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PNNL-36483

Irrigation Infrastructure and Modernization – Setting a Baseline

Estimates of Irrigation Water Conveyance Infrastructure Extents and Composition and the Potential Water, Energy, and Economic Benefits of Modernization in the Western U.S.

February 2026

U.S. DEPARTMENT OF ENERGY

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Key Findings

In the Western United States (U.S.), water delivery for irrigation is still largely managed using century-old equipment and designs. Modernization of this vital water conveyance infrastructure, such as piping of earthen canals, is known to improve water availability and water quality for farmers, while saving energy and enabling new hydropower. However, there is sparse information about the extent of irrigation water delivery infrastructure, which makes it challenging to estimate the cost of upgrades at scale and the potential benefits of accelerating modernization work.

This report estimates a variety of previously unquantified data points related to irrigation water delivery infrastructure in the Western U.S. to support stakeholders interested in nationwide modernization planning. The findings summarized below should be considered approximations, useful for understanding the scale, range, or variability of these indicators. Taken together, the findings of this report illustrate some of the challenges and opportunities involved in modernizing the agricultural water delivery infrastructure in the Western U.S. Accelerating the pace of modernization could strengthen the long-term resilience of U.S. food systems while providing significant economic, energy, water, and environmental benefits.

Doubling the pace of current irrigation modernization activities could create an estimated $30 billion in cumulative benefits by 2050, even without accounting for the value of increased water availability or energy generation.

Infrastructure Scale

- **Comparable in scale to the National Highway System,** there are an estimated **147,700 miles** of canals and pipelines move water from rivers, lakes, and reservoirs to farms and ranches across the 17 states in the Western U.S.
- Much of the U.S. irrigation infrastructure was **constructed over 100 years ago.**
- An estimated **64 percent (~95,000 miles)** of irrigation water conveyances remain unlined, earthen canals, which are prone to seepage and evaporation and require costly annual maintenance to remove debris, shore up banks, and keep water flowing. An estimated **27 percent (~40,200 miles)** of irrigation infrastructure are comprised of lined canals and **8 percent (~12,400 miles)** is piped. Importantly, even lined canals and piped systems may be decades old and in need of repair or replacement.
- An estimated **16 to 26 percent** of the water diverted for agriculture in the West is lost via seepage or evaporation before arriving at a farm. At the high end, this represents **10 – 13 million acre-feet of water**, equivalent to nearly **half the storage volume of Lake Mead**.

Modernization Pace and Benefits

- This analysis estimates **570 miles of irrigation canals are lined or piped each year**. At this pace, it would take **167 years** to update all remaining earthen canals.
- This study finds that **each dollar spent on modernization adds an *additional* dollar in value** to the West’s regional economy through indirect and induced economic impacts.

- Approximately **$1.15 billion is spent annually** on off-farm irrigation infrastructure modernization projects. Continuing at the present pace of modernization could cost an estimated $22 billion through 2050 while supporting an estimated **12,800 annual jobs**.

- Modernization of irrigation water conveyances conserves an estimated **138,000 acre-feet of water** annually. By 2050, **3.6 million acre-feet of water** could be available for other beneficial agricultural, environmental, industrial, and municipal uses.

- Many federal programs provide support for modernization, but available funding may not be matched to the scale of the infrastructure. On average, the Bureau of Reclamation's WaterSMART Program, an important funder of modernization projects, supports **10 miles of lining and 40 miles of piping** projects each year.

- **Drought costs the U.S. over $6 billion a year**. Modernization projects can help mitigate drought effects. Example: if water conserved through modernization efforts were directed to improve alfalfa hay yields, production could increase by an average of **7.3 percent** in the areas studied. This added productivity could result in an increase of **1,050 annual jobs** across these counties and **$43.6 million** of added annual economic activity by 2050.

Energy Used in Irrigation and Modernization Opportunities

- At a cost of **over $900 million**, an estimated **12,000 gigawatt hours** (GWh) of electricity was used to pump surface water from off-farm sources for irrigation delivery to crops in 2018.

- Replacing open irrigation conveyances with pipes can enable gravity to partially or fully pressurize the water supply, reducing pump energy requirements. Where surplus pressure exists conduit hydropower can be deployed to reduce pressures while producing electricity. This report validates an Oak Ridge National Laboratory study that previously estimated **540 megawatts (MW) of irrigation canal conduit hydropower capacity potential** in the Western U.S.

Acknowledgments

The United States Department of Energy’s Water Power Technologies Office funded the development of this report at the Pacific Northwest National Laboratory (PNNL) and Idaho National Laboratory (INL). This report is part of a larger Irrigation Modernization Project funded by the Water Power Technologies Office, seeking to enable the many benefits of irrigation modernization including the development of new hydropower installations in agricultural conduits.

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Acronyms and Abbreviations

DOI	U.S. Department of the Interior
EQIP	Environmental Quality Incentives Program
FCA	Farmers Conservation Alliance
GDP	gross domestic product
GIS	Geographic Information System
HR	high resolution
INL	Idaho National Laboratory
MW	megawatt
MW_{AC}	megawatts alternating current
MW_{DC}	megawatts direct current
NASS	National Agricultural Statistics Service
NHD	National Hydrography Dataset
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PRV	pressure reducing valve
RCPP	Regional Conservation Partnership Program
TSID	Three Sisters Irrigation District
USDA	U.S. Department of Agriculture
USDA ERS	USDA Economic Research Service
WEEG	Water and Energy Efficiency Grant
WFPO	Watershed and Flood Preventions Operations
WP	water productivity

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1.0 Introduction: Modernization Opportunities for Irrigation Infrastructure in the Western United States

Across the Western United States (U.S.),[1] a large system of canals and pipelines moves water from rivers, lakes, and reservoirs to farms and ranches, providing irrigation to grow crops and raise livestock. Much of the West's irrigation water conveyance infrastructure was initially constructed from the mid-to-late 1800's to the 1940's (Sojka et al. 2002). Water delivery to farms and ranches is still largely managed using century-old equipment and designs.

Unlined earthen canals are a common type of infrastructure used to deliver irrigation water in the Western U.S. and can vary greatly in size—from as small as a few feet across to over 50 feet—carrying large volumes of water. These canals can require costly annual maintenance, such as sediment and weed removal, or repairing areas damaged by burrowing rodents. Without maintenance, canals can become less capable of effectively and efficiently delivering water. Seepage and evaporation from canals reduces the water available for delivery, exacerbating drought challenges for farmers (Lancaster 1952; Hrozencik et al. 2022).

Modernizing off-farm water delivery infrastructure can reduce or eliminate seepage and evaporation from canals, create co-benefits such as energy savings and generation, and enable opportunities for on-farm improvements that may conserve water or increase agricultural yields (Gleick et al. 2011).

Off-farm irrigation modernization may take a variety of forms depending on local needs. Replacing canals with pressurized pipes—a common modernization technique—can reduce both maintenance and seepage (Lund et al. 2023; Robinson 1963) and, if appropriate conditions exist, create opportunities to install conduit hydropower (Kao et al. 2022). In areas where seepage contributes to aquifer recharge goals, piping can support improved control over where and when recharge occurs. Lining canals with concrete or other materials is another common approach to modernization that can reduce seepage in areas where piping is not the preferred option. When done in partnership with local and regional stakeholders, modernization projects in a water conveyance system may also incorporate features to support environmental restoration goals and other take advantage of other domestic energy opportunities, supporting the creation or retention of jobs in rural agricultural communities (Demars 2022; Kruis 2023).

On-farm irrigation modernization can include changes to improve water application efficiency as well as precision or regenerative agricultural techniques. Water application efficiency improvements, such as converting from sprinklers to drip irrigation, can increase the percentage of water that reaches and is stored in a crop's root zone (Bos and Nugteren 1990). Precision agricultural techniques, such as scientific irrigation scheduling, use soil moisture monitors in combination with weather and evapotranspiration data to determine the timing and amounts of water applied to maximize both crop yields and water conservation (Shannon, Clay, and Kitchen 2018). Regenerative agricultural techniques, such as cover cropping, reduced tilling, or rotational grazing can improve soil structure and water retention (Khangura et al. 2023).

Due to the scale of off-farm irrigation water conveyance infrastructure, which can span across many different landowners, modernization is often complex, time consuming, and costly. Many

[1] This report is focused on the 17 Western U.S. states sometimes referred to as the "Reclamation States": Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming.

local or regional stakeholders, as well as state and federal agencies, may be involved in an off-farm modernization project. On-farm modernization can be challenging as it requires transactions and analysis with many individual agricultural producers for whom project costs can be a concern. Existing programs assist both on-farm and off-farm modernization projects but are typically managed independently by different entities.

While the potential benefits of individual irrigation modernization projects or techniques may be well understood, there is sparse research exploring baseline irrigation water delivery infrastructure attributes in the Western U.S., the current pace of modernization activities and benefits accrual, and the potential costs and effects of scaling and accelerating modernization. Irrigation districts and other agricultural water delivery organizations, federal and state agencies, industry professionals, and other stakeholders supporting modernization project planning and deployment need such baseline information to better characterize how individual projects may fit within regional and national goals. This report examines several previously unquantified attributes, including:

- Baseline information regarding the scale of existing off-farm canal and pipe irrigation infrastructure and the extent of piping and lining,
- An estimate of water and energy use and benefits that could be achieved by current irrigation infrastructure modernization activities, and the potential for benefits to grow if modernization activities double or triple through 2050, and
- The economic benefits and costs of modernization at the current pace and under a doubling or tripling of project implementation.

This effort focused on the modernization of infrastructure associated with surface-water diversions and use and did not explore impacts on groundwater use or recharge, though potential interactions are noted in some areas. No single entity in the U.S. is responsible for overseeing irrigation infrastructure. As a result, data about irrigation infrastructure is not centralized. In addition, there are many support and funding programs, as well as regional and local factors, that influence the number and scale of irrigation modernization projects that move forward each year. The attributes and benefits presented here were calculated or estimated using the best available data collected from a variety of sources. The assumptions used in generating these estimates are included in each section, along with notes about potential follow-on research that could improve or expand these findings.

2.0 Estimate of Irrigation Water Delivery Infrastructure Length in the West

2.1 Introduction

Irrigation canals are permanent channels constructed to convey water from the source of supply to a delivery point for use by agricultural producers and are an integral part of an irrigation water conveyance system (USDA 2003). Though some organizations have internal estimates, no previous estimations of the total length of existing irrigation water delivery infrastructure in the Western U.S. were found in the literature search described in Section 2.2 below. This may be due to the lack of centralized data on irrigation water delivery infrastructure, the range of organization types that own water delivery systems, and the overall scale of the infrastructure involved. A baseline understanding of the length of Western agricultural water delivery infrastructure can help contextualize modernization efforts which may be underway in order to achieve energy, water, and agricultural goals.

2.2 Methodology

A literature review was conducted to determine if the extent of irrigation water delivery infrastructure in the Western U.S. had been previously estimated. The search used Primo, a tool produced by Ex Libris Group that enables searches across academic journals, books, e-books, and other sources. Searches were performed in Primo to look for any titles containing the phrases in quotation marks in column one, below, and each of the words in column two (example: “irrigation canals” AND “length”; “irrigation canals” AND “map”):

Table 1. Terms used in performing the title search in Primo.

“agricultural water conveyance”	“estimate”
"agricultural water distribution"	“estimating”
“agricultural water infrastructure”	“extent”
“irrigated agriculture”	“inventory”
“irrigation canal”	“length”
“irrigation canals”	“map”
“irrigation conveyance”	“mapping”
“irrigation infrastructure”	“measurement”
“irrigation network”	“quantification”
“irrigation pipeline”	“quantifying”
“irrigation system”	
“water conveyance”	

In addition, separate full-text searches were performed for each of the phrases listed in the table below:

Table 2. Terms used in performing the full-text search in Primo.

“extent of irrigation”
“inventory of irrigation”
“map of irrigation”
“miles of irrigation”
“length of irrigation”
“extent of canals”
“inventory of canals”
“map of canals”
“length of canals”

"agricultural conveyance"
"agricultural water conveyance"
"agricultural water delivery systems"
"agricultural water delivery networks"
"irrigation water conveyance"
"irrigation conveyance"
"irrigation conveyances"

None of these searches returned any results that included estimates of the extent of irrigation water delivery infrastructure in the Western U.S.

A general internet search was also performed using Google for the terms in Table 3. Only the first three pages of results were reviewed for each search:

Table 3. Terms used in performing a general internet search.

estimate of the length of irrigation conveyances in the US
estimate of the length of irrigation canals in the US
extent of irrigation infrastructure in western us
extent of irrigation canals in western us
miles of irrigation canals in western us
miles of irrigation infrastructure in western us
length of irrigation infrastructure in western us
length of irrigation canals in western us
inventory of irrigation canals in western us
inventory of irrigation infrastructure in western us

The general internet search terms yielded many results for canals owned by individual irrigation organizations but no comprehensive estimates of the length of irrigation infrastructure in the Western U.S. The largest scale estimates found were published in a U.S. Bureau of Reclamation (Reclamation) report that states the agency "…has constructed approximately 8,000 miles of canal, with 25,000 miles of distribution laterals in the Western United States," (Merten 2020).

In the absence of existing estimates or data, the 2024 version of the U.S. Geological Survey's (USGS) National Hydrography Dataset (NHD) provides a source of data to approximate the total irrigation infrastructure miles. The NHD derives hydrographic features, including canals, from elevation data through complex technical processes (Terziotti and Archuleta 2020).

The length of agricultural infrastructure in the 17 Reclamation States was computed using the USGS NHD NHDPlus High Resolution (HR) National Release 1 2022-07-06. The NHDPlus HR dataset contains different information for different kinds of flow lines in the U.S., including "NetworkNHDFlowline" and "NonNetworkNHDFlowline" shapefiles for which a "canal/ditch" feature type can be selected. Information on the differences between these two layers is not provided by USGS in documentation or metadata; however, a cursory review of the data in both shapefiles showed recognizable irrigation district infrastructure, including canals and pipes in sizes and locations consistent with a range of large main canals to small sub-laterals. Potentially spurious information was also seen, such as canal lines in areas with no known irrigation water delivery organization infrastructure or agriculture. In addition, some irrigation infrastructure that is visually identifiable using common online map applications was not represented in the data. The amount of spurious versus missing data is unknown, meaning it is possible for this dataset to either over or underestimate the total infrastructure miles.

Using Geographic Information System (GIS) software, the following steps were performed:

1. Using the NetworkNHDFlowline and NonNetworkNHDFlowline shapefiles included in the NHDPlus HR dataset, only flow lines with FCode 33600, “CANAL/DITCH” features were selected.
2. The selected lines were intersected with a state-boundary shapefile to create state level information.
3. For each state, the total miles of flow lines were summed.

2.3 Results

Results indicate an estimated total of 147,700 miles of irrigation canal and pipeline infrastructure across the Western U.S., comparable in size to the National Highway System, which covers about 161,000 miles (U.S. Department of Transportation n.d.).The state of California appears to have more than 36,000 miles of infrastructure and Texas, Colorado, Montana, and Idaho all exceed 12,000 miles (Table 4).

Table 4. Estimated miles of irrigation infrastructure in the Western U.S.

State	NetworkNHD (miles)	NonNetworkNHD (miles)	Total Length (miles)
Arizona	2,950	3,009	5,959
California	11,270	25,259	36,529
Colorado	15,613	826	16,438
Idaho	7,859	4,790	12,649
Kansas	596	106	702
Montana	7,411	5,482	12,893
Nebraska	582	16	598
Nevada	3,885	699	4,584
New Mexico	2,875	2,077	4,952
North Dakota	571	210	781
Oklahoma	202	10	213
Oregon	6,625	2,999	9,624
South Dakota	743	226	969
Texas	4,377	14,558	18,935
Utah	6,284	763	7,047
Washington	4,230	1,006	5,236
Wyoming	5,352	4,215	9,566
Total	**81,425**	**66,251**	**147,676**

3.0 Baseline Estimates of Existing Lining and Piping

3.1 Introduction

As noted in Section 2.0, a literature review found no previously published information quantifying or estimating the extent of irrigation infrastructure in the Western U.S. As a result, there are no estimates of the number of miles of irrigation water conveyances that are currently unlined earthen canals, lined with some material, or piped. As unlined canals tend to result in higher rates of seepage (Lund et al. 2023), baseline information on canal composition (unlined, lined, piped) can help to create an understanding of the scale of potential of modernization activities that could prevent seepage, among other benefits. In addition, this baseline can be compared to estimates of annual lining and piping work to consider the implications of the pace of current modernization activities.

In this section, using data reported by the U.S. Department of Agriculture (USDA), estimates are made of the number of miles of unlined earthen canals, miles of canals lined with some material, and miles of piped irrigation infrastructure. Importantly, the estimates made in this section do not consider the underlying condition of existing lining and piping. In some areas, irrigation water conveyances with lining and piping may already be decades old and, in some cases, reaching the end of their service life and needing replacement. The percentage of existing lined and piped infrastructure that is aging and in need of replacement is not estimated in this report.

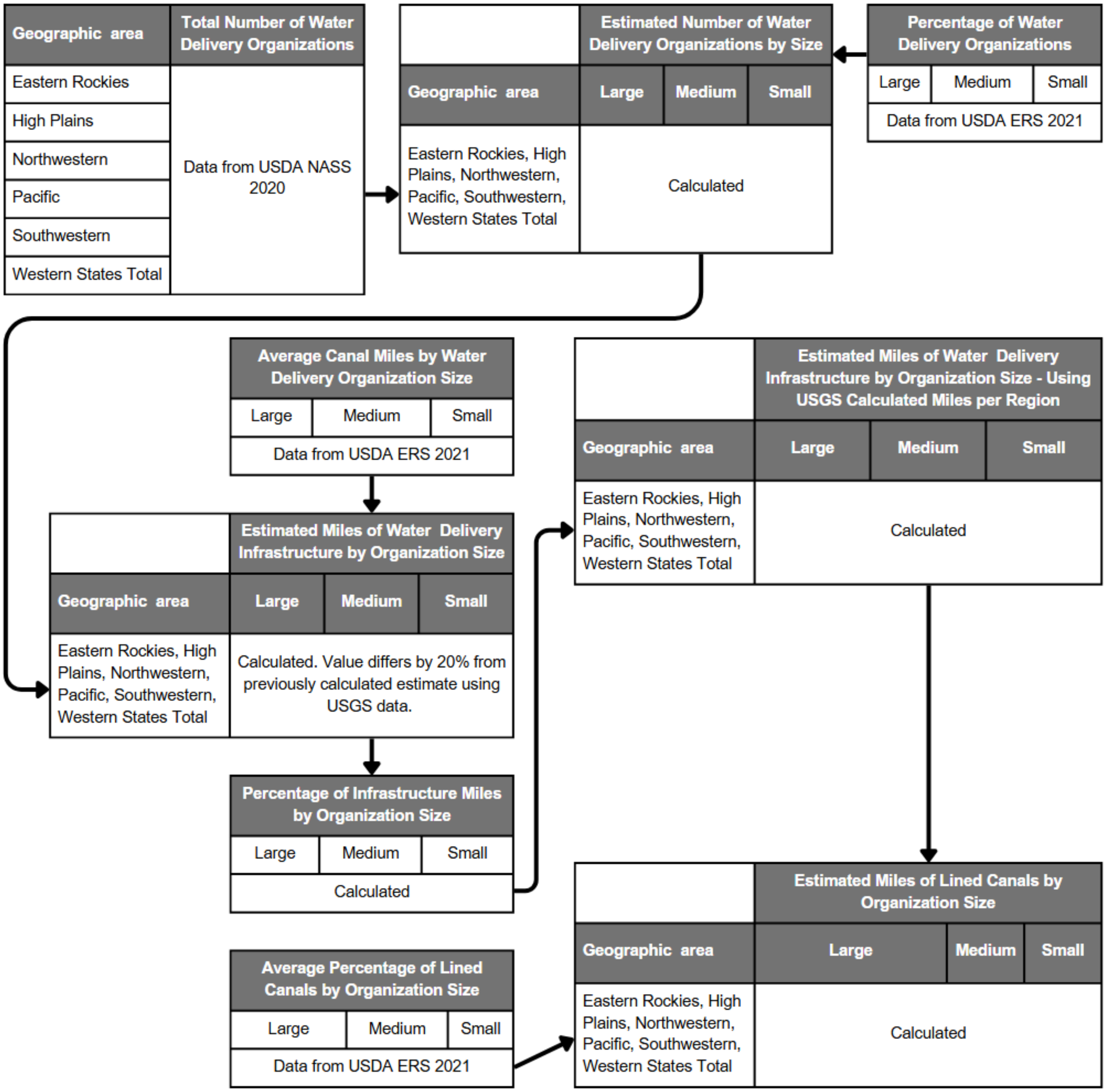
3.2 Methodology

The USDA National Agricultural Statistics Service (NASS) provides survey-based data on the total number of irrigation organizations in the U.S. broken out by region (USDA NASS 2020). Limitations of the survey data include a 44 percent response rate and a need to protect individual responses. Further work by the USDA's Economic Research Service (USDA ERS) distinguishes three size classes of irrigation organizations (large, medium, and small), the percentage of all organizations made up of each size class, and the average number of canal miles per organization based on size class (Hrozencik, et al. 2021). This data can be used to formulate an estimate of the total number of organizations of each size class in each geographic region, the estimated length of infrastructure miles in each region by size class,[2] and the relative percentage of total miles of infrastructure for each organization size class. By applying the percentage of infrastructure miles by organization size class to the previously estimated total miles using USGS data, it is possible to create a breakdown of infrastructure miles by region and size class.

The 2021 work by Hrozencik and his co-authors also presents averages of the amount of delivery system lining broken down by organization size. Using these averages and the estimates of system miles by organization size class and region, it is possible to create an estimate of the total number of lined miles. A block diagram showing how these estimates were made is below in Figure 1.

[2] Building up total miles in this manner results in an estimated 118,841 miles of infrastructure in the West, approximately 20 percent less than the estimate created using USGS data. These two estimates are in the same total ballpark but there are large differences between some regions. For consistency with other calculations throughout this document, the estimate of total miles by region calculated with USGS data is used.

Figure 1. Block diagram showing methodology used to estimate the total miles of lined canals.



Estimating the total number of piped miles is not as straightforward. The text below explains the methodologies used. Each method is followed by an additional table or block diagram to provide a visual reference to the processes used to create the estimates in this report.

A 2022 paper by Hrozencik and his co-authors provides summary results from a survey of irrigation organizations that includes percentages of piped infrastructure but without a breakdown by organization size class (Hrozencik, et al. 2022). Email communication with Hrozencik confirmed that the survey was representative of the organization size classes noted above, as reported by USDA NASS. The 2022 paper reports that 51 percent of organizations have no piping, that the average organization has piped 31 percent of its infrastructure, and that 22 percent of irrigation organizations have piped all of their canals.

Figure 2. Selected data on percentages of piped infrastructure among water delivery organizations, from Hrozencik, et al.

Metric	Data Source / Formula	Percentage
(A) Average Amount of Water Delivery Organization System Piped	Data from Hrozencik, et al. 2022	31%
(B) Percentage of Water Delivery Organizations with No Piping		51%
(C) Percentage of Water Delivery Organizations that are Fully Piped		22%

Estimating the number of miles of piped canals among water delivery organizations that are fully piped is the first step. The 2022 paper reports that 22 percent of irrigation organizations have piped all of their canals. For this estimate, it is assumed that small organizations are more likely to have fully piped their infrastructure than large or medium organizations due to the economics of piping projects. USDA NASS's work previously reported that 44 percent of organizations are small. This report assumes that only small organizations are fully piped and estimates that 50 percent of all the infrastructure miles associated with small organizations are piped. This 50 percent factor can then be applied to the previously estimated miles of infrastructure for small water delivery organizations by geographic region.

Figure 3. Block diagram showing methodology used to calculate miles of fully piped canals.

Metric	Data Source / Formula	Percentage
(C) Percentage of Water Delivery Organizations that are Fully Piped	Data from Hrozencik, et al. 2022	22%

Percentage of Water Delivery Organizations that are Small
44%
Data from USDA ERS 2021

Assumptions	
1.	Due to the economics of piping, small water delivery organization are more likely to have fully piped their infrastructure than medium or large water delivery organizations.
2.	For the purposes of this estimate, it is assumed that only small water delivery organizations are fully piped.

Calculation
If 44% of water delivery organization are small, only small organizations are fully piped, and 22% of all organizations are piped, then 50% of the infrastructure miles associated with small organizations are fully piped (44% - 22%).

	Estimated Miles of Fully Piped Water Delivery Infrastructure
Geographic area	Small Water Delivery Organizations
Eastern Rockies, High Plains, Northwestern, Pacific, Southwestern, Western States Total	Calculated as 50% of total small water delivery organization canal miles.

The next steps also use the 2022 paper by Hrozencik and his co-authors. If 51 percent of organizations have no piping, then 49 percent of organizations have some piping. If the 22 percent of organizations that are fully piped are represented within the 49 percent that have some piping, then 27 percent of organizations may be partially piped.

This report assumes that the 31 percent average amount of water delivery organization system that is piped is an average of the organizations that have *at least some piping* and does not include *all* organizations. This assumption is based on a similar statement being made elsewhere in the 2022 paper in reference to organizations with lining. To determine how many miles of piped infrastructure the 31 percent average represents, the 22 percent that are fully piped must be removed since they have already been counted. Fully piped organizations represent approximately 45 percent of organizations with some piping present. To complete this estimate, 55 percent of the 31 percent average (17 percent) is applied to the 27 percent of organizations that may be partially piped. These factors (27 percent and 17 percent) can then be multiplied by the estimated total miles of infrastructure calculated from USGS data.

Figure 4. Formulas and block diagram used to estimate the remaining miles of piped canals outside of systems that are fully piped.

Metric	Data Source / Formula	Percentage
(A) Average Amount of Water Delivery Organization System Piped	Data from Hrozencik, et al. 2022	31%
(B) Percentage of Water Delivery Organizations with No Piping		51%
(C) Percentage of Water Delivery Organizations that are Fully Piped		22%
(D) Percentage of Water Delivery Organizations Estimated to be Partially Piped	= 1 - B - C	27%
(E) Percentage of Water Delivery Organizations with Piping Present that are Fully Piped	= C / (1 - B)	45%
(F) Remaining Amount of Water Delivery Organization System Piping, on Average, After Subtracting Fully Piped Systems	= (1 - E) * A	17%

Geographic area	Estimated Miles of Remaining Piped Water Delivery Infrastructure, After Accounting for Fully Piped Systems
Eastern Rockies, High Plains, Northwestern, Pacific, Southwestern, Western States Total	Calculated as total canal miles * D * F

3.3 Results

Based on the methodology outlined above, it is estimated that there is a total of 40,000 miles of lined canals in the Western U.S. and an additional 12,000 miles of piped irrigation water delivery infrastructure. Using the estimated total 147,000 infrastructure miles, approximately 64 percent of agricultural water delivery infrastructure in the West remains unlined, while 27 percent is lined and 8 percent is piped. The tables below provide a breakout on each of these estimates by geographic region and organization size.

This estimate was made using the best available data but required many layers of assumptions in the methodology. This estimate, and others in this report, could be improved if more detailed data on water delivery organization infrastructure were collected or made available. A rigorous, publicly available survey and inventory of irrigation infrastructure, while a significant undertaking, would create an important baseline for future research, policy making, and modernization planning.

Figure 5. Irrigation infrastructure is comparable in size to the National Highway System. (Graphic by Ben Watson | Pacific Northwest National Laboratory)

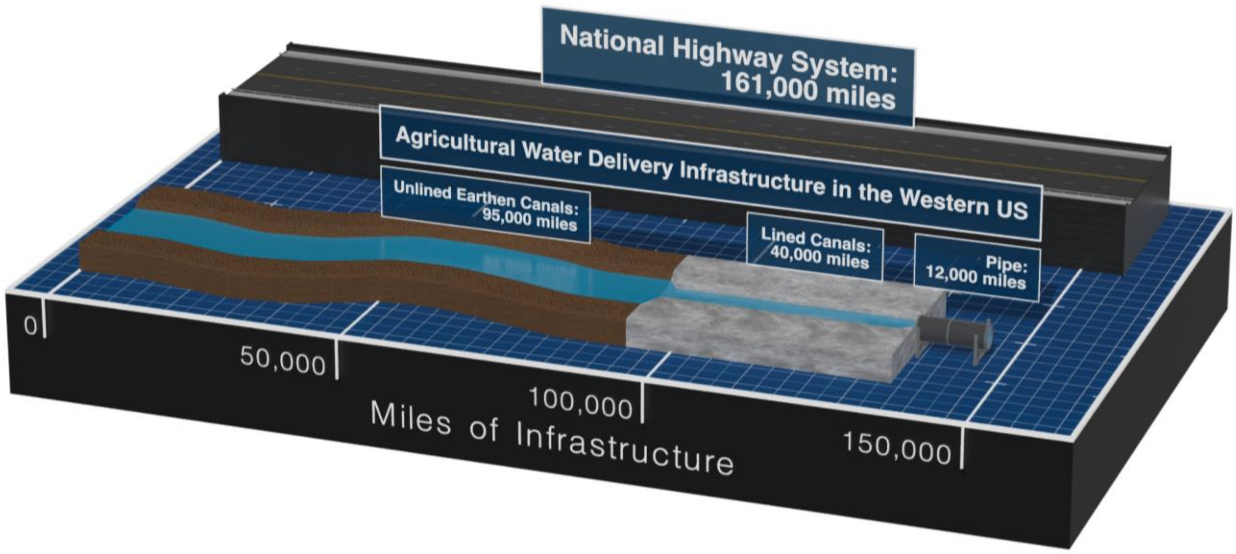


Table 5. Estimated miles of lined canals based on average percentage on lining and regional miles estimated by organization size by region.

	Miles of Lined Canals		
Geographic area	**Large Organizations**	**Medium Organizations**	**Small Organizations**
Eastern Rockies	9,213	880	507
High Plains	5,258	502	290
Northwestern	6,516	622	359
Pacific	9,738	930	536
Southwestern	4,254	406	234
	Total Estimated Lined Miles		**40,244**

Table 6. Estimated miles of piped irrigation water delivery infrastructure.

Geographic area	Estimated number of miles of fully piped infrastructure in small organizations	Estimated miles of piping in an average system after accounting for fully piped systems
Eastern Rockies	1,460	1,794
High Plains	833	1,024
Northwestern	1,033	1,269
Pacific	1,543	1,896
Southwestern	674	828
	Total Estimated Piped Miles	**12,355**

3.4 Case Study Examples and Discussion

Unlined earthen canals are subject to leaks and failures and can require significant annual maintenance to remain in service. Breaches in earthen canals happen many times every year and can result from multiple causes, such as rodent activity, heavy rain, or the underlying geology. Depending on the size of the canal and the amount of water being moved, a failure can create significant property or environmental damage. Cleanup and water service restoration can take days to weeks, sometimes resulting in crop losses and economic damages.

Recent representative examples of canal breaches and their impacts include:

- In July 2024, a 40-foot sinkhole opened when a lava tube collapsed underneath a large canal in the Central Oregon Irrigation District, shutting off water to 1,800 irrigators for a week during summer (Haugen 2024).
- In September 2023, heavy rain caused a canal to overtop in the Imperial Irrigation District, inundating homes and streets in the town of Niland, California (Brown 2023).
- In July 2022, a canal breach in Wyoming’s Pathfinder Irrigation District flooded parts of the community of Lingle and adjacent farmland (Cook 2022).

The age and condition of existing lining and piping can vary significantly, ranging from recently completed construction to works that are decades old. As with earthen canals, failures in older lined or piped systems regularly occur. In June 2024, a century-old pipe known as the St. Mary siphon catastrophically failed. The siphon previously connected two canals across a valley in Montana’s Milk River Irrigation District. Flooding damaged lands administered by the Blackfeet Tribe, causing road closures and disruptions to water and electric utility services (Bureau of Reclamation 2024).

According to the Bureau of Reclamation, the canal and siphon provided 60 – 80 percent of the water used for irrigation and potable uses in northern Montana. Repairing the system is not cost effective relative to full replacement of the siphon, which is estimated to cost $70 million. Water delivery may be unavailable for a year or more during design and construction.

Figure 6. The St. Mary siphon failure resulted in erosion and flooding. According to the Milk River Joint Board of Control, the two pipes are each 7.5 feet in diameter and were transporting approximately 600 cubic feet of water per second. (Photo credit: Bureau of Reclamation)

There may be many reasons why the West's irrigation infrastructure remains largely unmodernized, including:

- According to the USDA ERS, only 1 percent of the population works in agriculture and most irrigation infrastructure is in rural areas. It may be that relatively few people regularly see or interact with this water delivery infrastructure, creating a limited understanding of the scope and scale of the challenge for the general population.
- Despite apparent challenges with aging infrastructure, irrigation water delivery organizations typically manage to keep the water flowing to agricultural producers. Operating systems, which can be past their expected service life, may mask underlying problems that result in larger, more catastrophic failures.
- As described further below, current modernization processes are slow and expensive, and existing federal funding sources, while extremely important, may not be appropriately scaled to address the challenge in a reasonable amount of time.

This report does not investigate these possibilities as root causes for the status of irrigation infrastructure and modernization efforts, but anecdotal examples may help underscore the challenge of cost, timing, and federal funding availability.

Figure 7. Large diameter pipe installation. (Photo credit: Central Oregon Irrigation District)

Irrigation districts within Oregon's Deschutes River Basin, an area experiencing long-term drought, deliver water through 840 miles of unlined canals. The districts are working on modernization projects with Farmers Conservation Alliance (FCA), an Oregon-based nonprofit organization that pursues water management solutions that benefit both agriculture and the environment in partnership with rural communities. The organization works with farmers, ranchers, and irrigation districts to modernize their irrigation systems (Farmers Conservation Alliance n.d.).

FCA identified over 550 cubic feet per second of water savings and 38MW of conduit hydropower potential associated with piping the irrigation districts in the Deschutes River Basin. The organization estimates that at the current pace of modernization, it could take approximately 50 years to fully pipe the area (Megan Christian, email correspondence, February 6, 2023). In 2018, FCA projected the total cost of modernization in the basin to be nearly $2 billion. This scale of need in one basin, which represents less than one half-of-one percent of the West's irrigation infrastructure, is illustrative of the funding challenges for irrigation improvements.

4.0 Estimated Annual Miles of Lining and Piping

4.1 Introduction

Canal lining and piping projects, including rehabilitation of aging systems, can reduce seepage and evaporation and offer the potential to save or generate energy. To estimate the potential costs and benefits associated with canal modernization, it is important to understand how much lining or piping is currently occurring annually, on average, across the 17 states in the West. With that understanding, it is then possible to estimate how benefits and costs might change if the pace of lining and piping were accelerated by a factor of two or three between 2024 to 2050.

Centralized data related to canal lining and piping projects is limited and there are many federal, state, and local actors that may fund, support, or implement projects. Funding programs that can support canal lining or piping may also support other water conservation activities, which adds complexity to the task of trying to build a picture of current project flow and outcomes.

There are at least six programs offered by the USDA Natural Resources Conservation Service (NRCS) and the U.S. Bureau of Reclamation that may provide support for different aspects of irrigation modernization:

- NRCS
  - Watershed and Flood Preventions Operations (WFPO)
  - Regional Conservation Partnership Program
  - Environmental Quality Incentives Program
- Bureau of Reclamation
  - WaterSMART Grants
  - Title XVI
  - Aging Infrastructure

Each of these programs supports a variety of project types, which can include canal lining and piping. Among these programs only WaterSMART provides centralized data from which the number of canal miles lined or piped can be extracted. FCA also provided data for this report, supplying the number of miles of canals that were piped in Oregon through funding provided by NRCS WFPO.

Projects may also receive funding from state programs or locally raised funds. State funding programs can change frequently. No attempt was made to gather data from states or the large number of individual irrigation water delivery organizations that may move forward with projects each year.

4.2 Methodology

To create an estimate of the average annual miles of canals lined or piped, publicly available WaterSMART Water and Energy Efficiency Grant (WEEG) data from 2015 through 2023 for the West was analyzed, along with data from FCA, representing completed and scheduled piping projects for the state of Oregon between 2017 and 2026.

WEEG data represent projects that have received funding, which does not necessarily translate to implementation or completion. Acknowledging this limitation, for the purposes of this estimate, the data was treated as representing completed projects. To prepare the WEEG data and ensure it only captured irrigation-related lining or piping projects, projects deemed out of scope were removed, including records containing “city”, “municipality”, or “town”; descriptions containing “commercial”, “industrial”, “residential”, or “turf”; and project titles listed as “metering” and “groundwater.” This filtering resulted in a total of 275 WEEG project records.

WEEG data showed variability each year across the number of projects awarded and the number of miles of lining or piping. In addition, WEEG awards are not uniformly distributed across the 17 Western states. Based on this analysis, WEEG appears to support 39.6 miles of piping and 9.7 miles of lining each year, on average.

FCA’s data included 46 project records between 2017 – 2026, with an average of 22.7 miles being piped each year in Oregon. FCA’s data on future years (2025 and 2026 during the research phase of this report) is based on projects under contract with established funding.

While additional data on lining and piping was not available from any centralized sources, anecdotal evidence was gathered from conversations with irrigation district managers in Oregon between 2010-2024. This anecdotal evidence suggests that the total amount of piping in Oregon each year has at least doubled in recent years and that Oregon may be an outlier in the amount of piping that is now occurring annually. This same anecdotal evidence suggests that more lining projects are likely installed than are reflected in the WEEG data.

Relying on this anecdotal evidence, several assumptions were made:

a) Oregon is assumed to be an outlier in the amount of pipe that is installed annually. Based on the increase in piping that has happened in recent years, other state piping amounts are estimated at one-half of what is currently installed annually in Oregon, on average.

b) New lining projects were assumed to be occurring in each state at two times the amount that is funded through WEEG.

Using these assumptions, the total piping in the West was initially estimated as follows:

	39.6 miles	(WEEG average)
	22.7 miles	(FCA average)
+	192.9 miles	(1/2 the FCA average times 17 states)
	255.2 miles	(15 miles per state if divided evenly across 17 states)

The total lining in the West was initially estimated in this way:

	9.7 miles	(WEEG average)
+	340.0 miles	(Two times the WEEG average (rounded to 20) times 17 states)
	349.7 miles	(20.6 miles per state if evenly divided across 17 states)

Recognizing that canal lining and piping projects are not evenly distributed across all states, prorated state estimates were created based on the calculated number of canal miles in each state. Using this method, under the current pace of modernization, approximately 11 percent of all canal miles would be modernized by 2050.

Given the small number of organizations from which data was available, the small sample size, and the resulting limited confidence in the accuracy of the initial estimates, the methodology was changed to better broadcast that the results are informed, yet rough approximations. Two changes were made: 1) the current pace of modernization though 2050 was estimated to result in 10 percent of canals being lined or piped and 2) the total amount of lining and piping was split evenly. The even split was assumed because there was not enough data to determine if the WEEG and FCA data are representative of the split between piping and lining projects and no additional data was available to suggest a more accurate split.

These changes yield an estimate of 570 miles of canals being either lined or piped each year (285 miles each) across the 17 Western states. It is then possible to pro-rate the number of miles modernized in each state based on that state's share of the total calculated canal miles. Using these numbers, the total number of miles that would be piped or lined in each state through 2050 were calculated, along with the total if the pace of project implementation were to double or triple over the same time period.

4.3 Results and Discussion

This report estimates that, at present, an average of 570 miles of canals may be lined or piped each year (285 miles each) across the 17 Western states. This is equivalent to ~0.4 percent of the total calculated miles of water conveyance infrastructure. Using the methodology described above, this report estimates that 10 percent of all canal miles would be modernized between 2024 – 2050. If the pace of modernization were to double or triple, this percentage would likewise increase to 20 percent or 30 percent.

Importantly, prorating the miles of lining and piping that may be occurring by the miles of agricultural water delivery infrastructure in each state may not be representative of what is currently happening in the field. Creating more robust estimates would require additional centralized data that does not appear to exist at this time or a significant data gathering project across many stakeholders to create such data. Nonetheless, these estimates create a starting place to better understand the current and potential future benefits associated with irrigation modernization projects.

Table 7. Pro-rated annual canal lining and piping estimates and the total estimated number of modernized miles through 2050.

State	Combined, pro-rated annual piping and lining (miles)	Total modernized miles in 2050		
		Current Pace	2X Current Pace	3X Current Pace
Arizona	23	598	1,196	1,794
California	141	3,666	7,332	10,997
Colorado	63.4	1,650	3,299	4,949
Idaho	48.8	1,269	2,539	3,808
Kansas	2.8	70	141	211
Montana	49.8	1,294	2,588	3,882
Nebraska	2.4	60	120	180
Nevada	17.6	460	920	1,380
New Mexico	19.2	497	994	1,491
North Dakota	3	78	157	235
Oklahoma	0.8	21	43	64
Oregon	37.2	966	1,932	2,897
South Dakota	3.8	97	195	292
Texas	73	1,900	3,801	5,701
Utah	27.2	707	1,414	2,122
Washington	20.2	525	1,051	1,576
Wyoming	37	960	1,920	2,880
Total miles	**570**	**14,820**	**29,640**	**44,460**

5.0 Water Conservation Potential Associated with Lining or Piping Open Canals

5.1 Introduction

Irrigated agriculture, including crop and livestock production, is estimated to account for approximately 80 percent of the nation's consumptive water use (Schaible and Aillery 2021). In 2018, approximately 47 percent of the surface water used for irrigation in the Western U.S. came from off-farm sources, typically delivered by entities like irrigation districts (USDA NASS 2018).

As noted in the introduction, irrigation water delivery organizations in the 17 Western U.S. states experience losses in water conveyance due to seepage and evaporation from unlined canals or those with failing lining or piping. Canal lining and piping projects can reduce or eliminate seepage and evaporation (Lund et al. 2023; Robinson 1963). In areas where seepage contributes to aquifer recharge goals, modernization may be able to support improved control over where and when recharge occurs (Miller et al., 2021, Nelson 2023). While modernization may not be desired in all areas due to regional priorities around groundwater recharge or other issues, eliminating water losses in conveyance due to seepage and evaporation appears to be a common driver behind irrigation modernization processes where they are occurring (Perkowski 2019).

Due to the complex, interconnected nature of surface and groundwater resources and their uses over different geographic scales, there is disagreement in the academic literature around how canal seepage and evaporation are characterized, including the word "loss" and whether avoiding seepage and evaporation can properly be described as "water conservation" opportunities (Grafton et al. 2018; Langford et al. 2020). This report acknowledges this debate and the importance of research in developing a scientific understanding of how changes in water conveyance, delivery, and use in irrigated agriculture can inform decision making in different localities and at different geographic scales.

In the interest of concise reading and alignment with the vernacular used by many resource agencies, this report describes both seepage and evaporation from agricultural water conveyances as "water losses" and "water conservation" opportunities. This section estimates how much conveyance loss is happening in irrigation systems and how much water conservation could be achieved, in acre-feet, through lining or piping open canals under current and accelerated scenarios through the year 2050.

5.2 Methodology

The water conservation potential calculations in this report rely on three inputs which are calculated for each state: estimated percentage of conveyance loss at high and low levels, conservation achieved annually currently and under accelerated scenarios, and water availability for irrigation using high, medium, and low ranges.

Self-reported data from the USDA ERS show conveyance losses by state, ranging from 13 – 25 percent (Potter 2023). Conveyance losses vary based on location-specific factors (Sonnichsen 1993). Recent research noted the potential for under reporting in self-reported conveyance losses (Hrozencik et al., 2022). This report assumes that the ERS numbers represent a lower end estimate for conveyance losses. To show a potential range of conveyance loss, assuming the self-reported values may be low, a high-end loss for each state of 10 percent greater than the USDA ERS reported loss amount was estimated. This is a simplification of complex topic: conveyances losses may vary for variety of reasons including canal water levels that are affected by water availability (Mutema and Dhavu 2022).

Water availability was calculated for high, medium, and low scenarios based on reviews of historical water use data from different years from “Estimated Quantity of Water Applied by Off-farm Surface Water Suppliers,” published by the USDA Census of Agriculture Farm and Ranch Irrigation Surveys for 1998, 2003, 2008, 2013, and 2018. A proxy for the total diversion amount was generated using the data for acre-feet applied on a state-by-state basis and adding back the estimated conveyance loss. This was calculated as:

$$Total\ acre\text{-}feet\ diverted = \frac{acre\text{-}feet\ applied}{(100 - (percentage\ conveyance\ loss\ \times\ 100))} \times 100$$

Total conveyance loss for each state, in acre-feet, was computed by subtracting the acre-feet applied from the calculated total acre-feet diverted. Each of these values were also summed to create totals for the 17 states.

Climate data from the 9-month Standardized Precipitation Index for each October was downloaded from National Oceanic and Atmospheric Administration’s National Integrated Drought Information System. October was selected because the preceding nine months represent the majority of the irrigation season for much of the Western U.S. Matching these two datasets together, the high, medium, and low scenarios for water availability were identified: 1998 represents a “wet” year with high water availability; 2003 represents a medium scenario where some areas are in drought while others are wetter than average; and 2008 represents a drought year with low water availability for a large portion of the Western U.S. It is important to note that drought or higher than average precipitation tends to be regional in nature and does not span the West evenly. The selected years represent an approximation of these larger precipitation swings. The scenarios for high and low loss were applied across the drought year, average year, and wet year to calculate the amount of water diverted, lost in conveyance, and ultimately applied on-farm.

There is limited publicly available centralized data related to the current amount of water conservation achieved annually. As noted in Section 4.0, many programs may fund off-farm modernization work as part of a broader project portfolio. Water conservation is one of the potential benefits that may be achieved in these programs, however, water conservation may not be reported if it is an ancillary benefit and not the primary goal. In addition, it is possible that water conservation may come from projects beyond off-farm modernization efforts.

DOI performance reports and the Bureau of Reclamation's WaterSMART WEEG program are two sources of publicly available water conservation data. In addition, FCA provided water conservation data related to the off-farm modernization projects it supports. As described below, these DOI, WaterSMART WEEG and FCA data were used to generate estimates of water conservation that may be occurring, but for which data are unavailable.

DOI performance reports were used to obtain data for annual water conservation in acre-feet from 2012 to 2021 (U.S. Department of Interior n.d.). Included in this are data from WaterSMART WEEG and other DOI programs, only some of which may create water conservation through off-farm modernization projects. WaterSMART WEEG reports water conservation data. By subtracting reported WaterSMART WEEG conservation figures from the totals reported in the DOI performance reports, the amount of conservation attributable to the other DOI programs can be calculated.

Using the WaterSMART Data Visualization Tool, data for the years 2015 – 2023 was downloaded (U.S. Bureau of Reclamation n.d.). Data from off-farm irrigation modernization projects was selected, including the total miles piped or lined, acre-feet of water conserved, energy savings, total project costs, and federal funding. Projects outside of off-farm irrigation modernization were eliminated by removing entities and project descriptions reflecting city, municipal, residential, industrial, commercial, turf, non-irrigation, reservoir lining, and groundwater projects. The year 2018 was removed as an outlier because there is little WaterSMART WEEG data for that year.

On average, over the analyzed time period, WaterSMART WEEG represents approximately 50 percent (54,000 acre-feet) of the total water conservation reported in the DOI performance reports (113,000 acre-feet). However, because the water conservation reported by DOI also includes programs focused on municipal and industrial projects, the remainder reported by DOI must be reduced. In the absence of additional data, this remainder was reduced by 50 percent to account for the prevalence of programs supporting water conservation from other types of projects. This yields an estimated average of approximately 83,500 acre-feet of water conservation achieved annually that can be attributed to off-farm irrigation modernization projects, within the DOI performance reports.

FCA provided data from 31 projects in the state of Oregon, paid for by the USDA’s WFPO program, where water conservation is measured. FCA is expecting to achieve approximately 8,000 acre-feet of water conservation annually in Oregon from 2022 – 2026 due to a funding influx from the Infrastructure Investment and Jobs Act (IIJA). As a frame of reference, if this same amount of water conservation were achieved equally in all 17 Western states, it would total 136,000 acre-feet annually.

There are additional federal and state programs where unreported water conservation may be achieved related to off-farm irrigation modernization projects. Based on reviews of project types in published Extraordinary Maintenance Report Tables, the Bureau of Reclamation’s Aging Infrastructure Program stands out as one such federal program. Other programs, as noted in Section 4.0, include USDA’s WFPO, RCPP, and EQIP programs, and the Bureau of Reclamations Title XVI program. State programs and individual irrigation organization actions that result in water conservation must also be accounted for in an estimate.

WaterSMART WEEG was used as a reference program to estimate the potential water conservation achieved by other programs. The limited data available means that this is a coarse estimate. The Aging Infrastructure Program had $500 million in funding in 2023 and appears likely to be funding projects that could result in a significant amount of water conservation. However, water conservation may only be achieved for a few years if long-term appropriations are not secured for the program. To smooth out the potential water conservation over time, the impact of the Aging Infrastructure Program was estimated at one half of the WaterSMART WEEG amount annually.

Other potential federal and state programs, and individual irrigation organization actions that could result in water conservation from off-farm irrigation modernization, were also estimated as one half of the WaterSMART amount annually. This estimate was based on a review of program descriptions and available data about common project types from the other federal programs noted above and a limited review of state programs that can support water conservation from off-farm irrigation modernization in California, Colorado, Montana, Oregon, and Washington. The federal programs do not appear to focus on water conservation from off-farm irrigation modernization projects. At the state level, programs appear to change more frequently over time and are typically more limited in the scale of projects they are able to support.

The total average annual water conversation from WaterSMART WEEG, the remaining DOI programs, and the estimates above were summed and then pro-rated across the states based on water applied in each state, resulting in a total estimate of 138,000 acre-feet annually, equivalent to the FCA average if it were scaled across the 17 states analyzed in this report.

Scaling the piping or lining of open canals could increase conservation benefits. Based on available lining and piping estimates per year, 2× and 3× conservation scenarios are considered for double or triple the pace of piping and lining until 2050.

Limitations

Data on water loss is extremely limited. As a result, conveyance losses may be underestimated, which in turn limits the amount of potentially achievable water conservation that can be calculated. Data on current annual water conservation being achieved is also very limited. The 2× and 3× accelerated scenarios assume that the piping and lining achieved will produce double or triple the water conservation—up to the maximum limit of the estimated conveyance loss in each state.

5.3 Results

In the identified “wet” year, 1998, an estimated 50 million acre-feet of surface water was diverted for agriculture in the Western U.S., relative to 38 million acre-feet diverted in the “dry” year, 2008. Importantly, this does not account for groundwater pumped for agricultural use.

Conveyance losses were estimated to range from 10 – 13 million acre-feet of the diverted water between the “dry” and “wet” years in the high loss scenario. This is equivalent to nearly half the volume of Lake Mead, the reservoir created by Hoover Dam (Stern et al. 2025). When calculated as an average based on totals for the 17 states, between the low loss and high loss scenarios, 16 – 26 percent of diverted water may be lost to seepage and evaporation.

Using data from the Department of the Interior, the U.S. Bureau of Reclamation, and FCA, an estimated 138,000 acre-feet of water may be conserved annually through existing modernization work and programs. If this pace of modernization were to continue through 2050, a total of 3.6 million acre-feet of water could be conserved, making it available for other beneficial agricultural and environmental uses. Scaling and accelerating the piping or lining of open canals could double or triple this benefit.

Figure 8. Estimated state surface water diversions and water loss during the representative 2008 “dry year” compared to pro-rated estimated annual water conservation achieved.

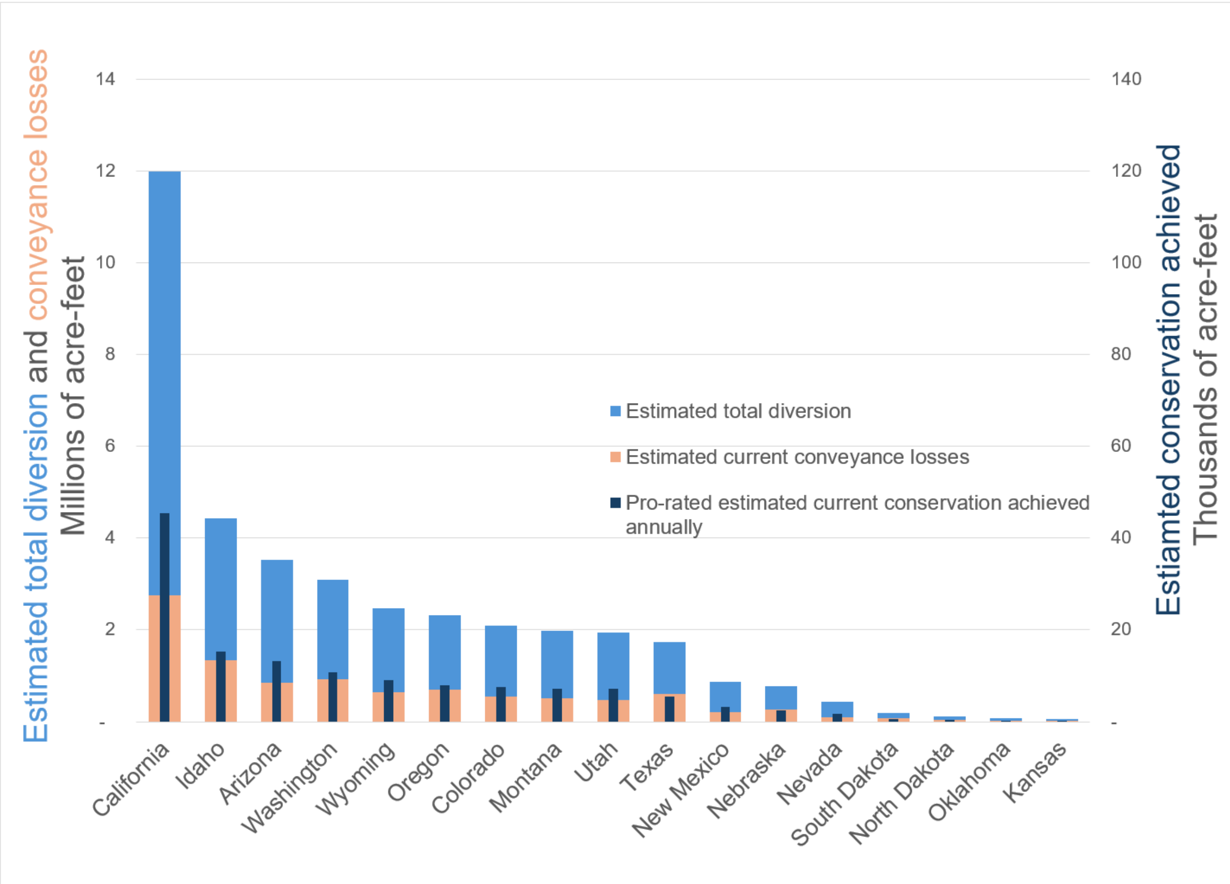


Table 8, below, represents the summary of estimated water conservation potential across the 17 Reclamation States. Based on the total water diversion in a wet, average, and drought year, these are divided into high loss and low loss scenarios across the three water availability scenarios. The total estimated conservation achieved by 2050 is also represented for the current, 2× and 3× accelerated conservation scenarios, with 10.76 million acre-ft conservation achieved across the country by 2050 for the most aggressive conservation.

Table 8. Summary of water loss, water conservation, and water availability estimates.

	High Loss (millions of acre-feet)			Low Loss (millions of acre-feet)		
Values	**Average Year**	**Drought Year**	**Wet Year**	**Average Year**	**Drought Year**	**Wet Year**
Sum of estimated total diversion	42.2	38.1	50.2	37.1	33.5	44.2
Sum of water applied	31.1	28.0	37.3	31.1	28.0	37.3
Sum of starting conveyance loss volume	11.1	10.1	12.9	6.0	5.5	6.9
Sum of total conservation achieved by 2050 at current conservation rate	3.6	3.6	3.6	3.6	3.6	3.6
Sum of 2× accelerated conservation	7.2	7.2	7.2	7.2	7.2	7.2
Sum of 3× accelerated conservation	10.8	10.8	10.8	10.8	10.8	10.8
Sum of water available in 2050 under current conservation rate	34.7	31.6	40.9	34.7	31.6	40.9
Sum of water available in 2050 under 2× accelerated conservation	38.3	35.2	44.5	36.8	33.4	43.5
Sum of water available in 2050 under 3× accelerated conservation	41.1	37.5	48.0	37.1	33.5	44.1

6.0 Economic Impacts from Irrigation Modernization

6.1 Economic Impacts from Irrigation Modernization Construction

6.1.1 Introduction

Nearly 75 percent of the nation's irrigated acres are concentrated in the 17 Western U.S. states and irrigated agriculture accounts for half of U.S. crop revenues (USDA 2018; Stubbs 2016). As noted earlier in this report, supplying water to produce these crop revenues requires a significant amount of infrastructure, comparable in scale to the U.S. highway system. When irrigation infrastructure is modernized, it drives increased spending on construction and repairs. This spending creates local economic benefits as materials are purchased, laborers are hired, and other local spending increases. If modernization were to accelerate, these economic impacts would also increase.

The input-output model IMPLAN—a widely used economic modeling software that estimates three different types of effects on the economy (IMPLAN n.d.)—was used to quantify the potential impact of modernizing irrigation infrastructure on the economy in the Reclamation States. The three effects estimated by IMPLAN are:

- Direct effects, or the spending directly input into the economy by an industry
- Indirect effects, or purchases by businesses to other businesses in the supply chain
- Induced effects, or the effect that spending from personal income has on different industries

Together, these effects give the overall economic impact that an event has in a region in one year. IMPLAN requires data on current spending patterns between industries and the regional make-up of businesses and industries. Importantly, input-output modeling offers a static view of the economy given the most recent year of data and does not reflect future changes in industries or regional patterns. Therefore, while results may reflect near-future economic impacts, extrapolating into longer-term future impacts may introduce more uncertainty.

6.1.2 Methodology

To understand the benefits of irrigation modernization on the regional economy of the Western U.S., the construction and maintenance spending in each Reclamation state was estimated using the current pace of irrigation system upgrades as well as 2× and 3× the current modernization rate.

In IMPLAN, the state-level spending on irrigation modernization was modeled as an industry output event for each of the 17 Reclamation States. One year of construction in each of these states was analyzed, with the assumption that subsequent years would see similar rates of construction, given the scenario (current pace, 2×, and 3×). IMPLAN industry events require the input of a dollar change in an industry's output. The software then uses regional dollar-flow data tables to calculate the direct, indirect, and induced effects and job impacts of that industry's output change on the regional economy.

6.1.2.1 Total Spending

Total spending on irrigation modernization was projected using the estimated canal miles modernized in each state as described in Section 4.0 using an assumed 50 percent, 35 percent, and 15 percent split between lining, plastic piping, and steel piping projects respectively. The estimated 50/50 split between piping and lining was continued from the estimates made in Section 5.0. The 35/15 split between plastic piping and steel piping was an assumption made based on the higher cost of steel relative to plastic pipes. A 50/50 split was assumed between plastic piping using polyvinyl chloride (PVC) and using high-density polyethylene. Using publicly available resources, such as environmental assessments and impact statements from 18 modernization projects from 2005 through 2023, an average cost per mile was calculated for each type of project (Table 9). These costs were adjusted to 2024 dollars using the average annual Consumer Price Index (U.S. Bureau of Labor Statistics 2024a). Canal mileage was broken down by project type and then multiplied by the per-mile costs of modernization for that type of project.

Table 9. Estimated average cost per mile by project type from 18 irrigation modernization projects (2005-2023)

Project Type	**Average cost per mile (2024 $)**
Steel piping	2,453,956
Canal Lining	2,191,205
Plastic piping average	1,592,960
PVC piping	*739,485*
HDPE piping	*2,446,435*

To find the total spending from 2024 to 2050, the net present value of the costs was calculated using a discount rate of 7 percent, with costs escalating annually at a rate of 4 percent. The escalation rate was chosen as the average between the producer price indices from the Bureau of Labor Statistics for plastics and concrete (U.S. Bureau of Labor Statistics 2024b; U.S. Bureau of Labor Statistics 2024c). The discount rate was selected after reviewing a study from Synapse Energy Economics, Inc. which estimated a discount rate of 5 – 8 percent for utilities (Borden 2023). The net present value was calculated using the following equation, where R is the total cost in period t, i is the discount rate, and n is the number of periods:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

6.1.2.2 IMPLAN Regional Economic Impact Modeling

To calculate regional impacts associated with irrigation modernization efforts, separate projects were created in IMPLAN for each western state. Calculations used IMPLAN's most recent data (2022) with a base dollar year of 2024. Each state's total spending on irrigation modernization was input as an industry output event using IMPLAN Industry 56, or "Construction of other new nonresidential structures," which includes the construction of new canals and irrigation pipelines. However, Industry 56 also reflects construction spending for many other purposes. To account for this, the IMPLAN default data was adjusted to better reflect irrigation modernization spending, as described below.

Within each state, the percentage of spending going towards different commodities is expressed as “Gross Absorption”. IMPLAN’s gross absorption rates for Industry 56 were adjusted to be more applicable for irrigation modernization by estimating the commodity spending as a percent of total project spending for eight different commodities (listed below) typically used in canal concrete/shotcrete lining, plastics piping, and steel piping. The historic project data noted above was used to find cost breakdowns.

These commodities included:

- Water systems (for pump stations)- Commodity Code 3049
- Other textiles (for geotextiles used in lining)- Commodity Code 3121
- Fabricated pipes- Commodity Code 3188
- Ready-Mix Concrete- Commodity Code 3204
- Steel wire (for fencing)- Commodity Code 3218
- Plastic pipes- Commodity Code 3258
- Engineering- Commodity Code 3457
- Management costs- Commodity Code 3469

IMPLAN contains data for each state’s regional supply coefficient, which is a measure of how much of a local supply of a commodity goes to solely local projects (IMPLAN 2017). The gross absorption rate was calculated as the product of the commodity spending and the regional supply coefficient using the following equation:

$$Gross\ absorption\ rate\ = \%\ spending\ on\ commodity \times regional\ supply\ coefficient$$

The results were input into IMPLAN.

6.1.3 Results

An estimated $1.15 billion in direct costs is spent per year on irrigation modernization projects in the 17 Reclamation States. Continuing the present pace of modernization through 2050 could cost an estimated $22 billion but would only modernize ten percent of the existing infrastructure. To modernize all remaining unlined canals (estimated at 95,000 miles in Section 3.0) at this pace would require 167 years. Tripling the speed of project implementation would reduce this time to 56 years. If all the estimated 95,000 miles of unlined canals were modernized in one year, it would cost an estimated $285 billion.

When reporting how construction of modernized irrigation systems affects GDP, the term “value added” is used, which is the total output without intermediate inputs or purchases of non-durable goods that are not related directly to the project (IMPLAN 2019). This value is comparable to GDP by sector.

The current pace of irrigation modernization construction supports an estimated 12,800 annual jobs and increases the Gross Domestic Product (GDP) of the regional economy by about $1.15 billion of added value through induced and indirect effects. Importantly, this means that each dollar spent on modernization projects adds an *additional* dollar of value to the regional economy. $1.15 billion is comparable to the entire GDP of Montana’s utilities sector in 2023 ($1.2 billion according to the U.S. Bureau of Economic Analysis). Doubling the pace of piping or lining of open canals would double the cost, while creating an estimated 25,500 annual jobs and adding an annual value of $2.3 billion to the regional economy. This would equate to nearly $30 billion in cumulative additional value relative to the current pace by 2050. At triple the pace, impacts on GDP are roughly tripled.

Table 10. Economic effects of irrigation modernization construction.

Current pace				
Impact	**Employment (Jobs)**	**Labor Income**	**Value Added**	**Output**
Direct	7,837	$539,693,848	$550,927,040	$1,148,059,801
Indirect	1,782	$158,963,388	$245,052,807	$525,536,652
Induced	3,149	$190,533,403	$355,945,172	$604,015,638
Total	12,768	$889,190,638	$1,151,925,020	$2,277,612,092
2× pace				
Impact	**Employment (Jobs)**	**Labor Income**	**Value Added**	**Output**
Direct	15,673	$1,079,387,695	$1,101,854,080	$2,296,119,603
Indirect	3,565	$317,926,776	$490,105,614	$1,051,073,304
Induced	6,298	$381,066,806	$711,890,344	$1,208,031,277
Total	25,536	$1,778,381,276	$2,303,850,039	$4,555,224,183

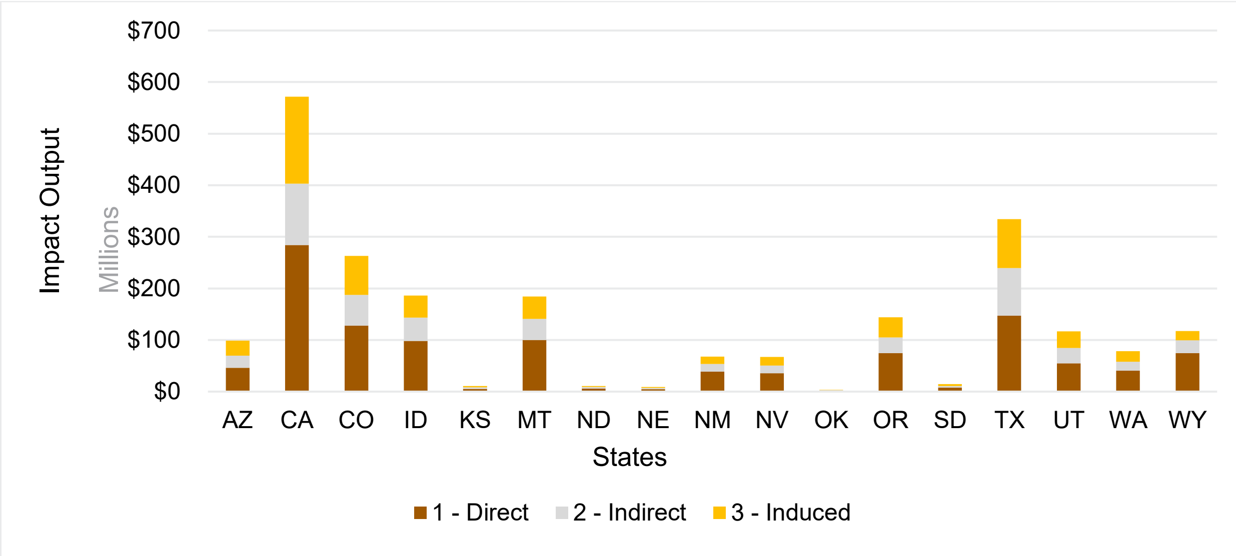
Direct impacts are the expenditures from modernization. Indirect impacts are the business-to-business purchases in the supply chain because of the initial expenditures and induced impacts are the effects of household spending.

The current rate of modernization supports an estimated 12,770 jobs per year with direct employment taking up 7,840 of those jobs; 1,780 of them from indirect impacts; and around 3,150 from induced sources. This equates to an average annual salary of $69,600 for each of these jobs, which is above the nationwide second quarter of 2024 median of $59,852 (U.S. Bureau of Labor Statistics 2024d). Results for double and triple the current pace of modernization roughly double and triple the number of added annual jobs, respectively.

Breaking down the indirect impacts by industry, the highest indirect impact is found in the ready-mix concrete industry, as canal lining requires a significant amount of concrete. Other affected industries include cement manufacturing, pipe and pipe fitting manufacturing, as well as sand and gravel mining. Induced impacts come from household spending. The highest induced impact comes from employees paying for housing.

Estimated state-by-state economic impacts vary, as shown in Figure 9. Though modernization was assumed to occur at the same rate across all these states, state-by-state canal mileage varies, as does the local share of industries producing construction materials that can be purchased by the projects. California sees the largest overall impact at over $570 million annually of added value from irrigation modernization, with a particularly large share from household spending due to earned labor income. Texas and Colorado see the next largest impacts at just over $330 million and $260 million annually, respectively. These states appear to lead in economic impacts due to the amount of canal mileage assumed to be updated annually, as well as the local share of production of construction materials and/or the cost of labor in these states.

Figure 9. Annual economic impacts of current irrigation modernization by state.



Legend: Direct impacts are the expenditures from modernization. Indirect impacts are the business-to-business purchases in the supply chain because of the initial expenditures. Induced impacts are the effects of household spending.

6.2 Estimated Economic Value of Crop Water Availability Impacts on Food Production

6.2.1 Introduction

Though only 1.2 percent of U.S. workers are employed by a farm, farming remains economically important, responsible for nearly $203 billion in U.S. GDP and 2.6 million jobs (USDA ERS 2024). Economic multiplier effects, the impacts that specific economic activities have on economic growth as a whole, create a total GDP contribution of roughly $1.5 trillion and over 22 million full and part-time jobs across agricultural and food sectors (USDA ERS 2024). According to the USDA ERS, approximately 20 percent of U.S. agricultural production is for the export market, making up 7 percent of all exports (U.S. International Trade Commission 2024). Irrigation is a key factor in agriculture's economic impact: only about 15 percent of agricultural lands are irrigated but they are responsible for approximately 40 percent of the country's agricultural production (Ruess et al. 2022).

Drought leads to serious declines in crop and livestock productivity. According to the National Integrated Drought Information System (NIDIS), drought costs the U.S. over $6 billion a year (NIDIS n.d.). The USDA ERS reports that drought conditions in the West in the summer of 2021 were particularly severe, exceeding all past droughts in the region since 2000. While recent years' drought conditions have improved somewhat, increases in high temperatures have made water even more critical to food production systems.

Water conservation projects implemented by irrigation water delivery organizations can reduce seepage and evaporative losses, increasing the reliability of water deliveries to agricultural producers. Improved water delivery reliability during times of drought may help reduce or avoid crop losses, potentially improving outcomes for jobs and economic productivity.

This section investigates potential changes in food production due to increased crop water availability because of water conservation achieved through irrigation infrastructure modernization. Conserved water can create a variety of uses and benefits that may differ based on annual water availability as well as local or regional needs and policies. Given this high degree of complexity, no attempt was made to estimate the broad impacts of water conservation over time across the West. Instead, this report looks at the potential benefit of increased water for one representative crop, alfalfa, across a sample of states and counties in one year. This effort was intended to provide an example of the potential benefits of water conservation that can result from piping or lining open canals to reduce water losses.

Alfalfa hay is a valuable, water-intensive crop with yields directly related to water availability (Klonsky et al. 2007; Orloff et al. 2015). According to the USDA ERS, in August 2021, approximately 52 percent of alfalfa hay acreage in the U.S. was in severe, extreme, or exceptional drought conditions. Alfalfa hay is an important feedstock for livestock and dairy operations. Decreases in alfalfa production affect production in these sectors, which in turn has impacts across other economic sectors.

6.2.2 Methodology

6.2.2.1 Tool Selection

To measure the potential impact of water availability on crop yield, the Food and Agriculture Organization crop-water productivity (WP) model, called AquaCrop, was used to measure crop yield response to water. AquaCrop requires a set of inputs, including climate, crop-type, irrigation and field management, and soil data. AquaCrop generates crop output in tons/hectare which were converted to tons/acre. One of the benefits of using AquaCrop is that all the data needed to run the scenarios investigated here could be found from publicly accessible sources. For example, current climate data, consisting of rainfall, minimum temperature, and maximum temperature, is available at the county level.

As seen in Table 11, simulations were run for one crop (alfalfa), five states (Arizona, California, Colorado, Idaho, and Washington), and 11 counties (Pima, Yuma, Merced, Tulare, Gunnison, Larimer, Mesa, Ada, Canyon, Grant, and Kittitas). The WP metric in AquaCrop was altered to reflect changes in assumed water availability. The default WP metric for alfalfa is 15 g/m^2. This default WP metric was used as the baseline scenario, which assumes no change in irrigation infrastructure. Additional scenarios were run to explore the current, 2×, and 3× modernization scenarios described earlier in this report. The WP metric for the current, 2×, and 3× scenarios were informed using the water conservation estimated in Section 5.0, which varies by state.

Once crop productivity changes were calculated, crop output data were used to calculate changes in county revenue for 2024 and 2050 for the different scenarios run, given current alfalfa acreage and prices. Lastly, the percentage change in revenue was used to inform a series of input-output economic analyses in IMPLAN to gauge the county-level economic growth from a change in crop yield. Economic parameters measured include employment and value added, where value added refers to GDP and represents the wealth generated from changes in agricultural activity.

Table 11. Overview of regions and crops identified for AquaCrop simulations

Crop	State	County
Alfalfa	Arizona	Pima
		Yuma
	California	Merced
		Tulare
	Colorado	Gunnison
		Larimer
		Mesa
	Idaho	Ada
		Canyon
	Washington	Grant
		Kittitas

6.2.2.2 Data

While the scope of this entire report covers the 17 Western U.S. states, the scope for this section was refined to cover only Arizona, California, Colorado, Idaho, and Washington. These states were chosen as representative examples of agricultural regions that have grappled with drought and water supply issues in recent years, and which may be affected by changes to water availability. From those states, Pima, Yuma, Merced, Tulare, Gunnison, Larimer, Mesa, Ada, Canyon, Grant, and Kittitas counties were selected as representative of important agriculturally productive areas within a state, or due to connection with long-term drought challenges, as have been experienced in the Colorado River Basin.

AquaCrop has a set of default data that exists within the application; however, additional climate data was collected to ensure the results accurately reflect the counties being assessed. County-level monthly average values for minimum temperature, maximum temperature, and precipitation for 2023 were downloaded from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information Climate at a Glance County Mapping application. Research for this report occurred in 2024, so 2023 was chosen as the base year to ensure a full year of climate data was available and to be consistent with other inputs.

AquaCrop has crop data for select major crops. Alfalfa was selected as the crop-type for this analysis because it is one of the top three crops for all the selected states, its yields are sensitive to water availability, and crop-type data for alfalfa is included in the AquaCrop application.

Using only one crop in these scenarios provides the ability to refine the amount of irrigation and field management data needed. Basin (also known as "flood") and sprinkler irrigation were selected as the main management types for alfalfa cultivation. These distinct on-farm water application methods have different water-use efficiency ratings. Individual agricultural producers may choose application methods based on the crop(s) grown, operational considerations, and many other local attributes, such as soils, topography, and seasonal water availability. A higher efficiency method is not necessarily "better" in all areas. However, where conversions to higher-efficiency water application methods make sense, there may be additional water conservation potential. Changing the management type in AquaCrop between basin and sprinkler enables this water conservation potential to be explored.

The default WP value of 15 g/m^2 was used for the baseline scenarios. Using the estimated water available in 2050, as calculated in Section 5.0, under current conservation, 2× accelerated conservation, and 3× accelerated conservation, the percentage difference in water availability was calculated and applied to the WP metric. It is important to note that the WP metric refers to all the ways water is managed and applied. Therefore, when only a single factor within WP is altered, the WP metric does not change significantly.

Lastly, soil data was selected based on the major land resource region in which the selected counties reside. For the selected counties, the soil type is either loam, sandy loam, silt loam, or clay loam.

AquaCrop produces several outputs; however, this report was primarily focused on tons/hectare (dry). The tons/hectare (dry) output was converted to tons/acre (dry) to estimate the change in crop yield. County yield estimates were derived and alfalfa price data from the U.S. Bureau of Labor Statistics was used to calculate changes in county revenue (in 2024 dollars). The change in agricultural output was then entered as an industry output event for Industry 10 “All Other Crop Farming” in IMPLAN for each county analyzed.

6.2.3 Results

If water conserved through current irrigation modernization efforts were directed exclusively to improve alfalfa hay yields in a few representative counties in five alfalfa-producing states, production could increase in these counties by an average of 7.3 percent. This added productivity could result in an increase of 1,050 annual jobs across these counties and $43.6 million of added annual economic activity by 2050. Additionally interpreted, the current pace of modernization driven by existing programs creates strong economic benefits.

This is merely an illustrative example, as water conservation could also be used to improve production of other irrigated crops or serve other local and regional needs, such as bolstering environmental flows in rivers and streams or groundwater recharge. Nonetheless, this example provides an estimate of the positive economic impacts that could be seen from agricultural productivity in these counties. Water conservation may also potentially reduce the need for food imports by enabling existing irrigated acreage to remain in production.

Table 12. Economic impacts of irrigation modernization on sprinkled alfalfa hay production.

Difference Between Baseline and Current Modernization Scenario, IMPLAN Analysis					
State	**County**	**Increased Tons/Acre (Dry)**	**Increased Revenue (2050 dollars)**	**Increased Number of Jobs**	**Total Additional Value Added**
Arizona	Pima	0.61	$ 2,146,077	89	$ 780,569
	Yuma	0.75	$ 19,763,903	109	$ 6,941,009
California	Merced	0.64	$ 25,910,213	174	$ 9,285,100
	Tulare	0.58	$ 17,835,221	124	$ 6,411,054
Colorado	Gunnison	0.23	$ 3,933,450	31	$ 824,323
	Larimer	0.29	$ 4,315,962	77	$ 1,181,615
	Mesa	0.33	$ 5,132,554	145	$ 1,439,536
Idaho	Ada	0.38	$ 2,159,717	32	$ 911,488
	Canyon	0.45	$ 9,825,851	53	$ 3,245,620
Washington	Grant	0.38	$ 28,766,377	120	$ 10,231,052
	Kittitas	0.36	$ 6,518,031	96	$ 2,365,915

6.2.3.1 AquaCrop Results

AquaCrop analyses indicate that an increase in WP, based on increased water availability, should result in an increase in crop yield across all states, counties, and irrigation practices. The largest increase in crop yield was found in the difference between the baseline and current modernization scenarios. This indicates that the current rate of irrigation modernization has a positive impact on crop yield. It is worth noting that the differences in the 2× and 3× acceleration scenarios roughly reflect diminishing marginal returns. This trend of diminishing marginal returns in crop productivity per acre may represent the upper limits of production on existing acres, which were held constant in this analysis.

6.2.3.2 IMPLAN Results

For sprinkler irrigation, shifting from baseline WP to the productivity at the current pace of modernization increases GDP in the modelled counties by an estimated $44 million. This change is by approximately $31 million in direct impacts, and $6.2 million from both indirect and induced impacts as both business-to-business and household spending increase. This change also causes an increase of 1,050 jobs in the 11 counties studied. When going from the baseline to double the pace of modernization, the difference is even higher: GDP increases by $50 million from $36 million, $7.1 million, and $7.1 million in direct, indirect, and induced impacts, creating 1,214 jobs. Comparing the current pace of modernization to a doubling of the rate increases GDP by $6.5 million from $4.6 million in direct impacts, and $970,000 each in indirect and induced impacts.

Basin irrigation yields similar but slightly smaller results. Shifting from baseline WP to the productivity at the current pace of modernization increases GDP in the modelled counties by an estimated $41 million.

The AquaCrop analyses of agricultural output from basin versus sprinkler irrigation methods showed small or no differences for most counties but larger differences for Ada, Grant, and

Merced counties (shown in Table 13 and Table 14). AquaCrop's main inputs include average minimum and maximum temperatures, precipitation levels, and soil type. Compared to the other counties studied, in Ada, Grant, and Merced counties, temperatures are higher, precipitation is lower, and the soil type drains more quickly. This suggests that places that are hotter, drier, or have quickly draining soils may be most sensitive to changes in water availability.

Table 13. IMPLAN results for sprinkler irrigation

SPRINKLER						
	Baseline-Current		Baseline-2x		Current-2x	
County	**Employment**	**Value Added**	**Employment**	**Value Added**	**Employment**	**Value Added**
Pima	89	$ 780,569	106	$ 922,537	16	$ 141,969
Yuma	109	$ 6,941,009	129	$ 8,211,529	20	$ 1,270,519
Merced	174	$ 9,285,100	190	$ 10,128,128	16	$ 843,028
Tulare	124	$ 6,411,054	135	$ 6,991,830	11	$ 580,777
Gunnison	31	$ 824,323	36	$ 973,262	6	$ 148,939
Larimer	77	$ 1,181,615	91	$ 1,395,543	14	$ 213,928
Mesa	145	$ 1,439,536	172	$ 1,702,377	27	$ 262,841
Ada	32	$ 911,488	38	$ 1,076,946	6	$ 165,458
Canyon	53	$ 3,245,620	62	$ 3,835,466	10	$ 589,846
Grant	120	$ 10,231,052	142	$ 12,086,253	22	$ 1,855,201
Kittitas	96	$ 2,365,915	113	$ 2,797,767	18	$ 431,852
TOTAL	1050	$ 43,617,279	1214	$ 50,121,637	164	$ 6,504,358

Table 14. IMPLAN results for basin irrigation

	BASIN					
	Baseline-Current		Baseline-2x		Current-2x	
County	**Employment**	**Value Added**	**Employment**	**Value Added**	**Employment**	**Value Added**
Pima	89	$ 780,569	106	$ 922,537	16	$ 141,969
Yuma	108	$ 6,866,052	128	$ 8,136,572	20	$ 1,270,519
Merced	231	$ 12,303,494	247	$ 13,146,522	16	$ 843,028
Tulare	124	$ 6,411,054	135	$ 6,991,830	11	$ 580,777
Gunnison	30	$ 812,526	36	$ 961,464	6	$ 148,939
Larimer	77	$ 1,181,615	91	$ 1,395,543	14	$ 213,928
Mesa	145	$ 1,439,536	172	$ 1,702,377	27	$ 262,841
Ada	2	$ 46,994	9	$ 245,739	7	$ 198,745
Canyon	53	$ 3,272,031	62	$ 3,861,877	10	$ 589,846
Grant	60	$ 5,126,503	84	$ 7,168,323	24	$ 2,041,819
Kittitas	96	$ 2,365,915	113	$ 2,797,767	18	$ 431,852
TOTAL	1015	$ 40,606,288	1183	$ 47,330,552	167	$ 6,724,263

7.0 Estimated Energy Use and Energy Generation Potential

Energy use is integral to irrigated agriculture in the West and substantial energy is required to pump surface and groundwater for on-farm application (Mongird 2023). Opportunities for energy generation also exist within agricultural water storage and delivery infrastructure, such as conduit hydropower capturing surplus energy from the flow of water through irrigation canals and pipes. Energy generation opportunities may help irrigation organizations offset their energy use and costs.

Energy costs and revenue generation opportunities can be key drivers in modernization projects pursued by irrigation water delivery organizations. A broader understanding of energy use, conservation, and generation opportunities within irrigation infrastructure supports federal and state agencies and other stakeholders to contextualize local or regional projects against state or national indicators or goals.

This section expands upon the work of prior researchers to:

1. Explore the electricity use associated with surface water pumping.
2. Review and attempt to validate previous estimates of agricultural conduit hydropower potential.

7.1 Estimated Energy Use in Surface Water Pumping

7.1.1 Introduction

Irrigated agriculture in the West is enabled in part by the pumping of surface and groundwater. Water pumping occurs in a variety of situations and by different actors to transport water to the desired location:

- Individual agricultural producers may pump water to irrigate crops, water livestock, provide frost protection, and other uses. This pumping often occurs from streams reservoirs, canals, or groundwater.
- Irrigation water delivery organizations may lift or push groundwater or surface water from streams, reservoirs, or canals to raise it to the elevation of the delivery infrastructure (canals or pipes), overcome a landscape feature, or pressurize a system.

Prior research estimated total energy use for agricultural pumping in 2018 at over 60,000 GWh, including 37,500 GWh of electricity use (Sowby and Dicataldo 2022). The U.S. Energy Information Administration (EIA) provides annual historical average retail electricity prices (EIA n.d.). Based on the EIA national average rate of 6.92 cents per kWh for industrial customers in 2018, the estimated electric energy used for pumping would have cost nearly $2.6 billion.

This section describes the estimation of total on- and off-farm energy use related to surface water pumping. These estimates only account for energy savings associated with electricity use. This is a simplification: USDA pumping cost data show significant uses of non-electric energy sources, such as diesel and natural gas, to pump both surface and ground water.

7.1.2 Methodology

To estimate the electricity use associated with surface water pumping in the Western U.S., the methodology developed and published in “The energy footprint of U.S. irrigation: A first estimate from open data” was used, with some minor exceptions noted below (Sowby and Dicataldo 2022). This methodology relies on deriving energy usage from pumping cost data available in the USDA’s *2018 Irrigation and Water Management Survey* (known as the *Farm and Ranch Irrigation Survey* in prior years).

On-farm electricity expenses are available from the USDA data. These are converted to on-farm electrical energy usage using the average 2018 retail price per kWh of industrial electricity from EIA data. The methodology in this report differs slightly from the 2022 study by using state average electricity rate data rather than the national average. The USDA data only accounts for energy use from on-farm pumping. Off-farm pump energy therefore must be estimated by indirect methods. The 2022 study used data from estimates of irrigation pump electricity use in California, which indicates that 72.6 percent of pump energy use was on-farm and the rest was off-farm (Burt et al. 2003). Unfortunately, similar data does not exist for other states. As the 2022 study did, and noting the inherent limitations of this assumption, this factor was extended to all the states studied, dividing the on-farm electricity use in each state by 0.726 to get the total electricity use.

The USDA Irrigation and Water Management Survey Table 13 provides data on electricity expenses per acre and total acres where surface water is applied in the open. Table 4 breaks down the total water applied in acre-feet between groundwater, on-farm surface water, and surface water from off-farm sources. Using these data, the energy costs that could be attributed to on-farm pumping of off-farm surface water sources were calculated. The total electricity use was calculated by adding the on-farm pump electricity use to the previously calculated off-farm pump electricity use.

7.1.3 Results

In the Western U.S., an estimated 12,000 GWh of electricity was used to pump surface water from off-farm sources for irrigation delivery to crops in 2018 at a cost of over $900 million. This was approximately 42 percent of all electricity used for pumping in the West, out of a total calculated 28,000 GWh and a cost of $2.2 billion. Based on the USDA data, ground water makes up only 44% of the water applied on-farm but represents approximately 58% of the energy use and cost.

Of the 12,000 GWh estimated to be used in pumping surface water, 65% (7,800 GWh) is estimated to be attributed to off-farm pumping done by irrigation water delivery organizations and 35% (4,200 GWh) is estimated to be from on-farm pumping of off-farm surface water. This is an interesting finding, but it is limited by the underlying proportional scaling from on-farm energy use discussed in the methodology. Research to produce additional off-farm pump energy use data could refine these results.

7.1.4 Discussion: Energy Savings from Piping and Case Study Examples

Modernizing off-farm water delivery infrastructure can create opportunities to reduce or eliminate surface water pumping requirements. Canals use gravity to move water past farms. Piping open canal systems allows gravity to partially or fully pressurize the water supply. The amount of pressure available depends on the elevation change in the system: larger elevation

Figure 10. An array of modern on-farm pumps, powered with variable frequency drives, on a lateral in the North Side Canal Company near Jerome, Idaho. Photo credit: Camilo Jose Bastidas Pacheco | Idaho National Laboratory.

changes can create more pressure. Depending on the level of pressure that is created, there may be opportunities to reduce or eliminate pumping and its associated energy use and cost. Not all on-farm electricity is a candidate for conservation via canal pressurization. Piping canals only reduces the electricity used in pumping surface water delivered from off-farm water sources. If surplus pressure is created beyond what is needed to supply agricultural producers, hydropower may be possible. However, piping does not always result in energy savings or hydropower potential. Examples from three irrigation districts in Oregon are presented below to show the range of potential outcomes that may be possible. Future research could explore quantifying the potential energy savings associated with piping and pressurization.

The Three Sisters Irrigation District (TSID) near Sisters, Oregon, delivers water from Whychus Creek to 196 farms on more than 7,500 irrigated acres in the Deschutes River Basin in central Oregon. In the late 1990's, TSID began modernizing their system. Through personal communications in May 2024, the former TSID manager reported that the district fully piped 64 miles of canals over a 26-year period. The piping effort eliminated seepage, enabled 32 cubic feet per second of water to be permanently restored in-stream in Whychus Creek, and improved water supply reliability for the agricultural producers served by the system. The new pipelines pressurized the district's water delivery system, eliminating the need for on-farm pumps and reducing energy use by 9,000 MWh annually. The pressurized pipelines also created multiple opportunities for hydropower production. Between 2014 – 2022, the district installed three powerhouses at the inlets to re-regulation reservoirs. Together, TSID's hydropower facilities can generate 1.2 MW of power with revenues used to pay back loans that helped finance the piping projects.

Alternatively, modernization projects may shift pumping from producers to water delivery organizations, or pumping may increase.

The Farmers Irrigation District in Hood River, Oregon, has nearly completed replacement of their open canals with pressurized pipes. In most of the district, gravity fully pressurizes the water lines. In one zone, however, gravity pressure was insufficient to pressurize the water supply. The district chose to install a centralized pumping station using highly efficient pumps operated with variable frequency drives. Installation of an efficient district-owned pump station enabled the removal of all remaining on-farm pumps in the district. In total, the district estimates energy savings of 1,450 MWh annually from eliminating individual on-farm pumps (Energy Trust of Oregon n.d.; Perkins 2013).

In contrast, the Ochoco Irrigation District near Prineville, Oregon is adding a pumping station and increasing energy use as part of a modernization project that will restore streamflow in McKay Creek and support the reintroduction of steelhead in the area (Central Oregon Daily News 2023). The district is constructing a pipeline and pump station to deliver water stored in a reservoir to agricultural producers. This will enable water to be left in McKay Creek but will also add a new electrical load and cost for the district.

7.2 Comparison and Validation of Estimated Irrigation Conduit Hydropower Potential

7.2.1 Introduction

Irrigation canals commonly use gravity to move water for delivery to agricultural producers. In areas with significant elevation relief, replacing open irrigation conveyances with pipes can enable gravity to partially or fully pressurize the water supply. Where surplus pressure exists in a piped system, it may be necessary to install a pressure reducing valve (PRV) to regulate pressures to desired levels and avoid phenomena like cavitation. Alternatively, conduit hydropower can be deployed to provide the same pressure reducing function while producing electricity. Common sites where conduit hydropower potential may exist in agricultural water delivery systems include drop structures, regulation reservoir inlets, long, piped stretches where pressures rise, and farm turnouts.

The hydropower potential associated with irrigation canals has been calculated using two notable methodologies at different scales in the U.S. Oak Ridge National Laboratory (ORNL) estimated this potential across the U.S. (Kao et al. 2022) while FCA estimated it for the state of Oregon (Farmers Conservation Alliance 2020). Both FCA and ORNL conclude that conduit hydropower projects are underdeveloped in the U.S. This section compares these two approaches to evaluate their similarities and differences with the goal of evaluating the accuracy of ORNL's estimates and their utility for understanding irrigation conduit hydropower potential across the Western U.S.

7.2.2 Methodology

ORNL produced a novel assessment of the potential for hydropower development on existing water conduits across the U.S. ORNL's assessment includes irrigation canals and ditches, pipes in municipal and industrial water and wastewater systems, and cooling water discharge pipes at thermoelectric power stations.

Figure 11. Piped delivery point where surplus pressure could produce hydropower. (Photo credit: Energy Trust of Oregon)

The ORNL assessment analyzed satellite imagery, topography, and existing datasets to develop a method for identifying existing canal drop sites and estimating their hydraulic head and annual water flows. Data sources include the Bureau of Reclamation's 2011 and 2012 canal resource assessment, imagery from the National Agriculture Imagery Program and Sentinel-2, national elevation and high-resolution flow line datasets from the U.S. Geological Survey, and an ORNL-created dataset on existing hydropower assets. The study focused on the 17 Western U.S. states in its assessment of the hydropower potential of irrigation canal systems.

A commercial drop-detection machine learning model was developed to identify canal drop locations with National Agriculture Imagery Program imagery paired with canal resource assessment data used for training the model. Equations were used to estimate the potential capacity and energy at each identified canal drop location, and remote sensing images were used to estimate the portion of the year when the canal has water flowing through it. Flow rate and duration were estimated based on simplified canal geometry and satellite imagery. Capacity and generation estimates were aggregated to the county and state levels to produce the overall estimates (Kao et al. 2023).

By comparison, FCA's method aggregated the hydropower potential identified during the development of 15 individual irrigation district modernization models representing approximately 34 percent of the agricultural acreage irrigated with off-farm water in Oregon. FCA's study, while not comprehensive, included many of the largest irrigation districts in the state. For each district, FCA used measured elevations and historical flow data as part of their process to build a digital model of a completely piped and pressurized system. The digital model identified locations where a PRV would be required to maintain optimal water delivery pressures. FCA estimated the power capacity and potential energy generation available at each PRV site using a standardized procedure.

FCA used district-provided data on historical daily flows or monthly average flow estimates. Where daily flows equaled or exceeded 30 percent of a turbine's expected design flow, FCA's methodology assumed the turbine will operate at full capacity. Below that level, FCA assumes the turbine will not operate. The total energy generated is estimated by summing the generation from each day of turbine operation day during the irrigation season. The baseline assumptions used in FCA's methodology include a completely piped and pressurized system and a total system efficiency of 75 percent. FCA does not consider sites with a power capacity of less than 5kW.

Methodological Differences

A key difference between the ORNL and FCA methodologies are the data sources utilized. The ORNL methodology used remote sensing imagery and a commercial drop-detection model driven by machine learning. Detailed canal characteristics were not used because these are not known at the state, regional, or national scales. Unlike the ORNL "Conduit Hydropower

Assessment", the FCA methodology does not rely on drop structures and estimated flows. FCA used known canal flow data to calculate generation potential for a smaller sample of agricultural canals.

Due to a lack of comprehensive national data, the ORNL assessment estimated the canal width, slope, elevation change, and segment length. These were input into Manning's equation to estimate flow velocity (ft/s) and discharge (ft^3/s). Satellite imagery data were used to calculate the length of time when water flows in the canal, which was validated via a comparison to data from multiple regions for canal flow. These flow estimates were then used for power and energy estimates.

By comparison, FCA used measured elevation and district supplied historical or estimated flow data to estimate potential hydropower capacity and generation. FCA also used district supplied data for the length of the irrigation season.

ORNL Limitations

Since the ORNL study assessed conduit hydropower potential across the Western U.S. and could only rely on limited data at that scale, several key assumptions were required. The feature detection approach used in the ORNL assessment to detect canal drops may exclude some suitable canal drop sites and cannot evaluate the hydropower potential associated with piping longer canal runs with steady elevation change. The ORNL study does not provide site-specific generation or cost estimates. Conventional rainfall-runoff models cannot be used to simulate canal flow, limiting the ability to estimate canal flow. The ORNL report acknowledges that this methodology may underestimate the full potential of conduit hydropower because it considers only gravitational head potential at drop structures and not the potential for excess head that could be generated during piping. The report notes that it is intended to represent a conservative analysis of hydropower potential for agricultural irrigation conduits.

FCA Limitations

The main limitation of the FCA study is that it only covers approximately 34 percent of the acres irrigated with off-farm water delivery in Oregon. Though not representative of the whole state, FCA's highly specific methodology could uncover more sites with conduit hydropower potential if it were applied more widely. However, the FCA methodology is time consuming and the results are limited to each individual agricultural water delivery organization.

7.2.3 Results

The approaches used by ORNL and FCA yield similar results for hydropower capacity in Oregon. ORNL estimated Oregon's hydropower capacity potential at 51.9 MW, which includes 19.3 MW identified by the U.S. Bureau of Reclamation in 2012 and 32.6 MW of new potential identified using the remote sensing-based method described above. Through their assessment of irrigation districts in Oregon, FCA identified a total hydropower capacity potential of 32.9 MW, which is similar in scale to the ORNL findings given the limitations and differences between the two studies.

Figure 12. Marc Thalacker, former manager of the Three Sisters Irrigation District in Central Oregon, stands in front of the district's 700 kW Watson Hydropower Facility after installation in 2014. (Photo Credit: Energy Trust of Oregon)

ORNL identified 182 canal drop sites in Oregon. Flow durations ranged from 2 months to 11.5 months, with an average of 9.1 months. Efficiency ranged from 72 percent to 86 percent, with an average of 75.4 percent.

FCA identified 101 potential hydroelectric sites with a combined total capacity of 31 MW. Of these, 68 sites had a power capacity between 5 to 100 kW, with a total capacity of 1.9 MW. FCA further identified 33 sites with power capacities greater than 100 kW, with a total capacity of 31 MW. The capacity potential identified by FCA is 64 percent of the ORNL estimate.

The ORNL and FCA approaches differed in their energy generation estimates for Oregon. The ORNL assessment estimated the energy generation potential for Oregon as 329.2 GWh/year. By comparison, FCA found that the energy generation potential for the sites they evaluated was 120.8 GWh/year, 37 percent of the ORNL estimate. The difference in generation estimates may be due to ORNL's use of estimated flows relative to FCA's district-supplied flow information. ORNL's methodology used sophisticated desktop measurements to determine canal flow capacity. This canal flow capacity was then assumed to occur for all months where satellite imagery showed water in the canal. In many irrigation systems in the West, however, canal flows may follow more of a curve, ramping up to peak flows during the hottest months and then ramping back down to the end of the season. By comparison, FCA's method of eliminating generation below 30 percent of a turbine's design flow could yield a more conservative result.

The FCA approach appears to validate the ORNL capacity estimates for Oregon and suggests that the ORNL methodology produced reasonable estimates of irrigation conduit hydropower capacity across the West. The two studies differ in their estimates of annual energy generation, suggesting further refinement may be needed.

8.0 Conclusion

Irrigated agriculture in the West is a critical part of the U.S. food system and is made possible through the infrastructure that moves water from its point of diversion to the producers who grow food and raise livestock. This report creates a set of baseline attributes to better understand the scale and some of the potential needs and opportunities present in this water delivery system. Due to a lack of centralized data, many assumptions were layered to develop these results. These assumptions limit the absolute accuracy of the calculations herein but allow for reasonable ballpark estimates that enable consideration of the challenges and opportunities associated with modernizing irrigation water delivery infrastructure. There is also ample potential to build on this work, increase the available data, and refine the results of this report. Future research could explore topics such as the amount of federal, state, and private funding that is spent on modernization annually or the energy savings potential associated with piping projects where gravity partially or fully pressurizes water deliveries, reducing pumping.

The findings in this report show that irrigation infrastructure in the Western U.S. is comparable in size to the National Highway System. Most irrigation conveyances are unlined earthen canals, more equivalent to a two-lane dirt road than a modern freeway. At the present pace, this report estimates that only 10 percent of irrigation infrastructure will be modernized past the baseline between 2024 – 2050.

Though the scale of irrigation water delivery infrastructure presents a significant challenge, the opportunities and benefits associated with its modernization are equally large. The water savings which could be achieved through canal lining and piping could increase agricultural resilience against drought while saving energy and creating new energy generation opportunities. Modernization projects also bring very real economic benefits within and beyond agriculture, with each dollar spent creating a new dollar in added value in the regional economy.

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