<tr><td>Other Hay</td><td>SCM</td></tr>
<tr><td>Almonds</td><td>SCM</td><td>1.599</td><td>2.387</td></tr>
<tr><td>Apples</td><td>SCM</td><td>0.396</td><td>0.486</td></tr>
<tr><td>Barley</td><td>AquaCrop-OS</td><td>1.591</td><td>1.304</td></tr>
<tr><td>Canola</td><td>SCM</td><td>0.051</td><td>0.047</td></tr>
<tr><td>Corn</td><td>AquaCrop-OS</td><td>28.533</td><td>20.304</td></tr>
<tr><td>Cotton</td><td>AquaCrop-OS</td><td>7.522</td><td>7.804</td></tr>
<tr><td>Dry beans</td><td>SCM</td><td>1.127</td><td>0.521</td></tr>
<tr><td>Grapes</td><td>SCM</td><td>0.000</td><td>1.791</td></tr>
<tr><td>Lentil</td><td>SCM</td><td>0.002</td><td>0.002</td></tr>
<tr><td>Millet</td><td>SCM</td><td>0.012</td><td>0.012</td></tr>
<tr><td>Oat</td><td>SCM</td><td>0.113</td><td>0.096</td></tr>
<tr><td>Orange</td><td>SCM</td><td>1.004</td><td>0.514</td></tr>
<tr><td>Peanut</td><td>SCM</td><td>1.013</td><td>0.424</td></tr>
<tr><td>Peas</td><td>SCM</td><td>0.048</td><td>0.025</td></tr>
</table>

Pecan	SCM	0.382	0.699
Potato	AquaCrop-OS	1.769	1.707
Rice	AquaCrop-OS	5.373	7.051
Sorghum	AquaCrop-OS	1.574	0.976
Soybean	AquaCrop-OS	14.313	9.809
Sugarbeet	AquaCrop-OS	0.801	0.912
Sugarcane	SCM	0.367	0.478
Sunflower	AquaCrop-OS	0.173	0.254
Sweet Corn	SCM	0.000	0.463
Tomato	AquaCrop-OS	0.717	0.769
Walnut	SCM	0.396	1.133
Durum Wheat	AquaCrop-OS		
Spring Wheat	AquaCrop-OS		
Winter Wheat	AquaCrop-OS	6.494	5.201
Total		**94.204**	**95.340**

***Table SI-2. Characteristics of six case study areas evaluated for the period 2000-2019*.**

Case study area	***Total irrigated area (km^2)***	***Most water-consumptive crops***	***Average annual irrigation consumption (km^3)***	***List of HUC8s included***
Rio Grande (Colorado, New Mexico)	1,670	Alfalfa, other hay, barley, potatoes, pecans	0.823	13010001, 13010002, 13010003, 13010004, 13010005, 13020101, 13020102, 13020201, 13020202, 13020203, 13020204, 13020205, 13020206, 13020207, 13020208, 13020209, 13020211, 13030101, 13030102
Great Salt Lake (Utah)	1,659	Alfalfa, other hay, barley, corn, winter wheat	0.759	16010101, 16010102, 16010201, 16010202, 16010203, 16010204, 16020101, 16020102, 16020201, 16020202, 16020203, 16020204
San Joaquin River (California)	5,108	Alfalfa, almonds, corn, grapes, walnuts, cotton, tomatoes, walnuts	4.432	18040001, 18040002, 18040003, 18040051, 18040006, 18040007, 18040008, 18040009, 18040010, 18040011, 18040012, 18040013, 18040014
Snake River (Idaho)	8,113	Alfalfa, barley, corn, potatoes, spring wheat, winter wheat, sugar beets	3.567	17040201, 17040202, 17040203, 17040204, 17040205, 17040206, 17040207, 17040208, 17040209, 17040210, 17040211, 17040212, 17040213, 17040214, 17040215, 17040216, 17040217, 17040218, 17040219, 17040220, 17040221
Platte River (Nebraska, Wyoming, Colorado)	12,842	Alfalfa, corn, soybeans, other hay	4.72	10180001, 10180002, 10180003, 10180004, 10180005, 10180006, 10180007, 10180008, 10180009, 10180010, 10180011, 10180012, 10180013, 10180014, 10190001, 10190002, 10190003, 10190004, 10190005, 10190006, 10190007, 10190008, 10190009, 10190010, 10190011, 10190012, 10190013, 10190014, 10190015, 10190016, 10190017, 10190018, 10200101,

				10200102, 10200103, 10200201, 10200202, 10200203
Lower Colorado River (Arizona, California)	1,612	Alfalfa, other hay, durum wheat, cotton, sugar beets	1.029	15030101, 15030102, 15030103, 15030104, 15030105, 15030106, 15030107, 15030108, 15030201, 15030202, 15030203, 15030204, 18100100, 18100201, 18100202, 18100203, 18100204

Table SI-3. Monotonic trend analysis for crop water consumption and revenue data, 2000-2019. *The second and fourth columns show the average annual change in irrigation water consumption and farm revenue, respectively, for each of the six study areas. The third and fifth columns denote the statistical significance for the detected monotonic trend. A positive value in trend signifies an increasing trend. In four of the study areas (i.e., excluding San Joaquin River and Great Salt Lake), irrigation water consumption has been steadily decreasing while farm revenues in those study areas have been increasing. In the Great Salt Lake basin, both irrigation consumption and revenues have increased. Irrigation consumption has increased while revenues have decreased in the San Joaquin River basin, though neither trend is statistically significant.*

Case study area	**Trend in crop water consumption (m^3/year)**	**Significance**	**Trend in farm revenue ($/year, 2020 $)**	**Significance**
Rio Grande (Colorado, New Mexico)	-10,175,573	$p < 0.0001$	$4,145,445	$p < 0.1$
Great Salt Lake (Utah)	14,852,690	$p < 0.005$	$9,086,122	$p < 0.0005$
San Joaquin River (California)	19,690,126	$p > 0.1$	-$ 20,438,016	$p > 0.5$
Snake River (Idaho)	-40,539,731	$p < 0.0001$	$36,372,177	$p < 0.0001$
Platte River (Nebraska, Wyoming, Colorado)	-33,539,335	$p < 0.0001$	$63,390,537	$p < 0.0005$
Lower Colorado River (Arizona, California)	-10,205,422	$p < 0.0001$	$8,599,240	$p < 0.005$

Case Study: Rio Grande, Colorado and New Mexico

Water development history

Indigenous tribes occupied small farming settlements along the Rio Grande for more than a thousand years by the time Spanish explorers arrived in the late 16th century.[3] Spanish and Mexican occupation of the region led to some expansion of irrigated farming, particularly in the 18th century and the first half of the 19th in the area we now know as northern New Mexico.[4]

Major depletions of the river's natural flow began in the San Luis Valley – located in the river's headwaters in Colorado – with arrival of settlers from the eastern US. Large irrigation canals were constructed in the valley in the 1880s to irrigate more than 120,000 hectares of new farmland.[5,6] River irrigation was supplemented with an estimated 2,000 groundwater wells by 1891 (there are more than 10,000 today).[7] The valley farms provided food for a rapidly growing population and produced fodder for immense herds of livestock that were exported from the valley to distant markets by newly established rail lines. By 1890 there was very little Rio Grande water flowing south into New Mexico during the summer growing season, a condition that persists today.[8,9]

The depletion of headwater flows in the San Luis Valley could be felt as far downstream as the Juarez Valley in Chihuahua, Mexico. Lacking water to irrigate fields that had been cultivated for centuries, the Mexican government lodged formal complaints with the United States beginning in 1894.[10] In response, an international water-sharing agreement known as the Rio Grande Convention was negotiated and adopted in 1906 that guaranteed delivery of 74 million cubic meters (60,000 acre-feet) of water to Mexico each year, or about 3% of the river's flow at Juarez. The Convention also allocated shares of water to the Mesilla Valley in New Mexico and the El Paso Valley in Texas.

The 1906 Convention was the first of two critically important laws that have helped sustain some semblance of the river's freshwater biodiversity by mandating that some portion of the river's water must flow all the way downstream from Colorado into Texas and Mexico. When negotiating the 1906 Convention, farmers in the Mesilla and El Paso valleys promoted the idea that a new reservoir was needed to capture whatever snowmelt runoff escaped diversions in Colorado.[11] The resulting "Rio Grande Project" constructed hundreds of kilometers of irrigation canals and pipes, as well as extensive levees to constrict the river's tendency to move around and damage farms during floods. The project's centerpiece was an enormous new reservoir named Elephant Butte, constructed in 1916, capable of storing two full years of average river flow. Irrigated land in the Mesilla Valley tripled in extent and shifted from away from alfalfa, corn, and beans; within a few years, 90% of farmers were growing cotton with mechanized farm equipment.[12] Today, only occasional flushes of monsoon stormwater pass through the "Forgotten Reach," the 240-kilometer river segment located downstream of farmlands irrigated by the Rio Grande Project.[13]

While the Rio Grande Project was being constructed, another group of settlers in the area around Albuquerque began developing their own plans for irrigation improvements that included drainage of water-logged land, construction of levees, and a new El Vado Dam on the Rio Chama, a major tributary to the Rio Grande in New Mexico, to facilitate increased irrigation. These plans were enabled by the formation of the Middle Rio Grande Water Conservancy District in the mid-1920s.[14]

As El Vado Dam was being constructed, Texas sued New Mexico to stop the development.[15] Similarly, fearing potential growth in water use in the San Luis Valley, New Mexico sought to restrain Colorado from further depleting the river. The resolution to these conflicts was the Rio Grande Compact, signed in 1938, that specified how much water Colorado must pass downstream to New Mexico, and reaffirmed that Texas would get the water it was allocated under the Rio Grande Project. In effect, a small portion of the river's natural flow was thereby assured to cross multiple state lines, thereby helping support the river ecosystem as well.[16]

Farmers dependent on the Rio Grande and associated aquifers have been experiencing severe water shortages in recent decades. Beginning in 2002, an intense 20-year drought that is greatly reducing the availability of river water for irrigation has led to greater reliance on groundwater in the San Luis Valley.[17,18,19] At the same time, commodity prices for alfalfa – a preferred feed crop for dairy operations – has increased substantially, enticing farmers to switch from growing potatoes and grains to producing alfalfa, which is a much more water-intensive crop. Steep aquifer declines since 2002 (Figure SI-1) have caused the state engineer to issue warnings of pending well shutoffs if aquifer levels cannot be restored to near 1970s levels.[20]

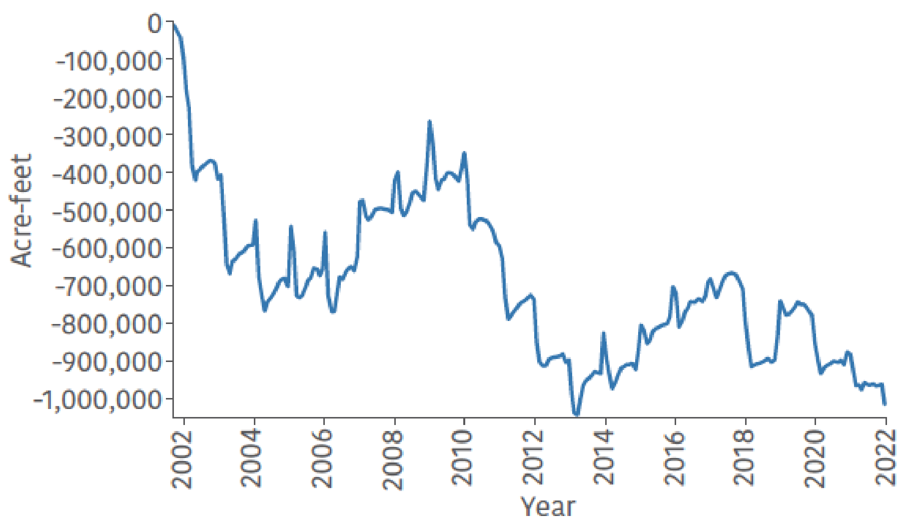

Figure SI-1. Aquifer levels in the San Luis Valley have plummeted in recent decades due to heavy pumping and substantially reduced aquifer recharge since 2000. Y-axis indicates volume of water lost from the aquifer. Flows in the Rio Grande at Del Norte, Colorado since 2000 have been 16% less than the long-term average, causing farmers to use more groundwater than is sustainable (Data for graph prepared by Davis Engineering Service, Inc. for the Rio Grande Water Conservation District; need conversion to metric).

Meager river flows and heavy irrigation use have also led to severe depletion of water storage in the Elephant Butte Reservoir on the Rio Grande in southern New Mexico. Farm water deliveries within the Elephant Butte Irrigation District were shut off in June 2021, months before the end of the growing season, when their reservoir was nearly dry (Figure SI-2).[21]

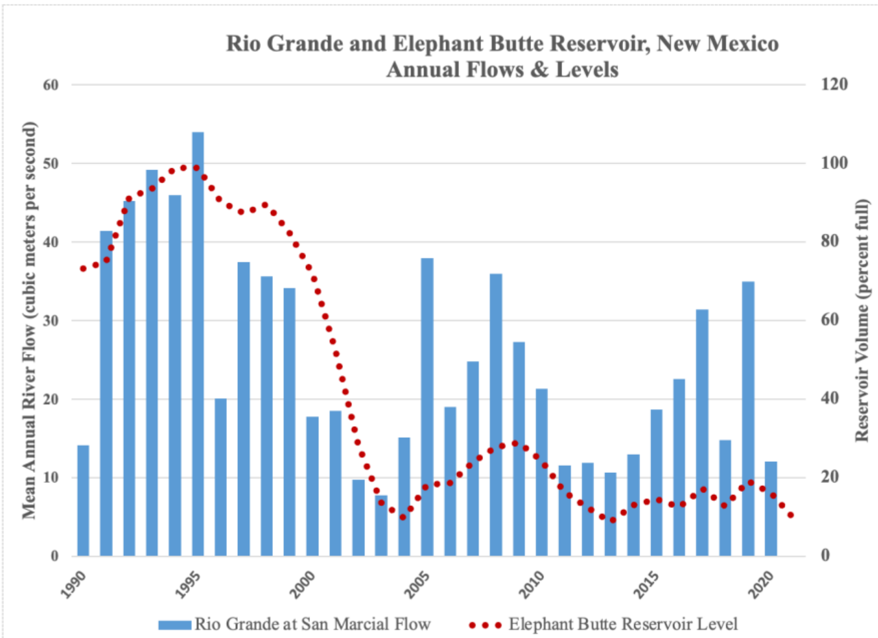

Figure SI-2. The water storage volume in Elephant Butte Reservoir in southern New Mexico has been heavily depleted since the mid-1990s due to greatly reduced inflow from the Rio Grande and heavy irrigation use.

Policy responses

In 2004, the Colorado legislature passed a bill creating a new groundwater district in the San Luis Valley. One of the primary goals of the district is to recover groundwater levels such that a long-term irrigation supply can be assured. The district subsequently set a target of fallowing 16,000 hectares (40,000 acres) each year, or nearly one-quarter of irrigated farmland, to achieve this goal. [22] The fallowing program began in 2014, and to date an average of 4,237 hectares per year have been taken out of production, using funding from a federal farm program to compensate participating farmers.[23] While the program produced hopeful results from 2013-2017 due to strong enrollment in the program, meager recharge and continued high volumes of pumping – stimulated by attractive prices for alfalfa – caused the aquifer to again plummet in recent years (Figure SI-1). The state engineer has threatened to shut off 3,000 groundwater wells unless farmers can find some way to recover depleted aquifer levels.[24]

Further downstream in New Mexico, the US Bureau of Reclamation – collaborating with the National Fish & Wildlife Foundation and the Middle Rio Grande Conservancy District – created a pilot "Environmental Water Leasing Program" beginning in 2020 to provide more river flow for the highly endangered Rio Grande silvery minnow (*Hybognathus amarus*) by paying farmers to fallow their farm acreage. In 2022, 191 farmers enrolled 1,034 hectares in the program,[25] reducing consumptive use by an estimated 8.65 Mm^3 (7,015 acre-feet).[26]

At the far downstream end of our study area in southern New Mexico, a US Supreme Court case is pitting the State of Texas against the State of New Mexico; Texas alleges that New Mexico's groundwater pumping near the state line is intercepting water deliveries required under the Rio Grande Compact. While a decision in the case is pending, the New Mexico Instream Flow Commission launched a Groundwater Conservation Pilot Program in 2021 that pays irrigators in this area to curtail pumping. A total of 515 hectares were enrolled in 2021.[27]

Given continuing aquifer and reservoir declines as well as recurring river drying in many reaches, much more will need to be done to reduce consumptive irrigation use to ensure water security for farmers and adequate environmental flows to support the river ecosystem.

Water Saving Potential through Crop Shifting

Our optimization analysis for the Rio Grande study area suggests that water consumption can be reduced by as much as one-third through crop shifting (Figure 6), primarily by reducing alfalfa and other hay, substituting mostly with potatoes and pecans, and retiring some portion of overall irrigated area (Figure SI-3 and Table SI-3). Figure SI-4 shows how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop. Table SI-3 summarizes shifts in the optimized crop mixture under the 25% crop reduction scenario.

Table SI-3. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction of crops)

Rio Grande	Alfalfa	Barley	Other Hay	Potatoes	Other Crops	Fallow
Current mixture	45%	12%	16%	13%	15%	0%
Optimized mixture	30%	11%	2%	17%	6%	34%

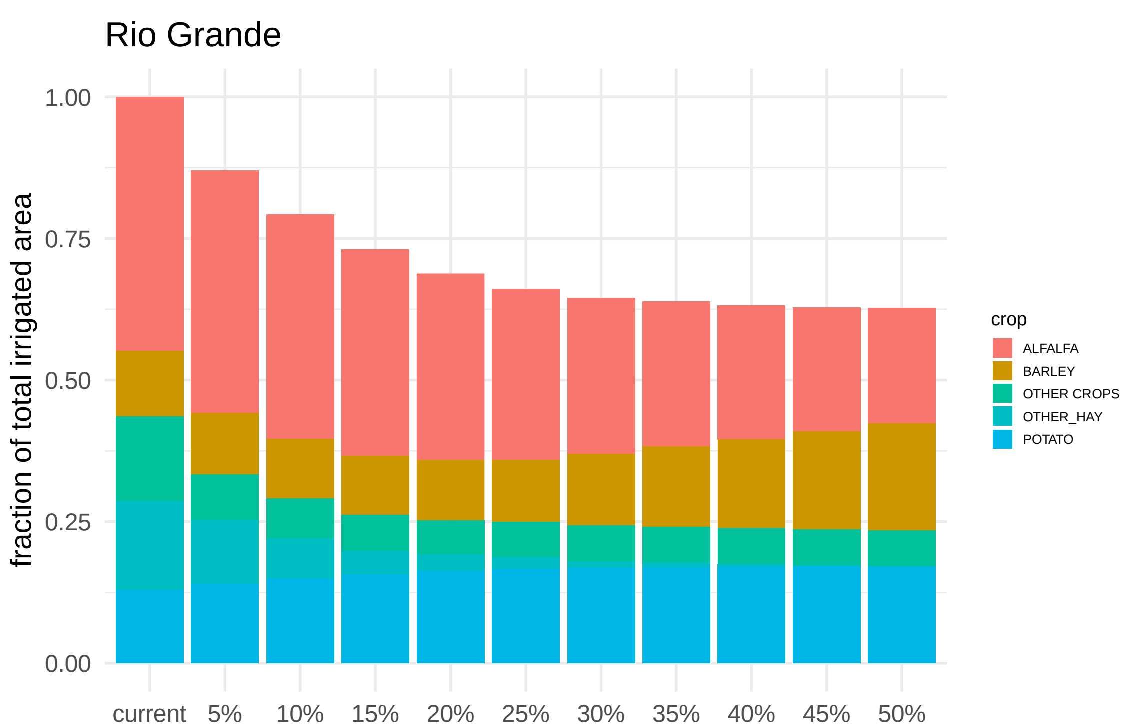

Figure SI-3. Optimizing the crop mixture along the Rio Grande to maximize water savings would involve reducing the irrigated area of alfalfa and other grass hay, while increasing the production of barley and potatoes and retiring up to one-third of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the *percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.*

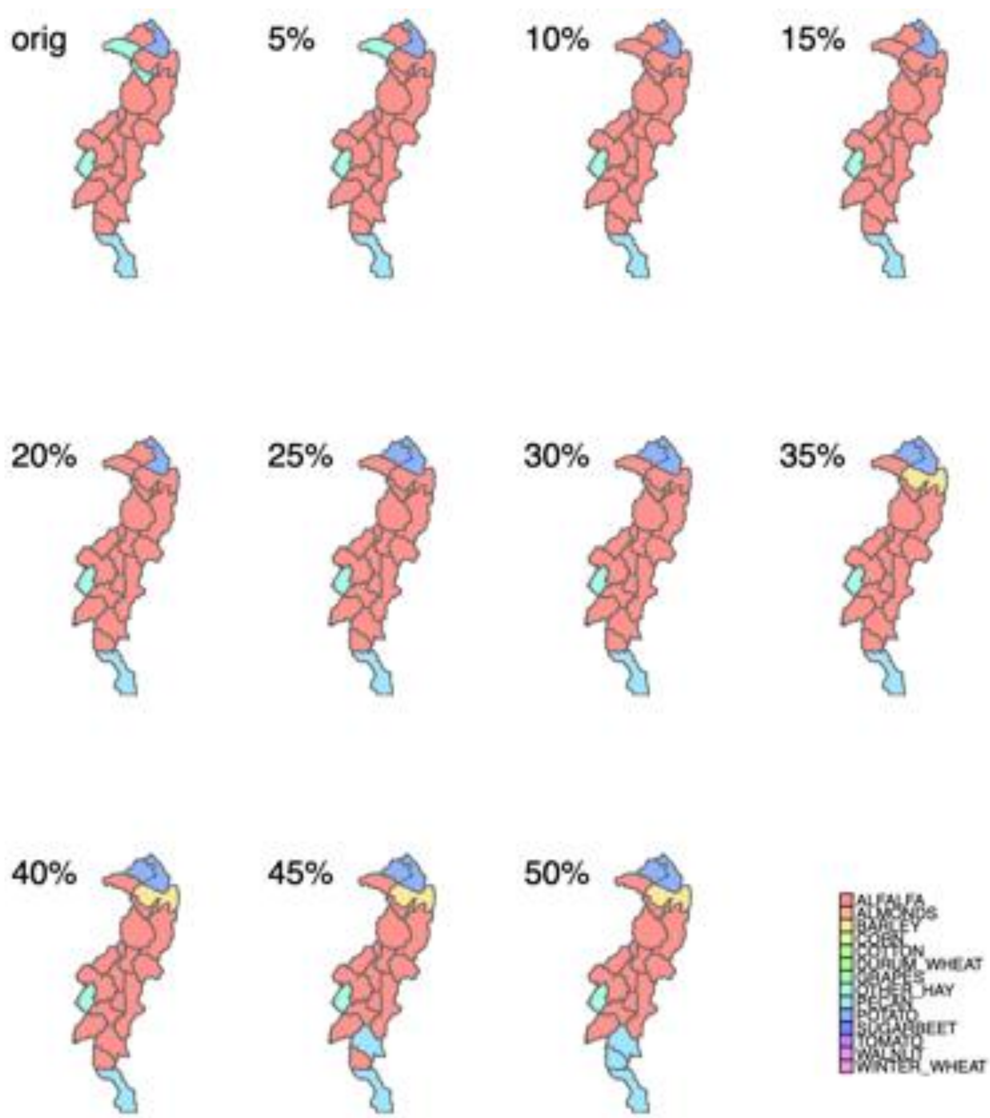

Figure SI-4. The dominant water-consuming crop within each HUC8 within the Rio Grande study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

Case Study: Great Salt Lake, Utah

Water development history

Utah's Great Salt Lake is a remnant of the vast Pleistocene era lake known as Lake Bonneville that once covered 52,000 km^2 (20,000 mi^2) with depths exceeding 300 meters (1,000 feet).[28] Until 15,000 years ago, the lake level was at a sufficiently high elevation to allow water to flow north from Lake Bonneville to the Snake River. However, the lake's level receded precipitously with climate changes over the last 12,000 years. Today's Great Salt Lake covers 5,500 km^2 (2,100 mi^2) and is a terminal lake with no outlet. The lake has continued to fluctuate with climate variation during recent centuries; from 1847-1978 the lake fluctuated within a range of 6 meters (20 feet).[29]

Vast wetlands along the lake's eastern shore were occupied by Native Americans beginning at least 10,000 years ago.[30] The Shoshone tribe referred to the lake as *Pi'a-pa*, meaning "big water", or *Ti'tsa-pa*, meaning "bad water."[31] In addition to foraging for plants and hunting animals in the area, Native Americans also farmed corn, beans, and squash at least as early as 900-1200 A.D.[32] Mormon settlers eventually gave it the present name after their arrival in 1847.

In recent decades, agricultural and urban water uses have become the dominant influence on lake levels (Figure SI-5), exacerbated by climate changes that are reducing water flows. Consumptive water use in the Great Salt Lake basin has now reduced inflows by 39%, with 63% of those consumptive losses going to irrigated agriculture.[33] As a result, the lake level has been lowered by nearly 7 meters (23 feet) since 1987,[34] and both its volume and area have contracted by three-fourths.[35]

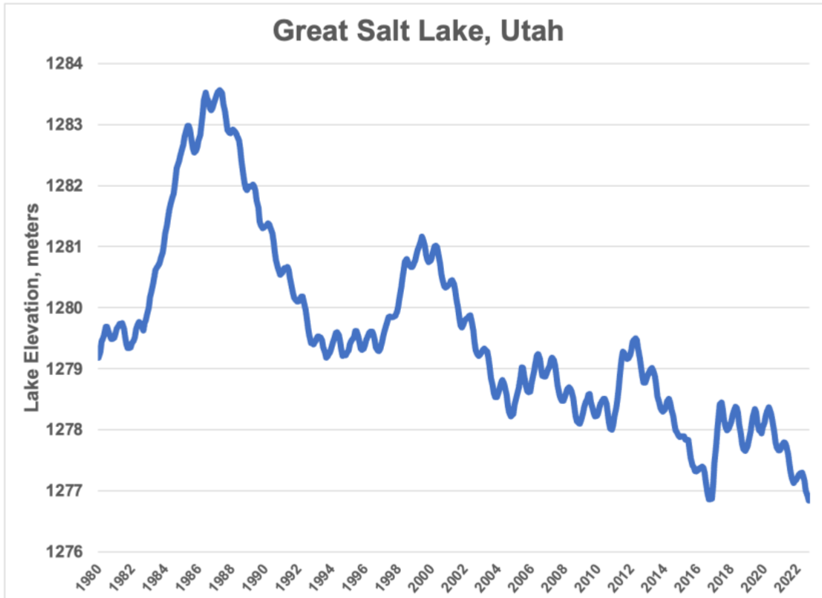

Figure SI-5. The water level elevation of the Great Salt Lake has dropped precipitously in recent decades, primarily due to heavy use of water from tributary rivers. (Data source: US Geological Survey, Great Salt Lake near Saline, Utah)

Water shortages have generally not been a big issue for farmers in this region due to the high relative priority of their water rights. Instead, farmers are facing pressure to reduce their water use and allow unused water to flow into the Great Salt Lake, or to provide additional water supplies for rapidly growing urban areas whose water rights are typically subordinate to farmer's rights during times of shortage. Utah was the fastest growing state in the country during 2010-2020, with a population increase of more than 18% during this period.[36]

Policy Responses

As the lake level has receded, it has exposed nearly 6,500 km^2 (2,500 mi^2) of dried shoreline that is known to contain high concentrations of heavy metals and arsenic that pose serious health risks associated with windblown dust.[37] In response to mounting calls for action to address this threat, the Utah legislature has in recent years passed a series of bills in the hope of stabilizing or raising the lake level. A bill passed in 2022 is intended to directly reduce water use in the basin. House Bill 410 (2022) creates the Great Salt Lake Watershed Enhancement Program and sets up a financial trust that can be used to lease or purchase water rights for the benefit of the lake.[38] The legislature allocated US$40 million for this purpose in fiscal year 2022.

Another bill passed in 2022 allocated US$5M to pay for removal of grass lawns,[39] intended to reduce outdoor watering that typically accounts for half of urban water use in the western US.[40] The rebates are available only in cities that have adopted ordinances restricting lawn areas for new homes and businesses.

Other recent legislation is designed to eliminate obstacles that limit the ability to reduce water use. For instance, House Bill 130 (2020) allows farmers to farm for only a portion of the growing season ("split season") and to sell or lease the remainder of their water rights each year for the benefit of agriculture, the environment, and other water uses.[41]

Given precipitous shrinkage of the lake in recent decades, the fate of the lake will clearly depend upon the rapidity and scale at which water-conserving measures can be implemented.

Water Saving Potential through Crop Shifting

Our optimization analysis for the Great Salt Lake study area suggests that water consumption can be reduced by as much as one-third through crop shifting (Figure 6), primarily by reducing alfalfa and other grass hay, substituting mostly with corn, and retiring some portion of overall irrigated area (Figure SI-6 and Table SI-4). Figure SI-7 shows whether and how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop.

Table SI-4. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction in crops)

Great Salt Lake	Alfalfa	Barley	Corn	Other Hay	Winter Wheat	Other Crops	Fallow
Current mixture	54%	9%	8%	14%	10%	5%	0%
Optimized mixture	48%	1%	26%	3%	0%	2%	20%

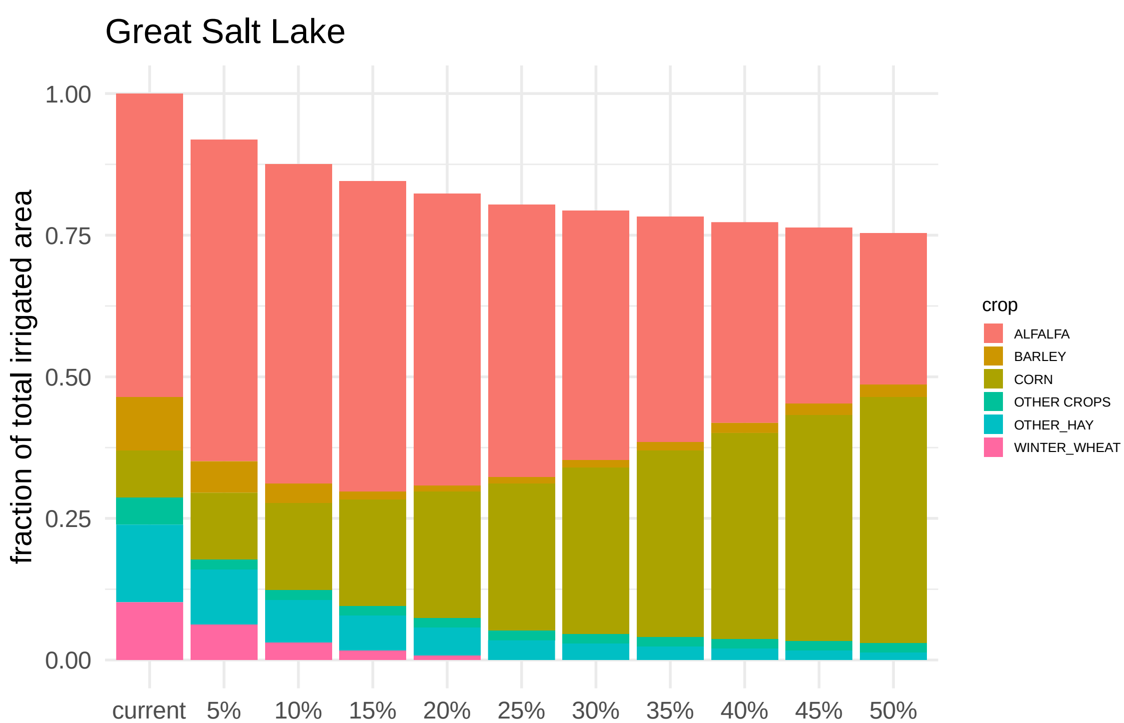

Figure SI-6. Optimizing the crop mixture in the Great Salt Lake study area to maximize water savings would involve reducing the irrigated area of alfalfa and other grass hay, while increasing the production of corn and retiring up to one-quarter of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.

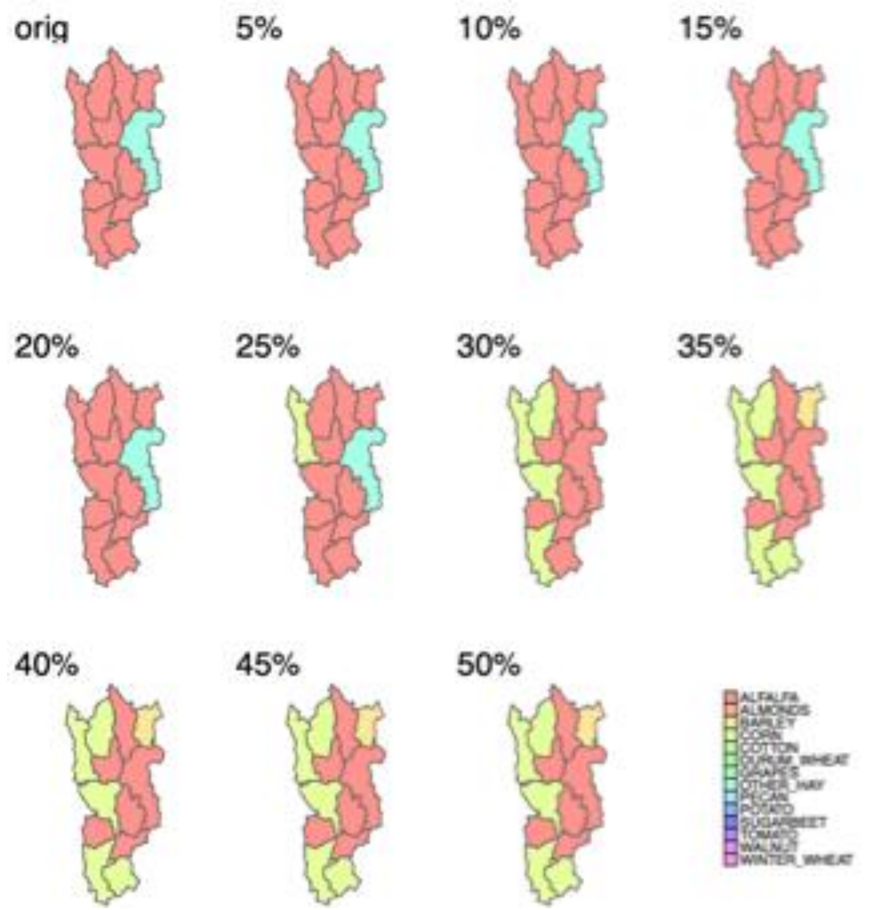

Figure SI-7. The dominant water-consuming crop within each HUC8 within the Great Salt Lake study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

Case Study: San Joaquin River in California

Water development history

Early European explorers traveling through the San Joaquin and Sacramento River valleys of central California encountered hundreds of small villages of Native Americans, some occupied by as many as twelve hundred individuals.[42] The indigenous inhabitants of the valley subsisted on diverse and abundant plant and animal life, including very large herds of tule elk (*Cervus elaphus nannodes*).

Native American culture and the natural ecosystems that sustained indigenous people were massively impacted following the discovery of gold in streams north of the San Joaquin valley in 1848. As thousands of gold seekers flocked into the valley, farms and cattle herds expanded rapidly to feed the growing population.[43] The US Homestead Act of 1862, which enabled settlers to gain ownership of quarter-sections (equivalent to 64.75 hectares) of public land if they would live on the land and improve it, further accelerated settlement in the valley. By 1880, nearly 81,000 hectares of irrigated cereals and alfalfa were being cultivated in the San Joaquin valley.

A Federal Reclamation Act of 1902 authorized federal construction of water projects in the western U.S. and subsidized water deliveries for irrigation. These federal projects, supplemented with California-funded infrastructure – including a Central Valley Project and a State Water Project – facilitated complete expansion of irrigated farms across the valley floor.

Today, the San Joaquin valley produces more than half of California's agricultural output. Its diverse crops and animal products are an important part of the nation's—and the world's—food supply. Local and imported water resources support more than 2 million hectares (5 million acres) of irrigated farmland, a population of more than 4 million, and an economy that generates an average of nearly US$160 billion in gross domestic product.[44] From 1988–2017, annual consumptive water use averaged 20.6 km^3 (16.7 million acre-feet), with 87% going to irrigated farming and the remainder consumed by natural vegetation and managed wetlands (10%) and cities (3%).[45]

San Joaquin farmers have been experiencing severe water shortages in recent decades, particularly in 2012-16 (Figure SI-8) and in 2020-22. Surface water deliveries were reduced by 32% in both 2021 and 2022, causing farmers to fallow more than 26,000 hectares (64,000 acres) and pump 40% more groundwater to meet irrigation needs on the remaining farmland.[46]

Policy Responses

San Joaquin Valley farmers have been experiencing recurring water scarcity for many decades during droughts. When river water is limited, such as during a recent 2012-2016 drought, farmers pump groundwater more heavily and aquifer overdraft is exacerbated (Figure SI-8). On average, agricultural water use exceeds sustainable supplies by nearly 2.5 km^3 million acre-feet per year or 11 percent of net water use.[47]

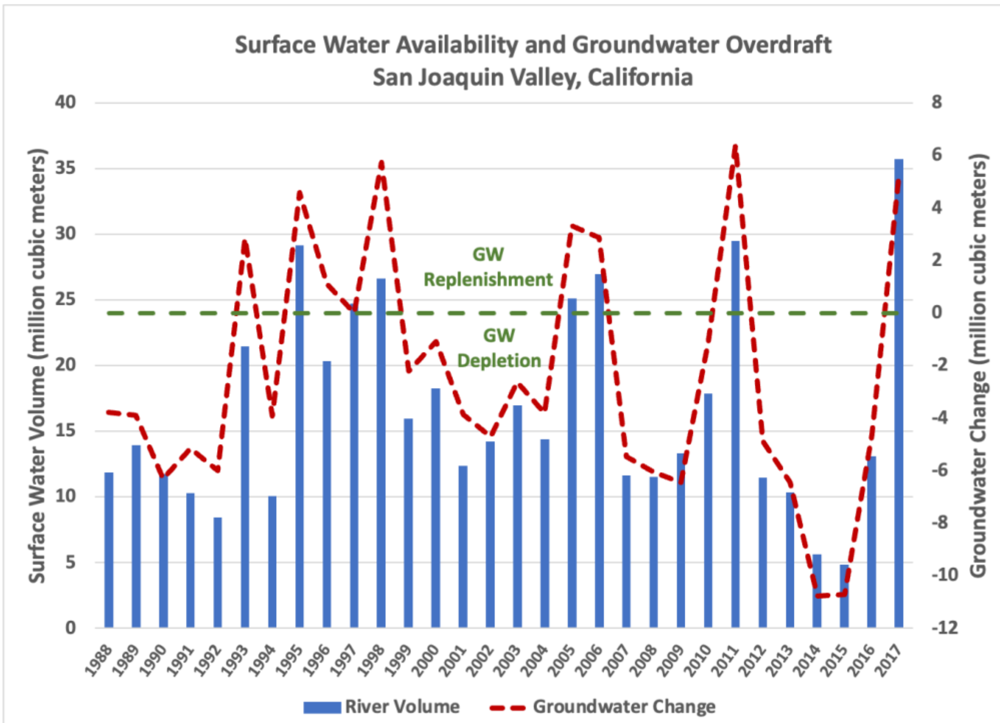

Figure SI-8. The rate of groundwater pumping in the San Joaquin Valley is strongly influenced by the availability of river water for farming. When river supplies are scarce, groundwater is pumped heavily, resulting in repeatedly severe groundwater depletion in recent decades (Data source: Public Policy Institute of California, unpublished)

In 2014, California passed a Sustainable Groundwater Management Act (SGMA) directing local agencies and stakeholders to develop institutions, plans, and implementation strategies to manage their groundwater resources sustainably for the long run.[48] The law defines sustainable management as the avoidance of six “significant and unreasonable” effects: (1) drawing down water levels too far; (2) depleting storage in the aquifer; (3) degrading water quality; (4) allowing seawater intrusion; (5) causing land to subside; or (6) using groundwater in ways that reduce other people's surface water or harm ecosystems.

It is expected that SGMA will spur investments in new water supplies for the San Joaquin Valley, but it will also likely entail idling of more than 200,000 hectares (500,000 acres) of farmland.[49] With the largest groundwater deficit in the state, the valley's water users will feel the brunt of this new law as harshly as any in the state.

A new agreement between state and federal agencies may help to ease some of the transition into farm fallowing under SGMA. The 2022 agreement allocates US$2.9 billion to pay rice farmers to voluntarily fallow some portion of their acreage, with the expectation that 14,000 hectares (35,000 acres) would be fallowed each year.[50]

Water Saving Potential through Crop Shifting

Our optimization analysis for the San Joaquin study area suggests that water consumption can be reduced by more than 40% through crop shifting (Figure 6), primarily by reducing alfalfa, almonds, corn, and cotton, substituting with tomatoes and grapes, and retiring some portion of overall irrigated area (Figure SI-9 and Table SI-5). Figure SI-10 shows whether and how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop.

Table SI-5. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction in crops)

San Joaquin River	Alfalfa	Almonds	Corn	Cotton	Grapes	Tomatoes	Walnuts	Other Crops	Fallow
Current mixture	16%	24%	17%	7%	10%	6%	5%	14%	0%
Optimized mixture	0%	11%	0%	0%	21%	21%	1%	0%	45%

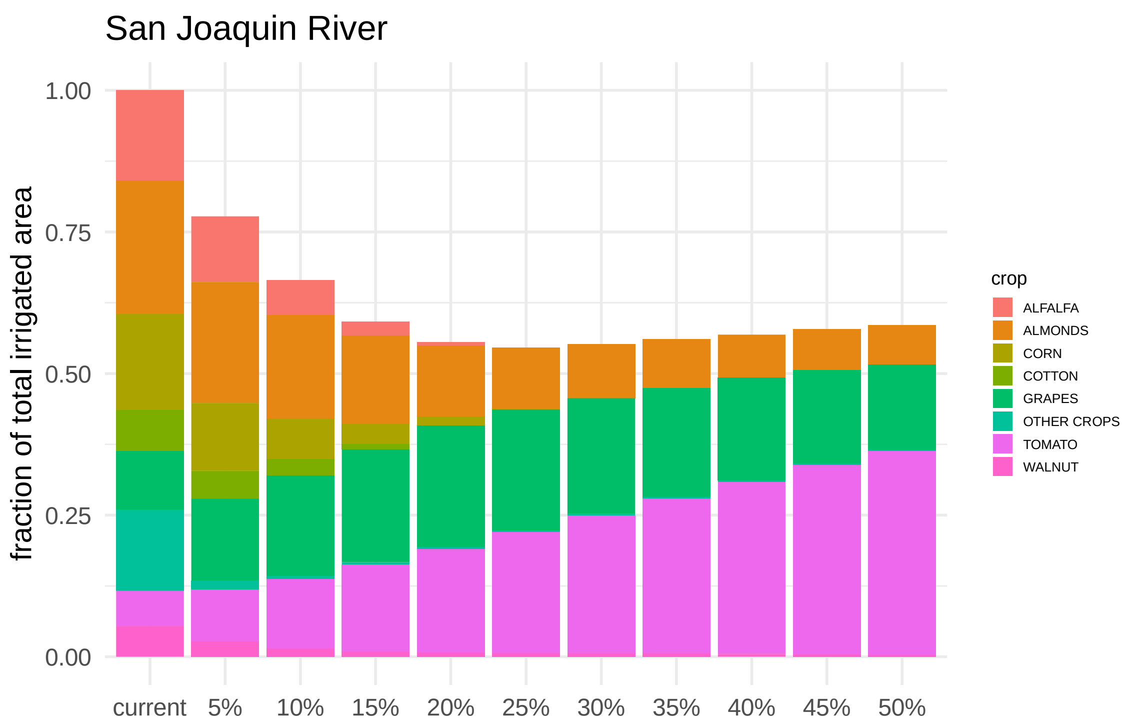

Figure SI-9. Optimizing the crop mixture in the San Joaquin study area to maximize water savings would involve reducing the irrigated area of alfalfa, almonds, and corn, while increasing the production of tomatoes and grapes, and retiring up to 45% of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.

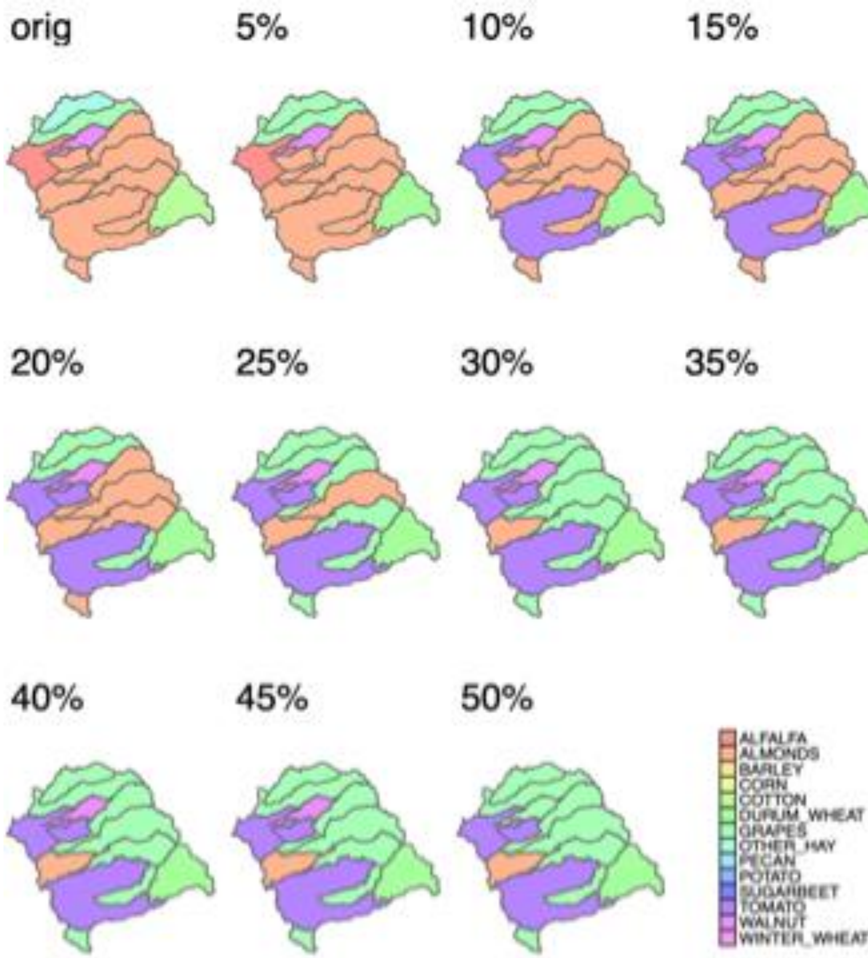

Figure SI-10. The dominant water-consuming crop within each HUC8 within the San Joaquin study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

Case Study: Snake River, Idaho

Water development history

The Snake River basin spans 280,000 km^2 and is the largest tributary to the Columbia River system. More than 70% of the basin lies in Idaho.

Indigenous peoples have resided in the Snake River area since at least the end of the last Ice Age, first showing up in the archeological record 12,000-14,000 years ago.[51] The Shoshone and Bannock tribes intermingled, traveling and hunting together as small, semi-nomadic bands of two or three families in the summer, searching for food throughout the river valley and into the surrounding mountains. Mormon missionaries brought irrigated farming into the area from the Great Salt Lake region in the mid-1800s, and a growing population of settlers eventually displaced most of the original inhabitants soon thereafter, as farms spread across the region.

Today, surface and groundwater withdrawals total more than 23 cubic kilometers (18.9 million acre-feet) per year, with 86% going to 15,000 km^2 (5,800 mi^2) of irrigated farms and another 11% to aquaculture operations. More than 180 different crops are produced within the basin. [52]

Milk and cattle are the top agricultural commodities within Idaho. The state is the second-largest alfalfa producer in the US, and the biggest water consumer in our study area (Figures 2b, 5 & SI-12), used mostly to feed dairy cows.[53]

Irrigated farms along the Snake River relied almost entirely on river water until the 1940s. Flood irrigation of farms resulted in substantial soil infiltration and artificial recharge of the Eastern Snake River Plain Aquifer, a large regional basaltic aquifer underlying much of the river valley, at the rate of 0.51 cubic kilometers (400,000 acre-feet) per year.[54]

In response to recurring droughts that reduced river flows, farmers began investing in canal lining and more efficient irrigation application (primarily by switching from flood/furrow irrigation to sprinkler application), which had the unintended consequence of decreasing aquifer recharge. At the same time, groundwater pumping increased rapidly beginning in the 1950s. The combined effects of reduced aquifer recharge and increased groundwater pumping caused the aquifer to begin losing water at a rate of 0.25 km^3 (200,000 acre-feet) per year from 1952-2015.[55]

As groundwater levels dropped, the discharge of groundwater from springs tributary to the Snake River also declined substantially, causing river diverters downstream of the springs to experience water shortages. Simultaneous aquifer and river depletion led to competition and conflicts between groundwater pumpers and river diverters.

Policy Responses

A moratorium on any new surface or groundwater rights was passed by the Idaho legislature in 1992 in response to declining river and groundwater levels (Figure SI-11) that were preventing the state water resources agency to adequately serve existing water rights holders that had not previously experienced water shortages, and to comply with an environmental flow requirement in the Snake River.[56]

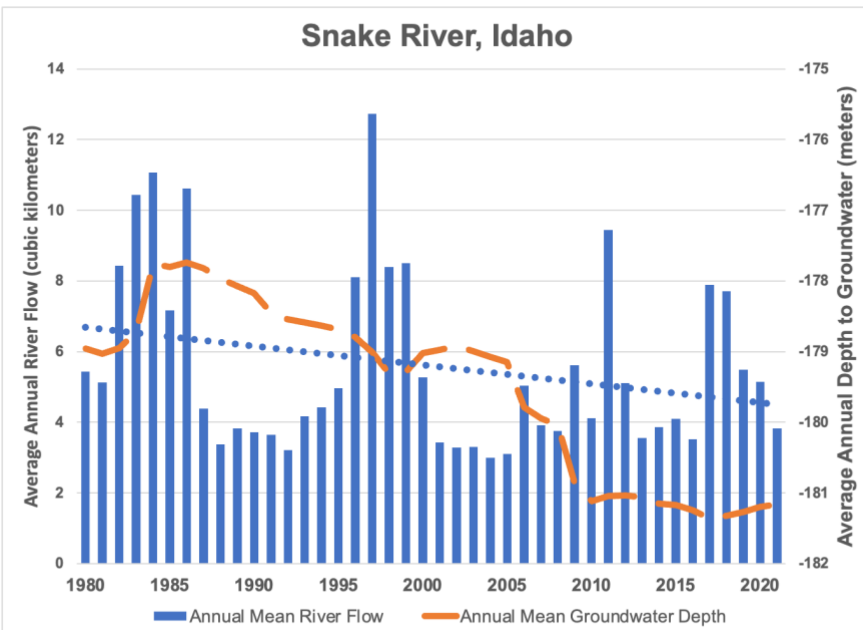

Figure SI-11. Annual river flows have been decreasing over recent decades, leading to shortages for surface water irrigators and necessitating greater volumes of groundwater pumping. Farmer investments in canal lining and improved irrigation efficiency have reduced groundwater recharge, and heavier groundwater pumping has led to declines in the Eastern Snake River Plain Aquifer (Data sources: US Geological Survey; Snake River near Minidoka and well ID 4327001124708).

Subsequently, the Idaho legislature in 2009 approved an aquifer management plan designed to eventually restore an average of 0.74 km^3 (600,000 acre-feet) annually to the aquifer; the phased plan called for restoration of 0.31 km^3 (250,000 acre-feet) per year in the first ten years through 2020. The strategies identified in the plan – to be funded by a mix of public and private sources – included shifting some portion of groundwater use to river water; managed recharge of the aquifer using surface water rights held by the state; and conservation investments including improved technology and irrigation efficiency, crop shifting, and rotational fallowing.[57] From 2015-2021, the program was able to restore an average of 0.34 km^3 (276,000 acre-feet) per year to the aquifer, primarily through artificial groundwater recharge using river water.[58]

Progress to date is hopeful, as groundwater levels have remained fairly stable since 2010 (Figure SI-11), but more aquifer restoration including reductions in consumptive water use on farms will be needed as aquifer recovery to date remains at less than half the level originally intended.

Water Saving Potential through Crop Shifting

Our optimization analysis for the Snake River study area suggests that water consumption can be reduced by nearly 60% through crop shifting (Figure 6), primarily by reducing alfalfa, barley, spring wheat, and winter wheat, substituting with corn and potatoes, and retiring some portion of overall irrigated area (Figure SI-9 and Table SI-6). Figure SI-10 shows whether and how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop.

Table SI-6. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction in crops).

Snake River	Alfalfa	Barley	Corn	Potato	Spring Wheat	Sugar Beets	Winter Wheat	Other Crops	Fallow
Current mixture	27%	18%	8%	14%	12%	7%	10%	4%	0%
Optimized mixture	9%	4%	12%	25%	0%	3%	0%	1%	46%

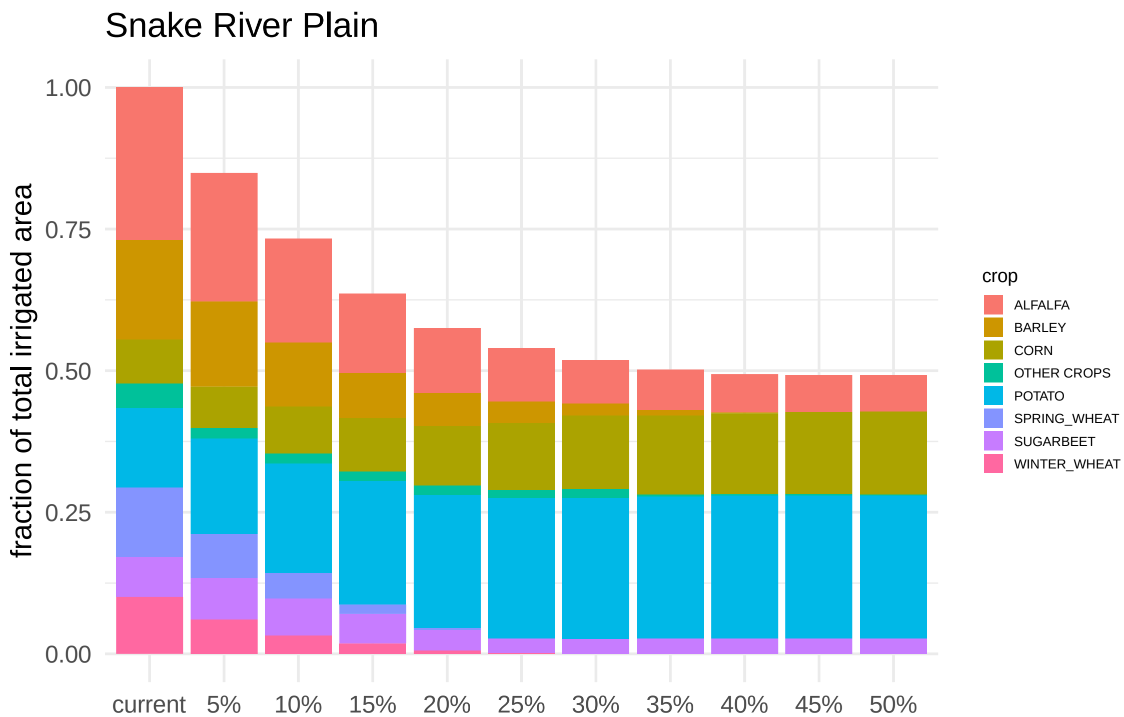

Figure SI-12. Optimizing the crop mixture in the Snake River study area to maximize water savings would involve reducing the irrigated area of alfalfa, barley, spring wheat and winter wheat, while increasing the production of corn and potatoes, and retiring up to half of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.

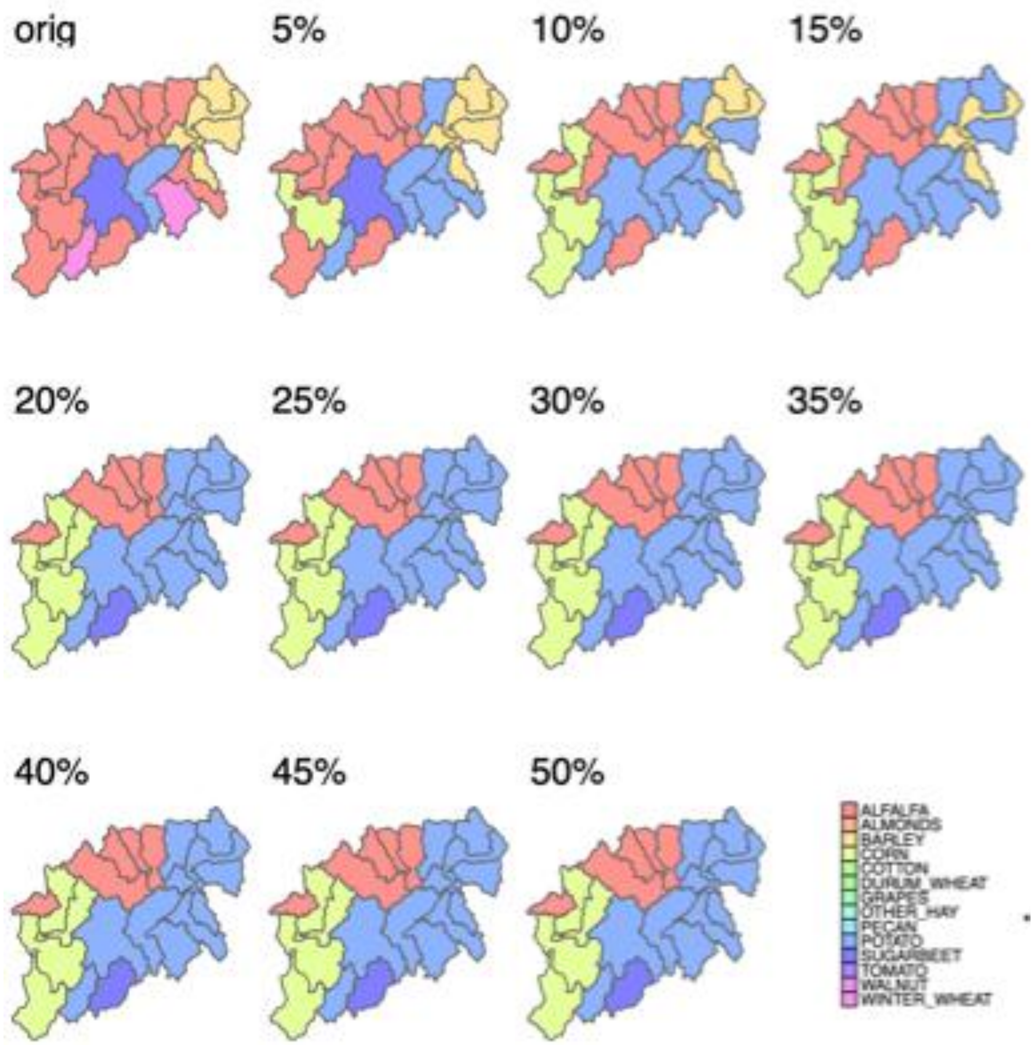

Figure SI-13. The dominant water-consuming crop within each HUC8 within the Snake River study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

Case Study: Platte River in Colorado, Wyoming, and Nebraska

Water development history

Multiple tribes of indigenous peoples lived intermittently along the Platte River for thousands of years before European exploration, traveling through the area in pursuit of bison and other wild foods.[59] Beginning in the 1840s, hundreds of thousands of settlers of from the eastern US began migrating westward on trails along the Platte River, and many settled into towns that would eventually become major Nebraskan cities. As populations grew, demand for agricultural products increased and the cultivation of land farther from the river required increasingly intensive irrigation. [60]

Today, 15 major reservoirs and roughly 200 smaller structures in the Platte River basin store 8.6 cubic kilometers (7 million acre-feet) of water to serve agricultural, industrial, and municipal uses.[61] Agriculture is the dominant water user (83%), followed by industrial use (16%).

Due to heavy water use in the North and South Platte tributaries, river flows downstream of the confluence are substantially diminished in the vicinity of Grand Island, Nebraska (Figure SI-14). The Platte River is bolstered further downstream by tributary inflows from the Loup River (see annual flows at North Bend in Figure SI-14). Water users along the lower Platte River rely heavily on shallow groundwater from the High Plains Aquifer that is replenished by percolating river flows, so the contribution of the Loup to the main river is very important. While annual water supplies in the lower Platte River generally tend to be sufficient for most water uses, peak irrigation demands in the summer months can create water shortages, typically in July and August. These shortages are exacerbated during drought periods. During the 2002-06 drought, groundwater recharge was insufficient to offset groundwater pumping along the lower Platte River, resulting in lowered groundwater levels (Figure SI-14).

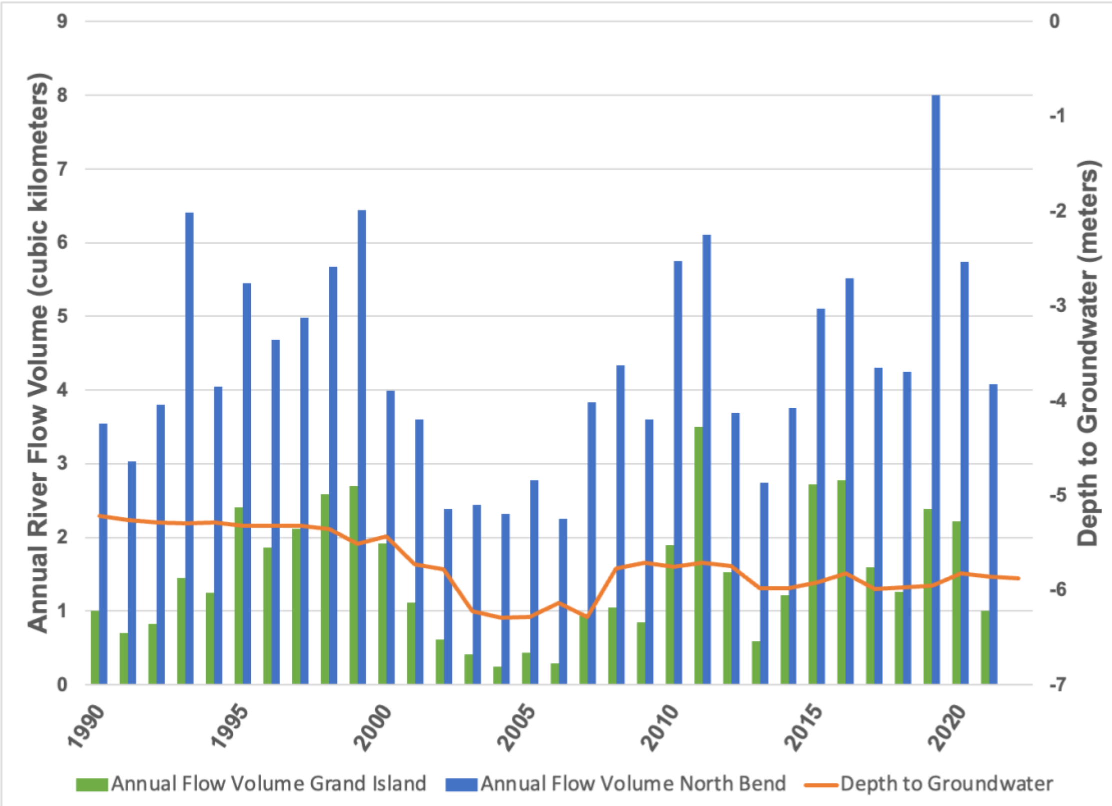

Figure SI-14. Annual river flow volumes at Grand Island, Nebraska (green bars) can be highly depleted by upstream water uses during drought periods such as 2002-06. The lower Platte River is replenished by inflows from the tributary Loup River, as indicated by higher annual volumes at North Bend, Nebraska (blue bars). Most water uses in the lower section of the Platte River depend upon groundwater pumping; percolating river water from the Platte River replenishes the extracted groundwater.

Policy Responses

A big concern driving many decisions about water use along the Platte River is the mandate to protect habitats of four species listed under the US Endangered Species Act: the whooping crane (*Grus americana*), piping plover (*Charadrius melodus*), interior least tern (*Sterna antillarum athalassos*), and pallid sturgeon (*Scaphirhynchus albus*). The US Fish & Wildlife Service – the federal agency primarily responsible for the recovery of listed species – worked closely with the US Bureau of Reclamation and the states of Wyoming, Colorado, and Nebraska to develop a recovery plan in 2006. [62] The overall water objective of the plan for its first phase (2007-2019) was to improve river flows by an average of 0.16 to 0.19 km^3 (130,000-150,000 acre feet) per year at Grand Island, Nebraska. This volume of water is stored in upstream reservoirs and then released to meet targeted environmental flows that include both spring high-flow pulses and monthly-varying minimum flows throughout the year.

As of the latest plan update in October 2019, the states had not reached the targeted flow recovery volume, but 0.11 km^3 (89,000 acre-feet) per year of flow restoration (~70% of low end of target range) had been achieved.[63]

Water Saving Potential through Crop Shifting

Our optimization analysis for the Platte River study area suggests that water consumption can be reduced by more than 20% through crop shifting (Figure 6), primarily by reducing soybeans, winter wheat, and grass hay, substituting primarily with corn, and retiring some portion of overall irrigated area (Figure SI-9 and Table SI-7). Figure SI-10 shows whether and how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop.

Table SI-7. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction of crops)

Platte River	Alfalfa	Corn	Other Hay	Soybean	Other Crops	Fallow
Current mixture	14%	54%	8%	15%	10%	0%
Optimized mixture	12%	67%	3%	2%	1%	15%

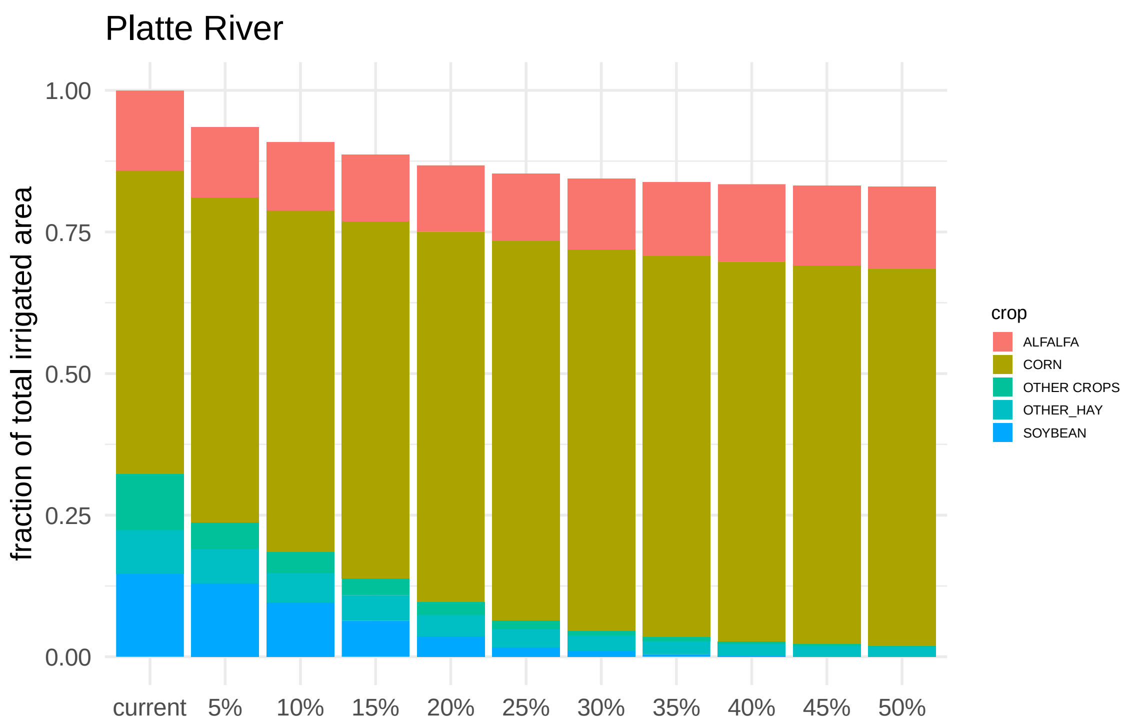

Figure SI-12. Optimizing the crop mixture in the Platte River study area to maximize water savings would involve reducing the irrigated area of soybeans, winter wheat, and grass hay, while increasing the production of corn, and retiring up to 20% of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.

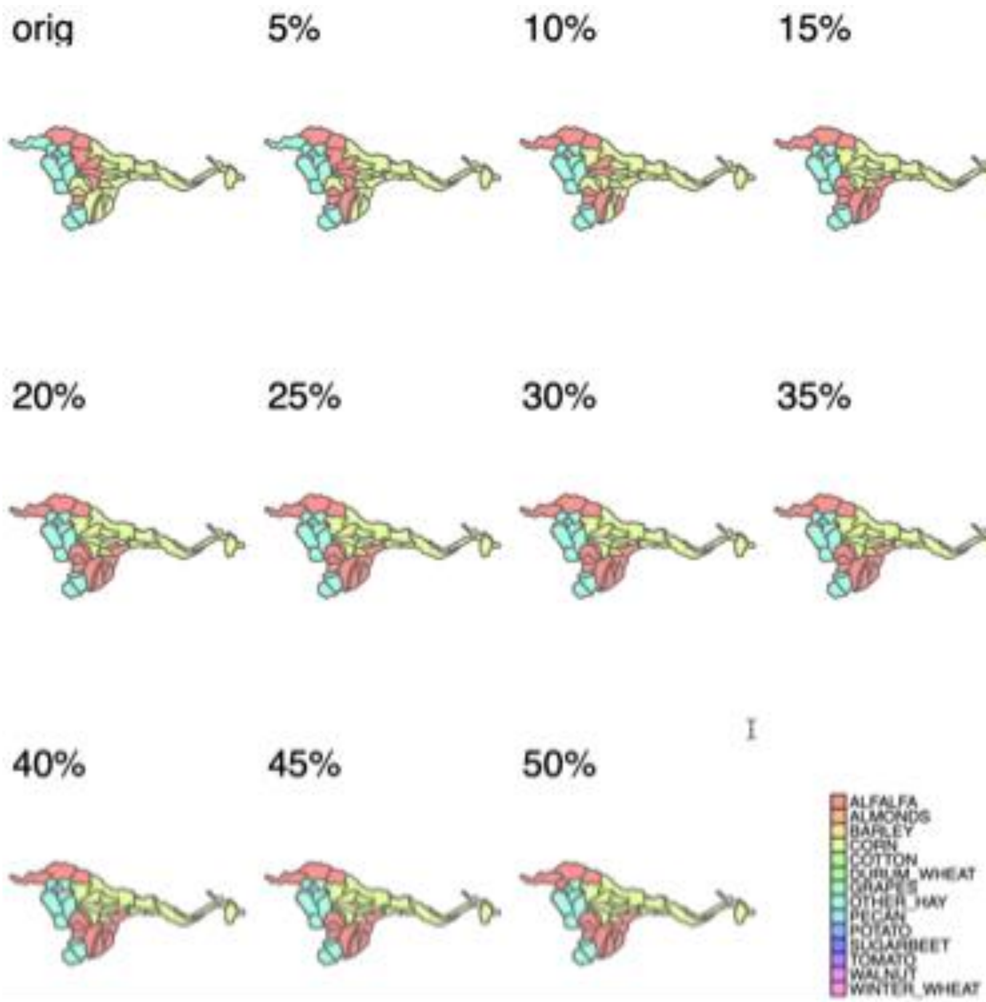

Figure SI-13. The dominant water-consuming crop within each HUC8 within the Platte River study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

Case Study: Lower Colorado River

Water development history

The Colorado River is the largest and longest river in the southwestern US, draining 637,000 km^2 (246,000 mi^2) and flowing from 2800 meters (9,000 feet) elevation in the Rocky Mountains of Colorado to its delta in the Gulf of California in Mexico. Ninety percent of the river's water originates from snowmelt in the Rocky Mountains.[64]

The earliest crop production in North America documented by archaeologists has been found in the Lower Colorado River area near present-day Tucson, Arizona, with maize remains dated to 5,000-5,500 years before present. Buried canals in this area indicate that irrigation began around 3,200 years ago.[65]

The first non-indigenous visitors to the Lower Colorado River near Yuma are believed to have been on a Spanish expedition in 1540 led by Hernando de Alarcon, under the direction of Francisco Vasquez de Coronado, who was searching for the fabled "seven cities of gold."[66] More than a century later, when farmers of European descent first settled in the Gila River valley (a major tributary to the Colorado River in Arizona) in the 1860s, they found an extensive system of irrigation canals built hundreds of years earlier by the Hohokam people, who disappeared from the area around 1450 AD.[67] The Hohokam used stone and wooden tools to build more than 800 km (500 miles) of irrigation ditches that sustained a population of almost 50,000 for hundreds of years. The system was, in fact, the largest prehistoric irrigation system in North America. The reactivation of the Hohokam ditches after 400 years of non-use inspired the city's naming as Phoenix, after the mythological bird that arose again from its ashes.[68]

The US Civil War of the 1860s greatly slowed westward migration of settlers from the eastern US, but in 1869 a war veteran named John Wesley Powell led the first expedition down the Green River and into the Colorado River, from Wyoming through the Grand Canyon in Arizona. Powell's expertise as a geologist and explorer led to his appointment as the first director of the US Bureau of Ethnology at the Smithsonian Museum,[69] where in 1878 he published a "*Report on the Lands of the Arid Region of the United States*"[70] in which he presciently asserted:

> "*When all the rivers are used, when all the creeks and the ravines, when all of the brooks, when all the springs are used, when all the of the reservoirs along the streams are used, when all the canyon waters are taken up, when all of the artesian waters are taken up, when all the wells are sunk or dug that can be*

dug, there is still not sufficient water to irrigate all of this arid region. I tell you gentlemen you are piling up a heritage of conflict and litigation over water rights for there is not sufficient water to supply these arid lands."

The future of water over-exploitation that Powell envisioned did not take long to unfold. In 1901, two agricultural developers built an irrigation canal that diverted Colorado River water into the Imperial Valley, attracting more than 7,000 settlers in the first three years.[71] Today, the Imperial Irrigation District – formed in 1911 – holds the largest water right (3.2 km^3/year = 2.6 million acre-feet/year) on the entire Colorado River system, equivalent to nearly 20% of the river's flow volume.[72] The irrigation district – which lies within our study area – is immensely important to the nation's food production, generating more than US$1 billion of agricultural revenue per year. While half of the farmland is devoted to producing alfalfa and other hay crops, the valley is known for producing two-thirds of the lettuce, carrots, broccoli, spinach, onions and other vegetables consumed in the United States during the winter months.[73]

The federal Reclamation Act passed in 1902 set into motion large-scale water infrastructure development across the western US. On the Colorado River, the first project under the Act was the construction of Laguna Dam, built to divert water to farmers in the Yuma Valley, within our study area. Next was construction of Hoover Dam, forming Lake Mead, which at the time was the largest dam in the world and the reservoir is still the largest in the US.

In recent decades, the water level in Lake Mead has declined rapidly; in 1999, the reservoir was nearly full, but is now three-fourths empty, a consequence of climate changes that have reduced the flow of the Colorado River by 20% while use of the river's water has decreased by only 15%, creating a deficit that is accommodated by removing water from storage in Lake Mead and Lake Powell on the Colorado River (Figure SI-14). In response to rapidly declining reservoir levels, the states relying upon the river – in close collaboration with the US Bureau of

Reclamation – have begun reducing deliveries of Colorado River according to each state's water rights priority, with Arizona being hardest hit thus far. In 2023, the State of Arizona will receive 21% less water from the river. These reductions in water availability are primarily affecting irrigation farmers at this point. [74]

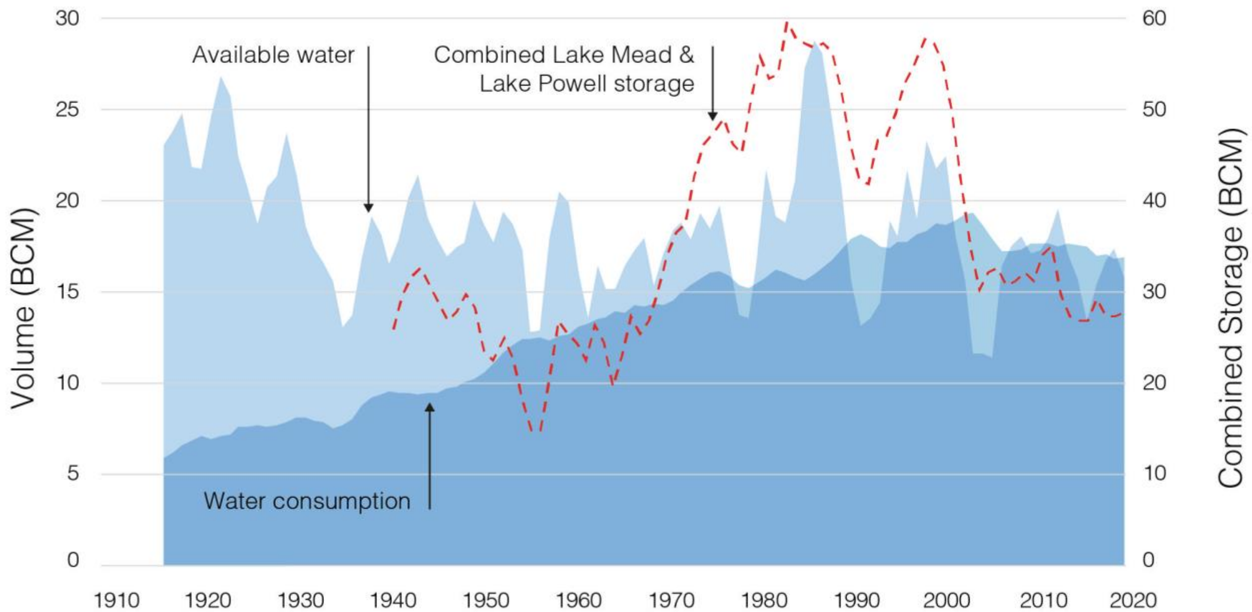

Figure SI-14. The total volume of water consumed has exceeded replenishment of the Colorado River in all but 5 years since 2000. As a result, water has been removed from storage in Lake Mead and Lake Powell to make up deficits, causing reservoir levels to decline precipitously (Data source: US Bureau of Reclamation).

Policy Responses

Three of the states sharing the Colorado River – California, Arizona, and Nevada – reached agreements in 2007 and again in 2019 pertaining to reductions in their water deliveries that become more severe as reservoir levels decline.[75] However, it is widely accepted that the agreed reductions have been insufficient to stabilize falling reservoir levels.[76]

In 2022, the US Inflation Reduction Act earmarked US$4 billion for water conservation in the Colorado River basin.[77] These funds will be used to compensate farmers willing to fallow their farmland to reduce water consumption and stabilize reservoir levels. The annual level of reduction in water consumption will depend upon the area of farmland fallowed, and the crops grown on those lands previously.

Water Saving Potential through Crop Shifting

Our optimization analysis for the Lower Colorado River study area suggests that water consumption can be reduced by more than 20% through crop shifting (Figure 6), primarily by reducing alfalfa, other grass hay, and durum wheat, substituting primarily with sugar beets, and retiring some portion of overall irrigated area (Figure SI-15 and Table SI-8). Figure SI-16 shows whether and how the dominant water-consuming crop in each HUC changes, depending on the level of allowable reduction for any single crop.

Table SI-8. Comparison of crop mixtures under current versus optimized scenario (25% allowable reduction of crops)

Lower Colorado River	Alfalfa	Cotton	Durum Wheat	Other Hay	Sugar Beets	Other Crops	Fallow
Current mixture	52%	8%	17%	12%	6%	6%	0%
Optimized mixture	48%	0%	3%	0%	19%	4%	26%

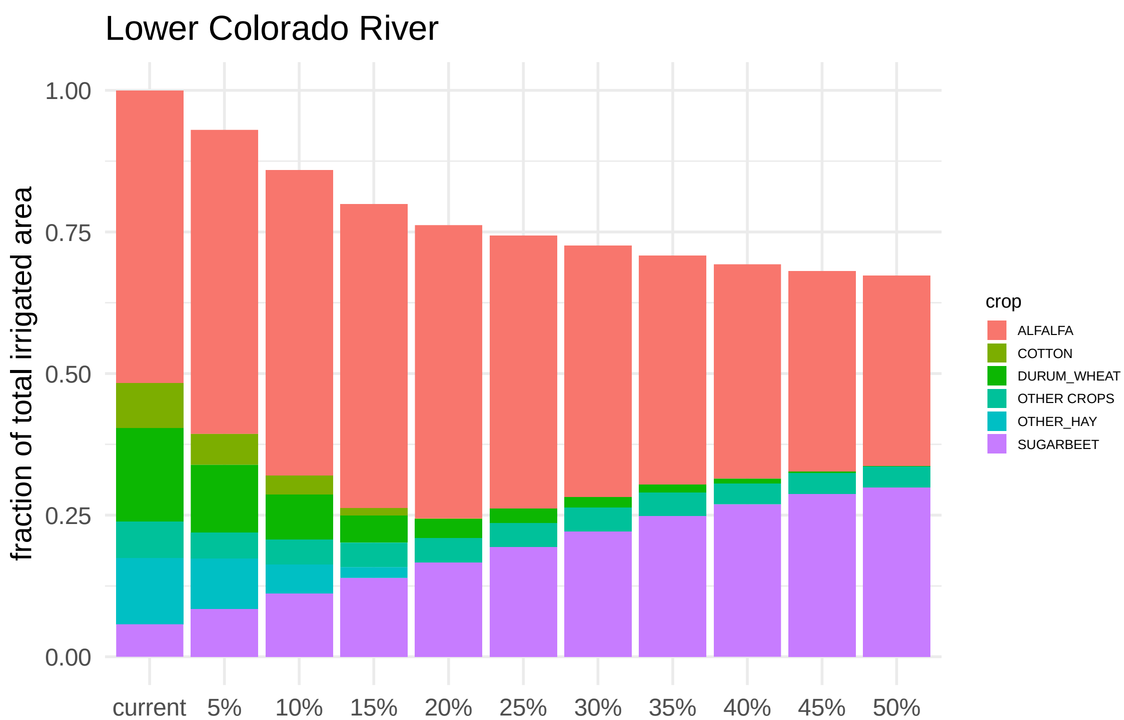

Figure SI-15. Optimizing the crop mixture in the Lower Colorado River study area to maximize water savings would involve reducing the irrigated area of alfalfa, other grass hay, and durum wheat, while increasing the production of sugar beets, and retiring up to 30% of irrigated area overall. Different scenarios shown here involve restricting the reduction of any single crop to the percentages shown on the x-axis. The y-axis shows the fraction of 2019 irrigated cropland dedicated to different crops under different scenarios.

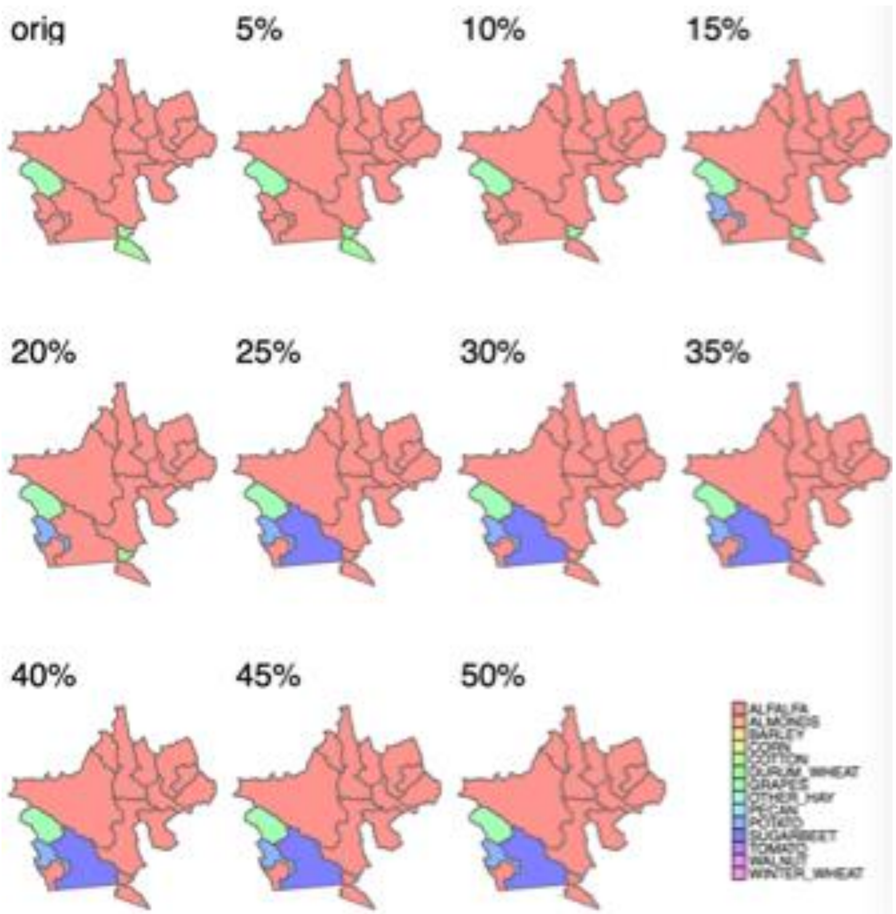

Figure SI-13. The dominant water-consuming crop within each HUC8 within the Lower Colorado River study area after optimization, using varying levels of restriction on per-crop reductions (percentages indicate level of restriction applied).

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